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16. Abstract

The project was split into two primary tasks. Task 1 concentrates on analyzing existing data from past field testing of a Multifunction Doppler LIDAR system. Using the developed tools, RTL has delivered 36 points of interest to the consortium members that have been analyzed and filtered by VT using our track stability criterion. These data files contain >3 sigma Doppler LIDAR transients that have been analyzed from a raw Doppler signal to represent physical vibration and displacement. The square of the lateral Doppler velocities is directly proportional to impact or rail vibration energy and, when combined with the time series information, can be used to calculate impact or vibration power. By integrating the Doppler velocities, it is possible to calculate relative rail motion although without an absolute gage reference this metric is only represented as gage variance. As part of the task 2 hardware efforts, 2 distance sensors from Keyence have been added to the LIDAR instrumentation package to provide absolute gage measurement that can be used as a constant of integration for the Doppler signal.

Task 2 focused on preparing and making the necessary improvements to the LIDAR instruments for future track testing. It was determined that designing and assembling a new set of digital platforms (you can think of them as special-purpose computers) would be important for the long-term success of testing the Multifunction Doppler LIDAR in track testing. During this study, two new digital platforms were assembled in addition to a second LIDAR Electro-optical unit. Further, new focusing lenses were assembled and the output laser power was increased to maximize the signal-to-noise ratio (SNR) of the LIDAR instrument. These electro-optical upgrades are expected to yield an SNR improvement of up to four times the previous units. Bench top system tests were performed with the new LIDAR instrumentation and the new instruments are now ready for field testing.

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Final Report VT-4

MACHINE LEARNING METHODS FOR TRACK CONDITION ASSESSMENT USING REPEATED INSPECTION DATA

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Executive Summary

The Railway Technologies Laboratory (RTL) at Virginia Tech has significantly advanced the science of using Doppler velocimetry methods to evaluate track stability. This report provides an overview of the progress made during the project.

The project was split into two primary tasks. Task 1 concentrates on analyzing existing data from past field testing of a Multifunction Doppler LIDAR system. Virginia Tech has conducted several studies with the prototype Multifunction Doppler LIDAR instrument as far back as 2006. Much of the data analyzed in this program comes from a past study using Doppler LIDAR velocimetry to evaluate down track distance and track geometry. Another more recent set of data was collected during a limited-scope track stability exploratory study with grant funding in 2019. The progress to-date has included a significant amount of software development in creating semi-automated Graphical User Interface (GUI) tools to assist in and accelerate the process for filtering and analyzing raw LIDAR data. The resulting suite of tools is intended to greatly reduce the amount of time needed between data collection and the analysis required to identify points of interest on the track. Rapid feedback on test data is essential for being able to return to specific locations on track and investigate the cause of rail motion.

Using the developed tools, RTL has delivered 36 points of interest to the consortium members that have been analyzed and filtered by VT using our track stability criterion. These data files contain >3 sigma Doppler LIDAR transients that have been analyzed from a raw Doppler signal to represent physical vibration and displacement. The square of the lateral Doppler velocities is directly proportional to impact or rail vibration energy and, when combined with the time series information, can be used to calculate impact or vibration power. By integrating the Doppler velocities, it is possible to calculate relative rail motion although without an absolute gage reference this metric is only represented as gage variance. As part of the task 2 hardware efforts, 2 distance sensors from Keyence have been added to the LIDAR instrumentation package to provide absolute gage measurement that can be used as a constant of integration for the Doppler signal.

Task 2 focused on preparing and making the necessary improvements to the LIDAR instruments for future track testing. It was determined that designing and assembling a new set of digital platforms (you can think of them as special-purpose computers) would be important for the long-term success of testing the Multifunction Doppler LIDAR in track testing. During this study, two new digital platforms were assembled in addition to a second LIDAR Electro-optical unit. Further, new focusing lenses were assembled and the output laser power was increased to maximize the signal-to-noise ratio (SNR) of the LIDAR instrument. These electro-optical upgrades are expected to yield an SNR improvement of up to four times the previous units. Bench top system tests were performed with the new LIDAR instrumentation and the new instruments are now ready for field testing.

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1. Introduction

Insufficient track stability poses a major challenge to the railroads. Often, this results in excessive motion of the track in vertical and lateral directions due to train forces imparted through wheel-rail interactions. In addition to increasing track and wheel damage, lack of sufficient track stability could lead to costly derailments. A loss of track stability is caused by a variety of factors including the health and integrity of railroad crossties, the loose or missing cut spikes or elastic railway clips, loose or weakened joint bars, or insufficient roadbed and ballast support. While the railroads are investing in different sensor systems (particularly vision-based systems) to identify these flaws, much of this evaluation is currently done by visual inspection from skilled maintenance-of-way engineers. Irrespective of the deficiency in the track structure, all these flaws should manifest themselves in the form of increased track movement and decreased track stability. It is through this increased rail movement that RTL endeavors to include track stability detection to the ability of its Multifunction Doppler LIDAR systems.

RTL has pioneered the use of Doppler LIDAR velocity measurements for both trackside and in-motion, vehicle-mounted rail applications. Over the past 15 years, we have demonstrated high accuracy, non-contact measurements of a wide spectrum of rail parameters including track speed, down track distance, track alignment, gage variance, and wheel slip. In the process of demonstrating these multifunction, non-contact capabilities of Doppler LIDAR, it has been noted that the data includes indications of track stability and lack thereof in the higher frequency content of rail vibrations and local rail movement. For instance, a characteristic "S" signature has been noticed that corresponds to joint bars and the magnitude of the response can be used to indicate the foundation "softness" from the joint or track foundation. The previous field data includes the tell-tale signs of change in track gage or rail cant in curves due to lateral forces that would indicate a lack of track restraint or lateral stability, in extreme cases.

1.1 Objectives

The primary mission of this project is to evaluate the feasibility of optical LIDAR sensors as an on-board, non-contacting means for assessing track lateral and vertical stability in motion. The successful deployment of the system will result in early and timely detection of track infrastructure stability issues, specifically any reduced vertical (tangent track) and lateral (curved track) stiffness. Our vision is to enable the U.S. railroads to detect any track "softness" without the need to solely rely on deploying a track geometry car or manually inspecting the track.

1.2 Overall Approach

Prior to the inception of this project and the consortium, RTL conducted several preliminary tests in partnership with Norfolk Southern Corporation as part of a grant-funded limited-scope exploratory study. These tests were conducted with the existing Multifunction Doppler LIDAR system on an NS Hy-rail truck on both mainline revenue track and also some secondary track and sidings. The test configuration was modified to have an increased 33 Hz data rate as well as changing the beam angles to intensify the lateral component for evaluating track stability and lateral motion. In addition to these preliminary track stability tests, RTL also has access to an extensive backlog of in-service test runs conducted during previous Multifunction Doppler LIDAR studies. While the data in these files were collected under a different system configuration that may not lend itself to high-resolution track stability data, it does constitute a significant sample set and opportunity to test analysis methods for evaluating track stability.

As such, the approach has been twofold: first to expand upon the analysis of existing data and second to prepare the existing LIDAR instruments for future testing. The first task focuses mainly on the recent preliminary testing where the LIDAR instrument was configured to maximize the track stability component in the multifunction system. The first task is entirely focused on a deeper dive into the available data. However, because this is now historical data where the current track condition has likely changed since the data was collected, all the analysis of the collected data is now backward facing where the vibrational and structural analysis must determine a simulation of the likely track condition that would have caused such a signature without the ability to verify the results against known field conditions.

The second task acknowledges that the existing LIDAR instruments are in need of upgrades to proceed with additional testing with confidence. The two existing LIDAR instruments, "Speedy" and "PXI" are 15 and 9 years old respectively, and are running the risk of a component failure that would render them inoperable (a typical computer is expected to last 3-5 years). Therefore, the second task is to develop replacement Lidar instrument computers for the future LIDAR development at RTL and to make the necessary improvements to make track stability measurements.

1.3 Scope

With the onset of the novel Coronavirus, the scope of this project was adapted to focus on the analysis of existing data and preparation for future testing.

1.4 Organization of the Report

The two tasks pursued in this project are each described in the following sections with the related subtasks, followed by conclusions.

2. Task 1: Detailed Analysis of Available Field Data

The Railway Technologies Laboratory at Virginia Tech (RTL) has conducted many Doppler LIDAR tests for railroad applications and, as such, has access to an extensive catalog of historical data from a variety of tests. The first Doppler LIDAR rail tests were conducted as far back as 2006 while the bulk of the available LIDAR data was collected around 2011 as part of a study using Doppler velocimetry for tachometer functionality and for measuring track geometry. Before the start of this project, RTL received a grant to conduct a limited-scope exploratory study into using the Doppler LIDAR instrument to evaluate track stability. The preliminary study included collecting new field data in partnership with Norfolk Southern Corporation around Roanoke, VA area. The exploratory study revealed promising results resulting in the RTL proposal for the AAR 2019 Grand Challenge in Railroad Technology. This task focuses on a much deeper analysis in preparation for future testing.

2.1 Detailed Analysis Tasks – Statement of Work

The analysis of existing LIDAR data will concentrate on:

- Appropriately filtering the signal to remove any out of band frequency content that is not essential for determining track stability
- Processing the filtered data for any signs of assessing vertical motion that is commonly indicative of soft track foundation
- Further processing the data for any signs of excessive lateral motion that is generally an indication of gage widening under lateral loads and lack of track lateral stability
- Crosschecking the track vertical and lateral motion with track charts and satellite imagery to determine the location and curvature of the track to determine if the observed phenomena make sense empirically.
- Consult with track engineers at NS to determine if they have any track geometry data from their Track Metrology Cars or experience with the specific locations of the track that could be used in support of the empirical crosscheck

This task will lay the foundation for additional track testing with the benefit of preliminary understanding from revenue service testing. Beyond honing the system setup and data collection and processing routines, it will allow us to make any improvements needed to the LIDAR system as described in Task 2.

2.2 Historical Data Cataloging

Throughout the past Multifunction Doppler LIDAR programs, RTL has collected an extensive back catalog of historical data covering hundreds of miles of revenue track, as shown in Table 1. At the same time, all the previous graduate students have since graduated and moved on from the lab, hence leaving a gap in the specifics of the tests. Although much of the pertinent information is documented, sifting through more than 10 years of program history and documentation has been proven to be a significant task.

Table 1: Matrix of Available and Relevant Historical LIDAR Test Data

Vehicle	Route	Test Partner	Date	Approx Length (mi)	LIDAR Beam Location	Data Rate	Comments
FRA R4	Western Maryland Scenic RR	ENSCO	15-Jun-11	4	Various	10 Hz	Jointed Rail, LIDAR System (Rev 1)
NS 36/38	Hagerstown, MD to Roanoke, VA	Norfolk Southern	10-Oct-11	220	Gage Corner	10 Hz	LIDAR System (Rev 1) Testing on Track
NS 36/38	Roanoke to Norfolk Round Trip	Norfolk Southern	28-Nov-11	500	Gage Corner	10 Hz	LIDAR System (Rev 1), Ground Calibration Run
NS 33/34	Roanoke, VA to Bristol, TN; Additional Testing with NS	Norfolk Southern	6-Jul-12	4080	Gage Corner	10 Hz	PXI LIDAR System (Rev 3), Positive Pressure Lens Housing
NS 36/38	Roanoke to Christiansburg Round Trip	Norfolk Southern	16-Jan-14	83	Gage Corner	10 Hz	PXI LIDAR System (Rev 3), To Walton Wye
NS Hy-rail	Walton to Narrows, VA	Norfolk Southern	6-Dec-18	30	Gage Corner	30 Hz	LIDAR System "Speedy" at 30 Hz, Mainline Test
NS Hy-rail	Around Roanoke, VA	Norfolk Southern	10-Jan-19	64	Various	30 Hz	LIDAR System "Speedy" at 30 Hz, Secondary Line
NS Hy-rail	Around Roanoke, VA	Norfolk Southern	10-Jan-19	35	Various	30 Hz	LIDAR System "Speedy" at 30 Hz, Secondary Line

2.3 Developing Semi-Automated GUI Analysis Tools

Given the large amount of data generated from each test run, one of the premier challenges with the Doppler LIDAR program has been handling the large data sets and generating analysis in a timely fashion. As the program matures beyond analyzing only the most recent test runs, the big data nature of the program necessitates the development of tools for quickly and parametrically evaluating field data. To that end, development time has been invested in creating user-friendly Graphical User Interface (GUI) tools to move the analysis from a command-line style process to a dedicated application. Additionally, Import and Edit tools have been generated to collect and compartmentalize the raw data and the related test parameters into a single file for future reference. The unified data structure can then be stored in a Test Catalog and Viewer tool to quickly differentiate between test runs and combine separate data files into a single test container.

2.3.1 LIDAR Data Import /Edit Tool

The first tool developed was an Import/Edit tool to transform the raw data files in a text file format into a native MATLAB structure. MATLAB structures can be loaded and manipulated faster than raw data files and creating a separate instance of the data for editing allows the original file to be preserved providing an extra data backup.

Key test parameters can be logged with the test data such as location, test vehicle, LIDAR targets, and sample rate. Once the raw data has been imported into a MATLAB structure, the Edit half of the Import/Edit Tool can be used to change or correct parameters without requiring a reimport of the raw data.

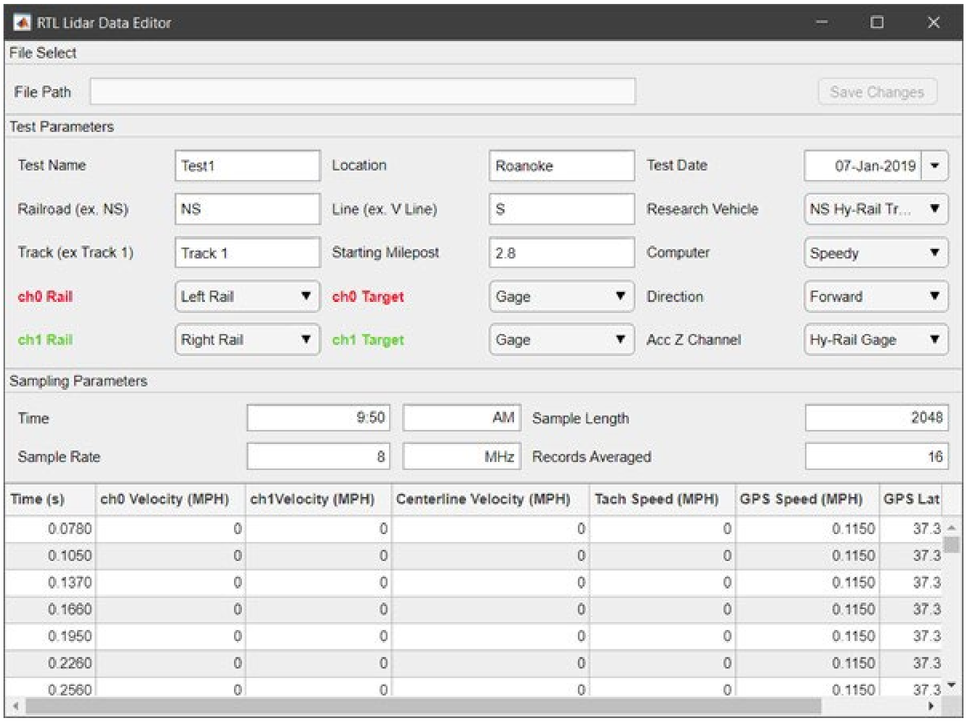

Figure 1: LIDAR Data Import/Edit Tool

2.3.2 LIDAR Test Catalog and Viewer Tool

All the imported LIDAR data is stored in a common program directory for the LIDAR analysis tools. The LIDAR Test Catalog and Viewer tool recalls all the currently loaded LIDAR data and allows the user to select and view individual tests. Key parameters such as the location, sample rate, and test data can be displayed in a file properties text box. The most helpful component, however, is being able to view the GPS trace of the LIDAR test quickly to determine where the data is located when searching for a specific data set. As the Track Stability Program continues to become a "big data" application, the ability to rapidly access specific data sets becomes essential.

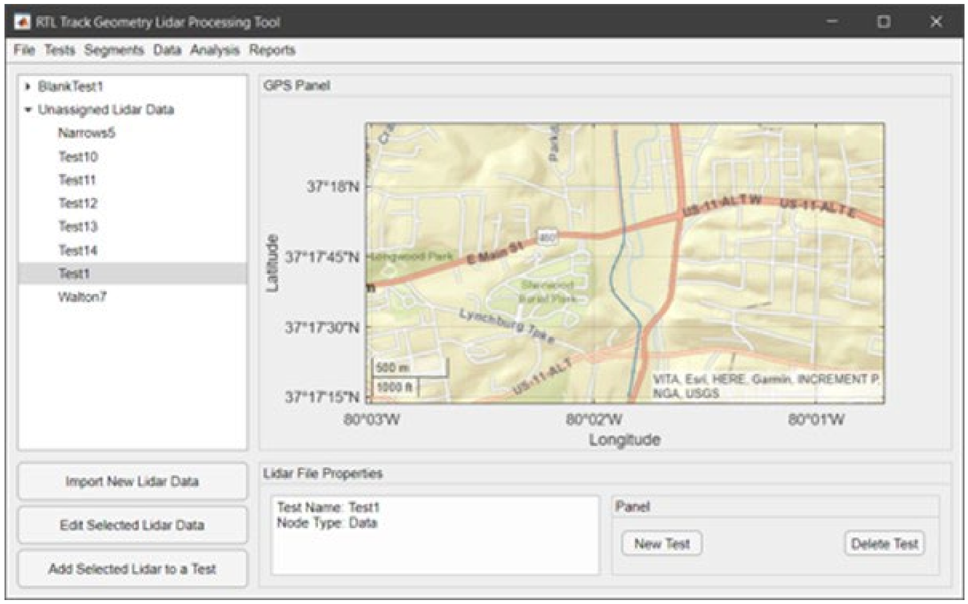

Figure 2: LIDAR test catalog and viewer tool

The LIDAR Test Catalog and Viewer Tool becomes the hub of the overall suite of LIDAR analysis programs. From this common window, raw LIDAR data can be imported and added to a pool of Unassigned LIDAR Data. Unassigned LIDAR Data can then be added to a "test" container. A LIDAR Test will consist of test "segments," which can represent separate test runs over the same section of track or multipart files where the acquisition was paused in the middle of a test. Future functionality will allow for the user to create "forks" in the LIDAR Test where each fork can have a different configuration of filters and analysis applied. This unified structure greatly improves the organization of large and complex data sets. This tool is fully functional although it has great potential for additional functionality.

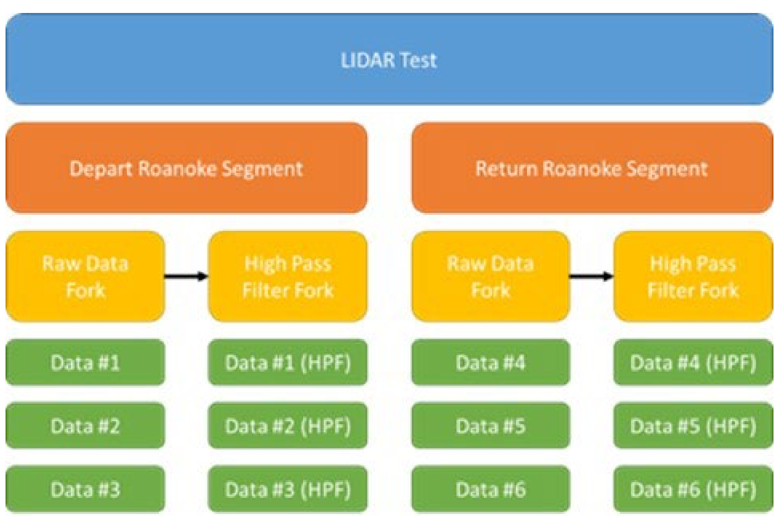

Figure 3: An example of LIDAR test data structure

2.3.3 Signal Preconditioning and Data Review Tool

The Signal Preconditioning and Data Review tool is the first GUI review tool that was developed for LIDAR analysis. Inherent to the Doppler peak detection algorithm is the occasional instance where the frequency peak drops below the threshold for the Rail Dynamics acquisition software to correctly identify. The Preconditioning and Data Review tool offers a graphical interface to view these low signal points and review short sections of low signal confidence. The tool also records a data health vector for each point to ensure that low signal points are tracked and flagged for future analysis. The tool also generates a report of the final data review that is saved and exported as a PDF. This PDF includes more detailed information about the data health and supplies plots of the signal traces and the GPS location of the anomaly. This report can be referenced in the future to make sure that any characteristic signals are caused by the actual track and not an artifact of a low Doppler signal. This tool is fully functional although it has great potential for additional functionality.

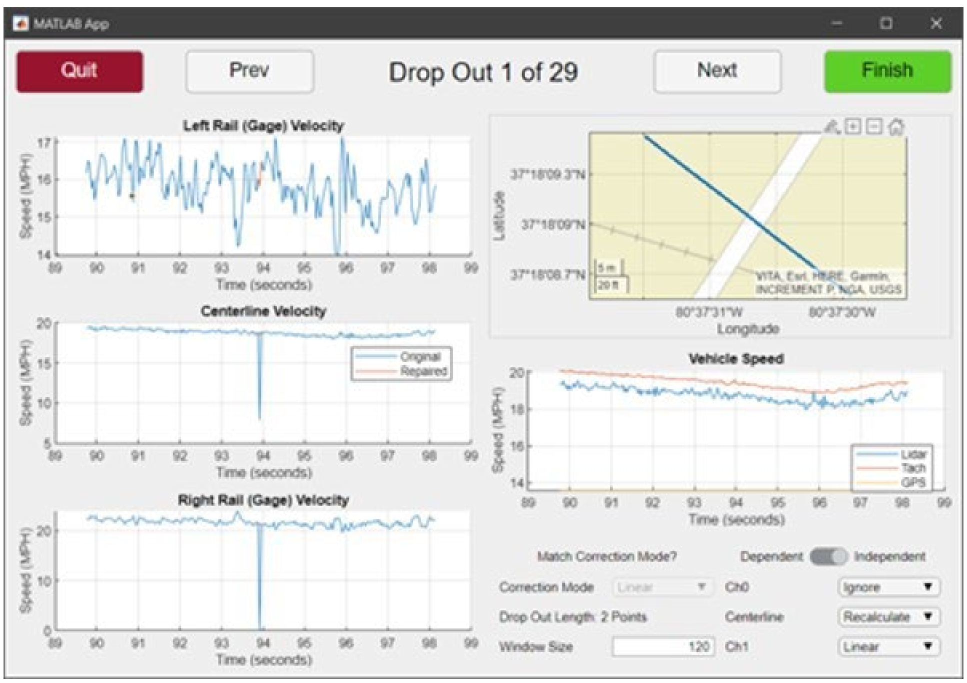

Figure 4: LIDAR Preconditioning and Data Review Tool

Development has continued on this tool since the interim report at the end of Q3. For longer test runs, such as a 137.4 miles test run from St. Louis to Kansas City, the time required for a full manual review became unsustainable. Over the 137.4-mile run, 88.92% of the manual checks were for samples where a single FWHM Doppler peak failed to resolve. A further 9.24% of the manual checks occurred where only two FWHM Doppler peaks failed to resolve. By increasing the automation threshold for this tool, it was possible to automate the appropriate linear interpolation for all these points. As a check for data integrity, a penalty is assessed to a data health vector associated with that sample. During analysis, it is very easy to determine if a point has been corrected in the preconditioning phase. This ensures that the veracity of the signal processing is maintained even while large portions of the preconditioning are automated. In total, this additional step reduced the manual preconditioning task to 1.84% of its original load.

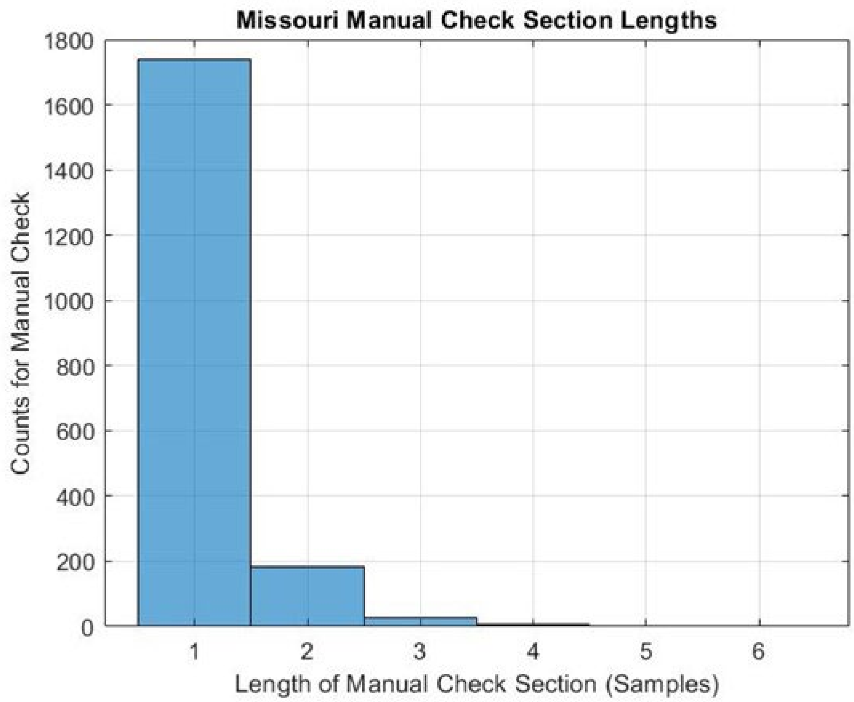

Figure 5: Distribution of Length of Manual Check Section Lengths. 98.16% of Manual Checks are less than 3 Samples long and can be fully automated.

2.4 Implementing MATLAB Script Templates for LIDAR Analysis

During Phase I (2020), the LIDAR test data analyzed as taken from several different test runs and configurations that the Multifunction Doppler LIDAR rig had been deployed in over the past 9+ years. As such, the analysis for each test run required significant customization to handle all the different test criteria. These scripts provide the development path for generating similar MATLAB Apps as the tools shown in the previous section while still allowing for much greater flexibility as the analysis techniques and requirements continue to advance.

2.4.1 Signal Processing and Filtering

The first step in the LIDAR analysis is to read in the preconditioned test data and optimize the Doppler scale factor. A tangent section of track while the train is moving at a consistent speed (not starting or stopping) is selected and the Doppler Velocity, GPS Velocity, and Tachometer Velocity are plotted together.

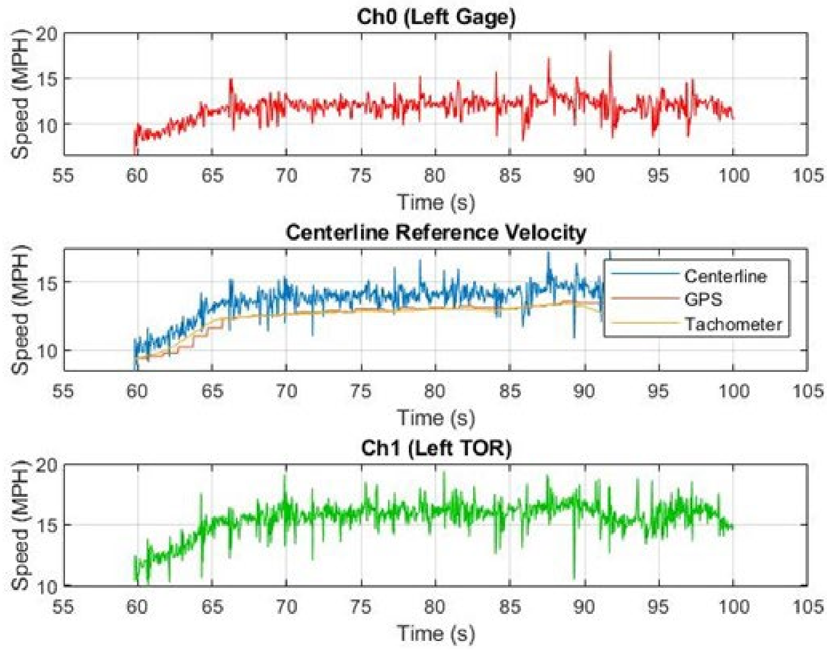

Figure 6: Doppler Scale Factor vs Reference Velocity for Tangent Section

A reference velocity is chosen and the component channel (Channel 0 or Channel 1) that is closest to the reference velocity is chosen as nominal. During installation, these beam angles are carefully set but still subject to some misalignment. Small angle deviations (<1 degree) are enough to cause offsets in the raw Doppler signal that must be corrected. The beam angle of the other channel is calculated and then used to scale the Doppler. In tangent track, the left and right component velocities should be exactly equal since the rails are the same length. (Recall that it is this differential velocity that allows the Multifunction Doppler LIDAR to measure track geometry and curvature.) This tangent section serves as a calibration section for specific test run.

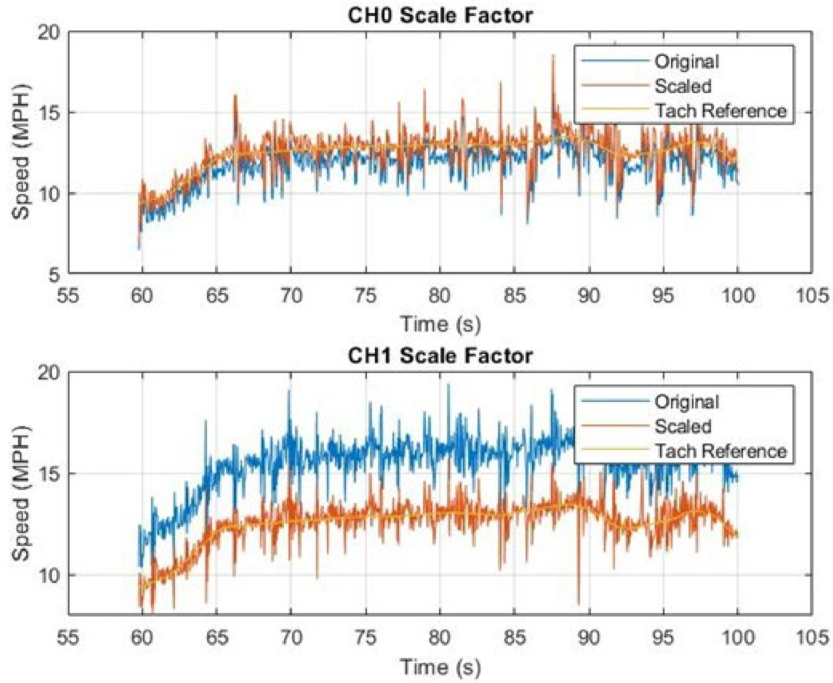

Figure 7: Scale Factors applied to each channel. Channel 0 was chosen as Nominal and the Tachometer was used for the Reference Velocity

A curved section of track is then selected, and the component channel Doppler velocities is plotted. Because the high rail in the curve is physically longer, the Doppler velocity for that rail will be faster than the Doppler velocity for the shorter low rail. The curved reference section is used to confirm that the channel assignments for the left and right rail are correctly assigned. Below is a sample of a curved reference section with a right-hand curve. In this section the left-hand rail is the high rail through a right-hand curve. Because the Channel 1 velocity is faster than the centerline velocity it can be demonstrated that Channel 1 is looking at the left-hand rail in this data set. Conversely, the Channel 0 velocity is slower than the centerline velocity confirming that Channel 0 is pointed at the right-hand rail that is the low rail in this curve. If it is found that one of the data files is recorded with swapped channel assignments, this can be corrected in the Test Catalog and Viewer Tool.

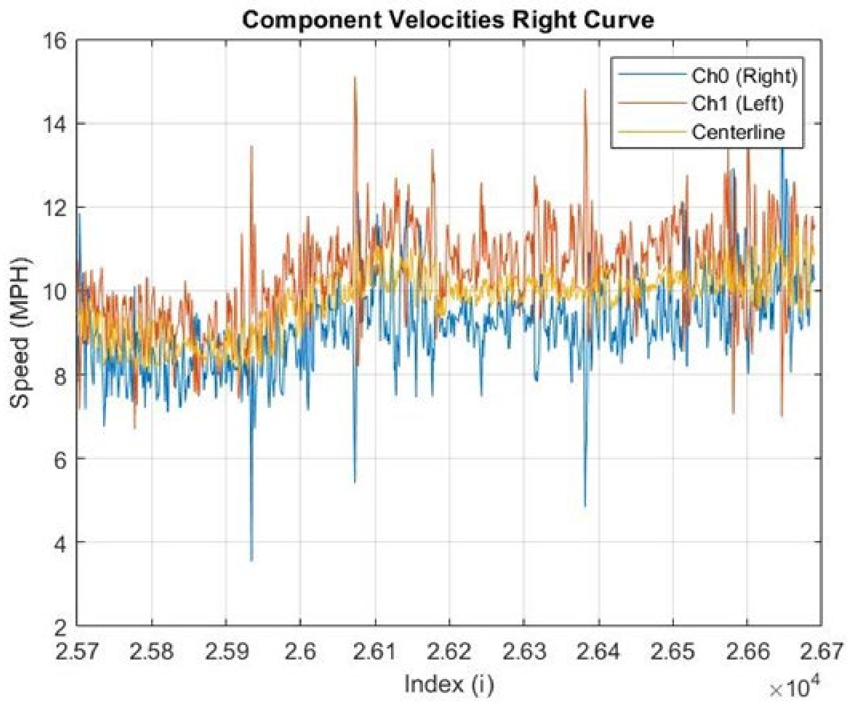

Figure 8: Component Doppler Velocities in the Curved Reference Section. The faster velocity for Ch1 indicates that this is the Left Hand, or High Rail, in a Right-Hand Curve.

The seek function for finding the Doppler peak takes a variable amount of time to complete. This creates a slight non-uniformity in the raw test data. Before applying filters, a Piecewise Cubic Hermite Interpolating Polynomial is used to create a uniform time series. The PCHIP function avoids overshoot while still ensuring that output passes through all the original data points. The uniform time series data will therefore not have any peaks caused by the PCHIP process.

The Doppler centerline velocity data is integrated from the start of the test to create a cumulative distance vector. Previous Multifunction Doppler LIDAR studies have shown this tachometer functionality to be incredibly precise when compared to other methods for tracking down track distance such as GPS units and tachometers. This distance vector is inherently non-uniform, but a similar PCHIP process can be applied to create a uniform spatial series.

Finally, high pass filters are applied to the time series and spatial series data. The down track velocity component in the raw Doppler LIDAR data is significantly low frequency and can be adequately attenuated with a high pass filter. The resulting signal is the vibration of the rail that has been correctly scaled using the nominal and calculated beam angles from the previous steps.

2.4.2 Statistical Tools and Identifying Points of Interest

With the High Pass Filter applied, the Doppler contribution of the longitudinal down track velocity is sufficiently attenuated. The resulting signal is the rail vibrational contribution to the Doppler signal. In the case of vertical, or Top-of-Rail, beams that vibrational contribution is from vertical vibration and the pumping of the track structure. Insufficient vertical track stability may be the result of degraded ballast structure allowing the rail and ties to pump up and down as the train passes. Vertical vibration can also be caused by loose cut spikes or elastic fasteners allowing the rail to move up and down off the tie plates and ties.

Gage face beams are used to measure the lateral vibration of the rail. Depending on the signal dynamics, lateral vibrations can be indicative of several different rail vibration modes. Because the beam is focused far from the foot of the rail, lateral motion can be caused by both pure lateral vibrational modes and also torsional modes where the rail is moving laterally caused by a torque about the foot of the rail.

The high-pass filtered data is plotted either versus time or distance. The standard deviation of the test run is calculated, and three and six sigma lines are plotted against the data. Points of interest are selected when the vibration exceeds these statistical limits, although interesting signals have also been identified in regions that did not exceed statistical significance.

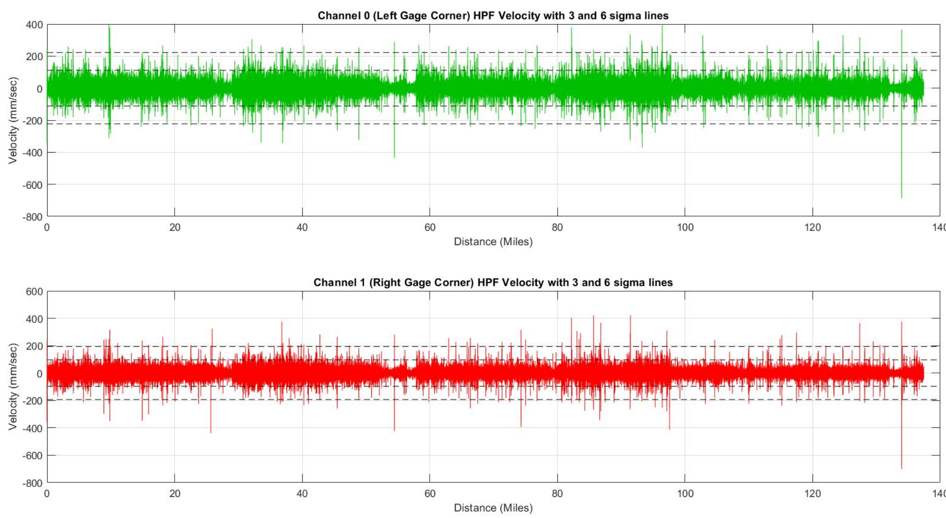

Figure 9: High-pass Filtered Data for Lateral Beams with 3 and 6 Sigma lines superimposed.

The statistical distributions of the high-pass filtered data are quite interesting. The distribution of the LIDAR data is not normal, although it somewhat resembles one, as shown in Figure 10. The peak of the statistical distribution is far higher and tighter than a normal distribution while the high sigma points are far more common. In the future, it is thought that a Cauchy distribution may be better suited for this type of analysis. Physicists use the Cauchy distribution, or Lorentzian profile, for resonance energy distribution that is a good match for the type of wheel impact and vibrational modes expected from track stability measurements.

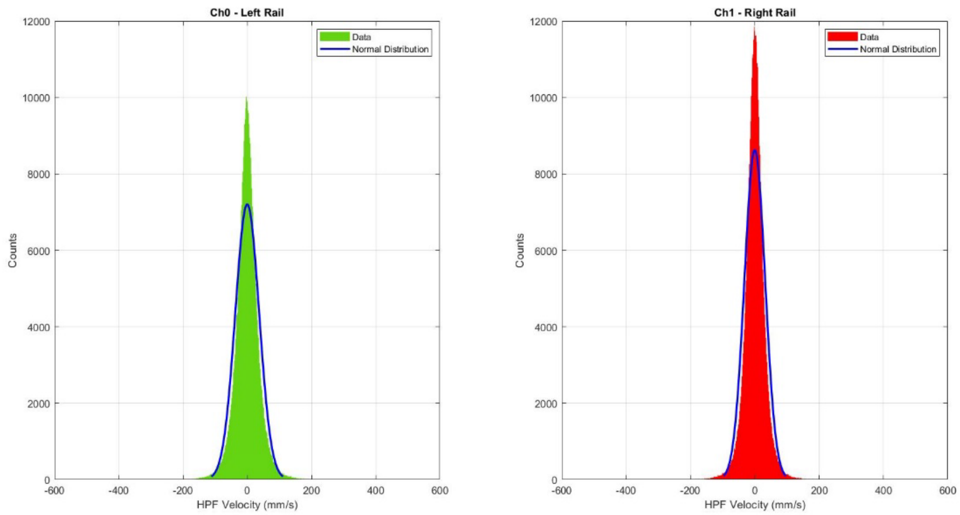

Figure 10: Statistical Distributions for Channel 0 and Channel 1 with a Normal Distribution superimposed.

Despite the high amount of points concentrated around zero, the number of points in excess of six standard deviations is quite significant. A normal distribution would expect 99.73% of values to be within three standard deviations. The test data, however, shows between 97.77% and 98.6%, that results in 5 to 10 times the expected outliers at 3-sigma! The 6-sigma outliers are even worse still. A normal distribution expects 99.9999998% of the data to fall within six standard deviations, which the 0.10% to 0.14% from the test data far exceeds!

	Ch0 – Left Rail		Ch1 – Right Rail	
Total Points	382,900		382,900	
Exceed 3 Sigma	8553	2.23%	5354	1.40%
Exceed 6 Sigma	533	0.14%	393	0.10%

Figure 11: Breakdown of points greater than 3 Sigma and 6 Sigma from the Missouri run

Statistical analysis of vibrational Doppler LIDAR data can be complicated and counterintuitive. Figure 9 above shows the high-pass filtered data from the long-distance Missouri test run. The data has numerous points that exceed 6-sigma including a very large deviation near the end. Doppler LIDAR detection is incredibly sensitive that allows the signal content to be very data rich. During analysis, it was found that the Doppler LIDAR is adept at finding many common track structures such as road crossings, switches and crossovers, and bridges. Many of the high sigma points have very common causes. Satellite reconnaissance and cross-referencing points of interest with track charts allows for many of these points of interest to be quickly explained.

This trait of the Multifunction Doppler LIDAR was already known by RTL from previous testing and high frequency track stability analysis once again holds this fact to be true. It is fully expected that the majority of mainline track (FRA Class 3 track or higher) on the Class 1 railroads would be sufficiently maintained against points of track instability. While not quite at the level of finding a needle in a haystack, points of interest for evaluating track stability are uncommon in most data sets and require a decent amount of signal processing to find.

For example, in the 137.4-mile Missouri run 10 points of interest were identified that had peaks in excess of 6 sigma. Out of those 10 points, only one of the points was in section of track that did not have an immediately identified cause. Out of the 10 flagged points, 5 of the points were switches, 2 of the points were road crossings, and 2 of the points corresponded with the train coming to a stop.

Point of Interest	**Result**
Montgomery City East	Switch
Montgomery City Central	Switch
Wellsville Central	Switch
Wellsville West	Road Crossing
Mexico	Switch
Moberly	Train Stop
Dalton	Road Crossing
Miami	Genuine Point of Interest!
WB Junction	Switch
Birmingham	Train Stop

2.4.3 Plotting and Export Tools

Once a Point of Interest has been identified, several plots are generated. A plot of the down track speed is examined to cross check longitudinal train dynamics for high vehicle acceleration or start / stop event. A GPS trace is also generated to describe the shape of the track in this section. These two plots, the down track speed and GPS plots, will often disqualify a Point of Interest as a rail transient as they will show if there is another common explanation to the high sigma peak.

Once a Point of Interest has been vetted as an actual rail transient signal, the high-pass filtered data is plotted in the time and/or spatial domain as needed to display the shape of the rail vibrational transient. A moving variance plot is often used to compare the magnitude of the rail transient on the left-hand rail to the magnitude on the right-hand rail. Some transients are strongly represented on both rails while sometimes the transient is only affecting one of the two rails.

Accelerometer data, if present, will also be plotted. The accelerometer data is very useful in describing the vehicle motion with respect to the rail motion. High accelerations can represent hunting or wheel slap where the rail vehicle is applying a percussive input to the rail. Uniform accelerations show situations where the rail is vibrating underneath the vehicle. In addition to accelerometer data, some of the tests on the Hy-rail vehicle also had a mechanical gage face signal that was recorded with the LIDAR data that can be used to diagnose other track deviations.

Finally, the Doppler LIDAR velocities can be integrated to find the gage variance down track. Integrations were always started from zero at the beginning of a test section. The past Doppler

LIDAR setups did not have an absolute position or velocity reference; hence, the integrated Doppler LIDAR velocities are in terms of gage variance. Because the track is maintained by the host railroad, it is fair to assume that the gage width is reasonably constrained. By starting the integration at zero for each section, any integrator drift over long sections of testing is sufficiently eliminated while still providing a useful metric for how the Doppler velocity measurements describe the track motion in physical, linear space. Moving forward in 2021, two Keyence absolute distance sensors will be added to provide the constant of integration for the Doppler LIDAR velocity allowing full gage measurements to be collected.

Table 2: Overview of Data Field in each Test Section Spreadsheet

Variable	Description
Time (s)	Test Time in seconds from the original test file. Does not necessarily start from "0"
Distance (ft)	Cumulative distance down track in feet from original test file. Does not necessarily start from "0"
Left / Right Rail Lateral Velocity (mm/s)	High-pass filtered Velocity scaled to the lateral component. This is a Doppler Lidar Velocity in millimeters per second
Tie / TOR Vertical Velocity (mm/s)	High-pass filtered Velocity scaled to the vertical component. This is a Doppler Lidar Velocity in millimeters per second
Centerline Velocity (MPH)	Unfiltered down track velocity in Miles Per Hour. This is a Doppler Velocity calculated by combining the Left and Right Channel Doppler Lidar Velocities
Left / Right Rail Displacement (mm)	Integrated Displacement Variance in millimeters calculated by integrating the High-pass filtered Velocity with respect to the uniform time series. Gage is assumed to be nominal (0 variance) at the beginning of the file. Vertical Displacement is defined with upward movement being positive. Lateral Displacement is defined as outward (field side) movement being positive.
Combined Gage Variance (mm)	The combined gage variance in millimeters from both the left- and right-hand rail displacements. Positive values indicate gage widening and negative values indicate gage narrowing. Gage is assumed to be nominal (0 variance) at the beginning of the file.
Rail / Tie Separation (mm)	This is the difference between the TOR movement and the Tie movement. Positive values indicate separation. Negative values indicate approaching (compression of track structure).

Every plot is collated in a reference document that is shared with the other consortium members. These summary documents contain all the plots, as mentioned, in addition to a small summary of the test environment for each point of interest as well as a preliminary analysis of the point of interest. In addition, the LIDAR data is included with the data summary document in Excel format. The Excel spreadsheet contains the data in three different formats. The high-pass filtered data is on the first sheet on the Excel document and contains all the high-pass filtered data used to generate the plots for that point of interest. The next sheet contains the uniform time series representation of the LIDAR data. Using the data on this sheet, any number of different filters can be applied to the cleaned and rectified test data. The final sheet contains the raw (but preconditioned) LIDAR data. A description of each of the different data fields is shown in Table 2.

2.5 Selected Analyses to Identify Stability Signatures

Thirty-six (36) points of interest were identified and analyzed from historical Doppler LIDAR data. The test runs from that the LIDAR field data was taken included test runs from as far back as 2011 and as recent as 2019. The Doppler LIDAR system was installed on the Norfolk Southern Track Geometry Cars, a Norfolk Southern Hy-rail truck, and the FRA R4 Hy-rail truck with a variety of beam configurations. Four batches of LIDAR analysis were transmitted to the other consortium partners with the fourth batch focused on the statistical distribution of the points of interest over a 137 mile stretch in the Midwest.

2.5.1 Point of Interest #1 – Belspring - Ringing Rail

This first point of interest was captured during the limited scope preliminary study in December of 2018. During this test, the Doppler LIDAR instrument was installed on an NS Hy-rail truck with lateral facing beams. This set up also featured an increased data rate specific for capturing lateral motion.

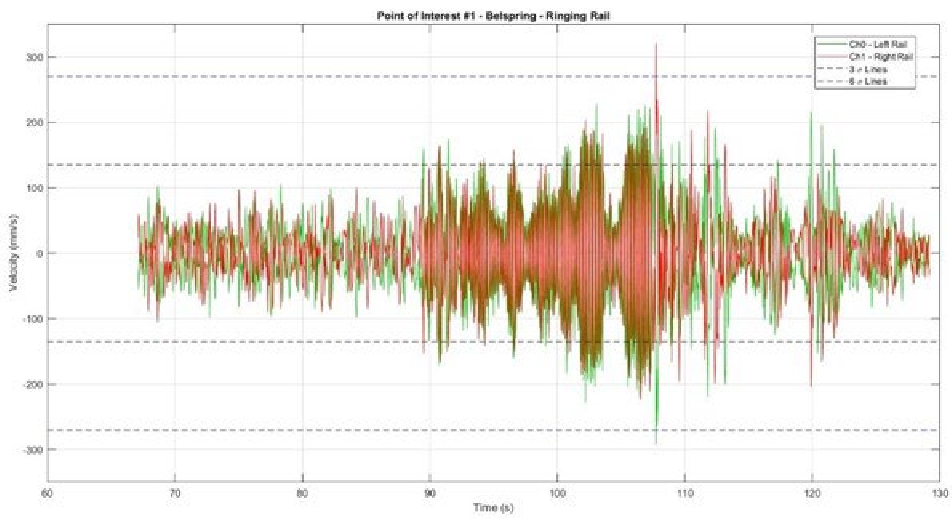

Figure 12: Belspring High-pass filtered Doppler LIDAR Overview

The LIDAR data in this section shows a clear ringing motion through a shallow 0.8-degree right hand curve that tightens into a 1.7-degree right curve. The ringing motion starts right around 90 seconds and immediately following a road crossing. The ringing continues very strongly for a significant amount of time until around 110 seconds. The track layout with the significant time stamps called out can be seen in the GPS trace in Figure 13.

Figure 13: Belspring GPS Trace with Relevant Time Stamps

A zoomed in view of the high-pass filtered Doppler LIDAR data shows a clear ringing waveform with the left and right rails 180 degrees out of phase.

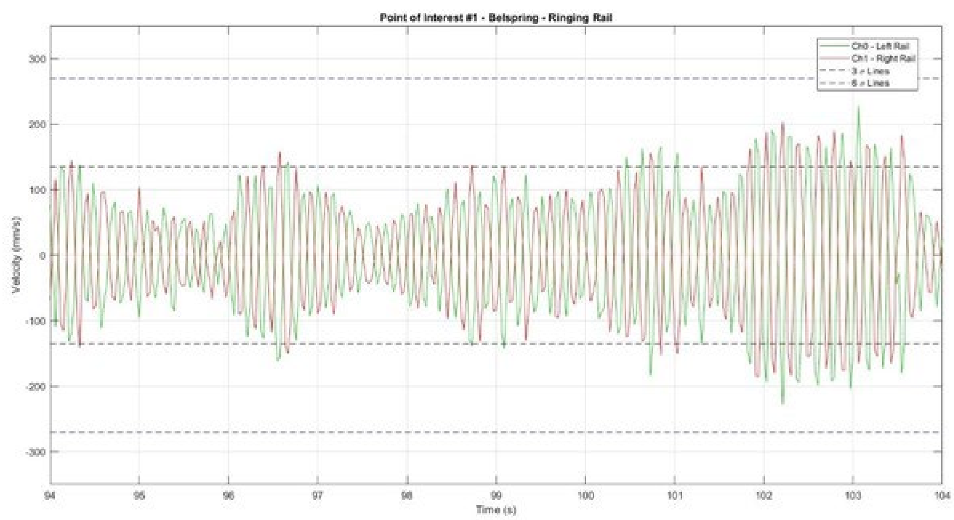

Figure 14: Belspring High-pass filtered LIDAR Data Zoomed in on Ringing Section

Typically, this kind of motion would be attributed to lateral vehicle motion typically referred to as "hunting." As the vehicle shifts towards the left rail laterally the Doppler for the left rail would increase and the Doppler for the right rail would decrees and vice versa. However, the lateral accelerometer data indicates that the vehicle is not shifting laterally and instead the rails are vibrating underneath the vehicle as a traveling wave. There is a strong peak in the Doppler LIDAR at around 5.3 Hz for both the left and right rails that is not present in the lateral accelerometer data. Converting to the spatial domain, this represents a wavenumber of approximately 0.157 ft^{-1} or 1 cycle every 6.36 feet. The "Q" factor of the oscillation is approaching 5 so the resonance is associated with an Eigen mode of the rail itself. It is appropriate to note that this type of rail instability is unlikely to be detected with sufficient fidelity by any instrument other than a non-contacting system such as the Doppler LIDAR. The underlying phenomena has been, and continues to be, the subject of a separate in-house investigation and analysis since it was first detected as a unique manifestation of a non-linear vibration.

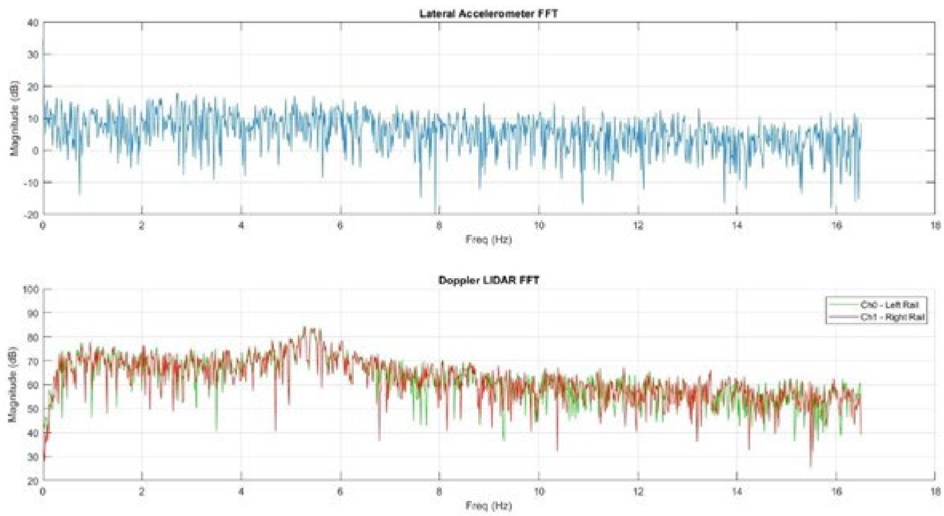

Figure 15: FFT of Vehicle Lateral Accelerometer and Doppler LIDAR Velocity

2.5.2 Point of Interest #4 – Glenvar Bridge

The second and third sample analyses in this report are both around curved sections of track that lead into a bridge. In both sections, Glenvar and Crab Creek, there are significant rail transients that occur in the lead up to the bridge that make it difficult to parse whether the bridge is the cause or simply an unrelated correlation. Both files were captured when the Doppler LIDAR rig was mounted on the Norfolk Southern Track Geometry Car.

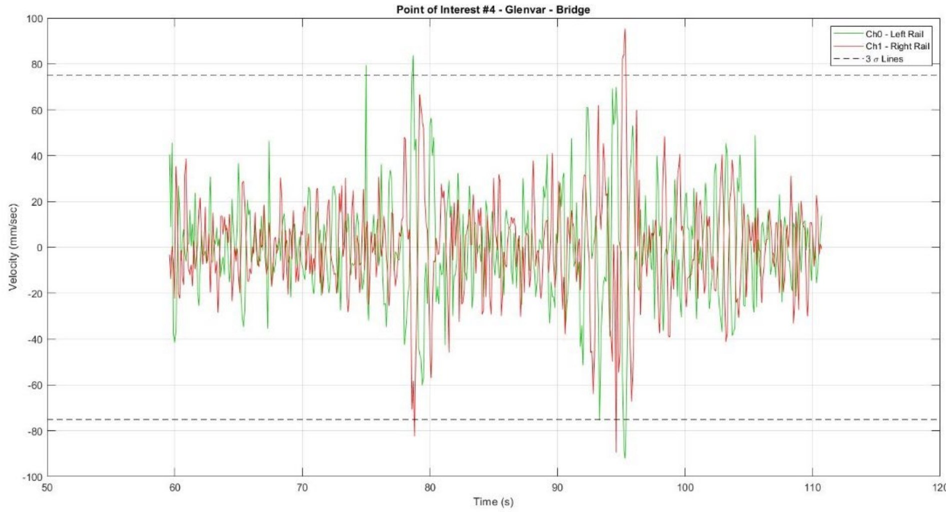

Figure 16: Glenvar Bridge High-pass filtered Doppler LIDAR Overview

The GPS trace below shows the test sector and the locations of the two large 3 sigma Doppler peaks. Note that the first Doppler peak is, in fact, far from the location of the bridge while the second Doppler peak is at the exit of the bridge. The curve in this section is a 3.0-degree right hand curve.

Figure 17: Glenvar Bridge GPS Trace with Relevant Time Stamps

By integrating the Doppler LIDAR velocity, it is possible to investigate the gage variance. The integration is started at zero, which assumes that the track gage is nominal far from the point of interest. The rail transient at 80 seconds shows a high amount of displacement in the component (left and right) rails with approximately 40 mm of motion peak to peak. At this spot, however, the overall gage remains relatively constant since the rails are moving in opposite directions. Without accelerometer data, which is not available for this test, it is impossible to know if this signature is from rail motion or vehicle motion.

The rail transient at 95 seconds, however, does create a 20 mm peak to peak pop in the track gage. The motion in both peaks has some relatively pure sinusoidal shapes that make the LIDAR signals more compelling. Further still, this motion has been noticed at similar places down track as shown in the next point of interest: Crab Creek Bridge.

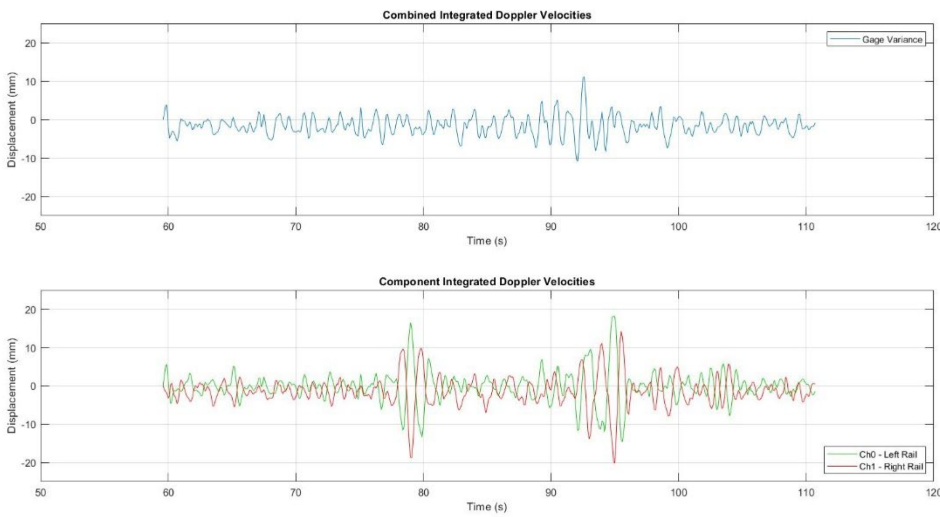

Figure 18: Glenvar Bridge Integrated Gage Variance from Doppler LIDAR Velocity

2.5.3 Point of Interest #11 – Crab Creek Bridge

The Crab Creek Bridge point of interest is very similar to the Glenvar Bridge point of interest. Combined, these two points illustrate a similar phenomenon that raise curiosity about the rail movements captured. Like the Glenvar Bridge, the Crab Creek LIDAR signal shows a disturbance far from the actual bridge at 2725 seconds. At Glenvar, this transient was located a bit before the entrance of the right-hand curve that the bridge section was on. At Crab Creek, this transient is closer to the exit of a similar right-hand curve and the bridge section is on tangent track.

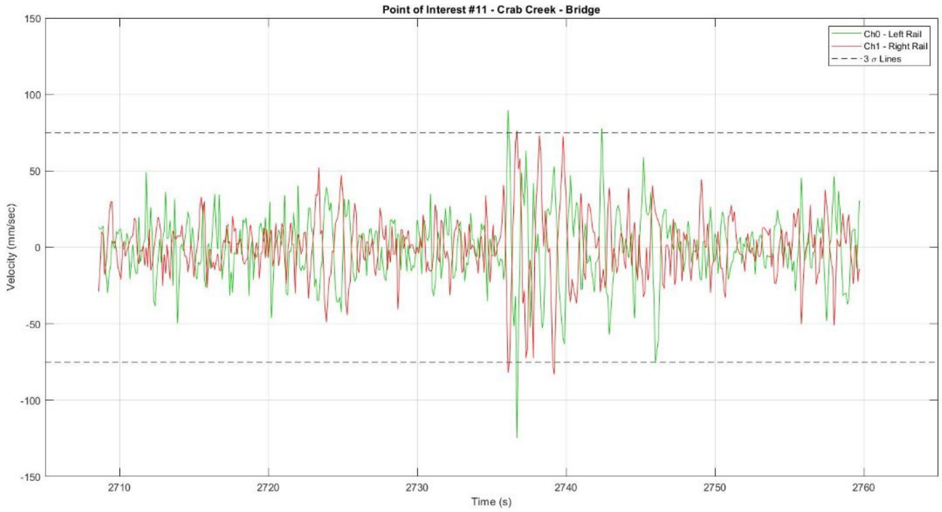

Figure 19: Crab Creek Bridge High-pass filtered Doppler LIDAR Overview

Looking at the time stamps on the GPS trace, the significant peak in the Doppler signal appears to be slightly before the actual bridge itself. Satellite imagery from Google Maps confirms that the actual bridge is quite short raising the question: is the bridge a cause of the rail transient itself of a secondary, or even unrelated, correlation? Because the data is historical, over 5 years old at this point, it is very difficult to relate Doppler signals with actual observations of the track.

Figure 20: Crab Creek Bridge GPS Trace with Relevant Time Stamps

Figure 21: Crab Creek Bridge Satellite Overview from Google Maps. Orange Arrow shows Direction of Travel

Without the supporting measurements from the accelerometers, which were not available for this test, it is not possible to resolve whether the Doppler LIDAR signals are measuring rail vibration or lateral vehicle movement (hunting). The similarities between Crab Creek and Glenvar suggest that this motion is repeatable at multiple locations and worth deeper investigation, likely through modeling and simulation by structural dynamists. The integrated Doppler LIDAR shows gage variance pops of around 20 mm peak to peak to be prevalent in this section of data. Because the square of the lateral Doppler velocity is also proportional to vehicle kinetic energy, it is possible to determine slap energy to model a dynamic input to track stability models from this interaction.

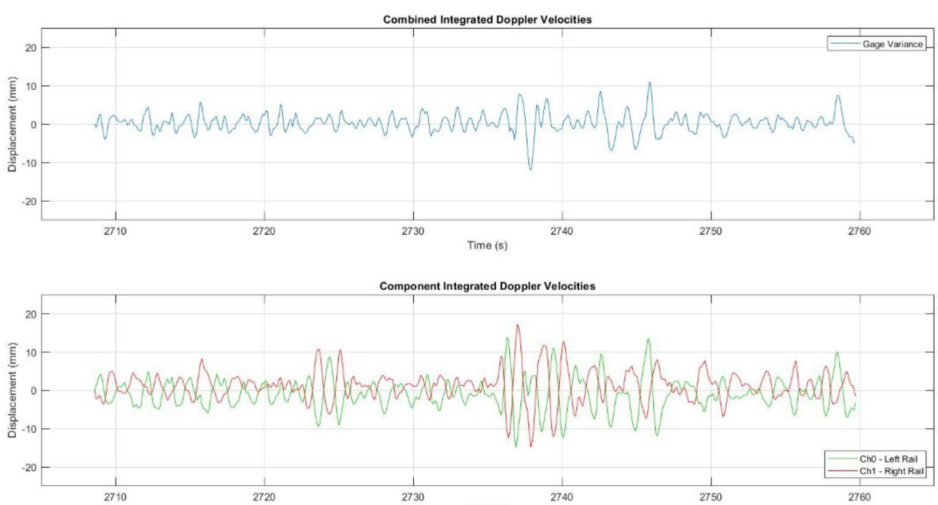

Figure 22: Crab Creek Bridge Integrated Gage Variance from Doppler LIDAR Velocity

2.5.4 Point of Interest #6 – Old Roanoke Road S Curve

Jumping back a bit, point of interest #6 has some interesting signal dynamics while traveling through an "S" curve. This point of interest was also taken on the Norfolk Southern track geometry car during the same run as the Glenvar Bridge and the Crab Creek Bridge.

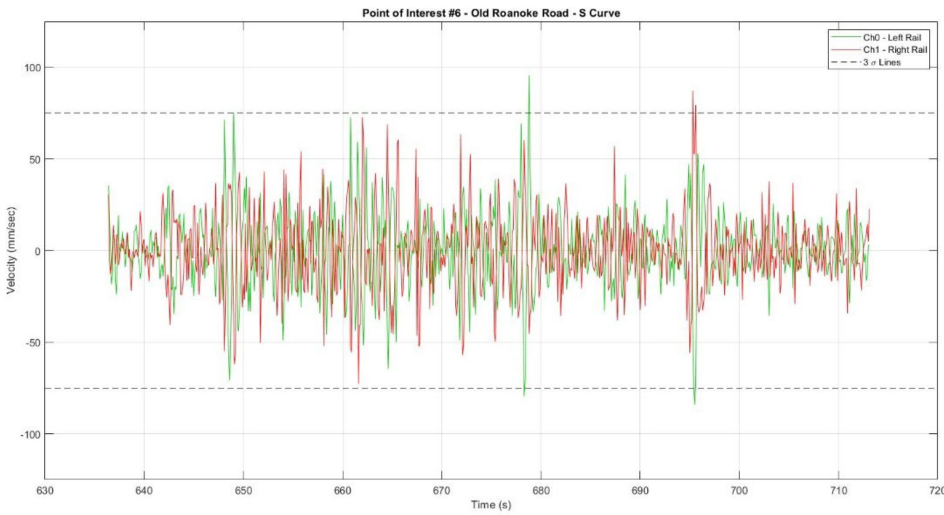

Figure 23: Old Roanoke Road S Curve High-pass filtered Doppler LIDAR Overview

The Doppler LIDAR signal has 3 sigma peaks that appear to have a cadence to them. This can be seen in the GPS trace when the time stamps are added along the test route. The GPS trace also shows that the peaks fall at critical points of the S curve. The peak around 680 seconds occurs directly at the reverse between the right-hand curve and the left-hand curve.

Figure 24: Old Roanoke Road S Curve GPS Trace with Relevant Time Stamps

This section of test data also lacks accelerometer data removing the ability to cross check vehicle lateral motion through the S curve. The lack of significant gage variance indicates that the Doppler peaks are more likely to be related to lateral vehicle shift (hunting) than rail vibration, but this cannot be determined from the available field data. Regardless, the lateral Doppler velocities can be used to calculate vehicle slap or impact energy. The signature in the component gage motions at 695 seconds likely indicates a vehicle slap against the outside rail due to the lack of gage variance during a period of significant lateral motion. The square of the Doppler velocity from during the vehicle slap in this section is directly correlated to the impact energy when combined with the vehicle weight. Using this measurement, it is possible to model vehicle slap impacts as dynamic inputs for structural stability simulations.

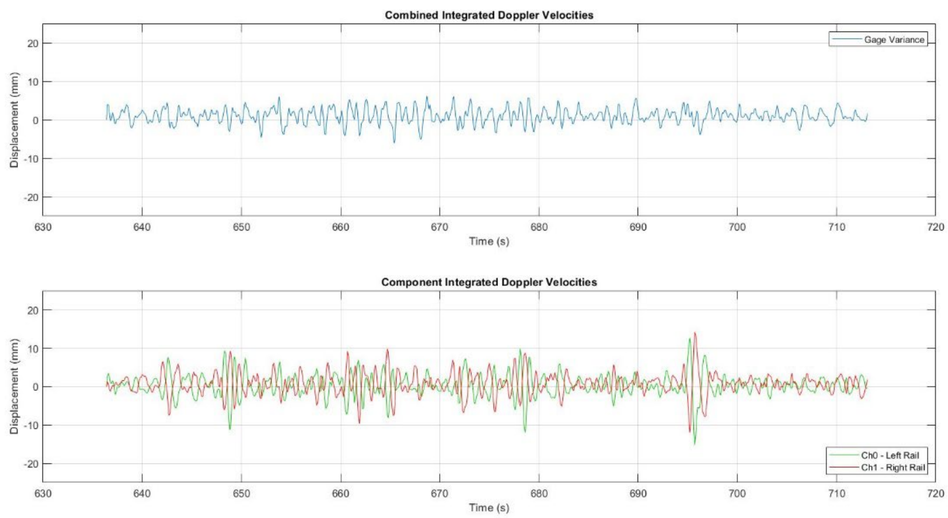

Figure 25: Old Roanoke Road S Curve Integrated Gage Variance from Doppler LIDAR Velocity

2.5.5 Point of Interest #19 – Railside Left Rail Tangent

Point of interest #19 is on a tangent section of track and the Doppler LIDAR rig was installed on a Hy-rail truck. The lenses were aimed at the left-hand rail with one beam on the Top-of-Rail (TOR) surface and the other beam on the Gage Face of the rail. In this configuration the Doppler beams can capture the simultaneous lateral and vertical motion of the rail.

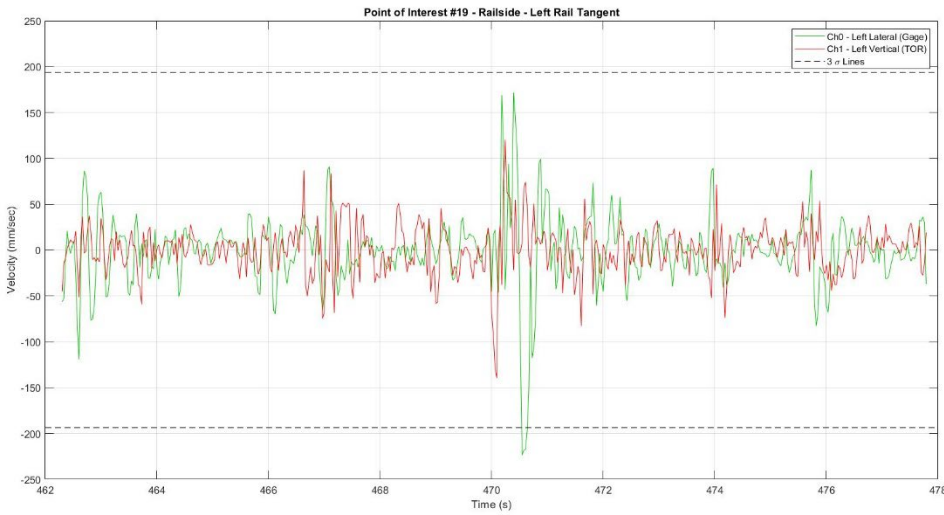

Figure 26: Railside Tangent High-pass filtered Doppler LIDAR Overview

The Hy-rail tests were conducted with an upgraded LIDAR software configuration that increased the data rate of the instrument. This increased data rate combined with the slower speed of the Hy-rail truck, particularly on secondary track, greatly increases the spatial resolution for the track stability testing. The decreased weight, however, also decreases the amount of force applied to the rail. The Doppler peak at 470 seconds can be found called out on the GPS trace below.

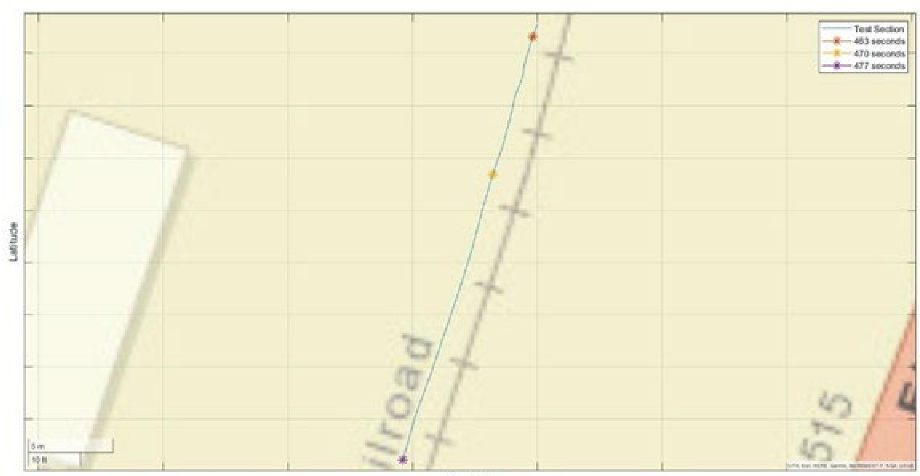

Figure 27: Railside GPS Trace with Relevant Time Stamps

Representing the lateral (X Axis) and vertical (Y Axis) movement of the rail over down track distance would have been an ideal application for a 3D plot. During analysis, the results from the 3D plots in MATLAB were difficult to read so instead a MATLAB animated plot called a Comet plot was used instead. The results of these Comet plots are stored in video .mp4 files and transmitted with the rest of the test data. A still frame from the end of the animation is shown below for reference.

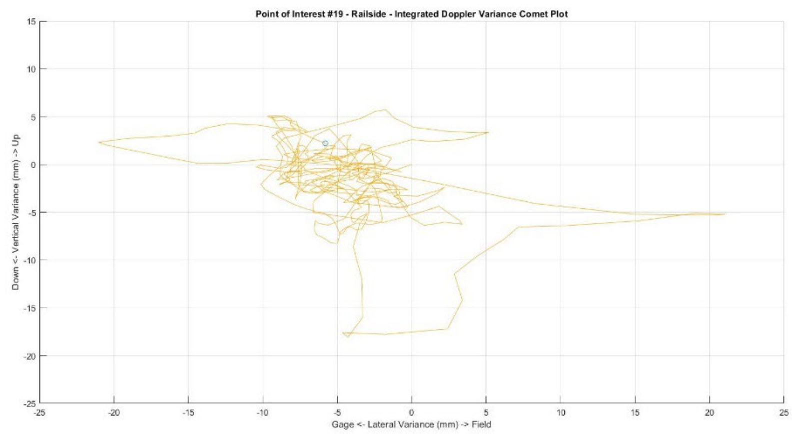

Figure 28: Railside Integrated Variance from Doppler LIDAR Velocity Plotted on a Comet Plot

The Comet plots demonstrate some key findings of the two-dimensional movement of the rail. First, much of the large motion from the rail movement is lateral. This can be further seen in some of the other Comet plots. Point of Interest #17 – Forest Lawn is a strong example of the typical, expected lateral movement. The Railside Comet plot is a perfect example of the orbital motion that has been frequently observed in the Doppler LIDAR velocimetry. The rail makes an orbital loop down and towards the field side as the rail is forced outwards and rebounds correspondingly upwards and towards the inside of the gage. The LIDAR beams are focused on the rail head. Logically, by considering the restraints between the rail and the ties it is believed that the rail often behaves as a torsional spring. This torsional deflection mode appears both in the vertical and lateral motion although more strongly in the lateral motion due to the moment arm from the foot of the rail to the gage corner.

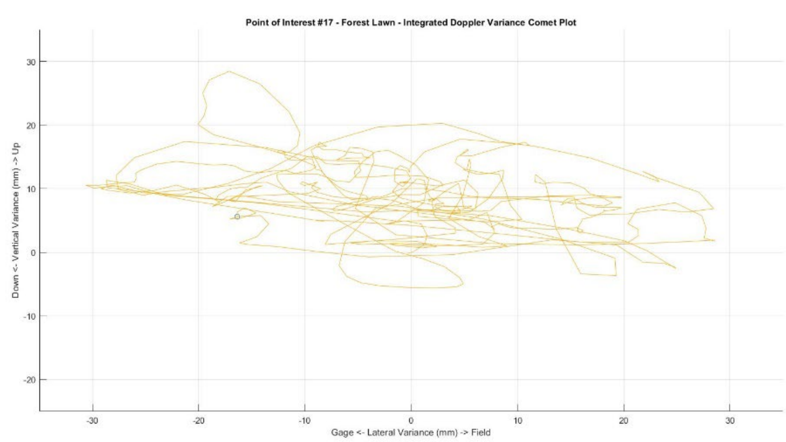

Figure 29: Forest Lawn (Point of Interest #17) Integrated Variance from Doppler LIDAR Velocity Plotted on a Comet Plot

2.5.6 Point of Interest #25 – Carter Tangent

Point of Interest #25 is also from a test run on secondary track while mounted on a Hyrail truck. For this test on a tangent track, the LIDAR beams were directed to the Top-of-Rail (TOR) surface and the tops of the crossties.

Figure 30: Carter Tangent High-pass filtered Doppler LIDAR Overview

The LIDAR data has velocity peaks with an even cadence that are called out on the GPS trace below. The ties are expected to have some added noise and cadence in the signal from where the beam passes between them and the ballast.

Figure 31: Carter GPS Trace with Relevant Time Stamps

Despite the expectation that the tie beams would have more noise than the TOR beams, a plot of a moving variance window over the high-pass filtered data shows the signal variance between the two LIDAR beams to be very similar. While the sampling and data rate of the Doppler LIDAR instrument is significantly increased for this test run, 33 Hz compared to a more typical 10 Hz from previous runs, the overall spatial resolution of the higher data rate is still approximately 1 sample per foot at 20 mph. Under these conditions, the spatial resolution is not fine enough to significantly measure the surface roughness of the ballast rock compared to the ties. In a future test, a very low speed test could be conducted to increase the spatial resolution for this instrumentation configuration.

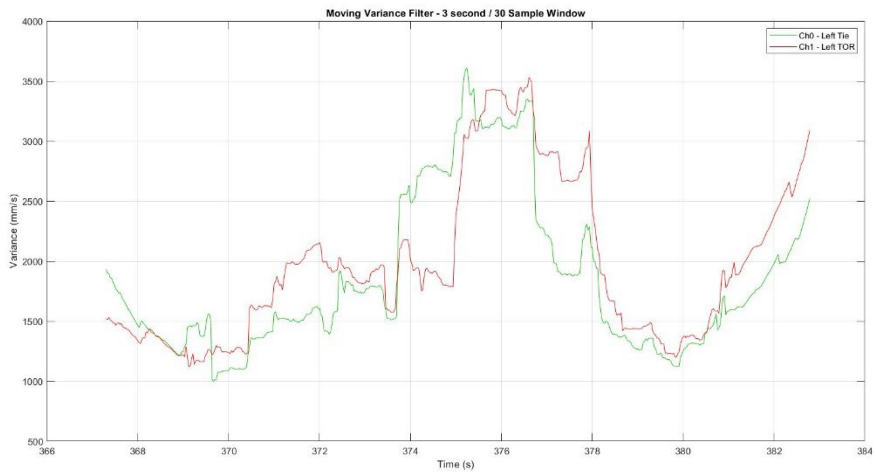

Figure 32: Carter Moving Variance Filter of High-pass filtered Doppler LIDAR Velocity

By integrating the high-pass filtered Doppler LIDAR Velocity, it is possible to approximate the separation between the rail and the crossties. Here, the velocimetry methods provide a strong benefit to capturing the rail motion since even if the track structure is greatly compressed in terms of absolute position, the downward velocity of the track elements may still have a significant Doppler signal allowing the integrated Doppler velocity to measure where the track was one time step prior. The integrated LIDAR data shows track structure compression of up to 30 mm.

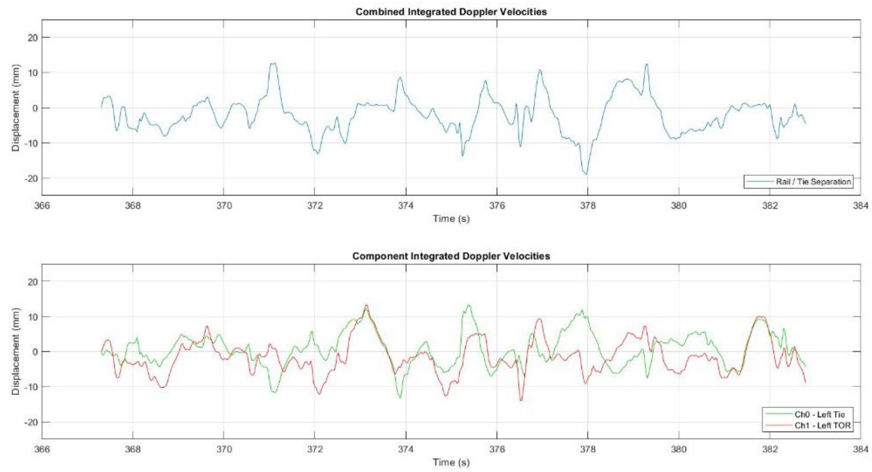

Figure 33: Carter Integrated Track Structure Variance from Doppler LIDAR Velocity

3. Task 2: Improving Prototype LIDAR System for Track Testing

The existing LIDAR instrument computers are significantly old at this point with 9 and 15 years of service respectively and have been replaced with upgraded LIDAR instrument computers. The upgraded LIDAR instrument computers feature modern, commercially available computer hardware and can be easily and quickly replicated. The new instruments also run modern versions of Windows that are both actively supported by Microsoft and can also run the legacy, proprietary RailDynamics software. Additionally, this class of LIDAR instruments were initially designed to evaluate track speed and distance and track alignment and will need some modifications to be re-purposed for track stability measurements. New electro-optical modules were constructed to maximize the Doppler signal, particularly for the lateral beams that are needed for track stability assessment.

3.1 Detailed Analysis Tasks – Statement of Work

The improvements that are anticipated include:

- Assessing the mounting configuration of the LIDAR heads to the moving platform (Hy-rail truck or Track Geometry Car) in terms of their ease of installation, accessibility, reduction of platform-induced vibrations, and maintaining adequate proximity to the railhead
- Determining the means for keeping the LIDAR heads clean for the duration of the tests, in particular, in cases where extended testing is necessary
- Sorting out the system installation issues, as related to wiring and installation of the LIDAR instrument computers and LIDAR Optical and RF enclosures
- Implementing any hardware and/or software improvements that may be necessary for ensuring successful future track testing

This task is intended to lay the appropriate groundwork for ensuring the success of future track tastings.

3.2 Develop and Commission New LIDAR Instrument Computers

To assess track stability, it was determined that a 4-channel LIDAR array would be ideal. The 4-channel configuration allows for both lateral and vertical motion to be recorded for both the left and right rail. Prior to this program, RTL had two existing LIDAR instrument computers: “Speedy” and “PXI.” Both computers are significantly old, with 15 and 9 years of history. It was determined that replicating the existing instrumentation capacity at RTL would be essential to ensuring the success of future tests. In addition, some improvements were made to the electro-optical LIDAR systems to increase the SNR of the Doppler LIDAR signal over previous implementations.

3.2.1 New LIDAR Instrument Computers

The first step of task 2 was to replicate the existing LIDAR computers. “Speedy” was built in 2005 and runs Windows XP, an operating system that has long been unsupported by Microsoft. “PXI” was built in 2011 and is based on the National Instruments PXI line of instrument computers. "PXI" runs Windows 7 that is also unsupported by Microsoft as of January 2020. Both "Speedy" and "PXI" use outdated computer hardware that is no longer readily available.

Figure 34: "Speedy" built in 2005

Figure 35: "PXI" built in 2011

The two new LIDAR instrument computers are called "Corsair" and "Blackbeard." Both computers were assembled in 2020 and run modern versions of Windows on modern x86/x64 hardware that is readily available. "Corsair" and "Blackbeard" are practically identical and run Intel 7^{th} Generation Core series CPUs. Windows offers a fork of Windows 10 Enterprise intended for embedded systems. This Long Term Service Channel (LTSC, formerly Long Term Service Branch, LTSB) is devoid of many consumer features offered in full installations of the Windows 10 that make it ideal for this application as an x86 instrumentation computer. The new LIDAR instrument computers use the same series of National Instrument DAQ cards to remain compatible with the existing Rail Dynamics software.

Figure 36: “Corsair” and “Blackbeard” built in 2020

3.2.2 New Laser Optics and Increased Laser Power

In addition to the new LIDAR instrument computers, an additional electro-optical assembly was required to support the full 4-channel array of LIDAR beams. This new VT electro-optical unit is identical to the LIDAR RF unit developed for “PXI” in 2011. Existing components from prior LIDAR programs greatly accelerated the speed of developing this second unit.

Figure 37: 2011 Integrated LIDAR RF unit

Figure 38: 2020 LIDAR RF unit under construction

To adapt the LIDAR RF and optimize the setup for measuring track stability, a couple of changes were made on the optical side. The first was an increase in lens size from 1in. diameter to 1.5 in.

diameter lenses. All prior LIDAR projects have used the 1 in. diameter lens size including the preliminary runs with Norfolk Southern in 2018-2019. Moving up to a 1.5 in. diameter lens grants an approximately 2x increase in LIDAR SNR at the cost of a shortening of the lens depth of focus. This change will also require different explosion-proof, positive air pressure housings if the installation is intended to be deployed in long term revenue service.

Figure 39: Past 1 in. diameter lens explosion-proof housings with positive pressure air line

Finally, the LIDAR laser power was increased to provide a further 2x increase in LIDAR SNR for a net gain of 4x in overall LIDAR SNR. Once the stability of the laser is guaranteed, there is a little tradeoff for the higher laser power beyond increased power draw for the laser and TEC (Thermo-Electric Cooler) and some additional wear on the components. For this prototype system, the meantime to failure (MTTF) should still far exceed the expected length of the project.

3.2.3 Non-contact Absolute Gage Sensors

Past tests relied on the data from the track geometry car to provide reference measurements such as gage, curvature, and alignment. During the 2018-2019 preliminary run, the mechanical relative gage sensor from the NS Hy-rail truck was routed into the Rail Dynamics collection software that provided a physical gage measurement sampled at the same time as the LIDAR data and stored in the same raw data file. This added functionality prompted the inclusion of two Keyence optical sensors for recording the absolute gage as well as the lateral shift of the test vehicle. With these two sensors, it is possible to track the lateral position of the vehicle by comparing the distance between the left and right-hand rail. By synthesizing the two measurements relative to the mounting points on the vehicle and adding the physical spacing of the sensor mounts it is also possible to calculate absolute track gage. The addition of the left and right absolute gage measurements provides another useful diagnostic measurement for determining the absolute motion and vibration of the rail. As mentioned in the analysis section, these gage measurements, in addition to accelerometer measurements, will be used to determine whether the rail vehicle is hunting back and forth laterally or if the rail is vibrating underneath the vehicle, or both.

Figure 40: Keyence left and right absolute gage measurement sensors

3.3 Validate and Test Complete System Configuration

With all the component pieces assembled and independently verified, the final step in completing Task 2 is to connect all the components and perform an integrated system test. This involves directing the LIDAR beams at spinning LIDAR targets, connecting all the auxiliary sensors such as the GPS, accelerometer, vehicle tachometer, and Keyence absolute gage sensors, and collecting sample data. If possible, we are investigating to see if a shakedown run with Norfolk Southern would be possible during the winter maintenance of their track geometry cars. A shakedown test on a track geometry car would allow for evaluating the system in actual field conditions and looking at revenue track conditions at track speed. At time or writing, planning is moving forward for a full shakedown run in January of 2021 during the Norfolk Southern calibration runs.

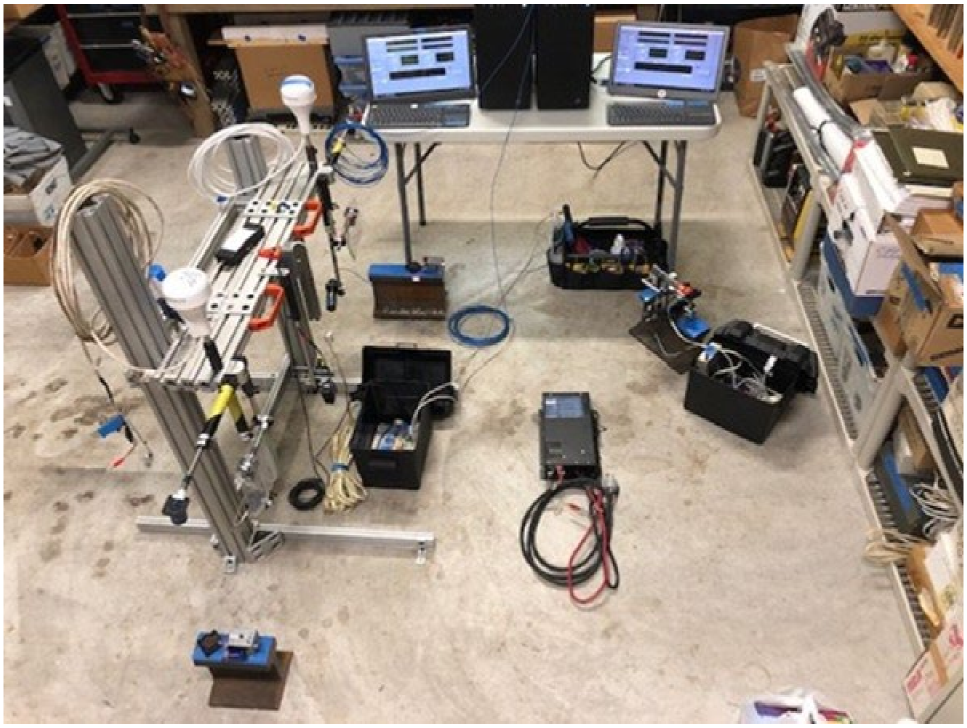

Figure 41: Ongoing integrated system testing

3.4 LIDAR Benchtop Reference and Development Instrument Computer

A third LIDAR instrument computer was also assembled. This system, named "Fractal" runs the same modern x86/x64 computer hardware and Windows 10 Enterprise LTSC operating system. "Fractal" is intended to be used as a benchtop reference computer when the other systems are deployed in the field. As a reference computer, it is possible to test and tweak configurations for the LIDAR software and RF and mirror any changes with the computers installed in the field. "Fractal" also serves as a development computer for future revisions of the Rail Dynamics software. Having a third development computer allows for modifications and development without risking a loss of functionality on the primary testing instruments. "Fractal" can also serve as a hot spare if either "Corsair" or "Blackbeard" encounter any issues.

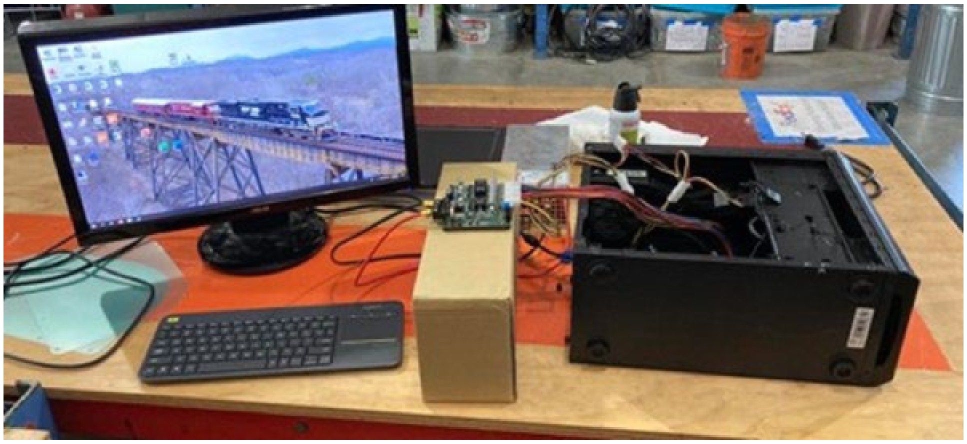

Figure 42: "Fractal" testing under a DC-DC ATGMS compliant power supply

One of the first tests conducted with "Fractal" was evaluating system performance using a DC-DC ATX power supply instead of a typical AC power supply. The DC-DC power supply can run the system off 12 or 24 Volts typically found in ATGMS installations. A single 2-channel instrument draws less than 100 Watts including LIDAR RF. This means that even when running a 4-channel configuration with 2 LIDAR instrument computers the overall system draws less than 200 Watts, therefore meeting the ATGMS specification. The typical power draw for the entire system is much closer to 70 Watts (including LIDAR instrument computer and LIDAR RF) bringing the overall system drawdown to around 140 Watts.

3.5 Vehicle Mounting Configurations

During the past six months, the COVID-19 Pandemic has severely restricted long-distance travel. We remain optimistic that in the future there will be opportunities to travel for conducting a series of onboard track testing. This section provides the required mounting configuration for such tests.

3.5.1 Previous Mounting Configurations

In the past, the VT-RTL LIDAR system has been installed on several rail vehicle platforms including the FRA R4 Hy-rail vehicle, both the NS 36/38 and the NS 33/34 Track Geometry Sets, and an NS Hy-rail truck equipped with a mechanical gage measurement unit. All these mounting strategies have relied heavily on structural aluminum extrusion and optical lollipop mounts. These mounting mechanisms are very flexible and highly adaptable lending themselves well to any similar vehicles.

Figure 43: LIDAR Rig on FRA R4 Hy-rail vehicle with multiple lenses installed

Figure 44: LIDAR Rig on NS 36/38 without explosion-proof housings

Figure 45: LIDAR Rig installed on NS Hy-rail truck with a mechanical gage sensor

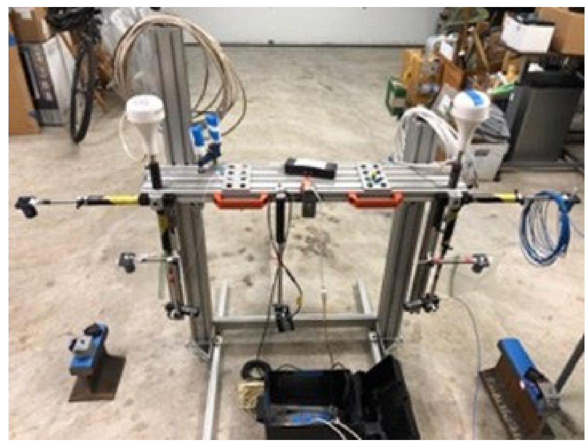

Figure 46: LIDAR test rig with 4-channel configuration during system testing

3.5.2 System Mounting for Track Testing

Using the extensive program history of Doppler LIDAR installations on rail vehicles, we expect the installation fixture design will be relatively straightforward for short duration testing. Short duration testing does not require the same amount of structural infrastructure for the LIDAR systems. For example, the long term installs on the Norfolk Southern equipment has required explosion proof housings to protect the lenses from rocks and debris and the addition of positive pressure hoses to keep dust and dirt of the lenses.

By contrast, short term installations can be adapted quickly using structural “T” slot aluminum framing, optical “lollipop” mounts, or even simple “C” clamps. Using this installation methodology, an early Doppler LIDAR test was conducted on one of the Norfolk Southern Research Cabooses using “C” clamps and “lollipop” mounts in 2006.

Figure 47: VT Multifunction Doppler LIDAR System Installed on Research Caboose in 2006 using simple C Clamps and Lollipop Mounts

3.5.3 System Mounting for NS Testing

The LIDAR rig for the NS 36/38 Track Geometry Set has been pulled out of storage at the lab and planning is underway to install the existing LIDAR rig for shakedown testing during the January 2021 NS validation runs. During this installation, detailed notes and observations will be made of the installation procedure that will be used to accelerate the ability to get the system installed for future onboard testing at test tracks such as at the Transportation Technology Center (TTC).

Figure 48: LIDAR system installed on NS 36/38

4. Conclusion

Virginia Tech has made significant efforts towards advancing the science of using Doppler LIDAR velocimetry to evaluate track stability while in-motion. Through analyzing historical LIDAR data, the findings of this research indicate a depth of insight into the manner in which the rails dynamically deflect and vibrate and fully demonstrates the high degree of capability in the Multifunction Doppler LIDAR system. The rail vibrations from the Belspring (Point of Interest #1) clearly demonstrate rail vibration modes that have not been measured before that the Multifunction Doppler LIDAR methods are uniquely suited to detect.

The similarities between the Doppler LIDAR signal at Crab Creek (Point of Interest #11) and the Doppler LIDAR signal at Glenvar (Point of Interest #4) suggest that there are unique and interest phenomenon around bridges that are worth studying in greater depth by structural dynamists. Structural modeling with these input parameters may provide an answer to these questions by working the problem in reverse (resolving the vibration through simulation where observing the track is no longer possible). The questions raised by these dynamics rail vibration signatures also merit further testing where careful inspection of the track structure may provide further explanations.

While the LIDAR signatures in the Old Roanoke Road S Curve (Point of Interest #6) are indeterminate as to whether their source is rail motion or vehicle motion, the square magnitude of these Doppler LIDAR signatures directly correlates to the available impact energy. When combined with the time data can also be used to find the impact power that describes the rate at that the energy is delivered to the rail. Given the mechanical design of the railroad track structure, the friction between the tie and the ballast suggests a system that would be very sensitive to a critical lateral force threshold where the static friction is overcome lateral restraint yields. This mechanic of track stability criteria suggests the need for detailed input parameters in terms of dynamic rail forces that the measurements of this section can provide.

Finally, the modified beam configurations at Railside (Point of Interest #19) and Carter (Point of Interest #25) further validate the "Multifunction" moniker applied to the VT Doppler LIDAR system. In these two examples, different beam angles and targets can describe in greater detail some of the compound rail motions of the track structure. Railside (and Forest Lawn) sections are able to describe an orbital rail motion amidst a strongly lateral deflection. The orbital loops also suggest a fundamental torsional bending mode in the rail.

The Carter point of interest describes and expansion and contraction of the rail elements on secondary track. Using these beam configurations, it is possible to quantify the pumping motion of the rails that is often visible when standing track side. The Doppler velocimetry methods also allow for greater sensitivity to rail motion by measuring Doppler velocity instead of absolute distance. By integrating, it is possible to estimate the displacement of the rail or tie one time step prior through integration, even if the distance between the two is closer than can be easily measured with Time-of-Flight (ToF) or vision-based systems.

In terms of hardware development and preparedness for additional field testing, Virginia Tech has replicated the LIDAR instrumentation hardware for the first time in almost a decade improving the reliability and extending the life of access to proprietary, existing RailDynamics software. In addition, the new Electro-optical units feature improved laser power and LIDAR lenses that increase the overall signal-to-noise ratio (SNR) of the LIDAR system. This in turn improves detection and reliability of the Doppler seek algorithms allowing for higher data rates with less need for time intensive manual post processing. Finally, RTL has added functionality to the Doppler LIDAR instruments by adding two Keyence absolute gage sensors to the data recording. These absolute distance sensors can measure the distance to the left and right rails independently to determine the vehicles position between the two rails and also a combined absolute gage measurement. Using the absolute gage measurement as a constant of integration, the lateral Doppler LIDAR velocities can now be integrated to find an exact, high-precision gage instead of just a relative gage variation.

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