

1 **New Analysis of Ground Penetrating Radar Testing of a Mixed Railway Trackbed**

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**1 ABSTRACT**

2 The overall aim of this project was to relate Ground Penetrating Radar (GPR) to ballast  
3 fouling.

4 The 10-year old University of Edinburgh full-scale trackbed was re-visited and the  
5 fouling of the ballast was re-calibrated following environmental changes, using the Ionescu  
6 fouling index. A series of GPR experiments were undertaken on the trackbed using a range  
7 of bowtie antennas from 500MHz to 2.6GHz. Scatter analyses of the GPR waveforms  
8 included area analyses, axis crossing analyses and inflexion point analyses. When predicting  
9 Fouling Index, a correlation coefficient greater than 0.9 was obtained by using a 500 MHz  
10 bowtie antenna in the parallel orientation in conjunction with a scan area analysis.

11 This paper will outline the recent work of other researchers and the detailed  
12 experimental programme at the University of Edinburgh.

## 1 INTRODUCTION

2 The “green agenda” combined with highway congestion has accelerated the demand for  
3 increased freight and passenger travel on the world’s railways. For example, according to a  
4 recent UK Department of Statistics publication (1) the distance travelled by UK national rail  
5 passengers has increased significantly and continuously since 1994/5 to 2006/7, from 28.7 to  
6 46.5 billion passenger kilometres. This amount of traffic is greater than the “high forecast”  
7 predicted at the time of rail privatisation in the UK in 1997 of approximately 42 billion  
8 passenger miles by 2007 (2).

9  
10 The principle objectives of this paper are to:

- 11 (a) revisit the status of the University of Edinburgh full-scale railway trackbed after ten  
12 years.
- 13 (b) relate Ground Penetrating Radar (GPR) to ballast fouling

## 14 Current State of Practice

15 A key component of the permanent way structure worldwide is the ballast, which supports  
16 stresses imposed upon the rails and in conjunction with the ties or sleepers, maintains their  
17 correct position. The ballast structure, featuring large voids, provides for necessary drainage  
18 of water and fouling material. Over time ballast deteriorates through a process of degradation,  
19 where the particles mechanically interact, or weather, and change shape; or, through fouling,  
20 where fine particles accumulate in the void structure. Subsoil intrusion is a major source of  
21 fouling, as are wind and waterborne sources that vary with localised environmental  
22 conditions. Such deteriorated ballast is defined as “spent” and fails to provide the drainage  
23 and mechanical functions required.

24 GPR scanning of ballast is starting to take over from traditional visual methods of  
25 inspection (3). This change in the maintenance regime is altering the response to ballast  
26 deterioration from a reactive one, and, consequently, cost-inefficient – to planned  
27 maintenance. This paper will look at further innovation in the interpretation of radargrams  
28 related to ballast fouling.

## 29 Principles of GPR

30 Ground Penetrating Radar (GPR) is a geophysical imaging method based on measuring  
31 reflected electromagnetic waves transmitted in the form of radar pulses in the microwave  
32 band of the radio spectrum (UHF/VHF frequencies). A transmitting antenna radiates pulses  
33 into the ground and a receiving antenna measures variations in the reflected signal time  
34 profile. Reflections occur as the signal moves through material interfaces between two media  
35 of differing dielectric properties.

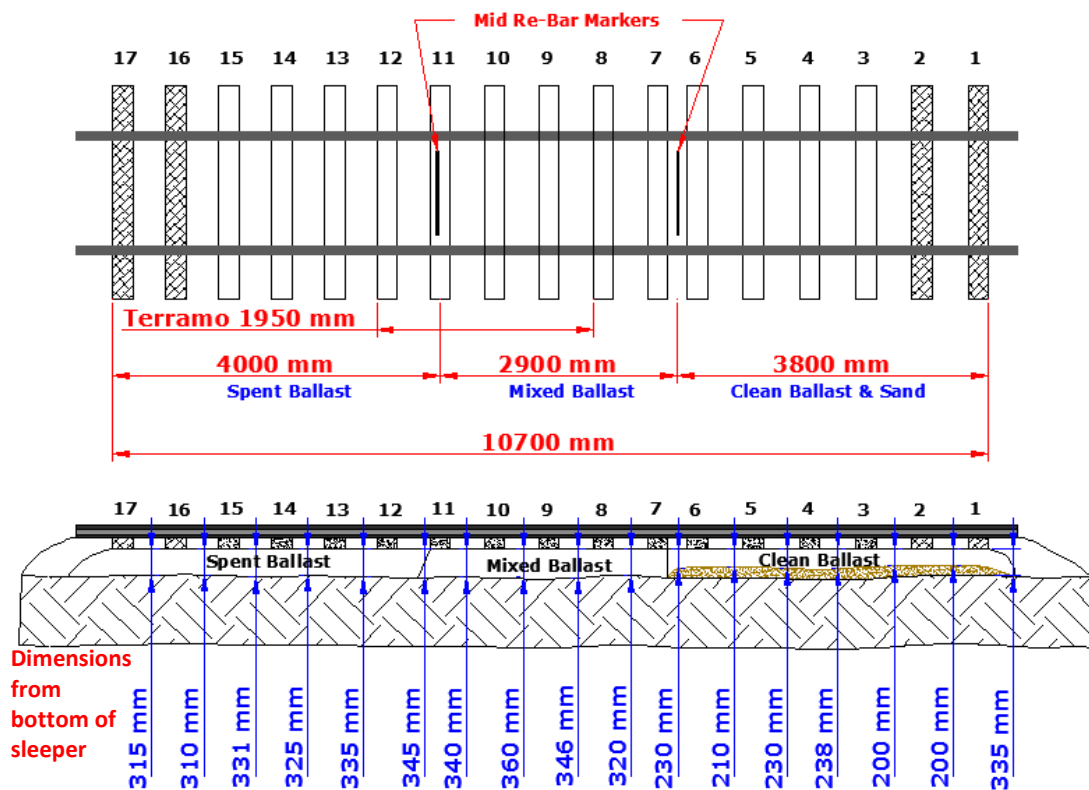


1 An experiment conducted at the University of Edinburgh found that signal  
 2 propagation varied with the condition of the ballast:  $1.73 \times 10^8$  m/s for dry clean ballast,  $1.60$   
 3  $\times 10^8$  m/s for wet clean ballast (5% moisture content), and  $1.45 \times 10^8$  m/s for dry spent ballast  
 4 (5).

## 5 TRACKBED ANALYSIS

### 6 University of Edinburgh Railway Trackbed

7 A section of trackbed was constructed at the University of Edinburgh as part of an earlier  
 8 project (2). The track is full-scale and 10m long, Figure 2. It is of uniform construction and  
 9 materials used, except that there was the deliberate addition of fines in some parts to induce  
 10 its "spent" nature. The track was built to British Rail Standard BR1203.



11 **Figure 2 Pilot-scale trackbed facility (2)**

### 12 Trackbed Analysis

13 Since construction, the test track has undergone physical changes that can be attributed to  
 14 weather conditions and experimentation. It was necessary to undertake a full analysis of the  
 15 ballast condition by means of particle size distribution (PSD) analysis in order to determine  
 16 the relationship between GPR data and ballast deterioration.

17 The purpose of analysing the PSD results was to determine the fouling index for each  
 18 crib. There are two distinct methods for calculating the deterioration of ballast developed by  
 19 Selig, et al, 1994 (5) and Ionescu, 2004 (6), with the latter adhering to Australian standards

- 1 that approximately conform to the material parameters used in British trackbed construction.  
 2 Since the trackbed was constructed to BR1203 specifications, the Ionescu method was used: -

$$F_I = P_{0.075} + P_{14}$$

Where:

$F_I$	=	Fouling index
$P_{0.075}$	=	% passing 0.075mm sieve
$P_{14}$	=	% passing the 14mm sieve

- 3 The categories of fouling developed by Selig & Waters were used in conjunction with  
 4 the derived fouling index formula to determine the condition of the test track. Applying  
 5 Ionescu's formula to the collected data returns the following results (Table 1): -

6 **Table 1 Ballast fouling index**

Crib No.	$F_I$	Category
1	1.60%	Moderately Clean
2	1.74%	Moderately Clean
3	1.41%	Moderately Clean
4	1.06%	Moderately Clean
5	2.40%	Moderately Clean
6	1.36%	Moderately Clean
7	4.41%	Moderately Clean
8	10.74%	Moderately Fouled
9	14.89%	Moderately Fouled
10	11.50%	Moderately Fouled
11	1.93%	Moderately Clean
12	22.23%	Fouled
13	24.94%	Fouled
14	15.90%	Moderately Fouled
15	17.06%	Moderately Fouled
16	30.73%	Fouled

- 7 A limitation of such a fouling index is that although the degree of fouling is related to  
 8 the spentness of the ballast, it is only a function of spentness. This is because fouling index is  
 9 solely a description of the fines content of a particular ballast sample but spentness is a  
 10 description of a collection of various other variables such as fines content, drainage  
 11 efficiency, and surface texture (7).

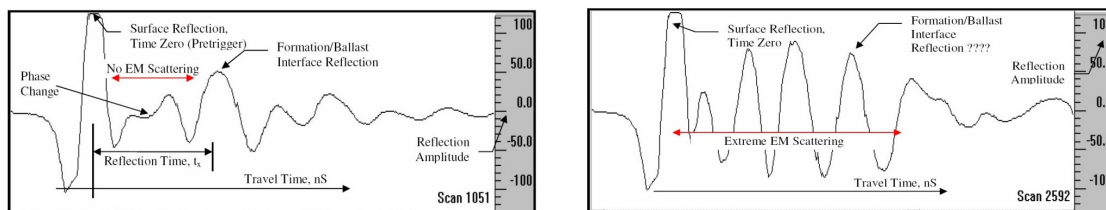
## 1 SCATTER ANALYSIS

### 2 Principles of Radar Scatter

3 Scattering losses can be described as extremely frequency dependant; scattering is known to  
 4 increase as the frequency increases. GPR signals are sent through many kinds of materials  
 5 and encounter many heterogeneous electrical and magnetic properties. Small-scale  
 6 heterogeneities generate weak or undetectable responses but their presence extracts energy as  
 7 the EM field passes and it gets scattered (8).

### 8 University of Edinburgh Research

9 Previous research at the University of Edinburgh (2) found that on studying the time-  
 10 amplitude plot of a single radar pulse reflection, it could be seen that where the ballast tested  
 11 was “spent” the signal plot featured “scattering” between the surface reflection response and  
 12 the ballast-formation layer interface reflection; where the ballast was not spent, there was no  
 13 “scattering” (Figure 3).



14 **Figure 3 Example of 500MHz antenna scan through clean (left) and spent ballast (2)**

15 Two antennas were used, a 900MHz and a 500MHz. The 500MHz antenna  
 16 demonstrated increased power and the lower centre frequency resulted in a greater depth  
 17 penetration over the 900MHz. The resolution was significantly lower (approximately halved,  
 18 consequent with the reduction in frequency). However, the reflection times through the same  
 19 media were similar. None of the antennas managed to produce reflections through the ties.

20 The 500MHz and 900MHz signals through the clean ballast gave no EM scattering,  
 21 and a clear formation reflection. Through the mixed ballast, there was increased EM  
 22 scattering, a less clear formation reflection, and a reduced propagation velocity consequent  
 23 with a greater dielectric constant. Through the spent ballast there was extreme EM scattering  
 24 making the formation reflection indistinguishable, and a further reduced propagation velocity.  
 25 The 900MHz signals demonstrated greater scattering than the 500MHz signals through the  
 26 same material.

27 The differences in results were attributed to the spent ballast having a greater fines  
 28 content with consequently fewer air voids, and poorer drainage efficiency and, consequently,  
 29 greater moisture content due to moisture retention from soil suction. Loss of voids (with a  
 30 very low dielectric value) and replacement with moist fines (with a significantly higher  
 31 dielectric value) resulted in the increased scattering and attenuation.

32 The experiments were repeated several times over one year in different weather  
 33 conditions. It was found that the clean ballast results varied by 5% to 7%; the spent ballast  
 34 results varied up to 25%. Ballast-saturation tests (7) determined that the greater variability of  
 35 the spent ballast was due to its ability to hold water due to soil suction or capillarity and  
 36 become saturated due to rain; the clean ballast is more free-draining and less affected by rain.

1 This University of Edinburgh research demonstrated that railway ballast could be  
2 fingerprinted using GPR.

### 3 Scattering Analysis and Fouling Detection

4 The GPR research at Edinburgh used bowtie antennas, whereas research at the Transportation  
5 Technology Center, Inc. (TTCI) in Pueblo, CO, used horn antennas (9) to detect ballast  
6 fouling. At TTCI, they found that with the use of 2GHz horn antennas that clean ballast gave  
7 a more scattered response than fouled ballast (10).

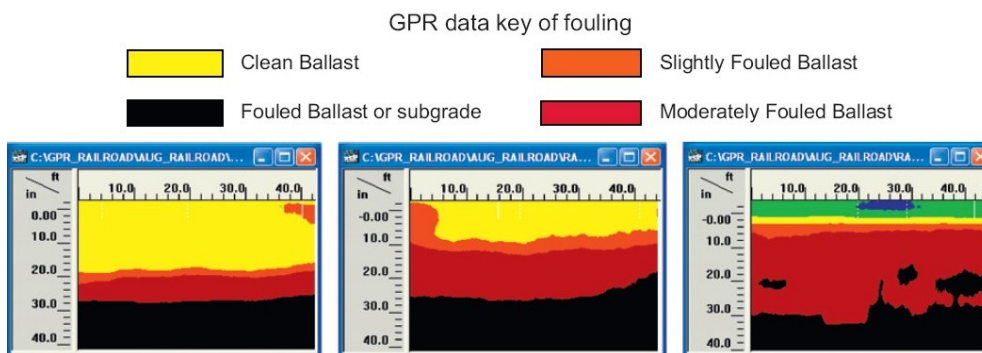
8 In contrast to traditional GPR data analysis, in which individual reflections are  
9 charted, the 2GHz horn antenna data from the ballast was processed to generate a  
10 representative scattering amplitude envelope, i.e., a running average between peak signal  
11 responses, that showed the average scattering amplitude versus depth.

12 A change in the size of the envelope was determined to indicate a change in ballast  
13 condition. A “gain restoration curve”, which was empirically derived from the amplitude  
14 correction required to achieve constant amplitude versus arrival time from data obtained over  
15 a section of thick, clean ballast, was applied to, presumably, discount the effects of  
16 attenuation.

17 It was determined that radar signals through the clean ballast scattered due to the void  
18 space present in clean ballast but not in spent ballast where it had been filled with fouling  
19 material. The fouled ballast was more homogenous in its structure due to the fouling material  
20 between the ballast particles, and consequently, the signal did not scatter as much.

21 The rationale for this was presented in subsequent research (11), which stated that  
22 because spent ballast has a “finer, well-graded particle size with fewer air voids” that “The  
23 clean ballast near the surface generates a significant scattering pattern, while the scattering  
24 pattern generated by the fouled ballast at the bottom is insignificant because the air voids in  
25 fouled ballast are much smaller than the signal wavelength”.

26 The results of this method of analysis can be seen in Figure 4.



27 **Figure 4 Typical results from scattering amplitude envelope analysis (11)**

28 Thus, “From the image analysis, ballast thickness, ballast fouling condition, and  
29 trapped water can be assessed” (11)

30 It should be noted that the above research at TTCI was all conducted on ballast  
31 composed of a clean layer of ballast, over a mixed layer of ballast, over a spent layer of  
32 ballast, all of varying thicknesses. This is in contrast to the Edinburgh experiments.

## 1 **International State of Practice**

2 The earlier research at the University of Edinburgh (12) showed that it is possible for GPR to  
3 determine the depth of a railway ballast layer and to gain an indication of whether the ballast  
4 is clean, mixed, or spent. The experiments relied on “all other things being equal” in order to  
5 determine good track from bad, or in this case, “spent” from “clean”. Recent work by  
6 practitioners has relied on the Edinburgh research and they have focused on developing high-  
7 speed data collection systems – using later Edinburgh research (3)

8 Given that the measurement metric used in the TTCI research is the “scattering  
9 amplitude envelope” and that, in any case, this would be expected to diminish with depth due  
10 to attenuation, the “scattering amplitude envelope” method, therefore, relies on discerning  
11 changes in the amplitude and relating that to changes in the ballast condition through  
12 empirically derived calibration with gain settings taken into consideration.

13 Therefore, an alternative measurement of “scattering” that is not attenuation related  
14 would be attractive to investigate.

## 15 **NEW EXPERIMENTS AT THE UNIVERSITY OF EDINBURGH**

### 16 **Objectives**

17 The objectives of this experimental work are to develop a method of analysing the incidents  
18 of scatter, rather than amplitude of the scatter, using a range of different frequency antennas.

### 19 **Experimental Procedure**

20 Gallagher, Figure 3, defined the increased scattering through a visual inspection of a signal  
21 plot, where the increased numbers of large peaks were a result of the EM wave being  
22 scattered by the smaller particles of the spent ballast. It has been stated that the signal from  
23 ballast can be assumed to be a random signal and that statistical analysis would be a more  
24 suitable method of analysis (11)

### 25 **Data Collection**

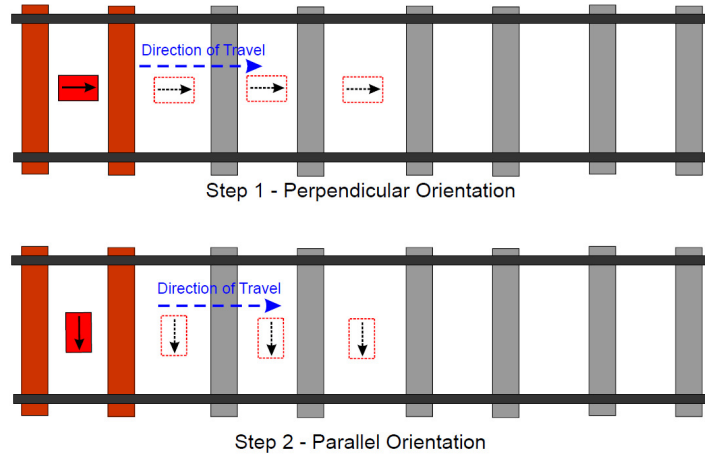
26 The track was scanned with a range of GSSI antennas of different frequencies: 500MHz,  
27 900MHz, 1.0GHz, 1.6GHz, and 2.6GHz.

28 The higher frequency bowtie antennas may not be suitable for detecting faults or  
29 anomalies in ballast and may be more suited to tasks such as locating objects in concrete.  
30 Their inclusion was intended to reveal trends in the analysis across the range of frequencies.

31 All data was collected using either a trolley or with a survey wheel designed to hold  
32 the antennas and measure distances travelled.

33 The data was recorded without any gain settings distorting the collected data.

1 The scanning procedure started with the antennas moving from Tie 1 to Tie 17.  
2 Given that bowtie antennas transmit from one side of their casing and receive at the other,  
3 this was undertaken twice with the antenna in perpendicular then parallel orientation, Figure  
4 5.

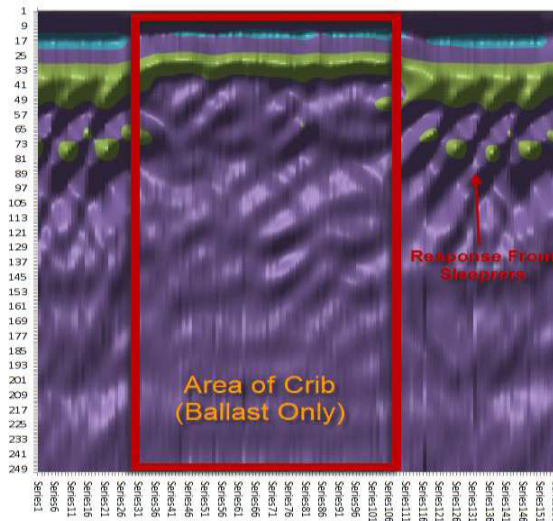


5 **Figure 5 Data collection method (13)**

6 A scan rate of 200scans/m was used, resulting in over 2000 scans for each run of the  
7 test track; although, 100scans/m was used for the 500MHz and 900MHz. Each scan was  
8 composed of 512 samples, giving over one million data values per run.

9 **Data Analysis**

10 The raw numerical data for each run was imported into an individual spreadsheet and contour  
11 plots of the radar data were produced and these were used to visually isolate the “cribs”  
12 (Figure 6) – those areas between the ties where the ballast is on the surface creating Crib 1 to  
13 Crib 16.



14 **Figure 6 Example of 3D contour plot used for crib isolation for 2.6GHz data**

1 In order to calculate the incidents of scatter for each crib, three metrics were devised: -

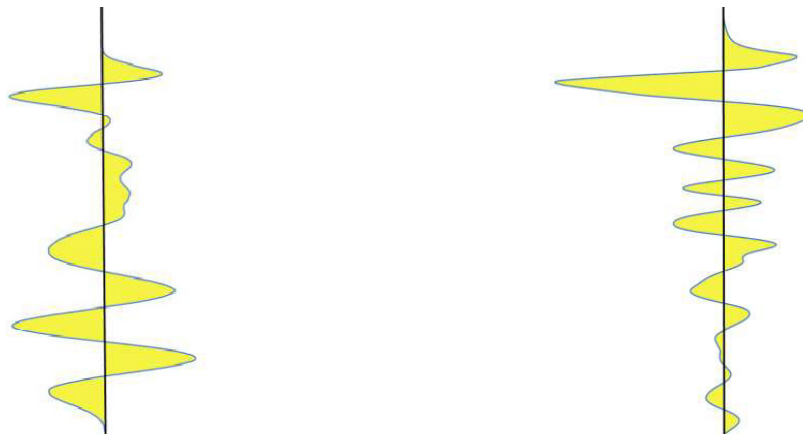
2 **Scan area** A numerical integration of a scan response to determine its “area” – the  
3 greater the magnitude of the responses, the greater the area.

4 **Axis crossings** The number of times the scan response crosses the zero amplitude axis  
5 – the more interfaces encountered by the signal, the more axis crossings.

6 **Inflection points** The number of times the gradient of the scan response changes through  
7 zero – the more interfaces, the more inflection points.

### 8 **Scan Area Analysis**

9 For each scan, the average signal value was calculated. This was taken as the zero amplitude  
10 axis for that scan. A simple trapezoidal rule was utilised to integrate some or all the 512  
11 sample values of each scan (Figure 7).



12 **Figure 7 Scan area for typical clean response (left) and spent response (right)**

### 13 **Axis Crossings Analysis**

14 For each scan, the average signal value was calculated. This was taken as the zero amplitude  
15 axis for that scan and the number of times that the signal crossed the average value was  
16 counted. Extrapolating from Gallagher’s findings from signal responses through spent ballast  
17 (2), it was anticipated that the more a signal is scattered, the more it should cross the axis.

1 A simple algorithm counted the number of crossing points. Any sample value that  
 2 was between a sample value greater than the average scan value and a sample value lower  
 3 than the average scan value, an axis-crossing was counted (Figure 8).

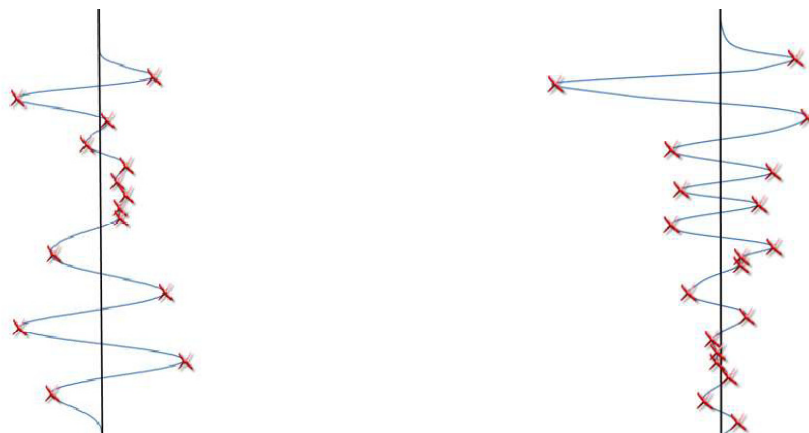


4 **Figure 8 Axis crossings for typical clean response (left) and spent response (right)**

#### 5 **Inflection Points Analysis**

6 For each scan, the number of inflection points was counted. Similar to crossing points, it was  
 7 anticipated that the more scattered a response, the more inflection points it should have.

8 The number of inflection points was calculated by using a variation of the algorithm  
 9 used to count the crossing points. Any sample value that was between two greater value  
 10 samples or between two lower value samples, an inflection point was counted. This method  
 11 did not require the location of the zero amplitude axis (Figure 9).



12 **Figure 9 Inflection points for typical clean response (left) and spent response (right)**

#### 13 **Time Range**

14 Given the different frequencies of each antenna, different depths of penetration were  
 15 achieved and recorded. It was noted at which of the 512 samples that the ground surface  
 16 occurred and where the response was visually considered to have become noise dominant.  
 17 Therefore, for the analysis different time ranges were used: -

- 1       • **Full-time range:** All 512 samples collected were analysed.  
 2       • **Common time range:** Only 5ns of data below the initial ground reflection was  
 3       analysed in order to limit analysis to ballast responses only.

#### 4 **Results & Discussion**

5 By using the Scan Area Analysis, the Axis Crossings Analysis, and the Inflection Points  
 6 Analysis metrics, the amount of signal scattering was identified. The data was analysed using  
 7 three different approaches to determining which sample ranges to use: the full 512 samples,  
 8 and a reduced common range (5ns).

#### 9 **FULL TIME RANGE**

10 The results of the scattering analysis for the full range of the scan are listed in Table 2. The  
 11 highest values for each section of analysis (area, crossings, and inflections) are highlighted in  
 12 red and the lowest in green.

13 **Table 2 Results of scattering analysis for full time range**

Antenna	Orien.	Range (ns)	Area Of Scan			Axis Crossings			Inflection Points		
			Moderately		Fouled	Moderately		Fouled	Moderately		Fouled
			Clean	Fouled		Clean	Fouled		Clean	Fouled	
500 MHz	Perp.	23	1269272	1820730	2088340	15.57	16.02	16.99	17.50	18.12	19.31
	Parallel	23	1179536	1568375	2059104	15.31	16.02	16.70	17.81	17.28	18.62
900 MHz	Perp.	20	696421	987018	1235757	27.69	23.48	24.05	45.92	37.05	36.17
	Parallel	20	817121	1077727	1555518	26.25	23.67	23.91	46.10	38.22	35.31
1.0 GHz	Perp.	20	703692	952372	974882	29.58	29.06	28.55	33.59	32.20	31.07
	Parallel	20	972730	1210584	1204123	26.67	25.77	26.97	32.79	31.68	31.89
1.6 GHz	Perp.	20	430589	416034	407551	21.86	19.86	19.41	56.49	52.07	54.22
	Parallel	20	383307	426471	423533	19.63	15.95	16.79	54.81	51.50	53.42
2.6 GHz	Perp.	10	333581	339728	338602	20.59	20.30	20.23	16.44	15.16	14.98
	Parallel	10	376546	394878	385945	20.27	19.98	19.56	23.48	22.48	22.04

#### 14 **Full Time Range Scan Area Analysis**

15 It can be seen that the clean ballast has the smallest area in most cases with the spent or  
 16 mixed ballast having the largest areas. This trend is more consistent at the lower frequencies  
 17 under 1GHz; this appears to correlate with Gallagher et al. 1999 (12).

#### 18 **Full Time Range Axis Crossings Analysis**

19 Similar to the area analysis, there is a difference in behaviour between high and low  
 20 frequency antennas. With antennas of 900MHz or over, the clean ballast features more axis  
 21 crossings than the spent ballast. Below 900MHz, the behaviour is the reverse with the spent  
 22 ballast having more axis crossings than the clean.

## 1 Full Time Range Inflection Points Analysis

2 The results are very similar to the axis crossing points analysis with the same behaviour  
3 occurring. Again, the 900MHz antenna appears to be the point at which the behaviour  
4 changes, with almost 20% more inflection points.

## 5 COMMON TIME RANGE

6 The results of the scattering analysis for the common time range of the scan are listed in  
7 Table 3. The highest values for each section of analysis (area, crossings, and inflections) are  
8 highlighted in red and the lowest in green.

9 **Table 3 Results of scattering analysis for common range**

Antenna	Orien.	Range (ns)	Scan Area			Axis Crossings			Inflection Points		
			Moderately		Fouled	Moderately		Fouled	Moderately		Fouled
			Clean	Fouled		Clean	Fouled		Clean	Fouled	
500 MHz	Perp.	5	519361	649110	493665	3.95	3.87	3.78	4.47	4.47	5.32
	Parallel	5	495875	585394	531113	3.38	3.96	4.26	4.77	4.40	5.25
900 MHz	Perp.	5	222113	242224	258231	6.91	5.58	6.72	9.14	7.91	8.44
	Parallel	5	201378	242690	253223	6.45	5.40	6.74	8.89	7.51	8.36
1.0 GHz	Perp.	5	149771	187753	190682	7.85	8.08	7.74	9.22	8.97	8.55
	Parallel	5	179378	218713	201614	6.84	7.24	7.21	8.81	8.75	8.76
1.6 GHz	Perp.	5	382593	362212	352233	9.89	9.73	9.50	11.04	11.30	10.86
	Parallel	5	353525	412695	403925	8.47	8.29	8.05	10.28	9.23	9.59
2.6 GHz	Perp.	5	299528	302294	300923	10.63	10.65	10.75	14.42	13.22	12.96
	Parallel	5	331064	347733	339890	10.55	10.50	10.36	14.32	13.55	13.05

## 10 Common Time Range Scan Area Analysis

11 The trend in results of the area analysis are broadly unaffected by a change in the time range  
12 analysed. The clean ballast once more has the smallest areas. As with the full time range, the  
13 antenna where a change in behaviour occurs is the 1.0GHz.

## 14 Common Time Range Axis Crossings Analysis

15 Unlike to the full range analysis, the trend in the results is of a more random nature.

## 16 Common Time Range Inflection Points Analysis

17 The trend in the results is also very similar to those of the full range. The 900MHz antenna  
18 contains significantly more inflection points for clean ballast while the 500MHz antenna has  
19 more inflection points in spent ballast. All of the high frequency antennas, with the exception  
20 of the 1.6GHz perpendicular antenna, have more inflection points in clean ballast than in  
21 spent ballast.

## 1 METRIC EVALUATION FOR FULL-TIME RANGE

2 In order to evaluate the effectiveness of this method of measuring the scattering, the  
3 correlation between the scattering analysis and the fouling index was investigated (Table 4).

4 **Table 4 Fouling index correlation factors for full-time range scattering analysis**

Antenna	Orien.	Scan Area			Axis Crossings			Inflection Points		
		Moderately		Fouled	Moderately		Fouled	Moderately		Fouled
		Clean	Fouled		Clean	Fouled		Clean	Fouled	
500 MHz	Perp.	0.499	0.019	0.809	0.378	-0.356	0.286	0.619	0.616	0.462
	Parallel	0.816	0.330	0.924	0.613	0.674	0.295	0.213	0.133	0.034
900 MHz	Perp.	0.502	0.569	0.740	-0.074	-0.157	-0.599	-0.392	-0.488	-0.719
	Parallel	0.648	0.634	0.756	0.041	0.076	-0.439	-0.340	-0.289	-0.802
1.0 GHz	Perp.	0.519	0.519	0.436	0.149	0.072	-0.336	-0.423	-0.296	-0.481
	Parallel	0.679	0.314	0.678	0.234	0.504	-0.061	-0.057	-0.006	-0.340
1.6 GHz	Perp.	-0.257	-0.228	-0.185	0.180	-0.388	-0.327	0.448	-0.079	-0.251
	Parallel	0.676	0.672	0.545	-0.551	-0.466	-0.274	0.136	-0.306	-0.221
2.6 GHz	Perp.	0.722	0.111	0.282	0.000	0.065	-0.120	-0.563	-0.683	-0.647
	Parallel	0.301	0.342	0.326	0.000	-0.140	-0.306	0.035	-0.721	-0.687

## 5 Scan Area Metric Evaluation

6 There was a strong correlation between the scan area metric and the fouling index for the full-  
7 time range. In order for the scan area metric to be true, the largest magnitudes of response  
8 should occur in the spent region of ballast.

9 The results indicate that for low frequency antennas scattering occurs more in spent  
10 ballast, which correlates to the work carried out by Gallagher et al 1999 (12). When the  
11 frequency of the antenna increases, it is almost impossible to distinguish between clean and  
12 spent ballast in terms of scattering. This appears to contradict the work of Al-Qadi et al,  
13 2008 (10) who stated that when using high frequency antennas scattering occurs more in  
14 clean ballast. However, it should be noted that Al-Qadi et al used horn antennas.

15 The noticeably improved results in lower frequency antennas may be due to the  
16 increased power of the antenna itself, with the lower frequency antennas less likely to  
17 interpret minor changes in particle size and constituency as a change in material layer, which  
18 ultimately results in a better indication of ballast depth and layer interfaces.

## 19 Full-Time Range Axis Crossings & Inflection Point Analysis

20 The results for axis crossings and inflection points are less promising. However, there are a  
21 large number of negative correlations for both metrics and very few strong correlations in the  
22 data. The large negative values are mainly for the full-time range data and suggest that there  
23 is a possible link between the scattering analysis and fouling index. The axis crossings metric  
24 does not appear to demonstrate any correlation in the data. Therefore, both these approaches  
25 were deemed inappropriate for determining the condition of the ballast.

26 It had been expected that when the range of data analysed was shortened to the depth  
27 of the ballast, ie, 5ns, that any correlation with the fouling index would be improved.  
28 However, the opposite was true. It may be that the sub-ballast material gives a different

1 response when under clean or spent ballast, and this may be due to drainage differences  
2 between clean and spent ballast.

### 3 CONCLUSIONS

4 The scattering analysis on data from bow-tie antennas clearly showed that EM waves in clean  
5 ballast have a much smaller area. This applies to all antennas and all the time ranges  
6 analysed.

7 For low frequency antennas (below 900MHz), there are more crossing points and  
8 inflection points for clean ballast for both the full range and shortened range. However, in  
9 the individual range that relates to the skin depth of each antenna, the spent ballast has the  
10 most crossing points for most antennas.

11 In the full time range analysis, the clean ballast consistently has the lowest area, most  
12 crossing points and most inflection points except for the 500MHz antenna. There is a clear  
13 distinction in the response from clean ballast to that of mixed or spent. The distinction  
14 between the mixed and spent is less clear.

15 The results with the low frequency antennas support Gallagher's theory that EM waves  
16 passing through spent ballast encounter more scattering.

17 When predicting Fouling Index, a correlation coefficient greater than 0.9 was obtained by  
18 using a 500 MHz bowtie antenna in the parallel orientation in conjunction with a scan area  
19 analysis.

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