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1 **An Investigation into the railway ballast dielectric properties using different GPR antennas and**
2 **frequency systems**

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11
12 **Abstract**

13 This paper presents an investigation into the relative dielectric permittivity of railway ballast using ground-
14 penetrating radar (GPR). To this effect, experimental tests are carried out using a container (methacrylate
15 material) of the $1.5 \times 1.5 \times 0.5$ m dimensions. GPR systems equipped with different ground-coupled and air-
16 coupled antennas and central frequencies of 600 MHz, 1000 MHz, 1600 MHz and 2000 MHz (standard and
17 low-powered antenna systems) are used for testing purpose. Several processing methods are applied to assess
18 and compare the dielectric permittivity of the ballast system under investigation. Comparison of results
19 identifies critical factors as well as antennas and central frequencies most suitable for the purpose.

20

21 **Keywords:** Ground-penetrating radar (GPR); Railway ballast; Non-destructive testing; Antenna frequency;
22 Antenna systems; Relative dielectric permittivity.

23

24 1. INTRODUCTION

25 The use of ballast aggregates for the construction of railroads is massive in railway engineering and the
26 effective assessment and health monitoring of their geometric, physical and mechanical properties is an issue
27 of major concern in terms of safety of the operations and costs of of the rail asset management. The railway
28 ballast usually consists of coarse aggregates with a relatively uniform grain size that are produced from crushed
29 rocks, such as gravel, limestone, basalt or granite. Among the most important structural and functional tasks
30 covered by the ballast aggregates, it can be cited i) the resistance to the vertical, lateral and longitudinal loads
31 exerted on the sleepers; ii) the reduction of the maximum stress from the sleepers area to a minor stress level
32 at the foundation and iii) the improvement of the water drainage across the whole track bed structure [1].

33 A track bed structure is made by a substructure (ballast, sub-ballast and subgrade), which lies underneath a
34 superstructure (steel rails, fastening systems and sleepers). The cyclic loading exerted by the moving trains
35 affects both of these main structural components, although the ballast and the sub-ballast layers are the
36 structural components that are subject to the major deformations. This occurrence may cause potential
37 segregation of the aggregates and the loss of the designed strength conditions.

38 The design thickness of a ballast and sub-ballast system ranges between 0.45 m and 0.75 m. These two layers
39 can be found together in new and rehabilitated rail lines, whereas old rail infrastructures are mostly composed
40 of only one layer of ballast above the subgrade [2]. Furthermore, new railroads are provided with a concrete
41 slab or a geotextile at the sub-ballast – subgrade interface. On the contrary, these protective systems are absent
42 from the oldest railways. This may be a serious concern in terms of the upward passage of the smallest clayey
43 and silty particles from the subgrade by capillary actions. The progressive filling of the inter-particle voids
44 within the ballast/sub-ballast layer by fine-grained materials may undermine the strength mechanisms between
45 the aggregate particles. This occurrence is known as “fouling” and it can be due to several causes, as discussed
46 by Selig et al. [3]. Mostly, the fouling occurrence may imply safety issues, such as the instability of the track,
47 hence, it may lead to potential derailment of trains.

48 Visual inspections, punctual drillings and diggings are the traditional methods used for the monitoring and the
49 assessment of ballast, all of which are performed at discrete intervals along the track. To this effect, it is worth
50 mentioning the impossibility to interpret the causes of damage when using these techniques, if the causes are
51 related to subsurface factors. In addition, it is impossible to provide continuous monitoring of the track

52 conditions. These methods are also time-consuming and labor-intensive, although they can provide very
53 accurate information [4].

54 In view of the above, it is crucial to ensure the effective monitoring of the ballast aggregates as well as the
55 early-stage detection of the main causes of damage in the construction, quality control and maintenance phases.
56 This allows to optimise the maintenance expenses as well as to maintain the track stability and the desirable
57 safety conditions.

58 The recent trend in railway engineering is to focus on the use of non-destructive testing (NDT) methods in
59 order to perform rapid and non-intrusive inspections of the track bed. Within these methods, the optical-based
60 two-dimensional (2-D) [5] and three-dimensional (3-D) [6] laser scanners and, mostly, the ground-penetrating
61 radar (GPR) are worthy of mention. The GPR geophysical inspection tool is used in a wide range of application
62 fields such as in planetary sciences [7], civil and environmental engineering [8], geology [9] and archaeology
63 [10], forensics and public safety [11]. In the area of transport engineering, GPR has been used mostly in:
64 highway engineering [12], for the inspection of flexible (both bound [13 – 16] and unbound [17 – 19] layers)
65 and concrete [20] pavements as well as in the monitoring of the subgrade soils [21, 22]. Applications of GPR
66 can be also found in airfield engineering [23] and for the monitoring of critical infrastructures, such as bridges
67 [24], [25] and tunnels [26].

68 The use of GPR in railway engineering has increased over the past 25 years. According to Roberts et al. [27],
69 the first attempt of using GPR for the investigation of railways can be dated back to 1985 [28]. This study
70 involved the use of ground-coupled antenna systems of 500 MHz central frequency mounted between the rails.
71 The authors reported difficulties with the interpretation of the results due to the low resolution of the collected
72 GPR scans. The use of higher investigation frequencies and air-coupled radar systems (mostly of 1000 MHz
73 [29, 30]) has increased in the years following. Air-coupled antennas with a central frequency of 2000 MHz are
74 being used more recently, and innovative frequency-based approaches have been developed accordingly [2,
75 31].

76 With regard to the assessment of the dielectric properties of the ballast aggregates, several studies can be
77 mentioned. Clark et al. [1] performed a set of experiments in the laboratory environment to evaluate the
78 dielectric properties of the ballast for a combination of dry/wet and clean/spent conditions. The authors argued
79 that the best results may be achieved using low-frequency antennas. Sussman et al. [32] showed the importance

80 of the mineralogy of the ballast aggregates in interpreting their electromagnetic (EM) behaviour. Nevertheless,
81 the authors emphasized also the relevance of the aggregates roughness and arrangement (within the track bed)
82 as factors affecting the dielectric permittivity of the ballast/sub-ballast layer. A comprehensive review on the
83 assessment of the EM properties of railway ballast can be found in [33].

84 In view of the non-uniqueness of the results above, this work focuses on analyzing the criticality of a number
85 of parameters within the assessment of the dielectric permittivity of clean ballast aggregates. To this effect, a
86 unique laboratory setup was built and a wide range of GPR antennas and frequency systems were used. The
87 influence on the dielectric permittivity value of i) the type of radar system; ii) the antenna frequency; iii) the
88 proposed data processing scheme; iv) the GPR method of data analysis and v) the arrangement of the ballast
89 aggregates, is analysed in this study.

90

91 **2. AIM AND OBJECTIVES**

92 The main aim of this investigation is to identify critical factors as well as antennas and central frequencies
93 most suited for the investigation of railway ballast.

94 To achieve this aim, the following objective are identified:

- 95 • to assess the dielectric permittivity of the ballast system under investigation (limestone ballast aggregates
96 in clean conditions) using air-coupled GPR systems with different central frequencies as well as several
97 processing methods
- 98 • to compare and analyse the results in order to single out the most suitable frequency of investigation, data
99 processing scheme and methods for data analysis with respect to different scenarios of ballast aggregates
100 arrangement.

101

102 **3. METHODOLOGY**

103 The geometric, physical and mechanical properties of the railway ballast aggregates are first assessed following
104 the main international standards in the field.

105 The experiments are carried out in the laboratory environment on a methacrylate container, that is filled up
106 and emptied three times with (same) ballast aggregates. To this effect, different scenarios are reproduced in
107 terms of aggregates arrangement within the volume of the container used in this investigation.

108 GPR systems equipped with different ground-coupled and air-coupled antennas and central frequencies of 600
109 MH, 1000 MHz, 1600 MHz and 2000 MHz (standard and low-powered antenna systems) are used for testing
110 purpose. A signal processing scheme is developed to filter out the useless information from the raw data. The
111 relative dielectric permittivity of the bi-phase system (i.e., air-ballast aggregates) is computed using the time-
112 domain signal picking (TDSP) technique, i.e., by the estimation of the wave propagation velocity within the
113 investigated medium (e.g., [34]), across the full range of frequencies used. With regard to the air-coupled
114 antenna systems, the surface reflection method (SRM) [35] and the volumetric mixing formula (VMF) methods
115 are also applied for the same purpose.

116

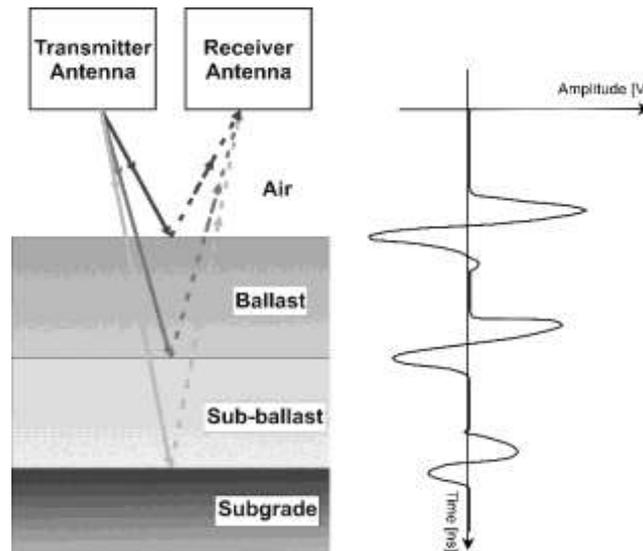
117 **4. THEORETICAL FRAMEWORK**

118 **4.1 GPR working principles**

119 A GPR system is usually configured by one transmitting and one receiving antenna(s), a control unit, a data
120 storage and a display unit. Overall, an EM impulse is emitted by the transmitting antenna towards the
121 investigated surface. The signal is then reflected and scattered by the dielectric anomalies in the subsurface
122 and collected by a receiving antenna. The properties of the materials can be estimated by several characteristics
123 that are extracted from the signal such as the time delays, the amplitudes of the reflection peaks and the
124 frequency modulations. A conventional analog-to-digital (A/D) converter is used to convert the extracted
125 information in such a way that a real-time displaying of the data as well as additional processing can be
126 performed. Ground-coupled or air-coupled antenna configurations are used as a function of the purposes and
127 the types of the investigation. In more detail, the choice of the antennas is usually driven by the required
128 penetration depth, the type of the soil to investigate and the (expected) size of the anomalies to detect. Fig. 1
129 shows a typical cross-section of a railway substructure and the relevant reflection pattern from a single GPR
130 measurement, or A-scan. The A-scan provides a punctual “one dimensional” (1-D) information about the
131 subsurface configuration. In Fig. 1, reflections are located at the electric discontinuities represented by the
132 interfaces of the substructure layers. It is worth noting that the two-way travel time taken by the signal to cover
133 the distance from the transmitter to the receiver is recorded in the vertical axis of an A-scan. This can be
134 converted into distance units (usually given in centimetres) by knowledge/assumption of the wave propagation
135 velocity in the medium, in order to display the depth of the signal reflections. On the contrary, the horizontal

136 axis of an A-scan represents the signal amplitude and it is usually given in Volts. A sequence of 1-D radar
 137 sweeps (A-scans) along the scanning line is used to create a 2-D matrix called radargram (B-scan). This is
 138 usually visualised in the real-time for immediate data interpretation. The vertical and horizontal axes of a B-
 139 scan represent the two-way travel time/depth information and the distance covered along the scanning line
 140 (usually given in meters), respectively.

141



142

143 **Fig. 1.** Typical cross-section of a railway substructure and the relevant A-scan from a single GPR
 144 measurement.

144

145

146 4.2 Estimation methods of the relative dielectric permittivity

147 4.2.1 The time-domain signal picking technique

148 The first step for the assessment of the relative dielectric permittivity ϵ_r [-] of the bi-phase system reproduced
 149 in the laboratory environment (i.e., the ballast aggregates and the inter-particle air voids - from now on referred
 150 to as the “ballast system”) is the calculation of the wave propagation velocity v [cm/ns] throughout a known
 151 thickness. This latter parameter represents the height h [cm] of a laboratory container filled up with ballast
 152 aggregates, as it is detailed further in Section 5.2. Hence, it is possible to estimate $v = 2h / \Delta t$ after measuring
 153 the time delay Δt [ns] between the two relevant reflection pulses of the GPR signal collected in the laboratory
 154 (i.e., the reflection pulses related to the surface and the bottom of the “ballast system”). The relative dielectric
 155 permittivity ϵ_r is therefore computed by working out the above expression of v into the following equation:

156
$$\varepsilon_r = (c_0/v)^2 \quad (1)$$

157 where c_0 is the speed of light in the free space [cm/ns]. This method (from now on referred to as “time-domain
158 signal picking” (TDSP) method) is used in this study for the estimation of the permittivity using the full set of
159 GPR systems and antenna frequencies available.

160

161 **4.2.2 The surface reflection method**

162 The surface reflection method (SRM) [35] allows for the evaluation of the relative dielectric permittivity ε_r [-
163] by comparison between specific reflection amplitudes as follows:

164
$$\varepsilon_r = \left(\frac{1+A_0/A_{PEC}}{1-A_0/A_{PEC}} \right)^2 \quad (2)$$

165 where A_0 [V] is the maximum absolute value of the signal amplitude reflected at the interface of the air/ballast
166 surface; A_{PEC} [V] is the maximum absolute value of the amplitude reflected by a metal sheet placed at the
167 bottom of the ballast system and larger than the antenna footprint (e.g. [36, 37]). This is defined as the effective
168 area illuminated by the antenna on the investigated surface [38]. The main function of the metal plate is to act
169 as a perfect electric conductor (PEC) preventing from unwanted reflections from the subsurface underneath
170 the metal sheet and allowing for the complete reflection of the signal.

171 It should be noted that the above formulation relies on the assumptions of i) homogeneity of the investigated
172 material, ii) negligibility of the electrical conductivity of the material and iii) plane wave approximation.

173

174 **4.2.3 The volumetric mixing formulae**

175 The volumetric mixing formula (VMF) theoretical model [39] is used to compute the dielectrics of the “ballast
176 system” by assuming a multi-phase configuration of the investigated medium. The implementation of this
177 method requires the knowledge of the relative dielectric permittivity value $\varepsilon_{r,i}$ [-] of each i^{th} phase component
178 of a mix with n phases as well as the relevant volumetric fraction φ_i (the sum of which is equal to 1). The linear
179 combination of these parameters provides the following relationship:

180
$$\varepsilon_r^\alpha = \sum_{i=1}^n \varphi_i \varepsilon_{r,i}^\alpha \quad (3)$$

181 where α is a geometrical fitting parameter varying between +1 and -1 [40, 41] and dependent on the inner
182 structure of the investigated medium [42]. In this study, a value of 0.5 is assigned to the α factor (e.g., 43, 44).

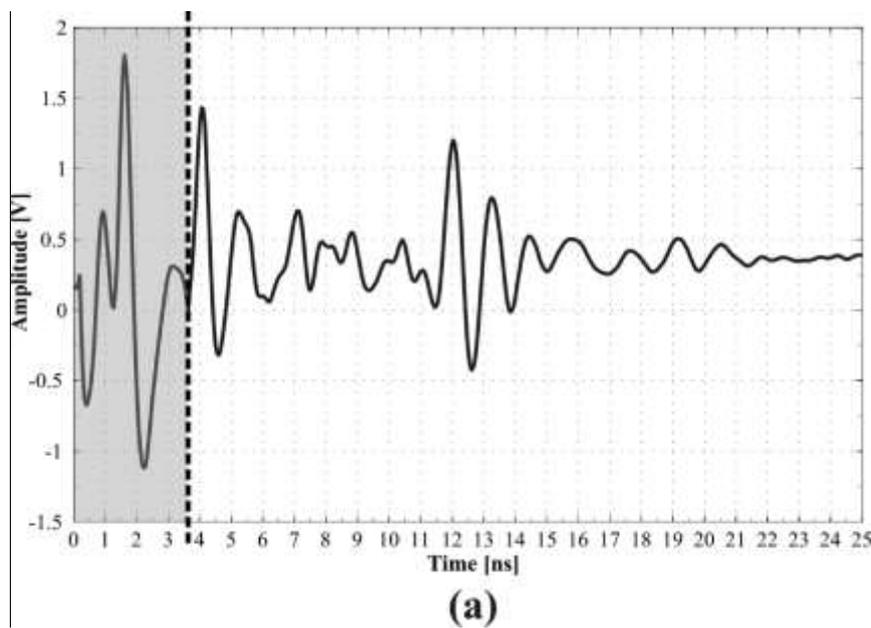
183 Given this assumption, the VMF expressed by Eq. (3) is known as the complex refractive index model (CRIM)
184 [39].

185 The relative dielectric permittivity values of the single multi-phase components are derived from the literature
186 [45] and no frequency dependence is considered in this study. The permittivity of the ballast aggregates (i.e.,
187 limestone aggregates), the methacrylate base of the tank and the air are here assumed equal to 6.50, 4.00 and
188 1.00, respectively.

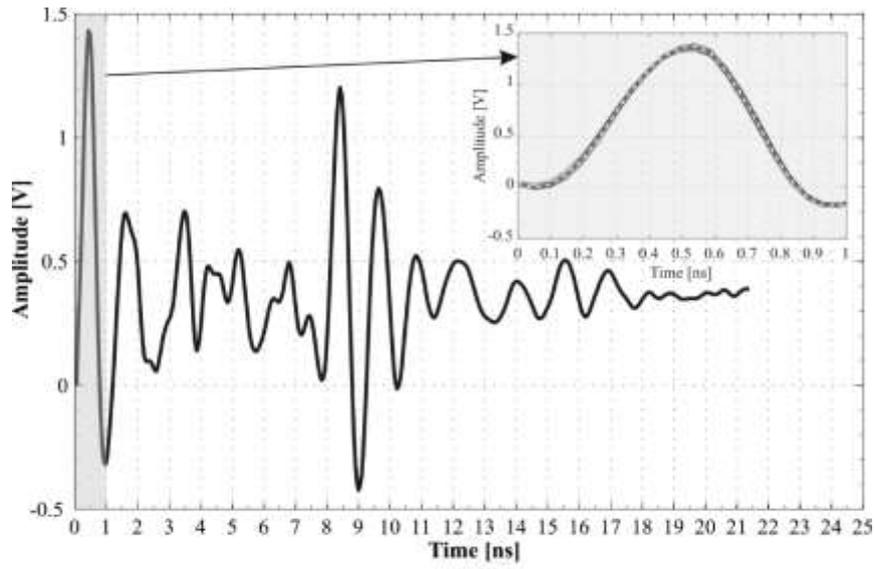
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190 4.3 The data processing scheme

191 A data processing scheme is applied to the raw GPR signals as a sequence of four steps, namely, a) time-zero
192 correction; b) signal stacking; c) zero-offset removal and d) band-pass filtering [46, 47]. The acquisition of the
193 GPR traces is carried out in static conditions such that the data processing was applied to A-scan data outputs
194 (e.g. Fig. 1). Fig. 2 reports the used processing scheme and the signal outputs at each of the aforementioned
195 four steps in the case of the 1000 MHz central frequency of investigation.

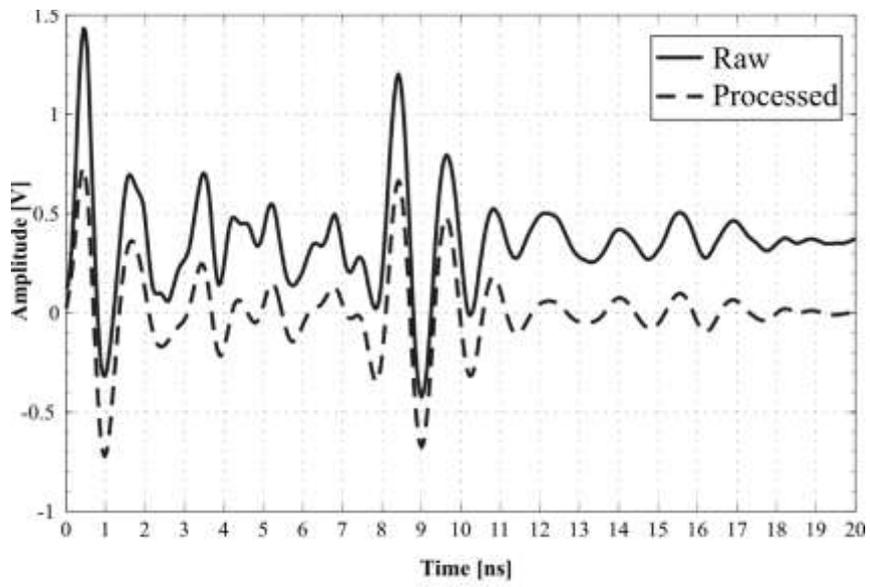


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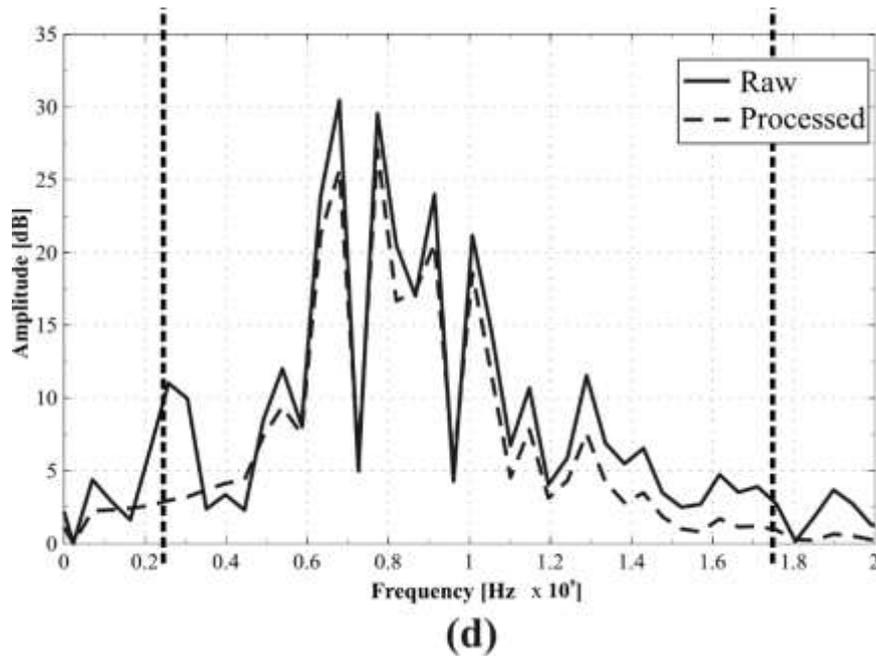
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(b)



198

(c)



199

200 **Fig. 2.** Data processing scheme and 1000 MHz GPR outputs obtained after filtering with the time-zero
 201 correction (a); the signal stacking (signal stretch “0 ns -1 ns” magnified at the upper right corner)
 202 offset removal (c) and the band-pass filtering (d).

203

204 The time-zero correction filter (Fig. 2a) is first applied to filter out all the useless reflections coming from the
 205 inner of the GPR apparatus as well as to set the zero-time at the zero-amplitude point between the negative
 206 and the positive peaks (i.e., the direct wave: the interface between the air and the railway ballast surface). This
 207 choice is motivated by the high stability of this point across a wide range of diverse surfaces and the relative
 208 ease of identification [48]. Inner reflections are identified for each GPR system by comparison between the
 209 signals collected at the various scenarios of ballast aggregates. Hence, the initial common parts of the signals
 210 (i.e., from the source point to the zero-amplitude point) are related to the reflections from the apparatus and
 211 filtered out. In the second step, the signal is averaged (stacked) over 100 traces according to the ASTM D6087-
 212 08 standard test method [36]. Stacking a number of traces collected at the same position increases the
 213 contribution coming from the target medium, whereas it reduces the random noise. Fig. 2b shows the average
 214 signal and the traces collected within the signal stretch “0 ns – 1 ns” of the time window (magnified at the
 215 upper right corner of the figure). The white dotted line in the magnified area of Fig. 2b represents the stacked
 216 signal and shows a relatively low variability of the traces collected. A zero-offset removal is subsequently
 217 applied such that an A-scans signal with a mean equal to zero is achieved (Fig. 2c). Following this step, a

218 band-pass filtering is applied to the signal considering a pass bandwidth of 1.5 times the central frequency of
 219 investigation with lower (high-pass filter) and upper (low-pass filter) boundaries evenly distributed around the
 220 central frequency [49, 50]. In view of this, Table 1 lists the high-pass and low-pass filters applied for each
 221 central frequency of investigation used in this study.

222

223 **Table 1** High-pass and low-pass filters applied across the whole set of central frequencies of investigation
 224 used in this study.

	Central frequency [MHz]			
	600	1000	1600	2000
High-pass filter [MHz]	150	250	400	500
Low-pass filter [MHz]	1050	1750	2800	3500

225

226 The frequency spectra in Fig. 2(d) represent the band-pass filtering in the case of the 1000 MHz central
 227 frequency of investigation, These are obtained after the application of the Fast-Fourier Transform (FFT) to the
 228 relative time-domain signals.

229 From now on, the GPR signals subject to the aforementioned data processing scheme will be referred to as
 230 “processed” GPR signals as opposed to the “raw” GPR signals.

231

232 **5 EXPERIMENTAL FRAMEWORK**

233 **5.1 Experimental design**

234 The experimental design is focused on the analysis of the EM behaviour of clean limestone ballast aggregates
 235 in dry conditions. A laboratory setup is arranged for testing the combination of differing factors, namely, i) the
 236 type of radar system; ii) the antenna frequency; iii) the proposed data processing scheme; iv) the GPR method
 237 of data analysis; v) the arrangement of the ballast aggregates. Tests are carried out in static conditions and all
 238 the analyses were focused on the A-scan data outputs (e.g. Fig. 1). A number of preliminary analyses are
 239 performed to investigate into the footprints of all the available radar systems [36, 37]. To this effect, the testing

240 conditions are reproduced using the GPR systems and the available PEC only. The effective areas illuminated
241 by the antennas on the PEC are determined following the manufacturer's recommendation on the systems'
242 beam of radiation and after double-checking the signal disturbance by practical tests. These provide a gradual
243 approach of a metallic reflector from the edge to the centre of the PEC while measuring with the GPR systems.
244 The footprint boundaries are therefore determined when a disturbance to the signal is noticed (i.e., the signal
245 is subject to edge effects). In view of the above framework, the largest dimension of the footprint at the PEC
246 surface turns out to be ~150 cm and it is taken as the benchmark for the side of the container. This investigation
247 is useful for the design of the dimensions of the container in order to assume the surveyed medium as
248 horizontally infinite with negligible border effects.

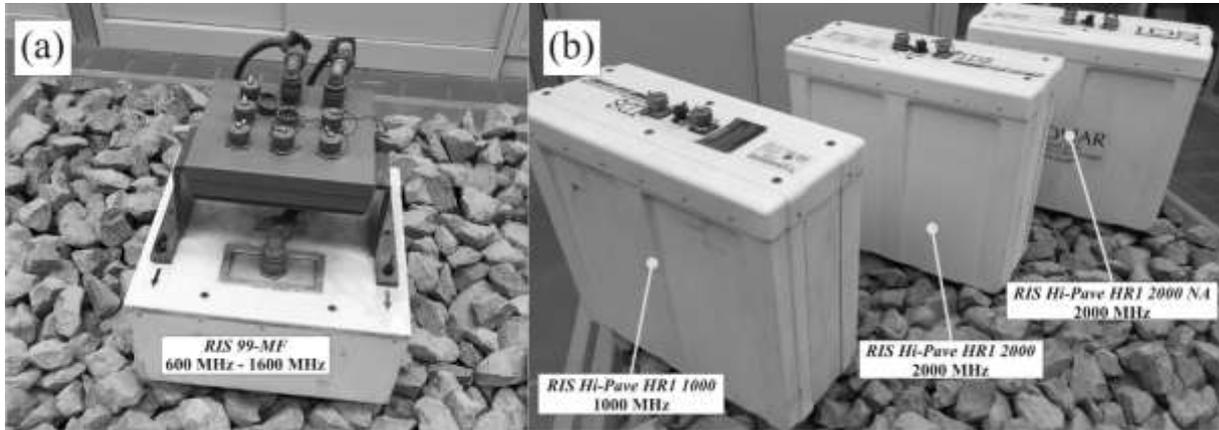
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250 **5.2 Tools and equipment**

251 Ground-coupled and air-coupled GPR antenna systems [50], manufactured by IDS Georadar (Fig. 3), are used
252 for testing purposes. The RIS 99-MF Multi Frequency Array Radar-System is equipped with 600 MHz and
253 1600 MHz central frequency antennas. The system collects data by means of four channels, i.e., two mono-
254 static and two bi-static. In this study, only the 600 MHz and 1600 MHz mono-static channels are used for data
255 collection. A time window of 40 ns is used for the acquisition of the signal. In addition, three air-coupled GPR
256 systems equipped with central frequency antennas of 1000 MHz (RIS Hi-Pave HR1 1000) and 2000 MHz (RIS
257 Hi-Pave HR1 2000 and RIS Hi-Pave HR1 2000NA) are used. Time windows of 25 ns and 15 ns were set for,
258 respectively, the 1000 MHz and the 2000 MHz GPR systems. It is worth emphasizing that the aforementioned
259 time windows are set according to the manufacturer's recommendation [e.g., 21, 51, 52]. Proper combination
260 of time window and sampling interval is mandatory to avoid over-/under-sampling of the signal collected,
261 hence to modify/lose information [53]. With regard to the 2000 MHz antenna systems, both a standard version
262 of the horn antenna for the European market and a low-powered version for the North-American (NA) market
263 are used. In this regard, it is known that manufacturers must comply with different regulations about the power
264 emission limit as per the country's specific needs [54]. The challenge is mostly in countries like the United
265 States where the threshold for the maximum power emission is very low. Due to this lower radiative power,
266 this type of GPR systems exhibit worst performances in terms of signal-to-noise (SNR) ratio [55]. It is therefore

267 important to test and compare the results to check the viability of low-powered GPR systems in assessing the
268 dielectrics of railway ballast.

269



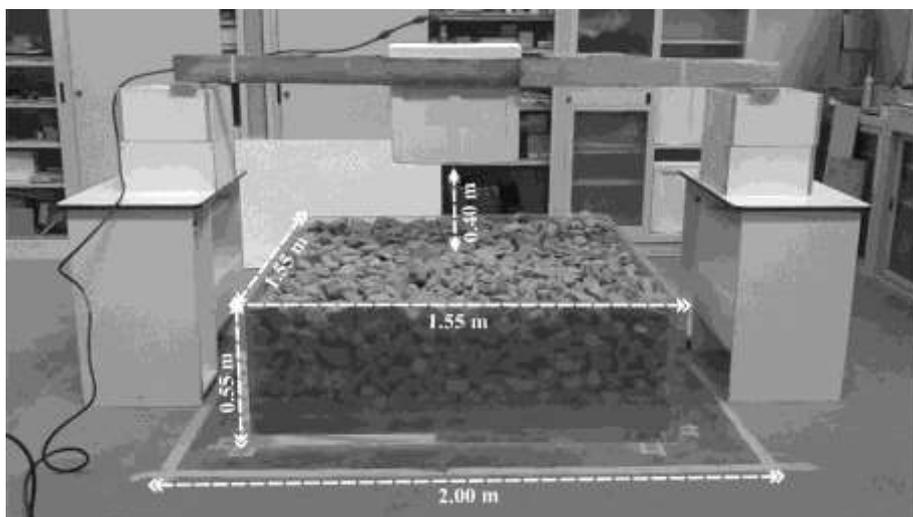
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271 **Fig. 3.** GPR equipment used for testing purposes: RIS 99-MF ground-coupled multi-channel GPR system (a),
272 and RIS Hi-Pave air-coupled antenna systems (1000 MHz, 2000 MHz and 2000 MHz (NA)) (b).

273

274 A square-based methacrylate tank is used for testing purposes (Fig. 4). The container has outer base side and
275 height of, respectively, 1.55 m and 0.55 m, and inner dimensions of 1.47 m (side of the base) and 0.48 m
276 (height). A $2\text{ m} \times 2\text{ m}$ copper sheet PEC is laid underneath the container, thereby allowing for the full reflection
277 of the EM waves propagating through the “ballast system”. It is also worth noting that the dimensions of the
278 investigated volume are designed to comply with the typical sizes of ballast layers in rail track beds.

279



280

281 **Fig. 4.** Experimental setup for the measurements carried out in the laboratory with an air-coupled antenna
 282 system.

283

284 5.3 Materials and laboratory testing

285 Limestone ballast aggregates, typically used for the construction of ballasted railroads, are utilised for testing
 286 purposes. Prior to the GPR tests, a thorough assessment of the main geometric, mechanical and physical
 287 properties of the ballast aggregates is carried out according to the EN 13450:2002/AC:2004 standard [56]. In
 288 addition to this standard, further standard test methods for the assessment of the percentage of voids [57] and
 289 the water content [58] are followed. All of the above properties are listed in Table 2.

290

291 **Table 2** Main properties of the limestone ballast aggregates assessed by using standard test methods.

Ballast property		Standard	Reference unit	Value	Class	
Geometric	Grain size	EN 13450:2013 [45]	EN 933-1:2012 [59]	% passing vs. sieve size (mm): 80 -63 -50 -40 -31.5 - 22.4	100 – 100 -79.9 – 30.6 – 1.2 – 0.3	A
	Fine particles content		EN 933-1:2012 [59]	% passing vs. sieve size (mm): 0.063	0.5	A
	Particle length		EN 933-4:2008 [60]	%	5.5	B
	Shape index - SI -		EN 933-4:2008 [60]	%	20.0	SI_{20}
Mechanical & physical	Resistance to fragmentation - LA_{RB} -	EN 1097-2:2010 [61]	%	20.0	$LA_{RB} 20$	
	Particle density - ρ_s -	EN 1097-6:2013 [62]	g/cm ³	2.8	/	
	Percentage of voids - φ -	EN 1097-3:1998 [57]	%	41.0	/	
	Water content - w -	CEN ISO/TS 17892-1:2005 [58]	%	0.2	/	

292

293 One test is carried out using the ground-coupled multi-frequency radar system, where 100 traces are collected
 294 for each of the aforementioned frequencies of investigation.

295 Calibration measurements complying with [36] and [49] are performed for the three air-coupled systems. To
 296 this effect, a reference distance of 0.40 m is set between the PEC and the base of the GPR apparatus. The same
 297 distance is maintained between the base of each air-coupled GPR and the surface of the ballast system. In view

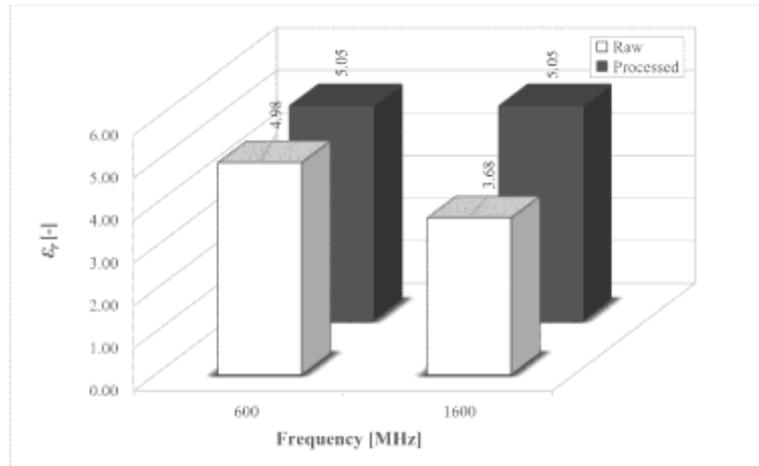
298 of the roughness of the ballast aggregates, these have been contained beneath the height of the container, which
 299 is taken as the benchmark for the height of the “ballast system”. Three main scenarios of arrangement of the
 300 ballast aggregates are reproduced in the laboratory by filling up and emptying the container. For each scenario,
 301 the full set of air-coupled GPR systems are used and 9 tests are performed.

302

303 6 RESULTS AND DISCUSSION

304 6.1 Ground-coupled antenna systems

305 The proposed processing scheme is applied to the raw data. Therefore, the dielectric permittivity values of the
 306 “ballast system” are computed for both the raw and the processed data using the TDSP technique. Both the
 307 600 MHz and the 1600 MHz mono-static channels are considered (Fig. 5).



308

309 **Fig. 5.** Raw and processed values of the relative dielectric permittivity for the acquisitions carried out with the
 310 600 MHz and 1600 MHz central-frequency antennas.

311

312 It is clear how the main difference between the raw and the processed data is in the case of the higher frequency.
 313 To this effect, if the following expression is considered for the incidence of the residuals ζ [%] (i.e, the
 314 percentage ratio of the difference between the raw (ϵ_{raw}) and the processed (ϵ_{proc}) dielectrics, and the raw value
 315 of the dielectric permittivity, taken as the reference):

$$316 \quad \zeta [\%] = \left(\frac{\epsilon_{raw} - \epsilon_{proc}}{\epsilon_{raw}} \right) 100 \quad (4)$$

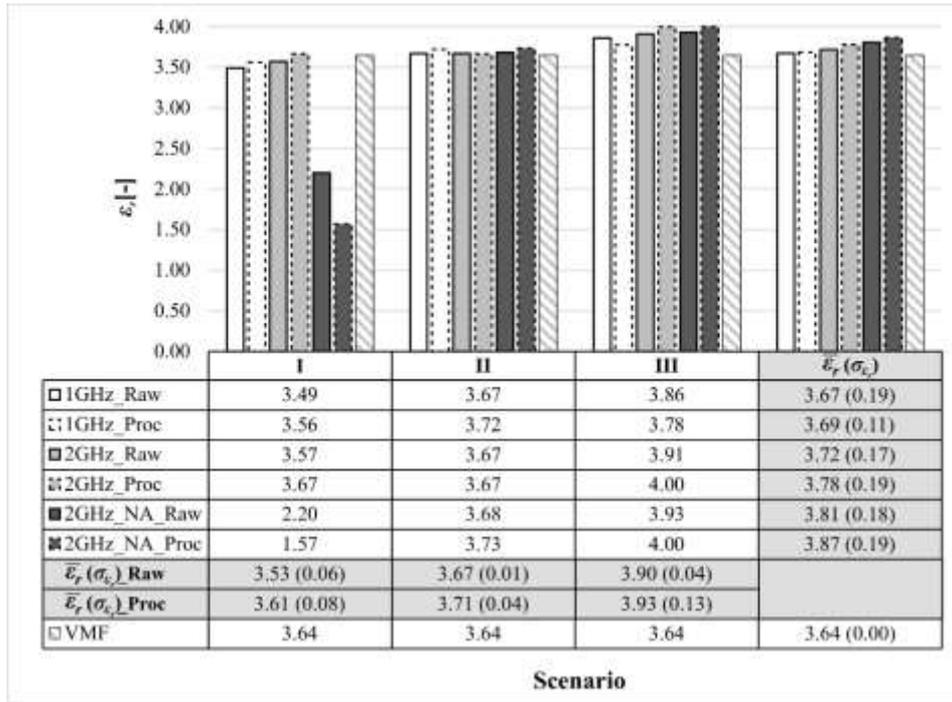
317 the values of ζ [%] are equal to 37.18% and 1.39% for, respectively, the 1600 MHz and the 600 MHz central
 318 frequencies. The application of the proposed data processing scheme leads to identical values of dielectric

319 permittivity. Nevertheless, it is worth noting how the processed values of relative dielectric permittivity are
320 1.0÷1.5 units higher than the dielectrics of similar materials, as indicated in several literature research [1, 31,
321 32]. Therefore, it can be argued that this antenna type is not well suited for the purpose of this study (i.e, the
322 assessment of the dielectric permittivity of limestone railway ballast in clean conditions) and, in general, the
323 complex material configuration can affect proper data collection with ground-coupled antenna systems. A
324 reasonable motivation for this occurrence may be related to the effects of ringing. As it was observed by
325 Narayanan et al. [63], it was indeed difficult to maintain the GPR apparatus during the tests within one eighth
326 of the wavelengths of the two antennas above the rough surface of the ballast aggregates at the top of the
327 container [64]. In this case, the low directivity of the ground-coupled antennas makes these systems more
328 sensitive to the coarse grain size of the aggregates as well as to the edge effects, which may both affect the
329 permittivity value [65].

330

331 **6.2 Air-coupled antenna systems**

332 Fig. 6 shows the values of the permittivity computed as a combination of each of the three air-coupled systems
333 and the three scenarios of “ballast system”. These dielectrics are derived from both the raw and the processed
334 signals using the TDSP technique. For the sake of comparison, the bar graph of the relative dielectric
335 permittivity calculated using the VMF model is also added. This equals 3.64 and it is obtained by substituting
336 the values of the multi-phase components given in Section 4.2.3 into Eq. (3).



337

338 **Fig. 6.** Values of the relative dielectric permittivity computed using the TDSP and the VMF methods for the
 339 acquisitions made with the 1000 MHz, 2000 MHz and 2000 MHz (NA) central-frequency antennas.

340

341 Overall, the permittivity values agree with the dielectrics of the same material as indicated in the literature [1,
 342 31, 32]. Exceptions are the permittivity values (both raw and processed) computed using the TDSP technique
 343 within the first scenario of aggregates arrangement with the 2000 MHz (NA) antenna. Hence, these outliers
 344 are excluded from the statistics.

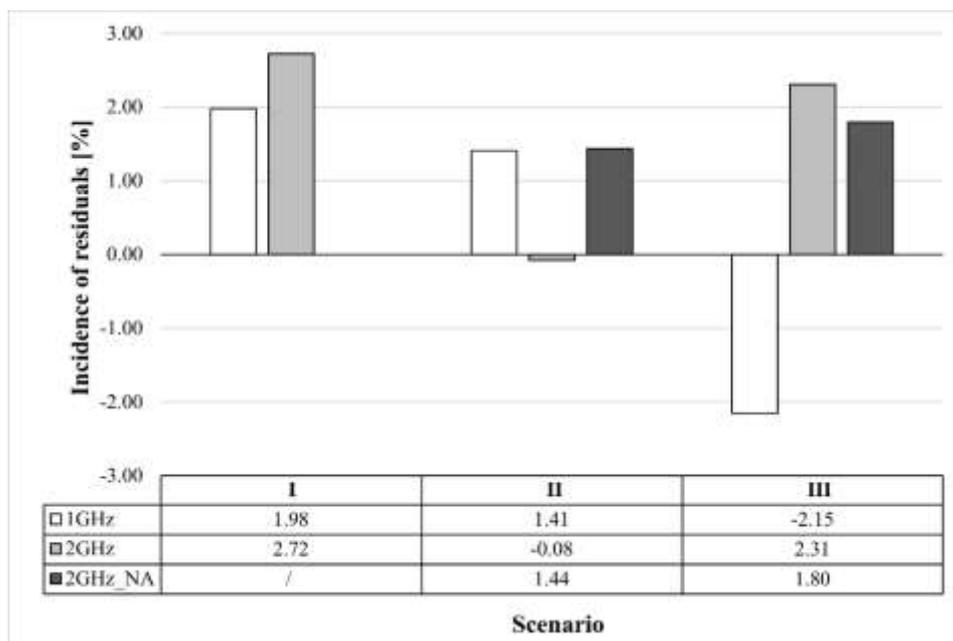
345 With regard to the dielectrics assessed with the TDSP technique, low peaks of variability are obtained for the
 346 whole set of the frequencies within each single scenario (i.e., $\sigma_{\epsilon_r} = 0.01 \div 0.13$, if the minimum and the
 347 maximum values of the standard deviation is considered). On the contrary, higher peaks are found if each
 348 frequency f_j across the three i^{th} scenarios s_i (i.e., $\sigma_{\epsilon_r} = 0.11 \div 0.19$) is taken into account. Thereby, it can be
 349 argued that the variation in the arrangement of the ballast aggregates (i.e., moving horizontally across the rows
 350 in Fig. 6), may affect the computed values of permittivity of the “ballast system” more than using differing
 351 frequencies of investigation across the same scenario (i.e., moving vertically across the columns in Fig. 6). Let
 352 us compare the three scenarios to three different sections of railway ballast layers that can be usually
 353 investigated along the rail track in the real-life conditions. Also, let us interpret the dielectrics found for the
 354 three antenna frequencies as the result of GPR data collected at the same i^{th} section (scenario) using a multi-

355 frequency antenna. The found standard deviations of the dielectrics mean that the arrangement of the
 356 aggregates has a higher impact on the value of the permittivity than the used central frequency (within the
 357 range of frequencies here available). This may be reasonably due to the twofold effect of the roughness at the
 358 interface between the air and the ballast as well as to the arrangement of the aggregates throughout the thickness
 359 of the “ballast system”.

360 The impact made on the value of the permittivity by the use of different frequencies across the three reproduced
 361 scenarios is represented by the trend of the average permittivity $\bar{\epsilon}_r$ in the fourth grey column of Fig. 6. In
 362 general, we can argue that the higher the central frequency of investigation, the larger the value of the
 363 permittivity. To this effect and with regard to the processed data only, $\bar{\epsilon}_r$ ranges from 3.69 (i.e., 1000 MHz) up
 364 to 3.78 (i.e., 2000 MHz) and 3.87 (i.e., 2000 MHz (NA)).

365 Concerning the applied data processing scheme and its effect on the assessment of ϵ_r , it is observed that the
 366 average permittivity values $\bar{\epsilon}_r$ of the processed data are slightly higher than the raw data. This occurs in both
 367 the average dielectrics computed across the i^{th} scenario s_i investigated (same frequency: $\overline{\Delta\epsilon_{r \text{ proc-raw}}} = 0.2 \div 0.6$;
 368 i.e., fourth grey column in Fig. 6) and the j^{th} frequencies f_j (same scenario: $\overline{\Delta\epsilon_{r \text{ proc-raw}}} = 0.3 \div 0.8$; i.e., two grey
 369 rows in Fig. 6) used. To this effect, Fig. 7 shows the incidences of the residuals (Eq. (4)) computed between
 370 the processed and the raw data for any combination of s_i and f_j . These results confirm that the proposed
 371 processing scheme returns mostly higher values, with residual percentages not exceeding $\pm 3\%$.

372



373

374 **Fig. 7.** Incidence of the residuals between the processed and the raw permittivity data computed using the
375 TDSP technique.

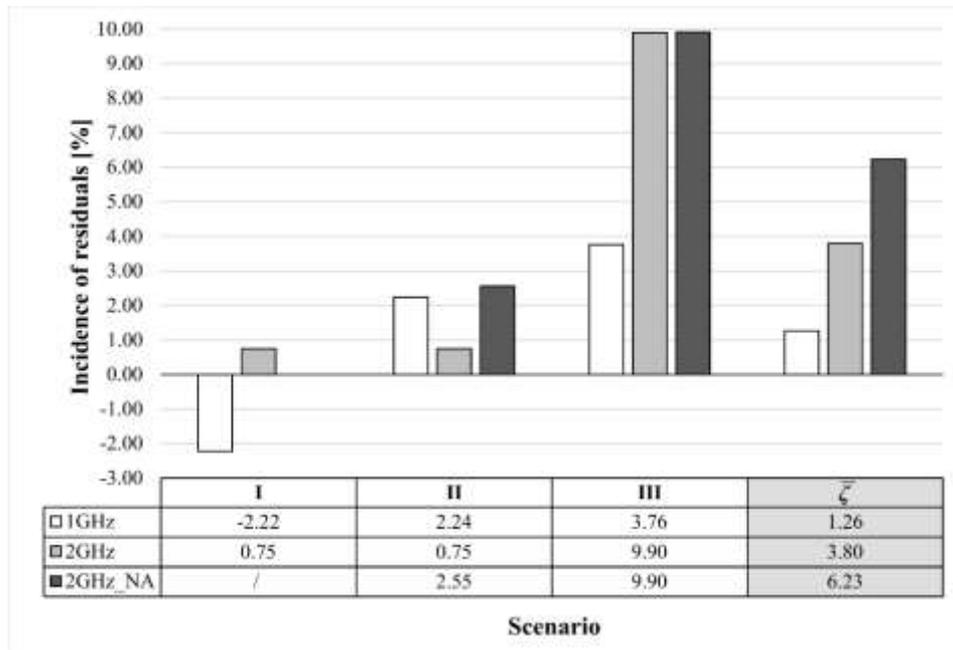
376

377 With regard to the GPR methods of data analysis, Fig. 8 reports the incidences of the residuals between the
378 processed values of dielectrics, computed using the TDSP technique, and the relative dielectric permittivity
379 value of 3.64 calculated by the VMF theoretical method. Overall, it can be seen how the permittivity assessed
380 by the VMF is lower than the dielectrics derived from the application of the time-domain-based technique. An
381 exception is the ϵ_r value calculated using the 1000 MHz antenna for the first scenario. Furthermore, lower
382 mismatches are observed in the case of the 1000 MHz antenna, whereas the use of the 2000 MHz antennas
383 returns broadly higher differences (with the exception of the 2000 MHz antenna in the second scenario of
384 aggregates arrangement). This is summarized by the average values of the incidences $\bar{\zeta}_j$ computed across the
385 various scenarios s_i investigated (i.e., each frequency in the fourth grey column in Fig. 8). Furthermore, it can
386 be seen that the low-powered antenna system returns the highest differences in terms of permittivity estimate
387 between the TDSP and the VMF techniques. Fig. 9 reports the comparison between the processed values of
388 dielectrics, computed using the TDSP technique, and the corresponding relative dielectric permittivity values
389 obtained with the SRM approach. For the sake of comparison, the bar graphs with the VMF permittivity
390 estimations are also included. It is evident that the SRM provides values of ϵ_r lower than the TDSP technique.
391 Thereby, it shows to be unsuitable for the assessment of the dielectric permittivity of railway ballast layers
392 within the analysed domain of investigation (i.e., the 3-D volume defined by the investigated “ballast system”).
393 This result may be reasonably due to a higher sensitivity of the SRM towards the roughness of the ballast
394 aggregates at the interface between the air and the “ballast system” in combination with the high
395 inhomogeneity of the material throughout the investigated domain. Indeed, the former occurrence has an
396 impact on the amplitude A_0 in Eq. (2), whereas the latter condition affects the major assumption of material
397 homogeneity. This is confirmed by the highest dielectrics obtained with the SRM in the case of the 1000 MHz
398 central frequency (i.e., $\overline{\epsilon_r}_{1GHz} = 2.56$ against $\overline{\epsilon_r}_{2GHz} = 1.74$ and $\overline{\epsilon_r}_{2GHz_NA} = 1.66$). As the wavelength λ_{1GHz} is
399 higher than the wavelength λ_{2GHz} of the 2000 MHz GPR systems (according to the quarter of wavelength
400 criterion [66]: $\lambda_{1GHz} = 7.5 \times 10^{-2}$ m; $\lambda_{2GHz} = 3.75 \times 10^{-2}$ m), hence, the effects of the inhomogeneity of the

401 system on the estimated value of dielectric permittivity are lower. In view of this, dielectrics closer to those
 402 obtained with the peak-to-peak (TDSP) estimation are reached.

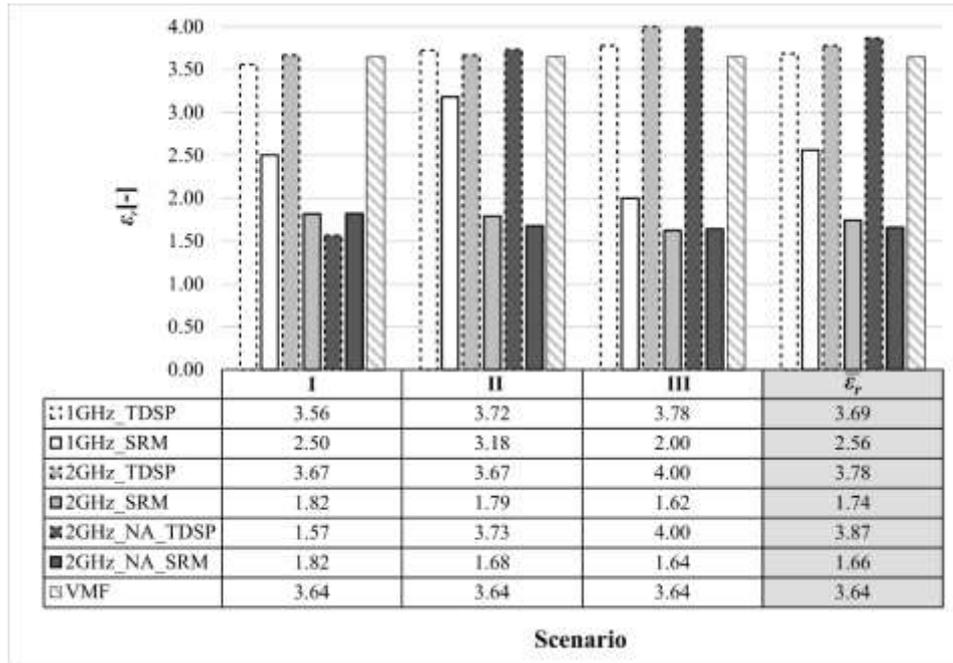
403 It is important to note that the inhomogeneity of the ballast is a critical issue across all the applied GPR methods
 404 of data analysis. However, the effects of this condition in the application of the TDSP and the VMF approaches
 405 turn out to be more contained. Firstly, in the TDSP method the estimation of the wave propagation velocity v
 406 across the thickness of the whole “ballast system” seems to limit the effects of the material inhomogeneity.
 407 Secondly, the assumption of $\alpha = 0.5$ in the VMF theoretical model of Eq. (3) turns out to be a good trade-off
 408 for representing the inner structure of the investigated medium.

409



410

411 **Fig. 8.** Incidence of the residuals between the processed permittivity data computed using the TDSP technique
 412 and the dielectric permittivity calculated by the VMF model.



413

414 **Fig. 9.** Processed values of the relative dielectric permittivity computed using the TDSP and the SRM methods
 415 for the acquisitions made with the 1000 MHz, 2000 MHz and 2000 MHz (NA) central-frequency antennas
 416 (dielectrics by the VMF method are also added).

417

418 7 CONCLUSION AND FUTURE PROSPECTS

419 This paper reports an extended study of applications of ground-penetrating radar (GPR) on the assessment of
 420 the electromagnetic (EM) properties of railway ballast.

421 The main geometric, physical and mechanical properties of clean limestone ballast aggregates are first assessed
 422 in the laboratory environment according to relevant standard test methods. A typical ballast layer of a track
 423 bed substructure is reproduced using a square-based methacrylate tank, with outer dimensions of 1.55 m length
 424 \times 1,55 m width \times 0.55 height. A copper sheet is placed beneath the tank to allow the complete reflection of the
 425 EM waves propagating through the material. The use of this perfect electric conductor (PEC) allows for the
 426 effective assessment of the EM properties of the material, which is the primary scope of this work. The
 427 container is filled up with the ballast aggregates and emptied several times in order to reproduce different
 428 scenarios of aggregates arrangement. Four GPR systems (in both ground-coupled and air-coupled
 429 configurations) investigating with five differing central frequencies are used for testing purposes. A processing
 430 scheme for filtering out useless information from the raw GPR data is developed.

431 The effects of the ringing and the low directivity of the ground-coupled antennas return lower dielectrics as
432 opposed to the reference literature values of permittivity for railway ballast layers as well as to the dielectrics
433 computed using the air-coupled systems. The main cause for this occurrence is linked to the roughness of the
434 ballast aggregates at the top of the container that makes the interface between the air and the top aggregates
435 highly irregular. These results may indicate unsuitability of the used ground-coupled system type for the
436 railway ballast investigation carried out in this study.

437 With regard to the used antenna-frequencies (air-coupled systems), results show that the higher the central
438 frequency of investigation, the larger the value of the permittivity computed by means of the time-domain
439 signal picking (TDSP) method.

440 The application of the proposed data processing scheme return slightly higher values of dielectric permittivity
441 than the raw, i.e., not exceeding $\pm 3\%$. This occurs across the investigated scenarios of aggregates arrangement
442 as well as across the used frequencies of investigation.

443 The use of the surface reflection method (SRM) appears to be not suitable for the assessment of the relative
444 dielectric permittivity of limestone railway ballast in clean conditions. This is due to a higher sensitivity of the
445 SRM towards the roughness of the ballast aggregates at the interface between the air and the “ballast system”
446 (i.e., effect on the reflection amplitude) in combination with the high inhomogeneity of the material throughout
447 the investigated domain (i.e., loss of the major assumption of material homogeneity from the SRM method).

448 On the contrary, a general agreement between the dielectrics computed with the TDSP and the VMF is
449 observed. Overall, it can be seen how the permittivity assessed by the VMF is lower than the dielectrics derived
450 from the application of the time-domain-based technique. In addition to this, lower mismatches are observed
451 in the case of the 1000 MHz antenna, whereas the use of the 2000 MHz antennas (in both the standard and
452 low-powered configurations) return broadly higher differences. The 2000 MHz (NA) frequency data processed
453 with the TDSP technique return the largest difference with respect to the dielectrics computed using the VMF
454 method.

455 With regard to the effects of the arrangement of the ballast aggregates on the dielectric permittivity (i.e., the
456 variability observed in the values of the permittivity), a different disposition of the aggregates, surveyed by the
457 same antenna, may affect the computed values of the permittivity of the “ballast system” more than using
458 different frequencies of investigation across the same section (scenario).

459 In view of the above results, the 1000 MHz air-coupled antenna system seems to be the most reliable and stable
460 GPR device (among the set of system types and frequencies used) for the purposes of this study. Indeed, the
461 use of this antenna frequency system allows for the lowest differences in terms of permittivity before and after
462 the application of the data processing scheme. The investigations performed with the 1000 MHz antenna
463 frequency provides also with the smallest differences between the dielectrics computed using the TDSP
464 technique and the VMF method. Furthermore, the permittivity data calculated with this frequency return the
465 lowest changes across the three different scenarios of particles arrangement provided.

466 Future research could task itself with the applicability of the obtained findings to real-case scenarios. Due to
467 the higher complexity of the investigation domain in terms of boundary conditions (e.g., presence of
468 tracks/sleepers, fouling, moisture within the track bed etc.), it is recommended to carry out first a survey at the
469 network level to divide the railway track into homogeneous stretches. This will allow to single out clean ballast
470 areas where to utilize the GPR systems and indications arising from this study.

471

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476

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