An Integrated System for Accurate Tie and Ballast Condition Assessment

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ABSTRACT

With trends in increasing rail traffic and the related increases in total annual tonnage hauled, the ability to apply consistent and regular maintenance procedures for the efficient management of track infrastructure in the context of diminishing track access times, and limited maintenance budgets is becoming increasingly more difficult. The historical approach of scheduling large consolidated zones for maintenance and rehabilitation is being challenged by the belief that a more detailed and accurately referenced analysis of in-situ track infrastructure condition would allow improved and more cost-effective asset management and maintenance decisions. Discussions with rail operators have identified that detailed track assessments (ballast and tie) must accurately identify, reference, and quantify localized deficiencies in both the ballast and tie components of the rail structure.

To meet these rail industry needs, RAIL RADAR™ has developed and implemented a sophisticated system for the non-destructive assessment of ballast and tie condition. This system integrates unique multi-channel ground penetrating radar (GPR), with high-resolution rail centered downward digital imagery, real-time differential global positioning system (GPS) and linear referencing technologies.

Although conventional GPR is an accepted technology for ballast structural investigations, the RAIL RADAR™ system extends conventional GPR technology by incorporating a surface

coupled array antenna system with the unique ability for the quantitative measurement of ballast material properties at each radar measurement point. Radar measured ballast material property variations have been correlated to variations ballast fouling and ballast moisture content.

Synchronized with ballast assessment is the acquisition of accurately referenced downward looking digital video images of the track. This high-resolution, rail-centered stereo imaging system provides the ability to safely and efficiently collect visual track data at high rail speeds and allows the subsequent objective analysis of tie and rail fastener inventory and condition parameters in the safety of the office. A sophisticated image post-processing and feature detection environment allows the automated classification, extraction and inventory of a wide variety of track components and condition parameters. The analyzed track components are extensive, but typically include ties, rail fasteners, joints and other track materials. The efficiency of the RAIL RADAR™ data collection and analysis allow the development of the network wide inventories from which any required condition or regulatory compliance statistics can be calculated and reported. Rail network digital videologs become a permanent record of track condition at the time of survey and allow the detailed review in the office.

All survey data components are linearly and spatially referenced to allow accurate reporting of inventory, condition assessment and detected anomaly results and simplify the integration of all reported data into geographical information system (GIS) based track-management systems. Additionally, the rigorous RAIL RADAR™ approach to referencing accuracy provides temporal stability for all collected data, and allows year-after-year condition assessment comparisons and track infrastructure performance modeling.

INTRODUCTION

Rail operators, under pressure from global trends of increasing rail traffic, increasing total annual tonnage hauled, limited maintenance budgets and diminishing track access times for rehabilitation and capital programs are increasingly challenged to apply consistent and regular maintenance procedures for the efficient management of track infrastructure. Through interactions with the rail industry, it was recognized that the efficiency of the time consuming and subjective task of track component assessments could be significantly improved with the development and integration of state-of-the-art non-destructive technologies for these assessments.

Many studies in the last two decades using conventional geotechnical ground penetrating radar (GPR) technologies for non-destructive ballast structural assessments have demonstrated the ability to report railbed as-built substructure parameters. Discussions with Canadian National Railway (CN) in 2002 identified the benefits to the rail industry of extending the application of GPR beyond non-destructive structural measurements to provide accurate and *quantitative* continuous in-situ ballast material property assessments. Similar quantitative material property measurement requirements were identified 15 years ago for the roadway industry which lead to the development of ground penetrating radar technology by Road Radar Ltd. which remains unique in the industry (Road Radar Ltd. is an allied company to RAIL RADAR™ Inc.) The ROAD RADAR™ system (patented in 1994) uses a multiple antenna configuration to collect radar measured material properties (pulse propagation velocity) as well as structural information at each measurement point.

Based on this technology, theoretical models for radar measured ballast property variations due to changes in ballast fouling and ballast moisture contents were evaluated during CN sponsored field programs in August 2002. This GPR field program included ballast sampling and laboratory material testing programs and confirmed the hypothesized correlation between ballast fouling and radar measured pulse propagation velocity; increases in ballast fouling result in diminished radar pulse velocity.

The recognition of the practical requirement to locate post-processed data features of interest in the field or to compare and analyze different data collection programs necessitated accurate positional referencing for all collected field data. The positional referencing approach developed for all rail data collection programs combines both Differential Global Positioning System (DGPS) and accurate linear referencing which includes rail landmark feature tie-in. The 2002 CN field trials confirmed the importance of field survey data referencing during the comparison of field extracted ballast samples with post-processed GPR ballast parameters. Correct referencing also facilitated the identification in the field of localized subsurface anomalies identified during post-processing.

Success with these initial field trials allowed Rail Radar™ to continue to develop innovative technologies with specific application to rail track component inventory and assessment. Additional dialogs with CN identified the necessity for integrated technologies capable of providing efficient inventories and assessments of rail ties and the associated track fasteners. From this interaction, Rail Radar™ developed sophisticated rail-centered downward looking stereo imaging system and the proprietary image post-processing and feature detection environment to allow the automated classification, and extraction of tie condition and track components parameters. This rail-centered stereo imaging system allows the simultaneous assessment of both gauge and field fastener components for both rails from a single image. Field trials of the integrated Rail Radar™ ballast, tie and fastener assessment system were conducted with CN in August 2005.

It has been recognized that the track image quality, referencing and presentation capabilities of this imaging system also provide a near ideal methodology for office-based track inspector training to help standardize tie and fastener inventory and defect classifications.

Currently, the fully integrated Rail Radar™ system provides the following non-destructive track data collection and analysis capabilities:

- Ballast inventory and assessment using patented GPR post-processing and analysis.

- Tie and fastening systems inventory and assessment using digital image post-processing and analysis.
- Rail joints and OTM using digital image post-processing and analysis.
- Precise data referencing using differential GPS, linear measurement and track landmark tie-in.

These capabilities provide the ability for objective and repeatable track assessments, making the RAIL RADAR™ system particularly well suited for forensic track analysis, assisting with due diligence and regulatory compliance evaluations, and when combined with a Track Information Management System or Track Network GIS allows comprehensive life-cycle cost and track performance analyses.

BALLAST INVENTORY AND ASSESSMENT

The RAIL RADAR™ ballast fouling assessment system was adapted from the patented Road Radar™ technology originally developed in 1994 by Road Radar Ltd. Like the Road Radar™ system, the RAIL RADAR™ GPR technology determines both the signal travel time and material dielectric values (calculated from pulse propagation velocity) at every measurement point for each detected subsurface layer. This makes the system self-calibrating for layer thickness measurements, by measuring variations in material properties, and eliminates the need for destructive calibration test-pitting. The RAIL RADAR™ System uses a patented high resolution multi-channel surface coupled antenna array based radar system. The GPR subsystem installs quickly on any rail vehicle and is integrated and synchronized with the image based tie assessment, and referencing subsystems.

Figure 1 High-Rail Installed RAIL RADAR™ GPR Subsystem

Ballast Inventory

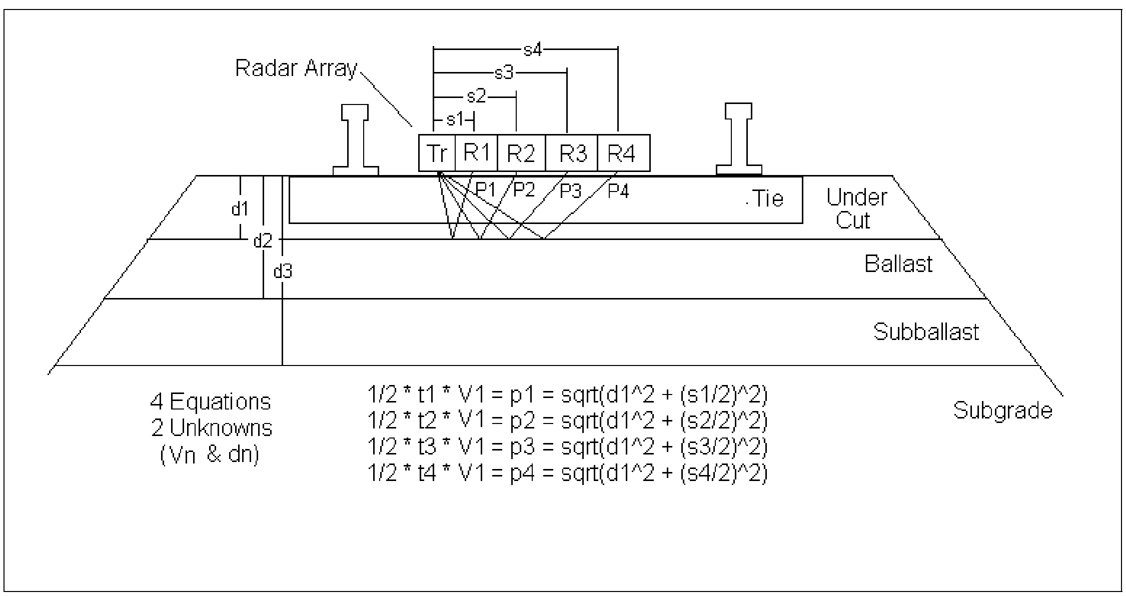

Figure 2 RAIL RADAR™ System Ballast Parameter Calculations

The system uses a single transmit antenna (Tr) and multiple 1.1GHz receive antennas (Rn) positioned at precise locations (sn) to provide accurate structural parameter (dn), and material property measurements (Vn) at each measurement point based on pulse arrival time (tn) for detectable layers in the railbed structure. The radar system acquires samples at any programmed distance, typically every 25-50mm (1-2 inches), and can typically resolve layers as thin as 40mm (1.5 inches) to a depth greater than 1.5m (5 feet) in normal railbed structures. The RAIL RADAR™ system has a layer thickness measurement accuracy of ±5%, and is able to survey through wooden or reinforced concrete (PCC) ties. The RAIL RADAR™ antenna array has been optimized for rail applications and can be configured to conduct surveys between or outside of the rails as required. RAIL RADAR™ data is acquired with a current maximum data collection speed of 40kph (25mph) and is post-processed to provide structural and material property parameter measurements at each radar data collection point.

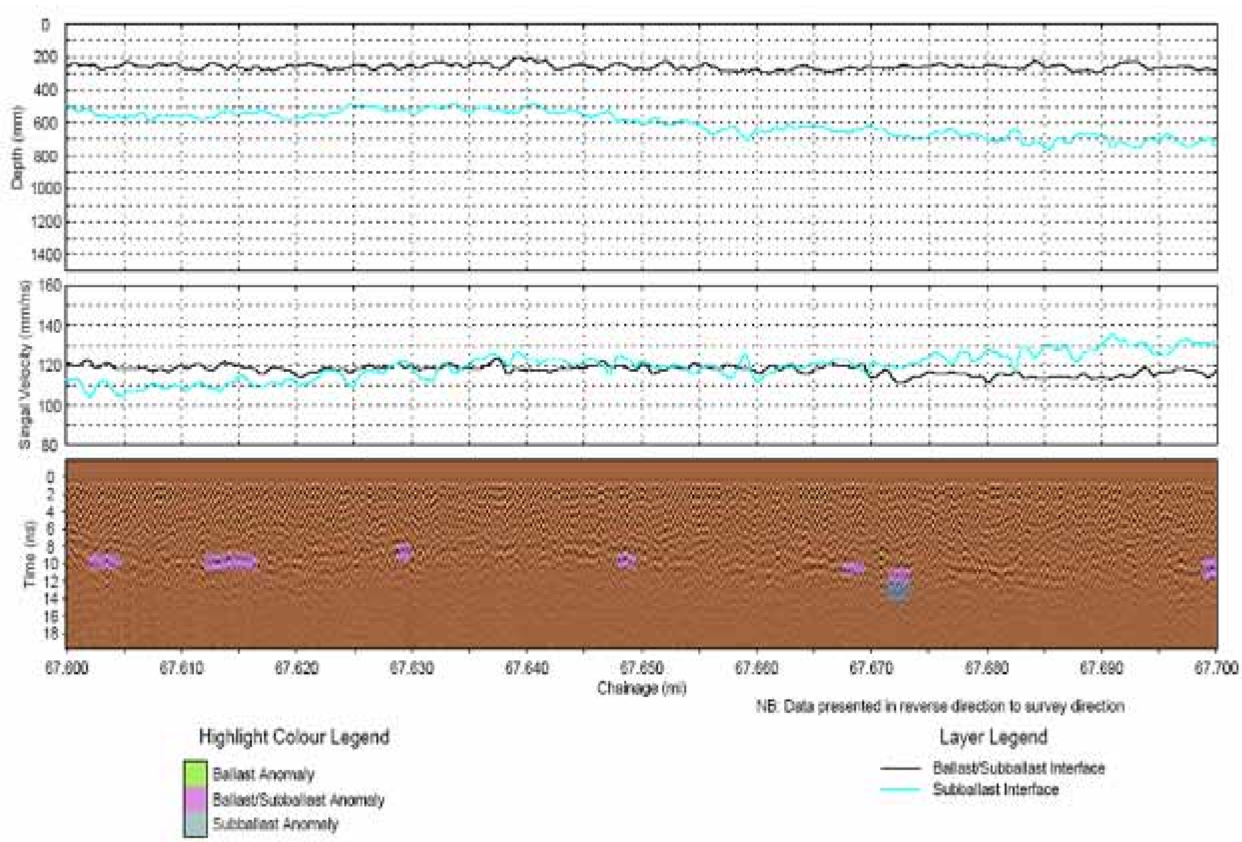

Figure 3 - Rail Radar™ Report including Structural Data,

Material Property Data, and Annotated Graphical Data

Ballast Assessment

Early discussions with CN identified the potential for non-destructive in-situ ballast assessments using the RAIL RADAR™ system's unique ability to measure both structural layer thickness and ballast material properties at high-rail track speeds. Based on the known aggregate deterioration mechanisms for the transition of ballast from new to fouled conditions under rail traffic loadings, the effects on radar pulse propagation (radar measured ballast dielectric) were modeled.

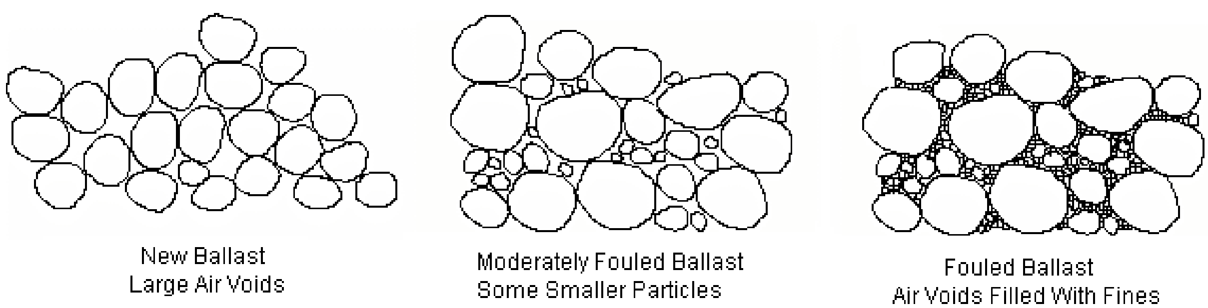

Figure 4 Ballast Deterioration depicted from New to Fouled Conditions

$$\varepsilon_{effective} = \sum vol_n \cdot \varepsilon_n$$

Equation 1 – Effective Composite Dielectric Model

The effective in-situ ballast dielectric ($\varepsilon_{effective}$) was modeled using the summation of the volumetric ratio of the constituent material dielectric values. This model predicted that conventional ballast materials should experience a significant decrease in radar measured pulse propagation velocity (10-30%) in ballast materials as they transition from new to a fouled condition.

Table 1 - Modeled Ballast Pulse Propagation Velocity at Radar Frequencies

Air ($\varepsilon = 1.0$) (% volume)	Ballast ($\varepsilon = 5.4$) (% volume)	Water ($\varepsilon = 81$) (% volume)	Effective Dielectric	Velocity (mm/ns)
25	75	0	4.30	145
15	85	0	4.74	137
10	90	0	4.96	135
5	95	0	5.18	132
5	90	5	8.96	100
5	85	10	12.7	84

During the trials conducted during 2002, RAIL RADAR™ data was acquired on 16 separate CN track segments in the Edson Subdivision west of Edmonton, Alberta, Canada. These segments were selected to include back tracks, sidings, and mainline sections representing ballast conditions ranging from significantly fouled to new ballast. Following the non-destructive testing using the RAIL RADAR™ system, field ballast samples were carefully referenced and extracted for subsequent laboratory sieve analysis.

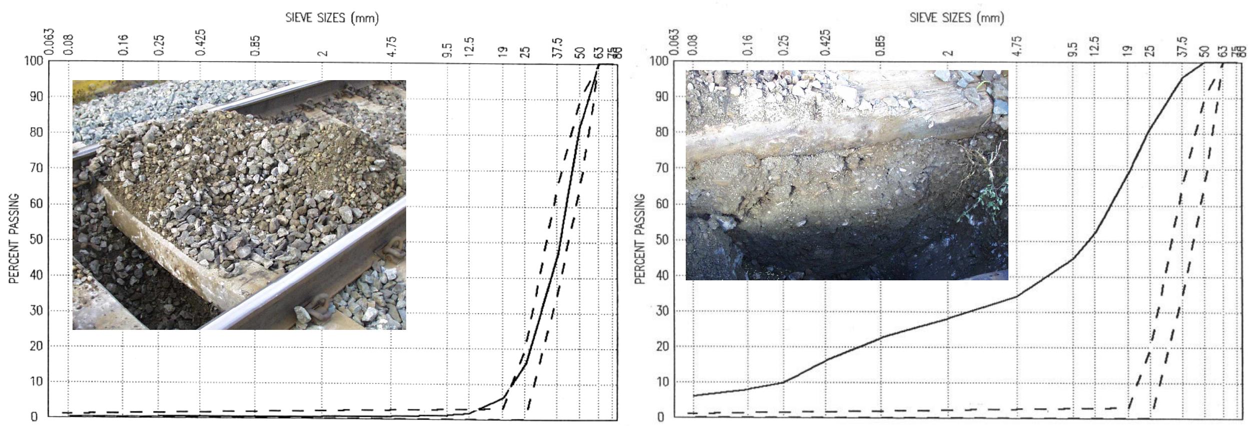

Figure 5 Field Samples Taken During CN Trials of Non-Fouled and Fouled Ballast Locations

During the CN field trial, radar measured ballast material property variations were correlated to variations in sieve analysis determined ballast fouling and ballast moisture content. The trial confirmed the modeled effects on radar pulse propagation velocity by increased fines associated with ballast fouling. This trial established conclusively that increased fines (increased ballast fouling) decreases radar pulse velocity. Additionally, it was demonstrated that increased fines permit increases in localized moisture content which significantly decrease radar pulse velocity.

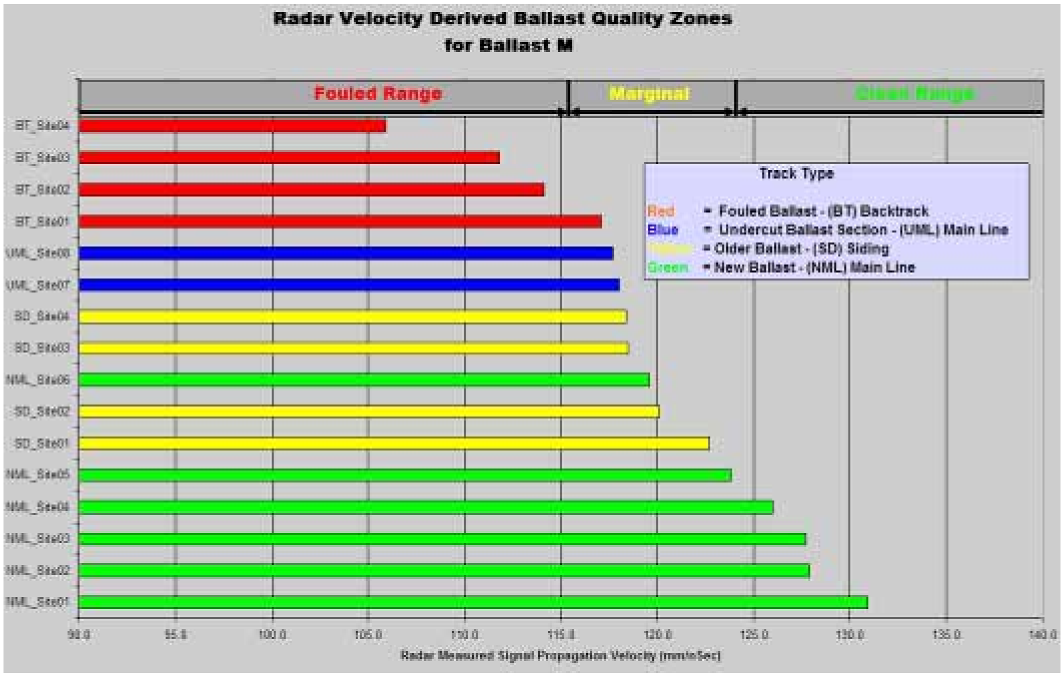

Figure 6 CN Trial Radar Measured Velocity and Ballast Condition Correlation

This trial also demonstrated the unique ability of the RAIL RADAR™ system to measure subsurface material properties (velocity/dielectric) at each measurement point which allows identifying in-situ variations in ballast material properties. For any conventional ballast material, the magnitude of these variations, in conjunction with gradation testing, can be analyzed to produce an objective and repeatable Ballast Quality Index (BQI) to accurately quantify ballast fouling. This objective BQI approach has been theoretically modeled and laboratory and field verified, and can be reported at any interval using client specified statistics.

Simplistically, the radar velocity based BQI asserts:

- Areas with ballast having higher pulse propagation velocities have more air voids than lower velocity areas for the same ballast material.
- Areas of conventional ballast material having velocities less than 20-30% (25-40mm/ns) of new ballast areas can be considered significantly fouled.
- Areas with ballast velocities exceeding the velocity of *acceptable* ballast quality areas (acceptable ballast velocity threshold) are indicative areas with fewer fines than *acceptable* ballast.
- Areas with ballast velocities below the velocity of *acceptable* ballast quality areas (acceptable ballast velocity threshold) are indicative areas with more fines than *acceptable* ballast.

RAIL RADAR™'s approach is to define *acceptable* ballast as ballast which meets client fouling specifications for ballast not requiring replacement; however any increase in fouling would degrade the ballast to requiring replacement. It is recognized that this specification may change based on criteria such as track classification and maintenance funding levels. More typically, it is far easier to identify definitive Good and Poor ballast areas and then determine the corresponding velocity thresholds for these areas. Once these areas are identified, site-specific Good and Poor ballast velocity thresholds can be established either through laboratory sieve analysis of field samples or through the analysis of RAIL RADAR™ measured velocities in these areas. Once

Good and Poor ballast velocity thresholds have been established, ballast condition assessment with relation to these thresholds can be calculated and reported (i.e. assessing and reporting a BQI).

Ballast Condition Overlay Plan Maps

RAIL RADAR™ Ballast Overlay Condition plan maps compare measured radar velocity in all detected ballast layers against Good and Poor (fouled) ballast velocity thresholds. These maps have been developed to classify and color code ballast condition for surveyed locations at client specified intervals. The classifications categorize the condition of the ballast into Poor, Fair and Good. The reported ballast conditions can be integrated with client GIS systems and are both linearly and GPS-referenced.

Ballast Undercutting Prioritization

Green segments depict areas assessed as good ballast condition (low ballast undercutting priority). Red segments depict areas of poor ballast condition (high ballast undercutting priority), and yellow represents areas of fair ballast condition. The yellow or ‘fair’ sections represent ballast in the marginal condition range which may be undercut if sufficient funding is available or if combined with other close proximity higher priority undercutting activities. Ballast gradation analysis could be undertaken in these areas to conclusively determine appropriate rehabilitation timelines and correlate radar measured velocity parameters.

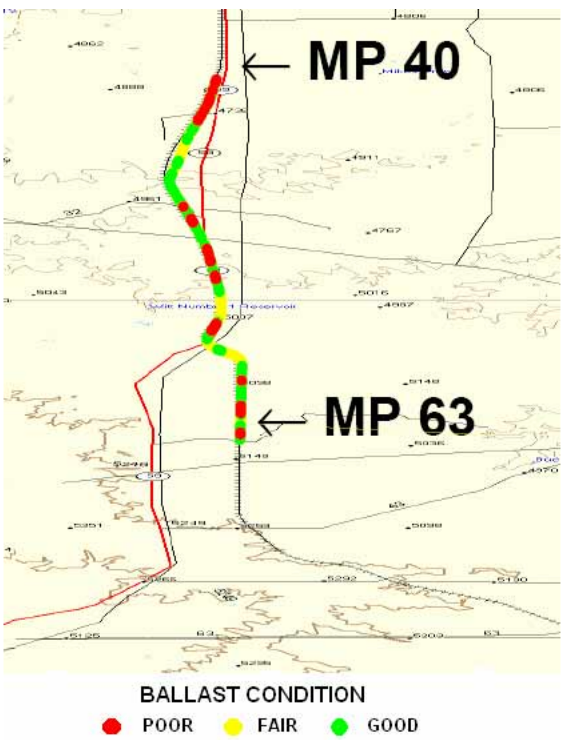

Figure 7 - Ballast Condition Overlay Plan Maps

The Rail Radar™ ballast classification process uses sophisticated post-processing techniques that compare actual GPR measured representative ballast material property parameters to client identified thresholds of acceptable and not acceptable ballast conditions.

TRACK COMPONENT INVENTORY AND ASSESSMENT

Discussions with various railroad companies identified growing industry need for technologies capable of providing efficient inventories and assessments of rail ties and the associated track fastener systems. In response to this need, RAIL RADAR™ developed a sophisticated rail-centered downward looking stereo imaging system and a proprietary image post-processing and feature detection environment to allow the automated classification, and extraction of tie condition and track components parameters. The efficiency of the RAIL RADAR™ data collection and analysis allows the development of network wide inventory, from which any required condition or regulatory compliance statistics can be calculated and reported. RAIL RADAR™ digital videologs are a permanent correctly referenced and survey date encoded record of track conditions, allowing detailed office based review.

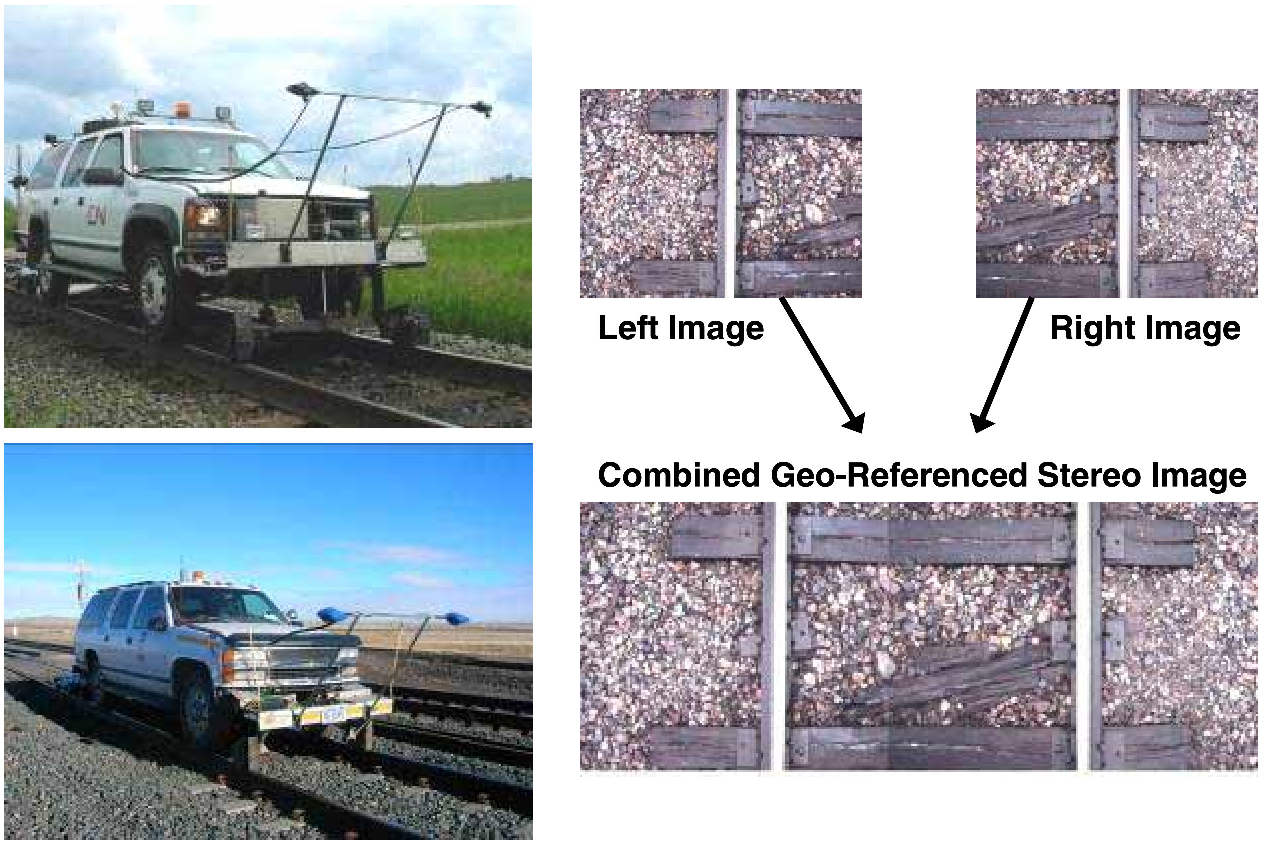

Figure 8 High-Rail Mounted RAIL RADAR™ Integrated Stereo Imaging System and Resulting Stereo Images

The imaging system consists of high speed digital cameras, configured as a fixed offset and position synchronized stereo imaging system. The resulting combined stereo image allows the simultaneous assessment of both gauge and field fastener components for both rails from a single image. The track component feature detection capabilities of the image analysis and post-processing environment are extensible, but typically include ties, rail fasteners, joints and other track materials. The imaging system installs quickly on high-rail vehicles, and is synchronized with RAIL RADAR™'s GPR and referencing systems. The images are collected continuously at survey vehicle speed.

Track Component Inventory

The integration of the RAIL RADAR™ downward imaging system with the linear and geo-referencing systems allows the detailed and accurate inventory of tie, joints, other track materials and features of interest. During post-processing, all ties are linearly and spatially located to provide a unique and repeatable identifier for each tie. These identifiers include geo-coordinates and tie count offset from the last milepost. This approach allows the establishing of a spatially referenced database (GIS) with condition and physical parameter data that can be maintained, analyzed and updated year over year.

In the case of ties, these inventory attributes include:

- Location (subdivision, track, latitude, longitude, elevation, count from last milepost)
- Physical Parameters (spacing, length, skew angle, adzed surface etc.)
- Plate Parameters (size, type, number and location of spikes etc.)

For other track components, inventory attributes include:

- Rail Joints (location, rail, etc.)
- Switch/Frogs (location, type etc.)
- Lubricators, Hotbox Detectors, OTM (location, type, etc.)

Similar attributes can be recorded for all track components of interest. As with other analysis results produced by the RAIL RADAR™ system, all Track Component Inventory data can be produced using GIS or attribute based maps.

Track Component Assessment

Track components are assessed through the post-processing and analysis of the combined and geo-referenced high-resolution track images. Each downward image is 1350 x 600 pixels and captures approximately 3 x 1.5m (10' x 5') providing a pixel resolution of approximately 2.5 mm (0.1 inch). RAIL RADAR™'s tie and fastening system defect analysis is based on feature identification and classification to provide an objective Tie Quality Index (TQI). This TQI analysis allows definition of client or regulatory specific attributes and features to characterize defective ties and fastening systems (spikes, anchors/clips, plates/pads). Client defined summary statistics based on TQI calculated for each tie can be reported at any interval.

The Rail Radar™ track component assessment provides a permanent record of rail tie, plates, spikes, joints and anchor hardware conditions at the time of survey.

Post-processed TQI attributes are graphically overlayed on position annotated video frames. These annotations include descriptive survey text, geo-coordinates, and linear referencing to uniquely identify each image frame. These annotated videologs allow the office review of all surveys and corresponding condition assessments. The delivery format for geo-referenced videologs is an indexed database and videolog GIS environment. This enhanced feature provides the operator with the ability to inspect any reported TQI parameter or network statistic using an interactive map and linked to the parameter reporting display window. The Rail Radar™ Track Data GIS tool (Figure 9) presents a two panel window with annotated videolog frames in the top panel and an interactive color coded survey alignment overlayed on a geo-referenced airphoto map in the lower panel. By selecting any survey location point on the geo-referenced map, the corresponding annotated digital videolog frame and TQI rating information is displayed. The same environment can display all calculated statistics and indices in graphical and tabular formats (Figure 10).

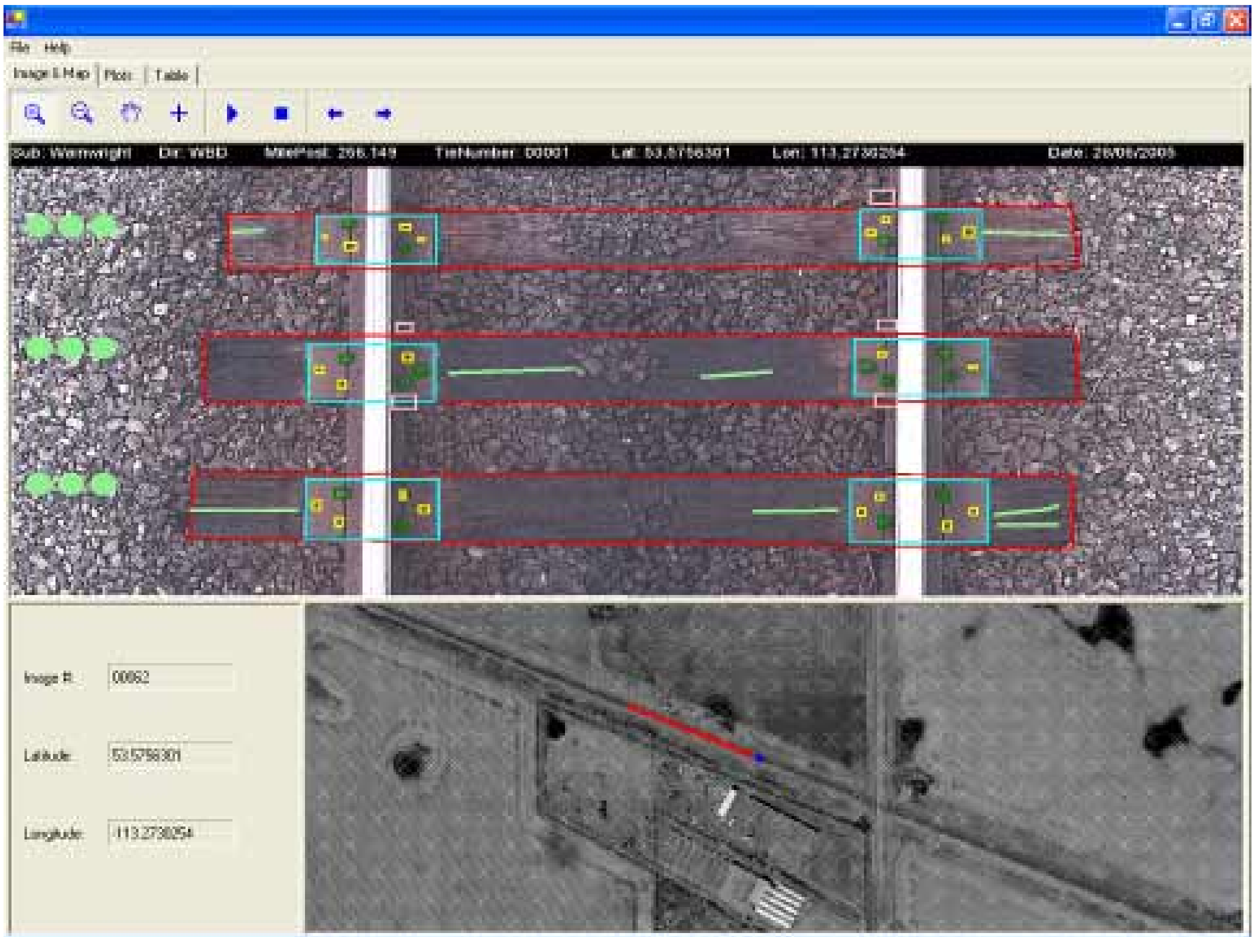

Figure 9 - Interactive Map Linked to the Parameter Reporting Display window

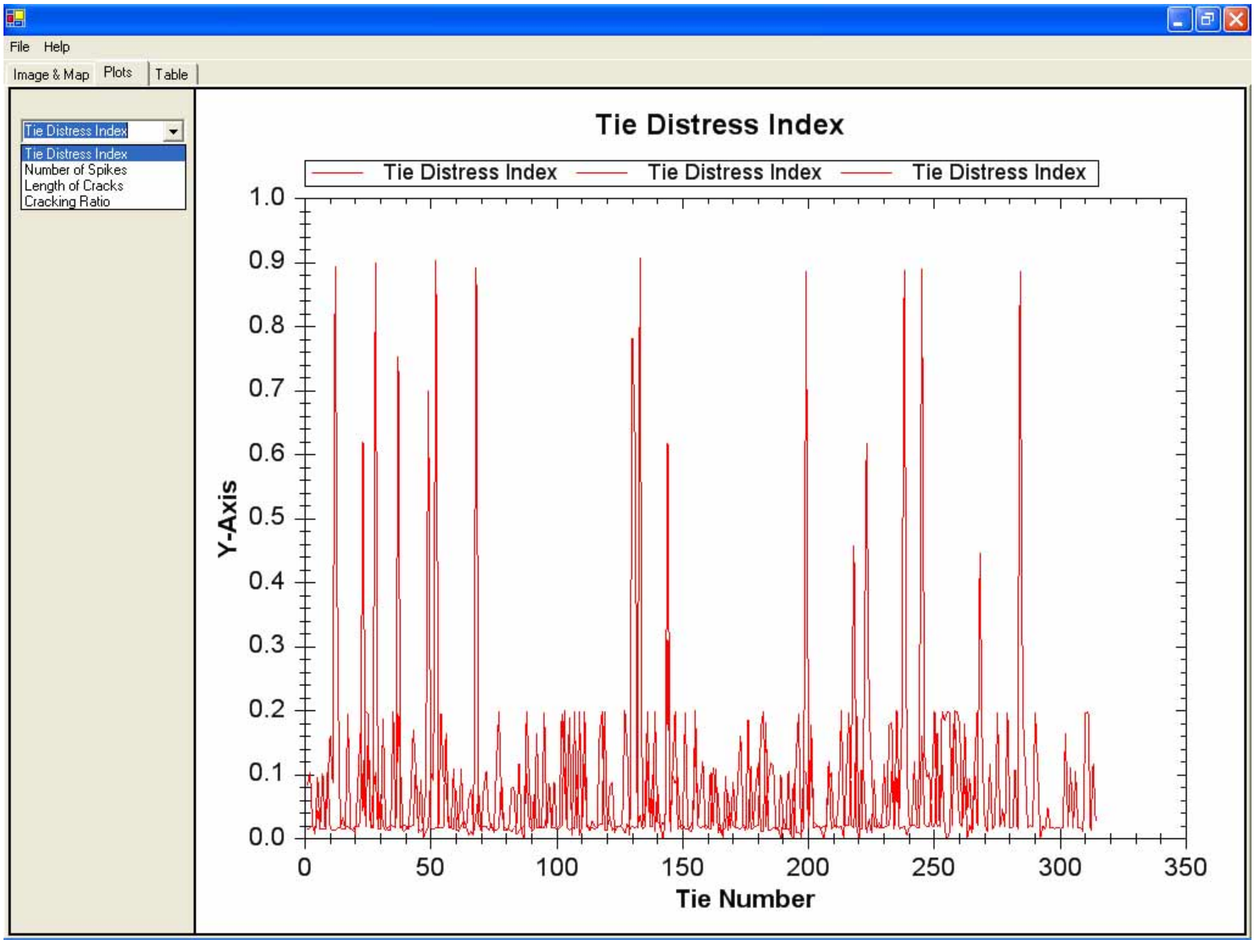

Figure 10 - Tie Distress Index

Examples of TQI parameters and the corresponding statistics include:

- Tie Condition (tie shape (broken), crack severity and density between rails, outside rails, color etc.)
- Spike and Anchor Parameters (presence, separation from tie etc.)
- Clip Parameters (shifted or missing)

Table 2 - TQI Example Parameters

Mile		Spikes Per Plate			Tie Condition							% Non-defective Ties in 39 Feet		
From	To	Min	Max	Avg	Poor (%)	Good (%)	Broken (%)	Adzed (%)	Total Length of Cracks (% < 1.5m)	Total Length of Cracks (% > 1.5m)	Total Length of Cracks (% > 3.0m)	X in 39'	X - Y in 39'	Y - Z in 39'
240.0	241.0	2	5	2.34	6	94	1	14	78	12	10	-	-	-
241.0	242.0	2	5	2.42	8	92	2	12	59	33	8	-	-	-
242.0	243.0	2	4	2.41	5	93	1	8	61	23	6	-	-	-

Note: these can be tailored to client requirements

Data Referencing

The tie imagery and ballast radar data is synchronized with onboard high accuracy linear and spatial referencing systems. All survey data is collected continuously at survey vehicle speed, with additional landmarks (mileposts etc.) directly encoded into the data stream. Rail Radar™ is capable of providing accurate spatial referencing in any client specified coordinate system or projection. This capability allows the straight forward integration of data into existing Track Management Systems using any commercial GIS format.

Rail Radar™'s focus on accurate referencing ensures the ability to locate survey analyses and results in the field. Additionally, accurately referenced data allows the comparison of network condition parameters on a year-by-year basis, and makes possible life-cycle cost analysis (LCC) to determine the most cost-effective approach for construction, rehabilitation and maintenance strategies allowing the estimate of time and costs at the network or project level.

CONCLUSION

To meet the increasing rail industry need for tools to assist with cost-effective asset management and maintenance decisions RAIL RADAR™ has developed and implemented a sophisticated system for the non-destructive assessment of ballast and tie condition. This system integrates unique ground penetrating radar, with high-resolution rail centered downward digital imagery, real-time differential GPS and linear referencing technologies.

A complete list of RAIL RADAR™ services include the following with fully integrated reporting:

1. Ballast Assessment
   - Sub-Structural Layer Thickness (including undercut ballast, ballast, sub-ballast and subgrade layers to a typical maximum depth of 1.5m or 5 feet).
   - Layer Material Properties (dielectric) for all detected layers.
   - Radar Detected Anomalies (structural, moisture saturated and material property related).
   - Ballast Fouling Overlay Maps
   - Ballast Undercutting Program Prioritization

2. Tie Characterization
    - Tie Inventory
    - Fastening System Inventory
    - Defective Tie Classification
    - Defective Tie Overlay Maps
3. Track Components
    - Rail Joints Inventory
    - Switch/Frogs Inventory
    - Lubricators, Hotbox Detectors, OTM Inventory
4. Infrastructure Referencing
    - Geo-Referenced Rail Alignments and Survey Data (DGPS)
    - Linear Referenced Survey Data and Landmarks
    - Mile Post Referenced Survey Data and Landmarks
    - GIS Based Ballast Review Environment
    - GIS Based Tie Review Environment
    - GIS Based Joint Review Environment
5. Reporting
    - Output formats to allow direct integration of survey data and analyses with client rail operations/maintenance systems

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