ROADSCANNERS

GROUND PENETRATING RADAR SURVEYS ON RAILWAY SECTION BETWEEN MONTEVIDEO – PASO DE LOS TOROS – URUGUAY

BEYOND THE SURFACE

GROUND PENETRATING RADAR SURVEY ON RAILWAY SECTION BETWEEN MONTEVIDEO – PASO DE LOS TOROS, URUGUAY

Contents

1. Introduction

Roadscanners Oy completed ground penetrating radar (GPR) surveys in co-operation with the client and VR track on railway section between Montevideo – Paso de los Toros in Uruguya. Measured section was single track, totaling approximately 273 km. This included Florida to Durazno section which was analyzed later as additional order. The measurements were performed during two days on January 11th and 12th, 2017. On same month 27 reference drillings were made and given for use as a reference information for GPR interpretations.

Objective of the survey was to define the status of existing railway structures with ground penetrating radar (GPR) technique. GPR was used for thickness measurements of ballast and subballast layers and in evaluation of moisture condition in granular layers. Layer depths were calculated from tie / sleeper surface as a 0-level.

GPR data was collected using railway engine, on which GPR and other measuring systems were installed. Data collection rate was controlled by an optical encoder (DMI), which was attached to train engine's wheel axle. Laser data, accelerometer, digital video and GPS coordinates were also recorded during the survey for mapping the railway environment. Measured data was processed using Rail Doctor v. 3.2 software. Reference drilling information were also linked to the project data using the same software. This integrated data was then interpreted in Rail Doctor utilizing multiple parameters specifically designed for purpose of mapping the condition of existing railway structures.

Track geometry data was not provided for this project but can be linked afterwards for additional analysis if provided later. Project team consisted of several parties with different task and roles. The main operators are shown in Table 1.

VR Track Oy	Auli Vanhoja	Drilling plans
Roadscanners Oy	Mika Silvast Bruce Wiljanen, Anssi Hiekkalahti Olli Ervelä	GPR project management GPR Measurements GPR Data analysis

Table 1. Project personnel and tasks

2. Measurements

2.1 Survey Objects

Measured railway track section starts from Montevideo and ends in Paso de los Toros. Total length of surveyed track is approximately 273 km. Everything was analyzed and included in this report. 96 km section between Florida – Durazno was analyzed later as additional order. Measurements were done using Geophysical Survey Systems Inc (GSSI) ground penetrating radar system and Roadscanners' CamLink system. Figure 1 shows GPS line on map for measured track.
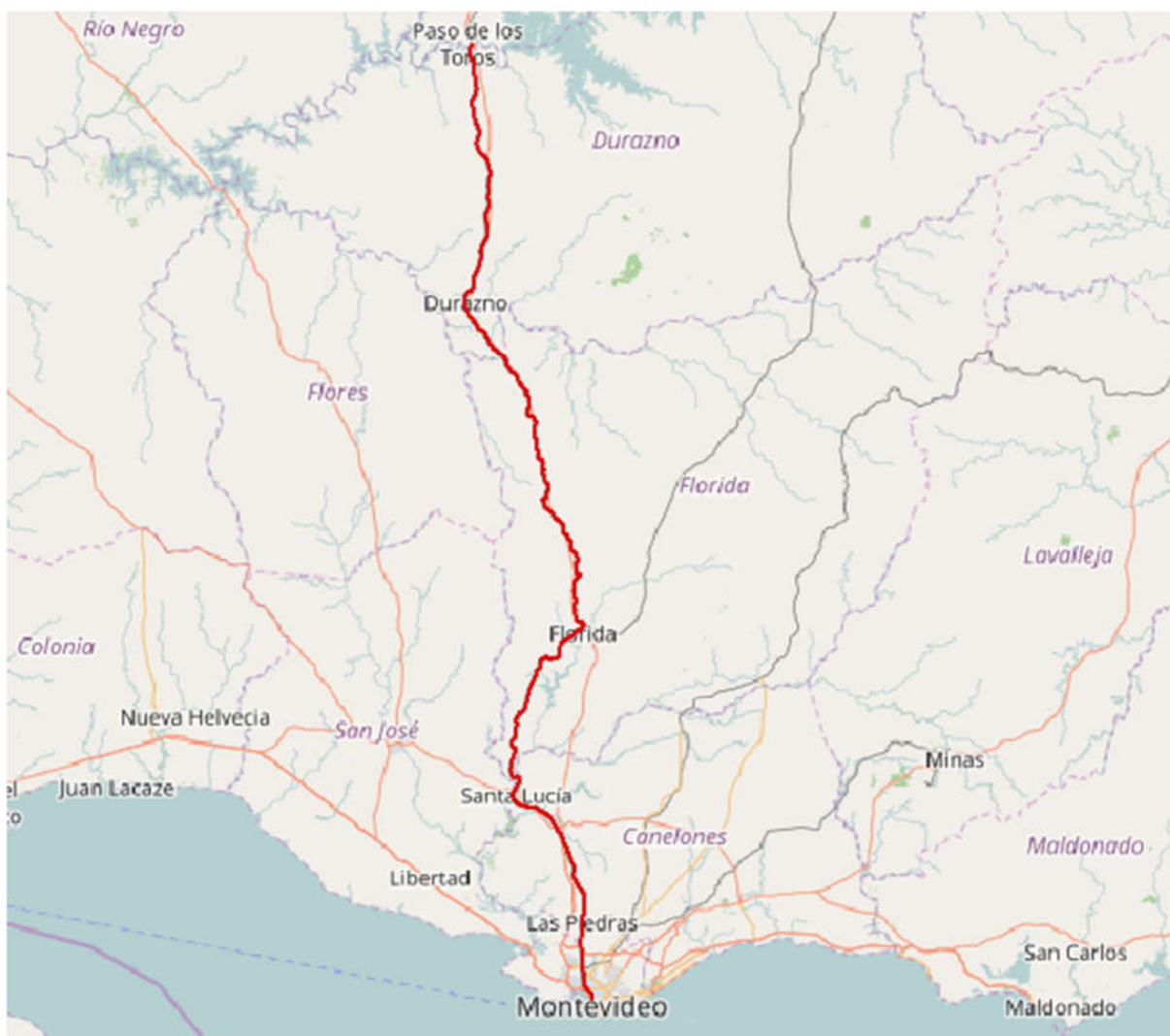

Figure 1 Measured GPS line from track

Figure 2 and 3 points out exact location of survey's start point. Distances indicated in attachments and in this report, are running distances in meters where starting point is acting as zero-origin. GPS coordinates for running meters can be read from Depths excel file.
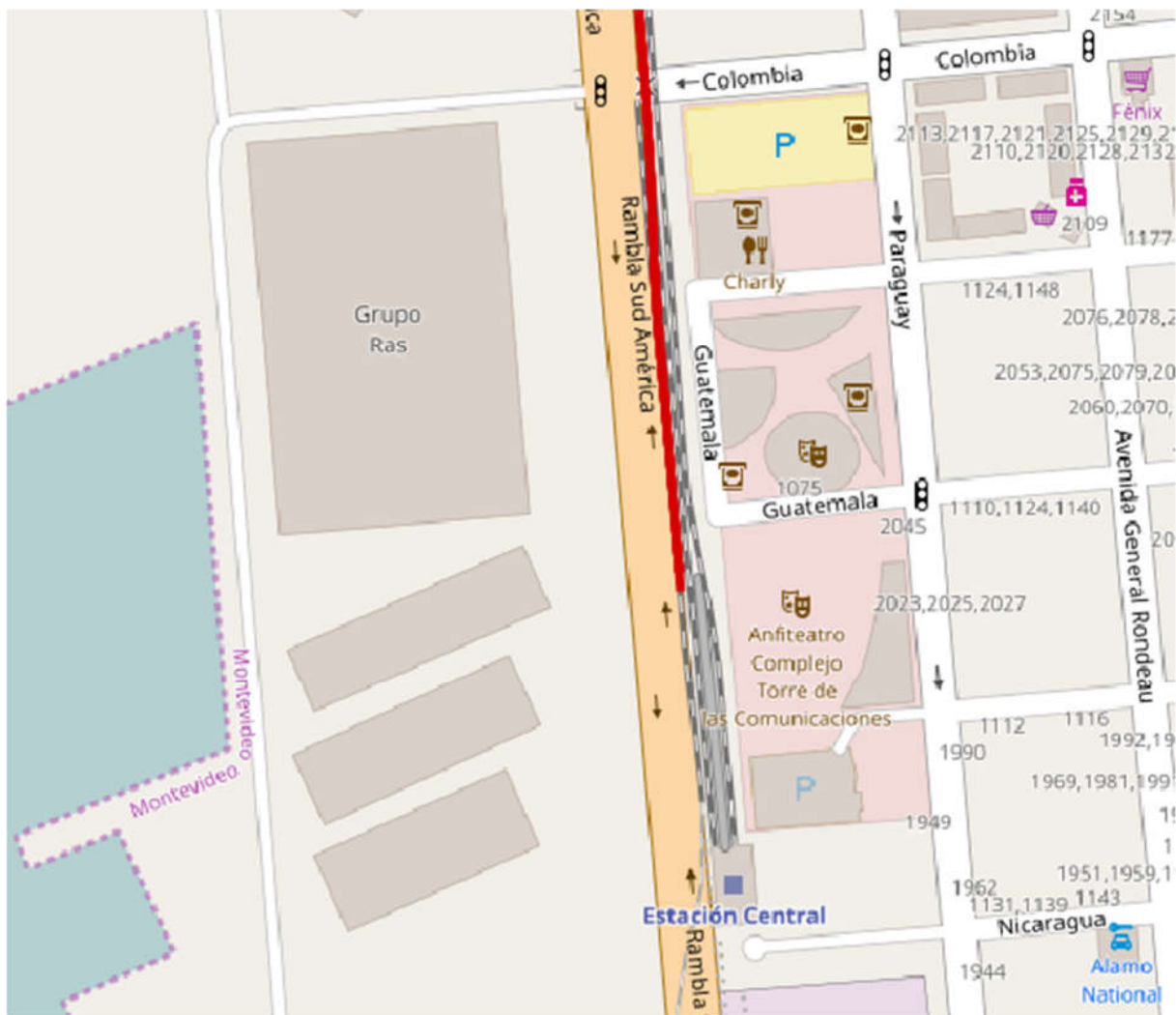
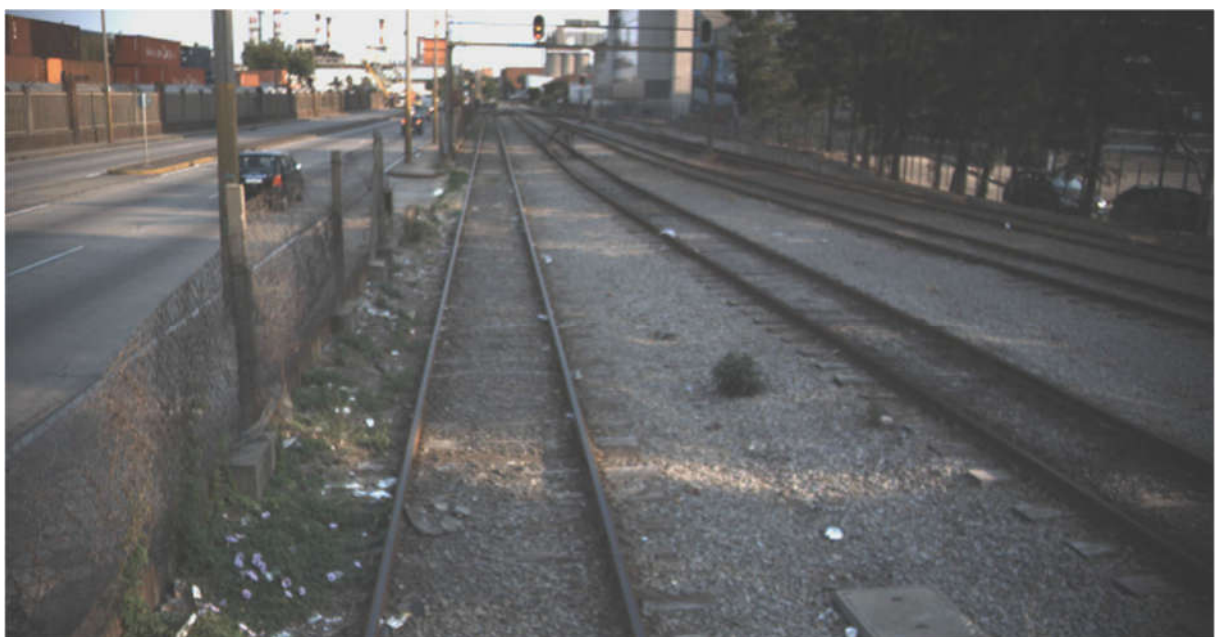*Figure 2 Start of survey – Running distance's zero is at start of the red line.*

Figure 3 Video image from start of survey

2.2 GPR Method

GPR antenna transmits a short electromagnetic pulse of radio frequency into medium. When the transmitted wave reaches an electric interface, part of the energy is reflected back while the rest continues at its course beyond the interface. The radar system will then measure time elapsed between wave transmission and reflection. This is repeated at short intervals while the antenna is in motion. Output signal (scan) is displayed consecutively in order to produce a continuous profile of the electric interfaces in the medium (Figure 4). The profile is shown in grey or color scale, where different shades or colors equal different magnitudes of the reflected amplitudes.
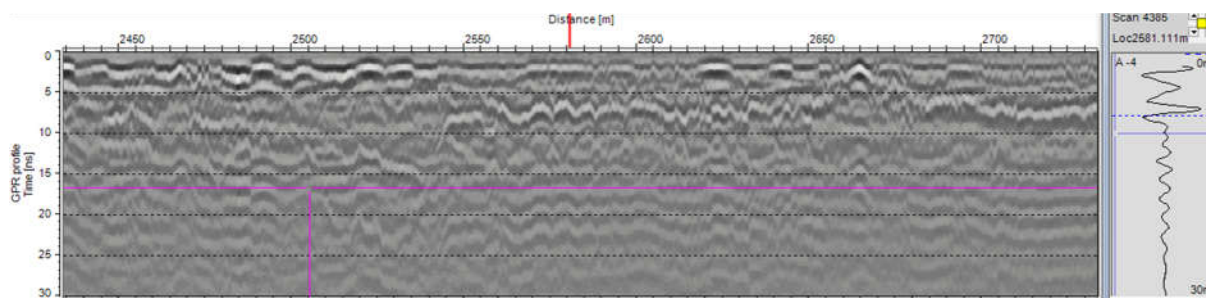

Figure 4. Example of processed GPR data profile (left) and single scan (right) from the railway measurement.

In general, the propagation speed of the wave and its reflection are affected by dielectric constant, magnetic susceptibility and electrical conductivity of the medium. Electrical material properties relevant for radar are dielectric permittivity and electric conductivity of the medium. They display variability according to medium type and presence of conductive minerals, presence of porosity and fracturing, and the alteration and mineralogy of fractures in fillings. The most important electrical property affecting to GPR signal is dielectric permittivity, which has an effect on the GPR signal's velocity in the material. The electrical conductivity of the medium contributes also to the attenuation of the wave and to some extent its reflection.

The antenna wavelength affects the ability of the system to identify objects of different sizes. For example, high frequency antennas with short wavelength have better resolution but shallow penetration depth, while low frequency antennas with longer wavelength have a coarser resolution but penetrate deeper into the medium. The degree of saturation with water, the salinity of water, and variation in porosity or fracturing intensity will also affect the net propagation of radar waves in the medium. The increase of water content in the medium will increase electrical permittivity (and decrease wave velocity) as well as decrease resistivity (increase wave attenuation).

The electrical conductivity of a medium influences the degree of attenuation in amplitude of electromagnetic waves. Significant attenuation takes place when electrical conductivity becomes greater than 0,010 S/m. If the conductivity is low and the number of electrical interfaces is high, multiple reflections will reduce penetration depth, while poor conductivity combined with a small number of interfaces will cause the wave to be attenuated as a function of the distance between the antenna and the reflecting interface. (Momayez et al., 1998; Saarenketo, 2006; Saksa et al, 2005).

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When applied to the analysis of railways, GPR may be used for detecting railway structures, determining layer thickness, ballast quality, moisture analysis and subgrade soil types. This information can further be used to analyze mixing of materials and structural defects. The reflections from different railway structure layers can be seen as continuous reflectors along the profile. GPR data helps to determine track subsurface conditions such as layer thickness, drainage problems and determining the degree of ballast fouling. Foremost among these advantages are fast measurement speed and results that provide a continuous subsurface profile of the survey target with differentiated structural layers.

2.3 GPR Equipment

GPR systems use discrete pulses of radar energy. These systems typically have the following four components (e.g. Saarenketo & Scullion, 2000):

1)   a pulse generator which generates a single pulse of a given frequency and power
2)   a transmitter antenna, which transmits the pulse into the medium to be measured
3)   a receiver antenna, which collects the reflected signals and amplifies the signal
4)   a sampler which captures and stores the information from receiver antenna.

There are two main types of GPR systems: traditional time-domain pulse systems and SFCW (stepped-frequency continuous- wave) frequency-domain systems. Traditional time-domain pulse system was used in this survey. The radar antennas are normally categorized in two groups: air-launched horn antennas and ground-launched dipole antennas.

The air-launched systems operate around 1-2 GHz. Penetration depth of horn antennas is limited to approximately 1 m. During data collection antennas are suspended approximately 0.3-0.5 m above the measured surface. Speed of the measurements is high, even up to 200 km/h. On the contrary, the ground-coupled antennas operate in a wide range of frequencies from 40-2500 MHz. Advantages of ground-coupled antennas are better depth penetration and better vertical resolution.

Figure 5 illustrates time-domain GPR method. This system transmits a short signal which is recorded as a pulse. Frequency spectrum of time-domain system is a bell-shape with the center frequency of antenna.
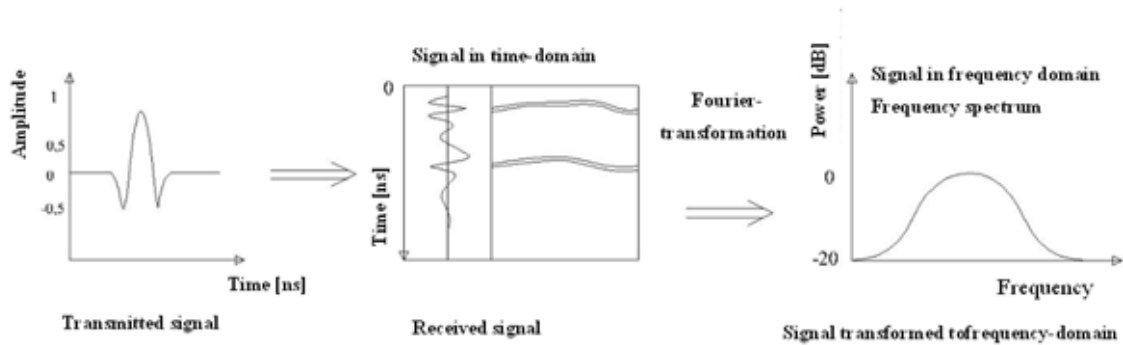
TIME-DOMAIN SYSTEM

Figure 5 Principle of time-domain GPR systems. (Modified From Passi, 2007).

2.4 System Installation and Data Acquisition

In this project GSSI (Geophysical Survey Systems Inc.) system was used with SIR-30 and 3 x 400 MHz antennas. Model 50400S antennas were used. The maximum penetration depth of the 400 MHz antenna is 2-3 meters, depending on subsoil properties. Typical measurement system is presented in Figure 6. In this measurement configuration, the antennas were suspended 0.30 meters above the ground to avoid damaging them. They were installed to a special rack system at three locations: one in track centerline and two in the end of ties (Figures 7 and 8).
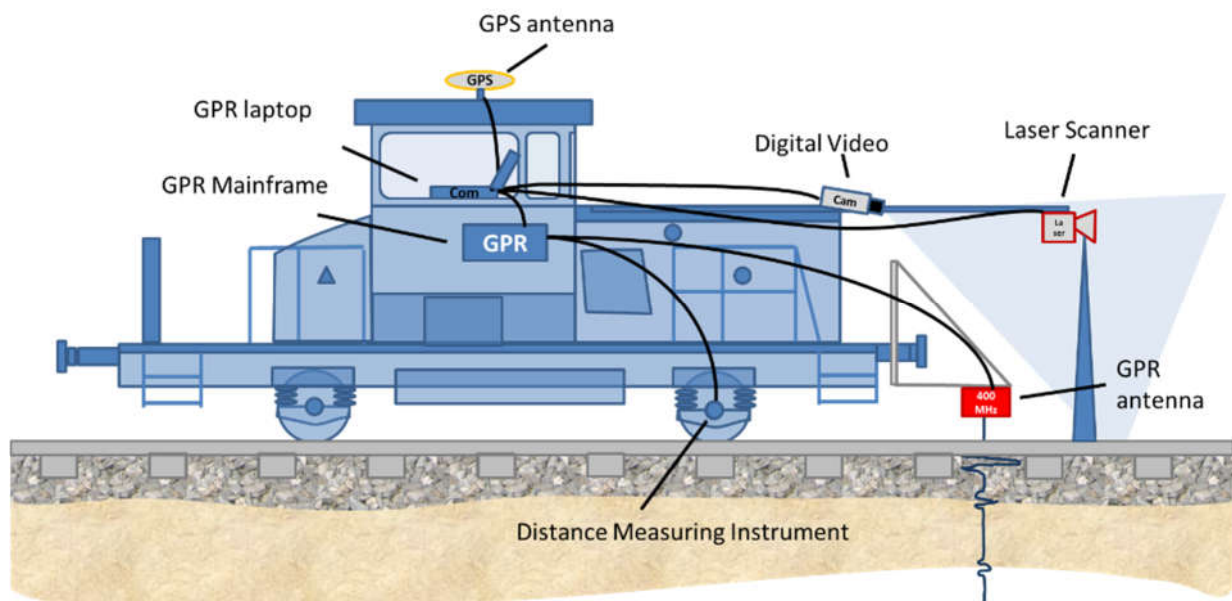

Figure 6 Typical measurement system

Figure 7 GSSI 2D antennas, video cameras, accelerometer and laser scanner mounted to rack system. Antennas are inside black boxes with orange handles.
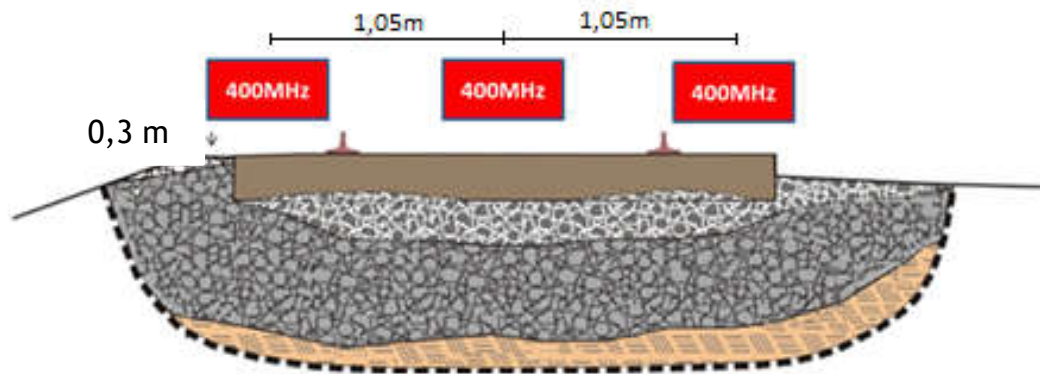
Figure 8 2D 400 MHz antenna locations on railway structure measurements.

Measurement speed in this survey was <50 km/h and measurement interval in longitudinal direction was 20 cm (=5 measurements/meter). Configured time-window of 110 ns was used for GPR. Laser scanner data, accelerometer data, digital video and GPS coordinates were recorded during measurement using RD Camlink software. From distance measurement DMI (distance measurement unit) and GPS antenna were used. DMI was attached to the axle of a measurement vehicle's wheel.

3. Data Handling and Viewing with Rail Doctor

3.1 Software description

The data processing, interpretation and analysis were performed using Rail Doctor v. 3.2 software from Roadscanners Oy. Rail Doctor is designed specifically for railway structural surveys, data analysis and maintenance planning. The software enables user to simultaneously view, interpret and analyze multiple datasets that use same coordinates (e.g., GPR data from different antennas, maps, digital video, railway databases and condition measurements). This kind of data combination allows user to conduct an integrated analysis of all available datasets on a single screen.

In railway applications, the program enables user to present railway database information as a form of bars for several different parameters (e.g., locations of switches, crossings, culverts etc.). Program also makes it possible to analyze track geometry data from different seasons and different years. Rehabilitation planning, statistical calculations and cost estimations can be conducted after data analysis using RD software. Project data can be viewed with lighter viewer software, which allows interactive viewing of results.

3.2 Project Structure

Rail Doctor uses project-based data handling. Project consists of different datasets that are linked to the project tree. These datasets can be organized and linked into corresponding sections / lines created in Rail Doctor (Figure 9). Different data types are explained in Table 2.
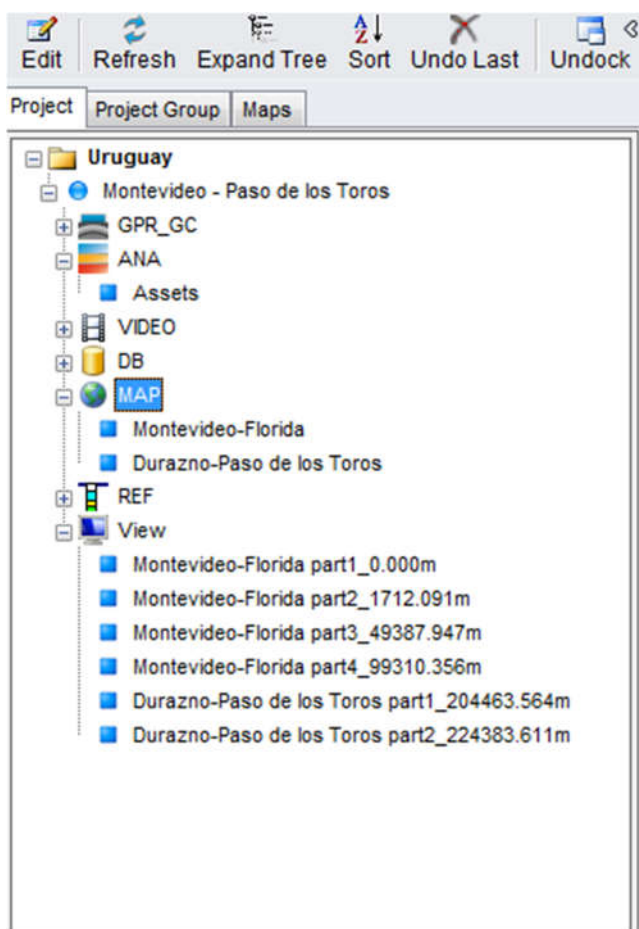
Figure 9 An example of Rail Doctor project –handling window.

DATA TYPE	EXPLANATION
View	Opens saved data views with fixed settings
VIDEO	Video files linked to project
GPR_GC	GPR data profiles
DB	Different databases e.g. track geometry, laser scanner data, moisture calculations
ANA	Analysis data e.g. asset data
REF	Reference drillings
MAP	Maps from measured section

Table 2. Rail Doctor Project data types with explanations.

User can open data views that are saved in advance by double-clicking the view name, e.g. "Montevideo-Florida part1". Different datasets can also be opened separately by double-clicking the data name from the corresponding data branches. Figure 10 presents saved data view in Rail Doctor viewer software.
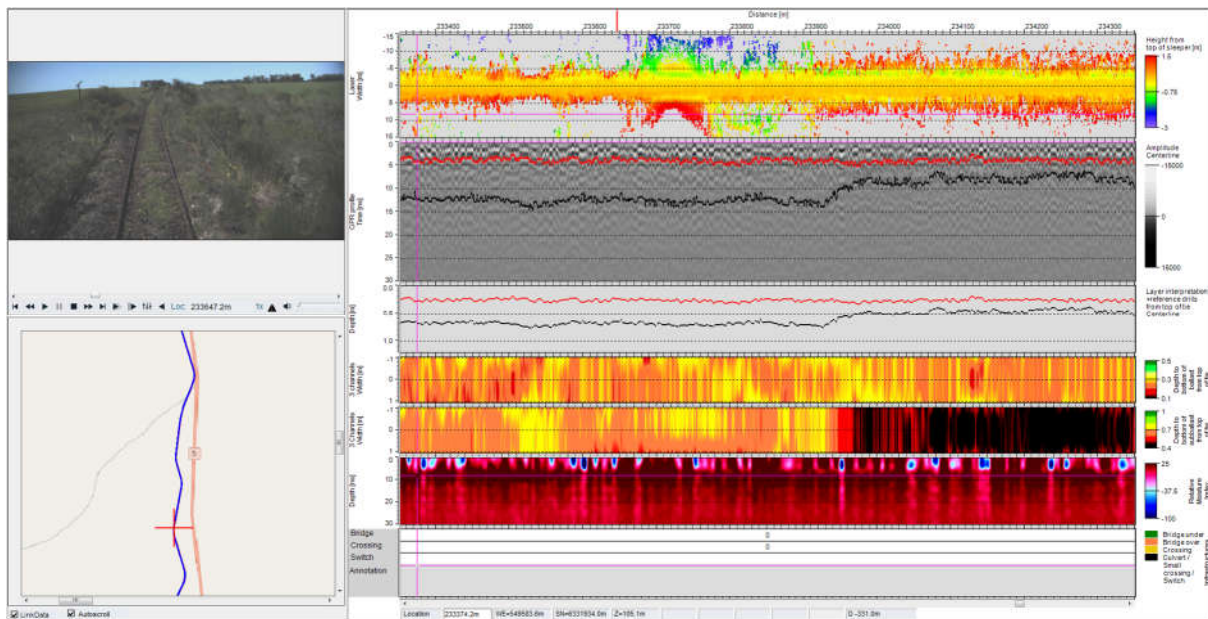
Figure 10 An example integrated view from the Rail Doctor user-interface with laser scanner surface map, interpreted GPR data, layer depth interpretations, layer interpretations as surface maps, relative moisture profile and analysis (asset) data. Digital video and map are displayed on the left side of window.

3.3 Data Processing and Visualization

In the processing phase, first step is to link GPR data to the Rail Doctor project and then scale it to correct length. Data is then processed using on-screen processing features of Rail Doctor software. The processing procedures comprised of a time-zero correction to top of tie reflection and horizontal filtering to reduce constant noise from the data (Figure 11). Further processing of GPR data is done on case basis.
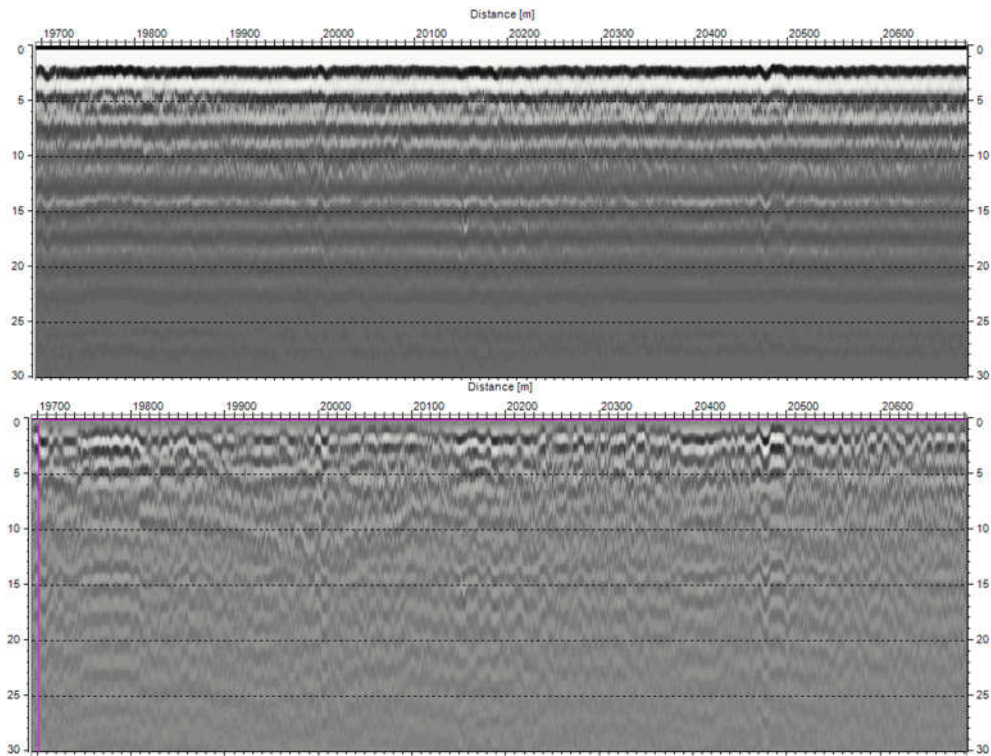
Figure 11 Example of GPR data before (upper) and after processing (lower).

Once the Rail Doctor -project file is completed, GPR data is interpreted using the software's semi-automatic layer tracking feature, which enables an effective user-controlled interpretations. Profiles of the interpreted GPR data are finally printed to profiles and numerical results can be outputted to tables and databases. Figure 12 shows an example of the Rail Doctor interpretation tool with structure interfaces from the data.
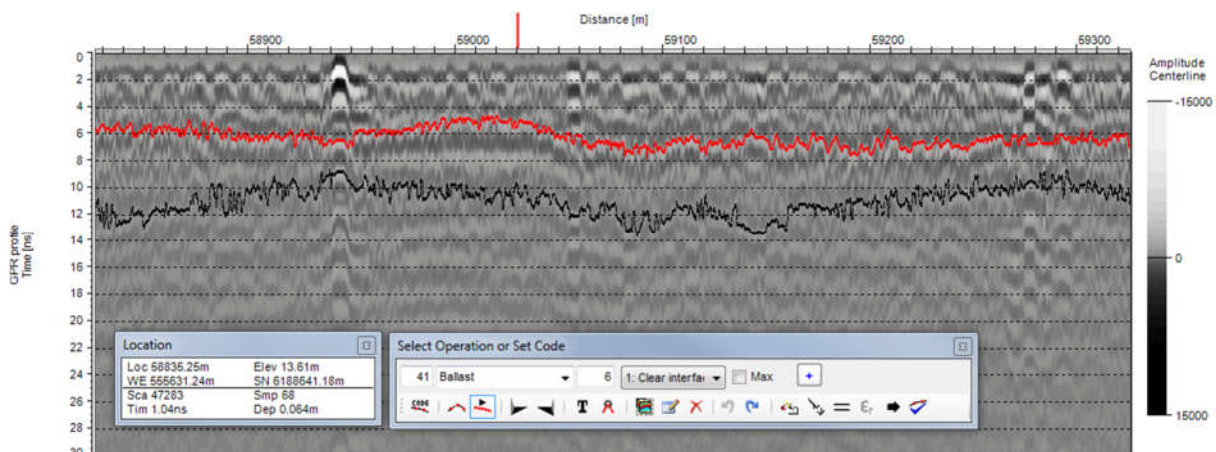

Figure 12 GPR interpretation tool in Rail Doctor view showing interpreted layers.

Interpreted data can be viewed as profiles. Figure 13 presents an example of GPR data as line interpretation. GPR data windows are typically in nanosecond depth scale thus line interpretation views are added. In these windows depths are accurately transformed to meter scale.
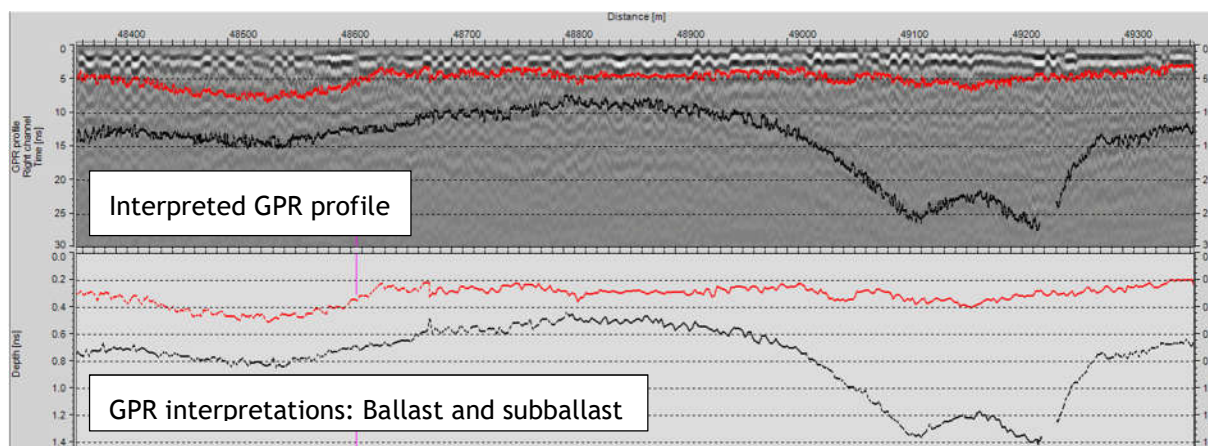
Figure 13 Example of GPR interpretation showed as profiles from centerline

Section from Montevideo to Paso de los Toros is very old thus railway's originally built layers have mixed quite a bit. Together with that and with clay and fine-material rich soil materials layer interfaces were in most cases relatively faint in the data which made interpretation challenging. Furthermore, some sections of track had steel sleepers which caused disturbances to data. Overall, due to conditions, GPR data quality was not optimum .. However, ballast and subballast interpretations were possible to draw yet leaving some uncertainties especially in subballast layer. Below in Figure 14 is an example from good quality GPR data from other location showing clear ballast, subballast and embankment bottom reflections.
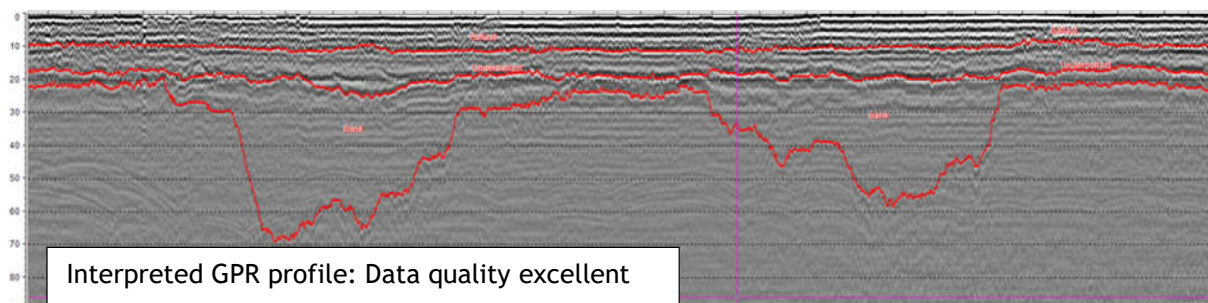

Figure 14 Example of good quality GPR data. Ballast, subballast and embankment layers are very clear.

3.4 Railway Information and Analysis Database

Rail Doctor enables it's user to import asset data to be viewed with other data in analysis bars. The analysis bars can include numerical information of different parameters and text annotations. Figure 15 shows example from analysis data. Analysis data window can include also different parameters such as ballast fouling, thickness and geometry data classifications. The analysis data is usually plotted under other profile data windows.
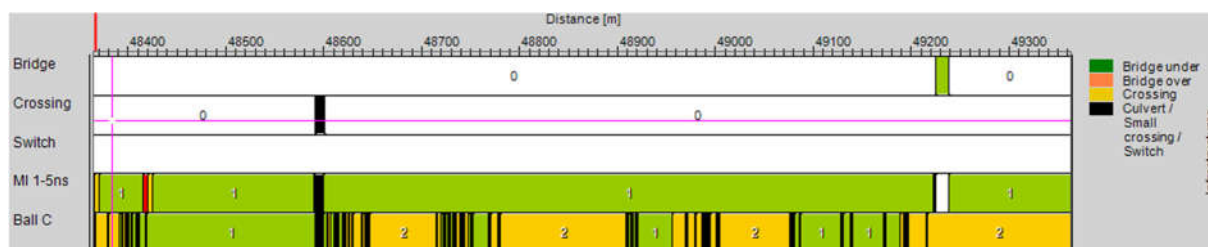
Figure 15 Locations of switches, bridges and crossings displayed in analysis bar. Moisture index (MI 1-5ns) and ballast depth classification from center channel (Ball C) were also analyzed to here and later printed on pdf maps.

3.5 Railway Structure Thickness and Moisture Problem Detection

Fouled ballast causes unevenness in the tracks and as such reduces the speed of train traffic. Another problematic issue is the low stability of structures in the soft subgrade areas. The worst time is during and after rainy seasons. Drainage problems together with thin structures can cause defects on the surface.

GPR is an effective tool in railway structure mapping. It provides continuous information about the structure thickness along the railway line. During interpretation, the drilling information can be used as reference data. The structure layer thickness and quality can be seen from the GPR data with additional information about subgrade quality and moisture. Special structures such as transition zones and culverts as well as subgrade failures and ballast pockets can be identified from the measurement data. When digital video, laser scanner and maps are used in the interpretation, other special features such as crossings, switches and bridges in the GPR data are easy to locate and verify.

Ballast and subballast thickness for this project is interpreted from all 3 lines in GSSI data. A relative dielectric value of 6 was used for interpretation of the ballast layer which gives a depth accuracy of +/-5 %. For subballast layer the relative dielectric value of 9 was used. The depths of the interfaces were calculated using these given dielectric values. 27 reference drillings in 176 km (~1 per 6 km) were used to make interpretations more precise. Later analyzed 96 kilometers didn't have drillings. Video, laser scanner and map data were used in the search for visual evidence that may help to explain any other data anomalies. Table 3 presents average layer depths for both analyzed sections.

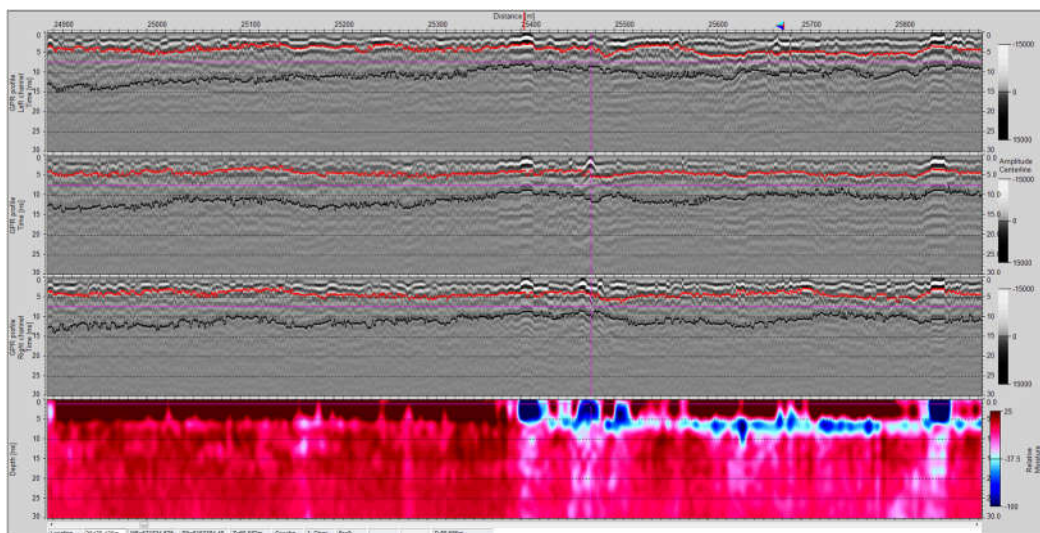| SECTION	BALLAST DEPTH	SUBBALLAST DEPTH
Montevideo-Florida	27 cm	58 cm
Florida-Durazno	28 cm	54 cm
Durazno-Paso de los Toros	26 cm	50 cm

Table 3 Average layer depths

Figure 16 An example data view from Rail Doctor, GPR interpretations from all 3 channels and average moisture profile from all channels combined.

The relative moisture profiles were calculated as an average value from left, center and right GPR profiles using a special frequency analysis technique that emphasizes the sections with higher moisture content than surroundings. It helps to determine trapped moisture and water holding tendency of the structure layers and granular subgrade soils. The moisture profiles are shown as color-coded surface maps which shows the moisture anomalies as red-blue colors. Figure 16 shows an example of the Rail Doctor view of GPR analysis of railway structures and moisture.

4. Results and attachments

Results of this survey are presented in pdf and excel formats. Additionally, on request results can be provided as a Rail Doctor project (including the project data and videos) and viewed with Rail Doctor Viewer software. Rail Doctor viewer is free to use software. Below is list of delivered attachments.

Attachments:
- PDF-profiles from result views (Figure 17)
- PDF maps with moisture index (Figure 18)
- PDF maps with ballast and subballast depths (Figure 19)
- Excel and pdf prints with 1 kilometer statistics (Figure 19)
- Excel file with layer thicknesses

PDF-profiles from result views (Figure 17) integrates project data together. If viewed with Rail Doctor viewer, video and map are also visible on view's left side. The first data window on top presents laser data as surface map. Orange color is 0-level (top of sleeper), blue color means that surroundings goes deeper and red color means higher surroundings than 0-level. By looking at laser data like this it is easy and quick to spot track objects such as bridges, crossings and switches and see when track is going in cutting (red surroundings) or possible in embankment (blue surroundings). Additionally, it is possible to order laser data in 3D Point Cloud or simple cross-section images.

Second window from top is GPR data from center channel. Ballast and subballast layers are interpreted here as continuous lines. With Rail Doctor viewer user can open GPR data from left and right channels as well. GPR data window's depths are in nanoseconds [ns].

In third window are layer depths from top of tie as line interpretation in meter depth scale. Reference drillings are added on top of interpretation lines to make comparison easy.

The fourth window presents graphically ballast depth interpretations from all 3 channels as color-coded surface map. Surface map is presenting how depths are changing in longitudinal and transverse directions. Fifth window is similar than previous expect shown parameter is subballast depths.

Sixth windows have results from relative moisture profiles. Bluer and darker the moisture profile is, the more moisture the track structure has on that section.

Last window marks track infrastructure information. There are locations of switches, crossings, bridges and stations which are analyzed from laser, video and GPR data. Additionally, it is possible to show moisture index and layer depth classifications as bars.
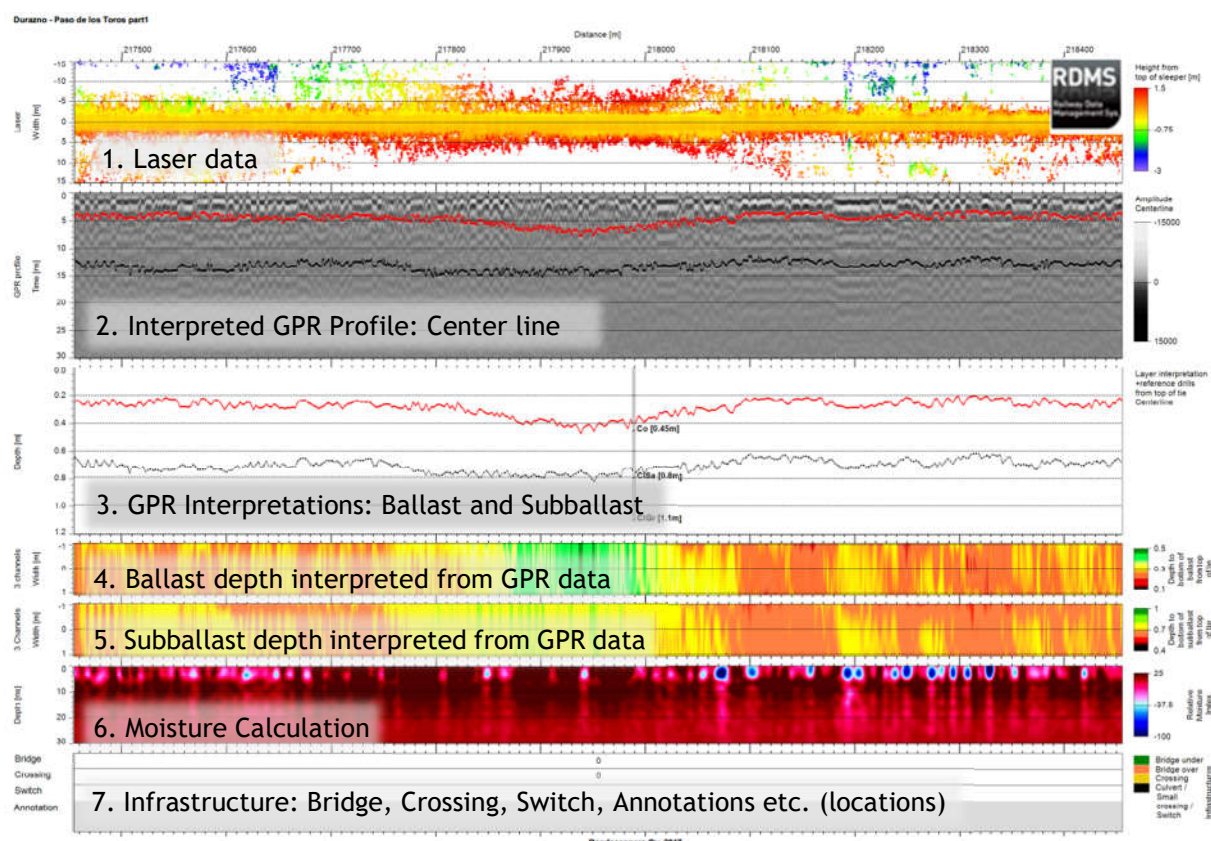
Figure 17 Rail Doctor project views are printed to pdf files which are attached to this report.

From moisture results, are calculated also moisture indexes from 3 different depths. Furthermore, these are classified to 4 (5) classes. Class 1 is relatively low moisture and class 4 is highest moisture class. There is also class 0 with no values. Class 0 has had its values removed because steel objects or other special structures that are likely to have unwanted distortion effects on calculation results. Classified moisture indexes are printed to PDF maps (Figure 18). Left line is moisture index from top layer (0-0.3m), center line is intermediate depth (0.3-0.6m) and right line is deep moisture (0.6-0.9m) between.
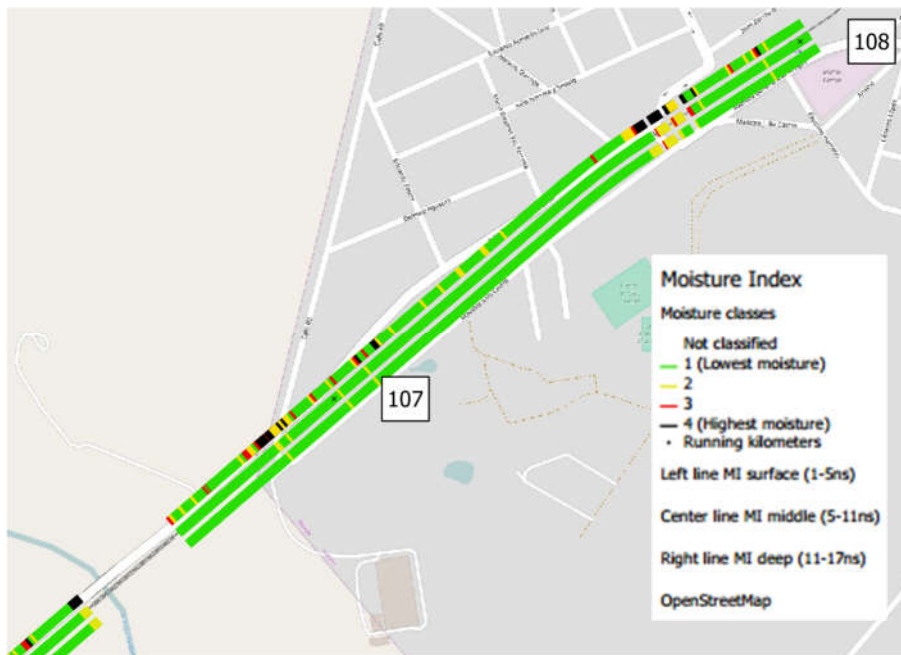
Figure 18 Moisture index classification from different depths on PDF maps

Figure 19a presents moisture index from Km-statistics. Every vertical bar indicates how many % of certain classified classes are at specific 1 kilometer section. Figure 19b displays ballast or subballast depths from all 3 channels printed on map view. Interpreted layers are also exported to excel file with GPS coordinates.
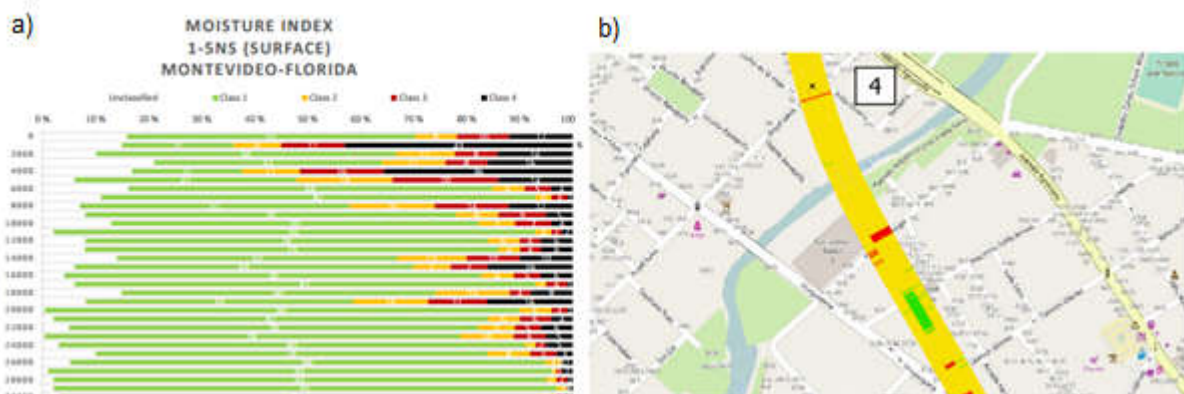

Figure 19 a) Km-statistics and b) layer depths on map views

5. Conclusion and Discussion

GPR is an effective non-destructive inspection method for railway structures and subgrade soil. Method gives continuous information concerning railway structures layer thickness, special structures and material properties. Combined with laser scanner technique and other supplementary data railway maintenance planning procedures are greatly enhanced compared to more traditional methods.

In recent years, GPR technology for structure inspection has improved to faster systems and higher frequencies. Processing and interpretation software has also been developed further for better visualization of processed data and faster calculations speeds. GPR technology helps to reveal the railway structure thickness and defects without excessive drillings and is a powerful non-destructive investigation method with several major advantages such as fast measurement speed, continuous survey lines and mapping of the different structure layers. With the GPR technique railway structures can be inspected in an effective way down to depths of several meters depending on circumstances, with the maximum speed of 200 km/h.

New development of frequency analysis for GPR signal produces information concerning the material parameters of structural layers such as moisture condition in granular layers and more clear interpretations of layers than before. However, in this project GPR data quality was not as great as it is in most projects. It is known that GPR can't see below clay or very clayish layers. Part of measured sections contained also steel sleepers which are unusual for North American and European railway's and these produced extra disturbances for GPR data. Because analyzed track is also very old it was presumable that structural layers had mixed significantly making interpretation work more difficult. Embankment were not possible to interpret but ballast was done with good results and subballast layer left slight uncertainties.

The use of integrated interpretation software enables the precise location of the survey data and provides an overview of the survey environment. Other information such as rail geometry and track stiffness data can be analyzed together with the thickness data to further enhance analysis. The benefits of GPR in railway condition inspections and monitoring are indisputable: it is a non-destructive, fast, reliable and cost effective method. The integrated analysis of railway data helps to define the root cause of the defects and it makes rehabilitation planning more accurate and thus more economical. Track geometry, kilometer pole locations and track maintenance history would be good additional information as reference data to get best possible overview of the condition of the measured track. These can be linked to project and added to integrated views if provided by customer. One other benefit from GPR surveys is lesser need to take drill samples so often as in traditional inspection have done. It is still recommendable to use drilling samples together with GPR data.

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Literature:

Hyslip, J.P., Olhoeft, G.R., Smith, S.S., and Selig, E.T. Ground Penetrating Radar for Track Substructure Evaluation, Federal Railway Administration, 2005.

Nurmikolu, A. Degradation and frost susceptibility of crushed rock aggregates used in structural layers of railway track. Doctoral thesis. Publication 567. Tampere University of Technology. 2005.

Silvast, M., Levomäki, M., Nurmikolu, A., and Noukka, J. NDT Techniques in Railway Structure Analysis. 7th World Congress on Railway Research. Montreal, Canada, 2006.

Silvast, M., Nurmikolu, A., Wiljanen, B., and Levomäki, M., Inspection of Railway Ballast Quality Using GPR in Finland. 9th International Heavy Haul Conference, Shanghai, China, 2009.

Smekal, A., Berggren, E.G., Silvast, M. Monitoring and Substructure Condition Assessment of Existing Railway Lines for Upgrading to Higher Axle Loads and Speeds. 7th World Congress on Railway Research. Montreal, Canada, 2006.

Loizos A., Silvast M. and Dimitrellou S., 2007. Railways Trackbed Assessment Using Ground Penetrating Radar Technique", International Conference on Advanced Characterization of Pavement and Soil Engineering Materials, Athens, June 20-22, 1817-1826.

Silvast, M., Nurmikolu, A., Wiljanen, B. and Levomaki, M., 2010. An inspection of railway ballast quality using ground penetrating radar in Finland. Proc. IMechE, Part F: J. Rail and Rapid Transit, 224 (F5), DOI 10.1243/09544097JRRT367, 2010 pp. 345-351.

Silvast, M., Nurmikolu, A., Wiljanen, B. & Levomäki, M. 2012. Identifying frost-susceptible areas on Finnish railways using GPR technique. Proc. IMechE, Part F: J. Rail and Rapid Transit, June 27, 2012. DOI 10.1177/0954409712452076.

Silvast, M., Nurmikolu, A., Wiljanen, B. & Mäkelä, E. 2013. Efficient track rehabilitation planning by integrating track geometry and GPR data. Proceedings of the 10th International Heavy Haul Conference, February 4-6, 2013, New Delhi, India

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