Guideline on Methods to Find Hot-Spots on Rail Networks

D1.2

Authors

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Executive Summary

Whilst the cost of monitoring equipment is reducing rapidly and our ability to collate, transmit, store and interpret data is constantly evolving, for linear networks which are spread over thousands of km, there is a need to identify which critical sections should be monitored. This report focuses on the guideline on methods to find hot-spots on rail networks and to quantify the performance of the infrastructure using non-intrusive methods. The approaches that were implemented on operating rail networks include:

1. A 182km long Ground Penetrating Radar (GPR) survey of the Croatian Rail network was performed. The interpreted data allowed potential hot-spots to be identified. At these locations more intensive investigation techniques that determine physical properties for the sections can then be targeted.

2. A demonstration of the capabilities of GPR to detect subsurface features including; boundary interfaces, ballast pockets, subgrade penetration, ballast pockets and mud-pumps was undertaken on the Norwegian rail network.

3. An investigation of the potential for GPR to measure water content changes in the ballast during a rainfall event was performed on a test-section of the Norwegian Rail network. The results were promising in that the post-processing of signals suggested that changes were qualitatively evident. However, data variability due to the test in the test procedures precluded the determination of quantitative correlation and further testing with stricter test protocols will be required to achieve this aim.

4. As train speeds increase it is crucial that dynamic amplification of ground settlement is avoided. The very soft clay and peat deposits prevalent in much of Europe have Rayleigh wave velocities as low as 200 km/hr. Identifying sections of the network where these deposits are present is crucial for efficient operation of higher speed trains. The shear wave velocity can be measured using geophysical techniques and in-situ or laboratory testing. This report describes a novel approach to compares train measurements with predictions using a numerical model.

5. Rock falls are a major hazard for rail operations in many European countries. The application of LiDAR data together with Gigapixel photography is demonstrated as a method of finding potential rock fall areas in Norway.

This deliverable describes the work completed for Task 1.2 of the Destination Rail project and meets all the objectives of the work described.
1. Introduction

Whilst the cost of monitoring equipment is reducing rapidly, our ability to collate, transmit, store and interpret data is constantly evolving. For railway infrastructure managers (IM) this a dynamic problem as the condition of assets is constantly changing due to ageing and external factors such as a change of adjacent land use or animal burrowing etc. In this report a range of methods of interrogating data collated over large sections of the network to provide markers for hot spots is investigated.

As an example Ground Penetrating Radar (GPR) is routinely collected using train-mounted antennae. Using a range of antenna measuring at different frequencies, a complete three-dimensional image of the section can be obtained. This allows detection of anomalies such as ballast pockets due to depression, animal burrows and the concentrations of water (through the distribution of water content). Extensive GPR surveys on the Croatian rail network were used to provide information on the location of potential problem areas (hot-spots). At these locations more intensive seismic methods and electrical tomography were applied to give more information on the issue at hand and allow for effective mitigation methods to be determined. In Norway the use of vehicle speed GPR to determine the ground structure and detect anomalies is demonstrated in Norway. A study of the potential use of GPR in tracking changes in moisture content during rainfall infiltration is also presented. As network operators increase track speeds, the issue of dynamic amplification between the moving train and soft soils is increasing in importance. The potential for this problem is dependent on the Rayleigh wave velocity of the ground that can be measured using a range of methods that require track possessions. The potential for using on train measurements to validate numerical models is examined in the report using data from a test site in Sweden. In the final section the combination of LiDAR and high resolution photography is demonstrated as an effective means of identifying rock fall susceptibility over large geographical areas.
2. Use of Geophysical Methods for Detection of Hot Spots

2.1 Introduction

The majority of the railway infrastructure in Europe is over one hundred years old and was not built to conform to modern standards. In common with many other EU member states, a lack of investment in maintenance and remediation projects in over the last 30 years has resulted in generally poor condition of many elements of important infrastructure, including earthworks, track and structures. To reduce risk IM’s often use traffic speed restrictions with limitations up to only 20 km/h on some sections. In the current economic climate, it is vital that we maintain and develop our transport network and optimize the use of all resources. A first step to optimizing the use of assets is to accurately identify those that are highest risk.

The incidence of major failure of critical sections on rail infrastructure is increasing. The current response is reactive i.e. when failures occur they are fixed. The location of the failure then becomes a hot spot on the network. Forensic analyses of these failures often note that indicators of distress were ignored due to lack of understanding or absence of a proper framework for decision-making. As the condition of assets is constantly changing due to ageing and external factors such as a change of adjacent land use, climate changes etc. it is necessary to give a guideline on methods for acquisition and analysis of data collated over large sections of the network to provide markers for hot spots.

As a method which can be effectively and routinely used on railway lines, Ground Penetrating Radar (GPR) can detect a number of features directly linked with asset condition by using a range of antenna measuring at different frequencies and at different depths. These features include ballast fouling, anomalies in railway embankments (including burrows), boundaries between layers, substructure condition, the water content of the soil etc. Even though method has some limitations, GPR surveys are regularly completed on modern rail networks and this report seeks to optimize the usefulness of data that can be obtained from this method which offers the advantages of reliability and speed. By early identification of hot spot locations, low-cost remediation can be applied and thus costs can be reduced and failures avoided.

In last few decades GPR has found its application in civil engineering (underground engineering, investigation of bridge decks, asphalt pavements, concrete pavements, concrete structures etc.). This rapid development and extensive usage led to preparation of number of guidelines and standards regarding GPR application (for example ASTM D6432-11). The significance of Ground Penetrating Radar in geotechnical engineering practice is recognized through a huge number of research activities such as COST Action TU 1208 Application of GPR in Civil Engineering which, to some extent, deals with protocols and guidelines for the application of GPR in transportation infrastructure.
2.2 Background to the method

The Ground Penetrating Radar (GPR) method is based on the emission of high frequency electromagnetic pulses in the subsurface (or structure) using suitable antennas. In the subsurface, the waves can be attenuated, reflected or refracted. After reflection, which is produced at boundaries between two materials with different dielectric characteristics, a wave returns to surface where it is received by a second antenna, Figure 1. This kind of system, when different antennas emit and receive waves, is called a bistatic system (Marčić, 2013.). In a system monostatic a single antenna is used for emission and receiving of waves. Depending on the antenna position during a GPR survey, systems are classified as air-coupled or ground-coupled. Additionally, a cross-polarized system can be applied where the transmitter and receiver are perpendicular. This configuration is efficient for detecting of sloping target relatives to the antennas operation direction (De Chiara, 2014a).

![Figure 1 Principle of GPR investigation (Annan, 2003)](image)

In order to evaluate geophysical method as useful, a change in certain physical characteristic must exist. In case of GPR survey, that physical characteristic is relative permittivity. The relative permittivity of a material for a frequency of zero is known as its dielectric constant. Higher dielectric contrast between two materials will result in stronger reflection in GPR image (Kang et al., 2010). An example of this can be seen on Figure 2, where series of hyperboles in the GPR image represent the position of underground pipes. The dielectric constant influences velocities of the electromagnetic waves and because of that, velocity analysis conducted in the post-processing phase can be used for the calibration of the dielectric constant. Typical electromagnetic properties of some materials, among which is dielectric constant, are given by Morey (1998), Table 1.
**Figure 2** Typical GPR image (Annan, 2003)

**Table 1** Typical electromagnetic properties of some materials (Morey, 1998)

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant, ( \varepsilon_r )</th>
<th>Electrical Conductivity (mS/m)</th>
<th>Velocity (m/s), ( v )</th>
<th>Attenuation (dB/m), ( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
<td>0.30</td>
<td>0</td>
</tr>
<tr>
<td>Fresh Water</td>
<td>81</td>
<td>0.05</td>
<td>0.033</td>
<td>0.1</td>
</tr>
<tr>
<td>Sea Water</td>
<td>80</td>
<td>( 3 \cdot 10^4 )</td>
<td>0.015</td>
<td>( 10^3 )</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3-5</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated Sand</td>
<td>20-30</td>
<td>0.1-1.0</td>
<td>0.06</td>
<td>0.03-0.3</td>
</tr>
<tr>
<td>Silts</td>
<td>5-30</td>
<td>1-100</td>
<td>0.07</td>
<td>1-100</td>
</tr>
<tr>
<td>Clays</td>
<td>5-40</td>
<td>2-1000</td>
<td>0.06</td>
<td>1-300</td>
</tr>
<tr>
<td>Limestone</td>
<td>4-8</td>
<td>0.5-2</td>
<td>1.12</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Granite</td>
<td>4-6</td>
<td>0.01-1</td>
<td>0.13</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Bituminous Concrete</td>
<td>3-6</td>
<td>0.5-1.5</td>
<td>0.12</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>Concrete (cured)</td>
<td>6-11</td>
<td>1-3</td>
<td>10</td>
<td>0.5-1.5</td>
</tr>
</tbody>
</table>

The frequency of the GPR survey determines two crucial survey parameters – the investigation depth and resolution. According to Annan (2003), who gives a comprehensive overview on GPR theory and application areas, GPR plateau usually occurs in the 1 MHz to 1000 MHz frequency range, even though application of antenna of higher frequency (2000
MHz and higher) is often used. When higher frequencies are used, a shallower investigation depth can be achieved, but the image resolution will be higher. Using lower frequencies results in lower resolution, but larger depths can be investigated. There are two types of resolution when conducting GPR survey, vertical and horizontal. Vertical resolution is, simply put, smallest distance in vertical direction at which two phenomena can be apart in order to see and distinguish them as separate phenomena, while horizontal resolution is the minimum horizontal distance between two phenomena at the same depth before the radar merges them out into one single event (Alvarez Cabrera, 2013). High conductivity material, such as clays, may absorb and attenuate signals leading to significant decrease in penetration depth. On the other hand, in low conductivity materials such as sand, penetration depth can reach up to tens of meters. Dielectric constant of granular sediments is dominantly governed by water content in that particular sediment. Higher water content usually means higher dielectric constant (due to fact that dielectric constant of water is as high as 81). Van Overmeeren et al. (1997) presented a relation between soil water content, dielectric constant and propagation velocity of radar waves in unsaturated sands, shown in Figure 3. Salinity of water does not have a large influence on dielectric permittivity, but it strongly influences conductivity and attenuation of electromagnetic waves (Jarzyna, 2012).

Figure 3 A relation between soil water content, dielectric constant and propagation velocity of radar waves in unsaturated sands (Van Overmeeren et al., 1997)

Topp et al. (1980) proposed a relationship between the dielectric permittivity ($\varepsilon$) and the volumetric water content ($\delta$), of the form:

$$\delta = -5.3 \cdot 10^{-2} + 2.92 \cdot 10^{-2} \cdot \varepsilon - 5.5 \cdot 10^{-4} \cdot \varepsilon^2 + 4.3 \cdot 10^{-6} \cdot \varepsilon^3$$

To underline, a GPR technology provides a rapid sampling and data acquisition with possibility of obtaining a large range of information. Additionally, with proper maintenance and regular calibration of the equipment, repeatability and reproducibility of data are excellent. However, not all collected data is of interest to a specific problem and detailed analysis is
necessary in order to identify main characteristics which are of interest. The advantages of the method come to the fore when using GPR on linear structures such as on rail networks, as described in the following.

2.3 Use on GPR on a rail network
A typical section of railway structure is given in Figure 4. The main elements of the railway substructure (known also as 'track substructure, track-bed'); consist of ballast, sub-ballast and subgrade (natural material and fill material).

![Figure 4 A typical materials for construction of railway line](image)

The ballast is 'a gravel or broken stone laid in a railroad bed' (Merriam-Webster, 2017) and has a crucial role in maintaining track stability by resisting longitudinal and transversal track movements while at the same time distributing the train. Also it can have some additional benefits such as facilitation of drainage from both rainfall and other types of water ingress. Below the ballast, a layer of sub-ballast is laid. Its role is in reducing stress to the subgrade by acting as a structural material layer while protecting itself from the downward migration of ballast stones as well as intrusion of fine particles from the subgrade.

Due to a series of factors such as degradation due to continual repetitive train loading, weather conditions etc. the overall condition of the ballast and sub-ballast changes with time and this has a significant influence on the performance of the track system. Whilst the effects of degradation are most significant on the ballast layer, Selig and Waters (1994) note that it is equally important to map and detect defects in sub-ballast and subgrade layers. De Chiara
(2014a) gave an overview of factors that can cause irregular settlements of these layers through mechanisms of progressive shear failure and excessive plastic deformation. Also, the problems can be encountered because of sandy formations, unbound formations, cohesive formations in wet conditions, clay and silt formations with frost susceptibility and attrition.

Since the axle load, train speed and flow pattern are constantly increasing (therefore leading to enhanced dynamic effects during operation), this results in faster degradation of the network. The detection and mapping of so called 'hot spots' is necessary in order to retain minimal requirements for safe and reliable operations as well as for optimising maintenance costs. The assessment of the ballast, sub-ballast and subgrade condition is still most often conducted by drilling the boreholes or excavation of trial pits. These investigation methods provide good informative, however they very expensive and time consuming and usually also require the closure of the track section for a relatively long time period (Manacorda, 2002). Because of this and the very small volume of material tested through invasive means, as a result, only very limited information is available along the network. Donohue et al (2011) describe a case history on the Irish Rail network which illustrates that the relatively small volume of soil tested in a borehole may miss the main structural features of the problem being considered. In order to decrease the costs and increase the efficiency of the investigation works, or to test a much larger volume of soil, the application of non-destructive measurement techniques such as geophysical techniques is recommended.

In order to overcome this time/cost issue, as well as ‘limited information’ character of destructive methods, the use of Ground Penetrating Radar (GPR) which can rapidly examine the entire structure is increasingly being implemented for the determination of railway line condition through continuous mapping of factors such as ballast thickness, layer thickness variations along the track, subgrade water content, ballast water pockets, locations and depths of elements such as subsurface drainage pipes, trenches, animal burrows and utilities.

In order to map all these different factors, a special GPR configuration must be properly defined containing antennas with different frequencies. The selection of antennas is dependent on the factor which needs to be mapped. As it can be seen from Fig 5, antennas operating at different frequencies allow variable depths of penetration and different resolution of the images to be achieved.
Higher frequency antennas emit electromagnetic waves with shorter pulse wavelength which enables interaction with smaller features. Therefore, these antennas can provide a high resolution profile of the ballast surface and data for analysis of potential ballast fouling. On the other hand, lower frequency antennae are used to locate potential anomalies in the sub-ballast and substructure, by mapping a range of factors such as boundaries between layers, defects etc. The operative must be aware of certain limitations associated with the method when using them in railway applications. The main one is the fact that interpretation of collected information is not straightforward because the acquired and interpreted information is not unique. For example, if layers have similar dielectric properties, their boundaries will not be recognized. To reduce uncertainties to a minimum, an expert is required both in the acquisition phase and especially in the analysis and interpretation phase when a final location of hot-spots is defined. Despite the number of advantages of method, it is still necessary in most cases on railway lines to conduct drilling and sampling investigation works, both as a means of obtaining physical geotechnical parameters and calibrating the interpretation of the GPR measurements. The scope and location of the intrusive investigation should be guided by the potential hot spots where anomalies have been detected by the GPR investigation. A combination of non-destructive investigation with optimized destructive testing methods, conducted only where it is essential, can give valuable information to persons who are managing particular rail section in order to prioritize the maintenance program by providing visualisation of the ballast uniformity, position of boundaries between layers etc.

Until recently rehabilitation measures were not considered until visible instabilities appeared on the network, as evidenced by visual inspection. The location of the fault or failure then becomes a hot spot on the network. Some examples of reactive approach are given below. During 2014, two rehabilitation projects were designed and implemented for the improvement of embankments stability at railway tracks in Croatia (FCE – 1, 2014, FCE – 2, 2014). The investigation works comprised of a geodesic survey, GPR and seismic refraction measurements, geotechnical boreholes, laboratory testing and non-destructive geophysical.
In Figures 6 and 7 the results of the seismic refraction and GPR measurements are presented for both locations.

The investigation works carried out at track R202 established that the railway embankment is located on an area of soft soil, with the seismic refraction survey identifying soils of very low stiffness in the area directly beneath the embankment. However, it was a GPR method which ‘guided’ the optimum position for the additional refraction survey and borehole drilling. The remediation method consisted of the installation of 0.6 m diameter, 4 to 8 m long, jet grouted piles, with strengthening of the embankment body by execution of gravel trenches on the longitudinal distance of 3 meters (above the jet grouted piles).

**Figure 6** Unstable embankment at km 132+200 to km 133+000, railway track R202 in Croatia, with belonging refraction profile and GPR profiles obtained during the assessment stage

**Figure 7** Unstable embankment at km 588+000 to km 588+110, railway M 202 in Croatia, with belonging refraction profile and GPR profiles obtained during the assessment stage
A second case study is the rehabilitation of the instability of embankments at km 588 + 000 to km 588+110, 202 track M 202 (FCE-2, 2014). At this location investigation works included also the implementation of a geodesic survey, GPR and seismic refraction as well as geotechnical drilling and laboratory testing. Some results are presented in Figure 7. Based on the investigation works it was shown that the principal cause of the instability was poorly maintained or absent drainage. The flow of water from the slope located above the track caused the retention of water in the embankment, primarily because of an inadequate drainage system. In order to improve the current situation, 22 drainage canals were designed where drainage pipes will be installed and will collect water from the embankment body and from a new concrete channel that will be located at the bottom of the upper slope.

Even though in both examples GPR gave information which was essential for positioning of additional investigation works, the main benefit of GPR comes to fore if it is used over significant portions of the rail network as a first-pass method for detection of potential hot-spots which require further investigation. This can give rapid information on the overall condition of lines even where instabilities have not yet occurred. Taking into consideration that one of the limitations of GPR is the slow rate of data acquisition over rough terrain, a GPR investigation of railway line overcome this issue. However, since the artefacts in the near surface (such as rail fastenings, reinforcing bars, etc) may scatter the EM energy leading to a reduction of penetration and signal with noise, it is important to consider these effects before start of investigation.

2.4 Equipment

The system used for GPR surveys of railway lines is relatively simple and easy to operate. It is generally composed of three parts: set of antennas, a control unit (which is ‘responsible’ for generation of the radar signal and for detection of received signals as a function of time), and the processing/display system (usually a laptop). However, due to need for multiple antennae for the acquisition of different level of information, a system needs to be prepared so that it can collect data from multiple antennas simultaneously. The frequencies of antennas shown in Figure 8 and given in Table 2 are widely accepted as the most suitable for railway application, taking into account the compromise between penetration depth and image resolution.
The set for the investigation of railways should include both ground-coupled and air-coupled units. The ground coupled antennae provide reliable results even in the most EM polluted survey sites with a high signal penetration and better vertical feature resolution. The air-coupled antennas can provide quick data collection with consistent signal and excellent resolutions, owing it to low ringing in the upper part of the range which is in focus for ballast inspection.

The application of particular antenna governs the speed of investigation. Saarenketo et al. (2000) mention that air coupled antennas, lifted to about 0.5 m from surface can lead to test speeds from 80 to 120 km/h. De Chiara (2014a) notes that during surveys, the ground-coupled antennas which are in contact with the surface, require a maximum test speed of

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**Table 2** Specification of antennas for investigation of railway substructure

<table>
<thead>
<tr>
<th>Air-coupled (AC)</th>
<th>Ground-coupled (GC)</th>
<th>Central frequency [MHz]</th>
<th>Penetration depth [m]</th>
<th>Resolution [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC</td>
<td>103</td>
<td>15</td>
<td>0.500</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>250</td>
<td>4</td>
<td>0.200</td>
<td></td>
</tr>
<tr>
<td>GC</td>
<td>380</td>
<td>4</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>1000</td>
<td>1</td>
<td>0.050</td>
<td></td>
</tr>
</tbody>
</table>
about 15 km/h. It can be concluded that the overall test speed is governed by choice of antenna, as well as on type of vehicle used to mount antennas, as it will be mentioned later.

The control unit, Figure 9, enables utilization of multiple antenna in single passage and must offer a level of customization and scalability second to none. Therefore, data acquisition is much less time consuming. A control unit must be connected with antennas through a multiplexer, a hardware extension which is essential in order to achieve a multichannel configuration. Taking in consideration number of antennas given in Table 2, a multiplexer, Figure 9, with at least 4 antennas connected at once is recommended.

![Figure 9 A control unit connected to a multiplexer](image)

Detailed specifications of control unit, used for investigations within the DESTRail project is given in table 3. Any control unit with similar specifications can be used for the investigation of railway substructure.
### Table 3 Some properties of control unit

<table>
<thead>
<tr>
<th>FEATURE DESCRIPTION</th>
<th>CONTROL UNIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>+10.8 to 14 V</td>
</tr>
<tr>
<td>Power consumption</td>
<td>5.5 Watt</td>
</tr>
<tr>
<td>Survey range</td>
<td>6.4 – 32 768 ns</td>
</tr>
<tr>
<td>PRF</td>
<td>12.5 – 200 kHz</td>
</tr>
<tr>
<td>Analogue bandwidth</td>
<td>5 – 4 000 Mhz</td>
</tr>
<tr>
<td>Sample / Traces</td>
<td>128 – 8192</td>
</tr>
<tr>
<td>Number of channels</td>
<td>1 – 16</td>
</tr>
<tr>
<td>Traces / Second</td>
<td>1 – 330</td>
</tr>
<tr>
<td>Software Gain</td>
<td>-20 to +80 dB</td>
</tr>
<tr>
<td>Hardware Gain</td>
<td>0 to 20 dB</td>
</tr>
<tr>
<td>Offset</td>
<td>+/- 128</td>
</tr>
<tr>
<td>Vertical Filters</td>
<td>LP and HP IIR &amp; FIR</td>
</tr>
<tr>
<td>Horizontal Filters</td>
<td>stacking, background removal, dewow, DC</td>
</tr>
<tr>
<td>Operating Modes</td>
<td>time, distance, one shot</td>
</tr>
<tr>
<td>Data Storages</td>
<td>hard disk, USB, flash card</td>
</tr>
<tr>
<td>Data Format</td>
<td>16-bit data</td>
</tr>
<tr>
<td>Interface</td>
<td>USB 2.0</td>
</tr>
</tbody>
</table>

In order to investigate the lines of interest in a fast and flexible manner, it is usually necessary to mount antennas on a proper vehicle. Figure 10 shows some possibilities by mounting system on a car modified for railways or directly on a train.
Mounting the antennas on car or train will result in rapid acquisition of data, however, the flexibility of the whole system is lower than the one which uses custom made cart. Also, for the investigation of shorter sections it is easier to assemble the cart on-site than to mount the antennas on a train. Therefore, for the Croatian Rail study where multiple short sections where to be investigated a special cart was developed for operation on tracks. The system had the advantage that it could be lifted on and off the track quickly and therefore surveys did not interfere with network operations. The custom-made cart made of light material (aluminium) is given in Figure 11.
For the purpose of adequate measurements of distance during data acquisition, a survey wheel in contact with ground is necessary. This distance measuring instrument (DMI) or odometer, Figure 11, is small sensor which uses a high precision magnet reader and allows the person who investigates to trigger the collection of traces in distance mode as well to position located defects from the acquired data. The other possibilities include odometers which are based on optical readers, but these can be obstructed by dust or dirt.

**Figure 11 A custom-made cart with position of odometer**
When it comes to software, it is equally important to have an adequate data acquisition software and data analysis / interpretation software. For this system defects or phenomena could be recognized during acquisition as the software showed a real-time visual display of the data. This was possible only because the acquisition software included series of features which enabled direct graphical feedback as well as a visual trace viewer. Even though in some cases it is possible to use the results from a GPR survey with very modest processing (Mori, 2009) and real time cursory analysis can be performed in the field, a data analysis and interpretation software needs to be designed to allow detailed enhanced analysis and interpretation for critical section.

Whilst conducting a GPR investigation with this equipment it is useful to record data using additional equipment which can be useful in later stages of data interpretation. In this case high quality digital photos and notes on phenomena which could have a direct influence on the determination of hot-spots were collected by the system operators, whilst a video (GoPRO) camera was also used on sections, these digital video recordings can result in a better visualization of investigated lines through identification of particular structures of interest (De Chiara, 2014a)

For the accurate positioning of all investigated profiles, a custom-made cart is additionally equipped with a GPS device which is used for accurate horizontal and vertical measurements where the GPS position is achieved by the precise measurement of the distance between the satellite and the receiver at an instant of time. The recommended accuracy of measurements is - horizontal: 3mm+ 0.5ppm (x baseline length), vertical: 5mm+ 0.5ppm (x baseline length). The equipment should have following items: geodetic antenna, power supply, receiver, RTK Base station, UHF radio.

**Figure 12** A system for detailed GPS position of investigated locations
2.5 Data acquisition

For the acquisition it is most important to a-priori calibrate equipment in order to prevent any hardware or software issues during collection of data, which can influence final result. As it was mentioned in previous chapter, a test speed must be defined based on antenna configuration. Application of ground coupled antennas (in contact with surface) will yield survey speeds from 15-20 km/h but this will also enable a better investigation accuracy. It is recommended to maintain this as maximum speed if GPR system will be used for mapping of both the ballast and sub-ballast / subgrade formations.

For the acquisition of data, a series of parameters must be defined, which include:

1. Selection of collecting modes: distance mode, time mode and one shot
   
   It is recommended to use distance mode for railway inspections since it is the most reliable approach. It utilizes an odometer for measuring the survey distance. For this mode, a proper horizontal sampling interval must be defined.

2. Wheel calibration
   
   It is very important to calibrate the survey wheel, odometer, before acquisition of data in distance mode. The calibration must be performed on flat ground, which should not be a problem due to position of wheel on rail. But attention is necessary in order to keep survey wheel always in contact with the rail (especially along curves).

3. Horizontal sampling interval (or sampling distance)
   
   This value is determined by the number of scans / unit. Since it is usual to define 1 unit as 1 meter, a sampling distance represents a value obtained through division of 1 meter with a number of scans. For example, 10 scans / unit give sampling distance of 0.1 m. The test speed is also limited by sampling distance since an increase of scans / unit will result in lower test speeds. Saarenketo (2006) proposes 10 scans / meter as adequate sampling density for both ground coupled and air coupled antenna, but for determination of condition of ballast a higher number of scan / meter should be used (for example 20 – 30 scans / meter which is sampling distance of 3 – 5 cm).

4. Vertical sampling
   
   This parameter defines the time interval between points on a recorded waveform. According to Annan (2003) the vertical sampling interval is controlled by the Nyquist sampling concept. Saarenketo (2006) concludes that for infrastructure surveying, a value of 512 scans can be used because of high storage capacity of newer GPR systems.

5. Antenna orientation
   
   Annan (1999) states that the antennas used for GPR are dipolar and radiate with a preferred polarity and that there is no optimal orientation for an equidimensional target. He further suggests that it may be advisable (on some occasions) to collect two data sets with orthogonal antenna orientations in order to extract target information based on coupling
angle. Since antenna orientation has an influence on the the subsurface footprint size, it is recommended to conduct testing prior to data acquisition in order to have insight on the influence of orientation on results.

6. **Antenna range (depth of penetration)**

The antenna range represents the value of nanoseconds in the 'time window' of the display. Therefore, it defines a penetration depth for each antenna. For lower frequency antennae, this value can be as large as 350 ns (usually lower values) for 100 MHz ground coupled antenna and 75-100 ns for 400 MHz antenna. For high frequency antennas, that is for 1000 MHz antenna, this value can be set to a maximum of 30 ns. The window should be however, at least one-third longer the target depth, as suggested by Saarenketo (2006).

7. **Dielectric constant**

It is necessary to input the dielectric constant of the material apriori. However, this value can be easily modified during processing phase.

8. **Auto filters**

Specific values for the filtering functions that can improve collected data can be set during the acquisition phase. The functions which can be used are LP/HP IIR frequency filter, stacking and background removal. More details on filtering will be given in data acquisition chapter.

9. **Auto gain**

The gain setting, and then signal amplification values can be defined during measurement. A user, however, must be careful with this part since applying too much gain can result in corrupted data. More on signal gain will be given in data acquisition chapter.

10. **Auto offset**

With this option, a starting position for the trace (zero offset) to be recorded can be modified because sometimes it gets shifted up or down. Adjustment should be made in order to get a reliable representation of the data.

11. **Distance and/or users’ markers**

This is an optional function where user can use markers to mark known positions, features or defects in investigated line. It can be useful in post-processing phase.

The distance of antennae to the track bed must be measured prior to the investigation. Therefore, the 1000 MHz air-coupled antenna is fixed 50 cm from the track bed, the 380 MHz antenna is fixed 15 cm from the track bed, whilst the ground coupled antennas of 100 MHz and 400 MHz are in contact with track bed making them less prone to influence of other EM signals which are not of interest.
As a benchmark for evaluation of the GPR method's potential, sections of the Croatian railway infrastructure were chosen because of their diversity and the fact that they were in a deteriorated condition. In collaboration with Croatian Railways, as a partner in the DESTination Rail project, a total of 182 km of sections were chosen, See Table 4, in different types of environments and train loading (international, regional and local lines). As the additional assistance in categorization, information on the section's condition (based on visual assessment) was provided from persons responsible for their management.

### Table 4 A list of Croatian railway lines used as a benchmark (Jurić Kaćunić, 2015a)

<table>
<thead>
<tr>
<th>SUPERVISORY CENTER</th>
<th>LINE</th>
<th>SECTIONS (from – to)</th>
<th>LENGTH (km)</th>
<th>TOTAL LENGTH (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VARAŽDIN</td>
<td>R201: Zaprešić-Čakovec</td>
<td>57+069 - 88+389</td>
<td>31.32</td>
<td>31.32</td>
</tr>
<tr>
<td></td>
<td>M501: DG-Čakovec-Kotoriba-DG</td>
<td>84+396 - 90+893</td>
<td>6.50</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>L103: Žabok-Đurmanec</td>
<td>0+206 - 16+186</td>
<td>15.98</td>
<td>15.98</td>
</tr>
<tr>
<td></td>
<td>R201: Varaždin-Ludbreg</td>
<td>228+067 - 223+974</td>
<td>4.10</td>
<td>4.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLAVONSKI BROD</td>
<td>M105: Novska - Tovarnik-DG</td>
<td>221+600 - 227+400</td>
<td>5.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>244+700 - 249+700</td>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>256+100 - 260+400</td>
<td>4.30</td>
<td>15.10</td>
</tr>
<tr>
<td></td>
<td>M303: Striz./Vrp. – Sl.</td>
<td>5+700 - 9+500</td>
<td>3.80</td>
<td>3.80</td>
</tr>
</tbody>
</table>

**Figure 13** A map of Croatian railway network (source www.find-croatia.com)
<table>
<thead>
<tr>
<th>Location</th>
<th>Reference</th>
<th>From - To</th>
<th>Length 1</th>
<th>Length 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Šamac – DG</td>
<td>M602: Škrljevo - Bakar</td>
<td>8+170 - 9+150</td>
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<td>0.98</td>
</tr>
<tr>
<td>Rijeka</td>
<td>Supervisory Center Rijeka, Total</td>
<td></td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Osijek</td>
<td>R202: Varaždin - Dalj</td>
<td>65+000 - 69+000</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td></td>
<td>L209: Vinkovci - Osijek</td>
<td>7+800 - 8+600</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>M301: DG - B. Manastir Osijek</td>
<td>4+900 - 5+000</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Supervisory Center Osijek, Total</td>
<td></td>
<td></td>
<td>4.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>M202: Zagreb GK Rijeka</td>
<td>486+900 - 487+000</td>
<td>0.10</td>
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<tr>
<td></td>
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<td>490+000 - 496+720</td>
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<td></td>
<td></td>
<td>506+490 - 517+100</td>
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<tr>
<td></td>
<td></td>
<td>520+250 - 523+470</td>
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<td>23.98</td>
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<tr>
<td></td>
<td>L104: Karlovac – Kamanje – DG</td>
<td>22+950 - 25+100</td>
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<td>2.15</td>
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<tr>
<td>Ogulin</td>
<td>M604: Oštarije – Knin Split</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>6+700 - 7+800</td>
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<td></td>
<td></td>
<td>16+700 - 19+500</td>
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<tr>
<td></td>
<td></td>
<td>65+000 – 65+200</td>
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<td></td>
<td>95+000 - 95+700</td>
<td>0.70</td>
<td>24.87</td>
</tr>
</tbody>
</table>
Some photos taken during the data acquisition phase are shown in Figure 14.
For large scale GPR investigation, such as the benchmark case described here, the data collected is typically in the order of several hundred Giga Bytes (GB). This data can be considered as 'Big Data' according to the classification of y Attoh-Okine (2014). Therefore, a proper management and interpretation of such a huge amount of data is critical to ensure it can be utilized in an optimal way. Such a large data can be subjected to series of phenomena such as heterogeneity, inconsistency or incompleteness. A detailed analysis and interpretation is necessary.
Before demonstrating the flowchart for processing of the GPR data, it is important to highlight the main variables which need to be addressed in order to properly identify the condition of the railway track bed. These include:

1.  wo-way travel time (TWT) of EM pulses through the substructure gives an indication of the layer thickness or depth to certain feature. It represents the time which it takes for the signal pulse to travel from the antenna to a feature and return back to the antenna. It is usually measured in nanoseconds. This variable can be indicator of the thickness of a layer, since a shorter TWT would indicate thin ballast layer. Amplitude of the signal.

2.  phase of the signal.

3.  velocity of the signal.

4.  the continuity of the signal which gives an information of the shape of the feature.

A number of researchers have used GPR to measure ballast quality (e.g. Leng et al., 2010; Selig et al., 2006). Figure 15 illustrates the contrasting behaviour of electromagnetic waves in ballast material of variable quality. When the wave passes through clean ballast, significant signal scattering can be expected as a result of the contrast between the dielectric constant of the aggregate and and air voids. On the other hand, if the ballast is fouled as a result of the migration of fine grained soil from below, a lower level of attenuation is expected. The attenuation is even larger if there is increase in moisture which can be expected with an increase of fined grained materials.
A typical GPR profile is shown on Figure 16, with different levels of signal scattering visible.

**Figure 16** A typical GPR profile with different levels of signal scattering visible, source([www.railway-research.org](http://www.railway-research.org))
It is clear that the behaviour of electromagnetic wave propagation is governed by the dielectric value of material through which it passes and by knowing its value the result will be more accurate and position / extent of hot spots will be more reliable. This parameter controls the signal propagation velocity and vertical and horizontal resolution of the scanned image. Saarakento 2006 gives an overview of values of dielectric constant which can be expected for both clean and fouled ballast. For dry clean ballast, the value of dielectric constant can be as low as 3, but for spent, wet, ballast this value can be as high as 38.5. Other authors, such as De Chiara et al. (2014b), also conducted research on the assessment of railway materials using dielectric properties. In this research, several GPR laboratory tests were performed in order to measure the dielectric constant values of the railway materials and their sensitivity to water content, fouling level and antennas frequencies. It was concluded that the dielectric constant value for dry clean ballast, depends on the antenna type and ranges from 2 to 4.1. When it comes to fouled ballast, the authors concluded that the higher the level of fouling and the higher the level of volumetric water content lead consequently to higher dielectric constant, where the dielectric properties are more affected by fouling variation than water content.

For the particular investigation of railway lines, a flowchart of processing is shown on Figure 17.
Figure 17 Flowchart of processing stages for railway substructure GPR investigation
Annan (2003) gives an overview of steps which need to be conducted for proper processing of the collected GPR data.

As a first step in data processing it is necessary to edit data in terms of data re-organization (scaling, cutting, merging, normalizing and reversing profile directions), data header or background information updates, repositioning and inclusion of elevation information with the data. This will lead to more adequate data for further processing and interpretation.

After data editing, a basic processing follows. This phase of processing can be, as suggested by Annan (2003), conducted during the acquisition of data through pre-processing. However, it is recommended to conduct it after acquisition due to higher precision and to allow for a more systematic approach. De Chiara (2014a) states that basic processing starts with zero-level application which should correspond with the surface of the investigated infrastructure in case that zero time may not have been detected precisely by the system during acquisition on the railway line. This basic processing usually consists of temporal filtering through a procedure known as 'dewowing of data', and is basically the removal of a long waved part of the signal that is caused by electromagnetic induction. After dewowing, a time gain follows using variety of tools such as square gain, exponential gain etc. This is mostly done because signal amplitudes are well detected in the upper layers and mostly poorly detected in the lower layers. However, the user must be careful since it is important to maintain amplitude fidelity. The next steps in the basic processing procedure include, according to Annan (2003), a time and spatial filtering in order to remove presence of noise from data, where time filtering means filtering along the time axis of the data set using variety of filtering techniques from bandpass filtering using fast Fourier transforms (FFT) through to various types of linear and non-linear time domain convolution filter operators.

Advanced processing phase will result in data significantly different from the raw, original information. These operations include deconvolution, a trace attribute analysis, FK filtering, selective muting, background removal, etc. The most widely used of these techniques are deconvolution and background removal. With the background removal tool, a horizontal band is removed, while the deconvolution removes the effect of the source wavelet for a better GPR interpretation.

Annan (2003) states that this level of processing is usually subjective and the user processes the data having in mind the purpose of the survey.

After the advanced processing phase, a visual processing stage follows where GPR profile is developing a shape which is easy to interpret, by increasing some features and reducing others, but being careful since lot of critical information can be lost. In this phase, for example, a detection of layer interfaces takes place, with two possible operations for their detection including picking the maximum reflection amplitude or picking the zero amplitude level, immediately before the maximum reflection amplitude (Saarenketo, 2006). Also a migration technique can be applied. Migration, as an image processing technique, will enhance the display of the inclined reflectors, such as sloping layers, in their real subsurface position, but electromagnetic wave velocities in the subtrack have to be determined prior to migration application.
For investigations within DESTination Rail, after acquisition of the data, a post-processing was conducted. All anomalies detected with lower frequency antennas were registered, as well as fouling and ballast intermixing with subgrade material detected with higher frequency antennas. The resolution of investigation was 1 m of length where two-way travel time, amplitude of signal and depth of ballast layer were identified, Figure 18. By combining the phase and manual layer pick methods the contact between the ballast layer and subballast layer was determined in a semi-automatic manner.

![Interpretation of GPR data with information on amplitude, TWT and depth of ballast layer](image)

**Figure 18** Interpretation of GPR data with information on amplitude, TWT and depth of ballast layer

The first level of categorization consisted of solely GPR investigation results. This categorization was supplemented with information of the condition provided by relevant railway supervisory centre and detailed inspections with photo and video documentation (with more than 5500 photos and 1.5 TB of video). This led to a second level of categorization where all investigated sections were divided into 5 categories, see Figure 19. They were marked from 1 (red colour) representing sections of bad condition, so called 'first level hot-spots', to 5 (purple colour) representing sections in an excellent condition. Based on this division, second level of categorization suggests additional investigation including standard in-situ geotechnical investigation and/or monitoring methods should be undertaken in order to get a detailed insight into condition of each section.
D1.2 Guideline on Methods to Find Hot-Spots on Rail Networks
DESTination RAIL – Decision Support Tool for Rail Infrastructure Managers

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>GRAPHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 19** Final categorization of investigated sections based on 5 categories

**Figure 20** Final categorization of investigated sections: example of section of bad condition

**Figure 21** Final categorization of investigated sections: example of section of good condition
A detailed methodology, as well as the results for each investigated section within the scope of the DESTination Rail project, will be given in deliverable within Task 5.1 on pilot projects.

As mentioned before, a GPR method presents the optimal geophysical method for detection of hot spots on railways, taking into consideration rapid data acquisition and data repeatability and reproducibility. However, GPR investigation can be supplemented with additional non-destructive geophysical methods which do not account rapid assessment, but can give additional information on trackbed condition. In this sense, seismic geophysical methods must be stressed out because, besides giving insight in engineering-geological profile of investigated section, they can be widely used for their potential in determination of some important engineering physical–mechanical characteristics of trackbed.

These methods include seismic refraction method for determination of velocity of longitudinal seismic waves and variations of spectral analysis of surface waves (SASW) such as multichannel analysis of surface waves (MASW) and continuous generation of surface waves (CSWS) for determination of velocity of transversal seismic waves.

2.6 Seismic geophysical methods

The seismic refraction method is based on an analysis of artificially created seismic waves that are generated from the surface. Those waves travel to a particular depth and return to the surface after refraction, i.e. breakage, at the boundaries of layers with different seismic velocities (Kovačević et al., 2013). Figure 22a shows the procedure for data acquisition, whereas Figure 22b shows the first wave arrivals, which following further treatment, result in a distribution of longitudinal P velocities at a depth along the investigated profile. A number of methods were developed to interpret the measurement results with the most commonly used method being the Generalised Reciprocal Method (Palmer, 1981), Delta-t-V Method (Gebrande et al, 1985), and the Diving Wave Tomography (Sheriff et al., 1982).

![Figure 22 Data acquisition (a) and diagram of the first wave arrivals (b) for method of seismic refraction (Kovačević et al., 2013)](image-url)
The refraction profile of the allocation of P velocities based on depth shown in Figure 23 represents the result of investigation works at the location of the railway line in Croatia using the seismic refraction method (Jurić Kaćunić et al, 2015b).

![Seismic refraction on-site data acquisition on railway embankment (a) with resulting profile of longitudinal velocities (b)](image)

**Figure 23** Seismic refraction on-site data acquisition on railway embankment (a) with resulting profile of longitudinal velocities (b)

A spectral analysis of surface waves (SASW) is a non-destructive geophysical method for measuring the velocity of S waves and is exceptionally useful in determining the elastic modulus of various materials at very small strains, as well as in determining changes of such modulus with respect to depth (Kovačević et al., 2013). The method is based on the dispersive characteristics of Rayleigh’s R waves and the fact that R waves at different wavelengths or frequencies propagate to different depths. Geophones are placed in predefined intervals, Figure 24, and they measure arrival time of the wave velocity generated by a vertical mechanical impulse on the terrain surface. Then, a Fourier analysis is carried out on the gathered signals, whereby the signal is transformed from the time into the frequency domain (Kovačević et al, 2008). As the velocity of the surface wave R is a good indicator of the velocity of an S wave, further analysis gives a result in form of shear velocity with respect to depth, as shown in Figure 24. The profile of the S wave velocity can determine the stiffness-depth profile.
1. (b)

**Figure 24** Acquisition scheme for SASW (a) with resulting profile of S wave velocities (b)

The theoretical background of the method described as a multi-channel analysis of surface waves (MASW) is equivalent to the SASW method. In comparison to the SASW method, which uses a wave generator and only two geophones, the MASW measurement equipment comprises a generator and a series of geophones, as shown in Figure 25, hence data acquisition can be carried out much quicker. On the basis of correlations of the velocity of surface S waves and ground stiffness at small strains, the profile allows the determination of values for the elastic parameters of ground at the respective location.

**Figure 25** Acquisition scheme for MASW (a) and CSWS (b)
It is however possible to use same equipment for data acquisition for seismic refraction method and multichannel analysis of surface waves. This can be additional benefit since the data can be collected at same time for both methods and during analysis / interpretation phase the different interpretation approaches can be adopted. Therefore, on railway lines it is recommended, after conducting a first pass GPR investigation, to conduct a follow-on refraction / MASW investigation at identified hot-spots. Even though these methods are non-destructive, it takes more time to install equipment and conduct acquisition of data in comparison with Ground Penetrating Radar.

For measuring of wave time travel through substructure, a vertically polarized ‘smart’ geophones can be used, Figure 27. These geophones are usually connected in larger groups (of cca 20 geophones), so called ‘strings’, Figure 28, which are then connected if longer profiles are necessary. The connection between strings is done through a SLIM device, Figure 29. After set-up, each geophone has its position and ‘name’ in investigation profile.

**Figure 26** A typical MASW profile

**Figure 27** A geophone for seismic refraction / MASW investigation

**Figure 28** Geophone strings in profile
A central control unit (CRU), Figure 30, represents a core of whole system were all elements are connected forming a meaningful configuration.

With respect to the computer used for data acquisition, any functional laptop can be used. A scheme of the data acquisition configuration is shown in Figure 31.
3. Detecting Anomalies and Water Distribution in Railway Ballast Using GPR

3.1 Methodology

Operation and maintenance of ballasted railway tracks can be an expensive and time consuming process. Therefore, much can potentially be gained from exploring more effective alternative methods of track inspection. The use of Ground Penetrating Radar (GPR) in transportation maintenance applications has seen an increase in the later years, and it is desirable to accurately study the extent of its abilities for this application.

This research examined whether it is possible to use GPR to detect anomalies such as ballast pockets, and distribution of water content in railway ballast? The main goal of the study was to assess the abilities of GPR in the following railway applications:

1. Detection of subsurface track body anomalies like ballast pockets and animal burrows.
2. Mapping the distribution of water in the track body.

The study involved thorough literature review to gather detailed information on the theoretical principles behind the GPR technology, and to assess the progress of recent studies on its applications. As such, the review included two slightly different approaches towards the material. Literature regarding the basic principles of GPR is widely available, and is largely uncontested between sources. Results from field and laboratory studies are also included here. Some of these are difficult to confirm from independent sources, but some extra merit is still given through publication in peer-reviewed journals. During the work with this study, some errors were still found in peer-reviewed sources, but the nature of these errors was attributed to careless mistakes from the authors (such as mixing up numbers from a separate source) rather than malicious intent.

Each source’s year of publication was taken into consideration as the GPR technology is rapidly developing over time. Especially in regards to available hardware and data processing power. Sources describing the basic concepts of track deterioration and GPR mechanisms are less time sensitive, as these are established concepts which remain true over time.

As the field of GPR research is relatively small (especially for railway applications), some researchers are recurring contributors to the source material. This is an inevitability that has been addressed by as much as possible confirming the validity of the most frequently featured researchers.

From the theoretical basis acquired through the literature review, a series of field tests were designed to test the GPR in real world conditions. An actual test of the equipment was deemed to be the absolute best method of confirming the GPR’s surveying abilities, and to uncover any major difficulties related to the implementation of the method. The theoretical
abilities of the system were tested, and all the necessary preparation were made to be able to use it on a railway track. The field study mainly consisted of two parts:

1. Test survey
2. Water distribution test

Performing the field study on a live track ensured a realistic testing environment, but also gave less control over the testing conditions. This resulted in the tests being affected by rainfall, and causing time window restrictions on the track due to traffic.

The analysis of the gathered data combined the theoretical and empirical data gathered from the literary review and the field study. While the field tests are considered a quantitative method, their interpretations are based on extensive knowledge of the underlying theoretical principles of the GPR system. The interpretations of these survey results should therefore be considered as qualitative research. Interpretation of field study results has been performed without bias, and solely based on the information available from the literature and field study. Extraction of in-situ core samples to confirm survey findings was regrettably not possible due to the live track testing conditions.

Ballasted railway tracks use a layer of crushed granulate material - known as ballast - placed between the sleepers and the subgrade. The ballast layer must perform several important functions to maintain the geometric stability of the track body and ensure safe and reliable operation of the railway.

The most notable roles of the ballast are to resist vertical, lateral, and longitudinal forces, distribute the pressure from the sleepers down to manageable levels for the subgrade, assist in absorbing shocks from dynamic loads, and provide immediate draining of any water away from the rails and sleepers through the ballast.

For the ballast to be able to perform these tasks, it must maintain a series of inherent properties. The hard angular particles of high strength rocks most commonly used gives strength and internal friction to the ballast body, while simultaneously leaving sufficient void space between the particles to facilitate drainage. However, over time the ballast will start to lose its strength and void spaces. This occurs either by mechanical deterioration of the aggregate material, or through contamination by introduction of foreign materials (fines, fluids, organic material etc.) into the ballast.

The ballast body can be categorised into four zones, as undertaken by Selig and Waters (1984):

- Crib - material between sleepers
- Shoulder - material beyond the sleeper ends down to the bottom of the ballast layer
- Top ballast - upper portion of supporting ballast layer which is disturbed by tamping
- Bottom ballast - lower portion of supporting ballast layer which is not disturbed by tamping and which generally is the more fouled portion.
The underlying causes and mechanisms which contribute to ballast deterioration and faults is an extensive subject. In this study we are focusing on a selected few situations which have been known to reduce the structural properties of the ballast or track body.

![Figure 32 Varying degrees of fouling in active railroad ballast (Roberts et al., 2009)](image)

Used to denote contamination by fines, ballast fouling, See Figure 32 can manifest itself in different ways, and have several different causes. It is considered the main contributor to ballast problems. (Selig and Cantrell, 2001). Selig and Waters (1984) divided the causes of fouling into five categories, with varying contributions.

1. Ballast breakdown (76%)

Ballast breakdown comes from the repeated cyclic loading from traffic on the track (as well as some material wear from tamping, initial transport and handling), where the angular edges of the ballast material are broken off into smaller pieces. Thus, over time this process both reduces internal friction within the ballast (reducing shear strength) as well as introducing fines (Indraratna et al., 2011).

2. Infiltration from underlying granular layers (13%)

Infiltration from underlying granular layers refers to the upwards migration of fines from lower ballast-layers.

3. Infiltration from ballast surface (7%)

Infiltration from ballast surface indicates intrusion from air- or water-borne debris, or spilled fines from passing trains (e.g. coal/ mineral ore).
4. Subgrade infiltration (3%)

Subgrade infiltration occurs when the finer grains of the subgrade migrate upwards into the ballast. This process is most commonly associated with the presence of undrained water in the track body.

5. Sleeper wear (1% for wooden sleepers)

Sleeper wear comes from the deterioration of the sleepers under cyclic loading from traffic. In addition to filling the void spaces used for drainage, the fouling materials (especially in combination with water) have a lubricating effect on the contact interface between the angular rocks. This reduces the internal friction of the ballast, compromising its ability to distribute pressure across the subgrade, See Figure 33. The fouling of the ballast reduces the stability of the track to a point where ballast cleaning or complete replacement must be performed to regain the desired track stability and strength. Significant fouling and inadequate drainage of ballast can also make it more susceptible to the formation of ice-lenses and thus frost heave in sub-zero temperatures. (Silvast et al., 2010b)

Under the repeated stress of passing wheel loads, fine grained or loose soils in combination with excessive moisture can cause depressions in the subgrade. A ballast pocket forms when a depression develops in the top formation or subgrade below the tracks. (Tzanakakis, 2013; Li et al., 2015) Now unable to drain properly, this depression will start to retain water, eventually filling the ballast pocket and further softening the subgrade.

Figure 33 Early stages of ballast pocket development (Tzanakakis, 2013)

Through the cyclic loading of passing traffic, the ballast and subgrade materials will mix, fouling the ballast while further expanding the ballast pocket into the subgrade, See Figure 34

Figure 34 Further development of the ballast pocket and subgrade deterioration. (Tzanakakis, 2013)
This type of subgrade bearing failure (with shear displacement) from ballast pockets will often contribute to undesirable track geometry changes through differential track settlement (Hay, 1982; Tzanakakis, 2013).

![Figure 35 Highly degraded subgrade and ballast geometry. (Tzanakakis, 2013)](image)

In addition to its detrimental effect on rolling stock, restoring track quality after such events is an extensive task, involving removal of all affected ballast and subgrade along with a regrading of the formation layer (RailCorp Network, 2009). If detected early, ballast pockets can be prevented from developing further by use of targeted drainage measures. Precise knowledge of the exact location and depth of the ballast pocket will allow for the most effective intervention while still avoiding large scale cleaning and renewal operations (Hyslip et al., 2005).

The activity of wildlife along the track presents several challenges in regards to railway operation. One such challenge comes from smaller animals burrowing dens or tunnels in the subgrade on embankments. This type of animal infestation is a regularly occurring problem in parts of the world, and may threaten the function of the track body drainage and ultimately the stability of the embankments (RailCorp Network, 2009; Network Rail, 2010).

As these burrows mostly occur in the subgrade, they are not resolved through the normal ballast maintenance procedures (cleaning/renewal), and must therefore be met with targeted inspections and burrow-filling measures upon discovery.

Without functioning drainage of the track, water will start to accumulate in the track body. The presence of trapped water in the ballast reduces its shear strength and stiffness as well as accelerating its deterioration and fouling process (Indraratna et al., 2011).

According to Selig and Cantrell (2001), causes of restricted drainage may include:

1. Ballast pocket formation from subgrade settlement
2. Fouled ballast shoulder
3. Low permeability boundary at edge of ballast
4. Ponding of water next to the track from lack of a ditch to carry water away from the track after exiting the ballast
5. Inadequate lateral slope on the sub-ballast surface to direct water to the side of the track.
In conditions where the subgrade is largely saturated with water, even a small content of water/moisture in the interface between ballast and subgrade layer can lead to formation of a muddy slurry. As passing trains induce a cyclic loading on the track, the slurry is pumped upward, fouling the ballast through to the surface. (Selig and Waters, 1984)

Being able to detect pockets of undrained water early would allow for rectification of drainage function before the ballast deteriorates to a level that would require more extensive renewal/cleaning operations. Detailed knowledge of the water distribution will help give important information towards the causes of, and possible solutions to the drainage failure.

To maintain and repair the track’s ballast, a method of ballast cleaning and renewal is applied. However, this is an expensive and time consuming process, disrupting train operations on the affected line. It is therefore necessary to only apply it where it is needed most, and to limit costly and less necessary use elsewhere.

The main way this is currently done is through visual inspection by railway maintenance staff, to identify potential problematic areas (Plati et al., 2010). Samples are then excavated from these sites for evaluation of the ballast. Often these samples are taken with given intervals over a stretch of track to attempt to approximate the ballast condition of the stretch as a whole (Hugenschmidt, 2000).

This is a destructive method of track inspection, which in addition to being time consuming, expensive, inaccurate as well as subjective in its findings, often requires interruption of regular traffic for long periods of time (Manacorda et al., 2001; Plati et al., 2010). There is significant potential for improvement in this process, using alternative non-destructive methods for track body and ballast inspection.

GPR is a technology that uses electromagnetic antennas, which are moved over a surface to detect reflections from subsurface features (Annan, 2009). The concept was first attempted by El Said (1956) as a way of measuring the water table in the Egyptian desert. Over the next three decades the concept found new applications such as ice-thickness measurements and archeological surveys. With the rapid development in computing power starting from the late 1980s, GPR started to be seen as viable technology for an increasing number of purposes up to the wide range of applications and studies we see today (Annan, 2003), See Figure 35.
Due to its ability to detect and map buried objects, GPR has seen use in many areas ranging from concrete rebar mapping to underground utilities detection (Annan, 2003; Lalagüe, 2015). In later years GPR has started to also be seen as a viable method for inspecting roads and railways. In these applications, the use of air-coupled antennas is preferred as they are not in direct contact with the surface and can therefore survey at high speeds. This is the antenna type which will be focused on in this study. The other variant of GPR utilises a ground-coupled antenna and is used more for direct accurate imaging across smaller surfaces such as concrete slabs (Lalagüe, 2015).

Ground Penetrating Radar can be used as a non-destructive method of surveying a stretch of track, and can be applied to achieve a continuous profile of the track bed structure (Plati et al., 2010). This grants significant advantages over the traditional approach of sample drillings and subjective visual inspection. GPR surveys of the track provides objective and measurable data about track bed anomalies and the ballast/formation interface. Its utilisation enables a confident prioritisation of the maintenance programme, reducing unnecessary costs by only carrying out work where it is needed (Gallagher et al., 1999).

Equipped with a properly shielded antenna, GPR is also able to survey track inside tunnels (Eide et al., 2001). The inherent properties of the GPR for revealing hidden objects/formations also make it a viable tool for detecting track deterioration anomalies at an earlier stage than with visual inspection. This enables smaller pro-active maintenance measures to prevent track deterioration from developing into large and expensive track faults.

GPR surveying relies on the propagation of electromagnetic waves and thus the magnetic and electric properties of the materials in the ground to create an image approximation of the subsurface without disturbing the surveyed area. At the interfaces between the different media (e.g. ballast/subgrade, subgrade/water table), there is a contrast in dielectric constant. This difference in constants causes a portion of the signal energy to be reflected back towards the receiver and registered as voltage amplitude in relation to time. A large difference in constants give a large signal reflection and thus a large signal amplitude. (Jack and Jackson, 1999; Plati et al., 2010; Indraratna et al., 2011)

For practical GPR purposes, the most defining electromagnetic parameters for subsurface materials are the electrical conductivity $\sigma$ and the dielectric permittivity $\varepsilon$. The electrical conductivity ($\sigma$) is a
measure of free charge movement in the material and it affects the attenuation of the signal. A high value of \( \sigma \) in a given medium will cause much of the EM-energy to be lost as heat through the conduction process. As such, surveying in media with high electrical conductivity (e.g. metals, saline solutions or clay rich environments) leads to high signal attenuation and effectively limits the signal penetration depth. These are known as “lossy” materials (Jack and Jackson, 1999). It also weakens the strength of reflected signals, rendering the GPR technique largely ineffective in these environments. Signal attenuation increases with both material conductivity and antenna frequency, see Figure 37 (Cassidy, 2009).

![Figure 37 Typical material attenuation values and ranges for common near surface materials (Cassidy, 2009)](image)

The signal attenuation from the presence of free water will increase with increasing signal frequencies up to approximately 19 GHz. Although this is well beyond the frequency scope of GPR radars, the effect is noticeable already at 1-2 GHz. This means high-frequency surveys may be even more limited in penetration depth performed on certain types of wet materials (Annan, 2003; Cassidy, 2009).

The dielectric permittivity (\( \varepsilon \)) characterises a material’s ability to store and release electromagnetic energy, and it is directly linked to the velocity at which EM waves propagate through the medium. An increased permittivity will decrease the signal propagation velocity (Cassidy, 2009). The term “dielectric constant”, or relative permittivity (\( \varepsilon_r \)) is often used when describing a material’s permittivity. It is defined as:

\[
\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}
\]  

(1)

where:

- \( \varepsilon \) is the dielectric permittivity of the material in question
- \( \varepsilon_0 \) is the dielectric permittivity of vacuum (\( 8.8542 \times 10^{-12} \text{F/m} \)) (Cassidy, 2009)

The permittivity of a medium will vary greatly with the presence of water, as free water will polarise under the influence of an applied electric field and increase permittivity with an increase in water content. Where most materials commonly found in railway ballast and subgrade typically
have dry permittivity of about 3-8, water has a permittivity of roughly 80 (Annan, 2009). The
dielectric constant of a ballast is linearly proportional to its percentage of water content (Fontul et
al., 2014).

This effect is not as prominent for bound water, (either frozen or as surface water bonded to
mineral grains) as the molecular rotation of the water is more restricted (Grote et al., 2005). For
practical purposes, frozen water can be considered a frequency-independent low-loss medium.
As a result, moisture levels need to exceed a certain saturation level in grained materials (over 1%
depending on grain size) to affect overall permittivity (Cassidy, 2009).

To relate the y-axis unit (time) to the actual depth of the detected interfaces, we need to know the
signal propagation velocity through the subsurface media. Its value will depend on the materials
EM-properties, voids and moisture content, See Figure 38 (Cassidy, 2009).

![Figure 38 Example of radargram resulting from railway track survey. Left: Longitudinal
profile. Right: Lateral profile and signal amplitude response](image)

Even when the material composition of a layer is known, the dielectric properties may not be
proportional to the volume fractions of each material component (Annan, 2009). This means there
will be uncertainties in GPR measurements related to signal velocity, and numbers should be based
on in-situ control testing or extensive quantitative data for similar material compositions (e.g. clean
ballast with certain grade, or similarly fouled ballast).

The relative permittivity can be used to calculate the relative propagation velocity for homogeneous
isotropic materials using the relation:

\[ v = \frac{c}{\varepsilon_r} \]  

where:

- \( c \) is the propagation velocity of light in vacuum \( (3 \times 10^8 \text{ m/s}) \)
- \( \varepsilon_r \) is the relative permittivity of the medium (Gallagher et al., 1999; Daniels, 2004)

However, the relative permittivity will be unknown for most practical situations (Leng and Al-Qadi,
2010). Several studies have attempted to quantify EM wave-propagation velocities for different
ballast fouling states and moisture contents (Sussmann, 1999; Clark et al., 2001; Fontul et al.,
2014).
Once the signal velocity is known or approximated, the depth of a signal reflection can be calculated using the equation:

\[ d = v \frac{t}{2} \]  

(3)

where

- \( d \) is the depth of detected interface
- \( v \) is the signal propagation velocity through the medium
- \( t \) is the two-way travel time of the signal (Transmitter → Interface reflection → Receiver)

The choice of frequency is of key importance when conducting GPR surveys. Different antenna frequencies will provoke different responses from the subsurface materials to a point where some results may only be visible in a given spectrum of frequencies.

1. A higher frequency signal will not penetrate as deep as a lower range frequency signal. This is because signal attenuation increases with signal frequency. Cluttering noise also increases with increased frequencies (Plati et al., 2010; De Bold et al., 2015).
2. Poorly defined interfaces can often be more clearly imaged using lower frequencies as penetration depth is increased and noise is decreased. Around 500 MHz seems optimal for imaging the ballast/subgrade interface (Jack and Jackson, 1999; Clark et al., 2001; Eide et al., 2001).
3. 800 MHz is often considered a good choice for ballast fouling assessments (Su et al., 2010; Shao et al., 2011).
4. Higher frequencies will give better scan resolutions (Su et al., 2010).
5. Frequency also affects signal scattering from air voids in the ballast. Scattering increases with the frequency, and when the size of air voids is near the signal wavelength this can generate significant scattering of the signal (Leng and Al-Qadi, 2010).

The frequency bandwidth of a GPR refers to the range of frequencies it can utilise in a survey. A broad bandwidth gives room to obtain both a deep signal penetration from low frequencies and the high resolution in the upper layers from the high frequencies. This optimises the sensing result (Plati et al., 2010). However, this limits the number of scans that can be performed per second and will in practice limit the maximum surveying speed (Annan, 2009).

The raw data from a GPR profile is comprised of one-dimensional time-amplitude representations (A-scans), put together to form two dimensional representations in the distance-domain (B-scans, see Figure 39) (Plati et al., 2010). The processing of signal data is performed to reduce noise, increase reflection contrasts and generally ease interpretation. The following are some of the main signal processing methods.
For air-coupled antennas, immediate signal reflection will occur at the surface interface. To avoid disturbance from these signals, time-zero corrections can be performed to adjust the earliest signal time from when the signal left the antenna, to when it first penetrated the surface. This establishes the surface as a common reference level and can also reduce the irregular reflection caused by sleepers (Hugenschmidt, 2000).

An unprocessed scan will display strong horizontal clutering-bands at exact time values, often as a result of reflections from rails. Reflections from actual layer interfaces however will vary in time across the B-scan. The absolute horizontal lines seen are not representative of the actual material layering and only works to disturb the correct interpretation of layer interface data. The filtering out of “false” layering is called background removal, and helps to even out the displayed values to accentuate true layer interfaces (Roberts et al., 2006).

A basic processing step where very low frequency return signals are filtered out. These low frequency signals are associated with dynamic range limitations of the instruments or inductive phenomena, known as wowing. As these signals are not objectively representative of the subsurface, but also dependent on antenna characteristics, they are usually filtered out or “dewowed” (Annan, 2003).

Vertical band-pass filtering (only allowing a defined frequency range) is done to remove high-frequency noise and interference from the scan results. Horizontal filtering evens out the changes between A-scans to better form a unity for the B-scan (Plati et al., 2010).

When signals propagate through the ground, they lose energy (signal attenuation). As a result of this, reflected signals from deep interfaces are weaker than the signals from similar interfaces at shallower depths, even for identical media. To more accurately illustrate the subsurface conditions, it is possible to apply a time-dependent amplification to the signals, known as time gain or range gain (Annan, 2009).

As high signal frequencies attenuate more than lower frequency signals, a problem occurs when GPR systems simultaneously scan using multiple frequencies. Known as wavelet dispersion, it...
manifests on the radar scans as a characteristic blurriness that increases with depth. Inverse Q-filtering is a method for compensating for this effect (Annan, 2009).

GPR scanning is vulnerable to uneven surveying surfaces causing sudden shifts and must therefore compensate for topography in its results, see Figure 40. Rail-mounted GPRs used on railways however, are largely unaffected by this due to the smooth nature of the rail’s vertical profile (Olhoeft and Selig, 2002; Annan, 2009).
Figure 40 Some common data processing steps applied to 500 MHz data (Roberts et al., 2009)
Although GPR technology shows promise for cost efficient and accurate ballast inspection, it does have limitations which are important to be aware of when considering it.

1. The dielectric constant of ballast will vary between ballast types and must usually be approximated for field surveys. Depth and thickness calculations will therefore suffer some inaccuracies unless more time consuming steps (in situ measurements) are taken to verify it (Leng and Al-Qadi, 2010).

2. Ballast fouling levels will usually change gradually towards the ballast/subgrade interface. Without a clear interface with sufficient contrast in dielectric properties, it is likely the GPR will not be able to accurately locate the transition/interface (Jack and Jackson, 1999; Leng and Al-Qadi, 2010).

3. When continuously surveying active track ballast, the readings are likely to be disturbed by reflections from sleepers, rails and similar surface installations. These block the signal from penetrating through, creating a shadow directly underneath which cannot be surveyed properly. This is true for both concrete and wooden sleepers (Gallagher et al., 1999; Hugenschmidt, 2000; Leng and Al-Qadi, 2010).

4. As a medium’s dielectric properties will vary both with degree of fouling and moisture content, it may be difficult to correctly attribute measured changes in value to either of the two. Surveys meant to compare a stretch of track taken at different times would therefore benefit from being performed at as similar weather conditions as possible (Olhoeft and Selig, 2002).

5. Presence of surface pollutants in the track (litter in station areas, wet leaves during autumn season etc.) may disturb GPR readings, as some of these objects produce strong signal reflections (Hugenschmidt, 2000).

The current high cost of track maintenance, paired with the significant potential offered by GPR technology has led to a wide range of studies on the issue. Railway track surveying is a fairly recent use for GPR, and work still remains to completely map the scope of its abilities and accuracy in this application. The following is an overview of some of the most relevant applications and studies performed on the subject.

Knowing the thickness of the track ballast layer will help maintenance personnel to assess the overall condition and performance of an active rail line. The layer needs a certain thickness to be able to distribute the loads from the sleepers across the ballast/subgrade interface, and if some areas have too thin layers, these areas will be prone to unfavourable riding conditions and accelerated ballast deterioration.

It is not uncommon for ballast layer thickness to vary along a stretch of track. Local repairs after derailments or embankment failures, varying ballast levels due to lower quality ballast or similar situations means the ballast/subgrade interface cannot be expected to remain at a level depth across the length of a track.

Several studies have been successful in determining continuous ballast layer thickness with a
high degree of accuracy using GPR surveying data (Gallagher et al., 1999; Eide et al., 2001). The clear interface reflection given by the transition between ballast and subgrade makes it possible to detect this. From the signal velocity we can calculate its depth, and thus determine the true thickness of the ballast layer. There are however some prerequisites for accurately using this method.

While the interface reflection from ballast/subgrade interface is usually strong, this is dependent on a high contrast in dielectric permittivity between the media. If the ballast has deteriorated, or in some way gradationally fouled near the bottom of the track bed, (e.g. through subgrade infiltration) this will give a much less defined interface signature, and therefore make it more difficult to distinguish the exact depth of the ballast layer (Plati et al., 2010; Fontul et al., 2014). A failure to precisely identify ballast/subgrade interface on GPR scans may therefore by itself be a sign of ballast fouling.

To make the ballast/subgrade interface more detectable with GPR, a special conductive geotextile has been developed. Placed between the two layers during the construction or ballast replacement phase, it ensures a clear electromagnetic signature at the bottom of the ballast layer (Carpenter et al., 2004).

Signal propagation velocity is a critical part of calculating depth, and it will vary with the dielectric properties of the surveyed medium. This is no problem for homogeneous materials with known dielectric properties, but the dielectric permittivity of ballast will vary with fouling level, void content, moisture content etc. (Leng and Al-Qadi, 2010). As a consequence, each case of ballast thickness surveying must be considered according to the current state of the ballast in question. Ballast fouling will most likely not be uniform across the depth profile of the ballast, further stressing the need for in-situ calibration.

From studies done on the subject, signal propagation velocities can be estimated for ballast based on its level of fouling. Combining the work from Clark (2001) and Sussmann (1999) gives the values in Table 2.
Table 2 Electromagnetic properties for different ballast conditions. (a) values from Clark (2001), (b) values from Sussmann (1999). Table adapted from De Bold et al. (2015)

<table>
<thead>
<tr>
<th>Material (*by volume)</th>
<th>Source</th>
<th>(\varepsilon_r)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>(a)</td>
<td>1.0</td>
<td>(3.00 \times 10^8)</td>
</tr>
<tr>
<td>Dry clean ballast</td>
<td>(a)</td>
<td>3.0</td>
<td>(1.73 \times 10^8)</td>
</tr>
<tr>
<td>Wet clean ballast (5 % water*)</td>
<td>(a)</td>
<td>3.5</td>
<td>(1.60 \times 10^8)</td>
</tr>
<tr>
<td>Dry clean</td>
<td>(b)</td>
<td>3.6</td>
<td>(1.58 \times 10^8)</td>
</tr>
<tr>
<td>Dry spent</td>
<td>(b)</td>
<td>3.7</td>
<td>(1.56 \times 10^8)</td>
</tr>
<tr>
<td>Moist clean</td>
<td>(b)</td>
<td>4.0</td>
<td>(1.50 \times 10^8)</td>
</tr>
<tr>
<td>Dry spent ballast</td>
<td>(a)</td>
<td>4.3</td>
<td>(1.45 \times 10^8)</td>
</tr>
<tr>
<td>Moist spent</td>
<td>(b)</td>
<td>5.1</td>
<td>(1.32 \times 10^8)</td>
</tr>
<tr>
<td>Wet spent</td>
<td>(b)</td>
<td>7.2</td>
<td>(1.12 \times 10^8)</td>
</tr>
<tr>
<td>Wet spent ballast (5 % water)</td>
<td>(a)</td>
<td>7.8</td>
<td>(1.07 \times 10^8)</td>
</tr>
<tr>
<td>Saturated clean ballast</td>
<td>(a)</td>
<td>26.9</td>
<td>(0.48 \times 10^8)</td>
</tr>
<tr>
<td>Saturated spent ballast</td>
<td>(a)</td>
<td>38.5</td>
<td>(0.58 \times 10^8)</td>
</tr>
<tr>
<td>Water</td>
<td>(a)</td>
<td>81</td>
<td>(0.33 \times 10^8)</td>
</tr>
</tbody>
</table>

1. The difference between the two sources for ballast in the same category ("Dry clean" has variations in value) is a testimony to the varying properties of different material types and compositions in the ballast types used. The table demonstrates the correlation fouling level and moisture content has on signal propagation velocity.

2. Fouled or "spent" ballast has a higher content of fines; hence its content of voids is less than for clean ballast. As electromagnetic waves travel faster through air than through ballast material, it will also travel faster in clean ballast than in spent ballast (De Bold et al., 2015).

3. The difference between dielectric constants for "saturated clean ballast" and "saturated spent ballast" comes not only from the lower void content for spent ballast, but also from the fact that spent ballast can hold more water than clean ballast (Clark et al., 2001; De Bold et al., 2015).

The actual properties of the surveyed ballast will most likely be somewhere between the categories seen in Table 2, but they provide a good approximation for field testing. Similar values were found by Hugenschmidt (2000); Eide et al. (2001) and Fontul et al. (2014). A relation was found by Fontul et al. (2014) where the dielectric constant increases linearly with an increase in moisture content or fouling, and fouling is the most affecting factor of the two. As the dielectric constant is affected both by moisture and fouling level, a change in its value cannot be directly attributed to either of the two factors. For accurate ballast assessment, it is therefore necessary to know precisely what is indicated by the GPR results. Several methods for separating the contributions of ballast density (fouling) and water content are described by Fontul et al. (2014).
Signal propagation velocity will also vary along the length of the track, as a result of local fouling, newly cleaned sections, local moisture or other factors. When operating with fixed signal propagation velocity, changes in dielectric constant along the stretch will manifest as changes in ballast thickness, even if the actual thickness remains constant. Where the signal velocity is higher than approximated, layer thickness will display as thinner, and vice versa. This is a result of the direct conversion of the signal's two-way travel time to depth from the signal velocity. If accurate ballast thickness measurement is the main purpose of a survey, in-situ calibration measurements of signal propagation velocity should be performed in relation to the uniformity of the track stretch (Gallagher et al., 1999).

For GPRs utilising a moveable antennas or multiple antennas in an array there exists a quick and accurate method for in-situ measurements of signal propagation velocity, called Common Midpoint test or Common Reflection Surface test. CMP refers to the test performed by moving a transmitter and a receiver away from each other, and CRS refers to the test performed by multiple static antennas in an array (Su et al., 2010; Kind, 2011).

As the separation between the antennas is known, measuring a common point with multiple or movable antennas will yield data regarding differences in signal travel time. These data can then be used to calculate the signal propagation velocity in that specific point on the track stretch (Gallagher et al., 1999; Su et al., 2010), See Figure 41.

This method requires the presence of a clear ballast bed interface reflection and limits the surveying speed to approximately 40 km/h (for fixed antenna arrays) according to Keogh et al. (2006). If the CMP test with moving antennas is used, the surveying rig must remain stationary for the duration of the test. (Su et al., 2010) Alternatively, real layer thickness can be controlled by digging trial pits in the ballast, although this is a more intrusive and time consuming method than the CMP/CRS test (Kind, 2011).

GPR enables ballast layer thickness measurements with high accuracy but is still reliant on in-situ calibrations and clear layer interfaces for optimal results. Changes in signal propagation velocity
along a stretch of track poses certain problems for thickness measurements, but the method is still an improvement over current methods (Jack and Jackson, 1999). Accurate and updated information regarding the ballast quality on the railway network is of key importance when managing track maintenance resources. Undetected areas of poor ballast quality may over time harm both track quality and rolling stock, but ballast cleaning or renewal is an expensive and time consuming method. The more is known of the track ballast state, the easier it will be to prioritise maintenance efforts where needed most, while limiting less necessary renewals. With GPR technology there are several ways of detecting and quantifying degrees of ballast fouling.

Using the same electromagnetic principles encountered when measuring ballast layer thickness, it is possible to register shifts in the dielectric constant of ballast. As the level of fouling directly affects the dielectric constant, this can help identify areas where ballast quality differs from desired values.

Surveying a stretch of track with good ballast quality, areas of poor ballast quality will register on GPR scans as areas with a thicker ballast layer. This as a result of the electromagnetic signal propagating slower through fouled ballast than in clean ballast, and thus increasing the signal travel time. It is important to note that these shifts in travel time may also come as a result of actual thicker ballast layers or local increases in water content (as water also decreases signal propagation velocity). In addition, this method does not clearly reveal boundaries of gradational fouling. As such, ballast fouling evaluation should not be based solely on the two-way travel time of the GPR signal.

Although this method is not sufficiently accurate for determining the level of ballast fouling in and of itself, it is useful for mapping the extent of “good” and “bad” ballast areas along a stretch of track (Jack and Jackson, 1999). Shifts in ballast thickness on survey scans indicate transitions between homogeneous sections, and can then be used for targeting ballast quality investigations (Brough et al., 2003). The absence of a clear ballast/subgrade interface may also be used as a general indicator that ballast has been at least gradationally fouled towards the bottom of the layer (Roberts et al., 2007).

Ballast fouling could also be assessed by taking advantage of the EM-scattering properties of ballast voids. When the wavelength of the electromagnetic signal is similar to the size of the voids, this creates significant scattering of the signal (Leng and Al-Qadi, 2010). The air voids in clean ballast are comparable in size to the wavelength of 2 GHz signals, and therefore produce significant signal scattering when surveyed with a 2 GHz antenna (Al-Qadi et al., 2010a). Conversely, data from fouled ballast would be expected to produce much less signal scattering, if any (Al-Qadi et al., 2008), See Figure 42.

Roberts et al. (2006) suggests that by using different frequencies and measuring signal scattering,
it is possible to approximate the size of the voids. This can in turn be used to assess the degree of ballast fouling. A downside is that the high frequency needed (>2 GHz) also causes high signal attenuation and therefore limits signal penetration depth.

![Figure 42 Scattering in radargrams with different ballast fouling conditions. Left: Clean | Centre: Partially fouled | Right: Fouled (Al-Qadi et al., 2008)](image)

The scattering seen in the centre section of Figure 16 clearly reveals the change in ballast quality occurring in the middle of the sample window. Here the ballast has deteriorated to a point where the voids no longer are large enough to cause signal scattering at the current frequency. Assuming the transition from clean to fouled ballast here is gradational (as is usually the case), lower frequency scans would not be able to identify the extent of the fouling as accurately.

To comprehensively display the scattering data, Roberts et al. (2006) uses additional data processing in what is called the “scattering amplitude envelope method”, See Figure 43. Here, changes in the amplitude of scattered signals is related to changes in ballast condition (De Bold et al., 2015). The amplitude envelope of the reflected waves is obtained using the Hilbert transform, encompassing both negative and positive peak amplitudes (Roberts et al., 2009). From the average scattering amplitude of signals for each depth, it is then possible to display void content distribution (and thereby ballast quality) in the ballast layer.

![Figure 43 Scattering amplitude envelope constructed from GPR data of gradationally fouled ballast (Roberts et al., 2009)](image)

Practical field tests of this method has produced promising results and consistency with actual data, but more control data is needed to verify the scope of its applicability and limitations. For
one thing the method will have difficulties differentiating between the contributions of water content and content of fouling materials (Roberts et al., 2006; Al-Qadi et al., 2010a).

A third approach to ballast fouling surveys with GPR is based on frequency analysis of the reflected signals, relating to the rate of signal energy attenuation through the medium. The Short Time Fourier Transform converts a portion of time-domain data to frequency-domain data, tracking the change in frequency spectrum over time, and thus over depth (Clark et al., 2004; Oppenheim et al., 2005; Al-Qadi et al., 2010a).

The changes in frequency allows for distinguishing various ballast fouling conditions and presence of moisture, even without clearly defined interfaces. What is obtained is effectively a continuous survey of material parameters in the subsurface, see Figure 44 (Silvast et al., 2010a).

Field and laboratory studies by Leng and Al-Qadi (2010) (see also Al-Qadi et al. (2010b)) indicate that using 2 GHz horn-antennas with STFT colour-maps will enable efficient detection of fouling and water accumulation locations as long as the dielectric constant used is accurate. The automatic categorisation and colour coding will enable analysis of survey data in shorter time, and limiting the need for specialised personnel. But the process will also restrict room for interpretation.

As the method will reveal information regarding ballast quality relative to depth, it may be considered superior to traditional core sample gradation tests, which only obtains data for the entire sample as a whole (Al-Qadi et al., 2010a).

Other methods for fouling detection currently under development are not featured here, but are described further in:

1. Discrete Wavelet Transform (Shangguan et al., 2012) and (Shangguan and Al-Qadi, 2014)
2. System based on magnitude spectrum analysis and support vector machine (Shao et al., 2011)

Although fouling does alter their dielectric properties, the ballast and subgrade are still relatively
homogenous materials. This makes it easier to distinguish foreign objects or track related utilities on a GPR scan even in most cases of ballast fouling (Uduwawala et al., 2005). Objects made from different materials will have different dielectric properties, and especially metals are easily detectable with GPR due to their high conductivity and strong signal reflection (Uduwawala et al., 2005; Indraratna et al., 2011).

Plastic pipes also give unique scattered signal shapes when surveyed with GPR, but this signal is much weaker than for metals. They also become more difficult to distinguish with rising moisture levels. This is especially true for soils with high inherent permittivity. The lossy nature of the high moisture soil does not mask the signature of the plastic and metallic pipes, but does decrease the signal strength of their reflection. Their detection is therefore dependent on filtering the data by subtracting the clutter from the received signal (Uduwawala et al., 2005).

Foreign objects will manifest with a hyperbolic inverted U-shape on the GPR response. As seen in Figure 45, the location of the object is indicated by the top of the hyperbola, and the shape of the “tails” give information regarding the signal velocity and depth (Annan, 2003).

The antenna frequency also affects the GPR’s ability to detect objects in the subsurface. Frequencies of around 1 GHz and higher increase the resolution and give finer texture radargrams. However, these frequencies generate scattering signals (noise) from voids in the ballast, which in turn make it difficult to detect layering and foreign objects (Indraratna et al., 2011). For optimal detection of hidden objects and utilities, lower range signal frequencies and low subsurface moisture content is preferable.

![Figure 45 Buried objects detected on a 450 MHz GPR scan (Annan, 2003).](image)

GPR has also seen promising results as a method for detecting the presence and extent of track
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bed anomalies like subsoil penetration, layer deformation or mud pumping (Hugenschmidt, 2000; Eide et al., 2001; Silvast et al., 2010b). These types of errors will manifest on radargrams as local anomalies in the ballast bed reflection, which stand out from the common trend along the scan. Identifying these may be problematic however, as the ballast bed interface will not necessarily present itself as a straight and even line.

The presence and extent of areas where subsoil has penetrated into the ballast have been reliably detected in one study by Hugenschmidt (2000), see Figure 46. As long as the contrast to the ballast's dielectric constant is present, subgrade penetration will be visible through characteristic shapes in the ballast bed interface reflection.

![Figure 46 A 900 MHz survey dataset revealing two ZOPs (Zones of Penetration) where subgrade has penetrated up into the ballast body (Hugenschmidt, 2000).](image)

Ballast pockets are seen as depressions in the ballast/subgrade interface reflection, and will be distinguishable on radargrams if their magnitude makes them sufficiently stand out from the surrounding trend. The same can also be said for other trackbed anomalies like gradual slumping of the subgrade. While the benefit of early detection of ballast pockets is substantial (allowing for repair with smaller precision drainage efforts), detection will be more difficult in the early stages of development. GPR is a good method of accurately determining the depth and lowest point of ballast pockets to accurately target drainage measures (Li et al., 2015).

Hyslip et al. (2005) demonstrates the use of generalised indices for automated systematic evaluation of substructure condition. These indices are based on the detection of the ballast/subgrade interface, and can be based on parameters like contours of layers, moisture content and the rate of change of layer parameters. This could in turn be combined with track geometry data, maintenance logs and GPS data to grant more extensive insight into track condition from only studying the available data. The development of a well calibrated index will lend substantial aid to the process of automatically detecting and classifying ballast pockets from GPR scans. Although this automatic indexing has not yet been fully developed, the work presented by Hyslip et al. (2005) is a promising proof of concept, Figure 47.
Mud pumping occurs when the load bearing capacity of the ballast fails, and a slurry of fines and water is pumped upwards through the ballast body by the cyclical loading of passing trains. The fines and water contribute to foul the ballast, which will in turn decrease the signal propagation velocity. Identification based on this characteristic alone may be difficult, as the upwards migration of fines from the subgrade will compromise the integrity of the ballast/subgrade interface. This can therefore render its reflected EM-signal weak or non-existent. Developing mud pumping sites may also manifest as subgrade penetration or wave-shaped reflections on GPR radargrams, before depositing fines on the surface and becoming easily detectable by visual inspection. For solutions utilising advanced signal processing for moisture or fouling detection, these areas can be identified by searching for localised areas with an increased degree of fouling, see Figure 48 (Göbel et al., 1994).
V-shapes on radargrams can be a result of ballast pockets, or deep cuts backfilled with ballast input as intentional drainage trenches to halt the further development of a ballast pocket (Eide et al., 2001; Li et al., 2010).

For railways situated in climate zones prone to sub-zero temperatures, the freeze/thaw cycles can have a detrimental effect on track performance. This is particularly true for heavy haul lines, as the occurrence of frost heave and thaw softening may directly affect the geometry and bearing capabilities of the track body.

For detrimental frost action to take place, three parameters must be fulfilled. In addition to temperatures below 0 °C and available moisture, the affected layer must be frost susceptible. In short this means it needs a particular composition of fines. The occurrence of such frost-susceptible material in the track structure may come from wrong use of subgrade materials or fouling from fines in the ballast layer.

Silvast et al. (2010b) performed a research project to study the potential of GPR to locate frost susceptible track sections. The approach used for detection of these situations was based both on the GPR’s ability to identify frost susceptible soil (in the same way it can detect fouled ballast) and its ability to detect water.

As previously seen, water is a dominant factor in determining the dielectric properties of soils and therefore the strength of the reflected GPR signal (Narayanan et al., 1999). However, there is a significant difference between the reflected signal strength from free water and that of bound water (e.g. frozen in ice), see (Grote et al., 2005; Cassidy, 2009). As a consequence, liquid water is much easier to detect with GPR than frozen water. The detection of ice lenses performed in the Finnish study was therefore reliant on liquid water being present around the ice.

The electromagnetic signal from the GPR is reflected back towards the receiver from the
interf

ces between structural layers. The larger the difference in dielectric values between the two layers, the stronger the reflection becomes. Both properties necessary for frost action (water content and fines) will increase the relative permittivity and electrical conductivity of the medium, relative to clean permeable materials. This difference creates a clear and strong reflection at the interface of frost-susceptible media, thus enabling detection (Silvast et al., 2010b).

The presence of water or fines also alters the frequency response of the GPR signal. Through the use of a STFT analysis, it is possible to differentiate between frost-susceptible and non-frost-susceptible materials (see Figure 49). This allows for more easily comprehensible colour coded scan profiles for determining potential problem areas (Silvast et al., 2010b).

![Figure 49 STFT processed GPR scans from: (a) clay subgrade, and (b) coarse gravel subgrade sections (Silvast et al., 2010b)](image)

In the study by Silvast et al. (2010b) (see Figure 49) GPR data allowed for estimation of frost susceptibility by utilising the STFT analysis method and comparing data from summer and winter-surveys on the same track sections. This also allowed for ice lenses to be detected, though not with absolute accuracy and under the precondition that liquid water occurs around the ice. As the dielectric constant of water is significantly larger than both that of ballast and that of fouling materials, the presence of moisture will have a noticeable effect on GPR survey data. Surveying a section under wet conditions will yield more intense radargram textures of features than under dry conditions, especially where materials retain the moisture more than the clean permeable
ballast (Hyslip et al., 2005; Indraratna et al., 2011).

Pockets of water should also be clearly visible on GPR scans, granted they are within the signal range depth (Narayanan et al., 1999). Experimental work with the Short Time Fourier Transform method and the amplitude envelope method have also been successful in accurate detection of water (Al-Qadi et al., 2008; Leng and Al-Qadi, 2010). Studies related to detection of leakage from water and sewage pipelines have found GPR to be a viable inspection method (Ayala-Cabrera et al., 2014). Not only for detection of leaks, but also to map how water will dissipate and distribute through the soil. For optimal results, an array of antennas is needed to be able to survey the ground in three dimensions.

Work published by Su et al. (2011) and Li et al. (2015) on the “wetting test” do provide evidence of GPR’s ability to detect water introduced to the ballast as a means of identifying fouled ballast. When water is detected as pooling inside the track body, it indicates poorer drainage qualities in the medium below, than above. Although no previous study has been found to directly apply GPR specifically for mapping the water distribution in ballast, these studies at least prove the concept of some of the necessary technological functions. To assess the viability of GPR systems for the applications mentioned in this study, a field test on live track was performed on the 27th of October, 2015. The purpose was to survey a live track section in realistic conditions, and to artificially implement track conditions and faults to assess their detectability in real situations.

Although the initial intention was to conduct the survey on a stretch known to have ballast pockets, this was in the end not deemed feasible. Existing ballast pockets could not be reliably located, and digging operations for artificial implementation of ballast pockets were considered to be too extensive and costly for this study. Focus was instead turned towards proving the accuracy and ability of the GPR to detect the factors needed to uncover ballast pockets. A successful mapping of the ballast/subgrade interface, detection of subsurface formations and anomalies would go a long way towards proving the GPR’s ability to detect the presence of ballast pockets.
The track stretch selected was a 500 m long section of Dovrebanen, see Figure 50, situated between Ler station and Lundamo station, in Sør-Trøndelag, Norway. The section consisted of an electrified single track with concrete sleepers on ballasted track, running partially on embankments, partially on cuts and partially level to the terrain. It was selected in part as it contained several features which would provide interesting results on the GPR scans, including mud pumping sleepers and level crossings. The utilised GPR system was a GeoScope™ GS3F system equipped with a V2429 antenna-array from 3d-radar AS, jointly owned by SINTEF and NTNU (See Table 3). The antenna was mounted to a Robel rail tractor supplied and operated by Jernbaneverket for the test, See Figure 51.

![Figure 51 3D-radar V2429 antenna-array mounted on Robel rail-tractor](image)

**Table 3 Specification data on the utilised GPR system. (3d-radar, 2009)**

<table>
<thead>
<tr>
<th>GeoScope GS3F (3GHz) - Antenna model V2429</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
</tr>
<tr>
<td>Radar waveform</td>
</tr>
<tr>
<td>2.4 m Number of antenna elements/channels</td>
</tr>
<tr>
<td>Space between antenna elements mm</td>
</tr>
</tbody>
</table>

The antenna system consists of air-coupled bow-tie monopole pairs of receivers and transmitters. A step frequency survey approach was used, where each antenna-pair surveys in several different frequencies in steps to cover the entire bandwidth spectrum. Each A-scan then includes survey data for the entire bandwidth for each antenna element, see Figure 52 and 53.
Figure 52a Antenna layout concept for similar array model with 21 antenna elements (V1821). Transmitter antennas (T) and Receiver antennas (R) are combined to create a series of elements/channels (3d-radar, 2009), Figure 52b High-speed acquisition setup with only three active antenna pairs for V1821 model antenna array. (3d-radar, 2009)

The frequency bandwidth range utilised in the survey was 200 MHz - 2.8 GHz. This was expected to grant sufficient signal penetration depth as well as giving high-resolution scans of the upper layer textures.

Most of the 29 available antenna elements were used, to give best possible data for the test surveys. This did however limit the maximum surveying speed to walking pace. By using fewer of the antenna elements, the surveying speed can be increased, at a cost to the lateral data coverage. Using only three antennas (as seen in Figure 52) will allow for surveying speeds of up to 90 km/h according to 3d-radar (2009). Successful use of the B2431 antenna model at 60 km/h was reported by Silvast et al. (2010b).

The antenna-array was mounted to a height of approximately 15 cm above the rail head. This height gives clearance to prevent antenna collisions, while simultaneously being close enough to the surface to ensure satisfactory signal conditions. The GPR is connected to a Distance Measuring Instrument (DMI) in the form of a small rubber wheel running on top of the rail head. This wheel (see Figure 53), feeds distance information to the system to trigger
scans in distance-based increments. The signal values from the wheel can be inversed from the operator PC, allowing for surveying in both directions of travel.

Figure 53 Left: The GeoScope radar unit and operator PC are located in the driver’s cabin of the surveying vehicle. Right: Mounted rubber wheel (DMI)

The connected operator PC runs a GeoScope software which allows for configuring the various survey parameters like number of active antennas, frequency range or sampling intervals. During the survey, it displays real-time data from one of the antennas, and can introduce markers into the dataset to correspond to surface features or other points of interest along the surveyed stretch.

The morning of the test surveys had seen intermediate intensity rain in the area, enough to consider the entire track body as “wet”. The rain had subsided within two hours before survey start, which would have given the track time to drain itself of excess water (not bound to surface of aggregate material). Any remaining pockets of water at time of survey would then be indication of a clear failure in the track’s ability to drain.

Despite the autumn season, the chosen stretch proved to be free of visible surface pollutants like wet leaves. The presence of these would most likely cause significant disturbances to the GPR readings due to the effect of moisture and biological pollutants on EM wave propagation. Air temperature remained consistent around 5 - 7 °C for the duration of the field study.

To ensure precisely spaced scan intervals, the GPR (Figure 54) had to be calibrated with the DMI wheel on site. A 25 m stretch was measured in the station area using two separate measuring systems, a measuring wheel along the rail and measuring tape. The GPR rig then ran the distance for correction of DMI length conversion factor. During this process, the rail tractor overshot the distance by approximately 0.1 m. This was however deemed within the necessary limit of accuracy, as the aim of the survey was not to precisely pinpoint features, but merely to detect and approximate their position.
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Figure 54 GPR rig schematic for the field survey. a) Antenna array, b) DMI, c) Radar unit and operator PC, d) External power source (generator)

Although poor signal penetration and interference from sleepers have been known to cause problems with interpretation of GPR scans, no effort was made to avoid surveying directly on top of sleepers (Eide et al., 2001). This was an intentional decision based on a desire to keep the surveying set-up as simple as possible to operate, and instead allow any necessary signal-clean-up measures to be performed in the post-processing phase of the survey. If such a configuration proved sufficient for the test survey, it could help in limiting the technical expertise needed for the data gathering phase of future track condition inspections.

The survey rig was run from the starting point to the end at an even pace. Real-time data from the GPR was displayed on the connected computer, whose operator immediately attempted to relate the revealed subsurface features to the visible surface features. This process worked to ease later off-site data interpretation, while continuously assuring the operators that the system was working as intended. For high-speed surveys over long stretches, the same effect can be achieved by combining the data with GPS-tagged photos taken in tandem with the scans.

For the first survey (see Figure 55), the goal was mainly to confirm that the system was working as intended, and to attempt to evaluate the subsurface conditions. Surveying was stopped some distance after passing over the site of the mud pumping sleepers. In the second survey (see Table 4), sampling intervals were decreased to obtain better quality of the B-scans. This increase was taxing on the system’s processing power, and caused the maximum surveying speed to be limited further. The length of the surveyed stretch was increased for the second test survey to also include a level crossing with timber surface.

Table 4 Test survey specifications

| Continuous scan between Dovrebanen | 517.600 km - 517.170 km | 517.600 km - 517.050 km |
| Survey vehicle speed: | 4 km/h | 3 km/h |
| Sample rate | 1 scan every 15 cm | 1 scan every 10 cm |
| Frequency bandwidth | 200 MHz - 2.8 Ghz | 200 MHz - 2.8 GHz |
The first test of water distribution detection was performed at a location near the beginning of the test survey section, running approximately level to the surrounding terrain (no embankment). The ballast here appeared to be of good quality on the surface (See Figure 56). However, shallow samples taken at the site revealed incipient light fouling in the top part of the ballast. It should therefore be assumed that the degree of fouling at that location increases somewhat towards the bottom of the ballast layer.

The collected ballast sample was later dried in the laboratory and found to have a water content of 0.9% (Table 5) measured in weight-percentage. This is consistent with the visual impression of the sample as very lightly fouled. The sample was taken before any additional water was introduced.
Table 5 Analysis results from laboratory-dried ballast sample

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Weight of wet ballast</td>
<td>17.556 kg</td>
</tr>
<tr>
<td>Weight of dried ballast</td>
<td>17.409 kg</td>
</tr>
<tr>
<td>Ballast water content (w)</td>
<td>0.901832 %</td>
</tr>
</tbody>
</table>

25 litres of pure liquid water was manually poured into an area at the top of the ballast (see Figure 57). It was then allowed to percolate through the ballast body while the GPR rig passed over it, scanning at recorded time-intervals. This behaviour was intended to yield information regarding the movement of the water in the lateral, longitudinal, and vertical direction as well as over time.

The water was poured solely on one side of the ballast crib (Figure 57) to allow the data from the opposite side to serve as a control, and to confirm the GPR’s ability to map the water distribution in the lateral direction. The water was not poured immediately adjacent to the rail, as signal interference from the rail could have masked the signals or otherwise complicated interpretation of the results.

![Figure 57 Water being poured into the ballast at the first test site, marked in red](image)

A test section of 30 meters (15 meters on either side of the poured water) was set up to be surveyed for the test. This would allow for comparisons with adjacent “dry” profiles and to better emulate the image characteristics of a continuous survey. The method of surveying all 30 meters every time lead to some slight timing problems with the scan intervals. This mostly caused slight delays in the planned scanning schedule, yielding less “natural” values of time increments. However, these scans are all within the desired time area and are considered fully valid for this purpose.
A “dry” scan was performed before any water was introduced, to serve as a control against the later “wet” scans, as outlined in Table 6.

The second test of water distribution detection was performed at a location where mud pumping had previously been discovered, and was still clearly visible by visual inspection of the track surface. The intention was to perform the same experiment as in the first water distribution test, only altering the parameter of ballast fouling level. This part of the track runs on a small embankment.

Mud pumping (Figure 58) is a ballast condition where fines and water form a slurry, which is pumped upwards by the cyclic loading of the track from passing traffic. This creates very localised areas where the ballast is particularly fouled, with mud filling a large share of the void spaces. The fouling will have a direct effect on the ballasts ability to drain away excess water, and this difference should be detectable in the results of the water distribution test.

Table 6 Specifications for water distribution test 1

<table>
<thead>
<tr>
<th>Water distribution test 1 - specifications Continuous</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan of stretch surrounding water pouring site</td>
<td>Survey</td>
</tr>
<tr>
<td>length</td>
<td>30 m</td>
</tr>
<tr>
<td>Survey speed</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Sample rate</td>
<td>1 scan every 10 cm</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
<td>200 MHz - 2,6 GHz</td>
</tr>
<tr>
<td>Scanning run</td>
<td>Time after pouring [mm:ss]</td>
</tr>
<tr>
<td>Dry run</td>
<td>0:00</td>
</tr>
<tr>
<td>Wet run 1</td>
<td>01:40</td>
</tr>
<tr>
<td>Wet run 2</td>
<td>03:50</td>
</tr>
<tr>
<td>Wet run 3</td>
<td>06:35</td>
</tr>
<tr>
<td>Wet run 4</td>
<td>10:35</td>
</tr>
</tbody>
</table>
The test was conducted with identical procedures and equipment as in the first test. 25 litres of pure liquid water was manually poured into an area at the top of the ballast (see Figure 58) and allowed to percolate through the ballast body while the GPR rig passed over it.

Due to time-window restrictions on the track, there was not sufficient time to scan for the same duration of time as in the first water test (see Table 7). However, the time should be sufficient to expose differences in water propagation time caused by differences in ballast conditions. This also prevented the collection of ballast samples, but the general condition of the surrounding area (mud pumping, Figures 58 and 59) is sufficient to assume that the ballast area in question is considerably more fouled than the test area for the first water distribution test. Some new ballast appears to have been added to the area, but not within the circled pouring area, and seemingly only on the surface.

Figure 58 Blue markings indicate the extent of mud pumping sleepers at the site of the second water test. Red circle indicates the area where water was introduced into the track.
Figure 59 Water test site 2. Fines from mud pumping clearly visible on sleeper ends and adjacent ballast. Water was poured into the area marked in red.

<table>
<thead>
<tr>
<th>Water distribution test 2 - specifications</th>
<th>Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>scan of stretch surrounding water pouring site Survey</td>
<td>30 m</td>
</tr>
<tr>
<td>Survey speed</td>
<td>3 km/h</td>
</tr>
<tr>
<td>Sample rate</td>
<td>1 scan every 10 cm</td>
</tr>
<tr>
<td>Frequency bandwidth</td>
<td>200 MHz - 2.8 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scanning run</th>
<th>Time after pouring [mm:ss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry run</td>
<td>0:00</td>
</tr>
<tr>
<td>Wet run 1</td>
<td>01:00</td>
</tr>
<tr>
<td>Wet run 2</td>
<td>02:25</td>
</tr>
<tr>
<td>Wet run 3</td>
<td>04:30</td>
</tr>
</tbody>
</table>

The initial plan for this test involved digging a very narrow passage into an embankment and surveying it with the GPR in an attempt to assess the detectability of animal burrows. However, after closer inspection of the test section, a number of problematic factors were discovered.

The embankments on the stretch were found to be slightly wider than expected, caused by shallow slope angles and deep ballast layers on the track shoulders. As a consequence, the closest and shallowest point where digging would be possible was over two meters to the side of the lateral extent of the rails, sleepers and GPR antenna array.

The compact medium, and permeating vegetation of the embankment substructure further complicated digging efforts. It was concluded that the available equipment would not allow for digging far enough into the embankment structure to approach the area directly underneath the extent of the sleepers. There were also concerns that too extensive digging might compromise the structural integrity of the embankment, making it a safety issue. The work was stopped to prioritise the other two field tests in the study.
It is difficult to predict exactly how the burrows would have manifested on the GPR radargrams, but some assumptions and be drawn from the available theory.

- While a pocket of air would present a contrast in dielectric constant (causing signal reflection), the reflection would likely be much weaker than those seen from water or metallic features. This is due to the fact that the latter's dielectric constants are much larger than those of air.

- As burrows may only occur in the subgrade layer, signal attenuation will likely cause the signal to be very weak by the time it reaches those depths. This would further complicate the detection process.

- Signal reflection would likely depend on the moisture content of the surrounding subgrade and whether there is pooling of water in the burrow itself.

Future attempts to detect animal burrows with GPR should be performed on existing burrows to ensure feasibility and to provide realistic testing conditions.

The data acquired from the field test was input into two different analysis software:
- Road Doctor™ from Roadscanners Oy
- 3dr Examiner from 3d-radar AS

Both of these software provided solutions for simultaneously displaying different aspects of the GPR data, as well as built-in data processing steps to make them easier to interpret. The inclusion of both software was done mainly for practical reasons, as well as due to some initial technical issues with the available computers. The following data processing steps were applied to all the GPR radargrams shown in this chapter:
- Interference removal
- ISDFT (Inverse Selective Discrete Fourier Transform)
- Background removal
- Autoscale

The GPR system includes very accurate timing units which record signal travel times to within a thousandth of a nanosecond. This high degree of accuracy is useful when analysing the results of surveys, but the uncertainties related to electromagnetic properties of the surveyed medium will still give room for much larger inaccuracies in practical applications. The knowledge that these errors are unlikely to be hardware-related helps in the interpretation of survey results, and to detect methodological inaccuracies.

The GPR scans collected from the two test surveys show clear and detailed information about the track structure. From the full scan shown in Figure 36 we can begin to identify certain subsurface features. As the readability of this scan will be limited in printed version, relevant windowed excerpts have been included in the following pages.

To approximate depth values from signal travel times, a dielectric constant of 8.0 has been used for all the radargrams displayed in this report. From what is known of the fouling condition of the ballast in the area, this value is seemingly too high. However, as a precise wave propagation velocity was not important for the purposes of the test surveys, no further
effort was taken to more accurately calibrate its value. The wave propagation velocity was more precisely calibrated for the water distribution tests.

It is important to note that the radargrams shown in the analysis part have not been fully optimised for display beyond the initial data processing methods listed in the beginning of this chapter. It is not the aim of this study to exaggerate the abilities of GPR technology, but it should still be mentioned that readability could be slightly improved using additional data processing. Use of such processing steps must be done with caution, as an inherent risk of “simplifying” data is the loss of potentially important information.

The performed test survey can be seen as a realistic case study, in the sense that no information about the track was available beyond what was clearly visible on the surface. This would also be the case for a real life implementation of the method.

This report will mostly use data gathered from test survey 2, as it covered the longest stretch. The quality of data was very similar in the two scans, meaning that a sampling interval of 10 cm does not yield obvious advantages over an interval of 15 cm for surveying over a distance. Example radargrams with different sampling rates are shown in appendix A.

For radargrams displaying “sample” as the y-axis label, this only refers to a scaling option for the viewing software (Autoscale). While their appearance is identical to those displaying time as the y-axis unit, the sample units themselves are not directly interchangeable with time values.

A significant feature in the survey radargram is the hyperbolic shapes (Figure 61 and 62) occurring in the subgrade between scans 1500 - 2200. This corresponds to the section 150 m - 220 m into the survey stretch which runs in a rock cut, with a small hill directly adjacent to the line on the left side.
Figure 60 Full length radargram from test survey 2. Data extracted from centre antenna
The hyperbolic shapes seen in Figure 61 are most likely caused by large rocks blasted from the rock cut, and subsequently used as filler for the track body. They seem unlikely to be caused by subsurface installations due to the number of objects, apparent orientation (as indicated by hyperbola shape), and the relatively weak signal strength. Especially metallic objects would produce stronger and more distinct signals. The horizontal cross-section seen in Figure 62 seems to indicate the stones are mostly situated in the middle of the track profile, but this could simply be a result of the signals near the edges being obstructed by the rails on the surface. As we are able to both detect these rocks and assess their depth, it should be possible to use this method to evaluate a track for similar subsurface anomalies.

The location of the mud pumping sleepers was already known before the survey, as they were clearly visible and distinguishable on the track surface. The challenge of the test survey was to be able to detect and separate them from the surrounding track structure. The mud pumping is clearly visible on the scans in Figure 63, with clear signatures from the affected sleepers mirrored at the ballast/subgrade interface. As their reflection is mainly contained to this depth, and not continuously echoed down through the subsurface, it strengthens the credibility of the radargram manifestation. This means we can more confidently assume that the signals are a response to subgrade penetration (and not echoing from surface reflections), although in-situ excavations are needed to confirm this.

The horizontal cross-section in Figure 63 shows the signal reflection from the depth of the ballast/subgrade interface. As the shapes of the sleepers are so distinguishable at the bottom of the ballast, it is apparent that the load distribution properties of the ballast has failed more or less completely, leading forces straight down, and causing mud to be pumped up between their “footprints”.

---

**Figure 61** Clear hyperbolic shapes indicating large buried objects

**Figure 62** Horizontal cross section combining data from all antennas at the depth of the top of the hyperbolas
Displaying scans collected from antennas further from the centre of the track yields a distinct and unexpected signal reflection (Figure 64). Further analysis of the scans revealed large shape variations in the registered reflection between the different antennas, strengthening the belief that the shape of the reflected signals did not represent the shape of any substructure feature.

From the horizontal cross section it is apparent that the strong signal reflections are originating from outside of the track body. Wave patterns are visible on both sides, but almost non-existent in the centre of the survey width (0 m). Also, at these depths the signal will normally have attenuated too much to yield a strong reflection from changes in dielectric constant. When the signals here are this strong despite their apparent depth, it may be a
sign that the signals have travelled in a less lossy material (e.g. air) and their depth is actually just a misinterpretation of their long signal travel time.

The disturbances occurred from the very beginning, until a point approximately 230 meters into the survey. Reviewing images and notes taken during the survey revealed a metal wire fence running along both sides of the track, terminating at the same point as the signal reflections. Even though the antennas only survey perpendicular to the bottom of the array, some signal scattering will still occur (this is also what causes the hyperbole shape from buried objects). In addition, the steel rails may have reflected much energy outwards to the wire fences, which was then returned and received by the antennas. This would also explain the lack of reflection registered on centre antennas, as these were shielded by the rails from receiving the signal. Alternatively, the edge channels of the antenna array may not be properly shielded, and may therefore be more susceptible to signal disturbances than centre channels. The occurrence of these types of signal disturbances emphasise the importance of having a basic understanding of the theory behind the GPR scans, as blindly interpreting any radargram features as actual subsurface realities will in some cases be outright wrong.

The timber-covered level crossing located near the end of the survey stretch was easily detected on the GPR scans, and is easily identifiable by its radargram manifestation alone (Figure 65). The scans appear to reveal a vastly different subsurface structure under the level crossing than in the surrounding track, with seemingly endless layering downwards. As the substructure is no different for level crossings than for regular track, this layering is not indicative of the substructure of the crossing, but rather an unintended effect of the GPR surveying method. As the surface of the crossing is covered with timber, the signal will both experience high attenuation and give off a strong reflection. This effect is amplified by the presence of water within the timber, as was the case during this survey. The wet timber causes complete attenuation, blocking the signal completely and leaving only echoes of the initial reflection as supposed representations of subsurface reflections.

Although such “false layering” should have been removed by the applied data processing (Background removal), the longitudinal extent of the layering was in this case too short for the software to detect as surface reflection echoes. This minimum value can be manually adjusted if desired.

![Figure 65 Left: Horizontal reflection stemming from a level crossing immediately ahead of the survey start. Right: Level crossing as manifested on the test survey radargram, with similar horizontal reflection extending to both sides, and a false layering effect downwards through the track body](image-url)
Both the radargrams in Figure 65 display a horizontal reflection extending from the level crossings (approx. 40 m), and fading away outwards from them. These are not part of the track structure, and the effect cannot immediately be attributed to errors caused by the electromagnetic mechanisms of the GPR. The most likely cause of these reflections is pooling of water in the area around the crossings.

The ballast surrounding level crossings will often be more fouled than elsewhere on the track, both due to additional ballast and timber deterioration from loading, and from spillage of fines and gravel. This would explain why this only occurs near level crossings and then fades out. The crossing roads are gravel roads trafficked mainly by a local farm with cars and assorted agricultural machinery. Although some spillage may be expected from these vehicles, the amount of traffic does not seem sufficient to cause this grade of fouling by itself.

The reflections occur at a depth approximately half way through the ballast layer. To cause such distinct reflections from water pooling, the lower half of the ballast must be nearly impermeable, indicating heavy fouling in that particular area. If the fouling was indeed caused by spillage from the road, it would be natural to assume the fouling to also appear similarly strong in the upper half of the ballast instead of this clear interface. The track is level at the site, and the road slopes away from the track on both sides, lending no aid to explaining why the water would accumulate near the crossing. The evidence for water accumulation as the cause is therefore inconclusive, and system error cannot be ruled out without core sampling or excavation of the site.

A major part of the test survey was also to attempt to detect and map the reflection from the interface between the ballast layer and the subgrade layer. From the surface samples collected as part of the water distribution test, the ballast quality is believed to be lightly fouled. The image presented on the radargrams in Figure 66 show a definite horizontal reflection, indicative of the contrast in dielectric constant from the ballast/subgrade interface. The reflection signal is not as strong as what might be expected from clean ballast, further supporting the belief that ballast has become more fouled near the bottom of the layer. Nevertheless, a definite reflection from the interface still means there is a sudden change in dielectric constant between the materials, meaning the ballast is not heavily fouled in any case.
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Figure 66 Top: The interface between ballast and subgrade layers as seen on the test survey scans. Bottom: The same image overlaid with a red line to aid interpretation

From what is known about the behaviour of EM-waves in ballast, it should be possible to more accurately assess the fouling condition from high-frequency wave scattering. The implementation of this method was not possible in this study. However, as the utilised hardware is capable of generating the high frequencies needed, it could potentially be included as part of future survey methods. This could yield more accurate information regarding the extent and distribution of fouling within the ballast.

When inspecting the reflection from this interface across the extent of the survey, it appears to be relatively even in depth, without sudden shifts in depth or reflection strength. This is indicative of a fairly uniform ballast composition and fouling state along the length of the surveyed section. The successful detection of the ballast/subgrade interface means that anomalies that would cause uneven layer formation, (such as ballast pockets) would be detectable from a study of the ballast/subgrade interface reflection. In the case of this survey, the interface is so level that even small anomalies stand out from their surroundings. As ballast pockets begin to develop, they may at first not be visible across all antennas. A thorough inspection will therefore entail studying a stretch of track with comparisons between signals from antennas with different lateral positions. This way it is possible to detect early stages of localised subgrade failure.

As it was not possible to extract core samples or otherwise confirm the findings from the survey in situ (beyond what was clearly visible on the surface), there will remain some uncertainty connected to the findings. Nevertheless, all the detected features have plausible explanations and their extent correlates well with surface features, all but confirming their existence. From the amount of detected features, it is clear that even with fairly simple setup and data processing methods it is still possible to detect a number of anomalies and features in the track body. Water remained in the track body from the previous rainfall, so some of the features have likely been accentuated due to local water retention, thus aiding their detectability. With the exception of the signal disturbances seen from the wire fences, no features depended on data from all channels to be accurately detected. Coupled with the minuscule difference in data quality between the two sampling rates, it seems clear that these surveys can be performed at much higher speed without appreciable data loss.
The water distribution data were analysed by carefully examining the peak amplitudes of reflected signals over the exact position of the poured water. Each run yielded signal amplitude data which was compared between runs to attempt to detect how the water was percolating through the ballast and subgrade. As the presence of water, or an increase in the amount of water will also increase the dielectric constant of the material, it will result in a stronger reflection signal. This is seen as an increase in amplitude on the GPR A-scan, where the signal’s return time will indicate the depth of the water.

The process of registering amplitudes was performed manually, within the viewing tool of the Road Doctor software. Each visible peak in amplitude was inspected, with magnitude and corresponding signal travel time registered from the info given by the software. The absolute accuracy of timing the peaks can therefore not be guaranteed, but much care was taken to ensure a correct reading. For the first water distribution test, readings were collected for three different locations along the track test area (see Figure 67 and 68). The purpose of this was to establish a control test of unaffected areas to determine how large variations in results would be from an unaffected site (c) and compare them to the results from the water pouring site (a). Site (b) would work similar to the control site (c), but some change would be expected in the deeper layers, as water from site (a) would likely distribute outwards as it percolated down through the ballast and subgrade.

![Figure 67](image1.png)
Figure 67 Location of features from the test surveys. Test survey 1 (orange) and test survey 2 (blue). Satellite image courtesy of Norge i Bilder

![Figure 68](image2.png)
Figure 68 Location of readings collected from the area of water distribution test 1. a) Water pouring site. b) Dry side of the same ballast crib as (a). c) Unaffected control site
To prove that the GPR is in fact able to map the distribution of water, the findings must be able to clearly detect changes in return signal strength between scanning runs. It must be possible to accurately locate these changes in each spatial domain and the development of these changes must correlate with the assumed movement of water through the track body.

No discerning differences were observed between dry and wet B-scan radargrams from the test. This was not surprising as the track body was already very wet from the rain, and the introduced water would not have made a significant visual difference. A test performed on completely dry tracks may show differences between dry and wet scans where the reflections of certain interfaces will be accentuated due to water accumulation. In this case, a closer study of the reflected signal amplitude was necessary to differentiate scan results, see Figure 69.

![Reflection signal amplitude through the medium at various approximated times after water was poured. Site (a), water distribution test 1 (Image meant for illustration of result. Accuracy of scaling not absolute)](image)

The amplitude development in Figure 69 illustrates the direct effect from the water being introduced into the ballast.

1. The dry signal is characterised by a strong initial signal reflection stemming from the signal’s first contact with the surface. Amplitude then moderates through the ballast layer before slightly subsiding at what is believed to be the subgrade.

2. The signal from 2 minutes after pouring does appear very similar to the dry run, but is also slightly stronger in the ballast section of the subsurface. Subgrade amplitudes appear mostly similar.

3. After 10 minutes, the effects of the water are seen more clearly. Peaks in the upper parts are distributed over a wider range of depths, and larger amplitudes are seen in the subgrade.
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### Table 7 Time and amplitude values for water distribution test 1, site (a)

<table>
<thead>
<tr>
<th>Water distribution test 1</th>
<th>Channel: 22</th>
<th>Water test, right side (a)</th>
<th>01:40</th>
<th>03:50</th>
<th>06:35</th>
<th>10:35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time after pouring [mm:ss]</td>
<td>01:40</td>
<td>03:50</td>
<td>06:35</td>
<td>10:35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Amplitude [ns]</td>
<td>W-Run 1</td>
<td>W-Run 2</td>
<td>W-Run 3</td>
<td>W-Run 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2432</td>
<td>3.052</td>
<td>2027</td>
<td>3.052</td>
<td>1757</td>
<td>3.052</td>
<td>2615</td>
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<tr>
<td>650</td>
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<td>5.737</td>
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<td>4.272</td>
<td>1317</td>
</tr>
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<td>659</td>
<td>10.498</td>
<td>518</td>
<td>12.451</td>
<td></td>
</tr>
</tbody>
</table>

A closer look at the amplitude and time values for the water given in Table 7 and Figure 70 reveals the water distribution more accurately. As the included time values are dictated by the times at which amplitude peaks were recorded, most of them are not identical between the individual runs. Since the water affected the reflected signal amplitude, the amplitude peak times were affected by the movement of the water between scanning runs. This can initially make it difficult to discern any pattern from the numbers alone. The introduction of water should in itself alter the dielectric properties of the medium, and alter the signal travel time slightly. The reason why some runs still register exactly similar travel times is due to a slight simplification inherent in the manual registering interface. However, the magnitude of these errors is very small, and is considered negligible for this test.

Key to understanding the data is to recognise the dry test for its large amplitude peak at the surface, followed by small amplitude peaks further down into the subsurface. While the initial peak amplitude (surface) is lower in the consecutive wet tests, the depth range of large amplitude peaks is increased.

For the time-range of 6-10 nanoseconds, there is a reduction of amplitude values on wet runs compared to those of the initial dry run. This seems to be contrary to the expected results, as no section should become drier as a result of the water pouring. The effect is prevalent across all the wet runs, but could simply be an outlier-value caused by methodological inaccuracies in the dry run.
Of the other plausible causes, most notable is the water pouring method itself. As the water was poured into the ballast, both the amount and velocity of the water far exceeded anything the track had previously been exposed to during normal operation. It is therefore likely that fines and other fouling material was washed out of the ballast, leaving a cleaner, less fouled ballast for the wet runs of the test. As clean ballast has less potential to retain water, it will also have less potential for high dielectric constants and high signal reflection amplitudes. This effect would have less impact deeper into the ballast and subgrade layers. As such, it could also have contributed to the apparent drop in signal reflection amplitude seen at surface level (3.052 ns) from dry run to the first wet runs.

Another interesting feature of the wet run values of site (a) is the apparent pooling of water occurring around 10.5 ns. This is most likely caused by the water being hindered by less permeable mediums, e.g. going from ballast to subgrade. The ballast thickness at the site is estimated to be approximately 0.5 m. Assuming the ballast fouling condition as lightly spent wet ballast, Table 1 indicates a wave propagation velocity of approximately $1.40 \times 10^8$ m/s. This gives the following travel time of the signal:

$$t = \frac{d}{v}$$

$$0.5\text{m} = \frac{1.40 \times 10^8 \text{m/s}}{2 \times 0.5 \text{m}} \times \frac{\text{t}}{2}$$

$$t = 7.143 \text{ns}$$

The difference in signal travel time between surface reflections and the indicated pooling of water is $10.498 \text{ns} - 3.052 \text{ns} = 7.446 \text{ns}$. The calculated t-value and the registered time of water pooling are very similar, indicating that the pooling of water is in fact occurring at the transition from ballast to subgrade.

From the trends seen in the amplitude data there seems to be a clear ability for the GPR system to register both depth and magnitude of changes in water content in a railway track body. However, the data collected from site (a) also contains data that cannot be directly attributed to the assumed behaviour of water in ballast, or the manual reading of the software results.

1. The surface amplitude values (at 3.052 ns) seen in Table 7 are highly fluctuating between wet runs. As these were not disturbed in the time between wet runs, they should remain more or less similar. This could be caused by methodological inaccuracies, where each scan is not performed over the exact same spot, but may be a few cm off.

Although the overall trend is mostly as expected, not all amplitude development follows the norm, but fluctuate back and forth between scanning runs. This can be seen from the graphs in Appendix B.

To assess the scope of normal variations for amplitude values, several control tests were performed. First was the data collected for site (b), which was in the same ballast crib, but opposite side (left) from the water pouring site (a).
Table 8 Time and amplitude values for water distribution test 1, site (b)

<table>
<thead>
<tr>
<th>Water distribution test 1 Channel: 11</th>
<th>Control test, left side (dry) (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time after pouring [mm:ss]: 01:40</td>
<td>03:5</td>
</tr>
<tr>
<td></td>
<td>06:35</td>
</tr>
<tr>
<td></td>
<td>10:35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Dry</th>
<th>Wet run 1</th>
<th>Wet run 2</th>
<th>Wet run 3</th>
<th>Wet run 4</th>
</tr>
</thead>
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<td>-----------</td>
<td>-----------</td>
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<tr>
<td>3604</td>
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<td>3455</td>
<td>3.052</td>
<td>3449</td>
<td>3.052</td>
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<tr>
<td>2850</td>
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</tr>
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<td>12.573</td>
<td>350</td>
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</table>

The values in Table 8 were expected to be unchanged between runs, with an exception for values from deep layers, as the water is expected to also distribute outwards as it percolates down through the track body. Yet there are several signal travel times whose amplitudes vary significantly between runs.

A graphic manifestation of the amplitude data (Figure 71) illustrates that the values still vary between runs, although not nearly as much as in site (a). The variations in amplitude values from site (b) also does not seem to be constrained to the lower depths, where water from site (a) could have contributed to the variations. From this, it is difficult to determine exactly how much of the variation is due to the measuring method, and how much is due to site (b) being affected by water poured at site (a).

A second control was performed at site (c), in the middle of a ballast crib far enough away from the water pouring site to avoid being affected by any activity there.
Table 9 Time and amplitude values for water distribution test 1, site (c)

<table>
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<th>Water distribution test 1</th>
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<th>Control test outside of wet area (c)</th>
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<tr>
<td>Time after pouring</td>
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<td>[mm:ss]</td>
<td>06:35</td>
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<table>
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<td>399</td>
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<td>0</td>
<td>399</td>
<td>10.254</td>
</tr>
</tbody>
</table>

As site (c) was not affected by water, it is obvious from the numbers in Table 9 that surface values may vary greatly, even without being affected by anything outside of the measuring method itself. There is also no pattern between sites in the way each run's surface values vary, which could have attributed the variations to factors related to the conduction of each run (e.g. water pumping from track loading by the surveying vehicle).

An important discerning difference between data from site (c) and site (a) and (b) is that for the former, amplitude peaks are almost always located at the same signal travel times. This indicates that the water pouring in site (a) indeed had an effect on the amplitude peak locations. It is possible to extract data from those times to quantify differences in amplitude values between survey runs. Similar comparisons cannot be done for site (a) and (b) because peaks located at different depths/travel times cannot be assumed to have identical EM properties, see Figure 72.
As seen from comparing the amplitude values in Figure 72 there is still a considerable variation in values, even when the actual conditions have not changed. To make sure these variations are not just caused by differences in the initial surface reflection strengths, Figure 73 displays the reflection amplitude values as percentages of initial reflection amplitude. As also this representation shows considerable value variations between scanning runs, it is apparent that the signal either does not attenuate equally between runs or is simply inaccurate in its interpretation of the medium’s dielectric contrasts. The variations seem to subside as the signal penetrates deeper into the medium, and values become more similar. It is therefore possible that signals with longer travel times can be viewed as slightly more accurate than those from shallower reflections.

![Survey accuracy control test](image)

**Figure 73 Signal reflection amplitudes at key signal travel times as percentages of initial reflection amplitudes**

The natural variations in the method are therefore substantial, which makes it difficult to draw definite conclusions directly from the data in site (a). However, viewing the data side by side graphically in Figure 74 shows that the water has definitely had an impact on the amplitude values through the subsurface. In addition, the data collected from the control test are a lot more consistent between runs, compared to the data from site (a).
In the second water distribution test, the goal was to register the distribution of water over time and compare it with the results found in the first test. As the mud pumping in the area would have significantly reduced the medium’s permeability, the water should percolate at a slower rate than in the cleaner ballast from Test 1. As the expected outcome was known, a verification of this through the GPR data would be a great contribution towards proving the GPR’s abilities in detecting and mapping water distribution in the track body.

The previously encountered effect where the rapidly poured water could wash out fines from the upper ballast sections is expected to also be a factor in this test, though it is difficult to say with certainty whether the density of the mud will dampen or accentuate this effect. As a result of time constraints on the line, data was not collected past the time 04:30 after pouring. Comparisons between the two tests must therefore be based on the trends seen within the first 5 minutes after pouring.

<table>
<thead>
<tr>
<th>Water distribution test 2</th>
<th>Channel: 11</th>
<th>01:00</th>
<th>02:25</th>
<th>04:30</th>
</tr>
</thead>
</table>

While the values may be difficult to interpret directly from the numbers themselves, a stepwise graphic projection (Figures 75-77) aides in describing the development of water distribution over time.
Figure 75 Development of amplitude-time data from dry run to first wet run. Water dist. test 2.

Figure 76 Development of amplitude-time data from first wet run to second wet run. Water dist. test 2

Figure 77 Development of amplitude-time data from second wet run to third wet run. Water dist. test 2
The gradual trend of the water is observable in Figures 75-75, where it follows a similar pattern to the ones seen in water distribution Test 1. Missing is the apparent pooling of water near the ballast/subgrade interface. This is just as expected since the nature of the fouling will minimise the differences in permeability between the two layers. However, seeing as the scanning in this second test stopped after 04:30, and water pooling was only observed after 06:35 in the first test, this alone is not enough to count as an observable difference between the two tests. As there also is no clear detectable interface of water to accurately detect its propagation down through the ballast, it is not possible to infer anything about the ballast condition from these data alone.

There is also no reason to believe the errors in the second test to be any smaller than those seen in the first test's control. Not all the observed trends in the second scan correspond to predicted or likely movement of water (e.g. the amplitude drop at 13.184 ns in wet run 2), which further indicates the presence of reading errors. As the muddy slurry which fills the ballast is very good at retaining water, this test most likely suffered due to the wet track conditions on the testing day. The medium would have been nearly saturated with water, to a point where contrasts between “dry” and wet runs were not substantial enough to give unambiguous results.

Wet clayey soils are known to be lossy environments (very high signal attenuation) for EM signals. It would have affected the signal strength of deeper reflections a lot more than what was the case in the first water test. This could explain some of the weak amplitudes registered in the lower parts of the time range, and the subsequent lack of signal development over time, see Figure 78.

A visual comparison of the test results indicates a tendency where reflected signal amplitudes vary slightly more in the upper sections (lower signal travel times) for water test 2, than for water test 1. As these differences seem to appear at lower depths in water test 1, this may be an indication of the expected result, where the cleaner and more permeable ballast lets water through more quickly than the muddy slurry in water test 2.

The results gathered from the two water distribution tests suffered under the wet conditions of the track, which caused difficulties discerning the differences between dry and wet runs.
Still, overall larger amplitudes are registered for wet runs than for the dry run. The direct one-
to-one comparisons between amplitude values cannot accurately describe the water
propagation due to the inherent inaccuracies and value variations in the test. However, the
patterns seen from the graphic overview are largely consistent with the expected results
from the test, and do represent the trend of water distribution through the ballast body.
Especially for the first water test. This has strengthened the hypothesis that water
distribution can be mapped from GPR data, but not conclusively confirmed it.

From the work in this study, it is clear that Ground Penetrating Radar holds much potential
for use in railway track inspection. The field surveys proved its ability to collect extensive and
accurate data from subsurface features, with minimal data processing and without disturbing
the track. While there were no ballast pockets on the surveyed stretch, the system
successfully detected the ballast/subgrade interface, subgrade penetration, mud pumping
and deep rock formations. As most track body anomalies will manifest as variations of these,
it is very likely that ballast pockets would be detected with this inspection method. Previous
studies support this conclusion and have already seen numerous successful detections of
ballast/subgrade interface, ballast pockets, subgrade penetration, buried objects and similar
features. Work is already being done to automatically detect and classify ballast pockets
through computer processing of GPR data.

With the accurate detection of ballast/subgrade interface, ballast fouling condition can be
approximated from simple signal travel-time comparisons. From the literature review it is
also apparent that data interpretation techniques have come a long way the last ten years.
Advanced signal processing can now extract more information from the GPR signal,
enabling detailed information on moisture content and the distribution and level of fouling.
The opportunities for automatic classification and color coding are likely to drastically reduce
interpretation times and room for subjective human error.

The GPR’s ability to map water distribution was all but confirmed from the theory, with
several successful cases of moisture detection based on advanced post-processing of
signals. However, field study results from this study proved only partly conclusive. There
were visible differences between scans of wet ballast compared to dry ballast. Nevertheless,
while the overall pattern of results was as expected, the inherent value variations within the
test were too large to decisively confirm the ability based on this test alone. This was likely
caused by unfavourable track conditions (already wet track).

It is therefore possible to use Ground Penetrating Radar to detect anomalies such as ballast
pockets in railway ballast. It is most likely also possible to map the distribution of water in the
ballast, as this was supported by the theory, but no definite answer was given from the field
study.

To further advance and build upon the discoveries of this study, several subjects should be
explored further.

1. Perform the water distribution test on confirmed dry track body (or in laboratory) to
   better differentiate between dry and wet scans. Also recommended to perform the test
   without moving the surveying rig between scans, to guarantee longitudinal consistency
   of the scanning site. (Not possible with the equipment used in this test).
2. Test surveys should also be attempted on dry track to assess the impact of water in this test survey.

3. Excavate core samples of surveyed stretch to further confirm the accuracy of the scans.

4. Perform surveys on closed track sections where full scale ballast pockets can be implemented and surveyed.

5. Survey for animal burrow detection on actual known cases of burrows.


7. Attempt practical application of the ballast void scattering method and the scattering amplitude method. The successful application of this method would be valuable for many railway lines with poor quality gravel sub-ballast in Norway.

8. Further explore the extent of detectable track anomalies and faults with GPR.
4. Identification of Critical Speed Hot Spots

Loads moving at high speed, such as superfast trains have long been recognised as sources of ground vibration. At low speeds, compared to the characteristic wave velocities of the medium, the ground response from a moving source is essentially quasi-static. That is, the displacement and stress fields resemble those for static condition but simply move under the load. However, as the speed of the load increases, dynamic phenomena take over and dominate the response. This is reminiscent of the supersonic condition in aerodynamics.

In the realm of elasto-dynamic theory it has become common to categorise moving-load problems as sub-seismic, super-seismic, and trans-seismic, depending on whether the load speed is less than the Rayleigh-wave velocity of the ground, greater than the compression wave velocity, or intermediate between these velocities. Studies on this subject have revealed that the sub-seismic regime represents a quasi-static condition, whereas the trans-seismic and super-seismic cases are characterised by large dynamic effects associated with the development of Mach lines and Mach surfaces in the ground response.

As the train speed approaches the critical speed, which is the speed that coincides with the Rayleigh-wave velocity of the ground, the magnitude and impact of the vibration is most often severe as compared with normal train-induced vibration, and are not only worrisome for human disturbance, but also raise concerns about the running safety of the trains, degradation of the embankment and foundation soil, fatigue failure of the rails, and disruption of power supply to the trains, see Figure 79.

Figure 79 Displacement of track when train approaches critical speed

Vibrations due to high-speed trains may occur on very soft soil such as peat and clay with very low shear wave velocities. For such soil conditions, critical speed problems may be encountered at speeds even below 200 km/h. Many places around Europe new high speed rails are planned and/or there is a desire to increase the speed on existing lines. A method for critical speed hot-spot detection is then needed. Considering that the critical speed is
closely related to the Rayleigh wave velocity of the ground, today the following methods are used to determine the critical speed:

1. Seismic measurement on the ground, e.g. MASW measurements to determine the shear wave velocity which is close to the Rayleigh-wave velocity.

The following Figure 80 show schematics of the tests and an example of the processing the field data which consist of vertical ground motion velocities at a number of points due to an impact source.

![Figure 80 Elements of MASW method: a) file testing and collection of vibration data, b) Dispersion curves with identified mode shapes, c) interpreted shear wave velocity profile using inverse modelling techniques](image-url)
2. Dynamic measurements of the track, using a Track Loading Vehicle (TLV) or a variation of it, namely Rolling Stiffness Measurement Vehicle (RSMV). The TLV uses a shaker to load the track dynamically at different frequencies and is measuring the response. From this information the critical speed can be calculated.

Figure 81 shows a schematic of the RSMV/TLV together with a typical output resulting from the processing of the stiffness computations along a railway stretch (Berggren et al. 2010).

3. A rough estimate of the shear wave velocity can be obtained using correlations with data from geotechnical site investigations, most prominently CPT, and/or laboratory tests.

For detection of hot spots all three methods require extensive measurements, which becomes very expensive and/or tie up the infrastructure for unacceptably long periods. Especially the latter is impossible at busy European railway lines.

A new method, ETL, is under development in Sweden, which allows for measurements from a running train at normal speed. Hence, large distances can be monitored in short time. The new method is well suited for inventory investigation to detect hot spots, since it is fast and relatively cheap compared with the conventional methods. However, the new method needs
to be combined with more comprehensive methods when countermeasures are planned in detail.

The idea behind ETL is that the dynamic amplification starts already at rather low speeds and, at the same time, the shape of the displacement curve under a loaded axle will change. The core of the method is to use measurements under a loaded axle of a train and compare these measurements with the corresponding deflection curve from a theoretical double-beam model. The double-beam model holds different structural parameters, that are estimated in the method.

The method is still under development but has been through validation by comparison with calculations using the rigorous frequency-domain model, VibTrain (Kaynia et al., 2000). In VibTrain the track embankment is modelled as a finite-element beam and the ground is represented with the help of the Green's functions for layered ground (Figure 82). This model properly handles the interaction between the embankment and the soil as well as propagation of the waves in the ground. These are key issues in computing the critical speed.

The validation was performed for the Ledsgård site, Sweden, where the ground conditions and critical speed is well known from earlier extensive measurements and calculations.

Figure 82 Key features of VibTrain consisting of layered ground, embankment modelled as an equivalent beam, and rails
5. Identification of Potential Rockfall Hot Spots

During the last couple of years, LiDAR, often together with gigapixel photography, has been used to identify and monitor potential rockfall areas in several areas in Norway. Identification of potential rockfall source areas are conducted using traditional field-based visual inspections as well as digital analysis of 3-dimensional (3D) terrestrial LiDAR scans and gigapixel photography.

Gigapixel photography is a technique that enables the creation of extremely high resolution panoramic images using a conventional DSLR camera. The panoramic images once created enable the visualization of the entire slope in great detail with the ability to zoom into the image to see individual blocks. The gigapixel images are an excellent tool for mapping active rock fall source zones through the identification of unweathered rock surfaces, which are generally indicative of a recent rock fall activity.

The two remote sensing techniques, TLS and gigapixel photography enable detailed mapping of potential rock fall source zones not possible using conventional tools (see Figure 83).
An ideal method of detecting damages in the track is use of vibration sensors mounted on either the train cars or on the bogies/axles. The advantage is that one could continuously monitor the track performance and map the problematic areas over a large network in a short time. Typical track damages include hanging sleepers and deteriorated ballast/sub-ballast. In the former case, local overloading of the ballast under sleepers could result in loss of contact between the two. This leads to redistribution of the axle load to the neighbouring sleepers, ultimately leading to several sleepers losing contact with the ballast. In the second case, local weakness in the underlying formation leads to overloading of the ballast/sub-ballast layers, eventually resulting in reduction of the stiffness properties of the track.

NGI has initiated a numerical study to investigate the possibility of using changes in track vibrations as an indication of track damage. The study has been carried out using both an extended version of VibTrain (Figure 84), which allows consideration of hanging sleepers, and the commercial code COMSOL. Figure 84 shows the finite element used in the simulation of moving train load and detection of hanging sleepers. Table 9 summarizes the soil parameters of the layers.
Figure 84 COMSOL Finite Element model of Ledsgård test site, Sweden, used in the numerical simulations

Table 9 Soil parameters applied in FE simulations

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Thickness</th>
<th>Density</th>
<th>$C_S$ [m/s]</th>
<th>$C_P$ [m/s]</th>
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<td></td>
<td></td>
<td></td>
<td>$V = 70$</td>
<td>$V = 200$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$V = 70$</td>
<td>$V = 200$</td>
</tr>
<tr>
<td>Crust</td>
<td>1.1</td>
<td>1500</td>
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</tr>
<tr>
<td>Clay</td>
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<td>65</td>
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</tr>
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<td>Clay</td>
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<td>1475</td>
<td>87</td>
<td>85</td>
</tr>
<tr>
<td>Half space</td>
<td>-</td>
<td>1475</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 85 compares the results of the 3D FE simulations with measurements for two passages of Swedish X2000 (x-axis showing distance along track and y-axis showing displacement in mm). The results confirm good performance of COMSOL and its suitability for the numerical simulation of damaged track. Note that the results in 10b are for train velocity exceeding the Critical speed.
To assess the impact of hanging sleepers on the track vibration (for the purpose of detecting track damage), NGI performed a series of simulations where the sleepers were removed sequentially from 1 to 4 (sleepers) as shown in Figure 86.

The numbers of 1, 2, 3 and 4 represent not only the number of missing sleepers but also the missing order. The geometry, material properties (1) and loading conditions in the FE model are all the same as those of the Ledsgård case. The analyses were performed for train speed = 100 km/h. The responses are compared with the case of no damage (referred to as intact track), at two points (R1 and R2) that are at 3.6 m away from the middle of the damaged region (between missing sleepers 1 and 2) and at the middle, respectively. The two response points are both taken on the rail.
Figure 87 plots the computed vertical velocities on the rail at point R2 for the four cases: a) intact track, b) 2 hanging sleepers, c) 3 hanging sleepers, and d) 4 hanging sleepers. As expected, as the number of hanging sleepers increase, the rail vibration (vertical particle velocity) increases. According to these results, the vibration increased by a factor of 5 for 4 hanging sleepers. This is quite a large increase which could be detected by comparing the vibrations along a track section. A sensor mounted on the bogie is believed to be sufficient for the purpose of vibration measurements and spotting of the damaged section.

![Graph showing vertical velocities](image)

**Figure 87** Increase in rail vibration as a result of increasing number of hanging sleepers. Vibration amplitude could increase by a factor of 5 for 4 hanging sleepers

Figure 88 plots the corresponding results (i.e. for intact track and for several hanging sleepers) for the maximum bending strain in the rail. The same trend is displayed by these results.
While more work is needed to confirm and finalize these findings and to incorporate normal variabilities in the measurements, these results point to the potential use of vibration measurements in spotting weak sections in a track and map hot spots of damaged track. More work is underway at NGI on this research.

6. Summary and Conclusions

Today, the evaluation of transportation infrastructure is done primarily using visual assessment. The incidence of major failure of critical sections of rail infrastructure is increasing and the current response is reactive i.e. when failures occur they are fixed. The location of the failure then becomes a hot spot on the network. Following incidence of failure,
the ballast, sub-ballast and subgrade condition is still most often conducted by drilling boreholes or excavation of trial pits. These investigation methods provide good information on the in-situ condition at the location of the boring, however, they are expensive, time consuming and often require track possession and closure.

In order to provide additional information on the entire structure, and reduce delays/closures the ability of Ground Penetrating Radar (GPR) to identify possible problem locations using quick-scan techniques was investigated in this report. Through continuous profiling along large sections of track in Croatia and on test sections in Norway, the ability to map features such as ballast thickness, layer thickness variations along the track, subgrade water content, ballast water pockets, locations and depths of elements such as subsurface drainage pipes, trenches, animal burrows and utilities were demonstrated.

In this report extensive recommendations for conducting GPR investigations on railway lines are given. These recommendations include application of optimal configuration consisting of ground coupled and air coupled antenna. The investigation in Croatia utilised ground coupled antenna which limits the investigation speed to 15-20 km/h. However, the extensive survey was completed on live railway tracks by simply removing the test cart when trains were due to use the line. In Norway, a train mounted system was with air coupled antenna than allow survey speeds of 80-120 km/h. Further, recommendations on data acquisition and data analysis are provided. Data acquisition should include a proper definition for a series of parameters such as selection of the collecting modes, wheel calibration, horizontal sampling interval (or sampling distance), vertical sampling, antenna orientation, antenna range (depth of penetration), auto filters, auto gain etc. During data analysis and interpretation, a flow chart was established consisting of four main phases: data editing, basic processing, advanced, processing and visual processing. Elements of each phase are described in detail. The behaviour of electromagnetic wave is dominantly governed by dielectric value of material through which it passes and by knowing its value the more results will be accurate and position and extent hot spots will be more reliable. This parameter controls the signal propagation velocity and vertical and horizontal resolution of scanned image. Recommendations for selection of suitable dielectric constants are also given. The GPR investigation in Croatia was used as a first-pass survey to identify potential hot-spots. Once identified these features were examined using more intensive geophysical and geotechnical methods that provide information on engineering properties of the subsoils.

As train operators increase the running speed of trains, problems with dynamic interaction of the train and underlying soft ground have been encountered at a number of locations. In order to identify potential problem areas the usual methods is to measure the in-situ soil stiffness using geotechnical laboratory and field tests and/or geophysics. In this report a technique for using train mounted sensors that measure displacement at normal train speeds was calibrated to a numerical model using data from a Swedish test site. Whilst additional validation is required, the method shows strong promise. Rock falls are a major hazard for many infrastructure managers. A demonstration project was undertaken in Norway in which the combined use of LiDAR and digital photography were used to identify unweathered rock surfaces which were are indicative of recent rock fall activity.
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Appendix A: Scan resolution comparison

Figure A1 Test survey 1 - Sample rate: 1 scan/15 cm

Figure A2 Test survey 2 - Sample rate: 1 scan/10 cm
Appendix B: Water distribution test 1

Figure B1 Development of amplitude-time data from dry run to first wet run - site (a)

Figure B2 Development of amplitude-time data from first wet run to second wet run - site (a)
Figure B3 Development of amplitude-time data from second wet run to third wet run - site (a)

Figure B4 Development of amplitude-time data from third wet run to fourth wet run - site (a)