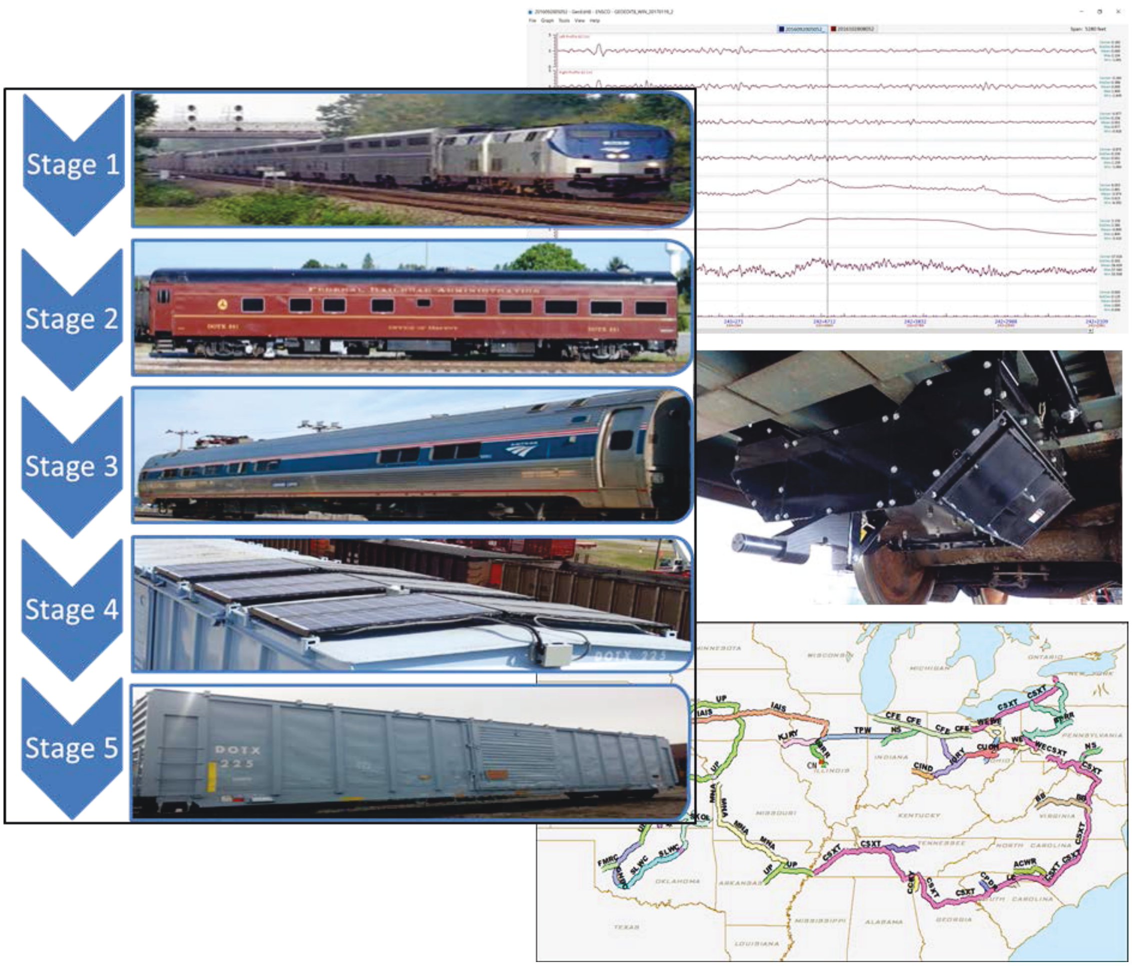
U.S. Department of Transportation

Federal Railroad Administration

Autonomous Track Geometry Measurement Technology Design, Development, and Testing

Office of Research, Development and Technology
Washington, DC 20590



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Final Report
March 2018

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13. ABSTRACT (Maximum 200 words) The Federal Railroad Administration's (FRA) Office of Research, Development and Technology has long advocated for the development and advancement of autonomous track geometry measurement systems (ATGMS) and related technologies to improve rail safety by increasing the availability of track geometry data. FRA's ATGMS research program has demonstrated the potential benefits and uses of the unmanned inspection approach as well as the requirements for information management. This report provides an overview of FRA's ATGMS research and development program with emphasis on its evolution from a proof-of-concept prototype to a fully operational measurement system. The report also provides a summary of lessons learned from the development of this approach and highlights FRA's vision for the role of autonomous technology in track inspection and safety assurance.			
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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

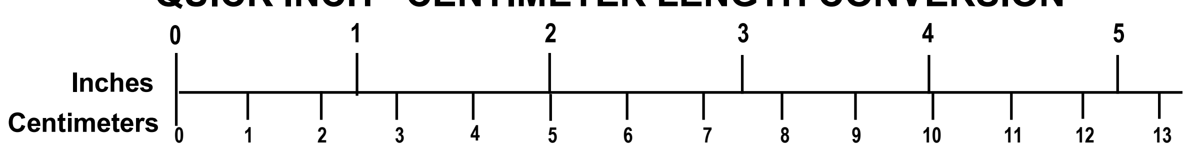
VOLUME (APPROXIMATE)

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)

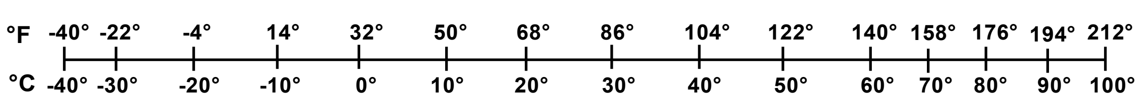
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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

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Executive Summary

This report documents the Federal Railroad Administration's (FRA) Office of Research, Development and Technology's (RD&T) successful development and demonstration of autonomous track geometry measurement system (ATGMS) technology. FRA is currently developing autonomous inspection technologies with the objective of improving railroad safety through enhanced conditional awareness. Autonomous track inspection is a process of inspecting the track from revenue trains using unattended instruments, with minimal direct involvement from operators. This technology allows dramatically increased inspection frequencies at reduced cost, when compared to traditional manned methods. Widespread use of autonomous inspection technology has the potential to increase the timeliness of track defect detection and remediation, thus improving the safety of the nation's rail system.

FRA's Office of Railroad Safety (RRS) currently uses ATGMS as part of its ongoing track geometry inspection operations. This transition of ATGMS to routine assessments as part of FRA's Automated Track Inspection Program (ATIP) has yielded positive outcomes for RRS, including an increase in inspection frequency with no reduction in data quality.

In addition to describing the development of the measurement system, this report includes an overview of technologies developed in support of ATGMS operation, including automatic filtering of track geometry defects, track determination and track degradation algorithms as well as remote data editing capabilities. Supplemental material providing details of various development efforts is provided in the appendices of this report.

1. Introduction

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) focuses on the development of new track inspection methods to enhance railroad safety and reduce in-service track failures. Today, the predominant methods for track assessment rely on visual inspection by track inspectors and automated measurement of track geometry from dedicated inspection vehicles. In the case of automated track inspection, these measurement systems are installed on dedicated inspection vehicles and operated by trained personnel. Automated inspections typically require scheduled track time as well as expensive systems and dedicated manpower.

FRA is currently developing autonomous inspection technologies with the objective of improved railroad safety through enhanced conditional awareness. Autonomous track inspection is a process of inspecting the track from revenue trains using unattended instruments, with minimal direct involvement from operators. This technology would allow for dramatically increased inspection frequencies at reduced cost, when compared to traditional methods. Widespread use of autonomous inspection technology has the potential to increase the timeliness of track defect detection and remediation, thus improving the safety of the nation's rail system.

1.1 Background

Autonomous rail vehicle performance measurement and track condition monitoring technology has been in development for many years. The use of an Autonomous Ride Monitoring System (ARMS) on Acela high-speed train sets, operated by Amtrak on the Northeast Corridor (NEC), was the first systematic implementation of un-manned track evaluation in the U.S. This system was based on technology developed by FRA's RD&T and ENSCO, Inc. The performance of the Acela high-speed train sets from a vehicle/track interaction perspective is monitored remotely through automated analysis of the measured carbody and truck vertical and lateral accelerations. The system identifies and reports track conditions of concern and/or poor performing vehicles for corrective actions.

The Maryland Transit Administration's (MTA) Maryland Area Regional Commuter (MARC) service became the second passenger railroad in the United States to equip a number of its trains with a similar system in 2002. In 2004, the Union Pacific Railroad (UP) became the first freight railroad in the United States to adopt the use of similar technology. ARMS units were augmented with axle-mounted accelerometers to identify battered joints, misaligned switches, damaged frogs, and other high-impact events. More than 200 systems of this design, known as Vehicle/Track Interaction (V/TI), are currently in use across Class I U.S. railroads [1].

The effectiveness of autonomous inspection technology by Amtrak, MTA, and UP prompted other industry service providers to develop variations of the technology; while unattended systems that record track geometry data were introduced in Europe in the early 2000s [3]. Based, in part, on the performance of these early systems, FRA recognized a need to provide the railroad industry with advances in technology to improve track inspection by reporting conditions to stakeholders in near real-time using relatively low-cost, modular system designs. Improving the accuracy and timeliness of track geometry data while reducing the life-cycle cost of track geometry systems and operations to encourage widespread adoption of the measurement technology is a key factor in achieving FRA's safety goals.

Track geometry is typically measured using a non-contact approach employing inertial and optical measurement principles. As illustrated in Figure 1, inertial sensors located within a beam mounted to the underside of a rail vehicle are used to locate a measurement reference frame, in this case the beam, in space relative to the track. Laser scanning sensors mounted to the beam are then used to determine the lateral and vertical location of the rails relative to the beam. A laser illuminates the rail and the light scatter highlights the rail's contour in a measurement plane; a camera images the laser light scatter and the x-y coordinates of the rail contour are determined. These coordinates are then combined with measurements made with the inertial sensors using a variety of methods to arrive at traditional track parameters such as gage, profile/surface, alignment, crosslevel and curvature.

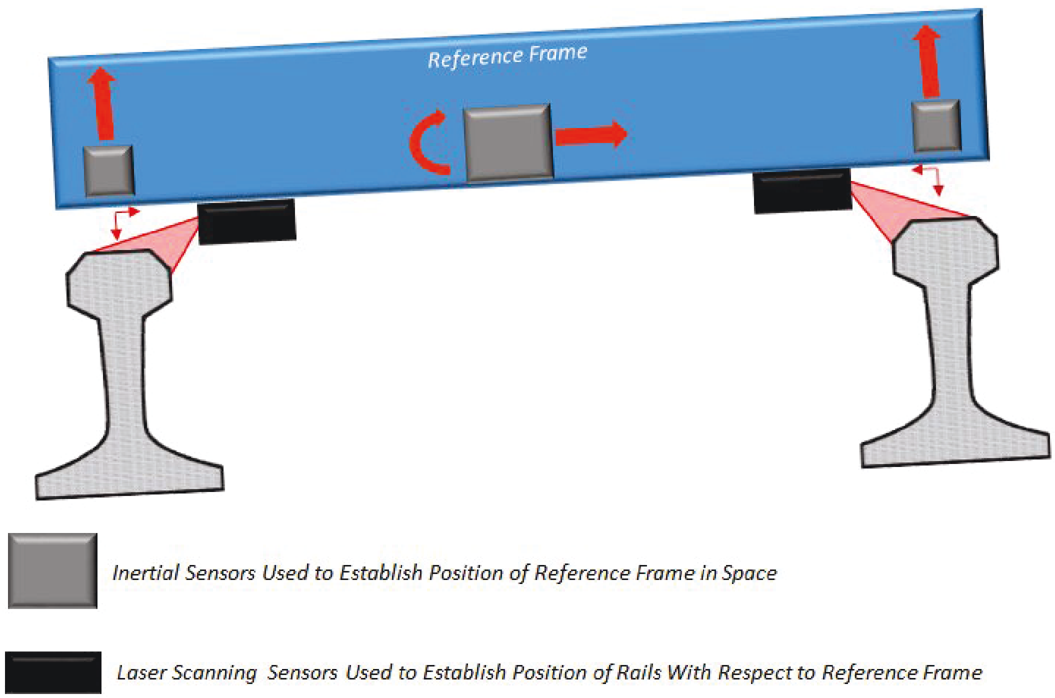


Figure 1: General Approach to Track Geometry Measurement

1.2 Objectives

FRA's RD&T began a multi-stage research program with the objective of developing an autonomous track geometry system to improve rail safety. FRA's vision was to create a relatively low-cost, unattended, self-powering geometry measurement system deployable on standard rail equipment, including freight cars, to collect and distribute accurate track geometry data in a time-efficient manner while running in a standard revenue train. Key aspects of this vision are an ATGMS that:

- Reduces life-cycle costs of geometry measurement operations
- Eliminates interference with revenue operations
- Increases inspection frequencies
- Provides high-quality data

The expected benefits of this approach are highlighted by an increase in the availability of track geometry data for safety and maintenance planning purposes, including the near real-time detection and reporting of exceptions to geometry thresholds and the identification of locations of areas with degraded track geometry.

The objective of the program was not to eliminate human inspection, or to replace manned automated inspection systems as a quality assurance method. FRA's goal was to create a more flexible, efficient tool for use in day-to-day quality control and maintenance planning activities.

1.3 Overall Approach

This report documents the FRA's successful development and demonstration program for autonomous track geometry measurement system (ATGMS) technology. Begun in 2006, the research program was organized into the following five development phases:

Stage 1: Long-Term Pilot with Standard Inspection Technology - The initial stage of development centered on the creation of a ruggedized pilot system using commercial off-the-shelf equipment to facilitate early evaluation. ENSCO developed the basic elements of an autonomous system during this stage with an emphasis on communication and processing software, including preliminary analysis tools. FRA and ENSCO partnered with Amtrak and CSX Transportation (CSX) to install the first ATGMS on an Amtrak Superliner II in revenue service operations as part of Amtrak's Auto Train service between Lorton, VA, and Sanford, FL, over CSX-owned track. The pilot system operated for close to 460,000 miles during this development stage.

Stage 2: Simulation of Standard Revenue Operations - The goal of this development stage was to test the extended range performance of the ATGMS and to verify the quality of ATGMS data by direct comparison with data gathered from a manned geometry car operating in the same consist. An ATGMS was installed on FRA's DOTX 221 passenger car and operated in consist with FRA's Automated Track Inspection Program's (ATIP) DOTX 220 manned inspection vehicle during surveys conducted over Amtrak passenger routes between fall 2011 and spring 2013.

Stage 3: Advanced Measurement Technology Development - The goal of this development stage was to engineer a new ATGMS configuration suitable for mounting directly to a carbody. To demonstrate and evaluate this approach, a carbody-mounted ATGMS was designed, constructed and installed on an Amtrak Amfleet coach, and operated in Amtrak revenue service along the NEC during 2012 and 2013.

Stage 4: Energy Harvesting Technology Development - This stage targeted the evaluation of technology that facilitates ATGMS use in a freight environment. For freight operation, ATGMS needs a dedicated source of power. Researchers considered solar, wind, fossil fuel, and fuel cell-based power sources during this effort. Fossil fuel was initially identified as the most feasible primary source of power for ATGMS, and a review of commercially available diesel generators resulted in a list of technical and operational specifications for a candidate diesel generator. ENSCO also evaluated methanol fuel cells. Historical data on solar power systems installed on railcars indicated that solar power can be effectively used as a source of power. Testing of prototype devices for wind power generation indicated that wind power is not a viable option for a secondary source of power generation because of nominal train speeds in freight operations.

Potential power sources were examined under different operational and environmental conditions to identify optimum configurations for deployment on an unattended rail vehicle.

Stage 5: Demonstration in Freight Service - The final stage of FRA's ATGMS development plan was a demonstration in normal freight service operation. ATGMS technology was demonstrated on a freight vehicle operating in typical revenue service to establish a vision for the use of this track assessment technology throughout the industry. FRA deployed its carbody-mounted ATGMS on a refurbished boxcar as part of a demonstration program conducted over 29 railroads, including 25 short line and regional railroads, between April 2016 and January 2017. Power systems specified during Stage 4 activities were installed on the boxcar to provide continuous power for the system. Data produced from the surveys was provided to the surveyed railroads in several forms to meet the individual railroads' needs.

1.4 Scope

The scope of this research included all aspects of research, technical development, testing, and system demonstration. The multi-phased approach to the work helped to guide the effort through logical, evolutionary steps. Each step in the process established a higher level of capability for the system progressing the technology towards the goal of full autonomy.

1.5 Organization of Report

This report is structured into five sections.

Section 1 documents the introduction and background of the ATGMS technology, as well as introducing the research program's overall approach.

Section 2 provides a synopsis of FRA's approach to the development of ATGMS technology, including an explanation of FRA's five-stage development plan and a description of FRA's current implementation of autonomous inspection.

Section 3 details key advancements in FRA's ATGMS technology, including major accomplishments and findings of each development stage.

Section 4 summarizes the consideration of analyses and processes that are crucial to the implementation of ATGMS, including geometry defect review and filtering, individual track determination and degradation analysis.

Section 5 summarizes conclusions from FRA's development and demonstration efforts and perspectives on the use of unmanned inspection technology in the rail industry.

Supplemental material providing details of various development efforts is provided in the appendices of this report. These appendices are as follows:

- Appendix A – ENSCO Document SERV-REPT-0000507 "Comparison of DOTX221 ATGMS and DOTX220 TGMS Geometry Exceptions and Foot-by-Foot Geometry Summary Report."
- Appendix B – ENSCO Document SERV-REPT-0000578 "DOTX221 ATGMS Operations Performance Report: Summer/Fall 2013 ATIP Amtrak Assessment Survey."

- Appendix C – ENSCO Document SERV-REPT-0000528 “Comparison of Track Geometry Measured with a Carbody-Mounted ATGMS and Amtrak 10002 Summary Report.”

2. ATGMS Research Approach

2.1 Technology Development Plan

FRA's RD&T established a five-stage technology development plan to transition ATGMS technology to the railroad industry. The five stages are depicted in Figure 1 and described below.

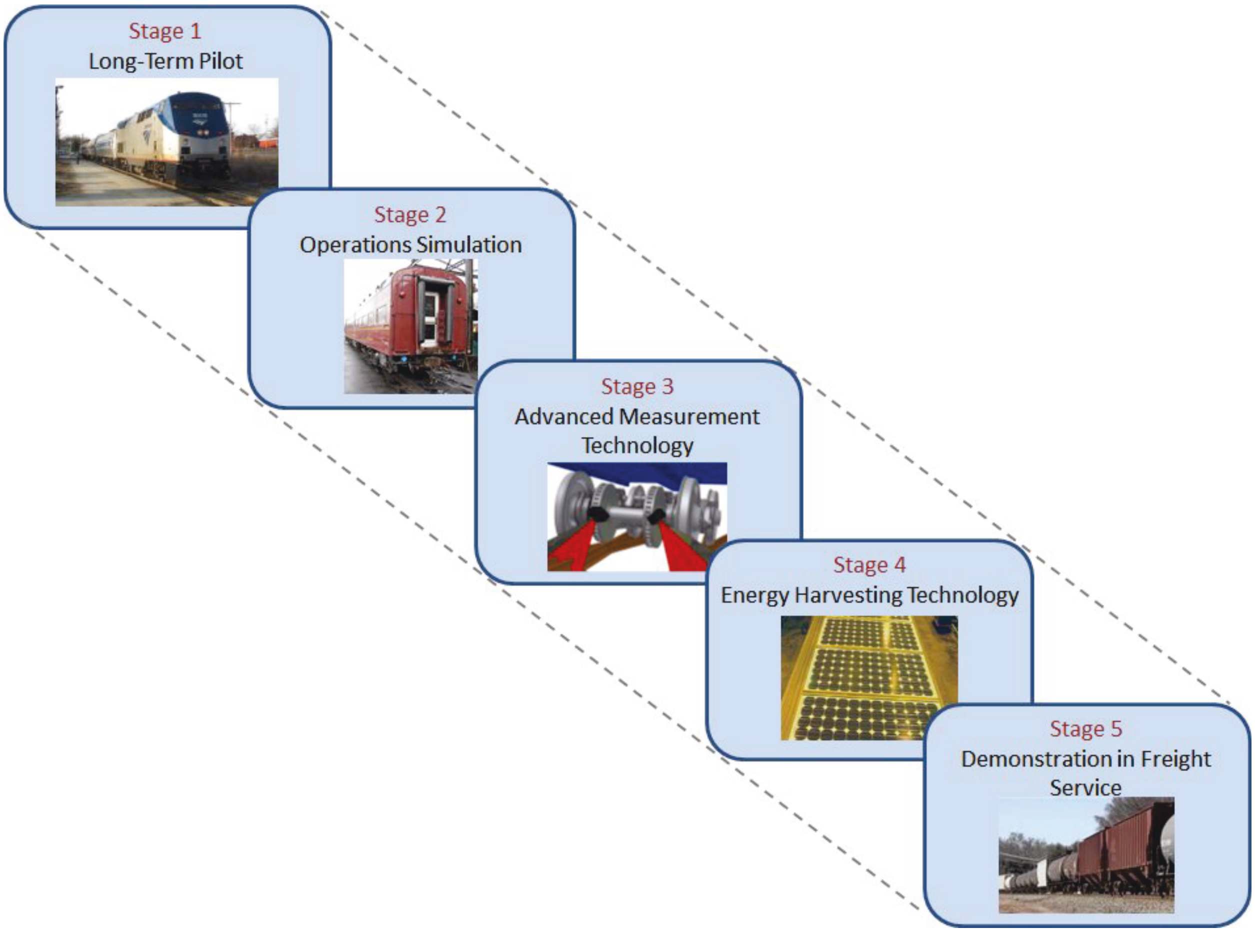


Figure 2: ATGMS Research Stages

Stage 1: Long-Term Pilot with Standard Inspection Technology

The initial stage of development was centered on the creation of a ruggedized pilot system using commercial off-the-shelf equipment to facilitate early evaluation. ENSCO developed the basic elements of an autonomous system during this stage with an emphasis on communication and processing software, including preliminary analysis tools.

This stage included an evaluation of various measurement approaches using a truck-mounted pilot system to identify operation and maintenance issues that resulted from long term, unmanned operations. FRA and ENSCO partnered with Amtrak and CSX to install the first ATGMS on an Amtrak Superliner II in revenue service operations as part of Amtrak's Auto Train service between Lorton, VA, and Sanford, FL, over CSX-owned track. The pilot system operated for close to 460,000 miles during this development stage.

This pilot ATGMS used standard geometry system components typically found on automated track geometry measurement systems. ENSCO configured the system to automatically transmit track geometry exception data, vehicle Global Positioning Satellite (GPS) location coordinates, and vehicle speed information via a standard cellular communications transceiver. Early versions of automated exception filters were employed in an effort to eliminate false alarms.

Stage 2: Simulation of Standard Revenue Operations

The goal of this development stage was to test long distance performance and to verify the quality of ATGMS data by comparison with data gathered from a manned geometry car operating in the same consist. This research simulated a routine operating condition, covering over 30,000 test miles.

ENSCO completed extensive refinements to ATGMS hardware and software systems as part of this development effort. The system was modified to allow for near real-time delivery of raw foot-by-foot sensor data from ATGMS to a central server via commercial cellular service. FRA's ATGMS was transferred to FRA's DOTX 221 passenger car and operated in consist with FRA's ATIP's DOTX 220 manned inspection vehicle during surveys conducted over Amtrak passenger routes between fall of 2011 and spring of 2013. Operation of ATGMS in conjunction with manned track geometry surveys allowed direct comparison of measurements collected with both systems to identify and address any remaining issues affecting data captured by the autonomous system. Detailed results of comparisons conducted in Stage 2 are provided in Appendices A and B.

Stage 3: Advanced Measurement Technology Development

The goal of this development stage was to engineer a new ATGMS configuration suitable for mounting directly to a carbody. Moving the system from a truck-mounted configuration to a carbody-mounted position provides numerous advantages, including a less severe shock-and-vibration environment, reduced exposure to mud, snow, and flying ballast, and less manual interaction with the system during periodic truck maintenance activities. System complexity and construction costs are also reduced, and ATGMS becomes a modular system with a simple interface to the carbody.

A key element of this stage was a demonstration in revenue service operations and a comparison of autonomously collected data that was captured by standard geometry systems. To demonstrate and evaluate this approach, a carbody-mounted ATGMS was constructed and installed on an Amtrak Amfleet coach, and operated in Amtrak revenue service along the NEC during 2012 and 2013. ENSCO compared the performance of the carbody mounted ATGMS to that of the system on Amtrak's 10002 manned geometry car over multiple runs. Appendix C contains results of this comparison.

Stage 4: Energy Harvesting Technology Development

This stage targeted the evaluation of technology that facilitates ATGMS use in a freight environment. For freight operation, ATGMS needs a dedicated source of power. Fossil fuel was initially identified as the most feasible primary source of power for ATGMS, and a review of commercially available diesel generators resulted in a list of technical and operational specifications for a candidate diesel generator. ENSCO also evaluated methanol fuel cells. Historical data on solar power systems installed on railcars indicated that solar power can be effectively used as a source of power. Testing of prototype devices for wind power generation indicated that wind power is not a viable option for a secondary source of power generation because of nominal train speeds in freight operations. Potential power sources were examined under different operational and environmental conditions to identify optimum configurations for deployment on an unattended rail vehicle.

Stage 5: Demonstration in Freight Service

The final stage of FRA's ATGMS development plan was a demonstration in normal freight service operation. ATGMS technology was demonstrated on a freight vehicle operating in typical revenue service to establish a vision for the use of this track assessment technology throughout the industry. FRA deployed its carbody-mounted ATGMS on a refurbished boxcar as part of a demonstration program conducted over 29 railroads, including 25 short line and regional railroads, between April 2016 and January 2017. Power systems specified during Stage 4 activities were installed on the boxcar to provide continuous power for the system. Data products from the surveys were provided to the surveyed railroads in several forms to meet the individual railroads' needs.

The overall timeline for the various development stages is illustrated in Figure 3.

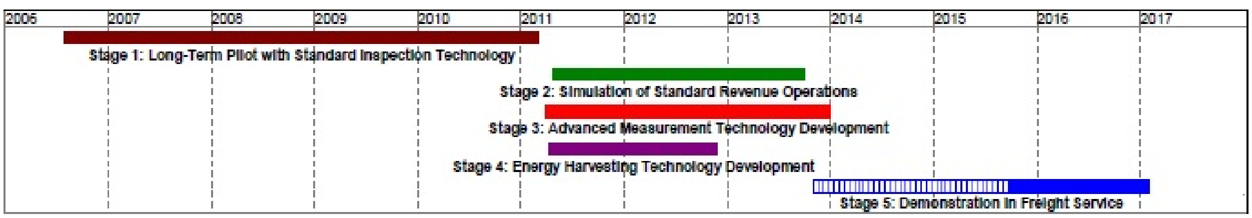


Figure 3: ATGMS Technology Development Timeline

3. ATGMS Technical Development

3.1 Measurement Approach and System Architecture

An operational schematic of FRA's ATGMS is illustrated in Figure 4. It consists of three major components, detailed below, that provides information needed for making decisions by railroad management and maintenance personnel:

1. **Data Collection Module** - This is installed and operated on a track-bound vehicle that transfers raw sensory data via a commercial cellular connection.

2. **Data Processing Server** – A server that receives and processes collected sensory data into actionable information stored in a searchable database.

3. **Web-Based Applications** – The applications include those dedicated to quality assurance and accessible reporting via a secure internet connection.

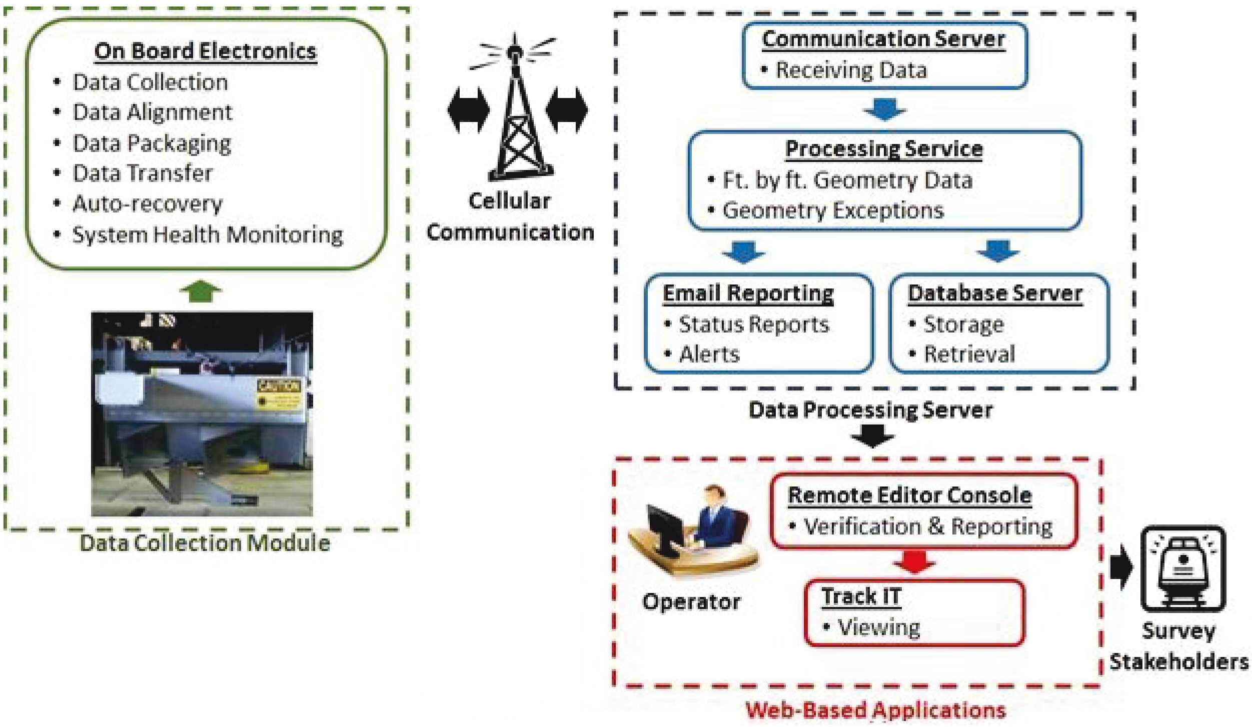


Figure 4: ATGMS System Architecture

The three major components of ATGMS architecture are comprised of several sub-modules, each performing specific functions as described in the sections below.

3.1.1 *Data Collection Module*

The data collection module consists of all equipment installed on the track-bound vehicle. This module has four major mechanical and electrical assemblies that together collect, package, and transfer foot-by-foot measurement data to ATGMS servers via a commercial cellular connection:

1. **Measurement Beam** – The mechanical structure that houses optical and inertial sensors. The beam is mounted either on the inboard truck frame above the primary suspension in the truck-mounted configuration, or to the carbody structure near one of the trucks in the carbody-mounted configuration. In both configurations, track geometry is measured approximately 34 inches from the center of the inboard axle.

2. **Onboard Electronics** – The electronic hardware installed in a rugged enclosure that can be mounted on the interior or exterior of the vehicle for full serviceability. The enclosure houses major components such as the signal processing unit, uninterruptable power supply (UPS) to protect against short-term power fluctuations, and communication hardware for transfer of data within the system, transmission of measurement data and system health status from the vehicle, as well as system set-up parameters and commands to the onboard system.

3. **GPS and Cellular Antennae** – This is mounted on the roof of the vehicle above the measurement beam to acquire location information as well as transmit and receive information.

4. **Tachometer** – The encoder mounted on the inboard axle closest to the measurement beam used to measure linear distance travelled along the track. The tachometer signal is used to trigger collection of foot-by-foot measurements and to synchronize data collected from different sensors.

3.1.2 *Data Processing Server*

Data collected on the vehicle is transferred to a data processing server via a commercial cellular connection. In addition to the foot-by-foot track measurement data, system diagnostic information is transmitted from ATGMS to the servers by status messages, which are hourly email notifications sent to the ATGMS operator/owner conveying the current status of onboard hard drive usage, processing load, and geographical location of the vehicle. Information is also transmitted from ATGMS to the servers using alert messages that are sent out when onboard electronics detect malfunctioning sensors or components.

When the ATGMS server receives a data packet, it performs a series of quality checks to ensure continuity of data and to acknowledge receipt of the data packet back to systems on the vehicle. The foot-by-foot geometry measurements are further analyzed to detect geometry exceptions outside established thresholds. Confirmed geometry exceptions, foot-by-foot geometry data, and location information are stored in the ATGMS database.

3.1.3 *Web-Based Applications*

ATGMS data information management and overall quality assurance is performed using two web-based applications, which are the Remote Editor Console and TrackIT®.

Remote Editor Console

The Remote Editor Console allows operators to review geometry exceptions detected by ATGMS in near real-time as part of FRA’s data quality assurance process. Operators can use the secure web-based computer application to make any necessary adjustments to the survey information, including track class or track designation and exception edits, and distribute exception summary reports to authorized recipients. The Remote Editor Console also provides operators with the means to remotely identify/address any suspected data quality issues caused by system malfunctions.

Reviewers can select a specific survey or a range of surveys using dates or survey numbers and perform all aspects of survey data management through the user interfaces shown in Figure 5 and Figure 6.

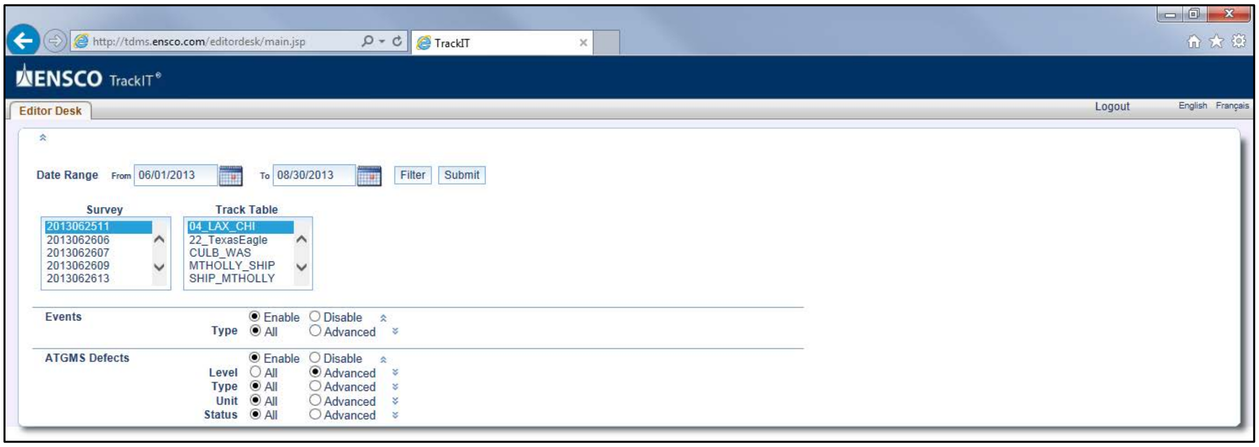


Figure 5: Remote Editor Console Survey Data Selection Display

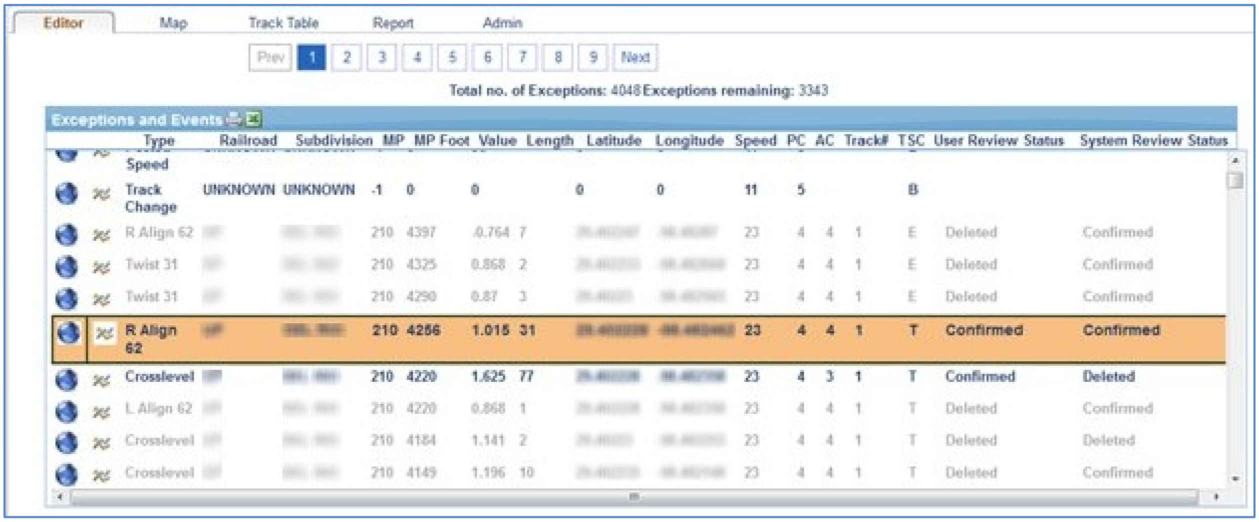


Figure 6: Remote Editor Console Survey Data Display

The user selects an event by clicking and highlighting the entry. Data selection allows the user to then view supporting information to analyze and validate the reported data. The available functions include:

- **Map** displays a Google™ Maps screen showing the location for the selected data for overall assessment and confirmation of individual track designation (see Figure 7).

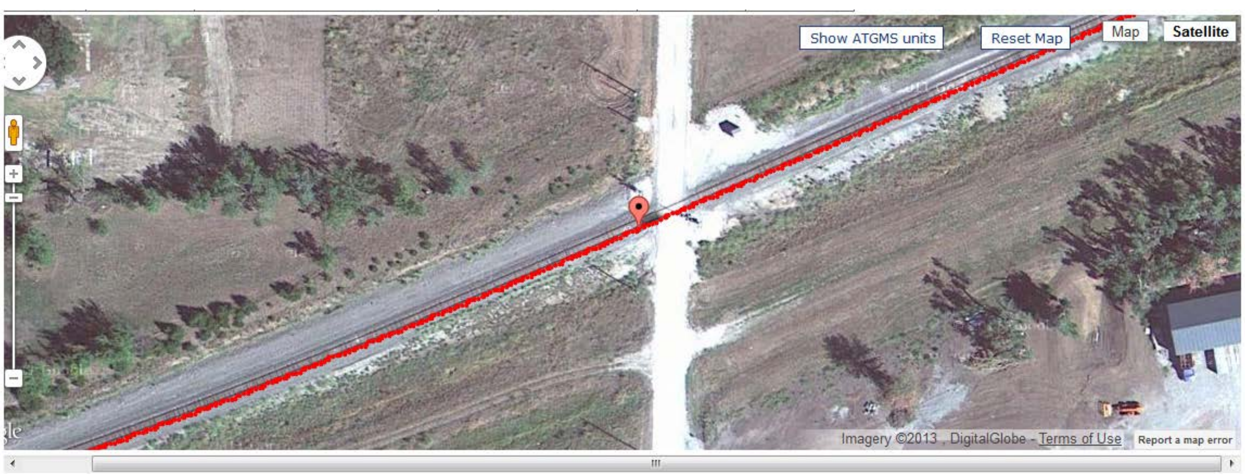


Figure 7: Remote Editor Console Map View

- **Strip Chart** displays a separate window in which a foot-by-foot illustration of the selected survey data is provided (see Figure 8).

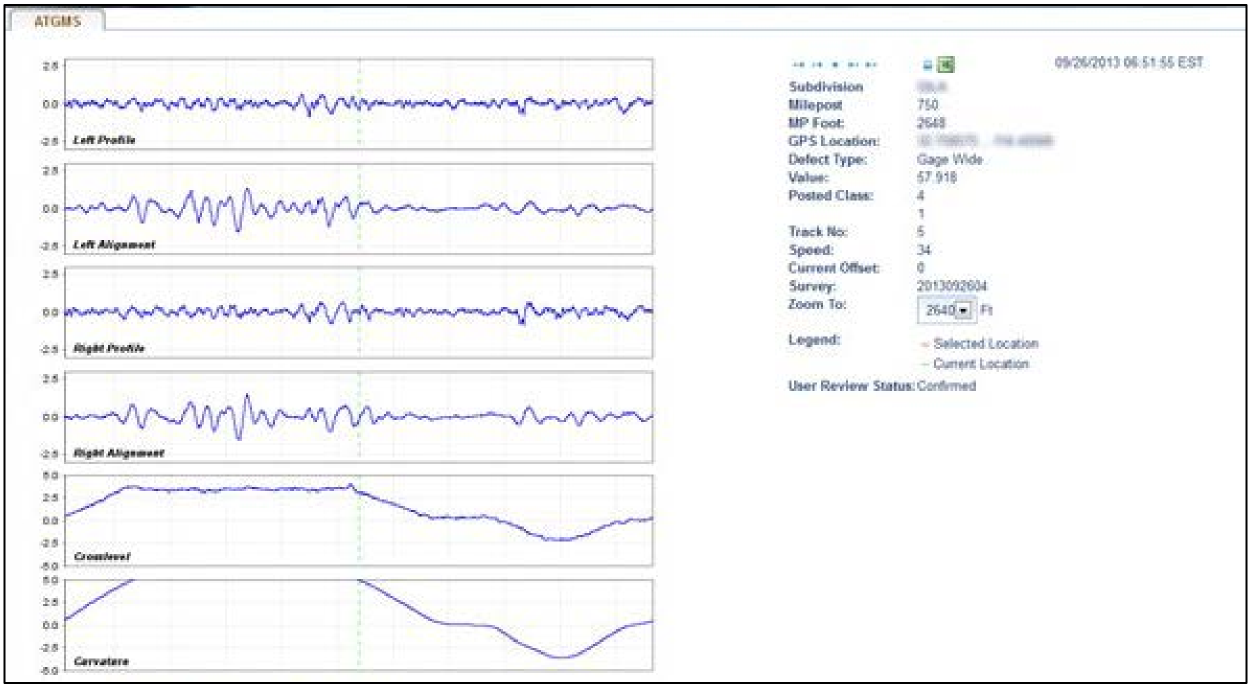


Figure 8: Remote Editor Console Strip Chart

- **Track Table** displays the available railroad-provided information regarding track class through the territory of interest (see Figure 9). A default track class is initially assigned to all survey results to initially identify potential track geometry exceptions; the default track class is configurable, but is typically established as Class 4. Reviewers select exceptions measured over portions of the survey and update the track class over that portion using information from the track table. The application will automatically generate or delete exceptions so that survey results correspond to the entered class. For example, if the reviewer determines that the surveyed class should be Class 3 between MPs 10 and 20 based on railroad provided information, then the reviewer can enter Class 3 for that MP range, and the system will delete all exceptions that were determined for higher classes. The reviewer is then left with Class 3 exceptions to be assessed.

Track Table | Report | Admin

MP	MPFeet	Track 1			Track 2			Track 3			Track 4			Track 5			Track 6			Track 7		
6	1056	0	0	4	3	30	4	3	30	4	3	30	4	0	0	4	0	0	4	1	15	4
7	528	3	30	4	3	30	4	3	30	4	3	30	4	0	0	4	0	0	4	0	0	4
7	3270	3	30	4	3	30	4	2	25	4	2	25	4	0	0	4	0	0	4	0	0	4
8	0	3	30	4	3	30	4	1	10	4	1	10	4	0	0	4	0	0	4	0	0	4
1	3696	0	0	4	0	0	4	0	0	4	2	15	4	0	0	4	0	0	4	0	0	4
1	4752	0	0	4	3	45	4	2	30	4	2	30	4	0	0	4	0	0	4	0	0	4
2	3696	3	45	4	3	45	4	2	30	4	2	30	4	0	0	4	0	0	4	0	0	4
3	2640	2	30	4	2	30	4	2	30	4	2	30	4	0	0	4	0	0	4	0	0	4
4	0	2	30	4	2	30	4	2	20	4	2	20	4	0	0	4	0	0	4	0	0	4
5	2640	2	20	4	2	20	4	2	20	4	2	20	4	0	0	4	0	0	4	0	0	4
5	4224	2	30	4	2	30	4	2	20	4	2	20	4	0	0	4	0	0	4	0	0	4
7	1584	2	30	4	2	30	4	2	20	4	2	20	4	0	0	4	0	0	4	0	0	4
7	4224	4	60	4	2	30	4	2	20	4	2	20	4	0	0	4	0	0	4	0	0	4
8	3696	4	60	4	4	60	4	4	55	4	3	40	4	0	0	4	0	0	4	0	0	4
11	0	4	60	4	4	60	4	4	55	4	3	40	4	0	0	4	0	0	4	0	0	4

Total no. of records 215

Figure 9: Remote Editor Console Track Table

- **Report** allows the user to configure, produce, and distribute survey reports. Two types of reports are provided to survey stakeholders from the Remote Editor Console. Non-Compliant Exception Reports (NCER) identifying track conditions that cannot support the current speed of the host train are immediately sent via email to FRA and railroad personnel. Track Assessment Reports (TAR) that summarize all events identified within a particular territory are distributed to FRA and railroad personnel at the end of each survey.

TrackIT®

Authorized end users such as railroad management, engineering, and maintenance-of-way personnel can view inspection results using TrackIT®, a secure web application for viewing information provided by multiple system deployments. Users can view geometry exceptions marked on aerial view maps, view strip charts showing sensor data, view data in tables, etc. Example displays are shown in Figure 10.

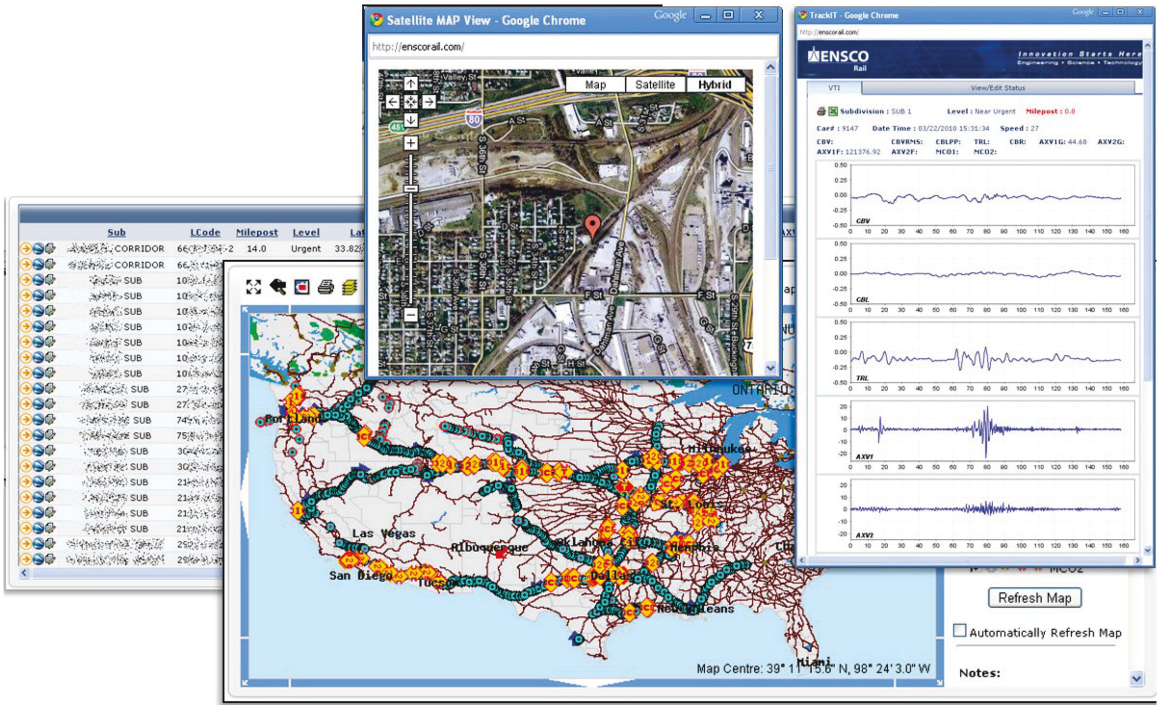


Figure 10: TrackIT® Data Viewing Displays

The sections below provide descriptions of the five main stages of ATGMS technology development including the goals, system development and configuration, testing, results, and lessons learned for each stage.

3.1.4 *Stage 1: Long-Term Pilot with Standard Inspection Technology*

ENSCO evaluated the early ATGMS proof of concept prototype on hi-rail vehicles as shown in Figure 11. Initial tests of the prototype system showed the potential for autonomous data collection, processing, detection, and reporting of geometry exceptions via a commercial cellular connection.

Figure 11: ATGMS Proof of Concept Testing on a High-Rail Vehicle

The first ATGMS proof of concept field test performed in March 2006 verified the overall system capabilities to properly collect and transmit track geometry data. Although successful in generating selected verifiable geometry results, this test highlighted the need for improving several technologies essential to autonomous performance and overall robustness of ATGMS including automatic determination of track class as well as self-identification and correction of sensor issues. Further field testing conducted in early May 2007 evaluated software remedies for detecting track class and vehicle direction of travel, dynamic sensor calibration based on long-term averages collected on tangent track, and corrected output of fiber optic gyroscopes based on filtered GPS data. Final field testing with the hi-rail vehicle in late May 2007 evaluated integration of a custom inertial measurement unit using standard sensors to address issues observed with the fiber optic gyroscopes and to verify software modifications improving track geometry calculations, including the determination of track class based on survey speed.

Tests on the hi-rail vehicle showed the viability of a fully equipped ATGMS employing cellular communication, and established the foundation for a long-term pilot program. The first pilot program, initiated in January 2008, focused on the evaluation of ATGMS on Amtrak Car 39000, a Superliner II sleeper car (Figure 12) in revenue service operation on Amtrak's Auto Train service between Lorton, VA, and Sanford, FL, over CSX track. The test bed on the Amtrak revenue vehicle fits the ideal operational scenario for initial use of the ATGMS repetitive operation of the test platform over a fixed route and availability of Head End Power (HEP) onboard the vehicle.

Figure 12: Stage 1 ATGMS Host Vehicle, Amtrak Car 39000

ATGMS operated on Amtrak Car 39000 from January 2008 to March 2011. During that time, ATGMS surveyed almost 460,000 miles of track, an average of approximately 153,000 miles per year. This extensive testing allowed identification of system deficiencies, facilitating design modifications that moved ATGMS toward increased robustness and reliability. Repetitively operating ATGMS on the 855-mile Lorton to Sanford route advanced testing procedures and established guidelines for subsequent ATGMS development stages. ENSCO analyzed track geometry data collected by ATGMS for consistency among the repeated runs and compared

ATGMS data to that collected by FRA's DOTX 220 manned track geometry inspection vehicle. In addition, CSX track inspectors field-verified a number of exceptions identified by ATGMS.

ATGMS operations on Amtrak Car 39000 also provided a rigorous testing ground for ATGMS hardware that contributed to advances in system reliability. Engineering changes made as a result of this testing included installation of a high precision GPS antenna, tachometer mounting improvements, and installation of laser/camera lens protection devices.

3.1.5 *Stage 1 Goals*

The main goal of the initial pilot study was to convert the ATGMS prototype into a field-deployable system using commercially available off-the-shelf equipment, and to evaluate the resulting system under revenue service operating conditions for an extended period of time. ATGMS technology development focused on the following:

- A ruggedized truck-mounted measurement beam and axle-mounted tachometer assembly with safety catch devices to contain components in case of catastrophic mechanical failure of the mounting structure. These measures were necessary because railroad personnel would not be inspecting autonomous data collection systems as often as they would inspect installations on manned inspection cars.
- A high-precision GPS receiver to accurately capture location information.
- A commercial cellular connection for transmitting track geometry exception data.
- Automated filtering algorithms for validation of geometry exceptions.
- An ATGMS server/database to receive and store detected geometry exceptions and corresponding foot-by-foot track geometry data. This data was to be available to authorized users via the initial deployment of the TrackIT® web application, providing capabilities to monitor survey data, create reports, and notify key personnel of serious track issues.

3.1.6 *Stage 1 System Configuration and Development*

ENSCO designed mounting hardware for the measurement beam in collaboration with Amtrak to ensure all fixtures were sufficiently robust to handle the dynamic load environment of the intended operation. To ensure installation and operation of ATGMS so that it would not jeopardize Amtrak passenger operations, safety catch devices were installed to contain the measurement beam in case of failure of the mounting structures.

The measurement beam was mounted to the A-End truck. Mechanical mounting fixtures were designed to withstand 25g vertical and 15g lateral shocks over fatigue life cycles consistent with Amtrak requirements. It should be noted, however, that the final design of the truck-mounted beam required removal of the measurement beam and mounting brackets from the truck frame in advance of any wheel or axle maintenance activities—an issue that would negatively impact the long-term viability of this design approach. Final installations of the externally mounted equipment are shown in Figure 13 and Figure 14.

Figure 13: Stage 1 ATGMS Measurement Beam on Amtrak Car 39000

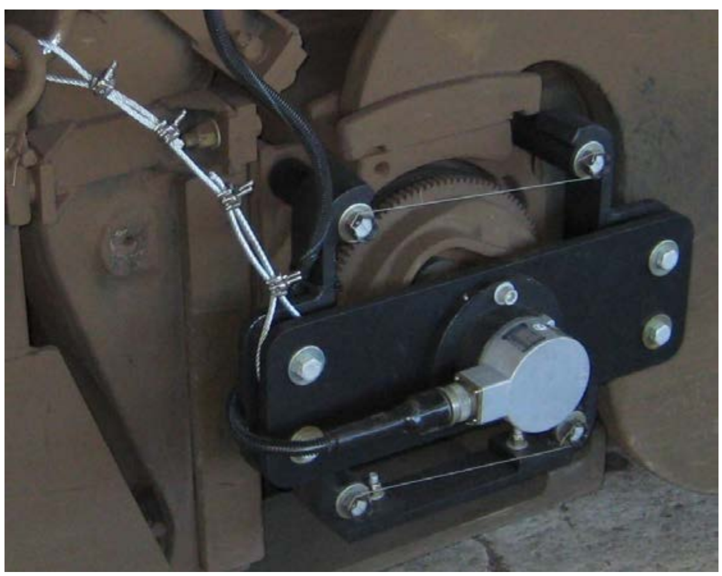


Figure 14: Stage 1 ATGMS Tachometer Assembly on Amtrak Car 39000

GPS location and linear distance measurement subsystems were updated to accurately mark track geometry measurements with location information. Signal processing and communication hardware were housed in enclosures that were temporarily installed in an equipment locker (Figure 15). HEP was used to power ATGMS.

Figure 15: Stage 1 ATGMS Electronics on Amtrak Car 39000

During Stage 1, the ATGMS processed geometry data on the vehicle and transferred exceptions to ENSCO's TrackIT® application in near real-time. ENSCO recognized early in ATGMS development that a large number of false alarms would be detrimental to the success of the system; therefore, ENSCO's development focused on creating and refining automatic data filtering on the TrackIT® platform. The ATGMS data flow employed during the initial stage of development is shown in Figure 16.

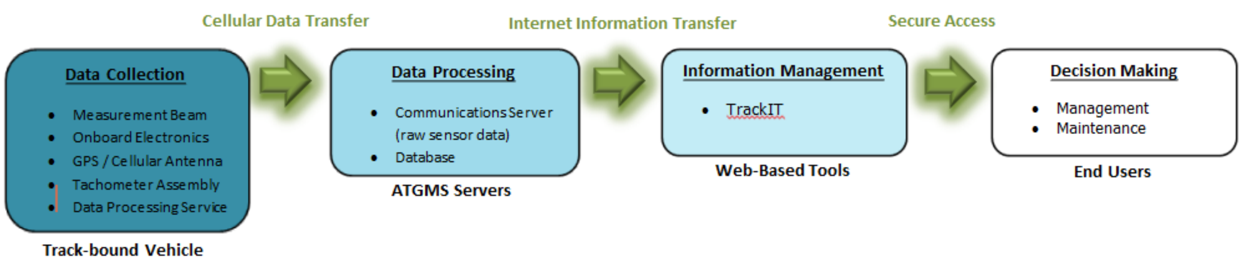


Figure 16: ATGMS Data Flow Employed in Stage 1 Development

Repeatable data was a critical aspect of the implementation of the pilot program with CSX. For the ATGMS test scenario, potential track defects identified for follow-up field inspection by CSX would have to be repeated over several consecutive surveys before CSX would deploy field personnel for remedial action. If repeated defects were found, a summary report of the location of interest was provided to the railroad for investigation. Defects that were believed to be an imminent threat for derailment were brought to the railroad's attention immediately. The first case of a confirmed exception employing this approach occurred in 2008. A narrow gage condition was detected during multiple northbound and southbound ATGMS surveys conducted in September and October; this event is shown in Figure 17. CSX was informed of the measurements, and it dispatched maintenance personnel to the location. They verified the narrow gage measurement.

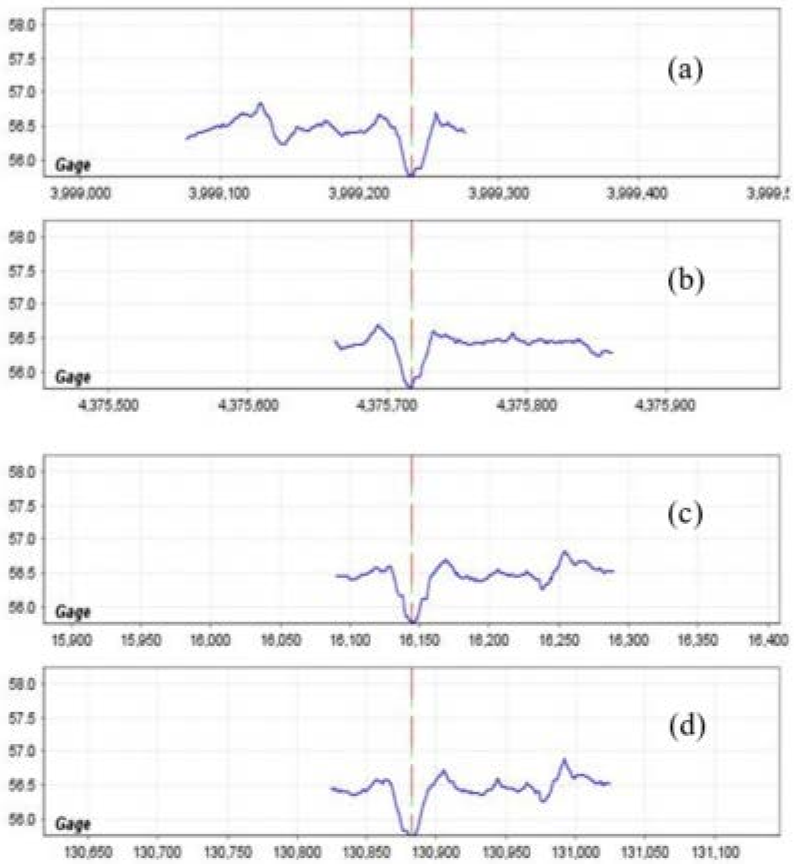


Figure 17: Repeated Narrow Gage Measurements Collected with ATGMS

(Narrow Gage Measurements - (a) 55.76, (b) 55.76, (c) 55.77, and (d) 55.74 inches)

During the first several months of operation on Amtrak Car 39000, ATGMS suffered multiple tachometer failures due to cracks in the tachometer mounting. The design of the mounting bracket was changed (Figure 18) in April 2008 and system inspection procedures were modified to monitor the tachometer condition. There were no further cracking issues observed during the remaining Stage 1 efforts.

Figure 18: Tachometer Modification

In late 2008 and early 2009, Amtrak Car 39000 was out of service for 11 weeks for a scheduled overhaul. A comprehensive weld inspection was conducted on ATGMS components and no major issues were found. During this time ATGMS underwent numerous upgrades, including:

- Software update to improve geometry processing and improved communication robustness
- Implementation of automatic exception processing algorithms
- Improved vertical accelerometer mounts to reduce chance of sensor saturation
- Replacement of tachometer coupler used to connect the unit to the axle and establishment of new inspection procedures
- Multiple Web site updates to improve the review and editing of exception data.

In April 2009, an Automatic Location Detector (ALD) sensor was added to ATGMS to detect switches. At approximately the same time, a Laser Protection System (LPS) was added to ATGMS to keep optical lenses clean over extended periods of time. An electro-mechanical device advanced clear film that covered the lenses based on a software-controlled timer to remove dust and dirt deposited in front of the optical sensors. Although the LPS provided protection for ATGMS optics, frequent malfunctions due to flying debris and issues with the film resulted in degraded or lost survey data from time to time. The LPS continued to be reevaluated and refined during Stage 1 and subsequent development efforts. Aside from LPS issues, the optical sensors worked well.

In November 2009, a high-resolution GPS antenna was installed and tested. While the resolution provided by the GPS was sufficient to distinguish which track the vehicle was on, applying an actual track number and track class to the survey data would require detailed information from the railroads to be cross-referenced to specific GPS coordinates in a look-up table. This testing revealed that with the proper reference information provide by a railroad, the autonomous system would be able to reliably identify track number and other important geo-referenced railroad information in multi-track locations.

3.1.7 *Stage 1 Testing*

ATGMS testing evolved throughout Stage 1. The baseline testing concept involved three methods for evaluating ATGMS survey data:

1. Comparison of ATGMS-collected data to data collected by the manned DOTX 220 track survey vehicle.

2. Comparison of multiple ATGMS-collected data sets over the same track.

3. Field validation of ATGMS-determined exceptions by CSX maintenance personnel.

ENSCO assessed foot-by-foot geometry data stored locally on ATGMS for diagnostic purposes by comparing it to data collected by the DOTX 220 manned survey vehicle on selected test zones traversed in February and October 2008 over the Auto Train route.

Statistics summarizing the differences between ATGMS measurements and track geometry measured by DOTX 220 in February 2008 are shown in Table 1. The results show that the differences between data captured from the manned and unmanned geometry measurement systems were within acceptable repeatability limits except for the average difference between gage and crosslevel. These differences were attributed to small initial differences between the two vehicles.

Table 1: ATGMS to DOTX 220 Data Comparison Results, February 2008

	Curvature (degrees/100 ft)		Crosslevel (inches)		Gage (inches)	
	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation
Difference	**0.0028**	**0.0580**	0.1836	0.1157	0.0372	**0.0372**
Threshold	*0.01*	*0.15*	*0.03125*	*0.0625*	*0.03125*	*0.0625*

	Alignment 31’ MCO (inches)				Alignment 62’ MCO (inches)			
	Left		Right		Left		Right	
	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation
Difference	**0.0001**	**0.0293**	**0.0001**	**0.0310**	**0.0001**	**0.0380**	**0.0000**	**0.0388**
Threshold	*0.03125*	*0.125*	*0.03125*	*0.125*	*0.03125*	*0.125*	*0.03125*	*0.125*

	Profile 31’ MCO (inches)		Profile 62’ MCO (inches)	
	Left	Right	Left	Right

	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation
Difference	0.0000	0.0442	0.0000	0.0484	0.0001	0.0489	0.0001	0.0539
Threshold	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*

(values exceeding targeted thresholds indicated with red/underline)

A strip chart overlay comparison of the data collected by ATGMS and the manned DOTX 220 in February 2008 is shown in Figure 19.

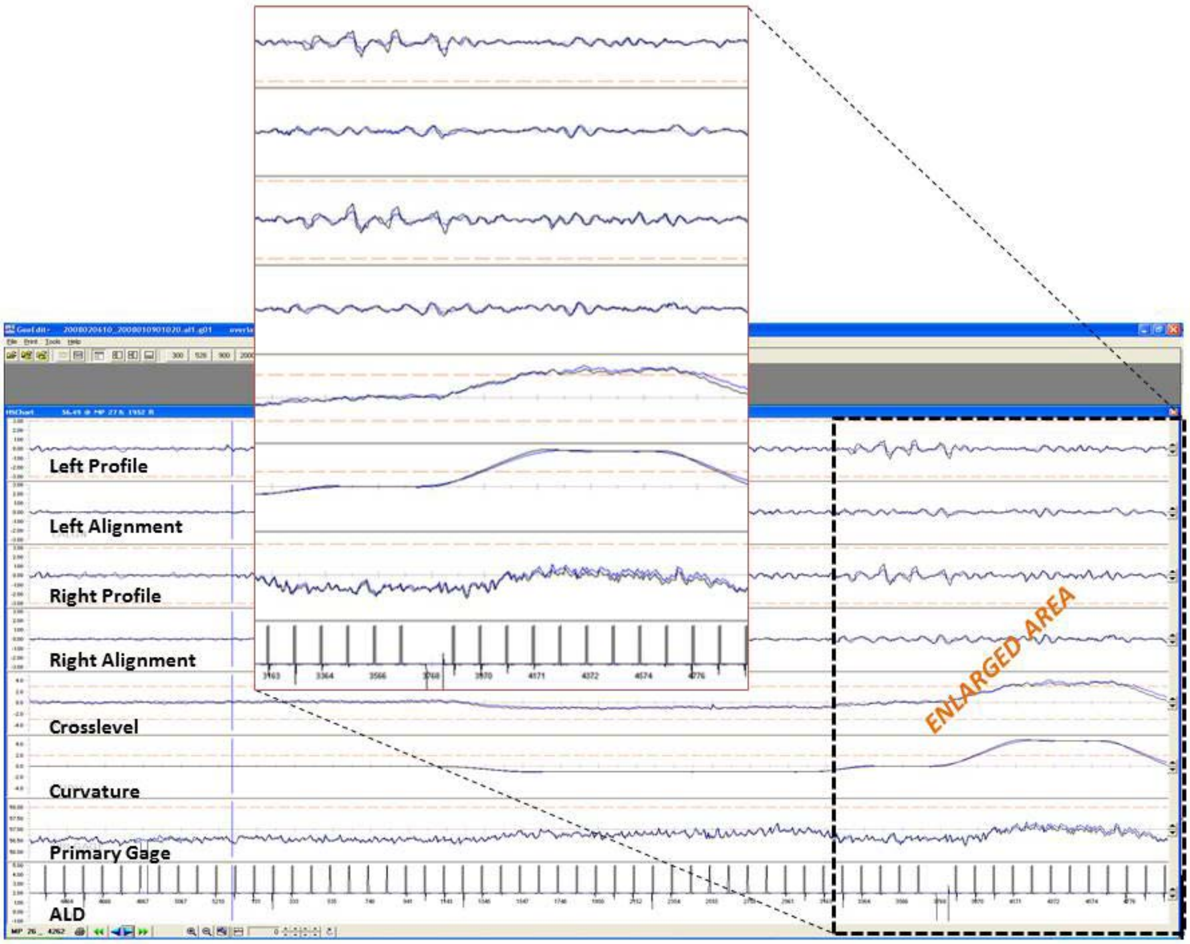


Figure 19: Track Geometry Data Overlay of ATGMS and DOTX 220, February 2008

Analysis of this early data revealed discrepancies in speed-sensitive data which was determined to be caused by a flawed tachometer calibration value. The tachomoter was re-calibrated, and the ATGMS software was adjusted to prevent oversampling of data at high speeds. Small differences in gage measurements were addressed through adjustments to gage system calibrations on ATGMS.

The repeatability of ATGMS measurements, particularly over time, was critical. Table 2 shows the repeatability of ATGMS measurements collected over an assessment zone measuring 7,000 feet in length during surveys conducted in February 2008 and July 2008. Comparisons of ATGMS measurements taken 5 months later indicates good agreement.

Table 2: Comparison of ATGMS Measurements over 7000-foot Evaluation Zone, February 2008 and July 2008

	Curvature (degrees/100 ft)		Crosslevel (inches)		Gage (inches)	
	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation
Difference	**-0.0048**	**0.0244**	**-0.0221**	**0.0617**	**-0.0092**	**0.0620**
Threshold	*0.01*	*0.15*	*0.03125*	*0.0625*	*0.03125*	*0.0625*

	Alignment 31' MCO (inches)				Alignment 62' MCO (inches)			
	Left		Right		Left		Right	
	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation	Mean Diff.	Std. Deviation
Difference	**-0.0001**	**0.0332**	**0.0001**	**0.0301**	**0.0001**	**0.0385**	**0.0002**	**0.0380**
Threshold	*0.03125*	*0.125*	*0.03125*	*0.125*	*0.03125*	*0.125*	*0.03125*	*0.125*

	Profile 31' MCO (inches)				Profile 62' MCO (inches)				Profile 124' MCO (inches)			
	Left		Right		Left		Right		Left		Right	
	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.	Mean Diff.	Std. Dev.
Difference	0.0000	0.0345	0.0000	0.0338	-0.0001	0.0380	0.0001	0.0374	-0.0002	0.0432	0.0001	0.0406
Threshold	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*	*0.03125*	*0.0625*

The remaining Stage 1 activities focused on general system improvements including the processing of track geometry exceptions, particularly with respect to filtering of false exceptions. Results of these efforts are discussed in Section 4.1.

3.1.8 *Conclusions and Lessons Learned*

Stage 1 efforts between January 2008 and March 2011 validated the feasibility of ATGMS. The deployed system achieved overall objectives and provided a test bed for improving the baseline hardware design, accumulating test data, testing software exception filtering algorithms, and refining test procedures for succeeding ATGMS development stages.

The major results of Stage 1 ATGMS development were highlighted by the following:

- ATGMS produced repeatable data over time, a key aspect to the reliability of the system and its data products.
- The system was generally reliable.
- Automatic data filtering was effective in removing instances in which certain conditions in the data yielded false exceptions, but improvements were warranted.

The following plans were established to address several issues in subsequent stages of development:

- Improvements to the truck-mounted measurement beam approach to minimize interference with truck and wheel set maintenance, and to reduce the need for custom-made support structures that significantly depend on truck type and vehicle loading environment.
- Enhancements to methods employed with the LPS to keep optical windows clear of dirt and debris.
- Increased health monitoring and automatic recovery features within the system to increase overall robustness and provide a more comprehensive look at system health and data quality than was done with the prototype system.

3.2 Stage 2: Simulation of Standard Revenue Operations

Stage 2 tested the ATGMS under long distance, revenue service operating conditions. ENSCO removed FRA's ATGMS from the Amtrak Superliner II and installed it on DOTX 221 (Figure 20, following inspection and refurbishment of the system. DOTX 221 is a sleeper-lounge car operated by FRA as a crew car during cross-country surveys on passenger train routes.

The system was altered to provide delivery of all raw sensor data, not just exception data, to the ATGMS server via a commercial cellular link. Collection and transmission of foot-by-foot data allows evaluation of overall track conditions, thus enabling users to identify track issues before safety thresholds are reached.

DOTX 221 operated in consist with FRA's DOTX 220 manned inspection vehicle (Figure 21) during ATIP surveys conducted over Amtrak passenger routes between fall 2011 and spring 2013. Tandem operation provided the opportunity to perform direct comparisons of foot-by-foot measurement and exception data collected with both systems. The operating scenario also enabled the DOTX 220 crew to conduct regular inspections of ATGMS and address any minor issues during cross-country operations.

Figure 20: Stage 2 ATGMS Host Vehicle—DOTX 221

Figure 21: ATIP Manned Geometry Inspection Vehicle—DOTX 220

3.2.1 *Stage 2 Goals*

The goals for Stage 2 development efforts include:

- Increase autonomy with near real time transmission of all ATGMS-acquired foot-by-foot sensor data via cellular transmission to the ATGMS server.

- Automatic transfer of additional system health status data and GPS location on a regular basis, providing information to augment monitoring, maintenance, operational, and technical troubleshooting efforts.

- Improved robustness through remote restart of the system.
- Automated email notifications automatically sent to specified stakeholders to inform them of ATGMS-identified exceptions, system alerts, and status.
- Validate data quality comparison of track geometry collection and analysis processes employed by autonomous and manned operations to establish and refine overall performance.
- Improved ATGMS installation to facilitate long-term deployment with minimal maintenance.

3.2.2 *Stage 2 System Configuration and Development*

ENSCO designed a new truck mount for ATGMS to accommodate structural differences between the Amtrak Car 39000 and DOTX 221. The modified measurement beam and structural modifications are shown in Figure 22.

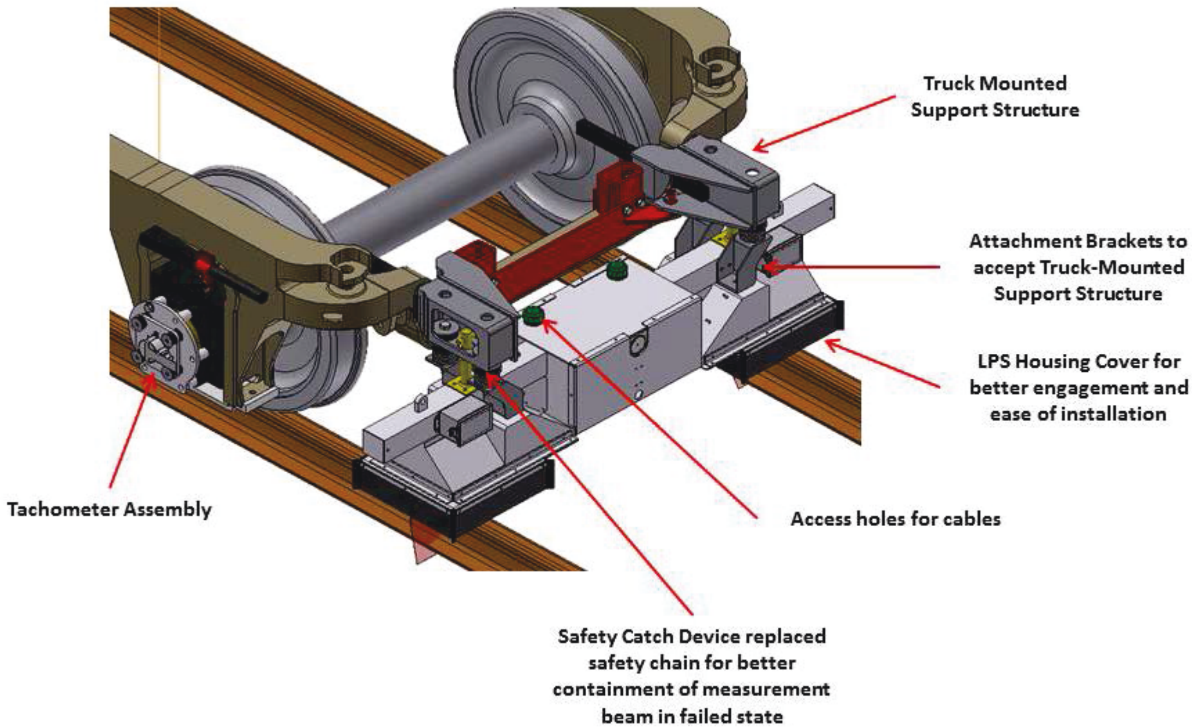


Figure 22: Stage 2 ATGMS Structural Modifications

Figure 23 is a schematic of the ATGMS configuration on DOTX 221 and Figure 24 shows the final installation of ATGMS on DOTX 221. The ATGMS was commissioned by undergoing repeatability testing on Norfolk Southern Corporation's Lurgan Branch between Shippensburg, PA, and Mount Holly Springs, PA.

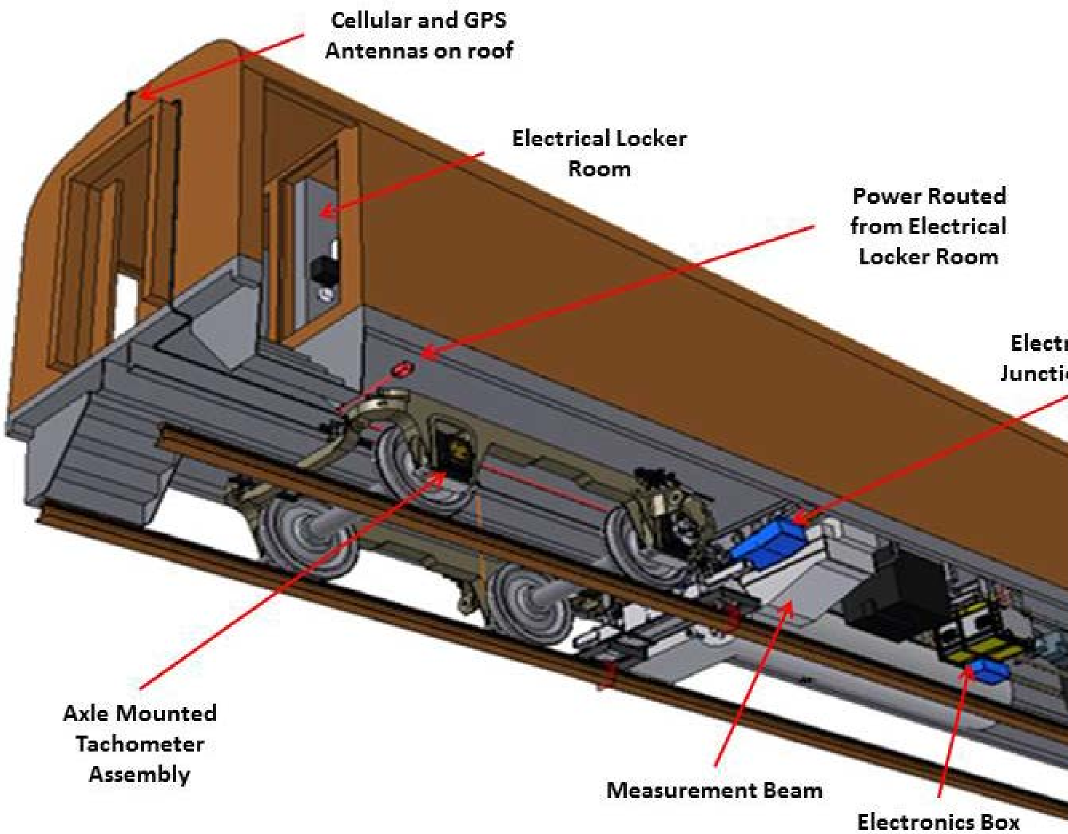


Figure 23: ATGMS Configuration on DOTX 221

Figure 24: ATGMS Installation on DOTX 221

For the DOTX 221 installation, ENSCO mounted ATGMS electronics on the exterior of the vehicle. A ruggedized, weather-sealed enclosure was selected to house the Signal Conditioning Unit (SCU), an Uninterruptable Power Supply (UPS), and a communications network switch.

The electronics enclosure support structure (Figure 25) was designed to withstand vehicle acceleration forces and allow mounting near the vehicle brake rack.

Figure 25: ATGMS Electronics Box on DOTX 221

Power to the electronics box was supplied by a transformer installed in the electrical cabinet to convert train-line 480VAC to 120VAC and an automatic power transfer switch installed to automatically switch ATGMS power to DOTX 221's backup generator when train-line power was not available.

At the start of Stage 2, ENSCO developed a new ATGMS data process. Raw, foot-by-foot sensor data was packaged, queued, and transmitted to ATGMS servers for processing, analysis, and storage in 528 foot packets, each containing a unique packet identifier. At the server, the packages were arranged by identifier and data processed for insertion into a database. To ensure all data packets were successfully transferred to ATGMS servers, an acknowledgement message was sent back to a data collection module on the vehicle upon receipt of each data packet.

As in Stage 1, an automated algorithm using specific pre-defined thresholds and signal processing methods was used to detect and verify validity of detected geometry exceptions. In addition, a web-based Remote Editor Console application (see Section 3.1.3) was developed to enhance ATGMS information management and quality assurance. The final architecture of ATGMS resulting from efforts conducted during Stage 2 is shown in Figure 26.

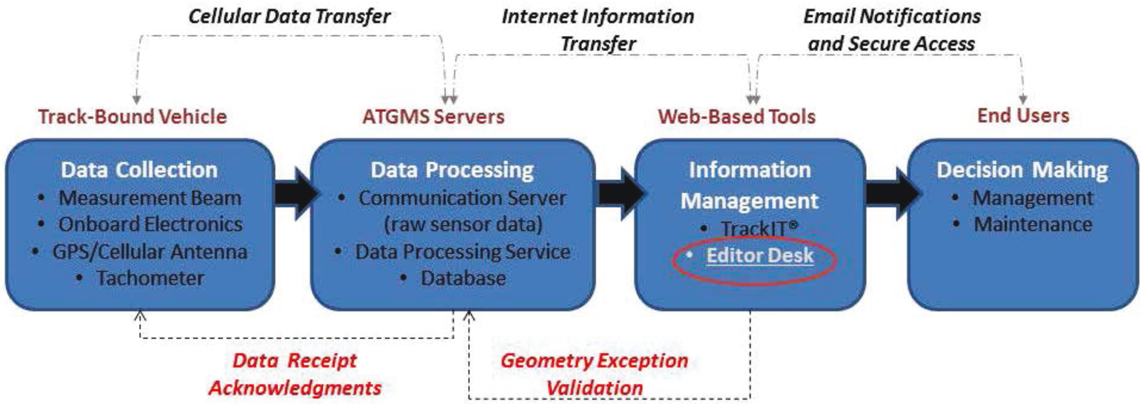


Figure 26: Stage 2 ATGMS Final Architecture

3.2.3 *Stage 2 Testing*

ATGMS on DOTX 221 was operated in consist with FRA's DOTX 220 as part of FRA's ATIP Amtrak assessment surveys between August 21 and November 4, 2011, during which time the system collected more than 4,300 miles of foot-by-foot geometry data. The 2011 run was used to identify and remediate issues related to hardware and onboard electronics, data transfer and overall quality as well as the automated detection and reporting of geometry exceptions. Analysis of the 2011 survey identified several hardware and software issues of varying degrees of criticality that were addressed in advance of 2012 operations.

DOTX 221 was operated in consist with DOTX 220 during Amtrak assessment surveys conducted between March and June 2012 over approximately 19,000 track miles; details of the survey are provided in Table 3.

Table 3: March 2012 Amtrak Assessment Survey

Origin	Destination	Survey Miles	Start Date	End Date
Washington, DC	New Orleans, LA	1,155	03/29/2012	03/30/2012
New Orleans, LA	Los Angeles, CA	1,939	04/02/2012	04/04/2012
Los Angeles, CA	Oakland, CA	468	04/06/2012	04/06/2012
Oakland, CA	Los Angeles, CA	468	04/06/2012	04/06/2012
Los Angeles, CA	Chicago, IL	2,222	04/09/2012	04/11/2012
Chicago, IL	New Orleans, LA	918	04/23/2012	04/24/2012
New Orleans, LA	San Antonio, TX	575	04/25/2012	04/25/2012
San Antonio, TX	Chicago, IL	1,305	04/30/2012	05/01/2012
Chicago, IL	Washington, DC	919	05/03/2012	05/04/2012
Washington, DC	Miami, FL	1,288	05/07/2012	05/08/2012
Miami, FL	Washington, DC	930	05/10/2012	05/10/2012
Washington, DC	Chicago, IL	777	05/21/2012	05/22/2012
Chicago, IL	Oakland, CA	1,791	05/23/2012	05/24/2012
Oakland, CA	Seattle, WA	916	06/01/2012	06/01/2012
Seattle, WA	Chicago, IL	2,203	06/04/2012	06/06/2012
Chicago, IL	Boston, MA	1,020	06/07/2012	06/07/2012

The performance of ATGMS was characterized by:

- Exceptions to the track geometry limits specified in the FRA Track Safety Standards detected by each system. Geometry exceptions reported by FRA's manned geometry inspection system on DOTX 220 were considered as "ground truth" for this analysis.
- Foot-by-foot track geometry data collected by the unmanned and manned systems over more than 314,000 non-consecutive feet of the survey. Areas for comparison were selected based on locations with track geometry exceptions as reported by the manned system onboard DOTX 220. Differences in gage, profile, alignment, crosslevel, and curvature measurements collected by the two systems were compared to established thresholds used by FRA to assess overall agreement between multiple measurement systems.

The analyses are detailed in ENSCO Document SERV-REPT-0000507, provided in Appendix A. For each portion of the overall survey, ENSCO considered numerous foot-by-foot geometry comparisons such as that illustrated in Figure 27. For each geometry parameter considered, the mean and maximum difference between measurements as well as the standard deviation between the measurements from the two systems were determined. The results were used to determine overall ATGMS performance.

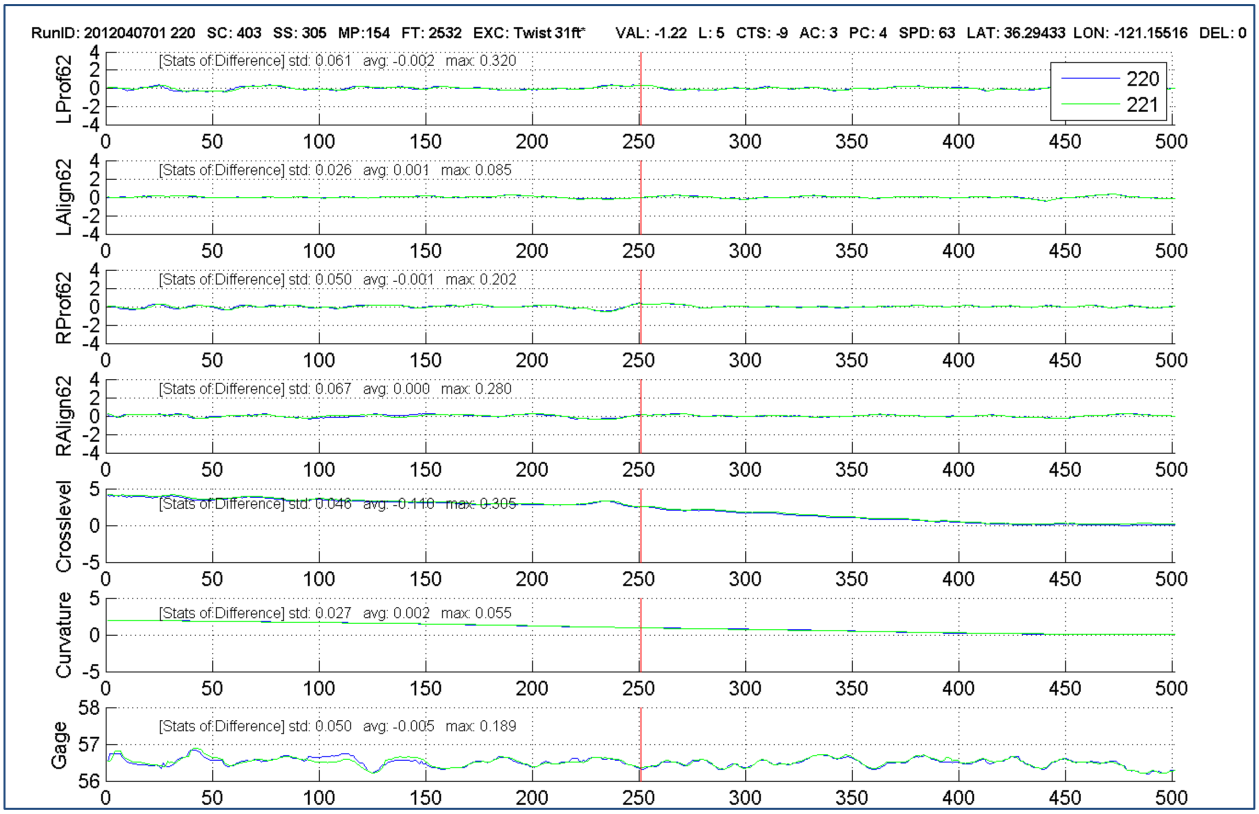


Figure 27: Comparison of Data Collected with DOTX 220 and ATGMS Between Oakland and Los Angeles—April 7, 2012

Summary statistics from over 351,000 feet of track are shown in Table 4. Despite crosslevel and curvature measurement differences being slightly higher than acceptable (which resulted in adjustment of calibration settings on the ATGMS), the analysis showed that that the quality of data collected by ATGMS on DOTX 221 was comparable to that collected by the manned track geometry system onboard DOTX 220.

Table 4: Statistics of ATGMS and ATIP Foot-by-Foot Track Geometry Data, March 2012 Amtrak Assessment Survey

Geometry Parameter	Mean Difference	Standard Deviation
Profile (Inches)	-0.005	0.083
Alignment (Inches)	0.000	0.055
Crosslevel (Inches)	<u>-0.078</u>	<u>0.110</u>
Curvature (Deg.)	<u>0.017</u>	0.031
Gage (Inches)	-0.011	0.031

(Results outside expected acceptable limits are shown in red/underline font)

Not all ATGMS-generated exceptions matched the 1,193 reported exceptions from the DOTX 220 manned track geometry inspection vehicle. Each of the mismatched exceptions was attributed to one of seven cause categories with the most critical factors affecting ATGMS performance being associated with:

- ATGMS speed-based class of track determination logic. Manned ATIP systems employ the actual class of track from track tables and slow order information provided by the railroad. At this stage of development, ATGMS used the measured vehicle speed. Therefore, if the vehicle speed was lower than the posted class due for any reason, the class of track used by ATGMS would be lower than what would have been employed by ATIP resulting in ATGMS not detecting geometry exceptions.
- Small differences in geometry measurements from the two systems resulting from the systems being on two different vehicles.
- Logic used with ATGMS failing to remove potential defects that were caused by track features that traditionally create issues for automated measurement systems, such as switches, or occasional data issues resulting from direct sunlight on the optical sensors. These events are typically removed from the survey results by experienced survey crews.
- Erroneous deletion and/or validation of exceptions in the automated exception processing.

Following assessment of the performance of ATGMS during the 2012 Amtrak Assessment Survey, ENSCO and FRA commenced with the development of the Remote Editor Console, described in Section 3.1.3, to augment ATGMS track class determination logic and automated exception editing.

The use of ATGMS in conjunction with Remote Editor Console was initially evaluated during surveys conducted with DOTX 221 in Amtrak revenue service operations on Washington, DC - Miami, FL, and Washington, DC - Chicago, IL, surveys conducted between December 2012 and April 2013. Following these tests, FRA conducted a complete evaluation of DOTX 221 ATGMS operations during the 2013 ATIP Amtrak Assessment Survey when DOTX 221 was not connected to the manned DOTX 220 inspection vehicle. Details of the assessment are presented in ENSCO Document SERV-REPT-0000578, provided in Appendix B.

The 2013 ATIP Amtrak Assessment consisted of 17 one-way trips starting in Washington, DC, on July 29, 2013, and ending in Washington, DC, on September 29, 2013, covering more than 19,000 miles of track as listed in Table 5.

Table 5: July 2013 ATIP Amtrak Assessment Survey

Origin	Destination	Route Miles	Start Date	End Date
Washington, DC	Miami, FL	1,235	7/29/2013	7/30/2013
Miami, FL	Washington, DC	1,164	8/1/2013	8/2/2013
Washington, DC	New Orleans, LA	1,152	8/12/2013	8/13/2013
New Orleans, LA	Chicago, IL	934	8/14/2013	8/15/2013
Chicago, IL	Emeryville, CA	2,438	8/19/2013	8/21/2013
Oakland, CA	Seattle, WA	913	8/27/2013	8/28/2013
Seattle, WA	Chicago, IL	2,205	8/29/2013	8/30/2013
Chicago, IL	Washington, DC	922	9/3/2013	9/4/2013
Washington, DC	Chicago, IL	780	9/6/2013	9/7/2013
Chicago, IL	San Antonio, TX	1,305	9/9/2013	9/10/2013
San Antonio, TX	New Orleans, LA	573	9/13/2013	9/13/2013
New Orleans, LA	Chicago, IL	934	9/16/2013	9/17/2013
Chicago, IL	Los Angeles, CA	2,265	9/18/2013	9/20/2013
Los Angeles, CA	Oakland, CA	464	9/23/2013	9/23/2013
Oakland, CA	Los Angeles, CA	464	9/24/2013	9/24/2013
Los Angeles, CA	Chicago, IL	2,728	9/25/2013	9/28/2013
Chicago, IL	Washington, DC	780	9/29/2013	9/29/2013

As exception data became available in the ATGMS database, an operator used the web-based Remote Editor Console to correct for actual track class as well as individual track number and to validate individual exceptions and overall track measurement quality by considering foot-by-foot geometry data, system health information, and other system data. Confirmed exceptions were sent to FRA personnel and railroad representatives.

As part of the data evaluation process throughout the 2013 Amtrak Assessment Survey, foot-by-foot geometry data collected over selected track segments on multiple days were compared to assess overall data stability. This evaluation data included two sets of geometry data collected on the same track between Los Angeles, CA, and Oakland, CA, on consecutive days; two sets of geometry data collected 40 days apart on the same track between Memphis, TN, and New Orleans, LA; and two sets of geometry data collected 19 days apart on the same track between Tempe, TX, and San Antonio, TX. Details of this analysis are provided in Appendix B. Statistics of differences between the sets of geometry data on the cited track segments showed that data collected with ATGMS were relatively consistent given changes that can be expected in the track over the periods of time considered. Table 6, taken from Appendix B, illustrates the repeatability of the ATGMS measurements over the same track over consecutive days; the only parameter outside the expected values was the difference in crosslevel, which necessitated additional adjustments to calibration parameters.

Table 6: Statistics of Difference between Foot-by-Foot Geometry Measurements Collected Between Los Angeles, CA, and Oakland, CA, September 23–24, 2013

Geometry Parameter	Mean Difference	Standard Deviation
Gage (Inches)	-0.00627	0.02865
Crosslevel (Inches)	0.05907	0.05386
Curvature (Deg/100')	-0.00872	0.05733
L Profile 31' (Inches)	0.00003	0.03736
R Profile 31' (Inches)	0.00005	0.03662
L Alignment 31' (Inches)	0.00007	0.02970
R Alignment 31' (Inches)	0.00004	0.03024
L Profile 62' (Inches)	0.00003	0.03983
R Profile 62' (Inches)	0.00003	0.03912
L Alignment 62' (Inches)	0.00004	0.03397
R Alignment 62' (Inches)	0.00001	0.03383
L Profile 124' (Inches)	0.00006	0.04260
R Profile 124' (Inches)	0.00005	0.04175
L Alignment 124' (Inches)	0.00005	0.05628
R Alignment 124' (Inches)	-0.00000	0.05616

(Results outside expected acceptable limits are shown in red/underline font)

Successful operation of ATGMS throughout the 2013 Amtrak Assessment program constituted conclusion of Stage 2 efforts. Evaluation of system performance during the 2013 Amtrak Assessment resulted in a series of recommendations for hardware and software enhancements targeted at improving ATGMS reliability as well as performance of the Remote Editor Console operations. These enhancements were addressed by FRA's RRS as the use of the remote measurement system was integrated into its standard operations.

3.2.4 *Conclusions and Lessons Learned*

Stage 2 efforts resulted in the successful demonstration of FRA's ATGMS on standard rail equipment while running in typical revenue service. ATGMS was re-engineered to allow for transmission of foot-by-foot raw geometry measurements to servers for processing, evaluation and distribution to survey stakeholders. Other key features of the technology that were either developed or refined during this stage included:

- Automated health and status reporting
- Self-diagnostics and auto-recovery features
- Improved hourly "status" email messages that provided detailed system and survey information
- On-demand "Alert" messages that automatically report sensor malfunction

- Self-diagnostic and auto-recovery features on the Data Collection Module to detect communication issues, corruption of data or configuration files, etc., and initiate a pre-defined sequence of actions to shutdown and restart the system.

A comparison of track geometry collected by ATGMS to that collected by the manned system onboard FRA's DOTX 220, illustrated that the two systems produced data of equal quality with differences between measured geometry data within acceptable limits established for measurements from multiple vehicles for this effort (see Table 4, Appendix A). Statistics of differences between multiple geometry surveys on selected track segments within short time periods showed that measurements collected with ATGMS were relatively (see Table 6, Appendix B). Exceptions generated by ATGMS and the manned system were compared and differences in reporting were attributed to several causes, among them being the speed-based class of track determination originally employed by ATGMS approach, and the automated exception validation logic used with ATGMS. To address these issues, ENSCO established a Remote Editor Console to allow for review of ATGMS-reported exceptions by experienced personnel in order to provide an additional level of quality assurance for results transmitted to FRA and railroad personnel. Although refinements and enhancements continued following the formal end of this stage, the performance of the system was such that FRA adopted this technology and employed it during FRA's RRS evaluations of Amtrak passenger routes starting in 2013.

3.3 Stage 3: Advanced Measurement Technology Development

Stage 1 testing revealed that the use of a truck-mounted measurement beam design has several drawbacks, including interference with truck or axle maintenance as well as the need for custom-made support structures. FRA initiated Stage 3 efforts in July 2011 to develop sensor technologies that facilitated the design of a carbody-mounted ATGMS, and to demonstrate that design in passenger service operations. A carbody-mounted ATGMS offers the benefits of minimal interference with truck and wheel maintenance activities, improved protection of the measurement platform from flying debris, and flexible installation on a wide range of vehicle designs resulting in reduced installation and maintenance costs as compared to traditional truck-mounted approaches.

Working in partnership with FRA, Amtrak offered use of Amfleet I passenger car 82602 as the host vehicle for the carbody-mounted ATGMS. The vehicle is shown in Figure 28.

Figure 28: Stage 3 ATGMS Host Vehicle, Amtrak 82602

Selection of Amtrak's 82602 as the host vehicle was based on its ability to provide HEP to ATGMS and joint operations on the NEC with Amtrak's track inspection vehicle designated as 10002. Amtrak's 10002, shown in Figure 29, carries a truck-mounted track geometry measurement system and is manned by a typical operations crew.

Figure 29: Amtrak's Manned Inspection Vehicle, Amtrak 10002

3.3.1 *Stage 3 Goals*

The Stage 3 goal was to develop and demonstrate new sensor technologies and processing algorithms to support a carbody-mounted ATGMS. ATGMS performance would be evaluated by comparing the quality of collected foot-by-foot geometry measurements and reported exceptions with data collected using the traditional truck-mounted, manned geometry measurement system aboard Amtrak's 10002.

3.3.2 *Stage 3 System Development and Configuration*

Migration from the Stage 1 and 2 truck-mounted ATGMS to a carbody-mounted system required numerous hardware and software modifications. Design considerations for the carbody-mounted ATGMS included:

- **Laser Scanning Sensor** – The central consideration for the carbody-mounted system was the laser scanning sensors design. Features of the sensors employed in the final version of the system included the following:
  - The lasers within the sensors had sufficient power to illuminate the rail from a higher location as compared to that associated with a truck-mounted system.
  - The sensor was designed to have sufficient visual range in both distance and viewing angle to maintain an image of the rail despite relatively large motion of the instrumentation beam relative to the track. Vehicle dynamics and track geometry on the NEC were used to establish range requirements corresponding to ±2 inches vertical/lateral motion of the measurement beam and ±3 degrees of carbody roll.
  - The lasers within the sensor were rated to be Class 3R, considered safe if handled carefully with restricted beam viewing. This requirement was established to maintain safety. The measurement system was configured to turn off laser power when the vehicle speed dropped below a configurable threshold. In addition, provisions for protective covers were included in the design of the measurement beam to shield the lasers from accidental viewing by railroad personnel or the public.

    Algorithms for data processing services were modified to account for the extended-range laser scanning sensors as well as overall carbody dynamics.
- **Instrumentation Beam Design and Mounting Approach** – ENSCO designed the ATGMS instrumentation beam to meet its fundamental requirements—housing inertial sensors, securing laser scanning sensors in the optimum location, providing protection from the environment while maintaining adequate access to all sensors and electronics for ease in servicing—while featuring a modular concept that allowed for convenient mounting to a wide range of vehicles.

  The final design of the carbody-mounted instrumentation beam is shown in Figure 30. The beam assembly is composed of the main aluminum weldment beam that houses the collection of sensors, an ALD sensor used to detect the location of switches, and a set of four mounting brackets for connection to the carbody.

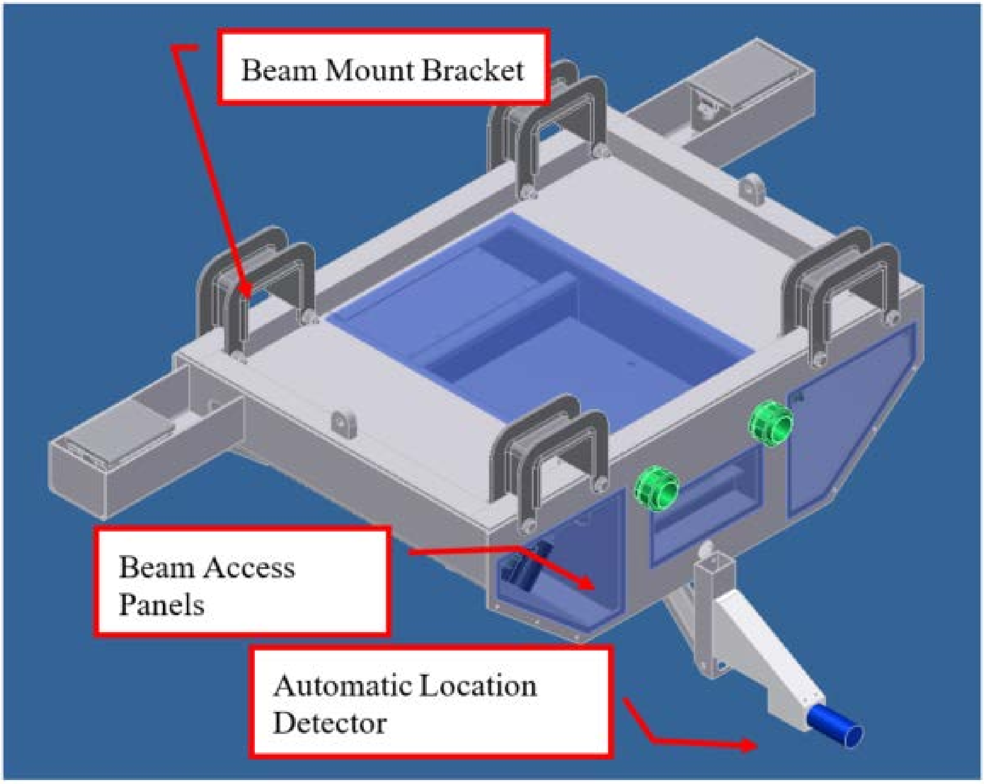


Figure 30: ATGMS Carbody-Mounted Instrumentation Beam

To attach the instrumentation beam to the vehicle, ENSCO designed a mounting frame assembly that is illustrated in Figure 31. The beam mount brackets shown in Figure 30 were designed to install around members of the beam mounting frame shown in Figure 31 by directly bolting the mount brackets to the frame. The beam mounting frame was attached to the center sill and crossbearer of the carbody floor using bolted connections. In case of primary connection hardware failure, the brackets will drop onto the beam mounting frame members preventing the beam assembly from dropping below the clearance profile for the vehicle. Illustrations of the overall mounting approach are provided in Figure 32. The benefits of this design are highlighted by the minimal interference with existing components of the vehicle and a relatively simple beam mounting frame.

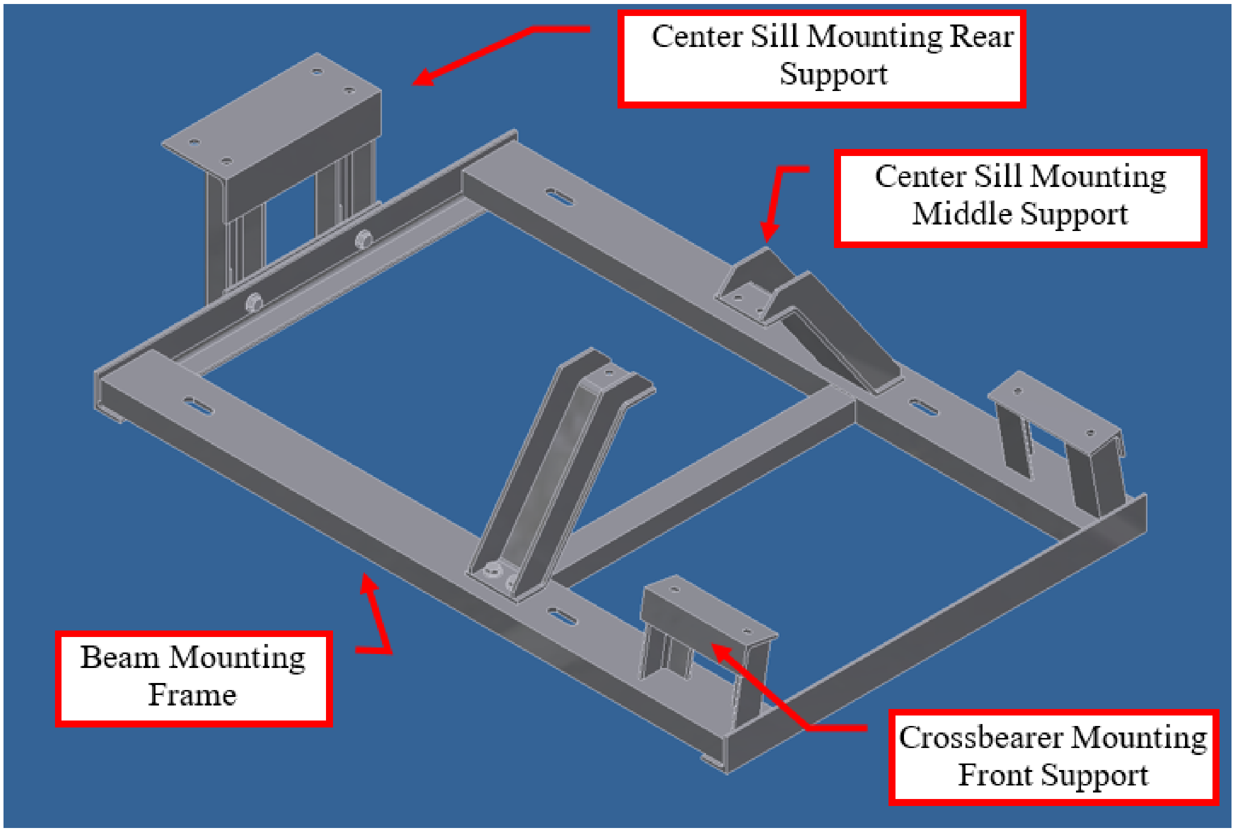


Figure 31: Custom Mounting Frame Assembly

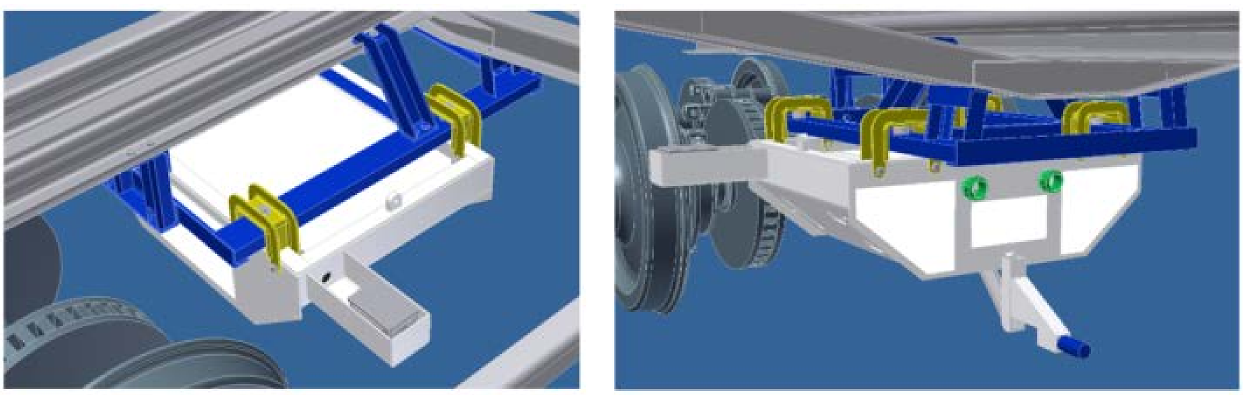


Figure 32: Illustrations of Mounting Approach for Carbody-Mounted ATGMS

- **ATGMS Electronics and Enclosure** – Minimal modification of the host vehicle was one of the goals of the carbody-mounted ATGMS design approach. Therefore, all electronics associated with the geometry measurement system were located on the exterior of the Amtrak vehicle. All data acquisition, signal conditioning and communication electronics were in a single enclosure depicted in Figure 33. Similar in design to the electronics enclosure employed in Stage 2 efforts, the enclosure employed in Stage 3 featured passive ventilation to increase heat transfer to maintain operational temperatures for components within the enclosure. Filter material was used with the air intake near the bottom of the enclosure and exhaust vent near the top of the enclosure to minimize the introduction of dust, dirt, moisture, and debris into the enclosure.

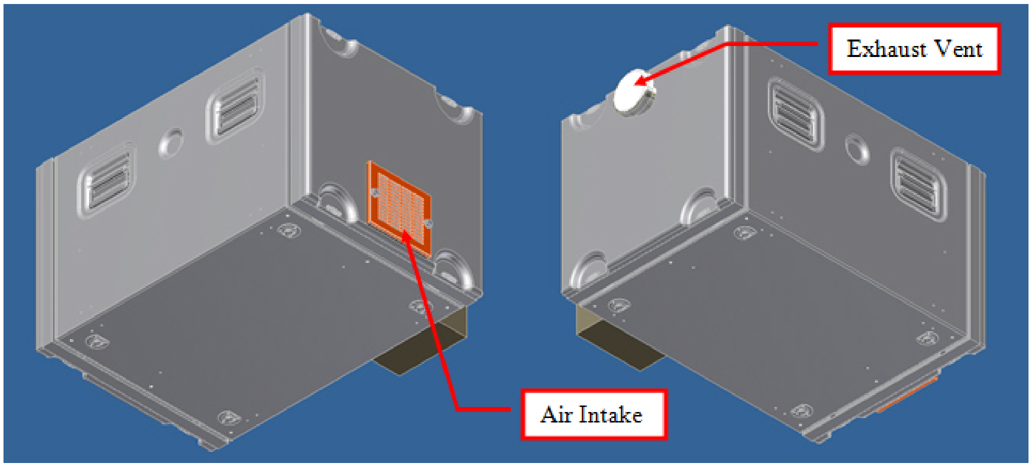


Figure 33: Carbody-Mounted ATGMS Electronics Enclosure

ENSCO employed mounting braces designed to be similar to auxiliary equipment mounting cross braces used on Amtrak equipment. Two such mounting braces were added to the underframe of the Amfleet I between existing structural members. A saddle designed to support the electronics enclosure was attached to the mounting braces. This arrangement is illustrated in Figure 34.

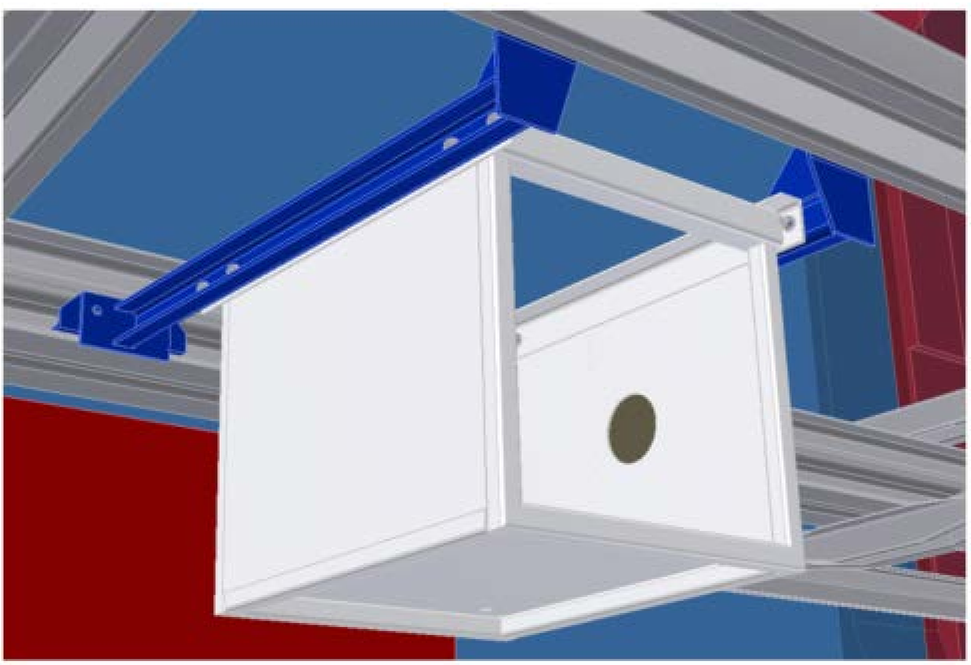


Figure 34: Electronics Enclosure Saddle and Mounting Braces

Amtrak provided vehicle HEP to the instrumentation through the vehicle's circuit breaker box. A dedicated circuit breaker, a transformer, and an automatic power switch were installed inside the existing electrical cabinet interior of the car near the B-end. All other elements of the power and electronics were located on the exterior of the vehicle. The final installation of the electronics enclosure is depicted in Figure 35.

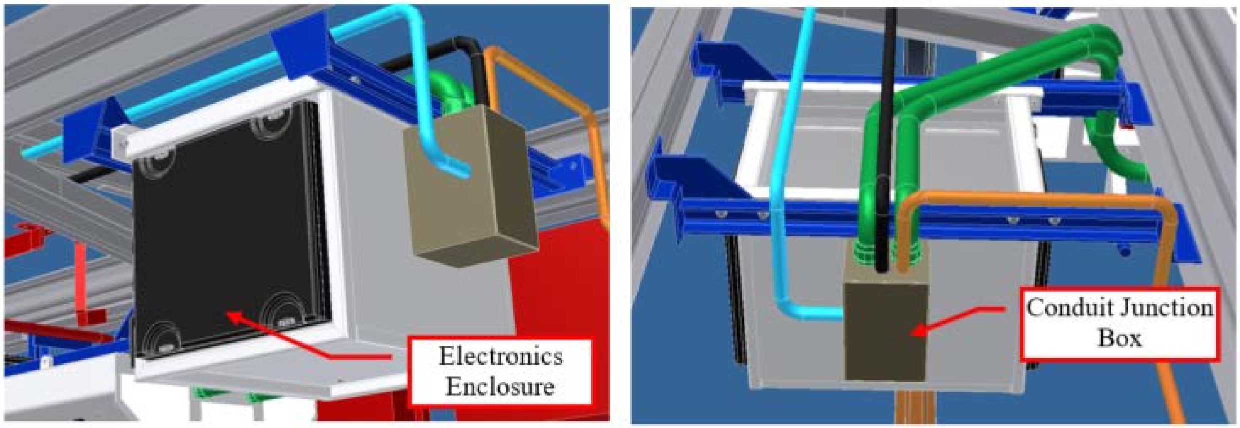


Figure 35: Illustration of ATGMS Electronics Enclosure Installation

- **Tachometer Assembly** - ENSCO implemented a tachometer mounting scheme based on the approach employed on the Budd Pioneer III truck on Amtrak's 10002 inspection car, as shown in Figure 36. The mounting arrangement utilized a channel arm that extends out from an attachment point located on the truck frame to provide a mounting surface for the stator portion of the encoder. This arm is designed to rotate about its attachment point to provide enough flexibility to allow the encoder to follow the slight vertical movement of the axle resulting from the flexing of the primary suspension. A rubber isolator was utilized at the pivot joint of the channel arm to compensate for any lateral movement of the axle. The encoder mount employs a bolt-on adapter that contains an isolated shaft that connects the axle to the encoder itself. ENSCO designed a safety catch system to prevent the parts from falling beyond the clearance envelope.

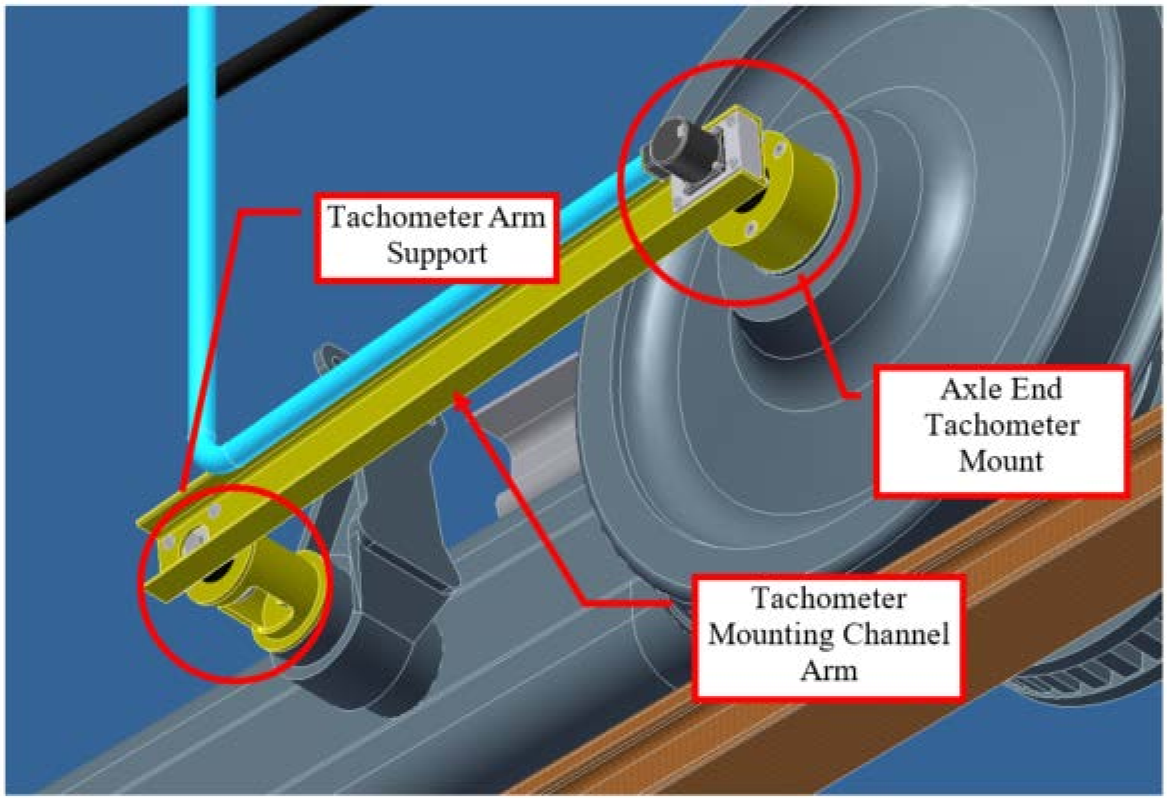


Figure 36: Amtrak's 82602 Tachometer Assembly Layout

Detailed stress analyses were conducted on all mechanical components. ENSCO installed the components presented in this section at Amtrak's Ivy City Maintenance Facility under the supervision of Amtrak personnel. GPS and cellular antennae were mounted on the roof of the host Amfleet I railcar at the A-end of the car as close to the car's centerline as possible. Figure 37 depicts the final layout of ATGMS components on Amtrak Car 82602; photographs of the installation are provided in Figure 38.

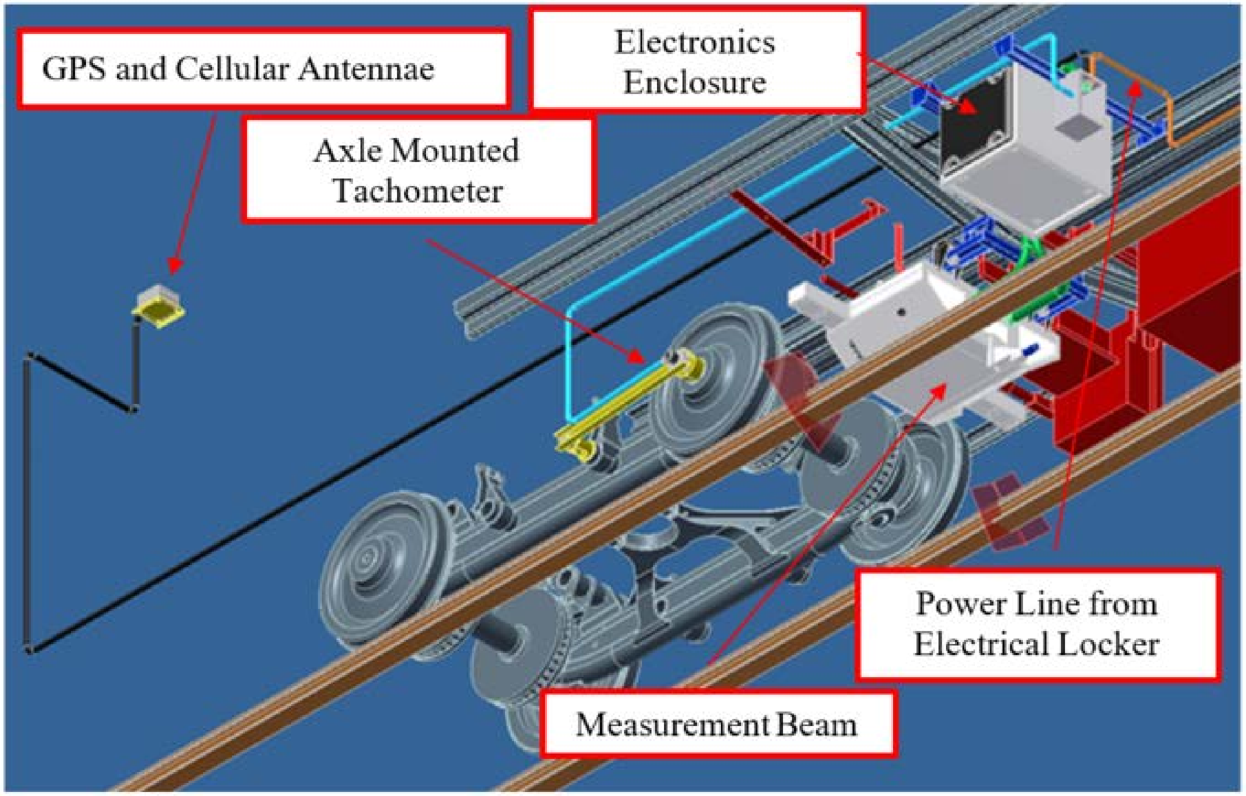


Figure 37: Carbody-Mounted ATGMS Configuration on Amtrak's 82602

Figure 38: Stage 3 Carbody-Mounted ATGMS Installation, Amtrak's 82602

Installation of the carbody-mounted ATGMS on Amtrak's 82602 was completed and accepted in August 2012. The system was commissioned immediately following installation by undergoing standard geometry car repeatability tests.

The carbody-mounted ATGMS operational approach was the same as that used during the initial efforts conducted under Stage 2 testing. All geometry data was transmitted to TrackIT® servers while exception reports, as well as status messages, were sent to ENSCO for analysis and review. The Remote Editor Console developed in the latter parts of Stage 2 development was not used during testing of the carbody-mounted system as the system development was not completed in time.

3.3.3 *Stage 3 Testing*

Amtrak operated Car 82602 as part of passenger revenue service on NEC, covering more than 50,000 miles between October 2012 and August 2013. Two round-trip surveys between Washington, DC, and Boston, MA, were conducted with ATGMS operating in the same consist with Amtrak's 10002 track inspection vehicle to evaluate the performance of the carbody-mounted system compared to that of a traditional truck-mounted system.

The first survey was conducted on October 21 and 22, 2012, and the results were used to adjust the ATGMS software. The data from the October 2012 tests indicated a problem with the tachometer assembly. ENSCO added reinforcements to the mounting system to eliminate stress on the electrical and mechanical connections.

The second survey was conducted on April 2 and 3, 2013. Foot-by-foot geometry measurements and geometry exception data generated between New York, NY, and Washington, DC, on April 3, 2013, were used to evaluate and document ATGMS performance with results from Amtrak's 10002 considered as the ground truth. It is important to note the following operational differences between the two survey vehicles during the April 2–3 survey:

- Amtrak's 10002 employed its inspection car crew to review exceptions identified by Amtrak's measurement system. ATGMS relied on an automated exception editor designed to identify candidate geometry exceptions and accept or reject events as "true" exceptions based on a set of mathematical rules. The manual geometry review process employed by the Amtrak approach relies on the operator's experience and ability to observe both track and environmental conditions when deciding if an event is a "true" exception or not.
- Personnel onboard Amtrak's 10002 were able to confirm proper track class designation. During NEC survey operations, ATGMS relied solely on vehicle speed to the determine class of track to identify geometry exceptions. Therefore, ATGMS is prone to declare a lower class of track if the train speed is below the posted speed, creating discrepancies in exception detection results

The analysis of the exceptions generated by both the ATGMS and Amtrak's 10002 during the April 2-3, 2013, survey is detailed in ENSCO Document SERV-REPT-0000528, provided in Appendix C; over which Amtrak's 10002 reported 63 exceptions. Not all ATGMS-generated exceptions matched the 63 exceptions. Mismatched exceptions were reviewed and associated with one of the following causes:

- Small differences in geometry measurements collected by the two systems
- Track class determination
- Cases of erroneous data in the ATGMS gage system
- Cases of missing GPS data in Amtrak's 10002 survey data analyzed

Alternatives to speed based determination of track class, such as detailed track maps based on railroad-provided information or real-time updating of information through a utility like the web-based application developed during Stage 2 activities, would provide additional quality control measures. Details regarding the exception analysis can be found in Appendix C.

As was done in Stage 2 efforts, geometry exceptions were used as markers for retrieving corresponding foot-by-foot geometry data collected by ATGMS and Amtrak's 10002 for detailed analysis. Analysts compared measurements collected over more than 17,500 feet of track located throughout the NEC. Results of this effort are shown in Table 7 (taken from Appendix C).

Table 7: Statistics of Difference between ATGMS and 10002 Foot-by-Foot Track Geometry Data, April 2013

Geometry Parameter	Mean Difference	Standard Deviation
L Profile 31' (Inches)	0.00000	0.0439
L Profile 62' (Inches)	-0.00000	0.0455
L Profile 124' (Inches)	0.00032	0.0523
L Alignment 31' (Inches)	0.00017	0.0394
L Alignment 62' (Inches)	0.00018	0.0614
L Alignment 124' (Inches)	-0.00000	0.1195
R Profile 31' (Inches)	0.00015	0.0559
R Profile 62' (Inches)	0.00000	0.0579
R Profile 124' (Inches)	0.00044	0.0689
R Alignment 31' (Inches)	0.00000	0.0649
R Alignment 62' (Inches)	0.00000	0.0786
R Alignment 124' (Inches)	-0.00030	0.1293
Crosslevel (Inches)	-0.02105	0.0975
Curvature (Deg/100')	0.00962	0.0528
Gage (Inches)	0.05663	0.0554

(Results outside expected acceptable limits are shown in red/underline font)

Except for the mean difference of gage and standard deviation of crosslevel measurements, statistical measures for all other measurement parameters met repeatability expectations. Both gage and crosslevel measurements can be typically addressed through reevaluation of offsets on a routine basis. Testing demonstrated that the carbody-mounted ATGMS produced data of equal quality when compared with that of a truck-mounted track geometry measurement system.

The carbody-mounted ATGMS was operated in revenue service on the NEC until August 2013. The ATGMS was periodically inspected at Amtrak's Ivy City Maintenance Facility. The system required minimal maintenance.

3.3.4 *Conclusions and Lessons Learned*

During Stage 3 ATGMS operations on Amtrak Car 82602, it was illustrated that the carbody-mounted system yielded all benefits expected over the previous truck-mounted track geometry measurement systems. The increased clearance between track and measurement beam minimized interference with truck and wheelset maintenance activities, and decreased the debris fouling of the laser and camera lenses. This tested the potential for ATGMS installation on a wide range of vehicles with reduced installation and maintenance costs.

Additional efforts to provide passive lens protection are envisioned to further reduce the amount of dirt reaching the optics, thus prolonging the time between scheduled maintenance activities. The passive ventilation built into the electronics enclosure did not have an appreciable effect on electronics performance; it did, however, introduce accumulated dust, dirt, and debris within the enclosure

3.4 Stage 4: Energy Harvesting Technology Development

In previous development stages, the ATGMS was installed on passenger rolling stock that provided sufficient electrical power to operate the measurement systems. Wide-scale deployment of ATGMS technology requires energy harvesting technologies that facilitate installation of unattended measurement systems on freight rolling stock without electrical power. Stage 4 of the ATGMS technology development plan was initiated in April 2011 to arrive at a specification for a system that could provide power to a typical ATGMS installation using a variety of power sources.

3.4.1 *Stage 4 Goals*

The goals of this stage were to arrive at the design, and system specification, for a self-contained, reliable, partially regenerative electrical power system (EPS) for ATGMS operations suitable for installation on a wide range of freight cars. In addition, the power system cannot interfere with normal operations of the host vehicle. Performance requirements for the envisioned system included:

- Minimum 200-watt continuous output power with power quality suitable for battery charging and direct powering of sensitive electronic devices.
- Energy generation sources considered, included diesel fuel, solar power and wind energy harvesting technology for battery charging with emphasis on minimizing reliance on diesel fuel.
- Automatic mixed power system control, charging, distribution, health monitoring and reporting.
- Mechanical design suitable for freight railroad environment and installation on rail car under floor assembly. The battery system may be designated for interior location.
- 90-day maintenance interval.

3.4.2 *Stage 4 Development*

ENSCO worked with New Way Solutions, LLC, throughout Stage 4 activities to specify requirements for an ATGMS-suitable energy harvesting power system. Previous research by New Way Solutions, under FRA contact, focused on the development and demonstration of a prototype energy harvesting power plant. During its early efforts, New Way Solutions developed an innovative power management electronics package that was not only considered a significant component within the requirements specification but also served as a test platform for wind energy harvesting tests conducted by New Way Solutions during Stage 4 efforts.

During Stage 4, ENSCO and New Way Solutions investigated:

- Operational and environmental conditions to be encountered by ATGMS, including vehicle speeds, wind conditions and solar radiation values, based on measured operational parameters and historical weather conditions
- Appropriate temperature, mechanical, and safety requirements for the equipment
- Features of candidate components, including batteries, solar panels and diesel generators as well as charge control system characteristics
- The likely contributions of wind energy harvesting to a deployed system
- Simulated electrical load inputs and outputs based on a computer-based model employing measured operational and environmental conditions.

Specifications were developed for a power system including recommendations for the size and number of components that would ensure 100% uptime of an ATGMS in typical freight operations.

New Way Solutions evaluated two types of wind turbines for railroad applications. The first design consisted of a rectangular air intake and a horizontally configured turbine with permanent magnet alternators (PMA) installed on each end of the turbine as shown in Figure 39. An axial turbine with a conical air intake prototype, as shown in Figure 40, was also evaluated. Over-the-road tests conducted in the fall of 2011 involving mounting the turbine arrangements on a pick-up truck to test the power generation as a function of air speed and wind direction at speeds up to 70 mph.

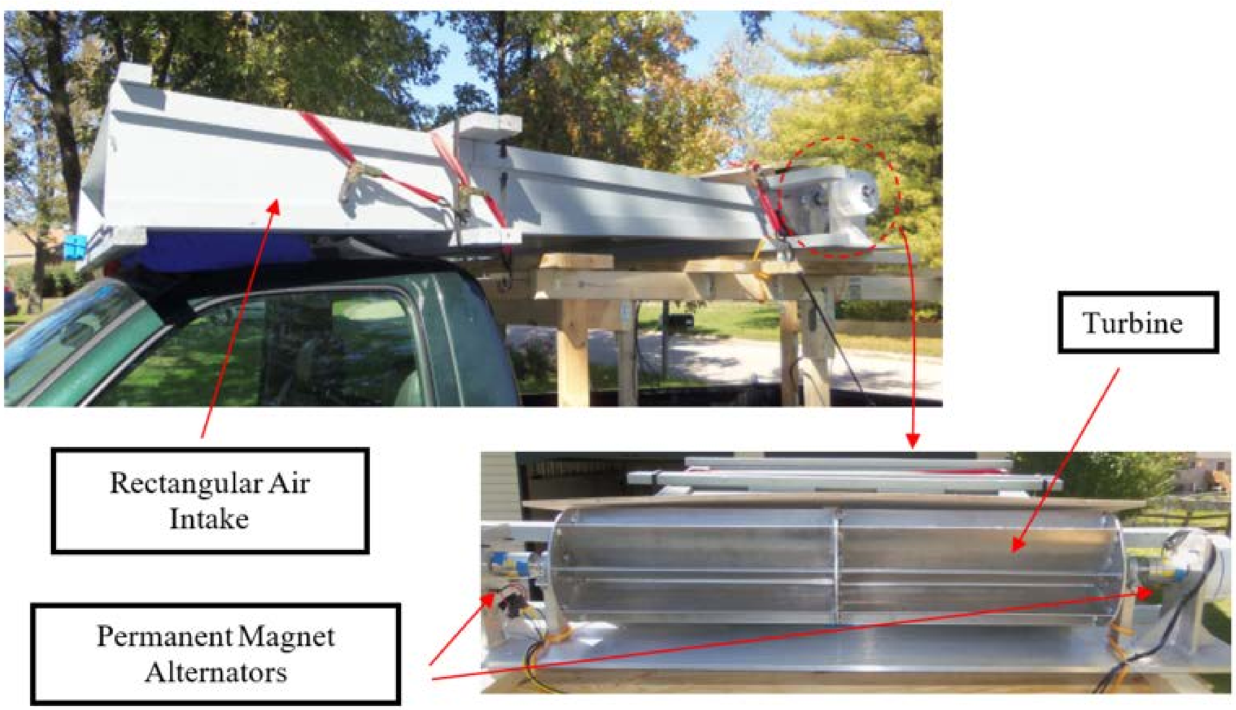


Figure 39: Horizontal Turbine and Rectangular Air Intake Configuration Prototype

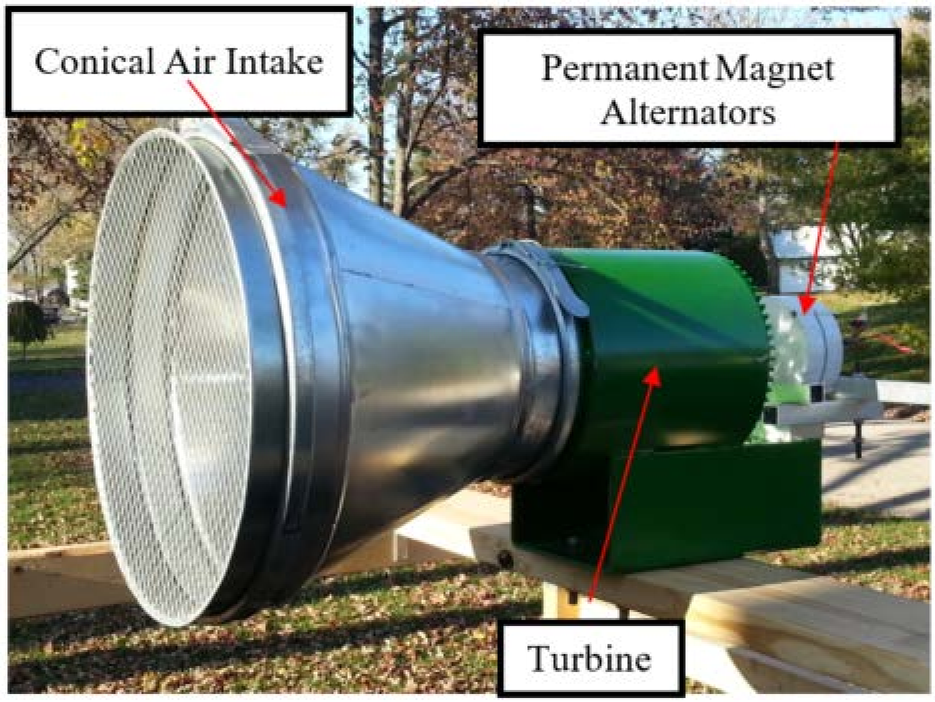


Figure 40: Axial Turbine and Conical Air Intake Configuration Prototype

Test results indicated that a wind turbine with rectangular air intake did not produce any measurable power throughout the entire speed range. The axial wind turbine with conical air intake produced a measurable power output at speeds above 30 mph. Given that typical freight trains spend much of their time traveling at speeds lower than 30 mph, it was concluded that wind power could not be used effectively as a source of power for ATGMS in freight operations.

Results obtained from an analysis of solar energy availability and fossil fuel power sources were input into a computer model developed for a parametric analysis of the overall EPS configuration. Variables in this model included:

- Number of solar panels
- Size of battery banks
- Fuel capacity of diesel generators acting both as one component of a power system and acting as the main source of power in the absence of alternative sources
- Percentage of battery bank depth of discharge (DOD)

Figure 41 illustrates the architecture of the power system resulting from the analysis. A key feature of the recommended system is the charge controller designed to autonomously manage the power generated by all sources to properly charge the battery bank and provide 100% uptime power to the ATGMS. The charge controller designed for this application can:

- Accept a maximum of forty 12-volt solar panels with a maximum rating of 5 kW
- Accept a diesel generator with a maximum rating of 3 kW
- Monitor the overall power system and generate status messages that can be transferred as part of ATGMS data via cellular communications

- Charge the battery banks using only solar power
- Turn the diesel generator on or off
- Accommodate other sources of power in the future. This accommodation was critical as FRA required that the power system be flexible to changes necessitated by operating scenarios and other drivers.

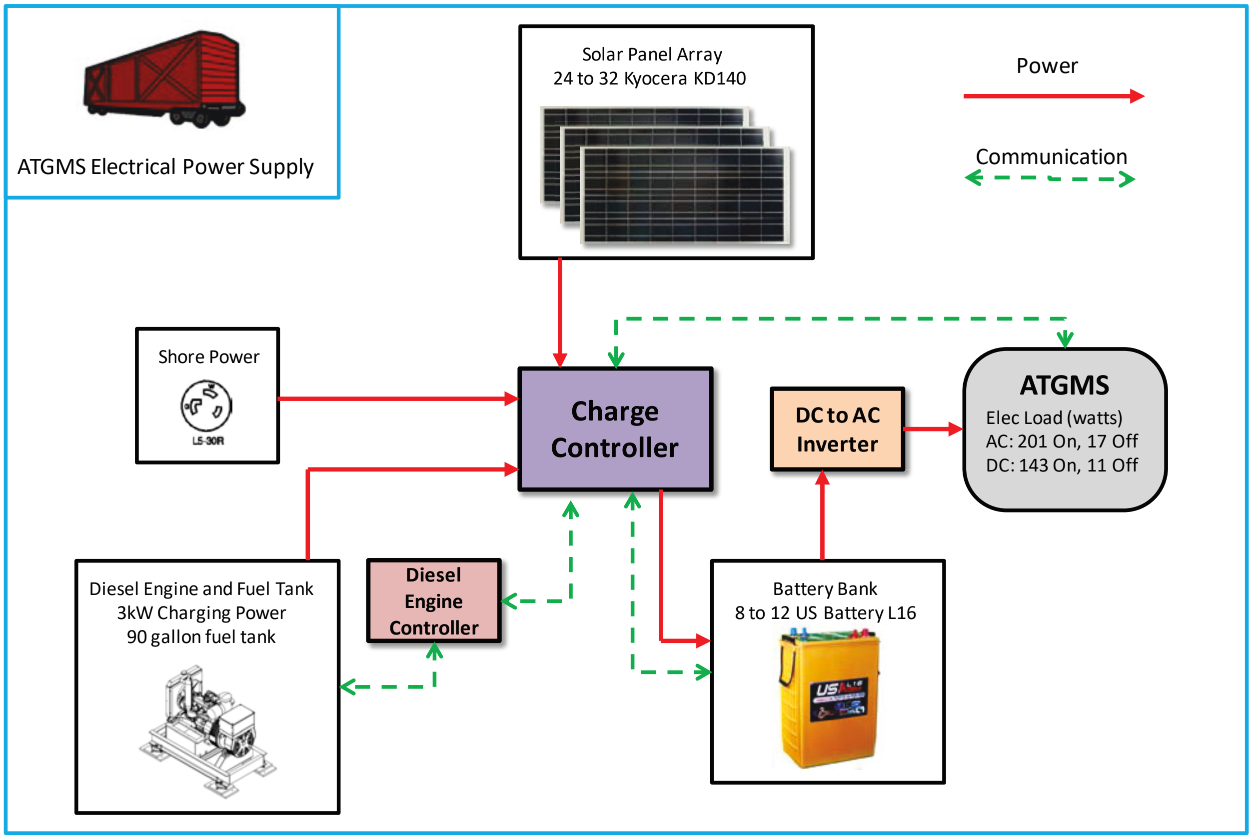


Figure 41: Proposed Electrical Power System Architecture

Details regarding the recommended configuration of the power system, along with other conclusions from this stage of research, are provided in the following section.

3.4.3 *Stage 4 Conclusions and Lessons Learned*

A computer model was used to evaluate several arrangements of the power production components. The resulting recommended designs are shown in Table 8.

Table 8: Summary of Electrical Power Supply Designs

Electrical Power Supply Design	Solar Power Components	Batteries	Diesel Generator	Notes
Conservative Approach	32 Kyocera KD140 solar panels	12 US Battery L16 batteries	1 diesel generator that can produce 3kW of charging power with a fuel consumption rate of 0.8 gallon/hr or less 90 gallon fuel tank	Arrangement will work with AC or DC ATGMS Assumes 2 hr wait period after stopping for shutdown
Efficient Use of Diesel to Reduce Solar and Battery Components	24 Kyocera KD140 solar panels	8 US Battery L16 batteries	1 diesel generator that can produce 2kW of charging power with a fuel consumption rate of 0.8 gallon/hr or less 135 gallon fuel tank	Arrangement will work with AC or DC ATGMS Assumes 2 hr wait period after stopping for shutdown
No Diesel Generator, Only Solar Panels and Batteries	32 Kyocera KD140 solar panels	12 US Battery L16 batteries	No diesel generator	Requires DC ATGMS Between 0.5 to 2 hr wait period after stopping for shutdown based on queued transmitted messages

The design and analysis process conducted within Stage 4 yielded several different conclusions and recommendations that will serve not only this effort, but will be a guide for similar activities.

1. Test results indicated that a wind turbine would not produce sufficient power for speeds typical of freight operation. Therefore, wind harvesting it is not recommended for use with an ATGMS mounted to a freight vehicle. However, a wind turbine was able to produce an appreciable amount of power at higher speeds such as those seen in passenger service. However, autonomous system use in passenger service generally does not require use of a power generation system.

2. Converting ATGMS to operate on DC power instead of AC power would have a significant improvement in performance.

3. Efficient use of a diesel generator needs to take into account the battery bank size, maximum power input accepted by the charge controller system, matching the charging run cycles to the required exercise cycles, sizing of the diesel generator itself and accommodations for a fuel supply. Features that will help decrease dependence on a diesel generator include some obvious choices, such as increasing the battery bank size, as well as other choices such as decreasing the shutdown wait time after the car stops and increasing the battery bank DOD in the charge plan.

These considerations led FRA to consider alternatives to diesel fuel generators, including methanol-based fuel cells.

Methanol is a liquid fuel that offers many advantages over diesel fuel. It is non-hazardous, with sensible precautions. Menthol is stable, has low volatility, and remains liquid over a broad temperature range. Fuel cells will require less routine maintenance than diesel generators, an important feature for unattended equipment. Methanol does not pose some of the long-term soil and water contamination issues as petroleum. Use of fuel cell technology allows for easier integration of the secondary power source into communication hardware. In addition, the use of fuel cells on an unattended vehicle allowed FRA to demonstrate the use of alternative fuels to the rail industry. For these reasons, FRA's freight car-based ATGMS used in Stage 5 efforts was equipped with a power system that employed both solar energy and direct methanol fuel cell technology as its primary and secondary sources of power for charging the ATGMS battery system.

3.5 Stage 5: Demonstration in Freight Service

In the final ATGMS development stage, FRA demonstrated ATGMS technology on a freight vehicle operating under typical revenue service conditions. The FRA carbody-mounted ATGMS was deployed on a standard box car and the system was demonstrated on short lines and regional railroads. Technology and procedures developed by FRA throughout the first four stages of this program were relied upon throughout these demonstrations.

The box car, DOTX 225, was purchased from Escanaba and Lake Superior Railroad (ELS) and refurbished and modified for ATGMS in October 2015. Images of the vehicle prior to and after refurbishment are provided in Figure 42. The vehicle was delivered to ENSCO's Chambersburg, PA, maintenance facility in February 2016 for system installation and testing.

(a) As purchased from ELS. (b) Upon completion of refurbishment.

Figure 42: FRA's Freight Boxcar DOTX 225

The ATGMS EPS was based on the system specified during Stage 4 efforts. The recommended design included the use of solar power as the primary charging method while using direct methanol fuel cell technology as a secondary source of power for charging the ATGMS battery system. While the methanol fuel cell technology was not tested during Stage 4 efforts, the testing performed under Stage 5 provided a suitable test bed to evaluate the technology. Communications with the charge controllers, the charger/inverter and the methanol fuel cells were configured so that remote monitoring and control of all components of the electrical system were available to the ATGMS operators.

The ATGMS freight service demonstration began in April 2016 and ran through January 2017.

3.5.1 *Stage 5 Goals*

The goals of this stage were to develop a self-powered freight car-based ATGMS system and demonstrate the system on short line and other freight railroads. ENSCO applied the results of the prior development stages for this effort.

3.5.2 *Freight Vehicle Configuration*

ENSCO worked with ELS on a refurbishment plan to prepare the boxcar for ATGMS integration. The vehicle was ballasted with fiber-reinforced concrete to bring it to an estimated weight on rail of 190,000 lbs. The carbody-mounted brake system was converted to a truck-mounted brake system to eliminate brake rod interference with the ATMGS beam. This required additional changes to the truck bolsters and side frames to allow the truck-mounted braking system installation. The wheelsets were also replaced, and reconditioned springs were installed in the suspension. Four-inch pipe was installed in the car prior to pouring the concrete floor to serve as a conduit to facilitate the installation of equipment under the car. Passive ventilation was provided through the addition of a roof as well as floor-level vents. Floor drains were installed along with a junction box for roof-mounted equipment. Boarding ladders and safety rails were added to the exterior of the vehicle to allow safe access to the interior of the vehicle. ELS also installed solar panel mounting brackets to the roof, painted and stenciled the car prior to delivery. Final refurbishment work is shown in Figure 43.

(a) Overall Car (b) Interior Preparations (c) Boarding System
Figure 43: ELS Refurbishments

3.5.3 *Instrumentation Beam Design and Mounting*

ENSCO designed a mounting assembly and measurement beam to account for the center sill of the boxcar. The final installation required a redesign of the Stage 3 measurement beam to allow for a new mounting structure, as well as to accommodate the sensor package design. Components used in previous stages were re-used when possible. For example, the computer rack used during Stage 3 housed the computer equipment inside the freight vehicle. The overall car layout is shown in Figure 44.

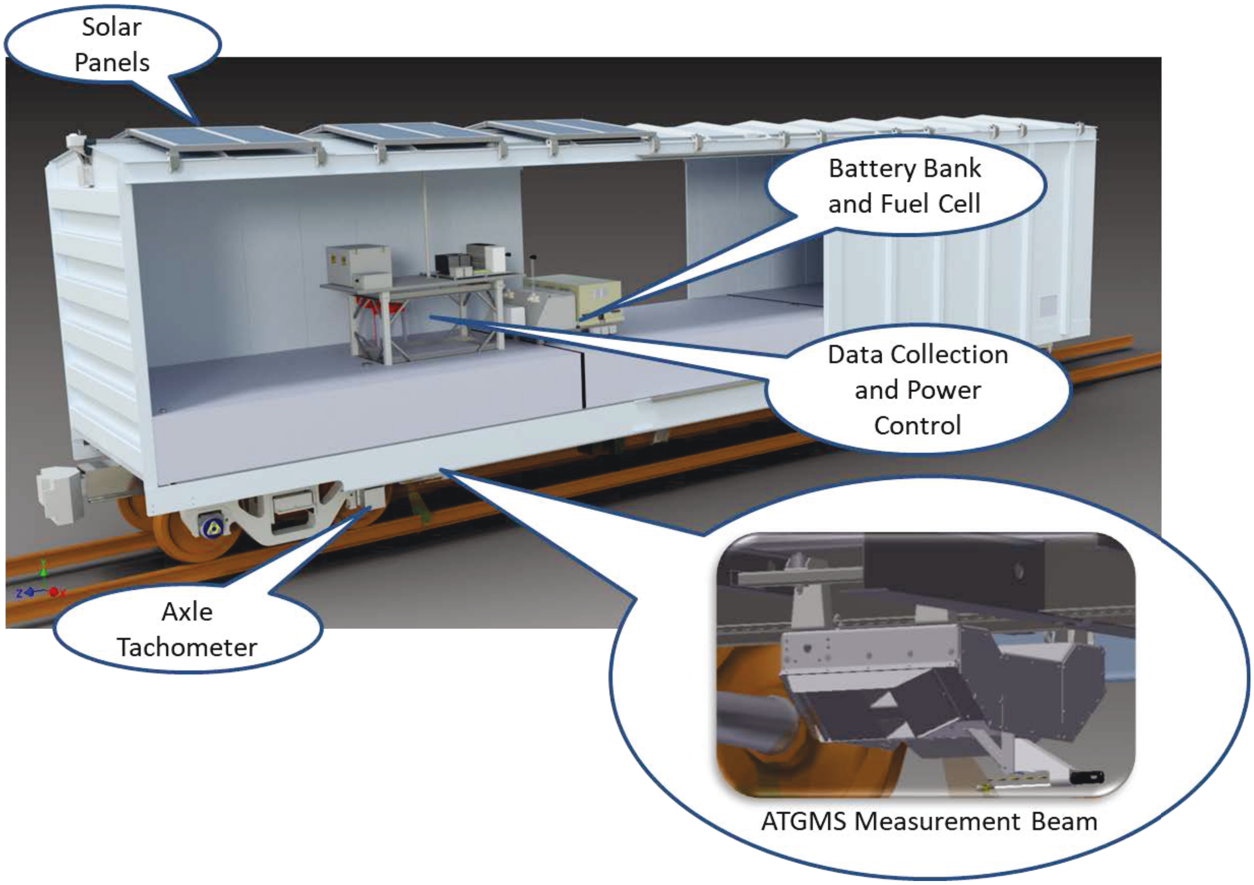


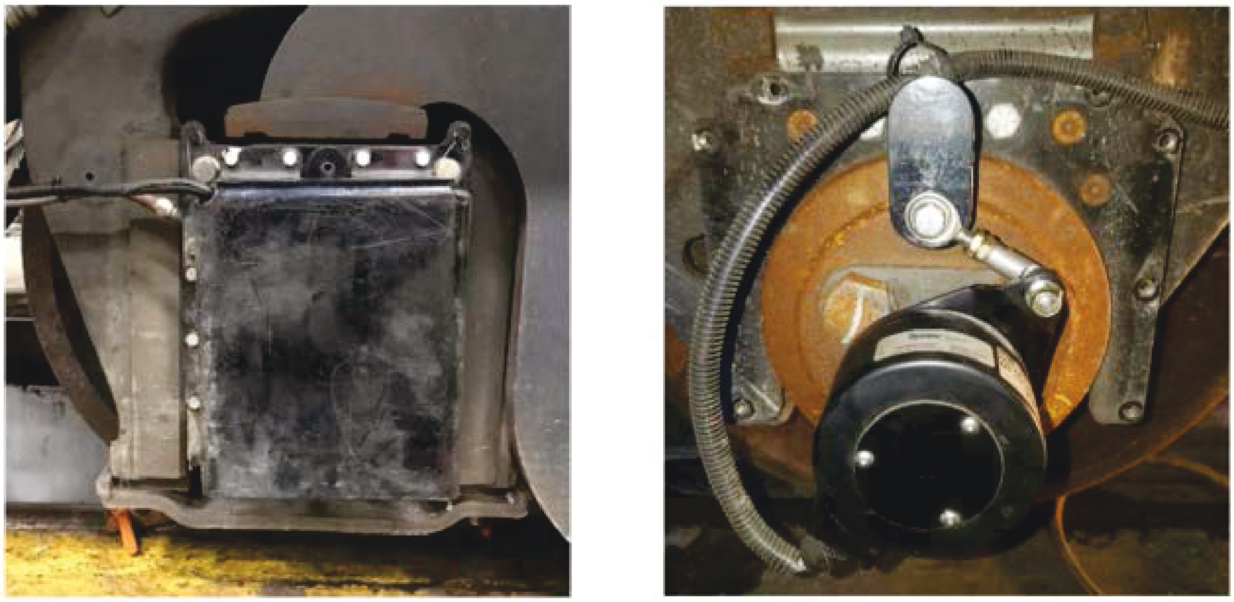
Figure 44: Arrangement of Measurement System and Electrical Power System Components in FRA's DOTX 225

The freight ATGMS was outfitted with the latest ATGMS beam configuration. The track geometry measurement system now employs digital signal processing techniques to reduce the signal noise and increase sensor stability. These improvements resulted in a more reliable and robust system. The digital system has a lower power draw as compared with the prior analog signal processing unit and the inertial sensors were consolidated into a single sensor package. The measurement beam is shown in Figure 45.

Figure 45: DOTX 225 Geometry Measurement Beam

3.5.4 *Tachometer Assembly*

The tachometer assembly was mounted on the left side of axle 2 on the A-end truck. A modified end cap with a built-in axle spike was installed by ELS in preparation for the tachometer installation. The tachometer design, shown in Figure 46, includes a tether to allow for lateral movement of the axle and a cover to protect the assembly from weather and impacts.



(a) Rock Cover **(b) Tachometer with Tether**

Figure 46: Tachometer Installation

3.5.5 *ATGMS Electronics Enclosure and Power System Installation*

ENSCO designed and fabricated a work table and electronics pallet to withstand significant force. The control components of the solar power system and the computer rack used in Stage 3 were installed on the work table inside the vehicle. The battery bank and fuel cell were installed on a customized battery pallet. The final installations of the table and battery pallet are shown in Figure 47.

Figure 47: Electronic Table and Battery Pallet

3.5.6 *ATGMS Power System*

DOTX 225 was equipped with a power system that employed both solar energy and direct methanol fuel cell technology as its primary and secondary power sources charging the ATGMS battery system. A schematic of the system architecture is illustrated in Figure 48. The power system consisted of 12 140W, 17.5V, 8A solar panels and a 110W EFOY Pro 2400 Duo methanol fuel cell with four cartridges powering a 24V battery bank consisting of 12 6V AGM batteries with a total power capacity of 22 kWh. The average load on the system was approximately 130 watts. Each solar charge controller controlled one six panel array of solar cells. Figure 49 shows the solar panels and other roof-mounted equipment including GPS and cellular antennas. Communications with the charge controllers, the charger/inverter and the methanol fuel cell were configured through a communications hub to enable remote monitoring and control of all components of the electrical system.

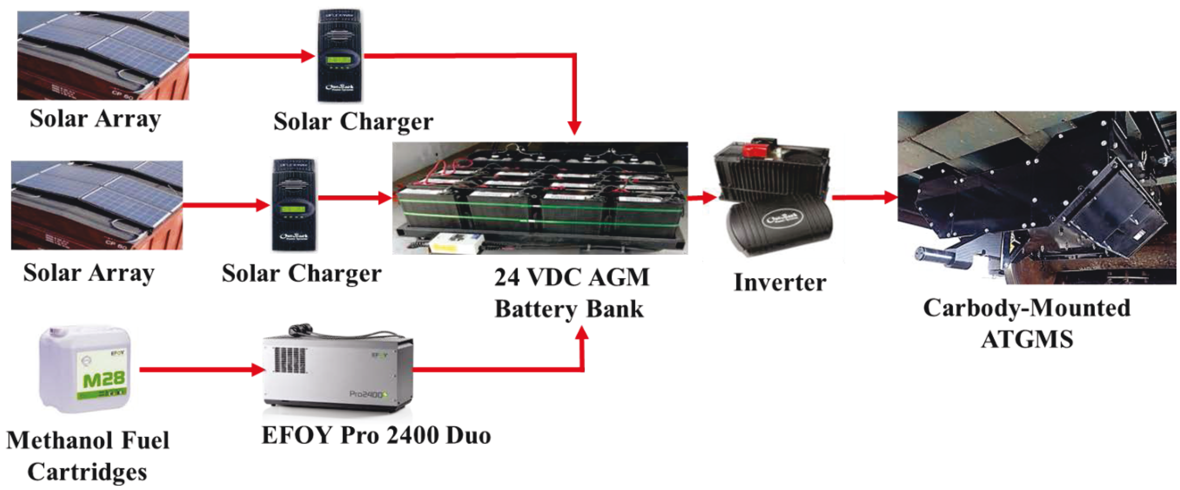


Figure 48: DOTX 225 ATGMS Power System Architecture

Figure 49: Roof-Mounted Equipment on DOTX 225

The power system performed without any issues during the 9-month demonstration. The solar charging system kept the batteries adequately charged with minimal need for the secondary fuel cell. In total, the fuel cell ran for 15 hours and consumed less than 1 liter of methanol. An illustration of the energy harvesting and usage throughout a 24-hour period is shown in Figure 50

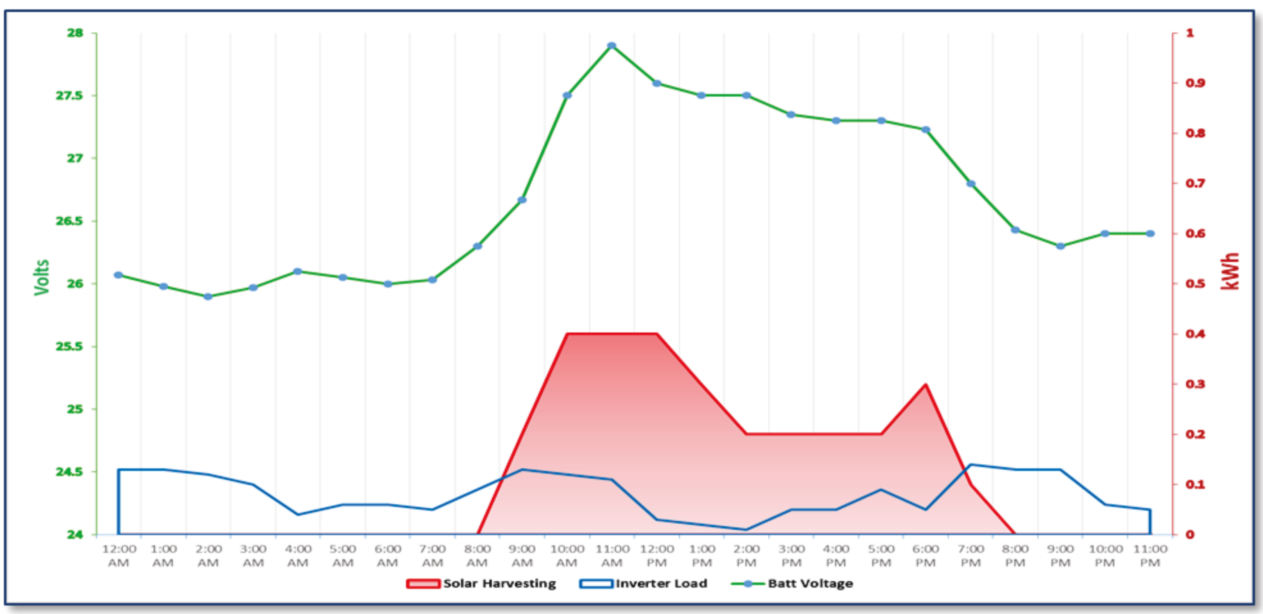


Figure 50: Performance of ATGMS Power System Over Typical 24-Hour Period

Installation of the measurement and power systems took place at ENSCO's Chambersburg maintenance facility between March 1 and March 30, 2016. Photographs of the power system are provided in Figure 51. Prior to releasing the vehicle for freight demonstration, the car underwent calibration and reproducibility analysis to verify the ATGMS performance. The results were within the acceptable standards established within FRA's Quality Assurance/Quality Control procedures.

Figure 51: Freight ATGMS Power System Installation

3.5.7 *Demonstration Test*

During the freight demonstration survey, the ATGMS box car was deployed nearly 300 days, surveyed over 12,700 miles, and provided track condition data for 29 railroads, including 25 short line railroads and four Class I railroads, as illustrated in Figure 52.

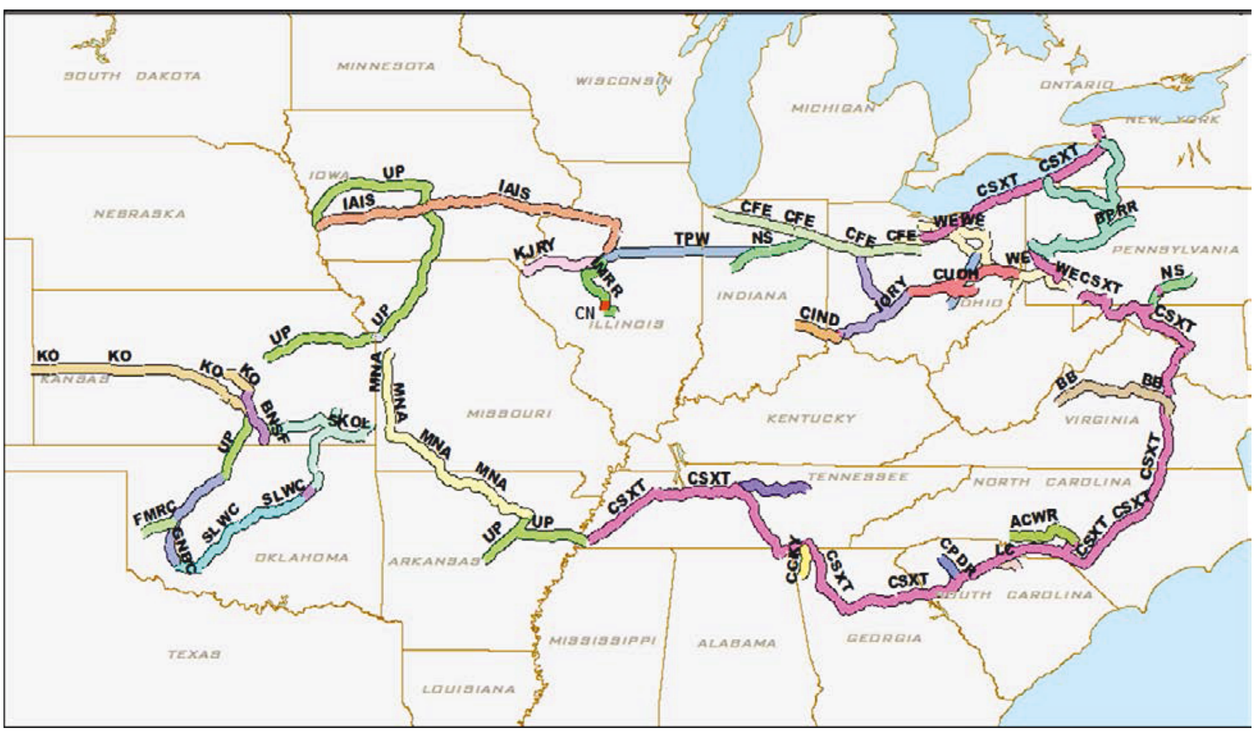


Figure 52: DOTX 225 Freight Demonstration Route

Participating railroads included:

- CSX Transportation
- Buckingham Branch Railroad
- Buffalo & Pittsburgh Railroad
- Wheeling and Lake Erie Railway
- Ohio Central Railroad
- Columbus and Ohio River Rail Road
- Ohio Southern Railroad
- Indiana and Ohio Railway
- Central Railroad of Indiana
- Chicago, Fort Wayne and Eastern Railroad
- Norfolk Southern Corporation
- Toledo, Peoria and Western Railway
- Keokuk Junction Railway
- Tazewell and Peoria Railroad
- Illinois and Midland Railroad
- Canadian National Railway
- Iowa Interstate Railroad
- Union Pacific Railroad
- Grainbelt Corporation
- Farmrail Corporation
- Stillwater Central Railroad
- South Kansas and Oklahoma Railroad
- Kansas and Oklahoma Railroad
- Missouri and Northern Arkansas Railroad
- Nashville and Eastern Railroad
- Chattooga and Chickamauga Railway
- Carolina Piedmont Railroad
- Lancaster and Chester Railway
- Aberdeen Carolina and Western Railway

Over the 12,787 miles of track tested by DOTX 225 during the demonstration, only 74.3 miles of data were not collected, resulting in a 99.994 percent success rate. The geometry system found approximately 20,000 "points of interest" based on railroad-defined exception thresholds. Several railroads requested that surveys be conducted one class higher than the posted class to identify areas for track improvements, while other railroads requested surveys at the posted class. Overall feedback from the railroads was positive with the participants often field-verifying the accuracy of the geometry exception locations and measurements. In some cases, survey stakeholders received automated track geometry testing for the first time, while others noted the benefits of conducing out-of-cycle tests without having to commit track engineering personnel.

The results of the inspection were delivered to survey stakeholders through the same reporting mechanism employed by FRA's RRS during Amtrak assessment surveys. Data products included Advisory Exception Reports (AER), Track Condition Reports (TCR) and data strip charts. The AER, shown in Figure 53, was delivered via email to a pre-determined list specified by the participating railroad either on the same day as the survey or the next business day. The AER included the GPS and MP-based location, including a web link to Google Earth™, for an exception with the length and type in the body of the email. Attached to the email was a strip chart, in PDF format, with the foot-by-foot track measurements surrounding the exception. The TCR, shown in Figure 54, was emailed to the railroad representatives at the conclusion of the survey. The TCR provided an overall summary for the line segment, including the number of each type of exception found on the entire track segment, in a tabular format.

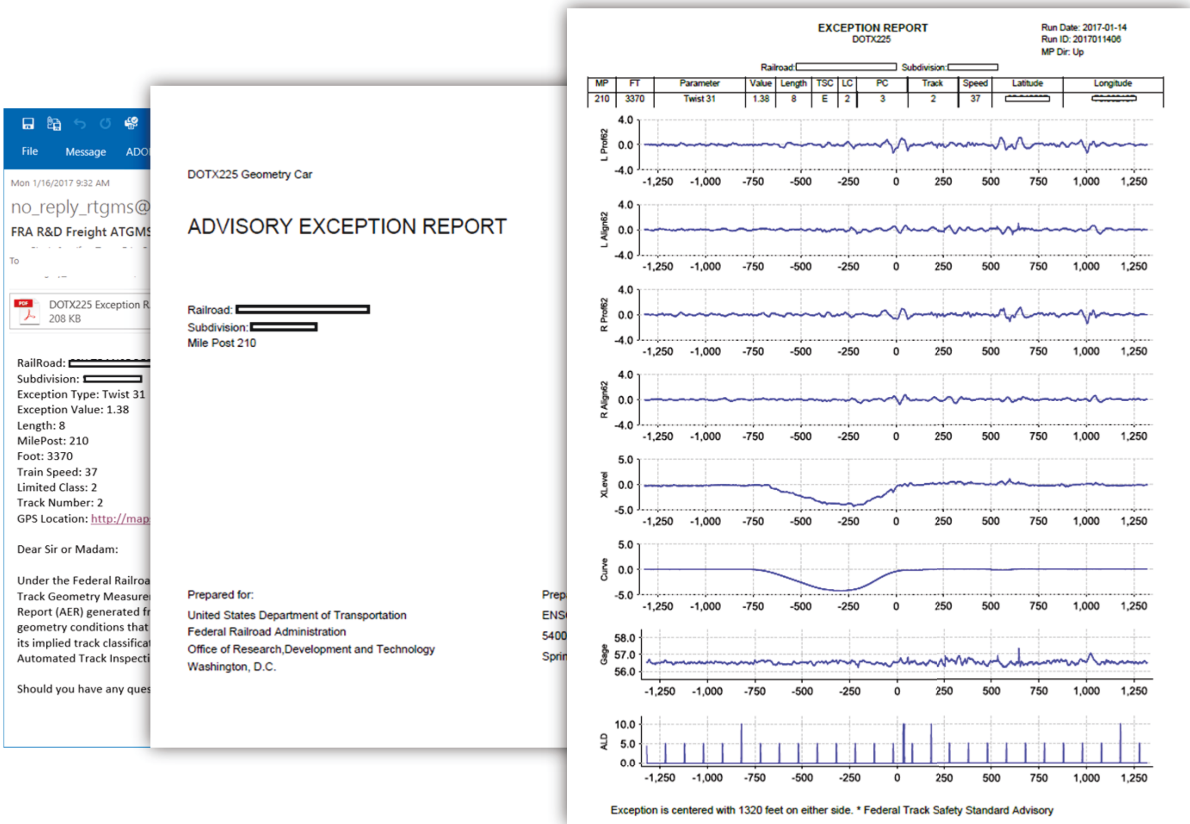


Figure 53: Example Advisory Excepion Report and Email

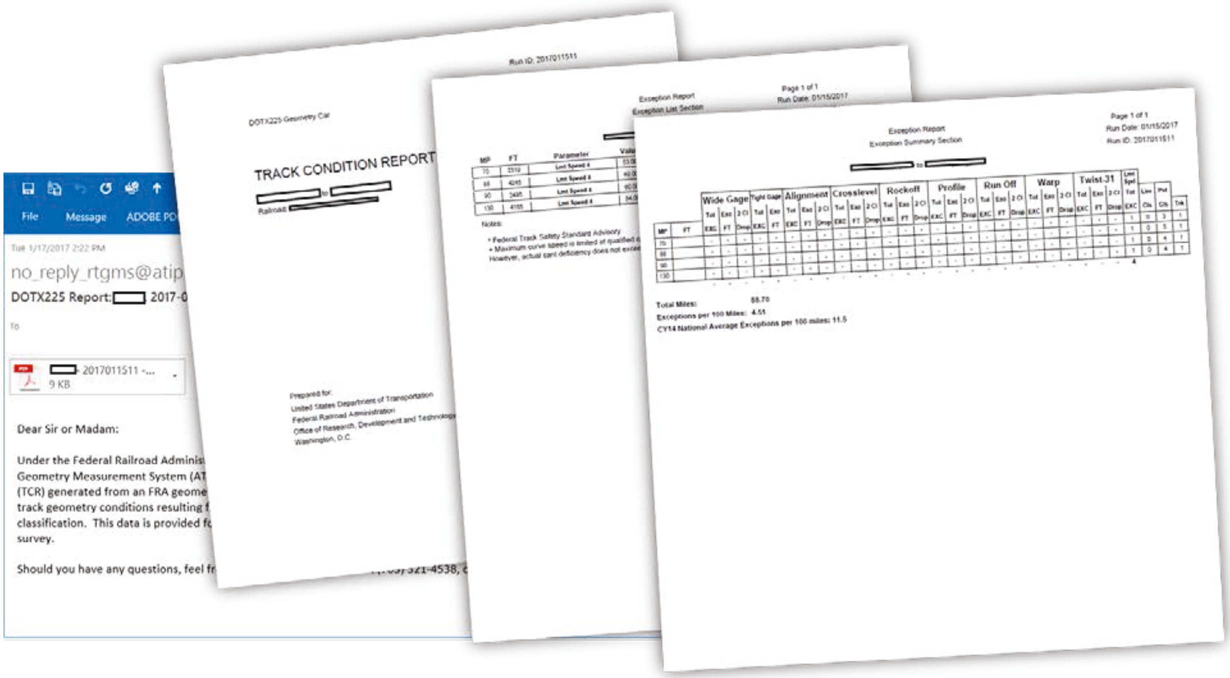


Figure 54: Example Track Conditioning Report

The accuracy of the ATGMS over the duration of the demonstration was assessed by comparing results from the initial reproducibility testing performed prior to the demonstration to a follow-up reproducibility test conducted at the end of the survey. The results for both tests are shown in Figure 55.

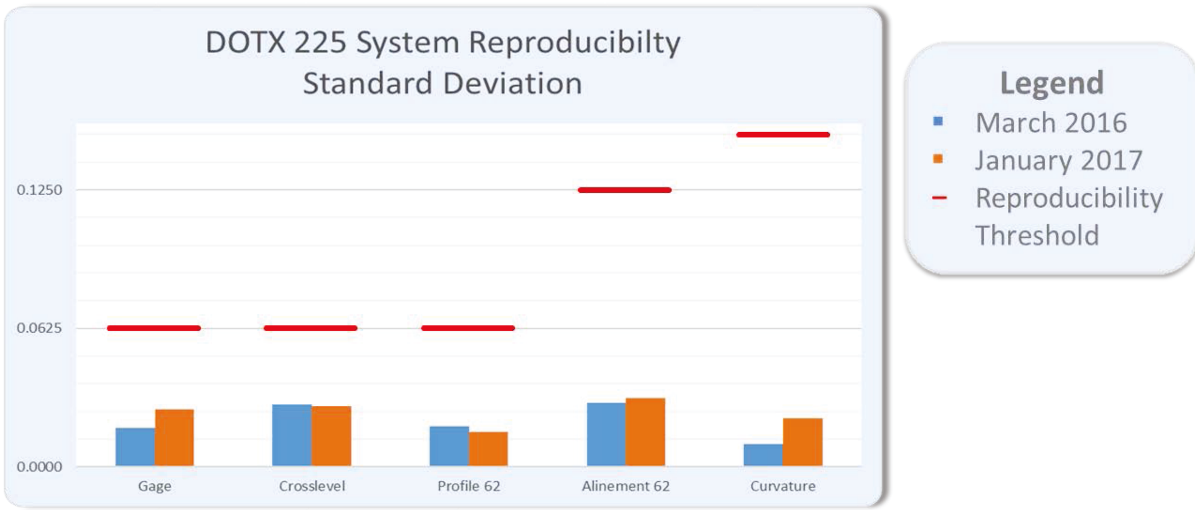


Figure 55: Comparison of Reproducibility Measurements from March 2016 and January 2017

The track geometry surveys collected over the same section of track at different times during the demonstration were compared to remotely verify system performance. An example of this type of comparison is shown in Figure 56. The two data traces were collected 38 days apart.

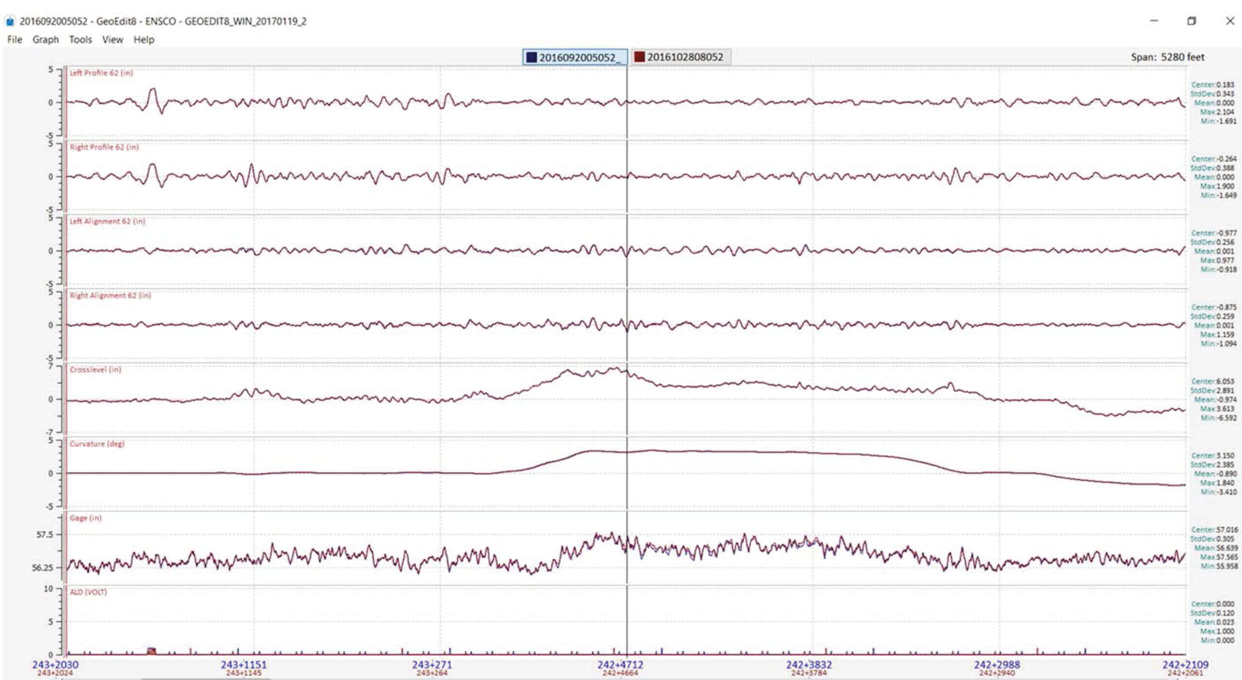


Figure 56: Example Overlay of DOTX 225 Survey Data Collected 38 Days Apart

Three maintenance visits were required during the 9-month demonstration. An initial visit was conducted shortly after the system began operations to resolve computer damage after the vehicle was "humped" in a yard. A second maintenance visit was conducted to perform a tachometer upgrade and to perform normal system maintenance. The final maintenance visit was conducted to resolve a computer error. Following this third maintenance visit, the system operated for 129 days without a visit.

3.5.8 *Conclusions and Lessons Learned*

Stage 5 efforts resulted in the successful demonstration of FRA's carbody-ATGMS on standard freight equipment while running in typical revenue service. The results of the freight service demonstration prove that ATGMS technology can be used effectively through freight interchange service to collect and distribute reliable track geometry data with little interference to revenue operations and minimal maintenance requirements. The track geometry data produced by ATGMS has proven to be accurate, and of equal quality to that of the manned geometry vehicles.

One opportunity for improvement in future carbody-mounted systems would be to include the rail profile images with the geometry exception data in the Remote Editing Console. Under certain conditions the carbody-mounted system's high angle of attack to the gage face increases the adverse effect rail head flow has on reporting narrow gage exceptions. The rail gage point is in the shadow of the gage face rail flow and is not measured correctly. Including a profile viewer would assist those reviewing and editing the data.

When comparing the operational support required for the demonstration test to traditional manned geometry car operations, ATGMS operations require minimal personnel support. ATGMS support activities included scheduling the surveys, coordinating the interchanges between railroads, gathering and creating the time table, and track chart and MP coordinates to build route tables. These tables were used to create the track centerline data, which correlated GPS coordinates and railroad identifiers within the autonomous geometry processing. In future testing, collecting this information prior to survey and creating accurate base maps prior to testing will alleviate some of the efforts required during testing. Other support responsibilities included monitoring the system, operating the Remote Editor Console, and distributing data to the stakeholders.

4. ATGMS-Related Analyses and Processes

Several processes have been developed to maximize the benefits and efficiencies of autonomous track inspection. The Remote Editor Console, employed by FRA to provide the highest level of quality control, is the most impactful of these processes. This section provides overviews of several other enabling processes developed and/or explored over the course of FRA's research program.

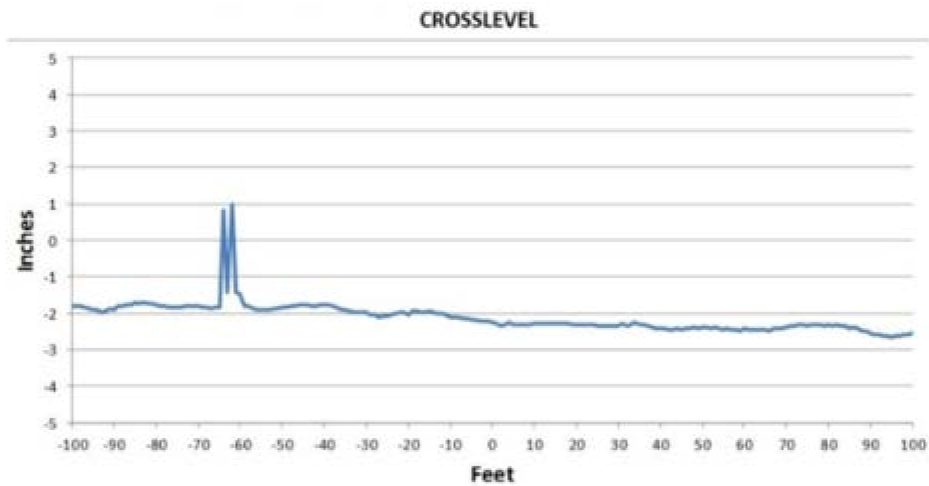
4.1 Exception Editing

Identifying and filtering exceptions is an important part of the quality control process. Automatic and manual techniques were employed to minimized the number of false exceptions in the data products.

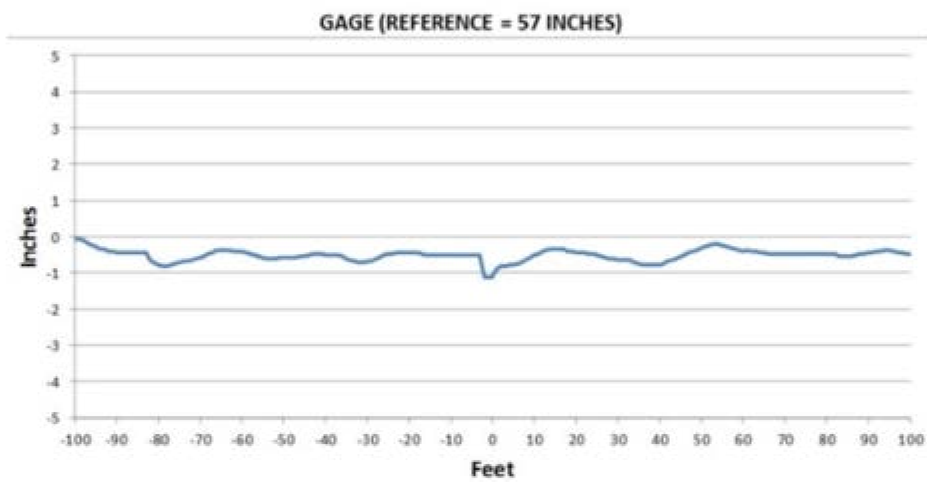
During Stage 1 efforts, ENSCO employed two different methods to identify and remove "false" geometry defects. These methods were based on decades of experience with manned track geometry data collection and years of developing false exception detection routines in autonomous track assessment systems such as ARMS.

The first method employed a human-trained decision model designed to recognize patterns associated with the actual experiences of human data editors and apply those patterns to potential measured defects. Edited data from thousands of survey miles was used to "teach" the program how to filter out false exceptions. The second method relied on a computational signature analysis algorithm that analyzed frequency components of the measured signals to identify those cases that exhibited higher-frequency components that would cause the reported geometry measurement to be questioned.

After initial development and several refinements, this two-pronged approach to exception editing proved effective at removing instances in which data appeared to correspond with false geometry defects. Illustrations of the types of false exceptions identified by the approach described above are shown in Figure 57. In Figure 57a, a false crosslevel deviation was automatically identified based on its unrealistic signature. In Figure 57b, a narrow gage exception was automatically identified based on the presence of a constant gage measurement followed by a relatively large change in gage over a short distance.



(a) False Crosslevel Geometry Exception



(b) False Gage Geometry Exception

Figure 57: Examples of False Geometry Exceptions Automatically Identified

This approach proved capable of filtering out exceptions attributable to signals suffering from dirty measurement optics, gage conditions found at diamond frogs and turnouts, as well as profile irregularities observed in crossovers. However, more improvements were required.

Assessments of exception filter effectiveness conducted in the spring of 2009 indicated that:

- In general, 25 percent of detected exceptions reported by the system were valid track events; the filtering approach employed at the time was not effective.

- A majority of false exceptions were associated with limiting speed, crosslevel, and alignment deviations. Discrepancies were attributed to inaccurate curve transition detection (i.e., proper determination of when the vehicle had entered a curve) and sensor anomalies (gage spikes, accelerometer saturation) that occasionally affected data quality.

ENSCO adjusted the system to address these deficiencies. Developers moved from a multi-phase approach to exception filtering in which it detected waveforms that were compared to a series of thresholds to eliminate obvious false exceptions with the remaining exceptions analyzed using a Support Vector Machine classifier. The classifier was trained using historical exception data to replicate the performance of operators trained for manned inspection car surveys. Although this approach provided some improvements, the rate of false exceptions being passed through as valid was still unacceptable.

In 2010, a new "decision tree" type approach was used in which each exception was assessed with algorithms that employed independent rules developed, in part, using data gathered during manned survey operations. These rules employed considerations of peak-to-peak values, noise levels and frequency components of individual waveforms associated with the detected exceptions. This approach yielded acceptable results. Comparisons of both a manual and automatic review of geometry defects detected over the Auto Train route indicated agreement with both accepted and rejected geometry exceptions in over 90 percent of the cases.

Although results of the automated filtering approach at the end of Stage 1 were encouraging, FRA and ENSCO did not observe the same level of success in evaluations conducted on routes throughout the country during Stage 2 and 3. In the analysis of ATGMS results compared to those collected with the manned system onboard DOTX 220, true exceptions missed by ATGMS were largely impacted by issues associated with track class determination as well as the exception validation logic used with ATGMS as compared to crew observations of track features. Consideration of these results following subsequent efforts in Stages 2 and 3 indicates that the relative success of the 2010 exception filtering method was likely attributable to the training data taken from the Auto Train route that was used to establish algorithms.

For applications in which ATGMS would be employed over captured routes on a regular basis, automated exception filters developed in the later efforts of Stage 1 effectively minimize false exceptions. For a wider range of operating conditions, or for the purposes of enforcement of safety standards, the use of the Remote Editor Console can provide additional quality measures. The Remote Editor Console allows FRA to employ procedures similar to those that meet the requirements of the International Standards Organization (ISO) 17025 certification employed in its manned survey operations, thereby, ensuring the quality of results reported to survey stakeholders.

4.2 Track Degradation Analysis

FRA recognized the need for a track degradation analysis tool to take advantage of increased inspection frequencies facilitated by ATGMS. A tool of this nature would automatically process data collected during multiple surveys on the same track to determine degrading track segment conditions, allowing stakeholders to identify track locations that require preventative maintenance. The approach is intended to efficiently process archived surveys from ATGMS or manned systems to estimate the rate of degradation.

ENSCO prepared a general phased approach to implementing track degradation analysis conducive to track geometry parameters as well as other data collected by FRA's RD&T. To minimize development time, a time series-based approach in which linear or non-linear extrapolation methods to determine degradation rates was recommended. As research in degradation models advances, the methods proposed could be shifted towards the use of more in-depth models that include the influences of various contributing factors.

The general track degradation analysis approach relied on the following steps that are fundamental to such analyses:

- Track Segmentation – Dividing the track into segments small enough to ensure uniform behavior throughout the segment
- Data Alignment – Align geo-referenced measurements from multiple surveys while ensuring that data of questionable quality is not included in the analysis
- Degradation Indices – Develop indices to monitor aggregate changes in measurements within each segment
- Degradation Forecasting – Establish models for trending and forecasting magnitudes of change as well as rates of change of track parameters within each segment. Given sufficient frequency of measurements, degradation modeling would be used to identify locations of concern prior to those locations reaching dangerous conditions

ENSCO recommended early implementation in the form of an offline tool utilizing track geometry data stored within the ATGMS archive. As the tool advances and routes are continually surveyed over time, the degradation analysis could be migrated to a near real-time application that allows analysis and identification of areas of concern as data is received on ATGMS servers.

4.3 Track Determination

The precise location of ATGMS on a given rail network, particularly in situations where multiple tracks run very close to one another, was essential for viability. Track determination is critical to find and correct geometry exception conditions efficiently. Multiple surveys can be properly aligned for long-term monitoring and analysis.

A survey of viable methods of track determination was prepared during Stage 2 [2]. Of the methods documented in the survey, an approach referred to as GPS Map Matching was recommended as the most appropriate means to reach FRA objectives. The method entailed matching the GPS location reported by ATGMS to dynamically segmented base maps that contain locations and designations of individual tracks, MP locations and track class information. An approach to creating these maps was described, but it was noted that detailed information from the railroads is necessary for initial development. Assuming this information will be available in the future, particularly given the advent of Positive Train Control (PTC), this approach represents the greatest chance for long-term success.

Given that this detailed track information is not readily available to FRA, individual track designation is accomplished through indications of track changes within the track geometry data (as evidenced by short curvatures near turnouts) coupled with information available to users of the Remote Editor Console such as track tables and satellite imagery.

5. Conclusion

FRA's RD&T has successfully demonstrated the use of autonomous geometry measurement technology to collect and distribute continuous track geometry data accurately and reliably while in standard revenue service. This has been demonstrated on a variety of vehicles operated in passenger service on a wide range of track conditions, as well as the demonstration of ATGMS in standard freight service for extended operations.

Demonstrations conducted have exhibited the benefits of using ATGMS in regular operations. FRA's RRS has relied on its approach to remote track geometry inspection since 2013. Lessons from FRA's development efforts and their use in track condition monitoring can serve as important guides for the entire rail industry as various forms of autonomous track inspection are adopted. Based on FRA's experience, operations employing staffed inspection vehicles can survey close to 20,000 miles of Class I mainline track over the course of a year. Employing autonomous track inspection equipment on revenue service equipment in passenger service resulted in approximately twice as much track being surveyed in half the time.

As a result of ATGMS technology, FRA has experienced a significant operational cost savings. Based on analysis of costs associated with passenger route assessments conducted in 2013, it is reasonable to expect a 30 to 50 percent reduction in survey costs per mile when compared to the costs of more traditional inspection approaches. These savings are likely to increase as optimized inspection strategies are followed. The transition of this technology to routine assessments conducted as part of FRA's ATIP in 2013 showed that increased inspection coverage and frequency can be achieved with virtually no negative impact on revenue service operations.

Automated exception filters developed in the later efforts of Stage 1 appear sufficient to minimize false geometry defects, especially in captive routes. For a wider range of operating conditions, the use of the Remote Editor Console can provide additional quality control measures. The Remote Editor Console allows FRA to employ well-established procedures similar to those employed in its manned survey operations, thereby, ensuring the quality of the survey results.

As with many technological advances, additional benefits can be realized through continued research and development. FRA and ENSCO have identified several technology areas for further improvement:

- *Autonomous Instrumentation Check and Calibration* - Experience has shown that the equipment employed by FRA has produced reliable data in a very stable fashion. The autonomous nature of this technology will only be enhanced with the development of reliable automatic, self-calibrating systems to minimize the need for manual instrumentation check and calibration activities.
- *Data Management* - Autonomous inspection technology offers many benefits to the railroad community, including high inspection frequencies and the resulting increase in data availability for improved forecasting and trend analysis. This approach to inspection also offers near instantaneous availability of data. This increase in data brings with it several challenges, including issues with handling the increased volume of data resulting from higher inspection frequencies, the creation of useful information and the manner in

which information collected with the system will be integrated into on-going inspection practices.

- *Track Class and Track Determination* - Accurate identification of individual tracks and determination of class of track are critical aspects of ATGMS operation as these directly affect the validity and location of detected geometry exceptions. As more detailed asset information becomes available through initiatives such as PTC implementation, methods to use such information to maximize accuracy of location determination and operating limits will need to be integrated into autonomous inspection systems' infrastructure. Until these capabilities are well-established, measures such as the Remote Editor Console or other approaches can address these needs.

These advances are likely to accelerate the adoption of this technology throughout the rail industry. As FRA's efforts to enhance conditional awareness using autonomous inspection systems continues, industry maintenance practices could become more preventative in nature, leading to an improvement in overall rail safety.

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Appendix A – Geometry Results Comparison – DOTX221(ATGMS) and DOTX220(TGMS)

Comparison of DOTX221 ATGMS and DOTX220 TGMS Geometry Exceptions and Foot-by-Foot Geometry Summary Report

Customer Contract Number: DTFR53-10-D-00002, Task Order 9
ENSCO Project Number: 3670.09

Prepared for:
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Executive Summary

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology has undertaken a multi-phase research program focused on the development and advancement of autonomous track geometry measurement systems (ATGMS) and related technologies to improve rail safety by increasing the availability of track geometry data for safety and maintenance planning purposes. Routine collection of track geometry measurements using autonomous, un-manned systems provides many advantages over single purpose, manned systems such as uninterrupted main line track operation and increased inspection frequency allowing for timely detection and monitoring of track locations with safety critical or degradation issues.

The first stage of FRA's development centered on the creation of the basic elements of a ruggedized pilot ATGMS. The second stage of development focused on use and improvement of the technology under revenue service conditions to demonstrate ATGMS accuracy and increase the autonomy of operation of the system. Major accomplishments within this stage, supported under Task Order 9 of FRA's Contract DTFR53-10-D-00002, included the evaluation of a truck-mounted ATGMS installed on FRA's DOTX221 while operated in consist with the FRA Automated Track Inspection Program's (ATIP) DOTX220 manned track geometry inspection vehicle over Amtrak passenger routes between September 2011 and June 2013.

This report documents the performance of the ATGMS as compared to the manned track geometry measurement system during surveys conducted throughout the United States between March and June 2012. Exceptions to track geometry limits defined in the FRA's Track Safety Standards produced by the two systems were compared to each other. Results of this comparison are presented in Section 2. Differences between exceptions produced by the two systems are attributed to seven specific causes. More than half of the observed differences between geometry exceptions produced by the two systems are attributed to class of track determination, which primarily affected ATGMS geometry exception reporting. Differences in geometry measurements from the two systems, particularly in profile and crosslevel, is the second leading cause of differences between geometry exceptions produced by the two systems.

More than 314,000 feet of track geometry data collected by the unmanned and manned systems were compared on a foot-by-foot basis, while areas for comparison were selected based on locations with track geometry exceptions as reported by the manned system aboard DOTX220. Differences in gage, profile, alignment, crosslevel, and curvature measurements collected by the two systems were compared with differences used by FRA to assess overall agreement between multiple measurement systems. Results of this analysis, presented in Section 3, show that the mean difference and standard deviation for crosslevel as well as the mean difference for curvature exceed the multiple system repeatability thresholds. Mean differences and standard deviations for all other measurement parameters meet multiple vehicle repeatability thresholds.

Results of the comparison of the manned and unmanned systems, as well as recommended improvements to FRA's ATGMS, are summarized in Section 4. Analysis presented in this report shows that improving class of track determination used with ATGMS and automated geometry exception editing will improve ATGMS performance to a level approaching that of manned geometry inspection systems.

7. Introduction

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology has undertaken a multi-phase research program focused on the development and advancement of autonomous track geometry measurement systems (ATGMS) and related technologies to improve rail safety by increasing the availability of track geometry data for safety and maintenance planning purposes. Routine collection of track geometry measurements using autonomous, un-manned systems provides many advantages over single purpose, manned systems such as uninterrupted main line track operation and increased inspection frequency allowing for timely detection and monitoring of track locations with safety critical or degradation issues.

The first stage centered on the creation of the basic elements of a ruggedized pilot ATGMS using commercial, off-the-shelf equipment to facilitate early development and evaluation. Emphasis was placed on cellular communication and data transmission, location information tagging, and geometry data and exception processing. The Data Collection module was configured to measure track geometry, analyze the measurements for any locations exceeding limits to the FRA Track Safety Standards and transmit "exception reports" to the server for storage and transmission to survey stakeholders. Automated filters employing a variety of statistics-based algorithms and logic rules were used to identify and eliminate "false" exceptions. Between January 2008 and March 2011 the pilot ATGMS was operated on Amtrak's 39000, a Superliner II railcar, during revenue service operations within Amtrak's Auto Train service that runs between Lorton, VA, and Sanford, FL, over CSX Transportation track. During that time ATGMS surveyed almost 460,000 miles of track, an average of approximately 153,000 miles per year. This extensive testing allowed identification of system problems and limitations, facilitating design modifications that moved ATGMS technology towards increased robustness and reliability.

Following the initial stage of development, the truck-mounted ATGMS was removed from Amtrak's 39000 and moved to FRA's DOTX221, a sleeper-lounge car, for use in Stage 2 development. The second stage of development focused on use and improvement of the technology under simulated revenue operations to demonstrate ATGMS accuracy and increase the autonomy of operation of the system. Major accomplishments within this stage, supported under Task Order 9 of FRA's Contract DTFR53-10-D-00002, included the evaluation of the ATGMS on FRA's DOTX221 while operated in consist with the FRA ATIP's DOTX220 manned track geometry inspection vehicle over Amtrak passenger routes between September 2011 and June 2013 referred to as the Amtrak Assessment program. Please note that for simplicity, hereafter FRA's ATGMS on DOTX221 and FRA's manned geometry inspection system on DOTX220 operated by ATIP personnel are referred to as ATGMS and ATIP, respectively.

This report documents the performance of the ATGMS installed on DOTX221 as compared to the manned track geometry measurement system installed on DOTX220 during Amtrak assessment surveys conducted between March and June 2012 in which the two cars were adjacent to each other within the survey consist during operations over approximately 19,000 track miles. The March 2012 Amtrak Assessment consisted of 16 one-way trips as indicated in Table A9.

Table A9: March 2012 Amtrak Assessment Survey

Trip	Origin	Destination	Miles	Start Date	End Date
1	Washington, DC	New Orleans, LA	1,155	03/29/2012	03/30/2012
2	New Orleans, LA	Los Angeles, CA	1,939	04/02/2012	04/04/2012
3	Los Angeles, CA	Oakland, CA	468	04/06/2012	04/06/2012
4	Oakland, CA	Los Angeles, CA	468	04/06/2012	04/06/2012
5	Los Angeles, CA	Chicago, IL	2,222	04/09/2012	04/11/2012
6	Chicago, IL	New Orleans, LA	918	04/23/2012	04/24/2012
7	New Orleans, LA	San Antonio, TX	575	04/25/2012	04/25/2012
8	San Antonio, TX	Chicago, IL	1,305	04/30/2012	05/01/2012
9	Chicago, IL	Washington, DC	919	05/03/2012	05/04/2012
10	Washington, DC	Miami, FL	1,288	05/07/2012	05/08/2012
11	Miami, FL	Washington, DC	930	05/10/2012	05/10/2012
12	Washington, DC	Chicago, IL	777	05/21/2012	05/22/2012
13	Chicago, IL	Oakland, CA	1,791	05/23/2012	05/24/2012
14	Oakland, CA	Seattle, WA	916	06/01/2012	06/01/2012
15	Seattle, WA	Chicago, IL	2,203	06/04/2012	06/06/2012
16	Chicago, IL	Boston, MA	1,020	06/07/2012	06/07/2012
		Total	**18,894**		

To characterize the performance of the ATGMS, the following comparisons were performed:

- Exceptions to the track geometry limits specified in the FRA Track Safety Standards detected by each system. Geometry exceptions reported by FRA's manned geometry inspection system on DOTX220 were considered as "ground truth" for this analysis;
- Foot-by-foot track geometry data collected by the unmanned and manned systems over more than 314,000 non-consecutive feet of the survey. Areas for comparison were selected based on locations with track geometry exceptions as reported by the manned system aboard DOTX220. Differences in gage, profile, alignment, crosslevel, and curvature measurements collected by the two systems were compared established thresholds used by FRA to assess overall agreement between multiple measurement systems.

A similar analysis was conducted to assess ATGMS using survey data collected by both ATGMS and the manned geometry system aboard DOTX220 during Amtrak Assessments initiated in August 2011; results of this initial comparison were used to identify and address technical/operational issues with the ATGMS.

For the analysis documented in this report, data from Trips 1 and 16 were removed from comparisons of exceptions and foot-by-foot geometry data due to ATGMS data quality issues during Trip 1 and missing ATIP location information (GPS latitude and longitude) during Trip 16. Therefore, only 16,419 track miles of data collected between April 2, 2012, and June 7, 2012, was used for the purpose of analysis presented in this report.

When comparing results provided by ATGMS and manned geometry measurement systems it is important to take into account their operational differences. In particular:

- Manned geometry measurement systems are able to utilize up-to-date posted class of track when ATIP crews edit geometry exceptions. ATGMS, at its current stage of development, relies on vehicle speed to infer class of track to identify geometry exceptions. Therefore, ATGMS is prone to identify a lower class of track based on vehicle speed in many situations than the crew would, creating a significant source for discrepancies in exception detection.
- Differences in vehicles weights and system calibrations result in slight differences in foot-by-foot geometry measurements, resulting in one system reporting an exception while the other does not.
- The automated exception editor employed within ATGMS is designed to review geometry exceptions and accept or reject events as "true" exceptions based on a set of mathematical rules. The ATIP manned geometry review process takes advantage of the operator's years of experience and their ability to observe both track and environmental conditions when deciding if an event is a "true" exception or not.

Results of the exception-based and foot-by-foot measurement-based analyses are presented in Sections 2 and 3 of the final report. Section 4 provides a summary of results and recommendations based on these analyzed.

8. Track Geometry Exception Analysis Results

A total of 1,193 geometry exceptions were reported by the ATIP manned inspection vehicle during Trips 2 through 15 of Table A9. As summarized in Table A10, only 60 reported ATGMS geometry exceptions matched those reported by the ATIP manned system. The mismatched geometry exceptions include 148 geometry exceptions detected but either deleted or not reviewed by the automated exception filters employed by ATGMS and 985 geometry exceptions reported by ATIP manned system but not detected by ATGMS.

Table A10: ATGMS Generated Geometry Exceptions Versus ATIP Reported Geometry Exceptions

		ATGMS			
		Detected and Reported	Detected but Deleted or not-reviewed	Not Detected	**Total ATIP Reported Geometry Exceptions**
ATIP	Detected and Reported	60	148	985	**1,193**

Matched geometry exceptions – Detected and Reported by both systems
Mismatched geometry exceptions – Detected by both systems but deleted or not reviewed by ATGMS
Mismatched geometry exceptions - ATIP reported geometry exceptions not detected by ATGMS

At the first glance, results shown in Table A10 indicate that ATGMS performed poorly and only matched 5 percent of the ATIP-reported geometry exceptions but a closer look at the underlying causes indicates that ATGMS performed reasonably well given its mode of operation.

The Pareto chart in Figure A58 ranks the identified causes of 1,133 (148 plus 985) mismatched geometry exceptions based on degree to which they contribute to differences between the two systems; a "cut-off" corresponding to 80 percent of the total number of events illustrated in the chart is provided for reference. The color scheme used in Figure A58 matches the color scheme used in Table A10. Dark/red columns represent the 985 ATIP-reported geometry exceptions not detected by ATGMS and medium shade/amber columns represent the 148 ATIP geometry exceptions not reported by ATGMS. These were detected but either deleted or not reviewed by the ATGMS automated exception editor.

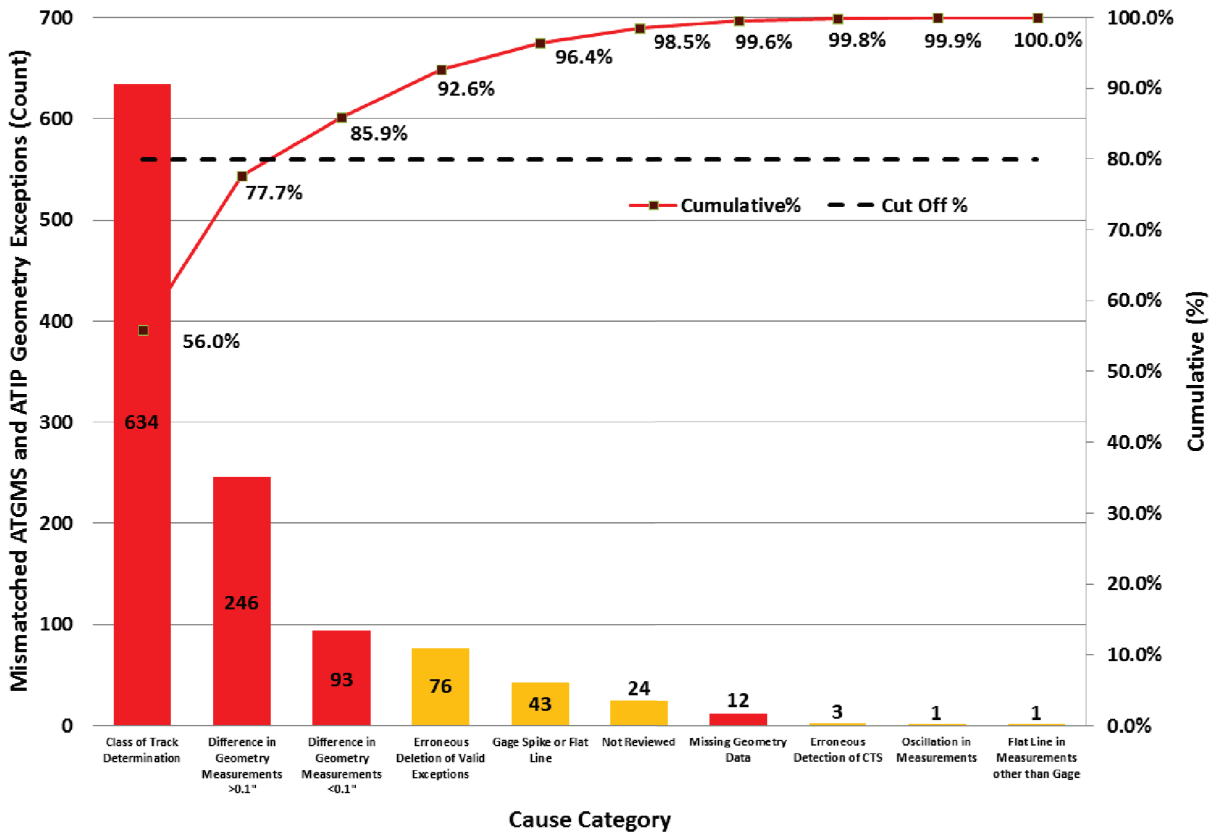

Figure A58: Distribution of Mismatched Geometry Exceptions into Categories of Causes

The following sections provide additional details into these two high-level issues.

8.1 Exceptions not Detected by ATGMS

Consideration of the distribution of 985 ATIP-reported geometry exceptions not reported by ATGMS by different cause categories in Figure A58 shows the following:

- Of the 985 ATIP-reported geometry exceptions not detected by ATGMS, 634 were caused by ATGMS erroneous class of track determination based on the vehicle's speed. At the time of the surveys considered in this report, track class is established based on the speed of the vehicle at any given moment in time. Determination of track class represents an area in which improvements could be realized through a number of different measures including manual review and correction or detailed, up-to-date geo-referenced track class designations that could be provided by individual railroads.
- In addition, 339 out of 985 ATIP reported geometry exceptions not detected by ATGMS were caused by differences in geometry measurements between the ATIP manned system and ATGMS attributed to differences in vehicle weights and minor system differences such as offsets. DOTX220, on which the manned system is located, weighs approximately 212,000 lbs with a fairly even weight distribution from end to end. DOTX221, upon which the ATGMS is installed, weighs close to 155,000 lbs with the vehicle being approximately 12,000 lbs heavier on the B-end where the track geometry measurement beam is mounted.

- The remaining 12 out of 985 ATIP-reported geometry exceptions not detected by ATGMS are due to missing ATGMS geometry data. This occasionally occurs when ATGMS is recovering from a system issue that requires system restart while the test consist continues to survey.

Once causes for mismatched geometry exceptions are identified, their effect on different types of reported geometry exceptions can be identified. Listed in Table A11 are the 985 ATIP-reported geometry exceptions not detected by ATGMS distributed into 11 geometry exception types and the 4 cause categories previously identified in Figure A58. As indicated by the numbers in Table A11 the erroneous track class determination by ATGMS mostly affected crosslevel and 62-foot cord alignment and profile measurements, differences in geometry measurements being more than 0.1 inches mostly affected crosslevel and 62-foot cord profile measurements, and differences in geometry measurements less than 0.1 inches mostly affected narrow gage measurement.

Table A11: Distribution of ATIP-Reported Geometry Exceptions Not Detected By ATGMS By Exception Type

Geometry Exception Type	Not Detected	Class of Track Determination	Difference in Geometry Measurement > 0.1 inches	Difference in Geometry Measurement < 0.1 inches	Missing Geometry Data
		Cause Category			
Crosslevel	176	114	49	7	6
Gage Narrow	50	0	3	46	1
Gage Wide	19	11	2	6	0
L Align 31’	8	7	0	1	0
L Align 62’	135	123	5	6	1
L Prof 62’	224	120	96	7	1
R Align 31’	11	10	0	1	0
R Align 62’	116	102	8	6	0
R Prof 62’	169	108	55	6	0
Warp >6”	0	0	0	0	0
Warp 62’	77	39	28	7	3
TOTAL	985	634	246	93	12

8.2 Exceptions Not Reported by ATGMS

Consideration of the distribution of 148 ATIP-reported geometry exceptions that were detected but deleted by the ATGMS automated exception editor in Figure A58 shows that of the 148 geometry exceptions:

- Seventy-six were incorrectly deleted by ATGMS automated exception filters. A review of foot-by-foot geometry measurements associated with these exceptions indicated that they were valid exceptions.
- Forty-three were deleted because ATGMS automated exception filters detected spikes and flat lines in the foot-by-foot gage measurement associated with these exceptions. Spikes and flat lines could be caused by factors such as direct sun glare or reflections from the ballast.
- Twenty-four were not reviewed by ATGMS automated exception filters. An exception may not have been reviewed if:
    1. Associated foot-by-foot geometry measurements were not available when automated exception filters queried the ATGMS database for the relevant data. This situation occurred when large amount of data was transferred to the servers causing delays between when an exception was detected and when associated foot-by-foot geometry measurements were became available in ATGMS database.

2. ATGMS automated exception filters could not classify the exception into any one of the pre-defined exception types.
3. ATGMS automated exception filters detected unexpected changes in foot-by-foot geometry measurements indicating missing data, bad data, or errors in calculations.
   - Three were deleted due to erroneous detection of curves and spirals as tangent by ATGMS Curve, Tangent, and Spiral (CTS) detection algorithm.
   - One was deleted due to high frequency oscillations in foot-by-foot geometry measurements.
   - One was deleted due to flat line in foot-by-foot geometry measurements other than gage.

Table A12 lists the 148 ATIP geometry exceptions detected but deleted by the ATGMS automated exception editor by the 11 geometry exception types and 6 cause categories previously identified in Figure A58. Erroneous deletion of valid exceptions, spikes and flat lines in gage measurement, and instances when ATGMS automated exception filters did not review exceptions mostly affected 62-foot cord alignment measurements. Erroneous deletion of valid exceptions also affected 62-foot warp measurements. Errors in curvature calculation, i.e. detecting curves and spirals as tangent, only affected the identification of crosslevel exceptions. Oscillations in foot-by-foot geometry measurements and flat lines in geometry measurements other than gage affected one 62-foot cord warp exception and one exception to alignment safety threshold.

Table A12: Distribution of ATIP-Reported Geometry Exceptions Detected but Deleted by ATGMS by Exception Type

Geometry Exception Type	Detected but Deleted or Not Reviewed	Erroneous Deletion of Valid Exceptions	Gage Spike or Flat Line	Not Reviewed	Erroneous Detection of CTS	Oscillation in Measurements	Flat line in Measurements other than Gage
	Cause Category						
Crosslevel	**9**	5	1	0	3	0	0
Gage Narrow	**1**	0	1	0	0	0	0
Gage Wide	**5**	4	1	0	0	0	0
L Align 31’	**1**	0	1	0	0	0	0
L Align 62’	**49**	20	17	11	0	0	1
L Prof 62’	**9**	5	4	0	0	0	0
R Align 31’	**0**	0	0	0	0	0	0
R Align 62’	**42**	15	14	13	0	0	0
R Prof 62’	**12**	8	4	0	0	0	0
Warp >6”	**0**	0	0	0	0	0	0
Warp 62’	**20**	19	0	0	0	1	0
TOTAL	**148**	**76**	**43**	**24**	**3**	**1**	**1**

Analysis presented in this report shows that two of the critical factors affecting ATGMS performance is track class determination and the ability of the system to discriminate valid exceptions from false exceptions in a consistently reliable fashion. Following this evaluation, FRA sponsored the development of a web application for remote editing of ATGMS exceptions. With the use of this application, ATGMS generated exceptions are presented to an experienced operator located at a remote site for review and editing. Based on available information such as track charts, timetables and aerial images, the user of the application will be able to provide critical inputs into the proper identification of tracks over which the system is traversing and the establishment of track class.

It is conservatively anticipated that operation of this web application will improve ATGMS track class determination by close to 90 percent, reducing the number of exceptions in this category from 634 to 63 exceptions. In combination with allowing an experienced user to review candidate exceptions prior to transmission to survey stakeholders, these improvements will significantly increase the percentage of ATGMS reported geometry exceptions that would match the reliability of geometry exceptions reported by a manned system.

9. ATGMS and ATIP Foot-by-Foot Geometry Data Comparison

Geometry exceptions are used as markers for retrieving corresponding ATGMS and ATIP foot-by-foot geometry data for comparison. Out of 1,193 ATIP reported geometry exceptions, 798 were used for identifying foot-by-foot geometry measurements for detailed comparison. Three hundred and ninety-five (395) of ATIP reported geometry exceptions were excluded because:

- Three hundred and forty-two represented multiple exceptions types, meaning that various geometry exceptions existed at the same location or within a span of several feet
- Twenty-nine had incomplete or missing foot-by-foot geometry measurements
- Twenty-four were found to be affected by ATGMS malfunctions

The foot-by-foot geometry measurements identified by the remaining 798 geometry exceptions were reviewed to remove measurement outliers and measurements made below cut off speeds of 28 miles per hour (mph) for track geometry calculation. Adjustments were made by removing a small segment of affected measurements from all geometry channels.

This process resulted in more than 314,000 feet of corresponding ATGMS and ATIP foot-by-foot geometry measurements for which resulting statistics were compared against accepted ATIP repeatability thresholds for track geometry data collected from multiple vehicles. These thresholds are presented in Table A13 and statistics resulting from the comparison is presented in Table A14.

Table A13: Repeatability Thresholds for Foot-by-Foot Geometry Data Multiple Vehicles

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Profile (Inches)	0.04419	0.08838
Alignment (Inches)	0.04419	0.17675
Crosslevel (Inches)	0.04419	0.08838
Curvature (Deg/100’)	0.01414	0.21210
Gage (Inches)	0.04419	0.08838

Table A14: Statistics of Difference Between ATGMS and ATIP Foot-by-Foot Geometry Data, March 2012

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Profile (Inches)	-0.0051	*0.0960*
Alignment (Inches)	-0.0001	0.0495
Crosslevel (Inches)	*-0.0711*	*0.1122*
Curvature (Deg/100')	*0.0152*	0.0299
Gage (Inches)	-0.0119	0.0330

Results indicate that mean and standard deviation for crosslevel measurement differences, the mean difference for curvature measurement, and the standard deviation of profile measurement differences exceed the multiple vehicles repeatability thresholds. The mean and standard deviations for all other differences between measurement parameters meet multiple vehicle repeatability thresholds.

10. Conclusions and Recommendations

Over 16,000 miles of track geometry measurements collected between April 2 and June 7 of 2012 by the ATGMS on FRA's DOTX221 while operated in consist with the FRA ATIP's DOTX220 manned track geometry inspection vehicle over Amtrak passenger routes were reviewed to assess agreement between the two measurement systems in terms of exceptions detected as well as foot-by-foot measurements. Exceptions reported by FRA's manned geometry inspection system on DOTX220 were considered as "ground truth" and used to assess performance of the ATGMS. A subset of reported exceptions from DOTX220 manned track geometry inspection vehicle were used to identify areas for comparison of foot-by-foot track geometry data collected by the unmanned and manned systems.

Comparison of foot-by-foot data collected by both systems shows that quality of data collected by ATGMS on FRA's DOTX221 is comparable with the quality of data collected FRA ATIP's DOTX220 manned track geometry inspection vehicle.

DOTX220 manned track geometry inspection vehicle reported 1,193 exceptions. Not all ATGMS generated exceptions matched the 1,193 reported exceptions by DOTX220 manned track geometry inspection vehicle. Mismatched exceptions were reviewed and the following seven categories of causes were identified:

- Class of track determination
- Difference in geometry measurements more than 0.1 inches
- Gage spikes and flat lines
- Difference in geometry measurements less than 0.1 inches
- Erroneous detection of CTS
- Erroneous deletion of valid geometry exceptions
- Flat line in geometry measurements other than gage
- Oscillations in geometry measurements
- Missing geometry data

Review of mismatched exceptions identified ATGMS automated, speed-based logic for class of track determination as the critical factor affecting ATGMS performance. Following assessment of the performance of the ATGMS compared to that of a manned system, a web application for remote editing of ATGMS detected exceptions by an operator was developed to augment ATGMS track class determination logic and automated exception editing until ATGMS technology matures to the point that it can reliably produce results comparable to manned operations. It is anticipated that use of this application will improve ATGMS performance in reporting valid exceptions by 90 percent.

Based on the results of analysis presented in this report, ENSCO has identified the following areas of ATGMS technology for further improvement:

1. **Track Class Determination** – Exceptions to track geometry limits defined in FRA's Track Safety Standards are different for each track class. Track class and associated posted speed are used to apply the proper track geometry limits. Therefore, accurate

determination of track class will improve ATGMS performance in reporting valid exceptions. In 2012, as part of ENSCO's internal research and development efforts, an approach for accurate determination of track number, and by extension track class and posted speed, based on railroad-provided information was developed and tested using limited information provided by a Class I railroad. This approach can be further improved and used to increase ATGMS performance in reporting valid exceptions where railroad-provided information

2. **Automated Geometry Exception Filters** – Automated geometry exception filters inspect validity of an exception by analyzing associated foot-by-foot geometry measurements according to a set of empirically derived limits and signal processing algorithms. Empirically derived limits are based on review of many reported exceptions of the same type by FRA ATIP's manned track geometry inspection vehicles. Signal processing algorithms are designed to detect outliers and anomalies caused by system malfunctions and/or environmental factors such as spikes, flat lines, and high frequency oscillations in geometry measurements. Both empirically derived limits and signal processing algorithms can be further tuned to improve ATGMS performance in reporting valid exceptions. In addition, automated geometry exception filters "exception list" can be expanded to include more exception types to reduce the number of exceptions that could not be classified by the filters, therefore, marked as "not reviewed."
3. **ATGMS Server/Database** – Improving synchronized processing of exceptions and retrieval of associated foot-by-foot geometry measurements will improve ATGMS performance in reporting valid exceptions by reducing the number of exceptions marked by automated exception filters as "not reviewed." Although the occurrence of these situations is relatively infrequent, data flow on ATGMS server/database can be improved to ensure availability of the foot-by-foot geometry data when validity of an exception is evaluated by automated exception filters.

Appendix B – DOTX221 ATGMS Operations Performance Report

DOTX221 ATGMS Operations Performance Report: Summer/Fall 2013 ATIP Amtrak Assessment Survey

Customer Contract Number: DTFR53-10-D-00002
ENSCO Project Number: 3670.09

Prepared for:
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Executive Summary

Using autonomous track geometry measurement systems (ATGMS) for routine collection of track geometry data provides many advantages over operating traditional dedicated track inspection vehicles. Inspection data obtained with autonomous systems can be collected more frequently without track time being consumed by dedicated inspection vehicles. The use of autonomous inspection technologies will result in earlier detection of track defects and changes in maintenance practices from reactive to preventative, ultimately reducing the number of track caused derailments throughout the railroad industry. Use of autonomous inspection technology also offers the promise of expanded coverage and lower overall inspection costs over traditional manned survey operations.

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) has undertaken a multi-phase research program in cooperation with FRA's Office of Railroad Safety focused on the development and advancement of ATGMS and related technologies to improve rail safety. Under Task Order 9 of Contract DTFR53-10-D-00002, an ATGMS was installed on FRA's DOTX221 and deployed in consist with FRA's DOTX220 manned inspection car. The two systems were compared as part of FRA's Automated Track Inspection Program (ATIP) surveys conducted over Amtrak passenger routes in 2011 and 2012. This testing demonstrated that the two systems produced data of equal quality. Differences between measured geometry data were within acceptable limits established for geometry measurements from multiple vehicles. Exceptions generated by the ATGMS and the manned system were compared and differences in reporting were attributed to (a) ATGMS speed-based class of track determination logic, (b) difference in geometry measurements from the two systems, (c) ATGMS automated exception validation logic versus crew observation of track features such as switches, and (d) erroneous deletion and/or validation of exceptions on both systems.

Subsequent research efforts focused on developing and implementing a secure web-based application for near real-time review and validation of geometry exceptions as part of FRA's data management and quality assurance processes. Using a web-based application called Remote Editor Desk developed by ENSCO, a reviewer can make necessary adjustments to control parameters such as track number and track class based on the latest information provided by railroads to validate geometry exceptions. The confirmed exceptions can then be sent to a list of designated recipients. Information available to reviewers to facilitate their decision process include detailed maps using a Google Maps™ display of geographical location of the selected data, displays of foot-by-foot track geometry measured in areas of interest and railroad-provided timetables and track charts.

The use of ATGMS in conjunction with Remote Editor Desk was initially evaluated during surveys conducted with DOTX221 in Amtrak revenue service operations between Washington, DC, and Miami, FL, and Washington, DC, and Chicago, IL, between December 2012 and April 2013 to identify issues and develop enhancements. Following these tests, FRA's RD&T conducted a complete evaluation of DOTX221 ATGMS operation during the 2013 ATIP Amtrak Assessment Survey to assess hardware, software, and processes developed with the goal of providing a sustainable inspection system for ATIP survey operations.

This report provides an overview of DOTX221 ATGMS and Remote Editor Desk performance during 2013 ATIP Amtrak Assessment Survey. There were several minor hardware and software issues identified during the test that were addressed or corrected during scheduled maintenance stops. Overall performance of the Remote Editor Desk for information management and quality assurance met FRA expectations. This report summarizes issues with the measurement system and the Remote Editor Desk that were identified during testing; issues addressed during testing are described and those items that require additional remedial action are described. Recommended enhancements to FRA's ATGMS system and Remote Editor Desk are detailed and evaluation of the repeatability of the system over selected track segments are summarized.

11. Introduction

Using autonomous track geometry measurement systems (ATGMS) for routine collection of track geometry data provides many advantages over operating traditional dedicated track inspection vehicles. Inspection data obtained with autonomous systems can be collected more frequently without track time being consumed by dedicated inspection vehicles. The use of autonomous inspection technologies will result in earlier detection of track defects and changes in maintenance practices from reactive to preventative, ultimately reducing the number of track caused derailments throughout the railroad industry. Use of autonomous inspection technology also offers the promise of expanded coverage and lower overall inspection costs over traditional manned survey operations.

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) has undertaken a multi-phase research program in cooperation with FRA's Office of Safety focused on the development and advancement of ATGMS and related technologies to improve rail safety. Under Task Order 9 of Contract DTFR53-10-D-00002, an ATGMS was installed on FRA's DOTX221 and deployed in consist with FRA's DOTX220 manned inspection car. The two systems were compared as part of FRA's Automated Track Inspection Program (ATIP) surveys conducted over Amtrak passenger routes in 2011 and 2012. This testing demonstrated that the two systems produced data of equal quality. Differences between measured geometry data were within acceptable limits established for geometry measurements from multiple vehicles. Exceptions generated by the ATGMS and the manned system were compared and differences in reporting were attributed to (a) ATGMS speed-based class of track determination logic, (b) difference in geometry measurements from the two systems, (c) ATGMS automated exception validation logic versus crew observation of track features such as switches, and (d) erroneous deletion and/or validation of exceptions on both systems.

Subsequent research efforts focused on developing and implementing a secure web-based application for near real-time review and validation of geometry exceptions as part of FRA's data management and quality assurance processes. Using a web-based application called Remote Editor Desk developed by ENSCO, a reviewer can make necessary adjustments to control parameters such as track number and track class based on the latest information provided by railroads to validate geometry exceptions. The confirmed exceptions can then be sent to a list of designated recipients. Information available to reviewers to facilitate their decision process include detailed maps using a Google Maps™ display of geographical location of the selected data, displays of foot-by-foot track geometry measured in areas of interest and railroad-provided timetables and track charts.

The 2013 ATIP Amtrak Assessment consisted of 17 one-way trips starting in Washington, DC, on July 29, 2013, and ending in Washington, DC, on September 29, 2013, covering more than 19,000 miles of track as listed in Table B15. Each of these one-way trips is referred to as a "segment" of the assessment for the purpose of reporting issues. In near real-time, as exception data become available in ATGMS database, an operator used the web-based Remote Editor Desk application to correct for actual track class as well as individual track number and to validate individual exceptions and overall track measurement quality by considering foot-by-foot geometry data, system health information and other system data. Confirmed exceptions were sent as Non-Compliance Exception Reports (NCER). Track Assessment Reports (TAR) covering surveyed track within territory of individual railroads were sent out at the end of each survey, when all track exceptions were confirmed by operators. The TARs include a tabular exception list as well as a summary of all confirmed track geometry exceptions for the reported geographical limits. NCERs and TARs were sent to railroad representatives and FRA personnel at the same time.

The scope of this report is to summarize assessment of DOTX221 ATGMS operations (hardware, software, and Remote Editor Desk) during 2013 ATIP Amtrak Assessment. Those issues affecting ATGMS operations on DOTX221 are categorized into ATGMS Sensors, Electrical and Electronics, Mechanical, Data Collection, Data Transfer, and Data Processing; these are presented in Section 2. Section 3 contains Issues affecting Remote Editor Desk operations; these are categorized into User Interface, Editing, and Reporting. Several enhancements to ATGMS software and hardware, and Remote Editor Desk were also identified and presented in Section 4.

As part of the data evaluation process, foot-by-foot geometry data collected consecutively on three selected track segments during the 2013 ATIP assessment were compared to assess overall data stability and repeatability. This evaluation data included two sets of geometry data collected on the same track between Los Angeles, CA, and Oakland, CA, on consecutive days; two sets of geometry data collected forty days apart on the same track between Memphis, TN, and New Orleans, LA; and two sets of geometry data collected nineteen days apart on the same track between Tempe, TX, and San Antonio, TX. Statistics of differences between the respective sets of collected geometry data on these track segments, presented in Section 5, confirmed ATGMS' repeatability throughout the assignment.

Table B15. 2013 ATIP Amtrak Assessment Survey

Train #	Segment				Survey Miles - Actual	Survey Miles - Scheduled	Survey Miles - Missed	Exceptions Generated	Exceptions Reported
	Origin	Destination	Start Date	End Date					
91	Washington DC	Miami, FL	7/29/2013	7/30/2013	0	1,235	1,235	-	-
98	Miami, FL	Washington DC	8/1/2013	8/2/2013	0	1,164	1,164	-	-
19	Washington DC	New Orleans, LA	8/12/2013	8/13/2013	1,150	1,152	2	1325	19
58	New Orleans, LA	Chicago, IL	8/14/2013	8/15/2013	931	934	3	693	30
5	Chicago, IL	Emeryville, CA	8/19/2013	8/21/2013	2,420	2,438	18	5428	122
14	Oakland, CA	Seattle, WA	8/27/2013	8/28/2013	207	913	706	263	119
8	Seattle, WA	Chicago, IL	8/29/2013	8/30/2013	1,893	2,205	312	1513	252
50	Chicago, IL	Washington DC	9/3/2013	9/4/2013	920	922	2	6311	22
29	Washington DC	Chicago, IL	9/6/2013	9/7/2013	778	780	2	1282	40
21	Chicago, IL	San Antonio, TX	9/9/2013	9/10/2013	1,279	1,305	26	2915	419
2	San Antonio, TX	New Orleans, LA	9/13/2013	9/13/2013	538	573	35	95	8
58	New Orleans, LA	Chicago, IL	9/16/2013	9/17/2013	934	934	0	689	43
3	Chicago, IL	Los Angeles, CA	9/18/2013	9/20/2013	1,876	2,265	389	2168	138
14	Los Angeles, CA	Oakland, CA	9/23/2013	9/23/2013	466	464	-	944	10
11	Oakland, CA	Los Angeles, CA	9/24/2013	9/24/2013	468	464	-	782	10

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422	Los Angeles, CA	Chicago, IL	9/25/2013	9/28/2013	2,701	2,728	27	4625	412
30	Chicago, IL	Washington DC	9/29/2013	9/29/2013	n/a	n/a	-	-	-

12. Issues and Recommended Actions for ATGMS Operation

Issues affecting DOTX221 ATGMS operations are categorized into ATGMS Sensors, Electrical and Electronics, Mechanical, Data Collection, Data Transfer, and Data Processing and are listed below. A short description of each issue is provided along with information on its relative impact as characterized by the number of one-way trips, or segments, that were affected by the issue, and the associated recommended actions.

12.1 Sensor Components

12.1.1 *Right Profile Accelerometer Cable*

During the survey between Washington, DC, and New Orleans, LA, started on August 12, 2013, the right profile accelerometer cable was hit and damaged by a wayside object. The connector was temporarily repaired in New Orleans and later replaced in Emeryville, CA, following arrival on August 21, 2013.

Impact: Partial Data Loss	**No. of Affected Segments:** 1	**Status:** Remediated
Recommended Actions: Relocate the profile accelerometer boxes to the opposite side of the beam and reroute the cable to provide better protection.		

12.1.2 *ALD Sensor*

The original ALD sensor failed on July 29, 2013 and was replaced on August 9, 2013. The replacement sensor exhibited drift issues and was replaced on August 22, 2013. No further issues were observed.

Impact: Partial Data Loss	**No. of Affected Segments:** 2	**Status:** Remediated
Recommended Actions: No further action required.		

12.1.3 *Right Rail Scanner*

Scanner S/N 14749 was removed due to low laser power in Washington, DC, and replaced with Scanner S/N 6604 on August 9, 2013. Scanner S/N 6604 was removed due to low laser power in Emeryville, CA, following arrival on August 21, 2013 and replaced with Scanner S/N 11567. Scanner 11567 ran without an issue during the rest of the assignment.

Impact: Data Degradation	**No. of Affected Segments:** 5	**Status:** Remediated
Recommended Actions: No further action required.		

12.1.4 *Global Positioning System*

Water in Global Positioning System (GPS) antenna junction box caused slow acquisition; the water was removed and the antenna/cable connectors were cleaned on August 9, 2013, in Washington, DC. Upon reassembly, all enclosure penetrations were resealed. Satellite constellation table was also updated.

Impact: Location Accuracy	**No. of Affected Segments**: 2	**Status:** Remediated
Recommended Actions: Modify GPS antenna junction box to prevent water accumulation. Update maintenance practices to inspect junction box routinely.		

12.2 Electrical and Electronics Issues

12.2.1 *Gage Computer Central Processing Unit*

Slow processor and increased processing demand overloaded gage computer Central Processing Unit (CPU) creating flat lines in data and large number dropped data packets. The gage CPU was replaced on August 9, 2013, in Washington, DC.

Impact: Total Data Loss	**No. of Affected Segments**: 2	**Status:** Remediated
Recommended Actions: No further action required		

12.2.2 *Network Hub*

ATGMS network hub lost power prior to arriving in Washington, DC, before Amtrak Assessment operations due to a shorted Laser Protection System (LPS) motor. On July 26, 2013, separated network hub power feed from LPS to prevent network hub drop outs caused by motor short.

Impact: None	**No. of Affected Segments**: 0	**Status:** Remediated
Recommended Actions: No further action required		

12.2.3 *Reset Board*

Existing reset board does not allow for remote operator to perform a hard system restart. On two occasions during the Amtrak Assessment, the Amtrak train crew needed to be contacted to manually restart the ATGMS due to system lockup. Replacement is recommended to increase system reliability.

Impact: Total Data Loss	**No. of Affected Segments**: 2	**Status:** Open
Recommended Actions: Replace existing reset board with one that allows for remote system restart.		

12.2.4 *Head-End-Power*

System did not survey following departure from Oakland, CA, on August 27, 2013, because Amtrak Conductor did not power the car before departure.

Impact: Total Data Loss	**No. of Affected Segments:** 1	**Status:** Closed
Recommended Actions: Consider independent power system.		

12.3 Mechanical Issues

12.3.1 *Laser Protection System*

Motor failed on film advance system. Replaced burned motor with a high torque/low speed unit. Temporarily removed right device due to issues with feeder mechanism. Removed clear film due to condensation and dirt accumulation.

Impact: Data Degradation	**No. of Affected Segments:** 8	**Status:** Open
Recommended Actions: Remove film-based laser protection system and implement shrouds over gage measurement system lenses to allow recess to provide mitigation of dirt.		

12.3.2 *Tachometer Mount*

Loose and missing hardware elements were identified during routine inspections and replaced on July 30, 2013, in Miami, FL. A new mounting plate was fabricated to eliminate isolators and installed August 20, 2013, in Chicago, IL.

Impact: Data Degradation	**No. of Affected Segments:** 0	**Status:** Remediated
Recommended Actions: No further action required.		

12.4 Data Collection Issues

12.4.1 *Alert Messages*

When sensor inactivity and out of range messages were enabled, gage sensor and LPS issues caused a flood of Alert Messages. ATGMS architecture is designed with Alert Messages having priority over raw sensor data packets and Status Messages causing raw sensor data packets not leaving the remote unit. Location information is needed in these messages.

Impact: Delayed Data	**No. of Affected Segments:** 1	**Status:** Open
Recommended Actions: Modify software to suppress the number of inactivity/out of range messages in the event of sensor failure.		

12.4.2 *Status Messages*

Power status is not reported correctly because it is generated by both computers, sent to the server, and combined. Status Message reporting was corrected on August 9, 2013.

Impact: Notification Accuracy	**No. of Affected Segments**: 2	**Status:** Remediated
Recommended Actions: No further action required.		

12.4.3 *Computer Reboot*

When ATGMS software restarts due to direction change or when maximum millage for a run ID is reached, corrupt files or overflow conditions are occasionally observed.

Impact: Total Data Loss	**No. of Affected Segments**: 2	**Status:** Open
Recommended Actions: Modify software to detect and correct corrupt files before starting TGMS. Modify software restart process to eliminate need to reboot computer.		

12.5 Data Transfer Issues

12.5.1 *Out-of-Order Data Packets*

Due to latency in cellular communication, some data packets would arrive at ATGMS servers outside the pre-defined anticipated 2-minute time window. The delayed data packets arrive at ATGMS servers out of order and are discarded. The approach was modified to wait until 10 packets subsequent to a missed packet were received before continuing processing. Additional consideration is needed to minimize data loss as a few out–of-order data packets were observed after modifications.

Impact: Total Data Loss	**No. of Affected Segments**: All	**Status:** Open
Recommended Actions: Reconsider approach to data transmission. Elimination of data loss may result in longer delays between remote collection and server processing in some situations.		

12.6 Data Processing Issues

12.6.1 *Location Offset*

A 200-foot offset was observed in location information. A software modification was issued to correct this issue on August 13, 2013.

Impact: Data Accuracy	**No. of Affected Segments**: 3	**Status:** Remediated
Recommended Actions: No further action required.		

12.6.2 *Offset in Profile Mid-Chord Values*

There is a random initialization issue that occasionally causes mid-chord offset (MCO) values for profile measurements to exhibit an offset at the start of a run. The only recovery method is to restart the Track Geometry Measurement System (TGMS) processor on the server.

Impact: Data Accuracy	**No. of Affected Segments**: 2	**Status:** Open
Recommended Actions: Investigate scenarios that exhibit profile DC offset in order to identify processing failure.		

12.6.3 *Server-Based Processor to Database Data Transfer*

On August 19, 2013, geometry exception data was dropped when pushed from the TGMS processor on the server to the ATGMS database. Restarting the TGMS processor resolved the issue. The missing data was later reprocessed without issue.

Impact: Total Data Loss	**No. of Affected Segments**: 1	**Status:** Hold
Recommended Actions: This is a single isolated incident in the 2+ years running the system. No action is recommended unless further recurrence is observed.		

12.6.4 *Milepost Detection*

Over the course of the entire Amtrak Assessment, 703 exceptions were not tagged with MP information; 267 of these were not tagged with GPS location information either. To resolve the issues with no MP identification, permission was given by three Class 1 railroads to use their MP location information. ATIP historical MP location information was also used to identify other locations of interest.

Impact: Partial Data Loss	**No. of Affected Segments**: All	**Status:** Open
Recommended Actions: Reconsider location determination methodology. Limit possible solutions to only railroad segments on the route being traversed.		

12.6.5 *New File on Railroad Change*

Transitioning from one railroad to another during a particular survey's data file, or "run ID", should have created a new run ID with prefix of A, B, C, etc., but this was not consistently achieved. Improvement to railroad determination algorithm is needed in order to efficiently separate data files according to railroad.

Impact: Data Accuracy	**No. of Affected Segments**: All	**Status:** Open
Recommended Actions: Revise railroad determination algorithm to limit possible solutions to only railroad segments on the route being traversed.		

12.6.6 *Incorrect Region Notification*

Whenever GPS information was missing, exceptions were incorrectly assigned to Region 1. The notification table was updated to remove Region 1 personnel for exceptions without GPS on August 16, 2013.

Impact: Data Accuracy	**No. of Affected Segments**: 4	**Status:** Remediated
Recommended Actions: No further action required.		

It is encouraged that all "open" issues and those for which recommended actions are provided be addressed prior to employing the ATGMS in the next scheduled Amtrak Assessment.

13. Issues Affecting Remote Editor Desk Operations

Issues affecting Remote Editor Desk operations are separated into categories corresponding to those impacting User Interface, Editing, and Reporting functions. These issues have been divided into two reporting categories – those resolved during survey operations and outstanding issues as of the end of 2013 ATIP Amtrak Assessment Survey. A short description of each issue resolved during the Amtrak Assessment is provided in Table B16. Outstanding issues with the Remote Editor Desk are presented in Table B17 along with an associated priority for remediation. It should be noted that issues associated with Remote Editor Desk operations did not have a direct impact on data collected by the ATGMS on DOTX221 but did affect the ability of operators to evaluate and report on survey results.

Table B16: Remote Editor Desk Issues Resolved During 2013 Amtrak Assessment Survey

Category	Description
User Interface	• Map didn't show information for subdivisions with the "&" character in their names; • Start/End city fields longer than 32 characters caused error message; • Exception count statistics on bottom of editor screen needed to be corrected; • Track table "submit" pop up window stopped working part way through a geometry file; • Added "Confirmation" pop up window to prevent incorrect exceptions from being sent via NCER; • Utility improperly applied track table when changing track number or class from exception list; • Needed to show space curve channels for runoff exceptions; • Corrected differences between ALD values on Remote Editor Desk and those shown in NCERs;
Editing	• Needed to exclude exceptions and curves without MP/GPS info from Editor; • Corrected issue where exceptions erroneously deleted when posted class raised; • Originally not able to change track number and posted class for exceptions that don't have corresponding track table entries; • Corrected situation when narrow gage exceptions deleted after changing posted class; • Corrected cases where applying the track table doesn't consistently delete exceptions; • Originally unable to change track number if there is no entry in the track table; • Curves that are not modified by operator have default track number assigned as opposed to actual track number – this was remedied;
Reporting	• Excluded exceptions and curves without MP/GPS info from reports; • Trimmed exception type on header of NCER's to eliminate blank space; • NCER strip chart corrected so it did not show cant channels; • Exception not always centered on NCER strip chart; • Application corrected so it sent email rather than TAR reports for run IDs with no exceptions; • File names of TARs and NCERs were not originally consistent with ATIP operations; • Needed ability to change the railroad when creating a report;

Table B17: Outstanding Remote Editor Desk Issues Following 2013 Amtrak Assessment Survey

Priority	Category	Description
High	Editing	Verify track number and position info on Curve records
High	Editing	Correct issue where system deleted exceptions after NCERs were sent
High	Reporting	Need ability to control the range of exceptions for ASCII file export
High	Reporting	Correct issue when NCERs failed to transmit properly
High	Reporting	Ability to define a range of exceptions that spans multiple pages
Medium	User Interface	Adjust turnout detection to improve identification
Medium	User Interface	Add red tick mark on Video Strip Chart to indicate location of exception
Medium	User Interface	Properly update summary numbers with multiple pages of exceptions
Medium	User Interface	Correct issue where application randomly locks out users when in Test Mode
Medium	Reporting	Add note to reports indicating turnouts are not exceptions
Medium	Reporting	Limit speed exceptions should not show "Limiting Class 0" on TARs
Medium	Reporting	Correct situation where the railroad is set to "UNKNOWN" in the subject line of TAR delivery emails when the railroad is not properly identified by exception locations
Low	User Interface	After login page, user must refresh browser to get query dialogue
Low	User Interface	Show ATGMS Units button works only in multi-window mode
Low	Editing	Investigate application lock up while sending NCERs
Low	Reporting	Investigate issue where BNSF internal exception tracking file contained bad information after "NO EXCEPTION" messages were sent

14. Recommended ATGMS Enhancements

Surveying 19,000 miles of track with ATGMS on Amtrak revealed a number of future enhancements that could improve its autonomous operations on DOTX221 or any other vehicle. Enhancements to the hardware and software associated with the measurement system and transfer of its data are provided in Table B18; these should be considered as additional recommendations beyond the correction of issues identified in Section 2. Enhancements to the Remote Editor Desk that will be instrumental in improving the efficiency of data review and reporting are indicated in Table B19.

Table B18: Recommended ATGMS Hardware and Software Enhancements

Priority	Category	Description
High	Hardware	Physically separate ATGMS and TDMS databases by employing an additional server to handle data processing tasks
High	Hardware	Upgrade the cellular modem from 3G to 4G to improve communication rates
Medium	Software	Add ability to export .dt1 files from ATGMS server
Medium	Software	Improvements to remote control/diagnostic tool (dispdbg)
Low	Software	Automate data overlay to self or other ATIP cars
Low	Hardware	Add a set of dedicated calibration tools

Table B19: Recommended Remote Editor Desk Enhancements Following 2013 Amtrak Assessment Survey

Priority	Category	Description
High	User Interface	Show time since last data received on server in header of exception list
High	Editing	Add ability to break run IDs for changing railroads and excessive file lengths on the server rather than the car
High	Editing	Add ability to edit track table in real-time and save/apply (similar to TrackIT® Console)
High	Editing	Remote Editor Desk needs to recheck deleted exceptions when higher track class is reapplied
High	Reporting	Express reported values consistently across all exception types in NCERs, TARs, etc.
Medium	User Interface	Show mileage in the run ID selection list box
Medium	User Interface	Show mileage in header of exception list
Medium	User Interface	Strip chart navigation buttons need to be larger and not move between clicks
Medium	Reporting	Need to have capability to run ATIP's Duplicate Exception Reports (DERs) on the ATGMS data
Low	Reporting	Exceptions should have unique ID numbers provided with exception name (BNSF is primary user)
Low	Reporting	Add ability to combine run IDs for "No Exception" messages sent to railroads

15. Analysis of Collected Foot-by-Foot Geometry

Foot-by-foot geometry data collected on three selected track segments at different times during the 2013 ATIP Amtrak Assessment Survey were analyzed to evaluate ATGMS' repeatability and Remote Editor Desk's utilization and operators' performances throughout the assignment. Results of this analysis are presented in the following sections.

Data used to analyze foot-by-foot geometry measurements included two sets of geometry data collected on the same track between Los Angeles, CA, and Oakland, CA, on consecutive days; two sets of geometry data collected forty days apart on the same track between Memphis, TN, and New Orleans, LA; and two sets of geometry data collected nineteen days apart on the same track between Tempe, TX, and San Antonio, TX. This comparison, although not a true measure of repeatability, was intended to indicate the general stability of the system.

Foot-by-foot geometry measurements associated with several random locations along each segment on both days were extracted. Invalid data segments were deleted before comparison; these segments included:

- Those in which measurements were made below 30 mph, the cut-off speed for a number of track geometry parameters;
- Areas of flat lines in gage, since gage is used to align two sets of data over the same track.

The remaining foot-by-foot geometry measurements represented a little more than 493,000 feet of track between Los Angeles, CA, and Oakland, CA; over 627,000 feet of track between Memphis, TN, and New Orleans, LA; and close to 277,700 feet of track between Tempe, TX, and San Antonio, TX. Statistics based on the differences between the various sets of aligned track data were compared against accepted ATIP repeatability thresholds for comparing any two data sets over the same track by two different vehicles; these thresholds are presented in Table B20. The summary of the consideration of the various ATGMS data sets are presented in Table B21, Table B22, and Table B23 with Mean Difference and/or Standard Deviation of any geometry parameter exceeding the acceptable repeatability thresholds highlighted in red/italics. Statistics of differences between the respective sets of collected geometry data on these track segments show that ATGMS' performance is very stable.

Table B20: Repeatability Thresholds for Foot-by-Foot Geometry Data, Multiple Cars

	Multiple Cars	
Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Profile (Inches)	0.04419	0.08838
Alignment (Inches)	0.04419	0.17675
Crosslevel (Inches)	0.04419	0.08838
Curvature (Deg/100')	0.01414	0.21210
Gage (Inches)	0.04419	0.08838

Table B21: Statistics of Difference Between Foot-by-Foot Geometry Measurements Collected Between Los Angeles, CA, and Oakland, CA

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Gage (Inches)	-0.00627	0.02865
Crosslevel (Inches)	*0.05907*	0.05386
Curvature (Deg/100')	-0.00872	0.05733
LProfile31 (Inches)	0.00003	0.03736
RProfile31 (Inches)	0.00005	0.03662
LAlign31 (Inches)	0.00007	0.02970
RAlign31 (Inches)	0.00004	0.03024
LProf62 (Inches)	0.00003	0.03983
RProf62 (Inches)	0.00003	0.03912
LAlign62 (Inches)	0.00004	0.03397
RAlign62 (Inches)	0.00001	0.03383
LProf124 (Inches)	0.00006	0.04260
RProf124 (Inches)	0.00005	0.04175
LAlign124 (Inches)	0.00005	0.05628
RAlign124 (Inches)	-0.00000	0.05616

Table B22: Statistics of Difference Between Foot-by-Foot Geometry Measurements Collected Between Memphis, TN, and New Orleans, LA

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Gage (Inches)	-0.01392	0.03738
Crosslevel (Inches)	*-0.08217*	*0.08456*
Curvature (Deg/100')	0.00188	0.01800
LProfile31 (Inches)	0.00008	0.04641
RProfile31 (Inches)	0.00006	0.04479
LAlign31 (Inches)	0.00000	0.03413
RAlign31 (Inches)	-0.00003	0.04202
LProf62 (Inches)	0.00008	0.05457
RProf62 (Inches)	0.00009	0.05252
LAlign62 (Inches)	0.00001	0.04373
RAlign62 (Inches)	0.00000	0.05125
LProf124 (Inches)	0.00009	*0.07716*
RProf124 (Inches)	0.00012	*0.07665*
LAlign124 (Inches)	0.00003	0.07184
RAlign124 (Inches)	0.00006	0.07670

Table B23: Statistics of Difference Between Foot-by-Foot Geometry Measurements Collected Between Tempe, TX, and San Antonio, TX

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Gage (Inches)	0.00719	*0.02469*
Crosslevel (Inches)	0.02910	*0.07908*
Curvature (Deg/100')	-0.00879	0.03530
LProfile31 (Inches)	0.00001	0.04956
RProfile31 (Inches)	0.00000	0.05120
LAlign31 (Inches)	0.00005	*0.03250*
RAlign31 (Inches)	0.00003	0.03184
LProf62 (Inches)	-0.00004	0.06698
RProf62 (Inches)	-0.00003	0.06929
LAlign62 (Inches)	0.00006	0.05830
RAlign62 (Inches)	0.00004	0.05723
LProf124 (Inches)	0.00004	*0.08745*
RProf124 (Inches)	0.00009	*0.08762*
LAlign124 (Inches)	0.00024	0.08570
RAlign124 (Inches)	0.00018	0.08544

16. Conclusions

The focus of FRA's RD&T during 2013 ATIP operations was the evaluation of ATGMS technology and operational procedures with the goal of providing a sustainable track inspection system for FRA's Office of Safety ATIP operations.

FRA Office of Railroad Safety's use of ATGMS without an accompanying manned survey car started in Washington, DC, on July 29, 2013, and ended in Washington, DC, on September 29, 2013, covering more than 19,000 miles of track. In near real-time, as track geometry data was recorded, transmitted and processed for exceptions to established thresholds, a reviewer used the web-based application to correct for actual track class as well as individual track number and to validate individual exceptions in addition to overall track measurement quality by considering foot-by-foot geometry data, system health information and other system data. A review of foot-by-foot geometry measurements collected on three selected track segments at different times during 2013 ATIP operation provided a general sense of ATGMS' repeatability and stable performance.

During the survey, the ATGMS and Remote Editor Desk operations were affected by a number of hardware and software issues. ATGMS operations were reviewed and issues affecting the system were categorized into Sensors, Electrical and Electronics, Mechanical, Data Collection, Data Transfer, and Data Processing. A review of Remote Editor Desk operations identified issues that were categorized into User Interface, Editing, and Reporting. A short description of each issue was provided as well as information on final status of the issue, its impact, and any additional recommended actions. Evaluation of the survey also highlighted a series of hardware and software enhancements that will improve ATGMS reliability as well as performance of Remote Editor Desk operations.

FRA's vision is to improve track safety and maintenance practices by enhancing conditional awareness using autonomous inspection systems. The interim result of FRA's five-stage ATGMS research program is a modular, unattended geometry measurement system that can be deployed on standard rail equipment to collect and distribute accurate track geometry data while running in a standard revenue train. FRA has employed this technology during Office of Railroad Safety evaluations and demonstrated that is a viable approach to safety assessment. Further improvement to this technology, as described in this report, will result in improved operations, efficiency and reliability benefiting not only for FRA but the industry as a whole.

Appendix C – Comparison of Track Geometry Measured with a Carbody-Mounted ATGMS and Amtrak's 10002

Comparison of Track Geometry Measured with a Carbody-Mounted ATGMS and Amtrak's 10002 Summary Report

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17. Executive Summary

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology has undertaken a multi-phase research program focused on the development and advancement of autonomous track geometry measurement systems (ATGMS) and related technologies to improve rail safety by increasing the availability of track geometry data for safety and maintenance planning purposes. Routine collection of track geometry measurements using autonomous, un-manned systems provides many advantages over single purpose, manned systems such as uninterrupted main line track operation and increased inspection frequency allowing for timely detection and monitoring of track locations with safety critical or degradation issues.

Basic elements of a ruggedized pilot ATGMS were developed under the first stage of FRA's development of the technology. The second stage focused on use and improvement of the technology under simulated revenue operations over Amtrak passenger routes to demonstrate ATGMS accuracy and increase the autonomy of operation of the system. The third stage was centered on development and evaluation of a carbody-mounted ATGMS. The objective of the carbody-mounted system's design was to minimize interference with truck and wheel set maintenance activities, better protect the measurement platform from flying debris and mud, and allow for installation of ATGMS on a wide range of vehicle designs with a lower installation and maintenance cost.

The major accomplishments for this stage, supported under Task Order 14 of FRA's Contract DTFR53-10-D-00002, included demonstration of the new sensor and processing algorithms to account for new techniques to measure track geometry from a location further away from the rails. For demonstration and evaluation purposes, a carbody-mounted ATGMS was installed and operated on Amtrak's 82602, an Amfleet I passenger car, in revenue service on the Northeast Corridor (NEC).

This report documents the performance of the carbody-mounted ATGMS as compared to a manned, truck-mounted geometry inspection system installed on Amtrak's survey vehicle designated as 10002 during surveys conducted on NEC between October 2012 and August 2013. Exceptions to track geometry limits defined in FRA's Track Safety Standards produced by the two systems were compared to each other. Results of this comparison are presented in Section 2. Differences between geometry exceptions produced by the two systems are attributed to five categories of causes. More than half of the observed differences between geometry exceptions produced by the two systems are attributed to differences in geometry measurements from the two systems. Class of track determination affected ATGMS geometry exception reporting and was the second leading cause of differences between geometry exceptions generated by the two systems.

More than 31,000 feet of track geometry data collected by the unmanned and manned systems were compared on a foot-by-foot basis; areas for comparison were selected based on locations with track geometry exceptions as reported by the manned system aboard Amtrak's 10002. Differences in gage, profile, alignment, crosslevel, and curvature measurements collected by the two systems were compared with differences used by FRA to assess overall agreement between multiple measurement systems. Results of this analysis, presented in Section 3, show that the mean difference and standard deviation for crosslevel as well as the mean difference for gage exceed the multiple system repeatability. Mean differences and standard deviations for all other measurement parameters meet multiple vehicle repeatability thresholds.

Results of the comparison of the manned and unmanned systems, as well as recommended improvements to FRA's ATGMS, are summarized in Section 4. Analysis presented in this report shows that improving class of track determination used with ATGMS and automated geometry exception editing will improve ATGMS performance to a level approaching that of manned geometry inspection systems.

18. Introduction

The Federal Railroad Administration's (FRA) Office of Research, Development and Technology (RD&T) has undertaken a multi-phase research program focused on the development and advancement of autonomous track geometry measurement systems (ATGMS) and related technologies to improve rail safety by increasing the availability of track geometry data for safety and maintenance planning purposes. Routine collection of track geometry measurements using autonomous, un-manned systems provides many advantages over single purpose, manned systems such as uninterrupted main line track operation and increased inspection frequency allowing for timely detection and monitoring of track locations with safety critical or degradation issues.

The first stage centered on the creation of the basic elements of a ruggedized pilot ATGMS using commercial, off-the-shelf equipment to facilitate early development and evaluation. Emphasis was placed on cellular communication and data transmission, location information tagging, and geometry data and exception processing. The Data Collection module was configured to measure track geometry, analyze the measurements for any locations exceeding limits to the FRA Track Safety Standards and transmit "exception reports" to the server for storage and transmission to survey stakeholders. Automated filters employing a variety of statistics-based algorithms and logic rules were used to identify and eliminate "false" exceptions. Between January 2008 and March 2011 the pilot ATGMS was operated on Amtrak's 39000, a Superliner II railcar, during revenue service operations within Amtrak's Auto Train service that runs between Lorton, VA, and Sanford, FL, over CSX Transportation track. During that time ATGMS surveyed almost 460,000 miles of track, an average of approximately 153,000 miles per year. This extensive testing allowed identification of system problems and limitations, facilitating design modifications that moved ATGMS technology towards increased robustness and reliability.

Following the initial stage of development, the truck-mounted ATGMS was removed from Amtrak's 39000 and moved to FRA's DOTX221, a sleeper-lounge car, for use in Stage 2 development. The second stage of development focused on use and improvement of the technology under simulated revenue operations to demonstrate ATGMS accuracy and increase the autonomy of operation of the system. Major accomplishments within this stage, supported under FRA funding, included the evaluation of the ATGMS on FRA's DOTX221 while operated in consist with the FRA Automated Track Inspection Program's (ATIP) DOTX220 manned track geometry inspection vehicle over Amtrak passenger routes between September 2011 and June 2013 referred to as the Amtrak assessment program.

To allow for installation of ATGMS on a wide range of vehicle designs, lower installation and maintenance costs as well as minimal interference with truck and wheel set maintenance activities, FRA's RD&T initiated development and evaluation of a carbody-mounted ATGMS. Major accomplishments of this stage of development included demonstration of the new sensor and processing algorithms to account for new techniques to measure track geometry from a location further away from the rails. For demonstration and evaluation purposes, a carbody-mounted ATGMS was installed and operated on Amtrak's 82602, an Amfleet I passenger car, in Amtrak revenue service on the NEC between September 2012 and August 2013, covering more than 55,000 track miles. Its performance was evaluated by comparing its results to that of the truck-mounted track geometry measurement system (TGMS) installed on Amtrak's manned geometry inspection vehicle, 10002, in the following manners:

- Exceptions to the track geometry limits specified in the FRA Track Safety Standards detected by each system. Geometry exceptions reported by the Amtrak's manned geometry inspection system on Amtrak 10002 were considered as "ground truth" for this analysis.
- Foot-by-foot track geometry data collected by the unmanned and manned systems over more than 17,500 non-consecutive feet of the survey. Areas for comparison were selected based on locations with track geometry exceptions as reported by the manned system aboard Amtrak's 10002. Differences in gage, profile, alignment, crosslevel, and curvature measurements collected by the two systems were compared to established thresholds used by FRA to assess overall agreement between multiple measurement systems.

An analysis of this nature was conducted to assess ATGMS using survey data collected by both ATGMS and the manned geometry system aboard Amtrak's 10002 during October 2012; results of this initial comparison were used to identify and address technical/operational issues with the ATGMS. For the analysis documented in this report, 346 out of 914 track miles of data collected on April 2 and 3, 2013, between Washington, DC, and Boston, MA, were used due to intermittent ATGMS operational and data quality issues during this survey.

Please note that for simplicity, hereafter Amtrak's 82602 ATGMS and Amtrak's 10002 are referred to as ATGMS and 10002 respectively.

When comparing results provided by ATGMS and manned geometry measurement systems it is important to take into account their operational differences. In particular:

- Manned geometry measurement systems are able to utilize up-to-date posted class of track when ATIP crews edit geometry exceptions. ATGMS, at its current stage of development, relies on vehicle speed to determine class of track to identify geometry exceptions. Therefore, ATGMS is prone to identify a lower class of track based on vehicle speed in many situations than the crew would, creating a significant source for discrepancies in exception detection.
- Differences in vehicles weights and system calibrations result in slight differences in foot-by-foot geometry measurements, resulting in one system reporting an exception while the other does not.
- The automated exception editor employed within ATGMS is designed to review geometry exceptions and accept or reject events as "true" exceptions based on a set of mathematical rules. The manned geometry review process employed by Amtrak and others takes advantage of the operator's years of experience and their ability to observe both track and environmental conditions when deciding if an event is a "true" exception or not.

Results of the exception-based and foot-by-foot measurement-based analyses are presented in Sections 2 and 3, respectively. Section 4 provides a summary of results and recommendations based on these analyzed.

19. Track Geometry Exception Analysis Results

A total of 63 geometry exceptions were reported by 10002 during the round-trip between Washington, DC, and Boston, MA, on April 2 and 3, 2013. As summarized in Table C24, only 18 geometry exceptions reported by ATGMS matched those reported by the 10002 manned system. The mismatched geometry exceptions include 4 geometry exceptions detected but deleted by the automated exception filters employed by ATGMS and 41 geometry exceptions reported by the 10002 manned system but not detected by ATGMS.

Table C24: ATGMS Generated Geometry Exceptions versus 10002-Reported Geometry Exceptions

		ATGMS			
		Detected and Reported	Detected but Deleted	Not Detected	**Total 10002-Reported Geometry Exceptions**
10002	Detected and Reported	18 (28.6%)	4 (6.3%)	41 (65%)	**63 (100%)**

Matched geometry exceptions – Detected and Reported by both systems
Mismatched geometry exceptions – Detected by both systems but deleted by ATGMS
Mismatched geometry exceptions – 10002-reported geometry exceptions not detected by ATGMS

At the first glance, results shown in Table C24 indicate that ATGMS performed poorly and only matched 28.6 percent of the 10002 reported geometry exceptions but a closer look at the underlying causes indicates that ATGMS performed reasonably well given its mode of operation.

The Pareto chart in Figure C59 ranks the identified causes of 45 (4 plus 41) mismatched geometry exceptions based on degree to which they contribute to differences between the two systems; a "cut-off" corresponding to 80 percent of the total number of events illustrated in the chart is provided for reference. The color scheme used in Figure C59 matches the color scheme used in Table C24. Dark/red columns represent the 41 10002-reported geometry exceptions not detected by ATGMS and medium shade/amber columns represent the 4 geometry exceptions reported by Amtrak's 10002 that were not reported by ATGMS; these were detected but deleted by the ATGMS automated exceptions editor.

The following sections provide additional details into these two high-level issues.

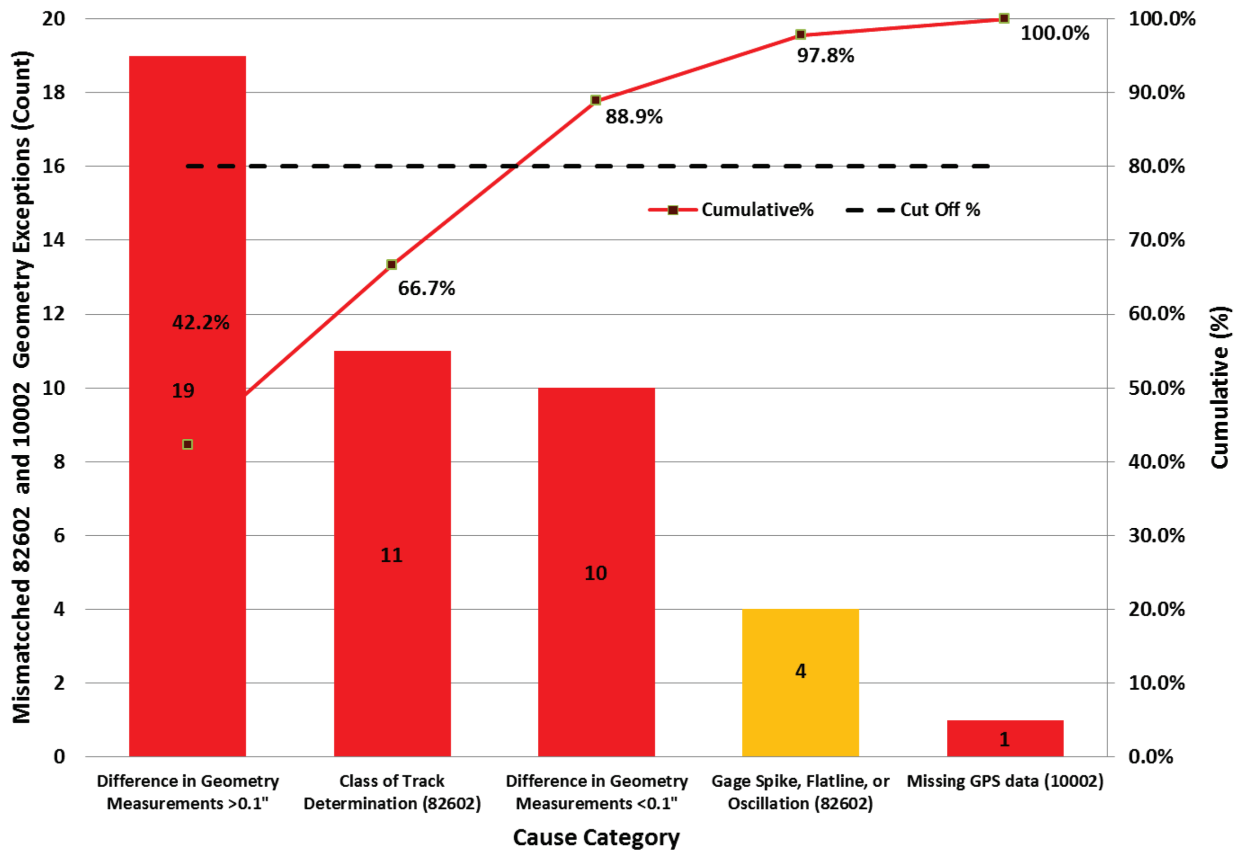

Figure C59: Distribution of Mismatched Geometry Exceptions into Categories of Causes

19.1 Exceptions not Detected by ATGMS

The Pareto chart in Figure C59 illustrates the distribution of 41 10002-reported geometry exceptions not reported by ATGMS by different cause categories. Consideration of Figure C59 shows the following:

- Eleven of the 41 10002-reported geometry exceptions not detected by ATGMS were caused by ATGMS' erroneous class of track determination, which is based solely on the vehicle's speed. Determination of track class is a functionality that can be improved through a number of different measures including manual review and correction or detailed, up-to-date geo-referenced track class designations that could be provided by individual railroads.
- Twenty-nine out of the 41 10002-reported geometry exceptions not detected by ATGMS were caused by differences in geometry measurements between the 10002 manned system and ATGMS attributed to differences in system installations (truck-mounted versus carbody-mounted) and minor system differences such as offsets.
- One out of 63 10002-reported geometry exceptions not detected by ATGMS was due to missing 10002 GPS data, therefore it was not possible to align associated foot-by-foot geometries for analysis.

Once causes for mismatched geometry exceptions are identified, their effect on different types of reported geometry exceptions can be identified. Listed in Table C25 are 41 10002-reported geometry exceptions not detected by ATGMS distributed into 11 geometry exception types and 4 cause categories in Figure C59. As indicated by the numbers in Table C25, differences in geometry measurements being more than 0.1 inches was the leading cause for geometry exceptions that were not detected by ATGMS.

Table C25: Distribution of 10002-Reported Geometry Exceptions Not Detected by ATGMS by Exception Type

			Cause Category			
		Not Detected	Difference in Geometry Measurement > 0.1 inches	Difference in Geometry Measurement < 0.1 inches	Class of Track Determination	Missing GPS Data (10002)
Geometry Exception Type	Gage Change	2	2	0	0	0
	L Prof 31’	5	2	1	2	0
	R Prof 31’	8	5	2	1	0
	L Prof 62’	3	1	2	0	0
	R Prof 62’	6	2	2	1	1
	L Prof 124’	1	0	0	1	0
	R Prof 124’	5	1	1	3	0
	L Align 62’	4	3	1	0	0
	R Align 62’	4	2	1	1	0
	L Align 124’	2	0	0	2	0
	R Align 124’	1	1	0	0	0
	TOTAL	41	19	10	11	1

19.2 Exceptions Not Reported by ATGMS

The Pareto chart in Figure C59 indicates that 4 out of 45 10002-reported geometry exceptions were detected by ATGMS but deleted by ATGMS automated exception filters. The automated filters detected spikes and flat lines in the foot-by-foot gage measurement associated with these exceptions. Spikes and flat lines could be caused by factors such as direct sun glare or reflections from the ballast.

Table C26 lists the four 10002-reported geometry exceptions detected but deleted by ATGMS automated exception editor distributed into two geometry exception types and two cause categories previously identified in Figure C59. Spikes and flat lines in gage measurement affected 31-foot cord profile measurements and oscillations in foot-by-foot geometry measurements affected 62-foot cord profile measurements, respectively.

Table C26: Distribution of 10002-Reported Geometry Exceptions Detected but Deleted by ATGMS by Exception Type

		Cause Category		
		Detected but Deleted	**Gage Spike and Flat Line (ATGMS)**	**Gage High Frequency Oscillations (ATGMS)**
Exception Type	**R Prof 31’**	**3**	3	0
	R Prof 62’	**1**	0	1
	TOTAL	**4**	**3**	**1**

Analysis presented in this report shows that one factor affecting ATGMS performance is track class determination. However, due to fairly consistent operating speeds on the NEC including Amtrak’s practice of quickly achieving posted speeds, track class determined by ATGMS in Amtrak’s NEC operations was generally more accurate than track classes determined by ATGMS in other operations involving freight corridors[1]. Following multiple evaluations similar to the one documented here, FRA sponsored the development of a web application for remote editing of ATGMS exceptions. With the use of this application, ATGMS generated exceptions are presented to an experienced operator located at a remote site for review and editing. Based on available information such as track charts, timetables and aerial images, the user of the application will be able to provide critical inputs into the proper identification of tracks over which the system is traversing and the establishment of track class. It is conservatively anticipated that operation of this web application will improve ATGMS track class determination by close to 90 percent, reducing the number of exceptions in this category from 11 exceptions to 1.

[1] ENSCO Document SERV-REPT-0000507 “Comparison of DOTX221 ATGMS and DOTX220 TGMS Geometry Exceptions and Foot-by-Foot Geometry – Summary Report.”

20. ATGMS and 10002 Foot-by-Foot Geometry Data Comparison

Geometry exceptions were used as markers for retrieving corresponding ATGMS and 10002 foot-by-foot geometry data for comparison. Out of 63 10002-reported geometry exceptions, only 35 were used for identifying foot-by-foot geometry measurements for detailed comparison. Twenty-eight of the 10002-reported geometry exceptions were excluded because:

- Twenty-seven represented multiple exceptions types, meaning that at the same location or within a range of several feet, various geometry exceptions existed
- One had incomplete or missing foot-by-foot geometry measurements

The foot-by-foot geometry measurements identified by the above mentioned 35 geometry exceptions were reviewed to remove measurement outliers and measurements made below cut off speed of 28 miles per hour (mph) for track geometry calculations. Adjustments were made by removing a small segment of affected measurements from all geometry channels.

This process resulted in more than 17,500 feet of corresponding ATGMS and 10002 foot-by-foot geometry measurements for which resulting statistics were compared against accepted ATIP repeatability thresholds for track geometry data collected from multiple vehicles. These thresholds are presented in Table C27 and statistics of analyzed data set is presented in Table C28.

Table C27: Repeatability Thresholds for Foot by Foot Track Geometry Data Multiple Vehicles

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
Profile (Inches)	0.04419	0.08838
Alignment (Inches)	0.04419	0.17675
Crosslevel (Inches)	0.04419	0.08838
Curvature (Deg/100')	0.01414	0.21210
Gage (Inches)	0.04419	0.08838

Table C28. Statistics of Difference Between ATGMS and 10002 Foot-by-Foot Track Geometry Data April 2013

Geometry Parameter	Mean Difference (Inches)	Standard Deviation (Inches)
L Profile 31’	0.00000	0.0439
L Profile 62’	-0.00000	0.0455
L Profile 124’	0.00032	0.0523
L Alignment 31’	0.00017	0.0394
L Alignment 62’	0.00018	0.0614
L Alignment 124’	-0.00000	0.1195
R Profile 31’	0.00015	0.0559
R Profile 62’	0.00000	0.0579
R Profile 124’	0.00044	0.0689
R Alignment 31’	0.00000	0.0649
R Alignment 62’	0.00000	0.0786
R Alignment 124’	-0.00030	0.1293
Crosslevel	-0.02105	*0.0975*
Curvature (Deg/100’)	0.00962	0.0528
Gage	*0.05663*	0.0554

Results indicate that mean difference of gage and standard deviations of crosslevel measurements exceed the multiple vehicle repeatability thresholds. Mean differences and standard deviations for all other measurement parameters meet multiple vehicle repeatability thresholds.

21. Conclusions and Recommendations

Over 914 miles of track geometry measurements collected on April 2 and 3, 2013, by the ATGMS on Amtrak's 82602 while operated in consist with Amtrak's 10002 manned inspection vehicle over Amtrak's NEC between Washington, DC, and Boston, MA. Exceptions to the track geometry limits specified in the FRA Track Safety Standards reported by Amtrak's manned system were considered as "ground truth" and used to assess performance of the ATGMS through comparison of the reported exceptions. A subset of the exceptions reported by the Amtrak system were used to identify areas for comparison of foot-by-foot track geometry data collected by the unmanned and manned systems.

Comparison of foot-by-foot data collected by both systems shows that track geometry measured by ATGMS compared well with that collected by Amtrak's manned inspection vehicle.

Over the survey considered, Amtrak's 10002 reported 63 exceptions. Not all ATGMS-generated exceptions matched the 63 exceptions reported by the Amtrak manned system. Mismatched exceptions were reviewed and the following five categories of causes were identified:

- Difference in Geometry Measurements >0.1 inches
- Class of Track Determination
- Difference in Geometry Measurements <0.1 inches
- Gage Spike and Flat Line in ATGMS
- Missing GPS Data in 10002

Review of mismatched exceptions identified ATGMS automated, speed-based logic for class of track determination as one factor affecting ATGMS performance. Following assessment of the performance of the ATGMS compared to that of a manned system, a web application for remote editing of ATGMS detected exceptions by an operator was developed to augment ATGMS track class determination logic and automated exception editing until ATGMS technology matures to the point that it can reliably produce results comparable to manned operations.

Based on observations during operations and the results of analysis presented in this report, ENSCO has identified the following areas of ATGMS technology for further improvement:

1. **Track Class Determination** - Exceptions to track geometry limits defined in FRA's Track Safety Standards are different for each track class. Track class and associated posted speed are used to apply the proper track geometry limits. Therefore, accurate determination of track class will improve ATGMS performance in reporting valid exceptions. In 2012, as part of ENSCO's internal research and development efforts, an approach for accurate determination of track number, and by extension track class and posted speed, based on railroad-provided information was developed and tested using limited information provided by a Class I railroad. This approach can be further improved and used to increase ATGMS performance in reporting valid exceptions where railroad-provided information
2. **Automated Geometry Exception Filters** – Automated geometry exception filters inspect validity of an exception by analyzing associated foot-by-foot geometry measurements according to a set of empirically derived limits and signal processing

algorithms. Empirically derived limits are based on review of many reported exceptions of the same type by FRA ATIP's manned track geometry inspection vehicles. Signal processing algorithms are designed to detect outliers and anomalies caused by system malfunctions and/or environmental factors such as spikes, flat lines, and high frequency oscillations in geometry measurements. Both empirically derived limits and signal processing algorithms can be further tuned to improve ATGMS performance in reporting valid exceptions. In addition, automated geometry exception filters "exception list" can be expanded to include more exception types to reduce the number of exceptions that could not be classified by the filters, therefore, marked as "not reviewed".

3. **Lens Protection System** – Through ENSCO internal efforts, a passive protective cover for carbody-mounted ATGMS' optics have been developed and evaluated. Use of this protective cover on another carbody-mounted ATGMS installation has shown that it improves quality of collected data by reducing accumulation of dirt on the optics and protects them from hits by flying debris.

Abbreviations and Acronyms

AER	Advisory Exception Report
ALD	Automatic Location Detector
ARMS	Autonomous Ride Monitoring System
ATGMS	Autonomous Track Geometry Measurement System
ATIP	Automated Track Inspection Program
CAN	Controller Area Network
CSX	CSX Transportation
CTS	Curve, Tangent, and Spiral
DGPS	Differential Global Positioning System
DOD	Depth of Discharge
EPS	Electrical Power System
ELS	Escanaba and Lake Superior Railroad
FRA	Federal Railroad Administration
GPS	Global Positioning Satellite
GUI	Graphical User Interface
HEP	Head End Power
ISO	International Standards Organization
LPS	Laser Protection System
MARC	Maryland Area Regional Commuter
MCO	Mid-chord Offset
MPH	Miles Per Hour
MTA	Maryland Transit Administration
Amtrak	National Railroad Passenger Corporation
NCER	Non-Compliant Exception Report
NEC	Northeast Corridor
NIST	National Institute of Standards and Technology
PMA	Permanent Magnet Alternators
PTC	Positive Train Control
RD&T	Office of Research, Development and Technology
RPM	Revolutions Per Minute
RRS	Office of Railroad Safety

RTGMS	Remote Track Geometry Measurement System
SCU	Signal Conditioning Unit
TAR	Track Assessment Report
TCR	Track Condition Report
TGMS	Track Geometry Measurement System
UP	Union Pacific Railroad
UPS	Uninterruptable Power Supply
V/TI	Vehicle/Track Interaction