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Reverse-time migration for evaluating the internal structure of tree-trunks
using ground-penetrating radar

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<http://dx.doi.org/10.1016/j.ndteint.2020.102294>

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1 **Highlights**

2

3 **Reverse-Time Migration for Evaluating the Internal**

4 **Structure of Tree-Trunks Using Ground-Penetrating**

5 **Radar**

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8 • A processing framework for detecting tree decays in

9 diseased trees.

10 • A real-field case study that demonstrates the

11 capabilities of the suggested method.

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26 **Reverse-Time Migration for Evaluating the Internal**
27 **Structure of Tree-Trunks Using Ground-Penetrating**
28 **Radar**

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44

45 **Keywords:** Ground penetrating radar (GPR), tree health monitoring, migration,
46 tree, decay, emerging infectious diseases (EIDs)

47

48 **Abstract:**

49 Modern socioeconomic factors such as global timber trade and international
50 travelling have contributed to the rapid increase of Emerging Infectious Diseases
51 (EIDs) of trees with devastating effects to the European forests and woodlands.
52 To that extent, numerous non-destructive methodologies have been suggested as
53 diagnostic tools in order to effectively monitor and maintain potential outbreaks.
54 Ground-penetrating radar (GPR) is an appealing method for tree monitoring as it
55 provides with a trivially deployable and efficient detection tool, suitable for
56 large-scale forestry applications. Nonetheless, traditional GPR approaches are
57 tuned for surface measurements and they are not compatible with the unique
58 measurement configurations associated with forestry applications. Within that
59 context, we present a novel-processing framework, which is capable
60 of addressing features with irregular measurements on closed surfaces. A
61 positioning method is described that exploits a wheel-measuring device in order
62 to accurately associate each A-Scan with its corresponding coordinates. In
63 addition, a processing pipeline is presented that aims at eliminating the ringing
64 noise due to the layered nature of the trees. Lastly, a reverse-time migration is
65 applied to the processed B-Scan in order to effectively map the reflectors present
66 within the trunk. The suggested scheme is successfully tested in both numerical
67 and real-field experiments, indicating the validity of the current approach.

68

69 **1. Introduction**

70

71 Emerging Infectious Diseases (EIDs) of trees -caused by pathogens, pests and
72 fungi- pose a major threat for forests and woodlands [1], [2]. Recent outbreaks
73 almost brought some species to extinction [3], [4] with devastating effects to the

74 European flora. It should be highlighted that from 1995-2010, a 13-fold increase
75 of EIDs has been recorded globally [2]. This rapid increase is due to anthropic
76 activities such as international travelling [2], global timber trade [1] and human
77 population increase [5]. Furthermore, climate change and the consequent rise of
78 the global temperature have added to this phenomenon [2].

79 Representative examples of recent outbreaks of EIDs are the ash dieback, the
80 acute oak decline (AOD) and the chestnut blight. Ash dieback is a prominent EID
81 that has invaded the United Kingdom (UK) in 2012 [1] and it has spread majorly
82 in central England and Wales [6]. Less than 5% of the ash trees are immune to
83 this disease and it is predicted that most of the ash trees in the UK are going to be
84 affected and die in the next twenty years [7]. AOD is a particularly aggressive
85 EID that can lead to tree mortality within a period of 3-5 years [8]. AOD has been
86 introduced to the UK in 2006 and since then has rapidly spread mostly in the
87 central part of England [9]. The effects of ash dieback and AOD to the forests and
88 woodlands of the UK resemble the effects of chestnut blight to the chestnut
89 population in the North America during the last century [10]. Chestnut blight
90 accidentally invaded North America in 1904 and rapidly spread within the
91 following 40 years [10]. The nearly four billion chestnut population of North
92 America almost brought to extinction with just small populations surviving in
93 the Pacific Northwest [10].

94 Tree decays and compartmentalisation of decays are robust diagnostic criteria
95 for EIDs [11] Due to the importance of decays to the overall health status of a
96 tree, numerous drilling approaches have been suggested for assessing the
97 internal structure of trees and detecting hidden cavities [12], [13]. Although
98 drilling methods are accurate and reliable, nonetheless, destructive techniques

99 can cause irreversible damage to the tree, making it more vulnerable to fungi,
100 pathogens and pests. In addition, drilling methods are constrained to a single
101 point and fail to provide a coherent and comprehensive image of the internal
102 structure of the trunk. Within that context, there is an on-going call for novel
103 detection approaches and modern diagnostic tools [2], capable of detecting early
104 decay in an efficient and practical manner.

105 Non-destructive testing (NDT) for wood monitoring [14] is a suitable candidate
106 for detecting early decays in tree-trunks and their components (e.g., tree roots
107 [15], [16], [15]). NDT provides with a robust set of tools that can map the
108 internal structure of trees without disturbing its layers. The most mainstream
109 amongst the NDT techniques -applied for forestry applications- is the electrical
110 resistivity [16] and the ultrasound tomography [17]. Both of these methods can
111 effectively assess the health condition of a tree. Nonetheless, the measurement
112 configurations of these techniques make them unattainable for large-scale
113 forestry applications in which numerous trees have to be assessed in a short
114 period of time.

115 To tackle this, common-offset (CO) ground-penetrating radar (GPR) has been
116 suggested as an efficient and practical approach for tree monitoring [18]. To that
117 extent, a technique based on the interpretation of B-Scans in polar coordinates is
118 described in [19], [20], a layer-based detection is presented in [21] and a
119 hyperbola fitting approach is discussed in [18]. Apart from signal processing
120 approaches, tomographic methods are particularly appealing for tree monitoring
121 applications due to the fact that the measurements are taken on a closed surface
122 using a dense configuration. Microwave tomography tuned for cylindrical host
123 media has been extensively applied for column investigations [22] and

124 biomedical applications [23]. Furthermore, tomographic approaches based on
125 the Born approximation and subject to CO-GPR configurations have shown
126 promising results when applied for tree monitoring and early decay detection
127 [24]. However, the resulting image may still be corrupted by artefacts,
128 decreasing the signal-to-clutter ratio and reducing the reliability of the final
129 results [24].

130 Migration is a mainstream processing tool that has been applied for both
131 seismic and GPR applications in an effort to focus the received signal and
132 increase the overall signal-to-clutter ratio [25]. The minimum computational
133 requirements combined with its accuracy, have made migration one of the most
134 extensively used approaches amongst GPR practitioners with a wide range of
135 applications ranging from landmine detection [26], [27] to topography mapping
136 [28]. Regarding forestry applications, a hyperbola summation -that
137 resembles Kirchhoff migration- has been suggested for tree measurements in
138 [29]. In contrast to typical migration schemes applied to GPR [25], the approach
139 described in [29] is not constrained to clinical half-spaces and thus, it can be
140 applied in a straightforward manner to any arbitrary topography. Although
141 preliminary laboratory results are promising [29], nonetheless real-field case
142 studies are necessary in order to provide concrete evidences regarding the
143 applicability of GPR for decay detection.

144

145 *1.1 Statement of the Problem*

146 CO-GPR has the potential to answer the on-going call for the modernization of
147 detection tools for arboriculture applications. In order for GPR to be established
148 as a mainstream forestry tool, processing methods have to be fine-tuned

149 accordingly and subsequently be subjected to a rigorous validation process. To
150 that extent, numerical models and laboratory experiments can provide useful
151 insights on the accuracy and efficiency of each investigated technique.
152 Nonetheless, numerical and laboratory data can widely deviate from real field
153 case studies and thus lead to an overestimation of the capabilities of GPR. Real-
154 field case studies, although essential, are often unattainable due to practical
155 considerations. In particular, a proper arboriculture case study should involve a
156 diseased tree that is going to be cut down after the completion of the
157 measurements. Furthermore, the fallen tree has to be cut into several slices in
158 order to get an insight on its internal structure for validation purposes. The
159 aforementioned procedure requires a dedicated and properly trained group of
160 foresters that is often not available.

161

162 *1.2 Aims and Objectives*

163 In the current paper, we present a more efficient and less time-consuming
164 focusing approach (compared to [29]) that is based on reverse-time (RT)
165 migration [30]. In particular, the method described in [29] is a hyperbola
166 summation that requires extensive 2D interpolations within the B-Scan. This
167 results to large computational requirements especially when applied to 3D
168 measurements. RT migration is particularly appealing for tree measurements
169 due to its minimum computational requirements and its flexibility when it comes
170 to rough topography. The most computationally intensive part of RT migration is
171 an inverse fast Fourier transform which, can be executed in real-time in typical
172 computers. The suggested scheme is successfully validated using both synthetic
173 data and a real-field case study that involves a diseased urban tree within the

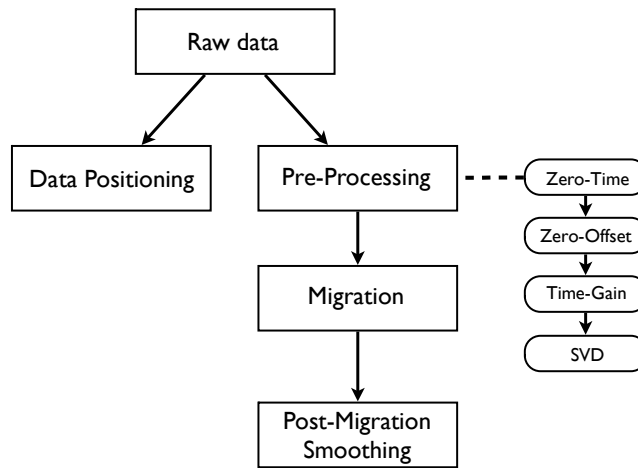
174 greater London area, UK. The proposed methodology was proven capable of
175 detecting decay of various sizes within the resolution of the employed antenna.
176 The current case study provides concrete evidences that GPR has the potential to
177 become an efficient tool for forestry and arboriculture applications.

178 The paper is organised as follows. Section 2 describes the theoretical
179 background of the RT migration as well as the processing pipeline that was
180 preliminarily employed. In addition to this, the positioning framework suggested
181 in [15] is discussed for the sake of consistency with presented results. Section 3
182 presents the numerical and real-field case studies accompanied with a detailed
183 discussion on the results. Lastly, the conclusions are drawn in Section 4.

184 **2. Methodology**

185

186 The proposed methodology consists of four distinct stages, namely, A) data
187 positioning, B) pre-processing, C) migration and D) post-migration smoothing
188 (see Figure 1). In the first step, the measurements are positioned along the
189 surface of the trunk using an arc length parameterization. Subsequently the raw
190 data are processed in order to eliminate unwanted clutter and ringing noise. The
191 first two steps are not sequential and thus the order can be reversed. The
192 processed B-Scan is then migrated. Lastly, a smoothing filter is applied in order
193 to eliminate migration artefacts. Notice that all the aforementioned steps require
194 minimum computational requirements and can be executed in almost real-time
195 using conventional mainstream computers.



196

197

Figure 1: Flowchart describing the proposed processing framework. (No colour in print)

198

2.1 Positioning Scheme

199

Typical CO-GPR systems position each A-Scan based on a wheel-measuring device that associates every received signal output with its associate position.

200

This configuration was designed for line measurements subject to flat surfaces

201

and fails to compensate for irregular topographies. Regarding tree surveys, it is

202

known that measurements are collected on a highly irregular surface. Thus, prior

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to any processing approach, each A-Scan should be accurately positioned along

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the investigated surface. To that extent, in order to convert the measured

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distance (from the wheel-measuring device) to its corresponding coordinates,

206

we employ an arc-length parameterisation [31], [32], initially described in [18].

207

The first step of the arc-length parameterisation is to digitize the investigated

208

surface using a sufficient (n) number of points along the surface of the trunk

209

$\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$. Subsequently, the vector $\mathbf{t} \in \mathbb{R}^n \mid 0 < t < 1$ is defined, which is going to

210

be used for the parametric representation of the shape of the tree [18]. A spline

211

interpolation is subsequently used in order to map the vectors (\mathbf{x}, \mathbf{t}) and (\mathbf{y}, \mathbf{t}) to

212

the continuous scalar functions $P(t)$ and $Q(t)$ respectively. Notice that the bounds

213

of \mathbf{t} do not affect the final output since the coefficients of the fitted polynomial

214

215 are adjusted accordingly. The position vector $\mathbf{F} = [P(t), Q(t)]$ represents the shape
 216 of the tree with respect to the arbitrary value t . The arc-length (s) of the
 217 positional vector \mathbf{F} throughout the vector \mathbf{t} is given by

$$218 \quad s(\tau) = \int_0^\tau \left\| \frac{d\mathbf{F}}{dt} \right\| dt = \int_0^\tau \sqrt{\left(\frac{dP(t)}{dt} \right)^2 + \left(\frac{dQ(t)}{dt} \right)^2} dt \quad . \quad (1)$$

219 where $\tau \in [0, 1]$ is a continuous variable along the boundaries of the arbitrary
 220 vector \mathbf{t} . The integral in (1) is evaluated numerically [15] using different τ values
 221 varying from [0,1]. A spline interpolation is then used in order to map the values
 222 of τ with respect to the distance s . Thus, the distance can now be expressed in a
 223 continuous manner with respect to t . Consequently; the position vector can now
 224 be expressed with respect to the distance $\mathbf{F} = [P(t(s)), Q(t(s))]$. This implies that
 225 the position of the antenna can now be calculated based on the distance (s)
 226 measured using a typical wheel-measuring device [18].

227

228 2.2 Pre-Processing

229 Prior to the RT migration, the raw B-Scan has to be carefully processed in order
 230 to transform the data in a suitable format for the following processing stages.
 231 The processing pipeline applied in this paper -similar to [18]- consists of four
 232 sequential steps:

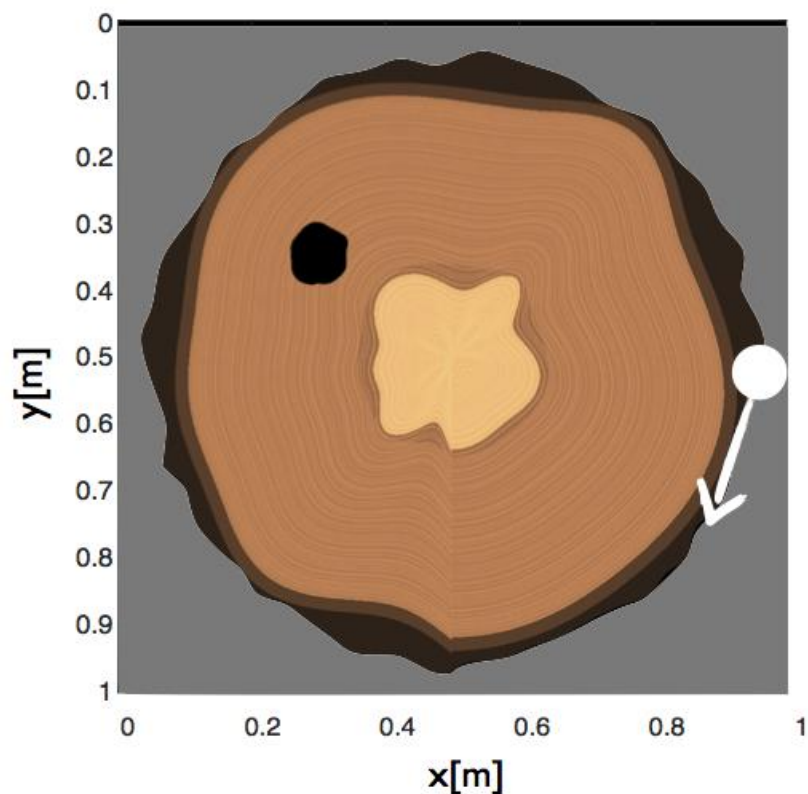
- 233 • *Time-zero removal*: in this step, the starting time t_0 of the pulse is
 234 estimated and the signal prior to t_0 is deleted. This step is particularly
 235 important since the estimated time-zero greatly affects the performance
 236 of the RT migration. The first peak of the derivative of the A-Scan with
 237 respect to time is chosen to represent the time-zero in the current paper.

238 • *Zero-offset removal*: in this step, static phenomena that corrupt the
239 received A-Scans are removed by fitting a second order polynomial to
240 the received signal [33].

241 • *Time-varying gain*: an incremental gain is applied in order to compensate
242 for the losses present within the trunk.

243 • *Singular value decomposition*: trees are complex media that consist of
244 distinct layers with different compositions and dielectric properties [18].
245 Due to the layered nature of trees, the raw B-Scan is corrupted with
246 ringing noise that masks the reflections from the decay and reduces the
247 overall signal-to-clutter ratio [18]. To tackle this, a singular value
248 decomposition (SVD) filter (similar to [18]) is applied here. The raw B-
249 Scan is treated as a 2D matrix $\mathbf{B} \in \mathbb{R}^{w \times v}$ where w and v are the number of
250 measurements and the number of time-steps, respectively. The matrix \mathbf{B}
251 is then decomposed via $\mathbf{B}=\mathbf{U}\mathbf{M}\mathbf{V}^T$, where \mathbf{U} and \mathbf{V} are the orthogonal
252 matrices that contain the left and right singular vectors of \mathbf{B} . The matrix
253 \mathbf{M} is a square matrix that contains the singular values of \mathbf{B} . These
254 singular values are placed in a decreasing order along the main diagonal
255 of \mathbf{M} . The rationale behind the application of the SVD filter is that large
256 singular values are typically related to dominant periodic patterns
257 arising from the repetitive reflections between the tree layers [18]. Thus,
258 setting the dominant singular values to zero and subsequently
259 reconstructing the matrix \mathbf{B} will result to a revised B-Scan with a lower
260 number of features associated with ringing noise [18]. The number of
261 dominant singular values to be filtered out is usually <10 . This number is
262 a hyperparameter that it is tuned via a trial and error procedure.

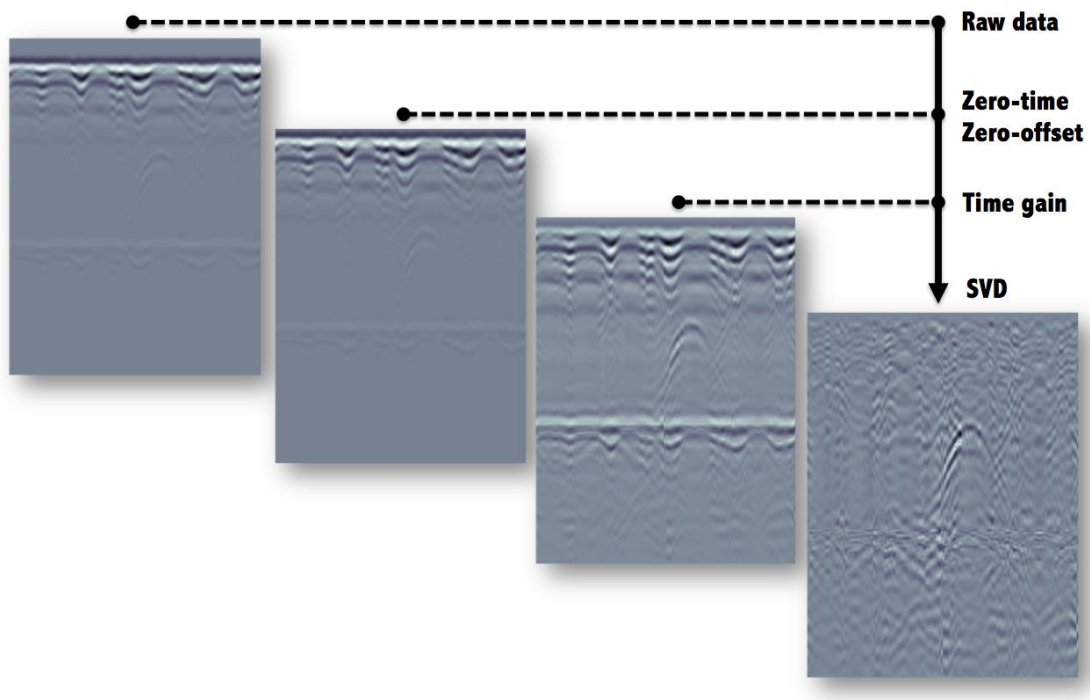
263 The above processing pipeline is tested in the numerical case study shown
264 in Figure 2. A generic hardwood consisted with four layers is simulated
265 using the finite-difference time domain (FDTD) method [34], [35], [36]
266 (more details on the numerical simulations are given in Section 3). An early
267 decay is simulated as a hollow chamber within the sapwood. The raw and
268 the processed data are shown in Figure 3. The static components and the
269 signal prior to time-zero are initially removed. Subsequently, a linear gain is
270 applied to each A-Scan. Lastly, an SVD filter, filtering out the three most
271 dominant eigenvalues, is applied to the data. From Figure 3, it is apparent
272 that the employed processing approach [18] can effectively remove the
273 ringing noise and can enhance the reflections from the early decay.



274

275 **Figure 2: A numerical case study for the investigation of the received signal of an early decay in a**
276 **generic hardwood scenario. The white dot represents the starting point of the scan and the arrow**
277 **shows the direction of the measurements. (No colour in print)**

278



280

281 **Figure 3: The employed processing pipeline applied to the simulated data from the case study**
 282 **illustrated in Figure 2. (No colour in print)**

283

284 *2.3 Reverse Time Migration*

285 RT migration using monostatic measurement configurations is based on the
 286 exploding reflector model [30]. This model approximates every scatterer with an
 287 equivalent source that is excited when the incident wave reaches the
 288 investigated target. The equivalent sources radiate towards the position of the
 289 antenna following the same path as the incident field [30]. Thus, reversing the
 290 received signals with respect to time and use them as excitation sources along \mathbf{F}
 291 will result to a radiated electromagnetic field collapsing at the coordinates of the
 292 scatterers as time approaches to zero. To compensate the two-way travel time,
 293 the velocity of the medium during the back-propagation is set to half the actual
 294 velocity [30]. The mathematical formulation for the RT migration in homogenous
 295 media is

296
$$E_s(\mathbf{r}_m, \omega) = k_b^2 \int_0^M g_e(\mathbf{r}_m, \mathbf{F}(s), \omega) E_{inc}(\mathbf{F}(s), \omega) ds \quad (2)$$

297 where E_s is the back-propagated field in the frequency domain, \mathbf{r}_m is the
 298 parameter indicating the coordinates within the trunk, ω is the angular velocity,
 299 k_b is the wavenumber assuming a homogenous velocity (half of the actual
 300 velocity), E_{inc} is the reversed received signal after processing, M is the
 301 circumference of the trunk and g_e is the Green's function for a homogenous space.
 302 The Green's function in the frequency domain equals with

303
$$g_e(\mathbf{r}_m, \mathbf{F}(s), \omega) = \frac{j}{4} H_0^2(k_b \|\mathbf{r}_m - \mathbf{F}(s)\|) \quad (3)$$

304 where $j = \sqrt{-1}$ and H_0^2 is the Hankel function of the second kind and zero order
 305 [24]. The migrated image is estimated after applying the inverse Fourier
 306 transform to E_s and subsequently set $t = 0$.

307 It should be noted that the exploding model on which migration is based on,
 308 does not take into account the presence of repetitive reflections between the tree
 309 layers. Therefore, a non-adequate elimination of the ringing noise will result to
 310 shallow artefacts due to the misinterpretation of the ringing noise as fictitious
 311 scatterers.

312

313 *2.4 Post-migration processing*

314 The post-migrated image is subsequently subjected to image processing in
 315 order to remove migration effects and enhance the quality of the signal. The
 316 resulting migrated image is initially squared and subsequently convolved with a
 317 2D homogenous Gaussian function

318
$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (4)$$

319 where σ is a unit-less variable that controls the intensity of the filter [37].

320
321 **Table 1: The extended Debye properties of the tree layers used for the numerical simulations [17].**

Tree Section Component	Water Content [%]	ϵ_∞	$\Delta\epsilon$	σ [$\text{W}^{-1}\text{m}^{-1}$]	t_0 (psec)
Cambium layer	70	9	43	1	9.23
Outer sapwood	30	6.1	12.36	0.033	9.23
Inner sapwood	25	5.9	9.66	0.02	9.23
Rings	10	5.4	3.1	0.0083	9.23
Heartwood	5	5.22	1.43	0.005	9.23
Bark	0	5	0	0	9.23

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3. Case Studies and Results

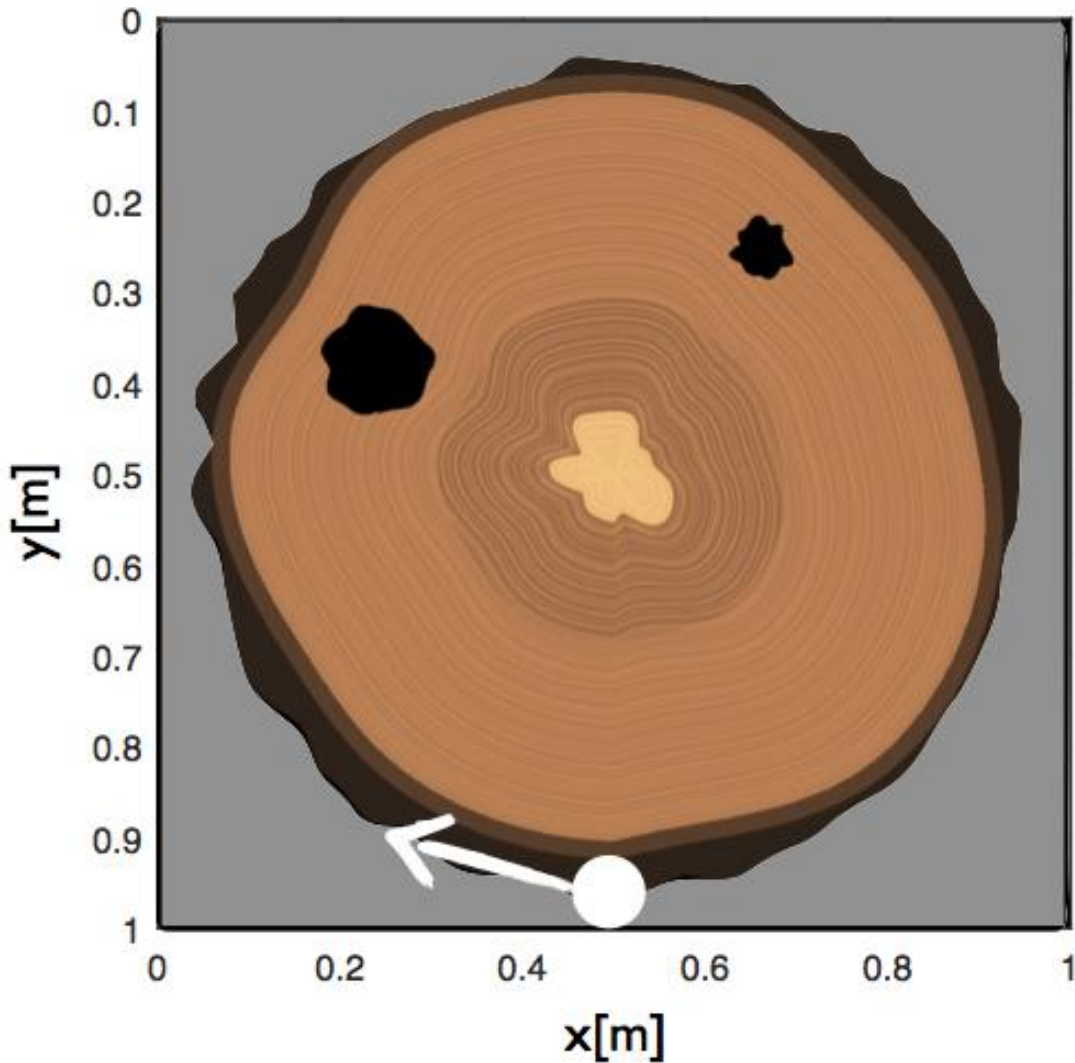
329 3.1 Numerical Case Study

330 In the current section, the proposed detection framework is tested using
331 synthetic but nonetheless realistic data. An FDTD method is used for the
332 simulations with a second order accuracy in both space and time [34], [35], [36].
333 The spatial discretisation step is set to $\Delta x = \Delta y = \Delta z = 1$ mm and the time
334 increment is chosen based on the Courant limit [34]. Regarding the excitation of
335 the system, a numerical equivalent of the commercial antenna GSSI 1.5 GHz [33]
336 is used for the simulations. Simulating the antenna in different positions along
337 the curved surface of the trunk requires the implementation of tilted excitation
338 sources. These scenarios give rise to numerical errors and instabilities due to the
339 constraints from the orthogonal grid of FDTD. To overcome this, instead of
340 moving the antenna along the trunk, the trunk is rotated while the transducer
341 remains still [18].

342 The numerical case study examined in this Section is a generic semi-saturated
343 hardwood. The simulated trunk consists of five distinct layers i.e. the bark, the
344 cambium layer, the outer-sapwood, the inner-sapwood and the heartwood. The
345 dielectric properties of the layers are estimated using a complex-refractive index
346 model (CRIM) [18] subject to the volumetric fraction of water expected in each
347 layer [18]. Subsequently, in order for the dielectric properties to be compatible
348 with FDTD, the complex permittivity is approximated with an extended Debye
349 model (see Table 1) [18], [38]. Lastly, two decays with different sizes are
350 incorporated within the outer-sapwood (see Figure 4). The decays are simulated
351 as hollow semi-cylindrical objects with their main axis being parallel to the main
352 axis of the trunk.

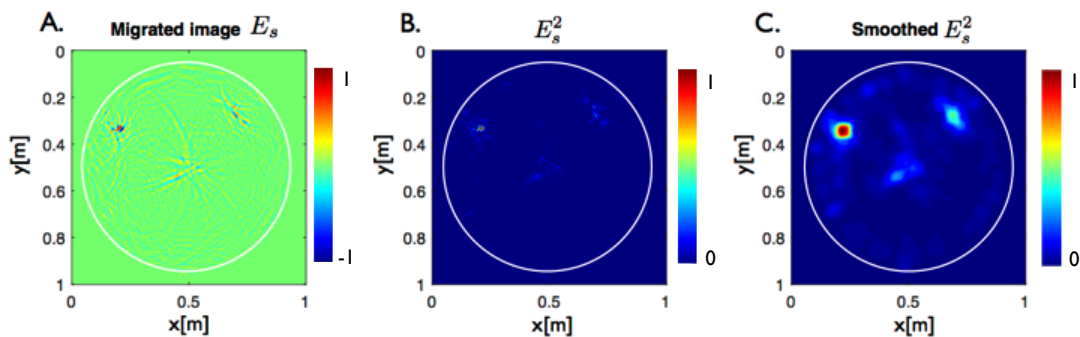
353 The raw B-Scan is initially subjected to the pre-processing pipeline described in
354 Section 2.2. Subsequently, the revised traces are reversed with respect to time
355 and used as input sources in equation (2). The bulk permittivity of the medium is
356 set to $\epsilon=16$. The migrated image is then squared and subsequently smoothed
357 using a Gaussian filter (kernel size equals to 30 and $\sigma = 15$). Figure 5 illustrates
358 the migrated image and the post-migration processing steps. Moreover, Figure 6
359 shows the effect of σ on the final outputs. Increasing σ results to a low-pass filter
360 that decreases migration artefacts and high frequency noise. Both of the decays
361 are accurately detected indicating the validity of the suggested methodology.
362 From Figure 5 is apparent that the relative size between the decays can be
363 extracted from the reconstructed image. Evidences are also given regarding the
364 presence of heartwood at the centre of the trunk.

365



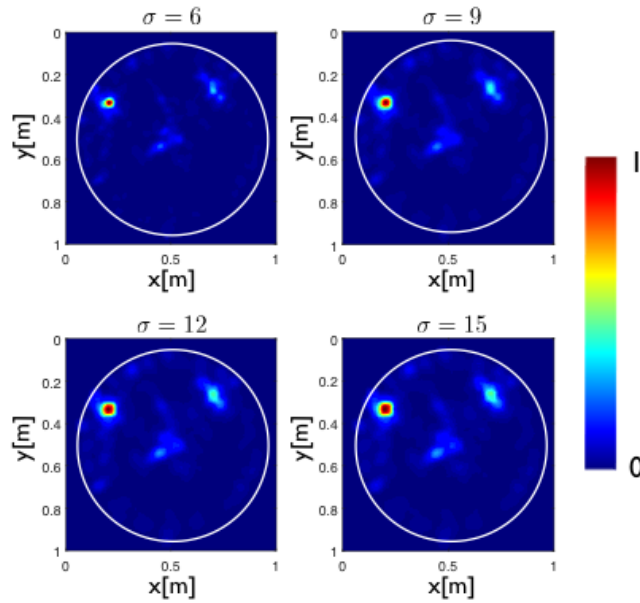
367

368 Figure 4: A numerical case study for the investigation of the received signal of two early decays in a
 369 generic hardwood scenario. The white dot represents the starting point of the scan and the arrow
 370 shows the direction of the measurements. (No colour in print)



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Figure 5: The reconstructed internal structure of the synthetic trunk shown in Figure 4.A) The
 resulting image using RT migration. B) Squaring the migrated image in order to increase the overall
 signal-to-clutter ratio. C) A Gaussian blur filter is applied in order to remove the migration-effects.
 The line of measurements is assumed circular to make the case study more realistic and challenging.
 (No colour in print)



377

378 **Figure 6: The effect of σ to the resulting reconstructed image. Increasing σ results to low pass filter**
 379 **that filters out high frequency noise and migration artefacts. (No colour in print)**

380 *3.1 Field Measurements*

381 The proposed detection scheme is now tested in a real-field case study from a
 382 diseased tree located at Gunnersbury Park, London, UK (see Figure 7). The
 383 employed antenna for this experiment was the dual-polarised hand-held antenna
 384 “Aladdin” from IDS GeoRadar (Part of Hexagon). The central frequency of
 385 “Aladdin” is 2 GHz, the time-step equals to $dt = 6.25e-11$ s and the spatial step of
 386 the measuring wheel is $\Delta = 1$ cm. Circular scans were collected every 5 cm along
 387 the main axis of the tree and parallel to the ground. The overall scanned area is
 388 1.35 m long and consists of 27 parallel circular scans. The inspected area has a
 389 semi-cylindrical shape with a varying circumference. The circumference of each
 390 section was accurately estimated and subsequently incorporated into the
 391 detection scheme by means of the measuring-wheel device attached to the
 392 antenna.

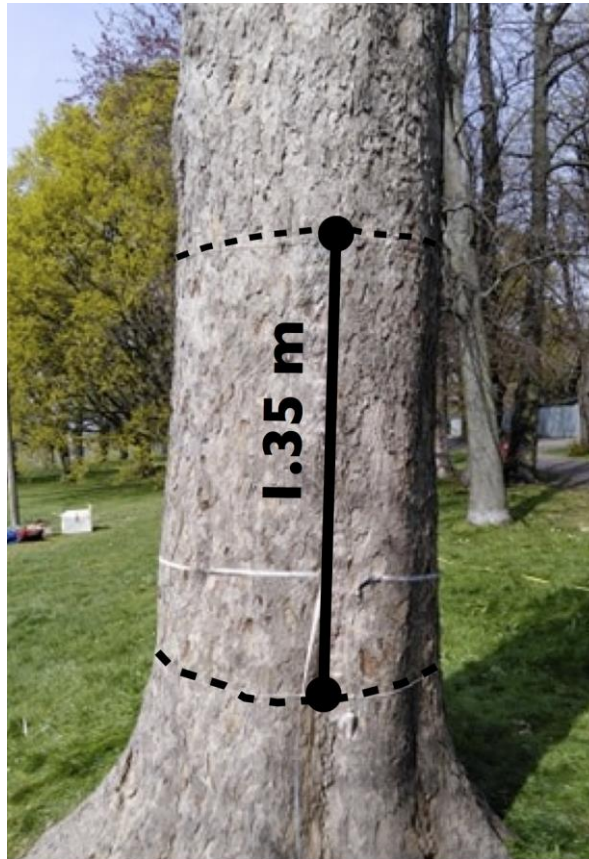
393 Prior to the measurements, the bulk permittivity of the trunk was estimated at
 394 $\epsilon \approx 30$. The permittivity was calculated based on the two-way travel time

395 needed for the wave to travel from one side of the trunk to the other. The
396 permittivity measurements were conducted using the 1 GHz horn antenna
397 system from IDS GeoRadar (Part of Hexagon). The high-directivity of the horn
398 antenna made it possible to get a clear reflection from the back of the trunk. To
399 further enhance the signal, a perfect conducting (PEC) sheet was attached to the
400 tree.

401 After the completion of the measurements, the tree was torn down (see Figure
402 8) and cut into several slices in an effort to get an insight of its internal structure.
403 From Figure 9, a dominant decay extending along the main axis of the trunk is
404 clearly visible. The decay has an irregular shape and a sharp transition from the
405 healthy sapwood. The diameter of the decay is approximately ~ 60 cm and does
406 not show any dominant increasing or decreasing trend along the trunk.

407 Figure 10 illustrates the reconstructed image using the methodology described
408 in Section 2. Every B-Scan is initially processed using a time-zero correction, a
409 zero-offset removal, a linear gain and an SVD filter (five dominant eigenvalues
410 are filtered out). Subsequently, an RT migration is applied to each processed B-
411 Scan subject to a homogenous medium with $\epsilon = 30$. The migrated images are
412 furthermore squared and smoothed using a Gaussian blur filter (kernel size
413 equals to 30 and $\sigma = 15$). The resulting 2D images are then combined to create
414 a pseudo-3D model of the trunk. From Figure 10, it is apparent that there are
415 clear evidences of a major feature at the centre of the trunk extending along its
416 main axis. This is in good agreement with the actual structure of the tree, shown
417 in Figure 9. A reconstructed slice of the tree and its corresponding processed B-
418 Scan are shown in Figure 11. The shape and the size of the decay are adequately

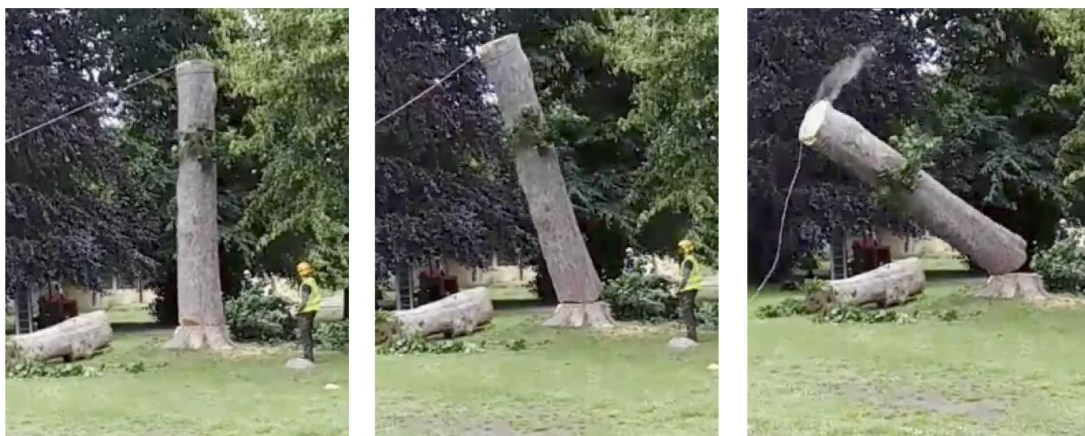
419 recovered. Discrepancies between the actual and the predicted shape are due to
420 local variations of permittivity within the trunk that deviate from the assumption
421 of a homogenous medium with $\epsilon=30$.



422

423 **Figure 7: The investigated tree at Gunnersbury Park, London, UK. The scanned area is highlighted**
424 **between the dotted lines. (No colour in print)**

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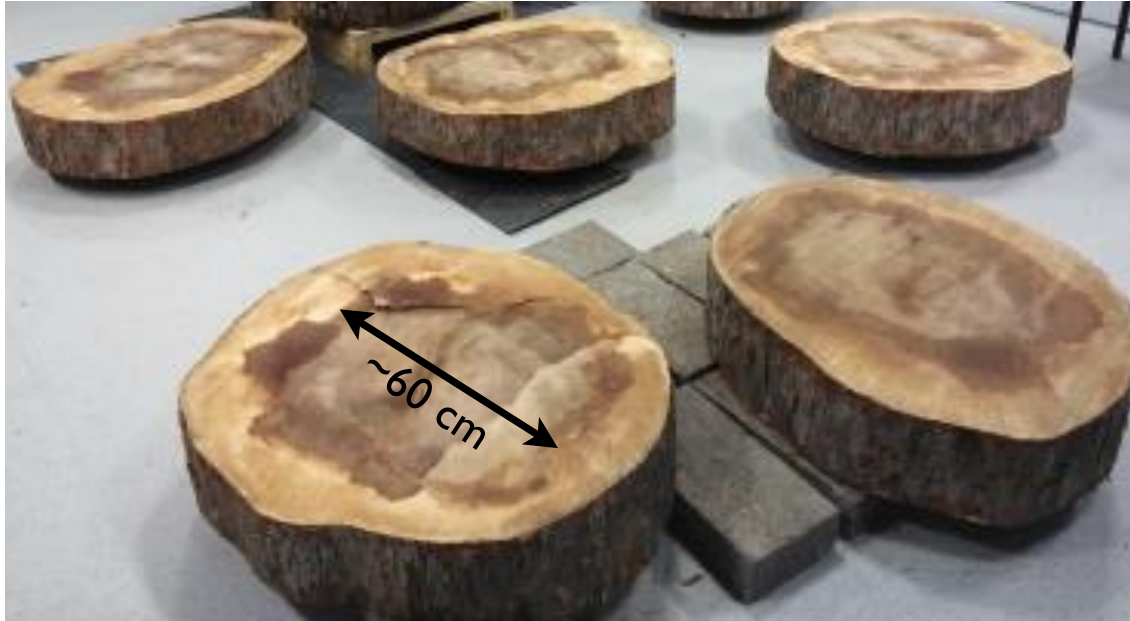
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Figure 8: The investigated tree was torn down after the completion of the measurements in order to
get an insight on its internal structure. (No colour in print)

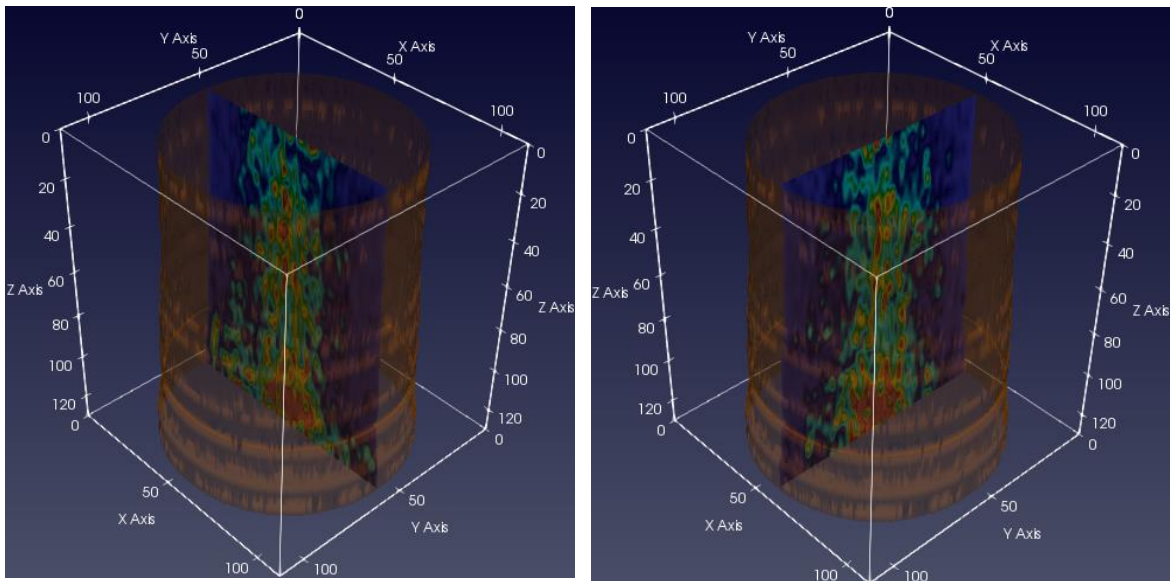
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Figure 9: Slices collected from the investigated tree shown in Figure 7. A dominant decay (with a diameter of approximately ~60 cm) extending along the main axis of the trunk is clearly visible. (No colour in print)

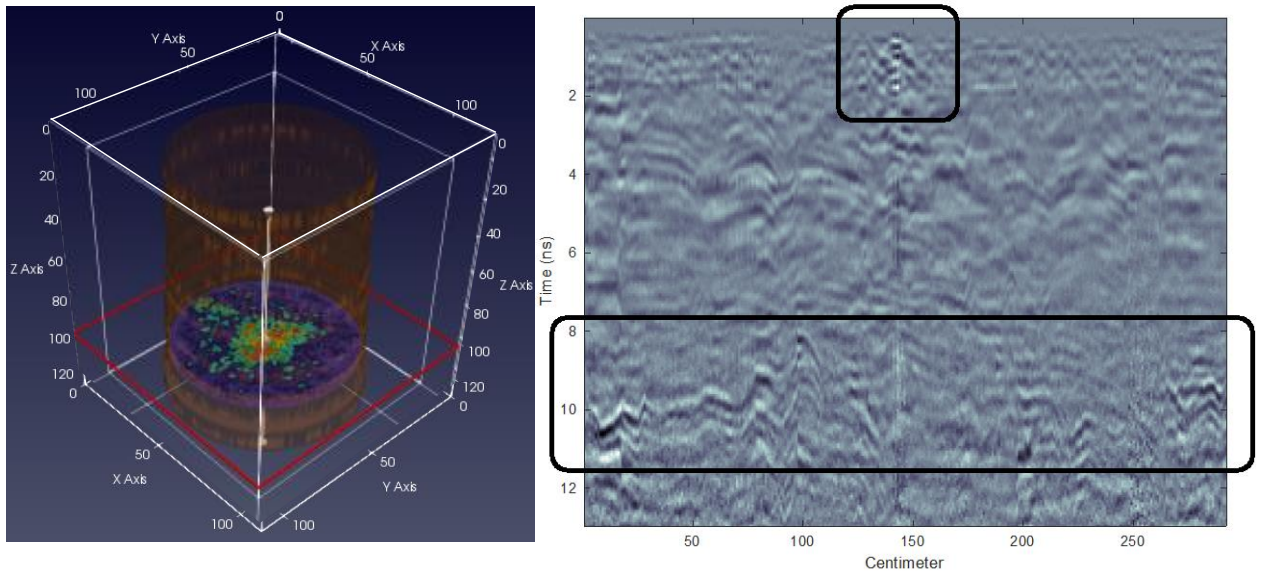
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Figure 10: The reconstructed internal structure of the scanned area shown in Figure 7 using the processing scheme discussed in Section 2. The axis are in cm. (No colour in print)

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450 **Figure 11: A reconstructed slice (left) and its corresponding processed B-Scan (right). Two main**
 451 **decay are apparent, one shallow with small size and one bigger one at the centre of the trunk. The**
 452 **reflections of the two decay are highlighted within the black boxes. (No colour in print)**

453

454 **4. Conclusions**

455

456 In this paper, a detection framework is described fine-tuned for detecting hidden
 457 decay and cavities in diseased trees. The main advantage of the described
 458 methodology is that it can be applied in a straightforward manner using
 459 commercial ground-penetrating radar (GPR) antennas without the need for
 460 bespoke systems and complex measurement configurations. The processing
 461 pipeline of the scheme primarily consists of a singular value decomposition
 462 (SVD) filter coupled with a reverse-time (RT) migration. This implies that the
 463 suggested methodology has minimum computational and operational
 464 requirements making it particularly appealing for large-scale forestry
 465 applications. The accuracy of the described framework is rigorously tested via
 466 numerical and real-field case studies. The results clearly suggest that GPR
 467 coupled with the proposed methodology is a robust detection tool capable of
 468 assessing the health conditions of trees in an efficient and practical manner.

469 Consequently, GPR can answer the on-going call for efficient arboriculture tools
470 and provide a viable alternative for tackling modern challenges related to
471 emerging infectious diseases of trees. The proposed methodology has been
472 validated using high frequency hand-held antennas. Future work will include the
473 application of lower frequencies in an attempt to increase the penetration depth
474 and the overall signal to clutter ratio. Lower frequency antennas are essential in
475 order to overcome the electromagnetic losses within the trunk and can
476 potentially increase the performance of the proposed methodology.

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479 **Acknowledgments**

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481 The authors would like to express their sincere thanks and gratitude to the
482 following trusts, charities, organizations and individuals for their generosity in
483 supporting this project: Lord Faringdon Charitable Trust, The Schroder
484 Foundation, Cazenove Charitable Trust, Ernest Cook, Sir Henry Keswick, Ian
485 Bond, P. F. Charitable Trust, Prospect Investment Management Limited, The
486 Adrian Swire Charitable Trust, The John Swire 1989 Charitable Trust, The
487 Sackler Trust, The Tanlaw Foundation and The Wyfold Charitable Trust.

488 This paper is dedicated to the memory of Jonathon West, a friend, a colleague, a
489 forester, a conservationist and an environmentalist who died following an
490 accident in the woodland that he loved.

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