U.S. Department of Transportation
Federal Railroad Administration

Nuclear Magnetic Resonance Trackbed Moisture Sensor System

Office of Research, Development and Technology
Washington, DC 20590

DOT/FRA/ORD-18/03

Final Report
February 2018

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 2018	Technical Report

4. TITLE AND SUBTITLE
Nuclear Magnetic Resonance Trackbed Moisture Sensor System

5. FUNDING NUMBERS
Contract Award #
DTFR5315C00013

6. AUTHOR(S)
David O. Walsh and Brian Barrett

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Vista Clara Inc.
12201 Cyrus Way, Suite 104
Mukilteo WA 98275 USA

Zetica Ltd
Units 15 and 16 Hanborough Business Park Long Hanborough, Oxfordshire
OX29 8LH
United Kingdom

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-18/03

11. SUPPLEMENTARY NOTES
COR: Hugh Thompson

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA Web site at http://www.fra.dot.gov.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

In this initial phase, conducted from March 2015 through December 2016, Vista Clara and its subcontractor Zetica Rail successfully developed and tested a man-portable, non-invasive spot-check nuclear magnetic resonance (NMR) moisture sensor that directly measured moisture on water content in railway ballast materials. All technical objectives were successfully completed, including a successful April 7, 2016, demonstration of the prototype sensor on an active railway line in Southeastern Virginia.

14. SUBJECT TERMS
Soil moisture, foul ballast, scanning technology, measurement, signal detection and sensitivity, nuclear magnetic resonance

15. NUMBER OF PAGES
47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500 *Standard Form 298 (Rev. 2-89)*

Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

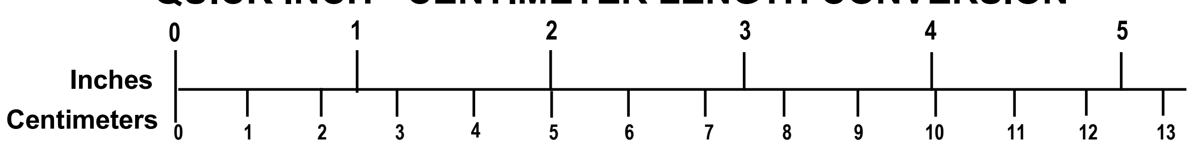
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

The authors wish to thank the FRA Program Manager, Mr. Hugh Thompson, for his encouragement and facilitation of this research. We also wish to thank CSX Transportation and ENSCO, Inc. for their assistance with the on-track NMR moisture measurements.

Contents

Illustrations

Tables

Executive Summary

In this initial phase, conducted from March 2015 through December 2016, Vista Clara and its subcontractor Zetica Rail successfully developed and tested a man-portable, non-invasive spot-check nuclear magnetic resonance (NMR) moisture sensor that directly measured moisture on water content in railway ballast materials. All technical objectives were successfully completed, including:

- Designing, assembling, and testing a new (40 in x 40 in) man-portable magnet/coil array that performs NMR measurements in railway ballast investigations.
- Integrating the new magnet/coil array with new transmit/receive and tuning electronics, off-the-shelf Javelin surface station that incorporates power supplies, an RF power amplifier, and a data acquisition system.
- Testing the integrated sensor in a shield room to demonstrate basic sensitivity to water content in four distinct depth zones ranging from 4 inches to 20 inches.
- Testing the integrated sensor in the field over test ballast materials and railway sections at Zetica test facilities in the United Kingdom.
- Successful test and demonstration of the integrated NMR sensor on an active CSX Transportation railway line in Southeastern Virginia.

The highlight of the research and development (R&D) program was the successful April 7, 2016 demonstration of the prototype sensor on an active CSX railway line in Southeastern Virginia. In a single day of on-rail testing over observed mudholes, the Trackbed Moisture Monitoring System (TMMS) sensor (referred to as TMMS sensor or NMR sensor) was demonstrated to provide clear detection and highly repeatable measurements of water content held in fouled ballast materials. Using a total scan time of 7.5 minutes, the TMMS sensor demonstrated a noise level and water detection threshold equivalent to approximately 1-2 percent volumetric water content, over the top three detection intervals (0–12.5 inches). TMMS-measured volumetric water content in the ballast materials of the problematic mudhole locations ranged between 6 and 17 percent.

These NMR-measured water content levels far exceeded the TMMS sensor detection threshold levels, and appeared reasonable given the near complete saturation of the inter-ballast pore space, which was observable at many of the mudhole locations. The deepest measurement shell was marginally useful for quantifying moisture content, with sensor noise and detection thresholds in the range of 10 percent volumetric water content. This significant loss of sensitivity in the deepest measurement shell was not unexpected and is consistent with all of our modeling and test results to date.

In addition to the planned R&D activities, Vista Clara performed additional R&D and design to improve the sensitivity and robustness of the NMR sensor in the field. This additional development included the design and testing of a simple electromagnetic shield that decreased the effective noise in the CSX measurements by a factor of 2 to 4. The company also performed follow-up modeling of a modified version of the magnet array that increased the magnet density by 50 percent and the aim of improving sensitivity at the deepest measurement zone by a factor of 2. Additional magnet beams and new frame components were manufactured to enable initial assembly and testing of the higher density magnet/coil array.

In summary, the prototype TMMS senor and NMR sensor has proven to be an tool effective tool for non-invasively and quantitatively measuring volumetric water content in fouled and un-fouled ballast materials. Improvements to the design and electronics over the course of this effort led to continual improvements in sensitivity. In our view, the prototype sensor is useful for ballast moisture detection and measurement in locations where external noise is not excessive (i.e., rural areas), and where rail sleepers are composed of wood and probably also concrete. With additional funding, including potentially commercial revenues, we expect this technology will continue to improve in performance, reliability and user operability.

1. Introduction

This report describes how a new, non-invasive, spot-check trackbed moisture sensor based on nuclear magnetic resonance was developed and demonstrated.

1.1 Background

Nuclear magnetic resonance (NMR) is a powerful non-invasive approach to physical measurement that has been widely used in medicine (medical MRI), chemistry (identification of organic and hydrogen-based substances), oil and gas development (NMR well logging), and groundwater hydrology [1]. The basis of the measurement is the detection of the weak magnetic moment that is present in the two hydrogen protons of each H2O molecule. The NMR measurement causes the magnetic moment of the hydrogen proton to precess about the ambient static magnetic field, and the resulting rotating magnetic field is detected by an induction loop. Thus, water is detected and measured directly and non-invasively, using magnets and induction coils remote from the volume of investigation [2].

Recently, Vista Clara developed a small scale (20 in x 20 in) NMR sensor called the Discus, for non-invasive measurement soil moisture content to depths of 9 inches. A larger scale (6.5 ft x 6.5 ft) version of the device had been assembled and successfully tested, which demonstrated that the Discus sensor concept can be extended and implemented in dimensions optimized for rail ballast investigations, with radio frequency (RF) power requirements similar to what can be generated by the existing battery-powered Discus NMR control unit. To optimize this technology for stationary trackbed investigations, the device was made larger without a significant increase in weight, a new magnet and coil array was optimized for between-the-rail ballast measurements, and new electronics were added to increase the number of measurement zones and improve sensitivity to expected low water content conditions. The influence of rails on the measurement was previously tested and it did not prevent the method from working.

The basic approach for this R&D program was to originally design a 3 ft x 3 ft Discus-type magnet/coil array that could measure trackbed moisture at depths up to 20 inches. Then the design would be manufactured, assembled and tested with new transmit/receive electronics and an existing NMR logging surface station. The testing would be performed at various stages of development by starting in controlled laboratory conditions, moving on to controlled field tests, and finally demonstration on an active rail line in the US.

1.2 Objectives

The objective of this research was to demonstrate the feasibility of developing a man-portable spot-check NMR sensor for detecting and measuring water content in trackbed ballast materials.

1.3 Overall Approach

This R&D program's goal was to design a 3 ft x 3 ft Discus-type magnet/coil array that could measure trackbed moisture to depths of up to 20 inches. Then the design would be manufactured, assembled, and tested with new transmit/receive electronics and an existing NMR logging surface station. Testing would be performed at various stages of development—starting in controlled laboratory conditions, moving onto controlled field tests, and finally a demonstration was performed on an active US rail line. A graphical overview of the sensor and its proposed use for measuring moisture content in trackbed ballast is shown in Figure 1 below.

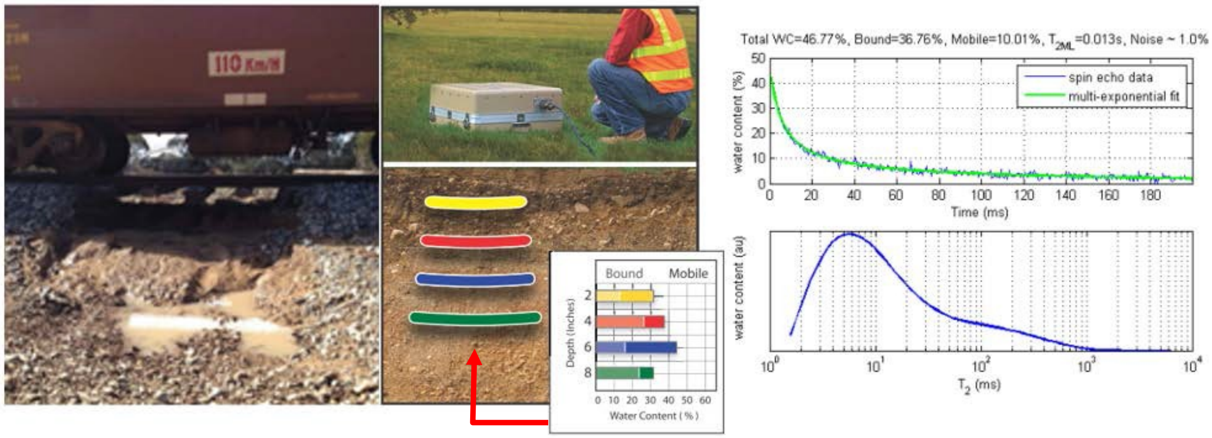


Figure 1: Fouling and excess water in ballast can affect trackbed stiffness and may directly or indirectly lead to trackbed failures (left). In addition to total water content, the NMR measurements provide information on the water-filled pore size distribution via the NMR T2 relaxation response (right).

1.4 Scope

The work focused on the design, testing, and development of a man-portable NMR-based trackbed moisture monitoring sensor.

1.5 Organization of the Report

This report summarizes, in approximately chronological order, the research that was performed and the results that the team obtained.

2. Assembly, Testing, and Results

2.1 Initial Design and Assembly of Magnet/Coil Array for 1.0m Man-portable TMMS Sensor

The design for the man-portable TMMS sensor is based on Vista Clara's patented[1] design for the Discus soil moisture sensor. This NMR sensor design arranges the array of permanent magnets in a one-sided Halbach configuration, which projects a strong static magnetic field primarily on one side of the array (the side pointing down into the ground or ballast). A concentric surface coil nominally co-located with the magnet array excites the NMR processes and the detection of water in the volume of investigation. The Halbach array and detection coil geometry result in NMR sensitive regions that are thin flat layers at different distances (depths) below the sensor array. By transmitting pulses and detecting NMR signals at different operating frequencies, individual sensitive zone layers can be selected for excitation and detection of NMR signals simply

Initially, the team used its own Matlab-based simulation software to model the sensitivity and power requirements for a 40 in x 40 in magnet/coil array with a 30-inch square detection coil. The signal-to-noise ratio (SNR), depth range and resolution, and power requirements for a range of magnets were modeled, and the team settled on an array of 9 linear magnets as a suitable compromise between sensitivity, depth of investigation, and weight.

Mechanical parts for the magnet holders and frame were designed in SolidWorks and machined in non-magnetic metal and fiberglass elsewhere. All outstanding fabricated parts were delivered in July 2015 and the magnet/coil array was assembled and fully tested in July. A photo of the assembled magnet/coil array and the first generation of electronics for transmitting, tuning, and receiving is shown in Figure 2.

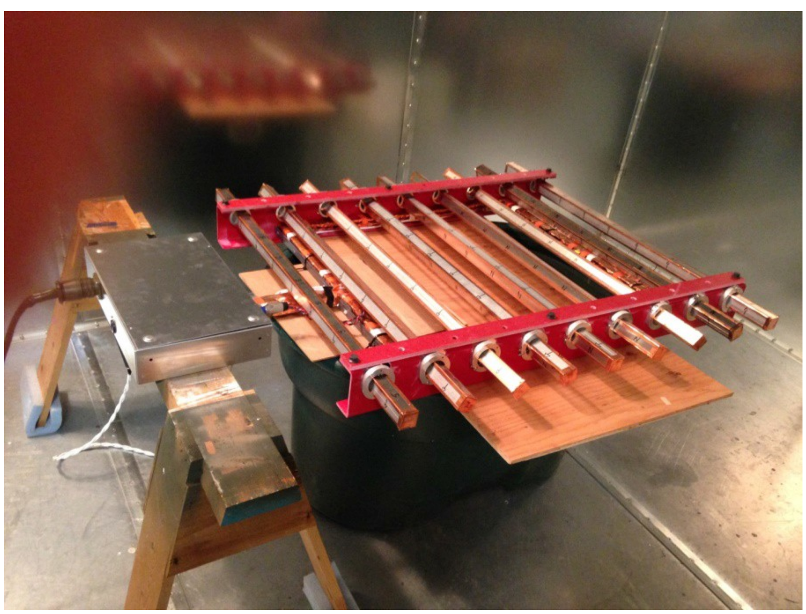


Figure 2: Assembled magnet/coil array with first generation detection electronics in shield room, performing initial detection tests over a plastic tank full of water.

Preliminary measurements were performed in a shield room to assess basic sensitivity (SNR) and

[1] US patent number: US 9429673 B2

minimum echo spacing, which is a key detection parameter especially for detection of bound water residing in fine sediments. The magnet/coil array was positioned over a 2 ft tall tank of water to provide a conservative measurement of the sensor response to 100 percent volumetric water content. The detection coil was tuned to four selected frequencies and experiments were performed to determine:

a) The required excitation pulse length for peak excitation and NMR response in the sensitive volume.

b) The peak signal to noise ratio for filtered spin echo data from 200 signal averages (200 averages can typically be performed in 10 minutes in a field setting).

c) The minimum echo spacing that can be achieved using the default electronics set up and fixed voltage supply settings.

Table 1 summarizes the initial measured sensitivity performance characteristics of the 3 ft. Discus sensor and compares to the Matlab-simulated “ideal” specifications, for a scan length of 50 averages. The minimum echo spacing of 0.4 ms and 0.5 ms were better than our design goal of 0.6 ms for this sensor. At the lowest frequency, the achieved echo spacing of 0.8 ms is close to the design goal of 0.6 ms. Overall, the initial results (obtained in a laboratory shield room) validated our software simulation models and demonstrated initial feasibility of using the newly assembled sensor electronics to detect and measure water in the depth ranges of interest and at within reasonable measurement times of 3–10 minutes.

Table 1: Shield room measurements performed after adjustment of active Q-damping electronics and control software, with comparison to Matlab-simulated sensitivity and measurement performance specifications, using 150A power supply.

Resonant Freq.	Meas. Depth	Peak SNR for 50 avg @ 100% water content (measured at minimum echo spacing)	Peak SNR for 50 avg @ 100% water content (modeled)	Optimal Excitation Pulse Length (measured)	Optimal Excitation Pulse Length (modeled)	Minimum Echo Spacing (measured)	DC Current draw at minimum echo spacing
77 kHz	20 in	4.4	13	130 µs	100 µs	2.0 ms	26 A
157 kHz	12.5 in	11.5	37	100 µs	30 µs	0.8 ms	71 A
242 kHz	7.5 in	34.0	75	50 µs	30 µs	0.4 ms	82 A
327 kHz	4.3 in	79.5	130	80 µs	30 µs	0.5 ms	87 A

2.2 TMMS Sensor Tests at Zetica Facilities in the UK, November, 2015

In November 2015, Vista Clara and Zetica tested the man-portable TMMS sensor at Zetica’s rail test facilities in England. The tests were supervised by a Zetica Technical Manager. The temperature was approximately 40°F with intermittent rain for the entire week of testing. The testing was largely successful. Most of the planned tests were completed including:

- Sensor test over native soils
- Clean ballast test in controlled dry and wet states
- Fouled ballast test in controlled dry and wet states
- Dry test track tests including wooden, concrete and steel sleepers

The only significant test that was not completed was testing over the test track after wetting with water. This test was not performed due to a TMMS electronics failure that occurred at the start of the last day of testing. It is possible that the failure was associated with condensation due to cold, rainy weather during the week of the tests.

The tests at Zetica facilities largely demonstrated the commercial and technical feasibility of a man-portable NMR ballast moisture sensor. The sensitivity of the sensor was very good for the upper three measurement zones (depths of 10 in or less), with most tests showing the sensor capable of detecting and accurately measuring volumetric water content down to levels of 2 percent or less, with a scan time of 8 minutes. The sensitivity of the fourth and deepest measurement zone (~ 18 in) was determined to be inadequate for the signal and noise conditions encountered at the test site. This result was not a surprise and was consistent with all of our sensor modeling and laboratory measurements to date.

The tests at Zetica facilities also showed that the TMMS sensor can be susceptible to various forms of radiofrequency interference (RFI), and at this site in particular AM broadcast stations at 198 kHz and 162 kHz were found to be a problem. We were able to avoid these two RFI sources by re-tuning the coil manually. It is recommended that additional efforts be made to reduce the susceptibility of the TMMS sensor to noise, and to generally improve the robustness of the electronics and packaging, prior to the next round of field tests.

2.2.1 TMMS Sensor Assembly and Initial Testing at Zetica Facilities

The TMMS sensor was assembled in the morning on November 3, 2015, and transported to the Zetica test facility at around noon. Preliminary tests were performed with the TMMS sensor on the ground to establish its proper operation and its compatibility with the two available generators. Initially, two noise sources were identified:

> *Source 1*: A burst-type wideband noise source was observed on all detection frequencies. It was determined that the standard Javelin processing software option with "impulse noise removal" was able to mitigate this noise source effectively.
>
> *Source 2:* We observed a very large narrowband noise source at 162 kHz, which was directly in the frequency band of the 3rd frequency shell. Out of an abundance of caution, we elected to rent a 6.5 kW gasoline generator, which we were sure would not be generating any conducted or radiate noise. Even after switching to the gasoline generator, the large noise band centered at 162 kHz persisted. In the end, we finally determined that the noise source was a French AM broadcast station centered at 162 kHz, and we also identified a similar high power BBC AM broadcast station at 198 kHz in the UK.
>
> On the morning of November 4, 2015, we retuned the TMMS sensor (by adjusting the hardwired tuning capacitance) so that the third detection frequency was at 168.5 kHz, and sufficiently removed from the 162 kHz interference to enable NMR detection.

Also, we increased the lowest frequency from 77 kHz to 87 kHz to avoid another interference source. Tests were performed on grass-covered soil and established noise levels equivalent to 1 percent to 3 percent water content for the top 3 measurement shells for 120 averages. The fourth (deepest) measurement shell exhibited much higher noise at the equivalent of approximately 12 percent water content for the same measurement time. We later determined that the calibration for the 4th measurement shell was high by a factor of approximately 2. Thus all reported measured water contents and noise levels for the 4^{th} shell are reported here with a 0.5 correction factor applied.

2.2.2 Tests of the TMMS Sensor on Grass and Native Soil

Following the retuning of the sensor, and final checks on system performance, we performed the following field tests with the sensor positioned on a grassy area as summarized in order in Table 2 below. A photo of the TMMS sensor performing measurements over native soil is shown in Figure 3 below.

Table 2: Summary of TMMS tests performed on grass covered soil, November 4, 2015. The term "Tr" is the repetition period of the NMR measurements.

Test Description	Scan Sequence	Measurement Time	Notes
Grass/soil (1)	Tr = 4s/120avg, Tr =1s/480avg	16.8 min.	Soil water contents 12% - 26 %
Grass/soil (2)	Tr = 4s/120avg, Tr =1s/480avg	16.8 min.	Soil water contents 12% - 27 %
Grass/soil (3)	Tr = 4s/120avg, Tr =1s/480avg	16.8 min.	Soil water contents 13% - 30 %
Grass/soil (4)	Tr = 2.4s/120avg, Tr =0.8s/480avg	11.2 min.	Soil water contents 15% - 31 %
Grass/soil with rails approximately 9 inches from each	Tr = 2.4s/120avg, Tr =0.8s/480avg	11.2 min.	Soil water contents 11% - 25 %
Grass/soil with rails approximately 9 inches from each	Tr = 4s/120avg, Tr =1s/480avg	16.8 min.	Soil water contents 12% - 28 %

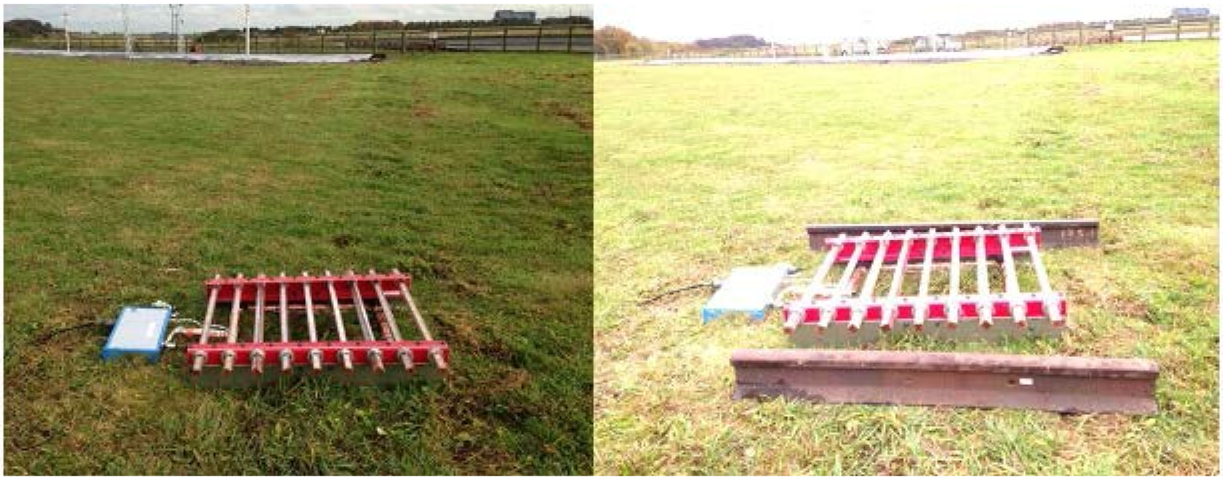


Figure 3: TMMS sensor testing over native soil, with and without rails on each side.

First, data were processed using the full dual wait time measurement and then the data were processed with only the short wait time measurement. It was determined that the longitudinal T1 relaxation rates of the NMR signals in the native soil were short enough that the long wait time data were not required for accurate water content estimation. Figure 4 below shows one data set processed with dual wait time and one with the short wait time only, for comparison.

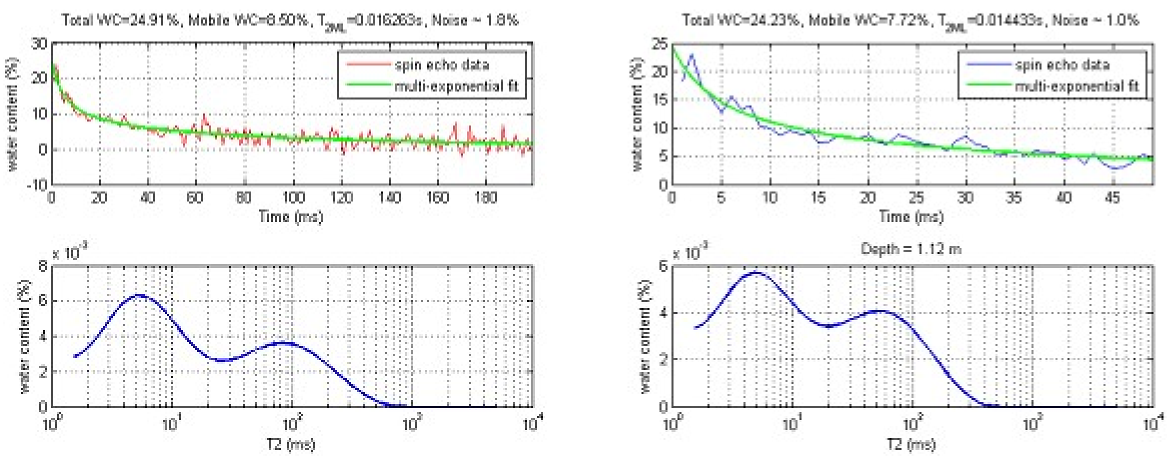


Figure 4: NMR measurement over native soil. Left: uppermost sensitive zone with full (dual-wait time) data set, measurement time = 16.8 minutes. Right: uppermost sensitive zone with short wait time data only, measurement time = 8 minutes.

The time domain plots of data from the first of three identical soil measurements are shown in Figure 5. These curves indicate high SNR for all measurement zones except the fourth (deepest) measurement zone. The data quality in the fourth measurement zone is degraded by a) the higher noise level relative to the NMR signal from water, and b) the 3x longer echo spacing (3 ms compared to 1 ms for the other three measurement zones). The relatively low SNR is consistent with all of our computer simulations and measurements to date. The longer echo spacing is a common difficulty when trying to achieve short measurement dead time with high-Q tuned induction coils at lower frequencies. The reduced sensitivity and performance at the deepest measurement zone is one of the two major limitations of the TMMS—as it was designed and implemented at the time of the Zetica field tests.

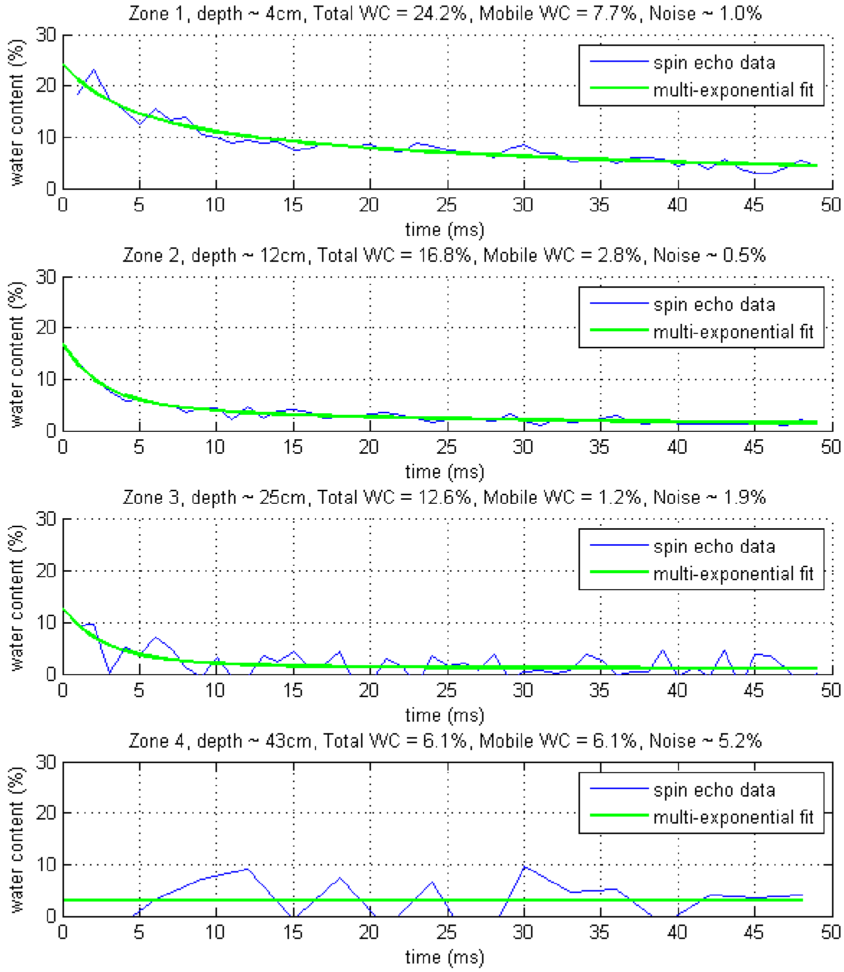


Figure 5: Soil NMR measurements taken without rails present at approximate measurement depths of 1.6 in, 4.7 in, 10 in, and 17 inches. Total measurement time is 8 minutes.

We performed three consecutive NMR measurements over the native soil in order to generate statistics on estimated water content variance due to noise. These statistics, shown in Table 3, indicate a high level of repeatability for total water content measured in the top three measurement zones.

Table 3: TMMS total water content estimation statistics from three consecutive scans over the same native grass and soil.

Depth Zone	Scan 1 (total water content)	Scan 2 (total water content)	Scan 3 (total water content)	Mean (total water content)	Std. Dev. (total water content)
1 (1.6 in)	25.7 %	27.0 %	30.2 %	27.6 %	2.3 %
2 (4.7 in)	16.7 %	15.8 %	16.9 %	16.5 %	0.6 %
3 (10 in)	12.4 %	14.7 %	12.8 %	13.3 %	1.2 %
4 (17 in)	2.3 %	6.0 %	8.9 %	5.7 %	3.3 %

Next we performed measurements with and without steel rails placed on either side of the sensor. These results, summarized in Table 4, indicate that the presence of the steel rails does not cause a significant bias in the estimated water content at any of the depths, but the presence of the two rails may increase the noise level in the sensor. Presumably any such noise amplification would be due to concentration of RF noise fields in the vicinity of the detection coil. It is also possible that the noise increased for some unknown other reason.

Table 4: Comparison of TMMS total water content estimates over native soil, with and without steel rails placed on each side of the sensor.

Depth Zone	Mean total water content (no rails)	Total water content (with rails)	Root Mean Square Noise Level (no rails)	Root Mean Square Noise Level (with rails)
1 (1.6 in)	27.6 %	27.6 %	1.4 %	4.2 %
2 (4.7 in)	16.5 %	13.9 %	1.2 %	2.1 %
3 (10 in)	13.3 %	14.4 %	3.5 %	7.8 %
4 (17 in)	5.7 %	5.8 %	11.0%	30.0 %

Finally, a soil core sample was collected at the center of the TMMS measurement location. The core sample, shown in Figure 6, was visibly wetter and appeared to have high clay content near the surface, and became visibly drier and containing less clay and more rock fragments towards the bottom of the sample. The core sample was divided into sections and sent to a local laboratory for grain size and water content analysis. Preliminary results from the laboratory analysis are in general relative agreement with the TMMS NMR-measured water contents, although the gravimetric analysis reports somewhat higher water content across all depths, as shown in Table 5.

Figure 6: Soil core sample extracted at the center of the TMMS soil measurement location.

Table 5: Comparison of TMMS NMR measured water contents and laboratory gravimetric water content measurements from extracted core sample.

Approximate Depth Zone	TMMS total water content (no rails)	Core sample approximate depth range	Laboratory TWC from core sample
1 (1.6 in)	27.6 %	0 – 5 in	40 %
2 (4.7 in)	16.5 %	5 – 10 in	27 %
3 (10 in)	13.3 %	10 – 15 in	25 %
4 (17 in)	5.7 %	15 – 20 in	15 %

2.2.3 Tests of the TMMS Sensor Over Engineered Ballast Boxes

We performed measurements with the TMMS sensor over two large ballast boxes, one containing clean ballast material and the other containing a mixture of clean ballast and mixed grain size fouling material. Each ballast box is approximately 20 in deep and is lined by cinder blocks. Figure 7 shows the TMMS sensor positioned on top of the "fouled ballast box." The particle size distribution for the fouled ballast box is shown in Figure 8.

Figure 7: Foreground: TMMS sensor taking a measurement on the "fouled" ballast box. The "clean" ballast box is visible directly behind the fouled ballast box.

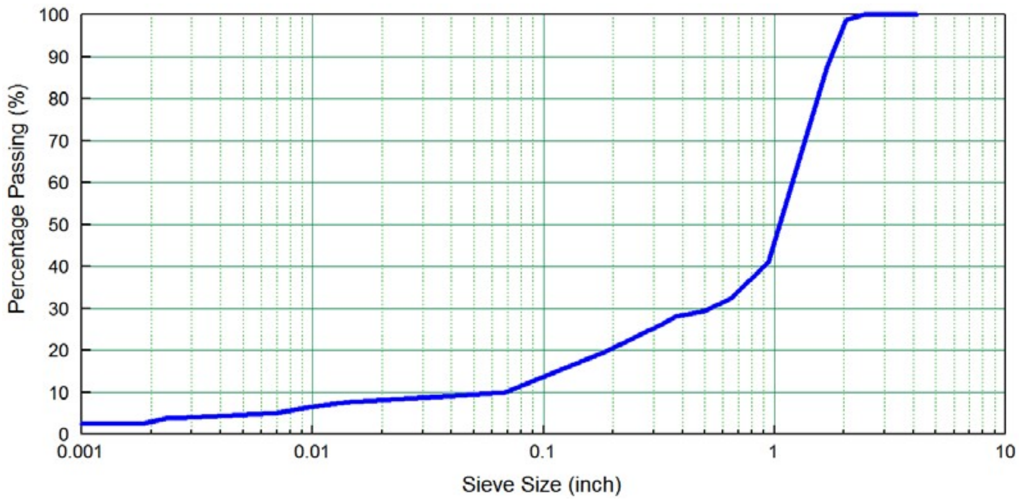


Figure 8: Particle size distribution of the "fouled" ballast box.

We first performed TMMS measurements with the ballast boxes in their "dry" condition. Both ballast boxes are housed in a tent, and the ballast boxes had been drained and allowed to "air dry" for approximately weeks prior to our testing. TMMS measured water contents for a single measurement over the dry "clean" ballast box are shown in Table 6. TMMS measured water contents and statistics for three consecutive measurements over the dry "fouled" ballast box are shown in Table 7. These measurements over ballast in the dry condition indicate that the NMR estimated water content is on the order of, or below, the noise level in the stacked spin echo data. Visual analysis of the NMR measurements in the clean ballast box in the top two depth levels indicated the presence of NMR signals from water on the order of 1 percent to 2 percent volumetric content. Variations in detected water content between scans 1, 2 and 3 are due to the effect of random measurement noise and are on the order of the mean RMS measurement noise.

Table 6: TMMS total water content estimates from a single scan over the dry clean ballast box.

Depth Zone	Total Water Content	Root Mean Square Noise
1 (1.6 in)	1.3 %	0.4 %
2 (4.7 in)	1.8 %	1.7 %
3 (10 in)	0.5 %	1.3 %
4 (17 in)	3.2 %	5.4 %

Table 7: TMMS total water content estimation statistics from three consecutive scans over the dry fouled ballast box.

Depth Zone	Scan 1 (TWC)	Scan 2 (TWC)	Scan 3 (TWC)	Mean (TWC)	Std. Dev. (TWC)	Mean Root Mean Square Noise
1 (1.6 in)	0.7 %	0.5 %	0.9 %	0.7 %	0.2 %	0.7 %
2 (4.7 in)	0.4 %	1.8 %	2.1 %	1.4 %	0.9 %	0.7 %
3 (10 in)	0.1 %	0.2 %	0.5 %	0.3 %	0.2 %	1.6 %
4 (17 in)	11.3 %	5.1 %	1.5 %	6.0 %	5.0 %	8.1 %

Next the clean ballast box was filled completely with water, and TMMS measurements were made over time as the ballast box was slowly drained. The purpose of this test was to demonstrate both accurate volumetric water content and also demonstrate the depth sensitivity responses of the four different detection volumes.

Figure 9 shows the measured spin echo signals and fitted NMR response curves for all four shells with the water table at the surface (ballast box full of water). The noise level for the shell four measurement is on the same order as the measured volumetric water content, which renders this measurement shell unreliable for the data acquired at these tests.

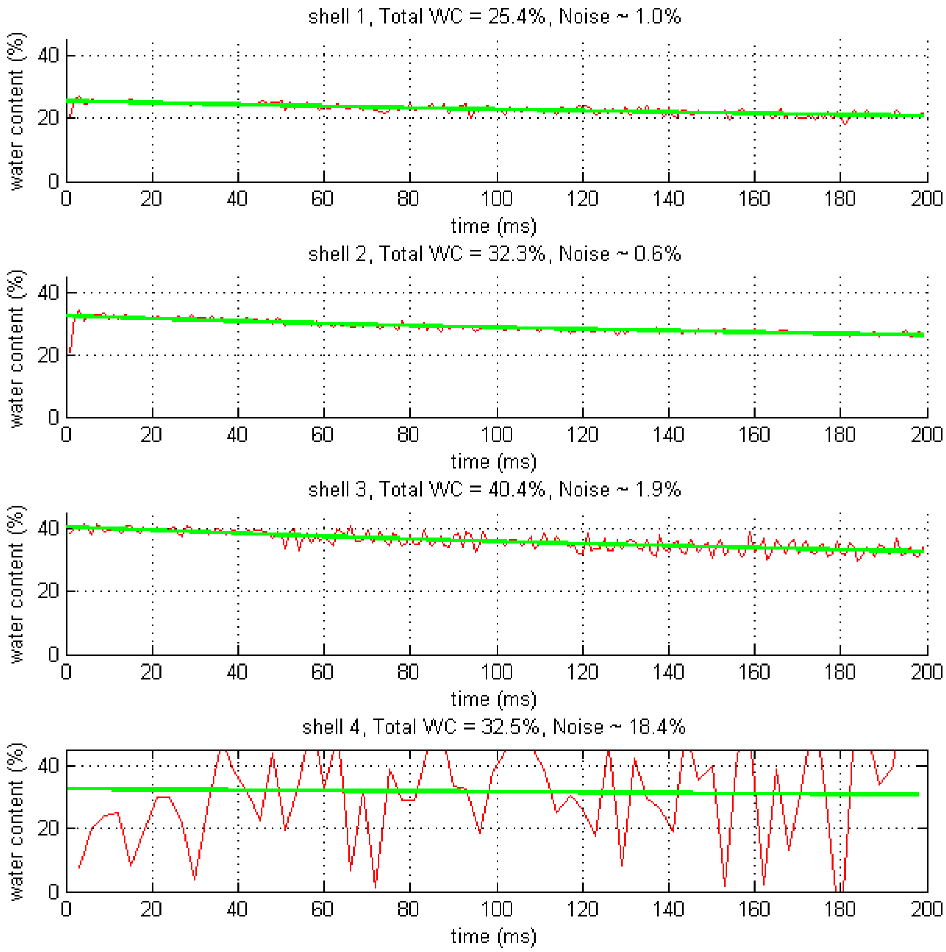


Figure 9: TMMS measured NMR signals for all four shells with the clean ballast box fully saturated with water.

The detected water content as a function of water table depth and detection shell is shown in Figure 10. This image shows that all four shells detected between 30 percent and 35 percent water content while the water table was at the top of the ballast box, which is an expected porosity value for clean ballast materials. With the water table at 4 inches below surface, the first shell detected almost no water content, indicating that its sensitive volume is almost entirely within the top 4 inches. The second shell indicates a drop in sensitivity between 0 and 4 inches, and essentially no sensitivity below 8 inches. The third shell shows no drop in sensitivity between 0 and 4 inches, and most of its sensitivity (largest drop in detected water content) was between 4 inches and 8 inches. The fourth shell shows some sensitivity between 0 and 12 inches, and displays most of its sensitivity between 12 inches and 20 inches.

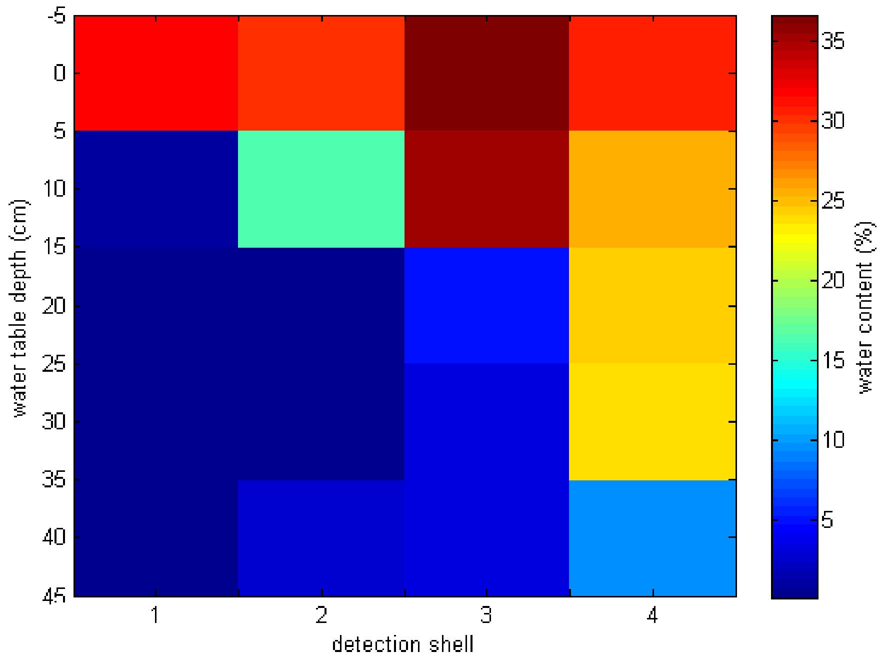


Figure 10: 2D map of water content detected by each of four detection shells, with the water table in the clean ballast box at different depths from the surface.

Finally, the fouled ballast box was wetted with a large amount of water, which was allowed to drain naturally. Then, just prior to the final TMMS measurement, it was wetted again and allowed to drain. The TMMS sensor was positioned upon the wetted fouled ballast box and a final measurement was performed. The measured NMR signals at the four depth zones are shown in Figure 11. The NMR signals are clearly visible as exponential decay signals in the top three measurement zones, while the NMR signals in the fourth zone are obscured by the much higher noise level for this measurement zone. The transverse T2 relaxation rates are relatively long and range from 30ms to 200ms. This indicates that the NMR-detected water is being held in relatively large pore sizes or on surfaces, due to surface tension or geometric/gravimetric water holding mechanisms.

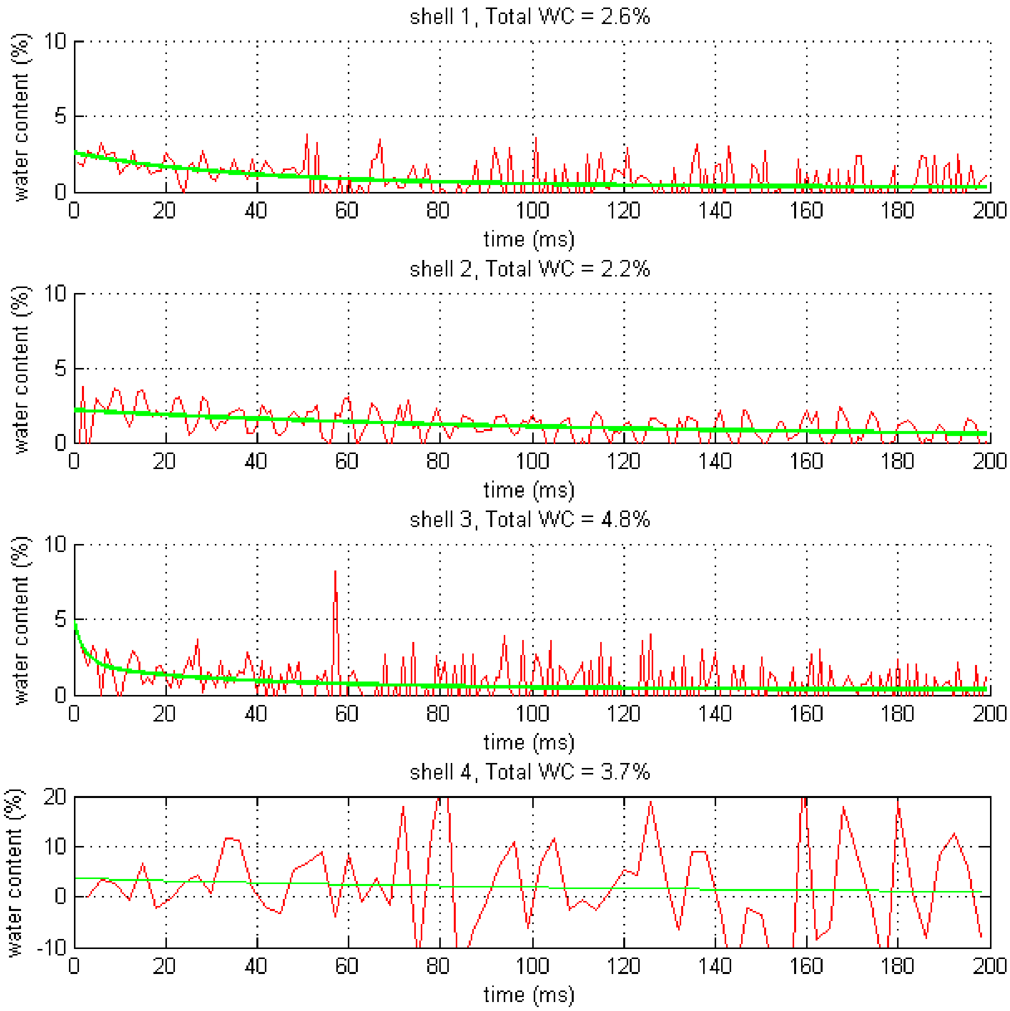


Figure 11: NMR signals with TMMS placed on wetted fouled ballast box.

Table 8 compares the TMMS-detected water contents, at all four depth levels, between the dry fouled ballast and wetted fouled ballast. These results indicate detection of a significant increase in water content in the fouled ballast as a result of the wetting event. It is noted that even in this wetted condition, the TMMS sensor still measures relatively low volumetric water content (between 2 percent and 5 percent) in this sample of fouled ballast material. This low level of water content is clearly detectable and above the ambient noise in the first three measurement zones.

Table 8: Comparison of TMMS-measured water content in fouled ballast box in dry and wetted conditions.

Depth Zone	Dry Fouled Ballast (TWC)	ed Fouled Ballast (TWC)
1 (1.6 in)	0.7 %	2.6 %
2 (4.7 in)	1.4 %	2.2 %
3 (10 in)	0.3 %	4.8 %
4 (17 in)	6.0 %	3.7 %

2.2.4 Tests of the TMMS Sensor on the Zetica Test Track

TMMS measurements were performed over various portions of the Zetica test track in its dry condition. The track had been covered by plastic sheets for approximately three weeks prior to and during our testing. We had planned to perform follow up measurements with the test track in a wetted state on the final day of testing. Unfortunately, we suffered an electronics failure in the receive electronics on the morning of the final day, and the Vista Clara PI was unable to repair the malfunctioning electronics on site.

The data from the test track are summarized as follows:

- Almost all measurements, in all depth shells and all track locations, yielded very small water content estimates—generally at or below the sensor noise level.
- The measurements over the wooden sleepers indicated detection of some water content in the wood itself.
- Noise in the top three levels varied over time, with most measurements showing nominally good noise levels on the order of 1 percent, but with some noise levels in the range of 2 percent–5 percent.
- The fourth measurement shell exhibited noise levels between 10 percent and 20 percent, which rendered it useless for low moisture content measurements.
- Measurements on top of concrete sleepers exhibited no significant differences compared to measurements over wooden sleepers: similar noise, very low measured water contents, very little shift in coil tuning frequency and Q-factor, and no particular transients or data artifacts.
- Measurements over the steel sleepers exhibited significant shifts in the coil tuning frequency (up to 15 kHz) and large increases in noise for the two upper measurement shells.

2.2.5 Summary of the TMMS Sensor Test Results at Zetica Facilities

1. The TMMS sensor provided adequate sensitivity and performance in the top three measurement zones and detected very low water content (2 percent–5 percent) in fouled ballast materials.
2. The fourth measurement shell, which corresponded to the deepest zone of investigation, was not sensitive enough to low water content in fouled ballast materials. In fact, we estimate that we will need to get a factor of 4 to 6 times the improvement in sensitivity in the fourth shell to make it useful in environments such as the Zetica test facility.
3. Since the TMMS operates in the low RF band, as is common in most low-field NMR

sensors, it is sensitive to radio frequency interference (RFI) in that range. During the team's tests at the Zetica test facility, the system was manually tuned at the site to avoid certain radio broadcast frequencies. The system in general will benefit from improved design measures aimed at reducing its sensitivity to external radiated noise sources, and also to assist in cancelling such noise sources in recorded data.

2.3 TMMS Sensor Improvements from January to April, 2016

Based upon the results of the Zetica field tests, significant improvements were made to the TMMS sensor to improve performance, boost noise resistance, and increase the robustness of its packaging. Prior TMMS tests indicated a source of ringing that interfered with detection of low- water content signals at some measurement frequencies. The magnet array was reassembled using improved electromagnetic shielding, which effectively suppressed the ringing artifact and enabled a successful test. Not only did the improvement boost signal integrity, it enabled the magnet array to be lowered 2 inches closer to the coil and improved the sensor's sensitivity, especially at the larger investigation depths.

The TMMS sensor was also outfitted with newly designed and assembled sensor electronics, as well as robust weather-resistant packaging. The new sensor electronics include quick-disconnect cable connectors that enable the low-profile on-track sensor to be quickly and safely disengaged from the rest of the off-track cables and electronics. We also assembled and tested a simple EM noise shield to reduce the TMMS sensors' susceptibility to RFI. The shield had only a small effect on the sensor's sensitivity to water (this effect can be calibrated) and a high level of RFI suppression was demonstrated when tested inside the noisy laboratory.

2.3.1 Improved Electromagnetic Shielding

Prior tests of the TMMS system indicated a low-level ringing artifact on some of the test data. Initially, this was mitigated by raising the magnets 3 inches above the detection coil. During the interim period (January–March 2016), we definitively identified that the ringing artifacts were the result of insufficient electromagnetic shielding. This deficiency was corrected by re-designing the magnet array holders and repackaging them. This design change eliminated the ringing artifacts from the observed data and enabled us to reduce the height of the magnets by 2 inches. Table 9 lists the final calibration frequencies, approximate depths of investigation, and relative noise levels for 50 averages. For field measurements, we typically perform 400 averages for each measurement (–10 minutes per measurement), so post-averaging noise levels could be lower in the field than listed in Table 9, depending on noise conditions in the field.

Table 9: The newly calibrated operating frequencies, nominal measurement depths and echo spacing for the TMMS sensor for on-rail testing in the US, April 2016.

Frequency (kHz)	Nominal measurement depth (in)	Default echo spacing (ms)	Noise level for 50 averages (% Water Content)
320	3	1	0.8
235	6	1	1.0
170	11	1	2.8
106	18	1.5	12.4

2.3.2 Improved Sensor Electronics and Packaging

Figure 12 shows the improved sensor electronics and packaging as of April 2016. The new electronics and packaging made the TMMS system more robust for field testing and will facilitate near-term commercialization of this technology.

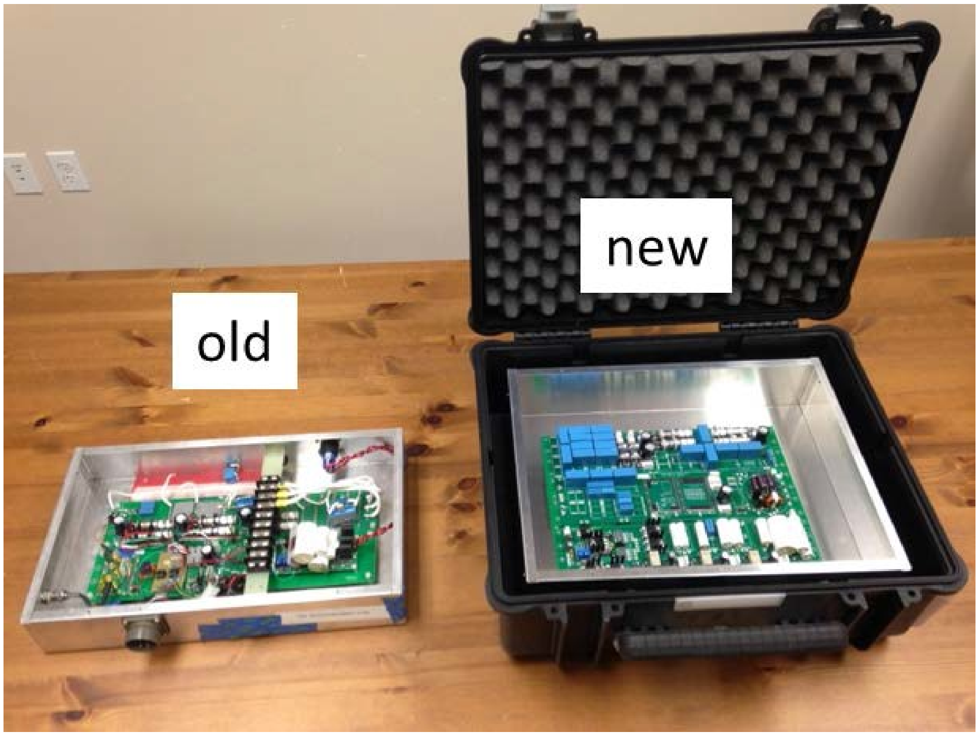


Figure 12: Comparison of first generation and second generation TMMS sensor electronics and packaging.

2.3.3 Computer Simulation of the Effect of Increased Magnet Density

New computer simulations were performed to predict the performance gains from increasing the sensor magnet density by 50 percent. These computer simulation results, shown in Table 10, indicate that increasing the magnet density would boost the peak signal-to-noise (PSNR) for the deepest sensitive zone by a factor of approximately 2, which is equivalent to increasing the signal averaging time by a factor of 4. The mechanical changes to this would be small, and the weight of the man-portable device would be increased by approximately 30 pounds. Given the expected improvement in sensitivity for the deepest measurement shell, this minor design modification should be considered for the man-portable device and would certainly be appropriate for any variant of the sensor that is mounted on a high-rail service vehicle.

Table 10: Comparison of 9-magnet and 13-magnet TMMS sensor performance.

Nominal measurement depth (in)	9-magnet array frequency (kHz)	9-magnet array PSNR	13-magnet array frequency (kHz)	13-magnet array PSNR
5	480	83	640	104
9	280	33	360	45
14	120	9.3	180	15.5
18	70	4.3	100	7.0

2.4 TMMS Sensor Tests in Virginia (April 2016)

2.4.1 Mobilization and Assembly

The TMMS sensor was disassembled and shipped by ground freight to a local assembly location in Northern Virginia, then it was assembled and tested locally in Northern Virginia (Figure 13). The system was transported to Richmond for on-track tests in a rented van. In Figure 13, note the copper mesh screen covering the TMMS sensor on the right. This copper screen generally reduced the noise level of measurements by a factor of 2 to 4 in field measurements in Virginia and appeared to be a very useful and inexpensive addition to the TMMS sensor design.

Figure 13: TMMS Sensor under assembly and testing at shipping location in Northern VA on April 6, 2016.

2.4.2 CSX Rail Line and Observed Ballast Conditions

On-rail tests were performed at a section of active CSX railway line between Richmond and Norfolk, VA, on April 7, 2016. The Federal Railroad Administration's (FRA) personnel selected test locations based upon track geometry and other measurements made previously that week.

The test locations were in rural, mostly forested areas, with some residential homes in the vicinity. There were few overhead powerlines nearby and no visible telemetry or power lines between or alongside the tracks. These conditions were very favorable in terms of noise and a newly added copper RFI screen was used, so the measured noise levels in the first three depth shells were only slightly above shield room noise measurement levels.

The selected test locations included three sections of track with one or more visible mudholes in the ballast. In some cases, the mudholes contained standing water and mud between sleepers. An Amtrak passenger train drove across a set these of mudholes at high speed, while test crew watched and filmed the noticeable track deflection. Figure 14 contains close-up photos of mudholes, and Figure 15 shows a photo of the TMMS sensor in between the rails during one measurement. The water content in the fouled ballast may have been temporarily increased by heavy rain from the previous night and this may have affected these particular measurements.

Figure 14: Close-up photos of some of the mudholes over which TMMS measurements were performed.

Figure 15: TMMS sensor on CSX rail line, April 7, 2016.

2.4.3 Summary of TMMS Measurements on CSX Rail Line

A total of fourteen TMMS spot check measurements were performed over three sections of the CSX rail line, at locations designated as:

- Milepost 67 (field notes indicate this is near milepost 67.53)
- Milepost 68.3 (field notes indicate this is near milepost 68.35)
- Milepost 68.7

Table 11 summarizes the test locations and measurements. Vista Clara did not identify the locations of the TMMS measurements by collecting GPS or any other geolocation measurements. Such information may be available from the ENSCO or FRA representatives who participated in the tests and demonstrations.

Table 11: Locations and brief descriptions of TMMS measurements on April 7, 2016.

Measurement Location/Name	Description and Notes
Milepost 67 Off Track	Measurement on gravel access road adjacent to rail line
Milepost 67 Mudspot 1	Located in center between Mudspot 2 and Mudspot 3
Milepost 67 Mudspot 2	Located West of Mudspot 1
Milepost 67 Mudspot 3 (scan1)	Located East of Mudspot 1 (1st of 3 measurements)
Milepost 67 Mudspot 3 (scan2)	Located East of Mudspot 1 (2nd of 3 measurements)
Milepost 67 Mudspot 3 (scan3)	Located East of Mudspot 1 (3rd of 3 measurements)
Milepost 68.3 Mudspot (center)	TMMS positioned over mudspot in center of track

Milepost 68.3 Mudspot (North)	TMMS positioned over mudspot on North shoulder of track
Milepost 68.3 Mudspot (South)	TMMS positioned over mudspot on South shoulder of track
Milepost 68.3 Mudspot (long T1)	TMMS positioned over mudspot in center of track-long T1 NMR measurement to determine if short T1 sequence was sufficient to estimate all water content
Milepost 68.3 100ft East	TMMS positioned 100 ft East of mudspot in center of track
Milepost 68.7 Mudspot 1 (scan 1)	TMMS positioned over mudspot in center of track (1st of 2 measurements)
Milepost 68.7 Mudspot 1 (scan 2)	TMMS positioned over mudspot in center of track (2nd of 2 measurements)
Milepost 68.7 Mudspot 2	TMMS positioned over mudspot in center of track, location ~ 50ft West of Mudspot1

2.4.3.1 Milepost 67 Off Track

This measurement was performed with the sensor on the gravel access road to the side of the rail line as shown in Figure 16. The measured water contents and noise levels are listed in Table 12, and these indicate relatively low volumetric water content (3 percent–5 percent) held in small pores. All water with NMR measured T2 relaxation rate of less than 33 ms was classified as bound water, and all water with NMR measured T2 relaxation rate of greater than or equal to 33 ms was classified as mobile.

Figure 16: TMMS sensor in approximate location of test conducted on gravel access road on side of rail line.

Table 12: TMMS-measured water content at test location on gravel road off the side of the tracks.

Depth Shell	Total Water Content	Mobile Water Content	Bound Water Content	T2 Mean Log	Noise
0-5"	4.2%	0.7%	3.5%	10ms	0.6%
5-10"	5.4%	0.6%	4.8%	8ms	1.0%
10-15"	3.3%	1.5%	1.8%	31ms	2.2%
15-20"	10.2%	2.4%	7.8%	17ms	6.4%

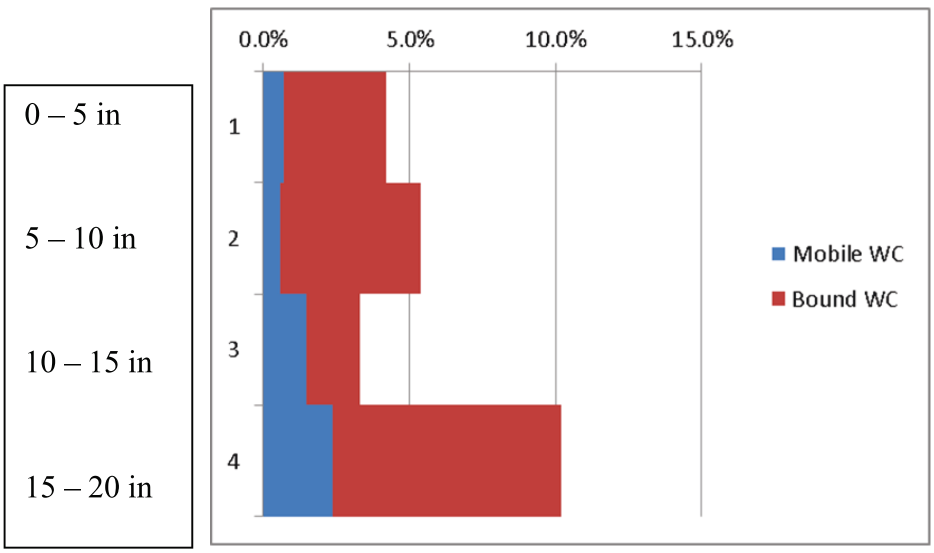


Figure 17: Milepost 67 off track, map of NMR measured water content vs. depth zone.

2.4.3.2 Milepost 67 Mudspot 1

The TMMS measurement at this location, shown in Figure 18, indicated between 11 percent and 17 percent water content through the top 15 inches of the ballast.

Figure 18: Photo of measurement location for Milepost 67 Mudspot 1.

Table 13: TMMS-measured water content at Milepost 67 Mudspot 1.

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	14.4%	3.4%	11.0%	8 ms	0.7%
5-10"	16.9%	7.4%	9.5%	22 ms	1.0%
10-15"	11.2%	2.9%	8.3%	8 ms	2.1%
15-20"	32.4%	0.0%	32.4%	5 ms	12.5%

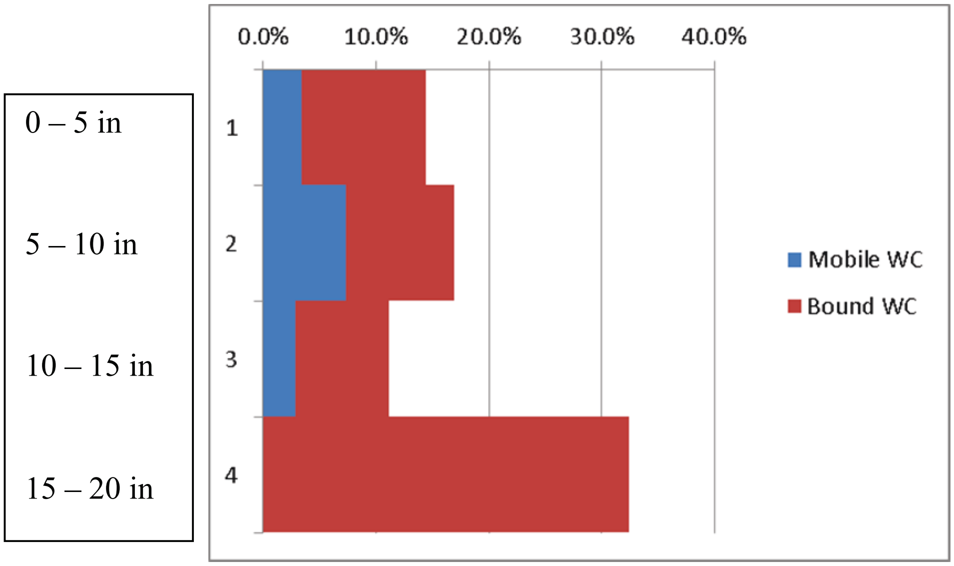


Figure 19: Milepost 67 Mudspot1, map of NMR-detected water content vs. depth.

2.4.3.3 Milepost 67 Mudspot 2

TMMS measured water contents for Milepost 67 Mudspot 2 are listed in Table 14.

Table 14: TMMS-measured water content at Milepost 67 Mudspot2.

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	8.8%	0.9%	7.9%	11 ms	0.4%
5-10"	12.2%	2.6%	9.6%	20 ms	0.8%
10-15"	19.3%	3.1%	16.2%	6 ms	1.9%
15-20"	2.5%	2.5%	0.0%	3102 ms	9.0%

2.4.3.4 Milepost 67 Mudspot 3

We performed three independent TMMS measurements at Milepost 67 Mudspot 3 (shown in Figure 20) to quantify the variance in TMMS-measured water content in the four different depth zones. The sensor was not moved between each of the measurements, so the only expected sources of measurement variance are sensor noise and ambient electromagnetic interference noise. The calculated variance statistics compiled in Table 18 indicate that the standard deviation of the TMMS water content measurement is less than 1 percent in the upper two zone, less than 2 percent in the third depth zone and around 10 percent in the deepest measurement zone.

Figure 20: Photo of measurement location for Milepost 67 Mudspot 3.

Table 15: TMMS-measured water content at Milepost 67 Mudspot 3 (Scan 1 of 3).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	14.4%	2.5%	11.9%	13 ms	0.4%
5-10"	17.2%	2.9%	14.3%	10 ms	0.8%
10-15"	8.1%	0.5%	7.6%	13 ms	2.5%
15-20"	19.5%	2.6%	16.9%	8 ms	9.5%

Table 16: TMMS-measured water content at Milepost 67 Mudspot 3 (Scan 2 of 3).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	15.3%	2.6%	12.7%	11 ms	0.5%
5-10"	17.3%	3.5%	13.8%	10 ms	0.9%
10-15"	12.6%	1.6%	11.0%	7 ms	1.9%
15-20"	27.8%	1.9%	25.9%	5 ms	13.1%

Table 17: TMMS-measured water content at Milepost 67 Mudspot 3 (Scan 3 of 3).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	16.0%	2.8%	13.2%	8 ms	0.5%
5-10"	16.4%	3.3%	13.1%	11 ms	0.8%
10-15"	10.4%	1.2%	9.2%	10 ms	1.8%
15-20"	5.3%	2.0%	3.3%	31 ms	9.2%

Table 18: Statistics of TMMS-measured water contents at Milepost 67 Mudspot 3.

Depth Shell	Mean (Total water content)	Std. Dev (Total water content)
0-5"	15.2%	0.7%
5-10"	17.0%	0.4%
10-15"	10.4%	1.8%
15-20"	17.5%	9.3%

2.4.3.5 Milepost 68.3

At Milepost 68.3, the team performed three measurements over an obvious mudspot: one in the center of the track and one on each side of the track as shown in Figure 21. The NMR measurements indicated that the water content in fouled ballast was concentrated in the center of the track. One additional measurement was performed over this mudspot, using a different pulse sequence with a longer wait time between measurements, and no significant difference was found in the measured water content.

Finally, we performed one measurement on the track 100 feet east of the mudspot, where there was no clear visual indication of ballast fouling, and at this third location the TMMS measurement indicated high water content between depths of 5 to 15 inches, but a reduced water content within in the top 5 inches. This is consistent with the fact that there was no surface indication of a mudspot, and likely indicates that the lateral extent of the mudspot is significantly greater than the extent of its surface expression. This highlights the special role that a TMMS could have when deployed to target incipient mudspots identified by ground penetrating radar.

Figure 21: Milepost 68.3, close-up of mud-fouled ballast and photos of three measurement locations.

Table 19: TMMS-measured water content at Milepost 68.3 mudspot (center of track).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	13.9%	5.1%	8.8%	13ms	0.5%
5-10"	15.4%	4.8%	10.6%	18ms	0.7%
10-15"	9.9%	5.3%	4.6%	36ms	2.9%
15-20"	4.6%	4.5%	0.1%	8ms	14.7%

Table 20: TMMS-measured water content at Milepost 68.3 mudspot (north shoulder of track).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	4.1%	1.3%	2.8%	15ms	0.6%
5-10"	6.6%	1.5%	5.1%	29ms	1.1%
10-15"	5.2%	0.8%	4.4%	21ms	2.3%
15-20"	15.6%	0.0%	15.6%	9ms	10.4%

Table 21: TMMS-measured water content at Milepost 68.3 mudspot (south shoulder of track).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	5.7%	1.5%	4.2%	11ms	0.8%
5-10"	8.9%	1.8%	7.1%	8ms	1.3%
10-15"	4.9%	0.8%	4.1%	21ms	2.6%
15-20"	45.9%	0.1%	45.8%	4ms	17.4%

Table 22: TMMS-measured water content at Milepost 68.3 mudspot (center of track), measured using long Tr pulse sequence. There was no significant difference from the result using the short Tr pulse sequence (Table 19).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	13.5%	5.1%	8.4%	13ms	1.0%
5-10"	14.4%	4.3%	10.1%	15ms	1.5%
10-15"	12.7%	1.9%	10.8%	24ms	4.5%
15-20"	16.3%	2.7%	13.6%	23ms	32.0%

Table 23: TMMS-measured water content at Milepost, 100 feet east of the mudspot measured in Table 9, Table 10, Table 11, and Table 12. At this location there was no clear visual indication of fouling at the surface of the ballast. However, the TMMS-measurement indicates high water content in fouled ballast, between depths of 5–15 inches.

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	5.4%	2.1%	3.3%	24ms	0.6%
5-10"	10.5%	3.0%	7.5%	13ms	1.0%
10-15"	14.9%	1.6%	13.3%	4ms	1.9%
15-20"	9.1%	9.1%	0.0%	3000ms	14.5%

2.4.3.6 Milepost 68.7

At Milepost 68.7, the team performed two TMMS measurements over a first mudspot to again test for repeatability. At this first mudspot, the TMMS-measurements indicated elevated water content mainly in the top 10 inches of the ballast. When one additional measurement was performed on a second mudspot, and at this location the TMMS measurement indicated elevated water content from the surface to a depth of at least 15 inches.

Table 24: TMMS-measured water content at Milepost 68.7 mudspot 1 (scan 1 of 2).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	9.7%	2.6%	7.1%	12ms	0.9%
5-10"	15.8%	3.3%	12.5%	8ms	1.2%
10-15"	2.9%	2.8%	0.1%	97ms	4.3%
15-20"	4.0%	2.0%	2.0%	51ms	16.6%

Table 25: TMMS-measured water content at Milepost 68.7 mudspot 1 (scan 2 of 2).

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	8.8%	2.9%	5.9%	15ms	1.1%
5-10"	12.1%	1.6%	10.5%	11ms	1.8%
10-15"	2.3%	2.1%	0.2%	63ms	3.1%
15-20"	31.0%	3.6%	27.4%	9ms	11.1%

Table 26: TMMS-measured water content at Milepost 68.7 mudspot 2.

Depth Shell	Total water content	Mobile water content	Bound water content	T2 mean log	Noise
0-5"	11.8%	3.0%	8.8%	27ms	0.9%
5-10"	7.6%	4.5%	3.1%	26ms	1.9%
10-15"	15.2%	2.2%	13.0%	4ms	2.1%
15-20"	30.7%	0.6%	30.1%	4ms	19.8%

2.5 Supplemental R&D Results

When the TMMS sensor was successfully demonstrated on an active CSX rail line in April, all of the technical objectives of this phase of the research were essentially complete. As of June 1, 2016, the team proposed that the remaining funds be used to perform one or more follow-on R&D tasks during the summer and fall of 2016.

2.5.1 Collaborative R&D Reporting

The Vista Clara PI and others at Vista Clara collaborated with ENSCO in preparing a formal FRA report on the multi-sensor rail testing that took place in Virginia in April 2016. These results, which included a section on the TMMS sensor and the April CSX rail tests, were presented to the FRA by ENSCO over the summer of 2016. A summary of the results including a summary of the TMMS sensor development and testing was submitted by ENSCO for presentation at the 2017 AREMA annual meeting.

2.5.2 Design and Assembly of a 13-Magnet TMMS Sensor Array

The TMMS sensor had significantly lower SNR and sensitivity for the deepest of the four NMR measurement zones, according to the computer simulations and testing conducted on the sensor. At the same time, conversations with rail industry regulators and operators, including FRA personnel and engineers and executives at Zetica, indicated that the rail industry requires information on ballast water content throughout the ballast. Hence, the existing TMMS sensor is significantly limited due to its relatively low SNR and limited capability to measure water content in the lower 1/3 of the ballast (between 14 and 20 inches deep).

The most straightforward way to increase sensitivity in the deepest measurement zone is to increase the static magnetic field in that zone, and increasing the density of permanent magnets in the Halbach array is the simplest way to accomplish that goal. As a result, Vista Clara designed an alternate magnet/coil array that has the same overall size and configuration, but has a larger number of magnet bars (increased from 9 to 13). Computer simulations previously indicated that this increase in magnet density will increase the SNR in the deepest sensitive zone by a factor of approximately 2.

Vista Clara completed the design of new fiberglass array parts to accommodate the 13 magnet array and ordered the manufacture in early fall 2016. We also ordered additional magnets and additional machined aluminum parts to construct the four additional magnet bars. Due to manufacturing delays, these parts were not delivered until the first week of December when the final contract extension had expired. As of the end of the project, we have all the parts required to assemble and test the 13-magnet version of the TMMS sensor. A photo of the newly manufactured fiberglass and aluminum parts for the 13-magnet version of the TMMS is shown in Figure 22, along with the existing nine-magnet array.

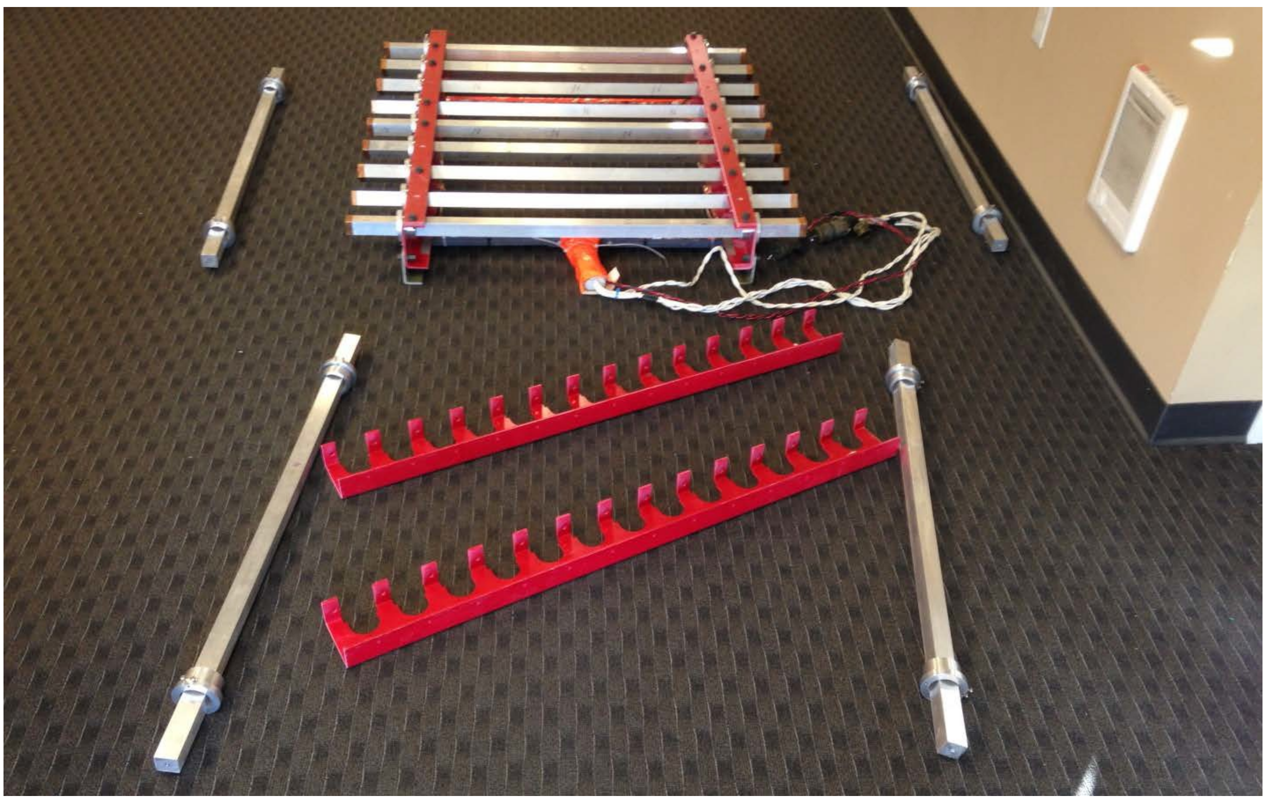


Figure 22: Newly manufactured magnet bars and fiberglass frame components to enable the future assembly and testing of a 13-magnet version of the TMMS sensor.

3. Conclusion

A two-man portable NMR trackbed moisture sensor for spot-check measurements was successfully designed, assembled, and tested in a range of environments including live testing on an active US rail line. With typical stationary measurement times on the order of 6–8 minutes, the sensor was shown to be able to detect and measure volumetric water content in the range of 2 percent or greater in the top 12 inches of ballast, and water content in the range of 15 percent or greater in the ballast at depths between 13 and 20 inches.

If increases in magnet density and anticipated continuous improvements in detection electronics and noise suppression methods occur, this sensor could become a technically and commercially viable method for non-invasive and unambiguous measurement of water content in the top 20 inches of trackbed ballast materials in a wide range of environments.

4. References

1. Butler, J. J., Christy, T, Fitzpatrick, A, Grunewald, E., Johnson, C. D, Knobbe, S., Lane, J. W., Munday, T., Reboulet, E., Turner, P., Walsh, D., and Zhang, H. (2013). A Small-Diameter NMR Logging Tool for Groundwater Investigations. *Groundwater*, *51*(6), 914–926. Available at: doi:10.1111/gwat.12024.
2. Lauterbur, P. C, and Liang, Z.P. (1999, November). *Principles of Magnetic Resonance Imaging – A Signal Processing Perspective*. IEEE Press: Piscataway, NJ.

5. Abbreviations and Acronyms

CSX	CSX Transportation
Te	Echo Spacing
EM	Electromagnetic
FRA	Federal Railroad Administration
T1	Longitudinal NMR Relaxation Rate
NMR	Nuclear Magnetic Resonance
PSNR	Peak Signal to Noise Ratio
RF	Radio Frequency
RFI	Radio Frequency Interference
R&D	Research and Development
RMS	Root Mean Square
SNR	Signal to Noise Ratio
T2ML	T2 Mean Log
TWC	Total Water Content
TMMS	Trackbed Moisture Monitoring System
T2	Transverse NMR Relaxation Rate
WC	Water Content