IDEA

Innovations Deserving
Exploratory Analysis Programs

*High-Speed Rail IDEA Program*

# Development of an Acoustic Broken Rail Detection System

Final Report for High-Speed Rail IDEA Project 42

Prepared by:
Ken Schwartz
Bay Area Rapid Transit District

*September 2004*

TRANSPORTATION RESEARCH BOARD
*OF THE NATIONAL ACADEMIES*

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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

# DEVELOPMENT OF AN ACOUSTIC BROKEN RAIL DETECTION SYSTEM

## Idea Program Final Report for the Period July 2003 Through June 2004 Contract Number HSR-42

**Prepared for**
**the IDEA Program**
**Transportation Research Board**
**National Research Council**

**Ken Schwartz**
**Bay Area Rapid Transit District**

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## ABSTRACT

This project investigated the use of ultrasonic acoustic propagation for detecting broken rail over long distances. The proposed system would use multiple wayside nodes spaced a mile apart to transmit and receive acoustic signals. The lack of a return signal implies the rail has broken. The system would use acoustic propagation in the rail as a digital communication network, allowing the system to provide broken rail protection without the installation of an additional wayside communication system. After a break has occurred the nearest nodes would use echo location to compute a range to the break. Acoustic interactions with rail were studied with frequencies from 3 kHz up to 80 kHz. Longitudinal waves in a few frequency bands were identified as having the lowest attenuation. The construction of a longitudinal wave transducer was attempted but was unsuccessful. Testing demonstrated that operation in the presence of 70 mph trains is possible except when the train is directly over the receiver. A prototype two-node system demonstrating the basic functionality of the system was constructed and operated at a range of 1.3 miles. Algorithms were developed and tested that allowed the prototype to find and track the optimal frequencies and send text data without communication other than through the rail. Algorithms for echo location were partially developed and tested. Environmental studies indicate that the optimal frequencies change 100 to 200 Hertz over the day-night cycle, and rain strongly attenuates the signal.

## KEYWORDS

**ultrasonic propagation, railroad, longitudinal wave, acoustic, broken rail detection, echo location, self tuning network**

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# 1.0 EXECUTIVE SUMMARY

The objective of this project was to develop a broken rail detection (BRD) system that detects complete breaks with wayside hardware. The system sends and receives ultrasonic acoustic guided waves through continuously welded rail. Unique characteristics of this system are an attempt to use longitudinal guided waves, a method of operation that finds and tracks the optimal frequency so that the system is always operated at resonance, and the use of acoustic signals through the rail for sending data.

Work done prior to the IDEA portion of this project concluded that acoustic BRD was a promising technology. Experiments indicated that longitudinal waves in rail have less attenuation, and travel at higher speeds than transverse waves. It was believed that such waves might be less affected by environmental factors. In an experiment on an 800 foot section of free rail (CWR that has not yet been installed) an end mounted transducer was excited with a tenth of a second burst of 13.6 kHz acoustic energy. The burst was detected after traveling over 5.3 miles, implying good range of a pure longitudinal wave in a perfect situation. Prior work also demonstrated the transmission of acoustic data under 70 mph trains at a range of 1.3 miles.

The proposed system would be composed of wayside nodes spaced a mile or two apart. Each node is composed of a single controller with piezoelectric transducers mounted to each rail. Binary data packets are sent from node to node acoustically using a simple protocol in a bucket brigade fashion. The inability to send data on any given link, is interpreted as a broken rail. The information that a rail has broken is sent back to the train control center acoustically via the unbroken rails. Then the nodes on either side of the break use echo location to compute a range to the break, and send that data back to the train control room. The system would not require additional cables for communication.

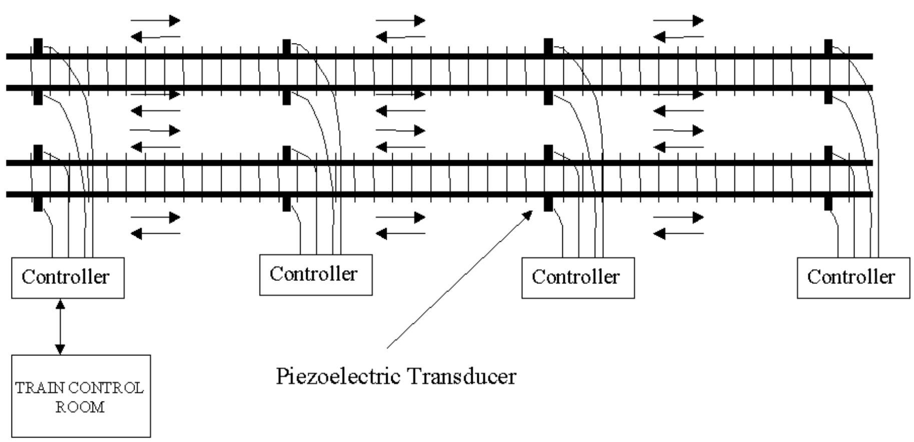



**Figure 1. Diagram of the proposed acoustic broken rail detection system.**

The work done for the IDEA project was broken down into two distinct efforts. Stage one included the study of acoustic propagation in rail, interaction with breaks, and echo ranging. In the second stage a specialized transducer was developed, and a prototype two node system was built using off-the-shelf equipment.

Reflections from partial and complete rail breaks were studied, and simple algorithms for detecting time of arrival of reflected signals were developed, coded and tested. Equipment was developed to test "time of arrival" algorithms. The system was first tested in the lab on a simulated plastic rail, allowing system components to be debugged before going out into the field. Many of the system components have been developed and integrated for field testing and demonstration.

A broad band transducer was developed to allow the study of guided waves in fixed rail. Unfortunately, this transducer could not generate longitudinal waves in the rail.

Unanticipated discoveries were made during the development of the prototype. These were:

- At a range of 1.3 miles, the bandwidths of the optimal transmission frequencies of off-the-shelf transducers mounted to rail were extremely narrow, in the order of five to ten Hz. The bandwidth seems to be unrelated to the resonate frequency of the transducers themselves. This made the tuning and communication algorithms more complicated than expected, requiring more development time.

- The optimal transmission frequency changes significantly with changes in rail temperature, on the order of 150 Hz over a day-night cycle. This effect was larger than expected and required additional testing to quantify.

- A piezoelectric transmitter mounted to a block that is bolted to the web, with the direction of the oscillation parallel to the rail, did not produce significant longitudinal waves, the wave mode that travels with lowest attenuation in free rail. The inability to generate longitudinal waves severely limits the range. The reason for the difference in response between free and fixed rail is unknown. Development of a transducer able to generate longitudinal waves appears to be a major hurdle.

- Rain increased the attenuation of acoustic waves by 40 db over a 1.3 mile length of rail. The signal was much smaller but still detectable. The effect will be a decrease in the data rate, and the ability to use echo ranging will be reduced. Longitudinal waves are expected to have less attenuation when wet.

There were considerable accomplishments in other areas. A system was developed that used simplified algorithms for detecting and determining the location of rail flaws. A two-node prototype that operates over a distance of 1.3 miles was able to find and track the optimum frequency for communication in the rail, and then use that information to send text messages acoustically. A system was built to measure and record the spectral response of the rail over a period of many days to understand how it responds to environmental factors. Considerable knowledge was gained in unanticipated areas that will require future development.

Any further development of this project would require:

1. Transducer and mounting systems that can efficiently generate longitudinal waves in rail.

2. Determination of the cause and solution of the increase in attenuation due to wet rail conditions.

3. Cost effective techniques for transmitting through or around bolted rail joints, insulated rail joints, turnouts and other special trackwork.

4. Fast efficient algorithms for discriminating between acoustic reflections caused by rail breaks, and those caused by normal discontinuities such as rail joints and switches.

# 2.0 INTRODUCTION

## 2.1 THE NEED FOR BRD

BART has been developing, and will soon be deploying the Advanced Automated Train Control (AATC) system, a new CBTC system that uses radio ranging to both track the location of trains and to communicate with them. AATC requires wayside radios spaced up to a mile apart, with identical radios on the lead and tail cars of each train. All data is passed from radio to radio in a bucket brigade fashion, eliminating the need for wayside cables. AATC will cost considerably less to install and provide better train control than a track circuit based systems. Track circuits will no longer be required for controlling the motion of trains; however, they may be required for other functions such as providing inputs to interlockings and for the detection of rail breaks. Development of an alternate method of broken rail detection will allow railroad and transit operators adopting CBTC technology to retire track circuits. Railroads may be reluctant to switch over to a CBTC based system if they need to install track circuits solely for the purpose of providing BRD. Hence, development of an effective and low cost alternative to track circuits will ease the adoption of CBTC.

## 2.2 SURVEY OF POTENTIAL BRD TECHNOLOGIES

At the start of the program Sandia National Laboratories was contracted to survey the available emerging technologies and determine which would be the best to pursue and possibly develop. The study concluded that the best candidate technologies were acoustic guided waves, rail strain gauges, optical fiber, propulsion return current, and simplified track circuits.

A short description of each technology follows.

- Guided wave acoustic transmission uses an ultrasonic signal that is injected into the rail, and listened for a mile or more away. Failure to receive the signal indicates a broken rail.

- Strain gauge based systems operate on the principle that continuously welded rail is usually under tension when it breaks and a break causes a reduction in the tension. The decrease in tension is detected with strain gauges that are attached to the web of the rail every few hundred feet.

- An optical fiber glued to the web of a rail will break when the rail breaks. There is a light source at one end and a sensor at the other, a few miles away. A break anywhere along the segment will cause a lack of signal at the receiver. Time delay reflectometry is then used to locate the break.

- On an electric railroad the propulsion return current is usually balanced between the two rails as it travels back to the substation. A rail break forces all of the return current to travel on a single rail causing an imbalance. The current will then equalize at the crossbonds that tie the two rails together every thousand feet. The detection of appreciable current through a crossbond indicates a break.

Each of the techniques has advantages and disadvantages. Guided wave acoustic transmission was selected as being the most promising, and BART is now engaged in a program to develop ultrasonic BRD into a working system.

## 2.3 OVERVIEW OF THE PROPOSED ULTRASONIC BRD SYSTEM

The system being developed utilizes ultrasonic transducers to generate acoustic vibrations in the rail that are detected by similar transducers a mile or more away. Figure 1 shows an overview of the proposed system. Failure to receive the ultrasonic signal will indicate a break. Data can also be sent down the rails acoustically by on-off modulating the transmitter. The information describing which rail has broken will be sent back to the train control center acoustically via the unbroken rails, no additional communication system is needed. The only requirement at each node is a modest power supply. When a rail break occurs the nodes on either side will attempt to measure the distance to the break. A burst will be sent which reflects off of the break. Measuring the time between the transmit burst and its return, allows the range to be computed. This information will be transmitted back to the train control room via the unbroken rails in a binary data format. The train control system will then slow trains and suspend automatic control near the break, requiring trains to cross the break under manual control. Maintenance workers will use the range data to quickly find the break.

## 2.4 ACOUSTIC TRANSMISSION FOR COMMUNICATION

A novel aspect of our system is the use of the rails for communication between the nodes, greatly reducing the wayside infrastructure, especially if electrical power is available locally.

The transmission of data via longitudinal waves is being developed for use in other industries. Sandia National Laboratories is developing an acoustic telemetry tool for transmitting data in the oil drilling industry (1). Oil and geothermal drilling companies would like to acquire real time data on the status of their drilling operation for both navigation and rock formation evaluation, but there are few options for transmitting the data back to the surface. The technology being developed at Sandia uses a piezoelectric transmitter near the drill bit to send acoustic compression waves up the tubular drill pipe to the surface. A prototype 10-Watt transmitter was able to transmit at 10 to 100 bits/second with a range of up to 14,000 feet.

Communication through rail has an additional complication because the optimal frequency and attenuation are affected by environmental factors such as noise, temperature and wetness that change over time. This is similar to problems seen in underwater acoustic communication networks, where the frequency, attenuation and noise of an acoustic channel between nodes changes slowly, and the nodes need to adapt to the new conditions in order to maintain communication.

## 2.5 ACOUSTIC ANALYSIS OF RAILROAD RAIL BY OTHER GROUPS

Other research groups are interested in developing an ultrasonic broken rail detection system. A few of these groups have performed experiments on BART's test track in order to learn about the modes of vibration and frequencies that are able to travel long distances, as well as characterizing the noise spectrum produced by trains. A number of frequencies ranges were found that looked promising from 18 kHz up to 55 kHz. These studies established that continuously welded rail is capable of propagating acoustic signals over reasonably long distances. Spoornet and the Institute for Maritime Technology of South Africa have been developing a commercial ultrasonic broken rail detection system that has achieved propagation distances up to 2.5 miles.

# 3.0 WORK DONE BEFORE THE IDEA PROJECT

## 3.1 BROADBAND TESTING OF FREE RAIL

Dr. W. Lu of the Sandia National Laboratories and Dr. A. Modjtahedzadeh of BART performed computer simulation and broadband testing in order to understand how acoustic energy travels in rail. Finite element analysis modeling illustrated a number of different vibration modes, but was unable to simulate a long enough piece of rail to predict how a wave would decay as it travels.

Experiments were performed that used impacts of projectiles to generate broadband acoustic excitation in free lengths of rail to search for the optimum modes and frequencies of vibration. At BART rail is stored in 800-foot long pre-welded sections; these rails provide a convenient environment for studying acoustic propagation. After the impact the acoustic waves travel up and down the rail, reflecting off of the ends. By filtering select frequencies, the rate of decay of specific components can be measured. Impacts on the end of the rail were used to excite longitudinal waves, and impacts on the web were used to excite transverse waves. Vibrations were picked up at the opposite end with a laser Doppler vibrometer and recorded using a Nicolet high-speed data logger; the recording system had a frequency response of 100 kHz. Figure 2 shows the raw acoustic data recorded during a longitudinal impact test.

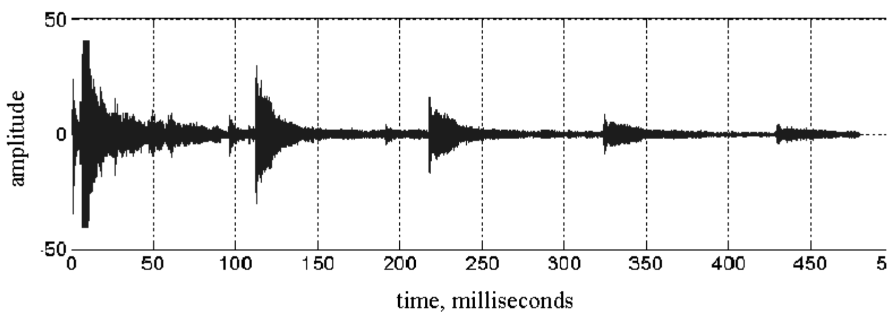



**Figure 2. Raw data recorded from a longitudinal broadband test on 800 foot rail.**

Waves of different modes and frequencies travel at different speeds and decay at different rates as they travel through the rail. They reflect off of the ends, and are detected by the laser Doppler vibrometer and are recorded. The distance traveled can be computed by counting the echoes.

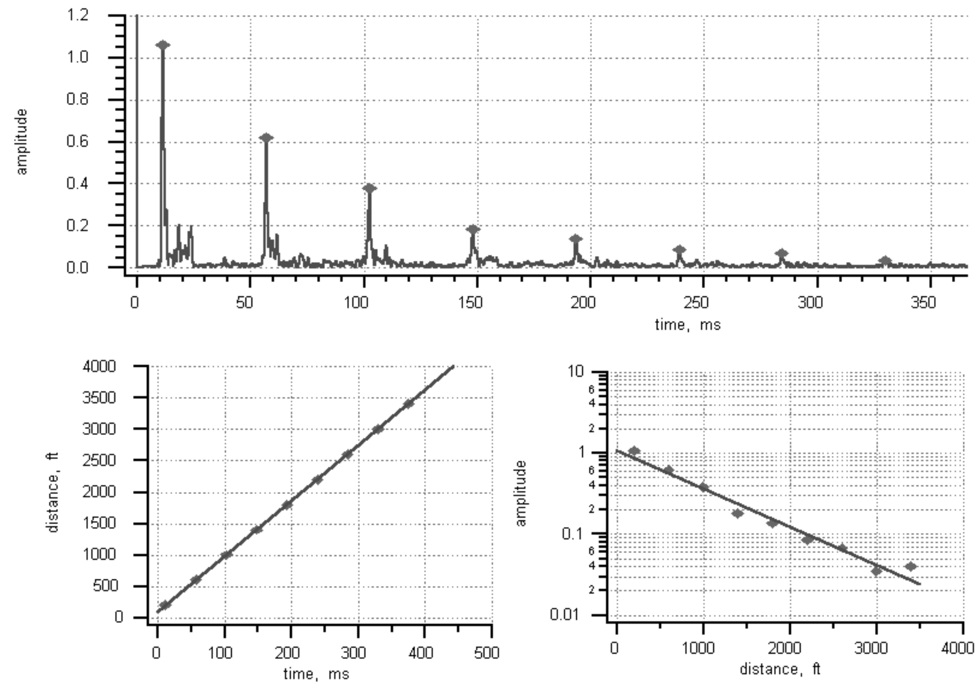



**Figure 3. Broadband test filtered for 29 kHz. Echoes are shown on the raw amplitude plot. The time and peak amplitude of each echo was located by hand; the time between echoes represents 1600 feet of travel. Velocity was calculated from the slope of the distance versus time plot. Attenuation was calculated from the slope of the distance versus amplitude log plot.**

Digital filtering of the recorded data allows a particular frequency to be selected, and its attenuation measured. Figure 3 shows data that has been filtered to examine 29 kHz, and then used to measure the attenuation coefficient and speed of that wave. The distance between any two peaks represents 1600 feet of travel, and in this case 8 echoes indicates that the wave has traveled over 2 miles.

Using these techniques the wave speed and attenuation were measured for a wide range of modes and frequencies. The results of many tests are shown in Figure 4. They indicate that the longitudinal mode of vibration at 3 and 18 kHz has the least attenuation, the highest wave speed, and should provide the greatest range. These speed measurements are used in later experiments to determine if the wave being measured is longitudinal or transverse when it is not possible to measure the attenuation.

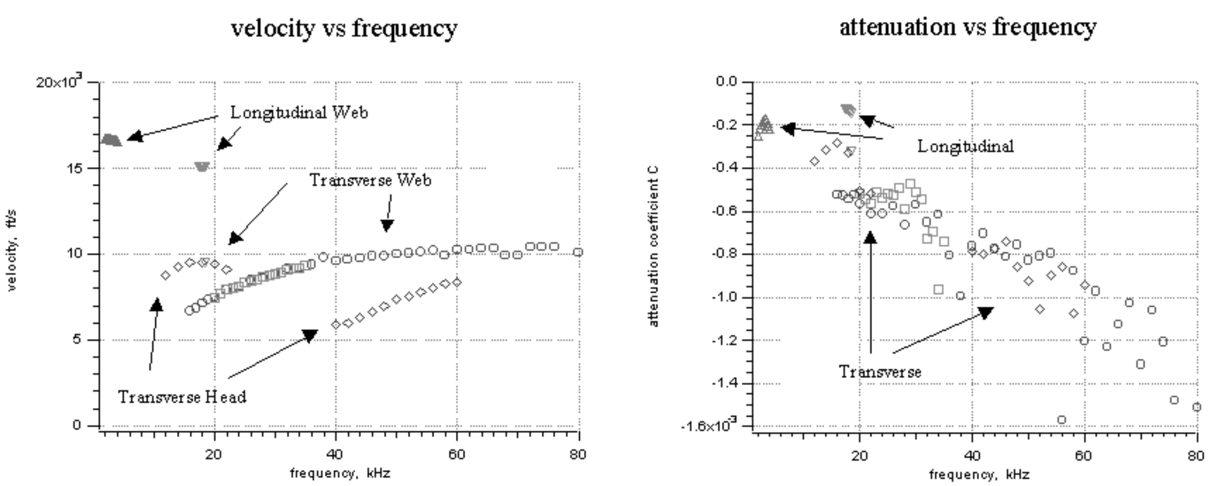



**Figure 4. Results of broadband testing. The longitudinal modes at 3 and 18 kHz exhibit the least attenuation.**

The attenuation coefficient describes the rate of decay of the amplitude of the signal as it travels through the rail according to the equation, $A=A_o e^{Cx}$ where x is the distance in feet from the source. Signals with an attenuation coefficient closest to zero will experience the least attenuation and give the greatest range. The groupings of triangles at the top of the attenuation versus frequency plot in Figure 4 show that the longitudinal mode of propagation at 3 and 18 kHz has the least attenuation.

## 3.2 PIEZOELECTRIC TESTING OF FREE RAIL

The proposed system would use some form of continuous wave ultrasonic transducer, such as piezoelectric, magnetostrictive, or EMAT. An experiment was run in an attempt to reproduce the results of broadband testing with a continuous wave transducer, and to see if piezoelectric transducers are able to generate enough acoustic energy to achieve a usable range. A piezoelectric transducer was mounted on the end of the rail in a way that was believed would excite longitudinal waves. (See Figure 6)

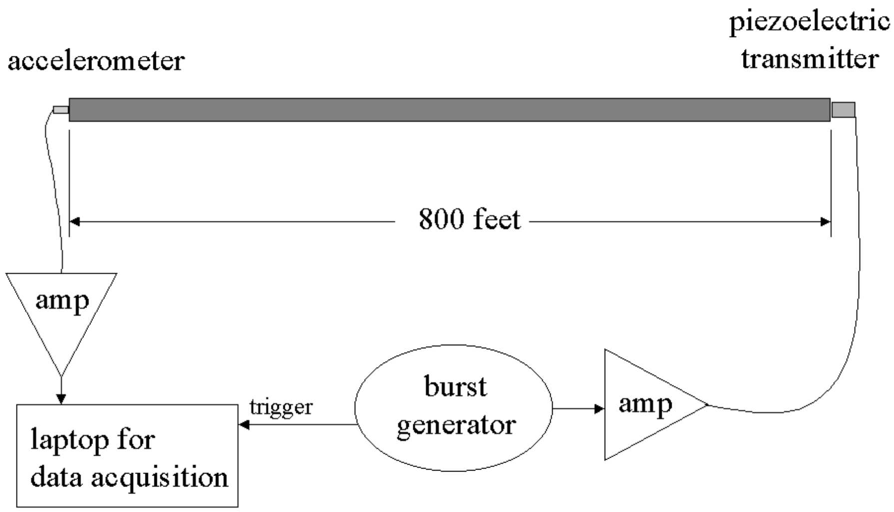



**Figure 5. Diagram of setup used free rail testing.**

**Figure 6. Shown is a transducer that is similar to the one used in the free rail longitudinal wave test. It was attached to the end of the rail with hot melt glue.**

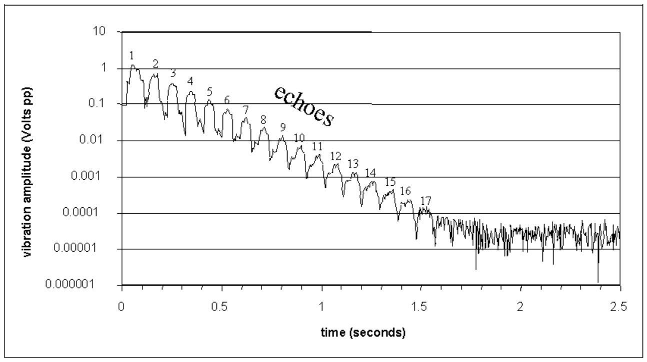



**Figure 7. A logarithmic plot showing echoes recorded during a longitudinal test on an 800 foot long free rail. The transmit burst was 0.1 seconds long at 13.595 kHz. The 17 echoes visible represent a distance traveled of 5.3 miles.**

Piezoelectric transducers were selected because of their high efficiency, and because we had previous experience with them. A few were built in an attempt to excite the frequencies that were observed in the broadband tests, especially those near 3 and 18 kHz. A large transducer was built that had a fundamental resonance of 7 kHz; a transducer with a resonance of 3 kHz would have been prohibitively large. A smaller transducer with a resonance at 30 kHz was also built. Two commercial off-the-shelf transducers that are manufactured for ultrasonic cleaning machines were also purchased. These units turned out to be the most robust and easy to use. Since BART's tracks pass through residential areas, it may be desirable to use the highest frequency that gives good range so that the system is inaudible.

The purpose of the experiment was to search for frequencies that traveled with low attenuation. A continuous wave transducer was used to send a long burst into the rail at a specific frequency. By observing the echoes it was possible to compute the attenuation coefficient of the few frequencies that seemed to travel the farthest. Acoustic energy in rail decays at an exponential rate and by plotting the amplitude of the recorded signal on a logarithmic scale as in Figure 7 the attenuation can be computed from the slope. The effect of increasing the transmit power would be to translate the plot upward vertically, but it would have no effect on the slope. The attenuation would be the same. All of the transducers were able to generate a reasonable amount of acoustic energy over a large range of frequencies.

The piezoelectric transducer used in this test was a dual frequency 25 and 40 kHz off-the-shelf unit made for ultrasonic cleaning machines by NTK, model number DA44525-46. It was directly driven by a Crown CE2000 amplifier, which was chosen because the output is able to swing 180 $V_{pp}$, and the frequency response is usable up to around 60 kHz... The signal was detected with an Endevco accelerometer, model 7259a-100 and the Endevco model 133 signal conditioner. The combination has a nearly flat frequency response up to 60 kHz. The signal was recorded on an IBM laptop computer with a 12 bit analog-to-digital converter running at 500 k samples per second. To excite the purest wave possible the transducer was glued directly to the end of the rail, and to detect the signal an accelerometer was glued to the other end, 800 feet away. The frequency spectrum was scanned manually by sending a burst, and then observing the raw acoustic signal on an oscilloscope. A number of frequencies were found which traveled reasonably far. The frequencies that traveled the farthest seemed to have a very narrow bandwidth, on the order of ten's of Hertz. Figure 7 shows a 2.5 second long recording of a 13.595 kHz burst that lasted a tenth of a second. It was digitally filtered and plotted on a logarithmic scale. The wave traveled over 5.3 miles as indicated by the 17 echoes. The attenuation is 16.75 dB per mile, and the speed is 17,650 feet/second, confirming the wave is longitudinal. It is unknown why 13.595 kHz was not seen in the broadband test data, or why 3 kHz and 18 kHz did not perform well.

### 3.3 LONG RANGE TRANSMISSION AT THE TEST TRACK

The next step was to see if rail behaves in a similar fashion when it is tied down. BART operates a 2.5 mile long test track, of which the longest continuous rail is 1.3 miles. The preferred transducer mounting would have been directly to the end, as in the free rail test. There are very few exposed rail ends on the BART system; therefore an alternate method of exciting the rail was developed. At one end of the rail a piezoelectric cleaning transducer was affixed to each side of the web using a mount that attempts to excite a longitudinal wave, shown in Figure 8. At the other end an accelerometer was glued to the web.

**Figure 8.** **Piezoelectric cleaning transducer mounted to the web. Two of these units are used, one on each side of the web.**

The transducer was driven with a frequency sweep to explore the spectral response of the rail. The sweep time was on the order of a minute. A slow sweep rate was selected because most spectral features are very narrow, on the order of tens of Hertz. The slow sweep allows enough dwell time at any single peak to excite a sizable oscillation, and to obtain good resolution in the recorded spectrum. The test indicated that a few frequency bands are able to travel the full 1.3 miles. Most were between 25 and 40 kHz, the strongest peaks were around 31 kHz. This experiment was not able to explore frequencies outside this range due to limitations in the transducer.

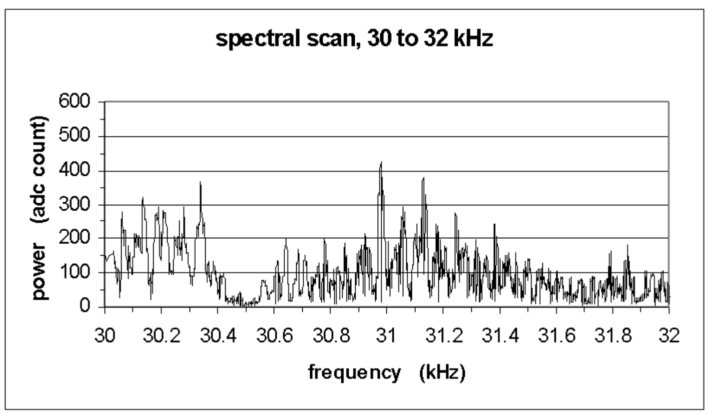



**Figure 9. Spectrum received over 1.3 miles using piezoelectric cleaning transducer.**

The transmitter was then set to operate at one of the peak frequencies, 31.065 kHz, and switched on and off manually. Figure 10 shows 10 seconds of the raw data from this test, recorded at a range of 1.3 miles.

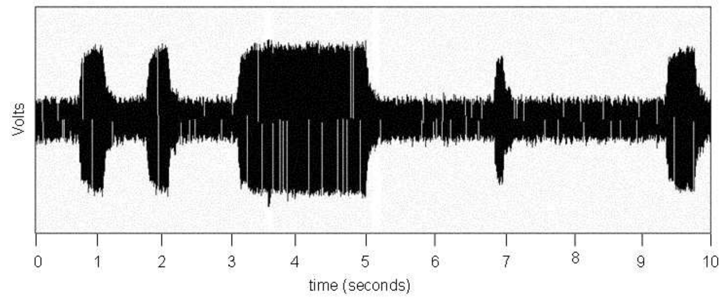



**Figure 10.** **Transmitter set for peak frequency, and switched on and off manually. Plot of the raw data at a range of 1.3 miles.**

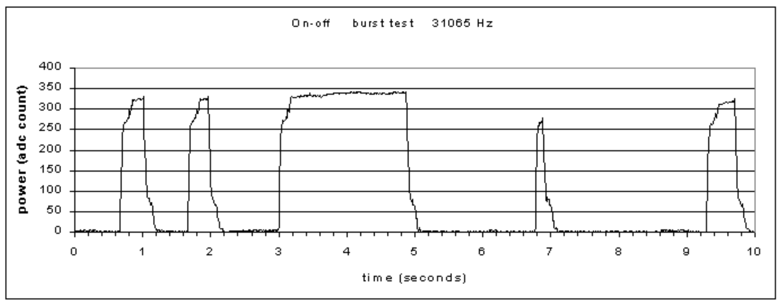



**Figure 11.** **Data from Figure 10 after digital filtering.**

Figure 11 shows the same data after processing with a relatively narrow band FIR filter to remove noise. The resulting plots indicate that even relatively brief bursts are able to travel the 1.3 miles with a good signal-to-noise ratio. This combination of transducer and mounting block has a rather high Q and seems to achieve full power in about 0.1 seconds, which will probably limit the data rate to a maximum of a few bits per second. Based on the kind of information being sent, this data rate should not be a problem.

A very small amount of the transmitted signal leaked into the recording equipment, and can be seen when the power shown in Figure 11 is plotted using a logarithmic scale (not shown). From the log plot the transit time was measured to be 0.7 seconds, giving a wave speed of 9800 feet/sec (2990 m/sec), a speed that is associated with transverse waves. This implies that the longitudinally mounted transducer on the side of the web was probably generating some form of a shear or transverse wave, and not pure longitudinal waves.

In the above plot, small features on the leading and trailing edges of the burst that last about 50 milliseconds, are believed to be caused by reflections off of an insulated joint a few hundred feet beyond the receiver.

### 3.4 TRANSMISSION ON THE TEST TRACK WITH A TRAIN

Tests were done to determine whether the system could operate in the presence of trains. The goal was to find out how close trains could be before the signal is overwhelmed by noise, and if filtering would be able to recover the signal. The equipment was set up as in the previous test, see Figure 9, and a 5-car train was run back and forth at different speeds. The signal is recoverable when 30 mph trains pass because they are relatively quiet; however, noise from 70 mph trains caused appreciable interference.

The transmitter was mounted at one end of the track and the receiver was in the middle, 1.3 miles away, where the train passed overhead at high speed. The transmitter was tuned to one of the peak frequencies, around 31 kHz, and then set to send a continuous string of 50% duty cycle two-second long beeps.

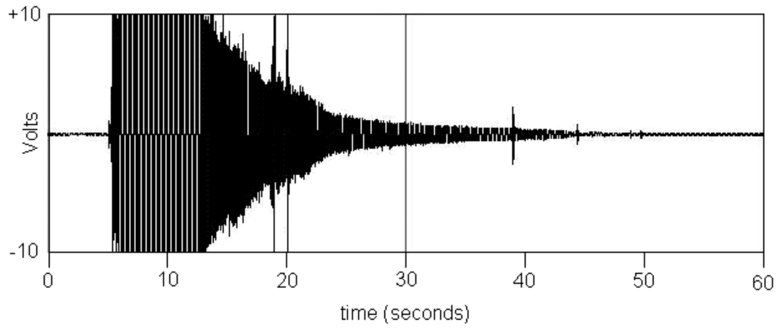



**Figure 12. Raw acoustic data showing a 70 mph train, and a 2 second long on-off modulated signal at a range of 1.3 miles.**

Figure 12 is a one minute long recording of the passage of a 70 mph train. The first 6 seconds are quiet because there is a switch a few hundred feet before the accelerometer, and the train isn't heard until it crosses the switch point. The train noise grows rapidly until it is directly over the receiver. At that time the analog to digital converter in the data acquisition system is saturating and some data is lost. The on-off signal is visible in the raw data in a high quality plot; however, the print quality of Figure 12 is not high enough to see it.

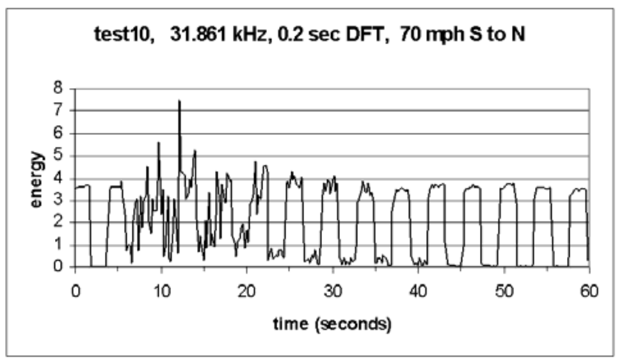



**Figure 13. A plot of the data recorded in Figure 12 after digital filtering. The on-off signal is clearly visible except when the train is directly over the accelerometer between 6 and 20 seconds.**

A narrow band FIR filter was used to extract the signal. Figure 13 shows the same signal after filtering. The signal was easily recovered except when the train was within a few of hundred feet of the receiver, even though the train noise is on the order of 1000 times larger than the signal. On runs where the train speed was 35 mph the signal is fully recovered.

It is expected that a few improvements will allow the signal to be recovered even when the train is directly overhead. These improvements include the use of a passive filter between the transducer and the sampler, to remove out of band train noise, and the use of an analog to digital converter with more dynamic range, 16 bits instead of 12. During this test the power wasn't measured, but previous tests indicate that the electrical power going into the transducer was probably between 10 and 50 Watts. Increasing the transmit power is another option. The joint between the transducer mounting block and the rail operates in shear, and squeals audibly at high power levels, indicating it is probably slipping and not coupling well. Improving the coupling will increase the acoustic energy delivered to the rail, and allow the transducer to operate at a higher power level. In this test the mounting block is bolted through a hole in the web, and the aluminum block touches the rail in only two places. One possible solution would be to conform the mounting block to the curve of the rail, and then bolt and glue the mounting block to the web.

If it is possible to make the underlying acoustic communication system unaffected by passing trains, then the development of a data communication system will be easy. However, a robust communication system can still be built even if trains occasionally make communication impossible. Such a system will require a network communication scheme where data is resent when packets are lost.

# 4.0 TASKS DONE FOR THE IDEA PROJECT

The work done for the IDEA project was broken down into two stages. In the first stage an algorithm was to be developed that could analyze echoes from breaks and flaws, and compute the range. In the second stage a prototype and a variable frequency transducer were developed. Stage one and two were started concurrently in order to better utilize the skills of the two researchers on the project. It was believed that the break detection algorithm could be added to the prototype when it was completed. The echo ranging algorithm took longer than anticipated and was not completed. Also, testing with the hardware and software developed for the prototype system indicated that environmental problems exist that should be addressed before completing the echo ranging algorithm.

## 4.1 STAGE 1

In this stage we were to develop an algorithm that uses echoes to determine the distance to a break, and the development of an algorithm that can discriminate between an echo from a distant break from noise and reflections caused by known track features.

The first step was to record signal profiles of reflected signals from rail breaks. Initial testing used cleanly cut rail ends as simulated vertical breaks, the primary goal of this research. Testing was also done across field welds, with joint bars, and in the lab using plastic rail.

These experiments demonstrated that we are able to generate acoustic signals that are able to propagate reasonable distances, and that a clean cut will cause a strong reflection. The next portion of work was directed at devising a way to automate the echo ranging process. The primary difficulty is tuning the frequency of the transmitter to one of the resonance peaks of the transducer/rail system. Off-the-shelf piezoelectric transducers that were used for the prototype are very peaky, and the combination of the transducer and rail must be tuned very precisely to obtain the maximum range.

Searching for the optimal frequencies is easy when the transmitter and receiver are located far from each other and there are no echoes. A slow frequency sweep can be sent and the received spectrum can be computed using a Fourier transform. The best frequency shows up as a peak in the spectrum. The difficult part of this scheme is communicating the best frequency from the receiving node back to the transmitting node.

When only one node is searching for the optimal frequency the problem is more difficult. If the node had good communication with the next node down the line just before the rail broke, it can be assumed that the best frequency to use will not change too much. Therefore, a good frequency to use would be the last one used for normal communication. The change in frequency due to the release in tension will probably be small, because the stress is released on only the last couple of hundred feet. Even if this technique is used, in order to take the best possible range measurement the frequency will probably need to be fine tuned.

The final robust design will need to be able to find the optimal frequency even if there wasn't communication between the nodes before the break occurred, or if the change in frequency is great. The technique that was implemented used a simple exhaustive search.

### *4.1.1 Echo Testing on Free Rail*

The first implementation of this algorithm was implemented in the lab using a 32' x 6" x 1/2" piece of Lexan plastic to simulate a length of rail. The speed of sound in plastic is less than half that of steel and the attenuation is much greater. The attenuation increases rapidly with frequency necessitating the use of very low frequencies, between 2 to 10 kHz. The peak frequency was 2.4 kHz. Even though this system is quite different from steel rail it aided in the development of algorithms that allow the computer to automatically tune the transmit frequency. The burst was computed, sent to a high speed DAC and then the piezo transducer, and then the reflection is recorded using an accelerometer and high speed ADC. The burst was composed of a small number of cycles, usually, from 5 to 50. The use of a low number of cycles is required to achieve good distance resolution when using a long wavelength. The rise and fall times of the burst were softened by applying a Hanning window envelope. The smooth envelope ensured that the acoustic energy generated is spectrally pure, allowing the frequency to be controlled with a great deal of precision. The system could ping the rail, change the frequency, and ping again a few times per second. In this way the echo strength as a function of frequency was plotted. As the program ran it pinged at a slightly higher frequency every shot, and by looking at the echoes it was possible to see what frequencies had the lowest attenuation. An interesting feature was seeing echoes from glue joints within the rail.

This program displayed the acoustic return and then used a simple threshold to compute a range to the end of the rail. However, we have not completed an automatic routine to interpret the echo data and compute a reliable range to the end of the rail in an environment with multiple echoes and other sources of noise.

A version of this program was used to record the echoes in an 80 foot long piece of 119 lb/yd rail. The result is shown in the form of a spectrogram shown in Figure 14. The transmitter was an NTK DA44525-46 transducer bolted to a mount that was glued directly to the end of the rail. An accelerometer was glued to the other end.

The spectrogram covers the frequency range from 28 kHz to 37 kHz along the vertical axis, and displays 30 milliseconds of each recording on the horizontal axis. The vertical white feature at 5 ms shows the first pass of the acoustic signal, and the second vertical feature roughly 18 milliseconds to the right is the second pass after traveling 160 feet. The data is normalized such that the amplitude of the first beep is always one, allowing the measurement of effects due to the rail and not of the transmitter.

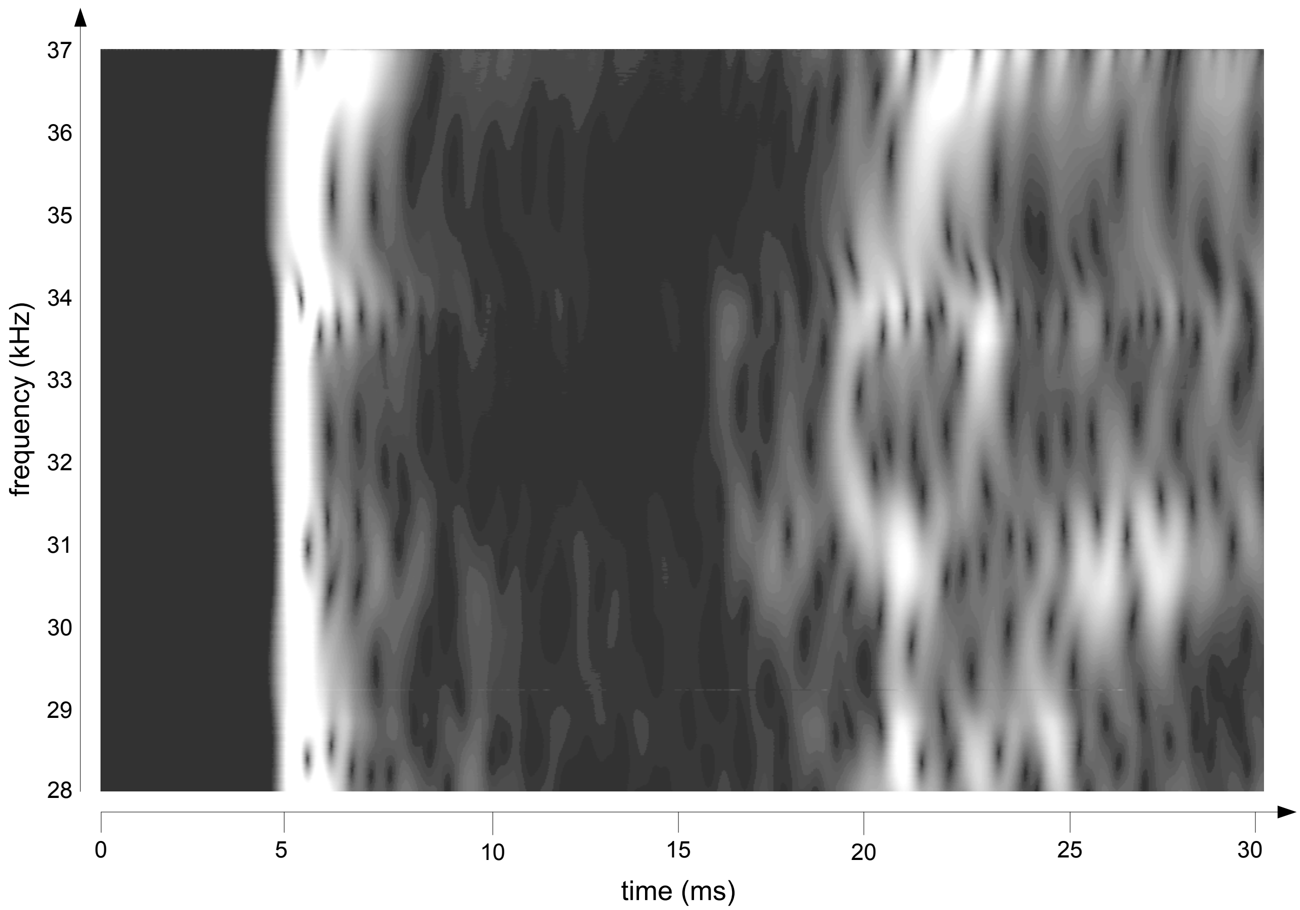



**Figure 14. Spectrogram of longitudinal echoes in 80 foot long segment of rail.**

The transmitter was screwed to an aluminum block that was glued with epoxy to the end of the rail. Based on the wave speed it appears that a longitudinal wave was not excited. Figure 15 is a plot of the speed as a function of frequency, which is measured from the first peak to the second. The average speed seems to be around 8600 feet per second. In previous tests, waves that traveled a long distance in free rail had nearly double the speed, around 17,600 feet per second. Figure 15 is a plot of speed as a function of frequency, and Figure 16 is a plot of attenuation This implies that it may be difficult to excite a longitudinal wave, or the rail was too short to excite a longitudinal wave.

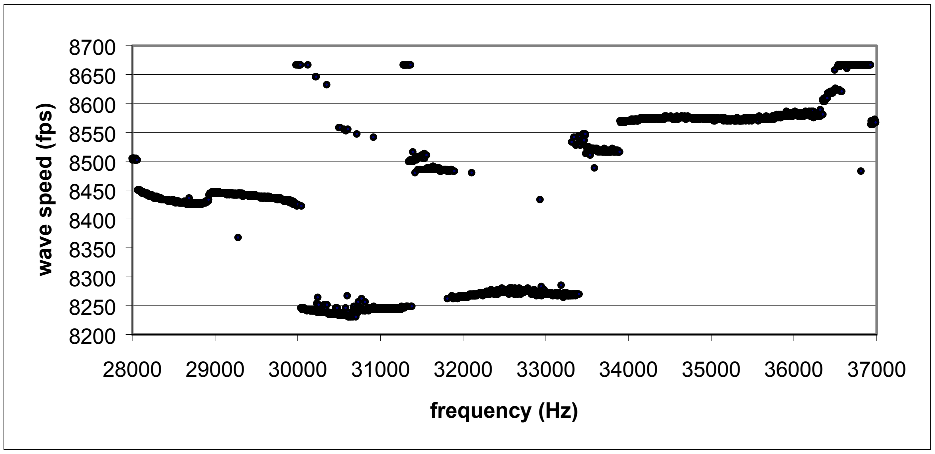



**Figure 15** **Echoes on an 80' length of rail, wave speed as a function of frequency. The speed implies the wave is transverse, because longitudinal wave travels around 17,000 fps.**

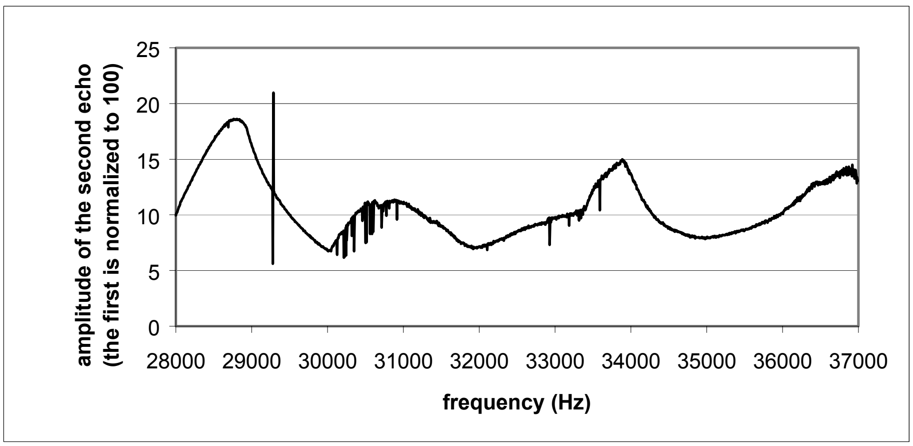



**Figure 16.** **Echoes on an 80' length of rail, plot of the response as a function of frequency.**

In this test the attenuation varied by a factor of two as seen in Figure 16. The peaks are on the order of 1 kHz wide, as opposed to tens of Hz as seen in long range tests. It is unknown what is causing this discrepancy.

### *4.1.2 Ranging Algorithm*

When the transmitter and receiver are co-located a continuous sweep cannot be used to find the optimal frequency and a different method must be used. If the break is close to the node, almost any frequency will travel far enough, and the range can be computed simply by measuring the time of flight to the break and back. However, if the break is far away the transmit frequency needs to be selected carefully, because the attenuation needs to be low enough to allow a round trip. If the break is 1.3 miles away, at 31 kHz the round trip time will be on the order of 1.4 seconds. The present system is not able to receive at the same time that it is transmitting. Therefore, if a sweep is used the sweep time cannot exceed the round trip time of 1.4 seconds. This may not be enough time to put appreciable energy into any particular resonance if the sweep range is broad.

If the project is continued an algorithm will be developed that will search for breaks in a robust manner. The difficulty is that a technique that is able to locate a break close to the transmitter will be different from one used to locate distant breaks. The final algorithm will probably follow these steps as it tries to range off of a newly detected break.

1. Look for close breaks. Ping at the last good frequency using a very narrow pulse, and listening for a short period of time. The recorded return will be filtered to remove noise, and then searched for a peak. This first attempt may be good for only a few hundred feet. At a range of 100 feet the echo will be back within 20

milliseconds, allowing only a couple of hundred cycles to be sent, and limiting the amount of energy transmitted.

2. Look for medium range breaks. If no echo was detected, then a longer burst will be sent, and the listening time extended. The processing will be the same as above. This process can be repeated a number of times, while listening for echoes up to a couple of thousand feet away.

3. If no echo was found, then it is assumed that the break is farther away than a few thousand feet and that the energy has decayed too much before completing the round trip. In that case it is necessary to find the optimal frequency and burst width that is able to travel long distances. Following are a few techniques that may do this.

The system we have implemented is a simple exhaustive search. An initial frequency is chosen, and a burst sent, recorded and then the data is filtered to remove noise. The initial frequency will be the last one used for communication. In order to decrease noise and increase the signal to noise ratio, it may be necessary to add the output of a number of shots. If no echo is detected the frequency is increased a few Hertz, and the process is repeated. If the frequency range to be scanned is +-50 Hz from the initial frequency with steps of 5 Hz, then 20 pings are required to cover the range. If a ping takes 5 seconds to send, receive, and process, then the search will take on the order of 2 minutes. If multiple pings are required per frequency, then it will take proportionally longer. Averaging together 10 pings per frequency step will require 20 minutes. This algorithm has been implemented in the lab on simulated plastic rail and it works, but has not been tested in a robust fashion on real rail.

Another technique to search for the optimal frequency when locating breaks at long distances may be to use quick sweeps, on the order of 100 Hz in width. The reflected energy will be recorded and then processed using an FFT. The frequency peak found in the spectrum will be used to search for the break with pings. Then a range can be computed using the time of flight.

All of these schemes require the node computer to evaluate an acoustic recording and automatically determine the distance to the break. Even if the transducer is operating at the peak frequency, and the burst width provides enough energy, and the recording captures a reflection of the echo, it may still be difficult to extract the break location from the data. Features on the rail may cause reflections, such as rail joints and switches. It may be difficult to differentiate such reflections from an actual break. A possible solution may be to occasionally record the normal reflections in a distance versus energy format, and then when a break occurs, compare that data with the new recording in order to differentiate the signal from the break from noise. In order to safely control trains the nodes on each side of the break will provide a range, and the location of the break will be accepted only if the sum add up to the length of rail between the nodes.

## 4.2 STAGE 2

Development of an optimize transducer and a 2-node prototype.

### *4.2.1 Broadband Transducer*

A wide band piezoelectric transducer was developed in order to search for the optimal frequencies and modes of vibration in the rail.

The goal is to be able to operate the system even when there are trains nearby. The architecture of the system software will be simpler if the nodes are able to communicate at all times, and are not interrupted by train noise. This requires operating the system in a way that gives a high signal-to-noise ratio. The spectrum of acoustic energy at the receiving node is very peaky as can be seen in Figure 9. In some cases the power received at a peak can be 100 times the power received just tens of Hertz away from the peak. Therefore, if the system can be operated at a resonance peak, then the signal to noise ratio can be very good, and operation in the presence of trains may be possible.

Our plan was to explore the rail's response using a broadband and adjustable transducer that is able to excite a wide range of frequencies, and then design a specialized transducer to excite only the optimal mode and frequency. In order to obtain good range the rail response needs to be well characterized, so an adjustable broadband transducer was built. Figure 16 is a diagram of the transducer, and Figure 17 is a picture. By adjusting the number of PZT disks, Belleville spring washers, and the end mass, the output spectrum can be manipulated.

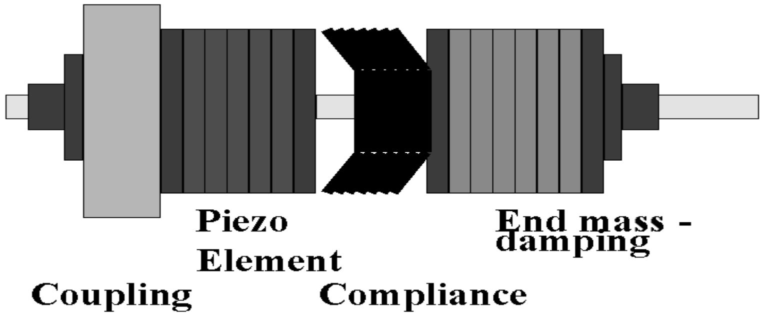



**Figure 17. Diagram of the adjustable frequency broadband piezoelectric transducer.**

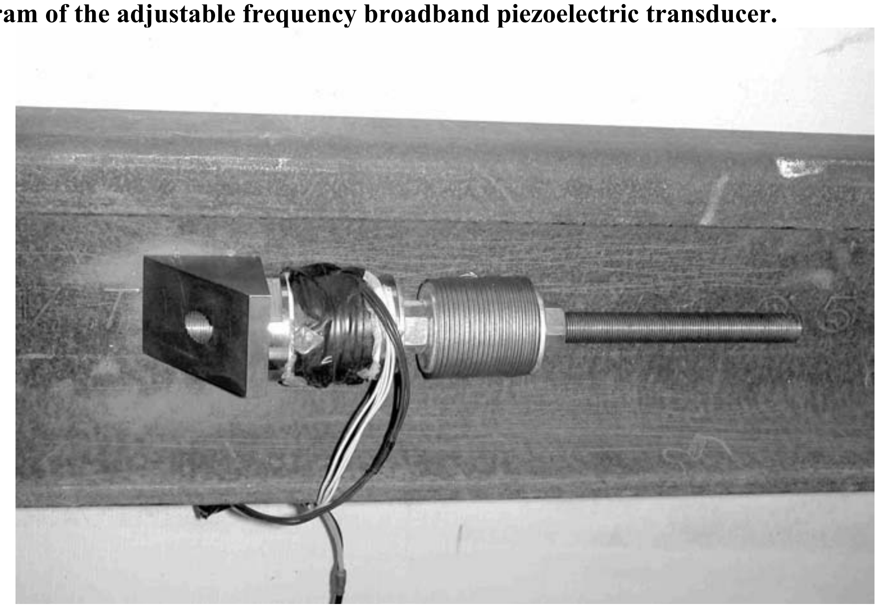


**Figure 18. Image of the broadband transducer.**

The broadband transducer was designed to excite a longitudinal mode of vibration. Experiments on the test track indicate that longitudinal waves were not produced. As a result, additional development of the system was discontinued.

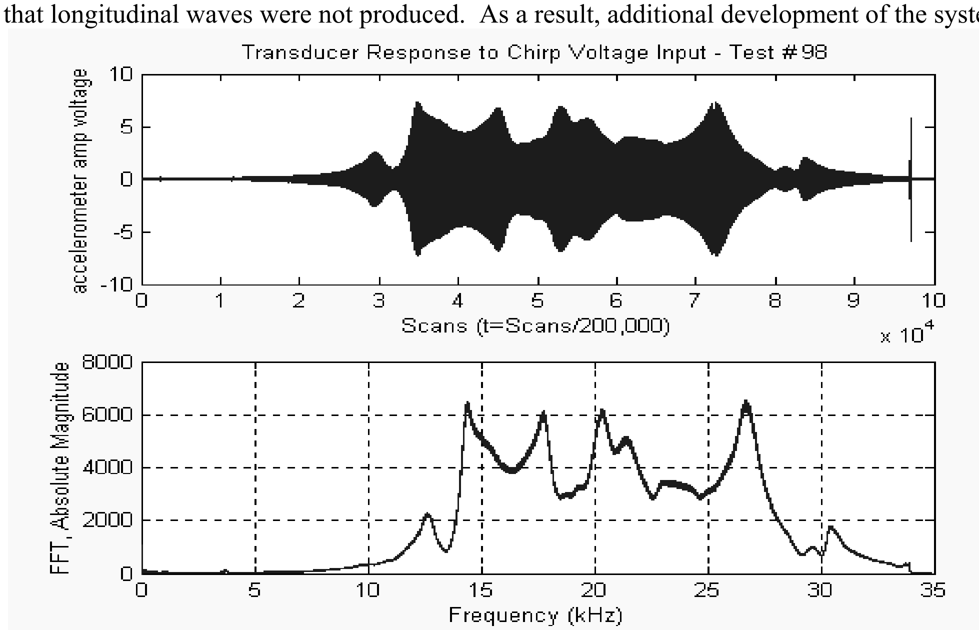



**Figure 19. Plots showing the output of the broadband transducer**.

*4.2.2 Self Tuning Communication System*

Work before the IDEA project attempted to operate the system at the transmitter's resonance peaks in order to obtain the maximum acoustic power. In the lab, the resonance peaks measured with an accelerometer correlated well with peaks in current consumption. If that occurred on installed rail, it would have been easy to build a controller that uses current consumption for feedback. Testing revealed that after traveling a long distance the peaks seen in the received spectrum didn't seem to correlate with transmitter current consumption, and the approach was abandoned. This implies that the feedback loop for controlling frequency needs to include the response of the transmitter, the rail, and the receiver. This requires the receiving node to be able to communicate information about the received acoustic power level back to the transmitting node.

In order to build a practical system the two nodes need to be able to find and track the optimal frequency. When both systems are first turned on, neither knows which frequencies will get through, and the question that needed to be answered was, could a simple and robust system be designed that could automatically find the best frequencies without requiring an external communication system. A prototype system was built to answer this question. Initially the hardware, algorithms, and software required for establishing communication were put together. Then, simple algorithms were used to send text data from one node to the other.

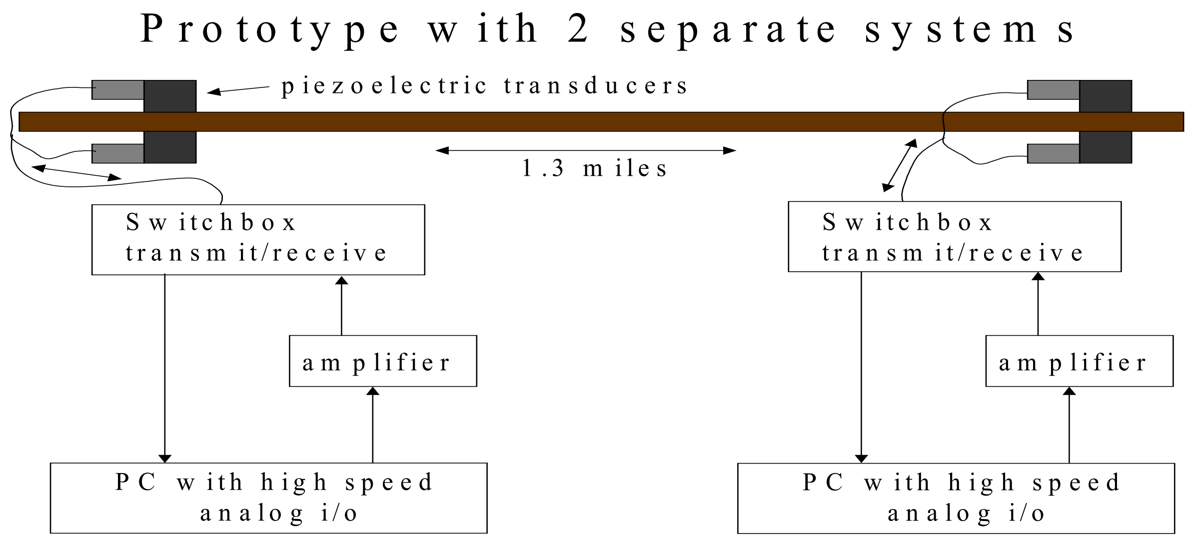



**Figure 20. Diagram of the 2 nodes used in the automatic tuning experiment.**

The prototype was composed of two identical systems or nodes. Each node has a laptop computer with a data acquisition card, signal switchbox enabling the same transducer to be used for transmitting and receiving, a high power amplifier for transmitting, and custom software. The piezoelectric transducer is used for both transmitting and receiving ultrasonic signals. The transducers used are similar to the ones used in sections 3.2 and 3.3, except they are designed for single frequency use. They are made by NTK, model E24528K, with a resonant frequency of 28 kHz, and the selection was based on availability and price. New transducers were purchased because the setup required 4 similar transducers. The E24528K transducers appeared to be nearly as good as the dual frequency DA44525-46 transducers on the 1.3 mile test track. The signal from the dual frequency transducer may have been slightly stronger, possibly due to the fact that it has twice the number of piezoelectric rings.

The technique that was implemented requires one node to be a master and the other a slave. The master initiates communication, and the slave follows as directed. The system starts out with the master sending a frequency sweep, for example a sweep from 25 kHz to 35 kHz in 5 seconds. The slave records the signal, computes a frequency spectrum, and searches for the most powerful peak. It then transmits a long pure tone at the peak frequency back to the master.

The hypothesis was that if one node transmits to the other at a specific frequency peak, then that frequency would work in reverse, at least reasonably well. Restated, it was believed that reasonable two-way communication would be possible at the peak frequency that is found by only one node. After initial communication was established, the nodes would be able to search for the absolute best frequency for each direction, even if the frequencies are not the same.

Initially a slow sweep is used to excite the rail. At the same time the receiving node records the sweep and computes a spectrum using a Fourier transform which is then searched for peaks. This technique is able to get within a few Hertz

of the absolute peak frequency. Then a fine-tuning routine was used to "zero in" on the peak. The fine-tuning routine that was implemented allows the master node to command the slave to increase or decrease it's transmit frequency. In this way the master can adjust the frequency of the slave a mile away, and tune it by measuring the received power. A simple fine tuning algorithm is able to increase the received power by a few percent.

### *4.2.3 Two Node Tuning Algorithm*

Figure 21 steps through the procedure that was developed to establish the initial communication. Upon startup, one node is defined to be the master, i.e. the node that initiates communication, and the other is the slave, which follows. At that time they are both are free running, i.e. their actions are not synchronized in time.

Step 1. The master sends a slow sweep which lasts 5 seconds, and then listens for 5 seconds. This cycle is repeated until the slave communicates back to the master.

Step 2. The acoustic signal travels down the rail, which acts like a filter passing only certain frequencies. The signal seen at the receiving node is a peaky spectrum (similar to FIGURE 9) that repeats every 10 seconds.

Step 3. The slave records for 10 seconds, ensuring that it records enough data to capture at least one entire sweep. Note that the 2 nodes are not synchronized, meaning that the slave may record the last 2 seconds of the sweep, 5 seconds of silence, and then the first 3 seconds of the next sweep. It will then search through the data looking for the peak frequency. The technique that was implemented searches for a peak in the amplitude of the recorded signal, and then computes an FFT of a small portion of the data. This worked for the test case because the size of the signal received at a range of 1.3 miles was over two times the amplitude of the noise. At greater ranges where the signal is down in the noise the FFT should be computed over the entire 10 second recording. The process of recording and searching is repeated indefinitely until the same frequency is found in a few recording cycles. This is to avoid coming to the conclusion that system noise is a signal from the master.

Step 4. After the slave finds the peak frequency it changes modes and attempts to communicate the frequency that it found to the master. It sends 5 one second long beeps at the peak frequency to the master. This is long enough to ensure that at least one of the beeps lies clearly within the master's 5 second long recording window.

Step 5. The master is still in the sweep-listen loop described in step 1. The recording period is used to detect the one second long beeps coming from the slave that are communicating the desired frequency to use. In our test case the signal amplitude was over twice the size of the noise, allowing a simple search algorithm to be used. A search for the location in the record of the amplitude peak was used, and then an FFT was used to obtain the frequency. Then an FIR filter was used over the entire 5 second recording, and a search was made for one second long beeps. The detection of a beep implies that both nodes know the frequency to use for communication. The next step is for the master to tell the slave to stop sending the beeps. The slave's cycle time in step 4 is 20 seconds, so the master sends 20 seconds of one second long beeps in order to make sure at least one is received during the slave's recording window. The slave processes its data through an FIR filter, and if a one second beep is detected it will stop transmitting. At this time both nodes have the best frequency. After the master sends its 20 seconds of beeps, it listens for 20 seconds. If no beeps are detected in those 20 seconds, then the master assumes that the slave has heard the acknowledgement.

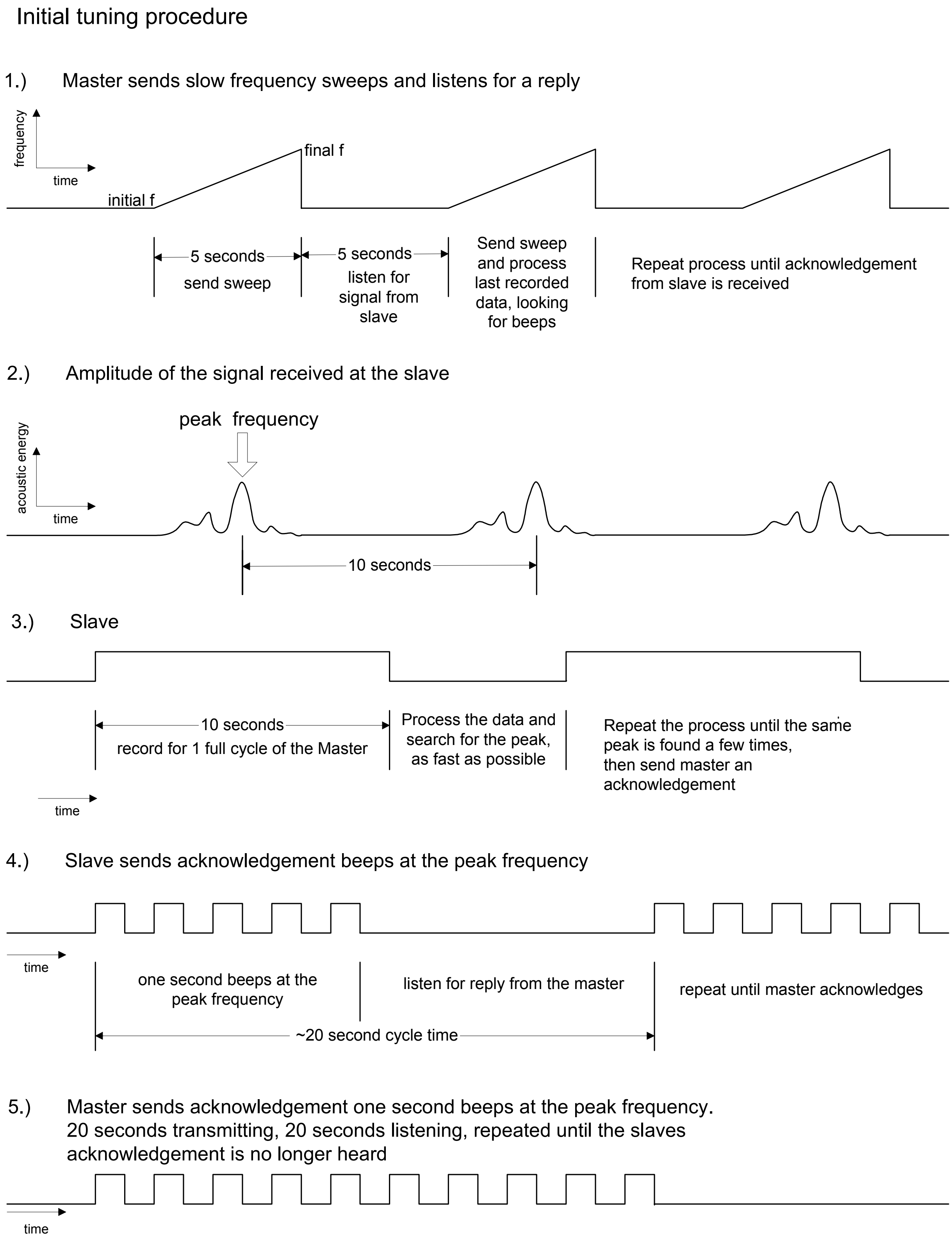



**Figure 21. Diagram showing the frequency tuning routine.**

The software controlling the nodes was written in C, using the National Instruments Labwindows development environment. A graphical user interface was put together to allow a human operator to control the various components.

In a manual fashion the important functions of the system were demonstrated, the initial wide range frequency scan, fine-tuning, and data transmission. The system operated properly even with simplifications that were included in order to get Windows to operate in real time. After the initial automatic tuning procedure, data was sent. There was no attempt to achieve a high data rate, but using a very simple protocol, data was sent at about 1.5 seconds per bit. The low data rate was due to difficulties in making windows operate in real-time. One bit per second should be easy to achieve with no significant changes other than better real-time software. The upper limit with off the shelf cleaning transducers is probably on the order of 10 bits per second due to their high Q.

Testing has proven that off-the-shelf cleaning transducers can be used for bi-directional communication, and that a frequency that is good from one node to the other will also operate well going in the other direction. In most cases the strongest signal in each direction was obtained using the exact same frequency.

As the temperature changes the peak frequency will change, and the system needs to be able to track the changes. After the initial tuning, communication between the nodes will be composed of packets of binary data. Using the master slave analogy, the master will send a data packet to the slave, and as the slave decodes the data it will compute the signal strength. The slave will then send an acknowledgement back to the master saying “message received” along with a one bit message indicating the frequency shift, for example plus or minus one half of a Hz. Using this scheme the slave will effectively be dithering the masters transmit frequency about the peak frequency. An important feature of this system is the lack of a need for stable clocks in any of the nodes. All frequency changes are relative from node to node, and the system is able to follow changes anywhere in the system, whether they are due to the rail tension, the heating of the transducers, or drift in the computer’s clocks.

At a range of 1.3 miles the raw signal amplitude is on the order of 4 times the noise. This occurred using a few tens of watts of transmitter power. Unfortunately the system is not able to operate when high-speed trains are directly upon the receiver because the signal to noise ratio is a little low. More transmit power may allow continuous operation that is unaffected by train traffic. However, if the need to operate when trains are close is relaxed, then the range can be increased. It should be possible to go a few miles with the signal decaying somewhat down into the noise. Such a test would have to be performed to determine the maximum range that can be obtained.

## 5.0 ADDITIONAL TESTING

### 5.1 ENVIRONMENTAL TESTING

In the proposed system each pair of nodes would track the optimal frequency by changing the transmit frequency a small amount every time a data packet is exchanged, effectively dithering about the peak. It is important that the tracking algorithm not get lost if the frequency changes more rapidly than is unexpected. This requires detailed knowledge about how the frequency spectrum changes as the temperature changes. Up to this point experiments were run at discrete times so it was not possible to discern how the spectrum changes over time. It is important to know whether a single peak moves smoothly as the tension changes, or if it shrinks as a nearby peaks grow. Such knowledge influences the design of the tracking algorithm. An experiment was run in order to characterize spectral changes over time.

The hardware and software tools developed were modified to record the rail's response to environmental changes, specifically the diurnal variation in temperature. The rail was excited at one end of the test track with a slow sweep and the signal was recorded at the other end. From the data a spectrum was computed and saved to disk. The rail and air temperature was also recorded. This process was repeated every 2.5 minutes for 5 days; over 4300 spectrums were recorded. Each spectrum recorded the response from 25 kHz to 35 kHz with a resolution of 1 Hertz.

The equipment setup was the same as that used in section 3.3, with the addition of the ability for the computer to trigger the sweep generator. The transmitter was a dual frequency cleaning transducer NTK model DA44525-46 mounted in the longitudinal direction. It was chosen for its ability to excite a relatively wide range of frequencies in a manner similar to the proposed final system. The transducer was driven by an analog function generator that produced a sweep one minute in duration. The signal was received with an accelerometer, Endevco model 7259a-100 with a 60 kHz cutoff.

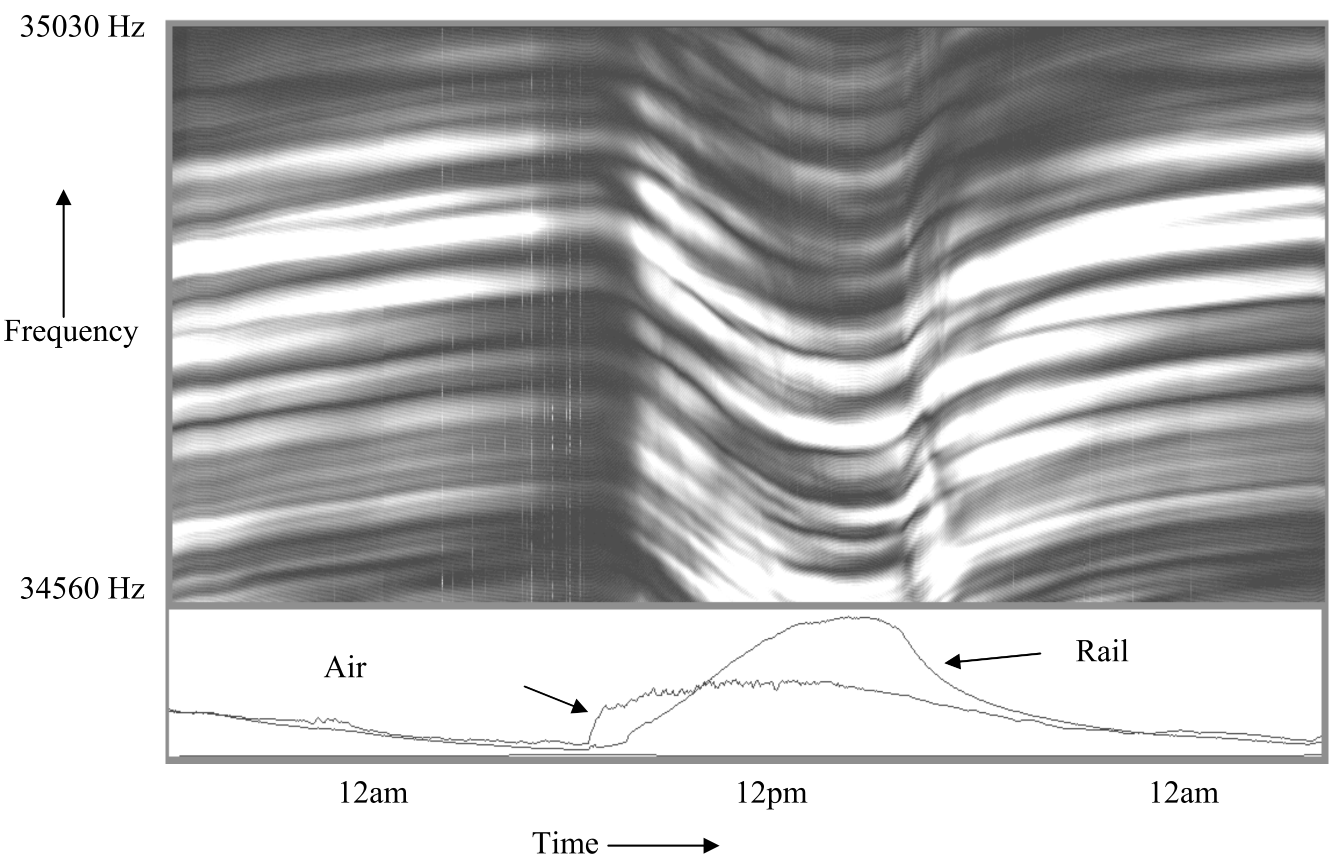



**Figure 22. Spectrogram showing the response of the rail to day/night temperature variations. The rail temperature ranged from 37 F to 94 F. The optimal frequency shifted 100 Hz.**

Figure 22 is a small portion of the spectrogram covering 470 Hz for a period of one full day. Light areas indicate frequencies where a lot of acoustic energy was received, and dark areas represent little energy. On this day the rail

temperature experienced a 57 degree change, from degrees 37 F to 94 F. The optimal frequency decreases as the temperature increases. During this time period the change in the optimal frequency was around 100 Hertz. A portion of the spectrogram was plotted versus temperature (not shown) instead of time. It shows that the frequency change is linear with respect to temperature.

A similar experiment was performed in the lab to see if the observed change in frequency was due to the transducer changing as the temperature changes, or if it was due to the rail tension. The transducer was bolted to a six-foot long section of rail and heated through a temperature range of 60 degrees F, as spectrums were recorded. The spectrogram showed a decrease of around 9 Hz as the transducer was heated. This implies that the large frequency change observed in Figure 22 is due almost entirely to changes in the tension of the rail.

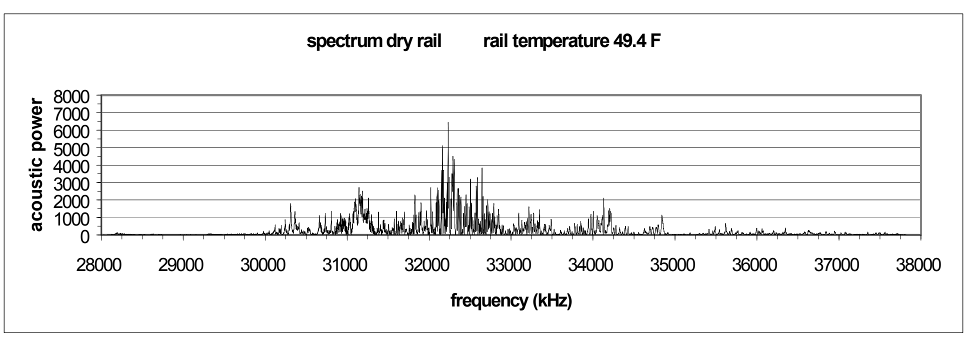
The above spectrogram is included because it clearly shows the frequency change over time; however, it does not show a portion of the spectrum with very strong resonance. In areas of strong resonance the rail response appears to be broken down into a few broad regions, whose width is on the order of 200 Hz. Each of those regions is composed of 10 to 15 very narrow peaks, and the spacing between the peaks is on the order of 10 to 15 Hz. The broad (~200 Hz wide) regions change in frequency as the temperature changes, however, as the temperature changes the narrow peaks pull in frequency 5 to 10 Hz and then die off as a neighboring peak grows. The frequency response changes most rapidly soon after sunrise when the rail starts heating. At that time a particular resonance peak will last for around a half-hour before dying off and being replaced by a neighboring peak. During the night a particular peak may last 8 hours. This gives an idea how frequently the nodes will need to search for optimal frequencies. The narrowness of the individual peaks is probably due to different modes of oscillation in the transducer, and the broad regions are due to the rail. However, in the lab on a 6 foot section of rail, the peaks are far broader, implying that some sort of interaction between the transducer and a mile of rail is causing the peaks to get very narrow.

On some days the rail temperature went from 58 F to nearly 133 F a change of 75 F. During this transition the rail may have transitioned from being in tension to compression. There appears to be no obvious change in the spectrum when this occurred.

It was hoped that the peaks would move smoothly as the temperature changed, because a control system able to track the peaks would be easy to implement. Instead a more rigorous peak tracking algorithm will be needed. A possible scheme is to monitor the received power of every transmission. When the power has decayed to some pre-determined threshold value the system would perform a frequency sweep and locate the present strongest peak. During normal operation the sweep will be easy to implement because there will always be digital communication between the nodes using the former frequency peak. In other words, a possible algorithm would have the master send a binary message saying it will be sending a sweep, and then send the analog sweep. The slave will start recording at precisely the correct moment and when done it will compute an FFT on the data, and find the new peak frequency. It will then send a message back to the master acknowledging reception of the sweep at the former peak frequency, and then a long beep at the new peak frequency. The master will then record the incoming beep and compute its frequency.

## 5.2 SIGNAL ATTENUATION DUE TO RAIN

A decrease in signal strength was observed in the 5 day spectrogram that seemed to correlate with rainfall. A follow up experiment was performed in order to understand the response to rain. The experiment in section 5.1 was repeated with the addition of a rain gauge. The results indicate a clear decrease in the received signal during the rain storm. The rainfall gauge was not calibrated; however, the precipitation rate was on the order of 0.25 inches per hour.



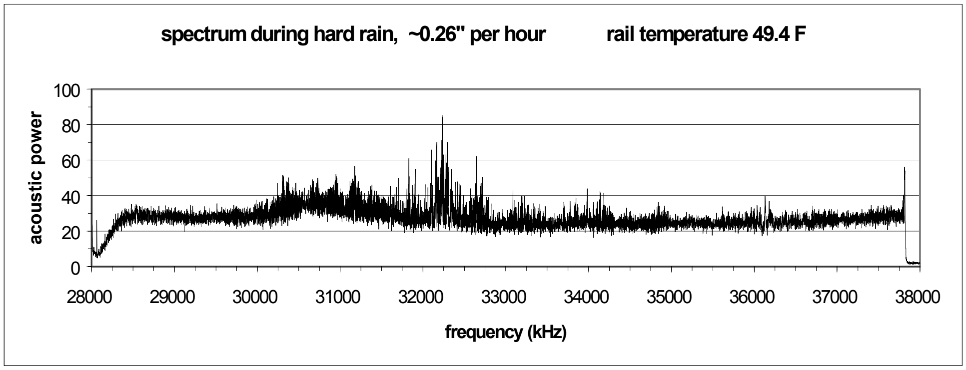



**Figure 23. Spectrums recorded before, during, and after a heavy rain.**

The first spectrum was taken one day before the rain, when the rail was dry, and the second was taken during a rainstorm. The dry rail spectrum was chosen for comparison because the rail temperature was identical to the wet rail case, which makes the peaks line up. Both of these spectrums were acquired with the same amplifier gain. (Note: The vertical scales in the above plots are different.)

The acoustic signal is still detectable when it is raining. In both of the above plots the peak frequency is 32,233 Hz, however when it was raining the amplitude was decreased to about 1.5% of the dry rail value. The signal is still many times the background noise level, as can be seen in the above plot. The sweep went up to 37,833 Hz so the level of the power above that is representative of the noise. Around 38 kHz the value of the noise is around 2. When it was raining the signal amplitude was still 40 times the amplitude of the noise.

The results of this experiment indicate that there is probably high enough signal level to communicate from node to node when it is raining. However, the data rate may be lower, the interference from trains will be greater, and the ability to echo locate off of distant breaks will be more difficult. How much this would impact operation of the system is presently unknown.

## 5.3 EXPERIMENT TO EXCITE LONGITUDINAL WAVES IN FIXED RAIL

Prior to the IDEA project, experiments on free rail showed that longitudinal waves have less attenuation than transverse waves. As part of the IDEA project, an experiment was set up to see if longitudinal waves could be generated in rail that is tied down. It was hoped that longitudinal waves would travel farther and not be attenuated by rain as much as transverse waves.

The experiment is difficult because it requires the use of a section of rail that is tied down with both ends exposed, a situation that does not normally occur in the BART system. For this experiment a track in the Hayward train storage yard was taken out of service for a day. A maintenance crew disassembled an insulated joint at one end, cut the rail at the other, and pushed the exposed ends aside giving access to the ends. The rail in this test weighed 90 lb/yd as opposed to BART mainline rail, which is 119 lb/yd. It was on ballast and tied down to concrete ties every 2 feet. A piezoelectric transmitter was glued with epoxy to the end of the rail on the web, and an accelerometer was glued to the other end on the web, 720 feet away. The transducer configuration was the same as that done for testing on the free rail. The procedure for taking data was similar to that of the experiment done in section 4.1, which produced a spectrogram of the response of a 78' long piece of 119 lb/yd rail.

A burst 1000 cycles in length was computed and sent to the transmit transducer; simultaneously one second of vibration data was recorded from an accelerometer. The recording was written to disk, then the frequency was increased by 2 Hz, and a new burst was computed and sent. This process was repeated 3000 times in order to cover a range of 6 kHz. This was used to produce a detailed map of the echo response from 28 kHz to 34 kHz. The data was filtered at the transmit frequency using a FIR filter, and the power plotted in the form of a spectrogram, as a function of time and frequency. The signal strength is given by the brightness; white when acoustic energy is present, black is quiet.

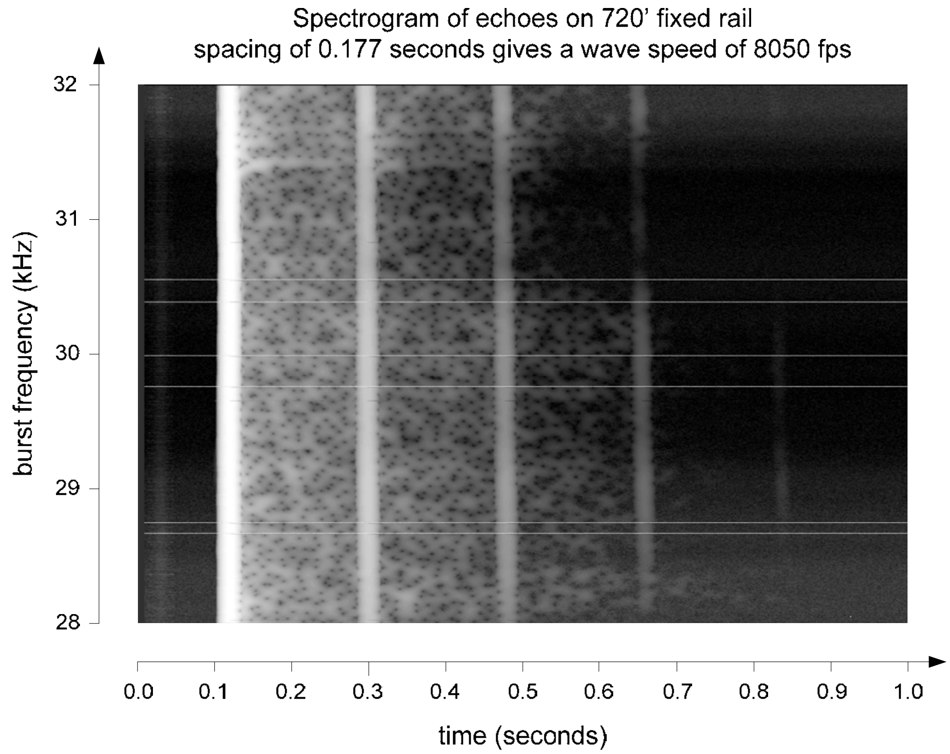



**Figure 24.** **Spectrogram of fixed rail, longitudinally excited.**

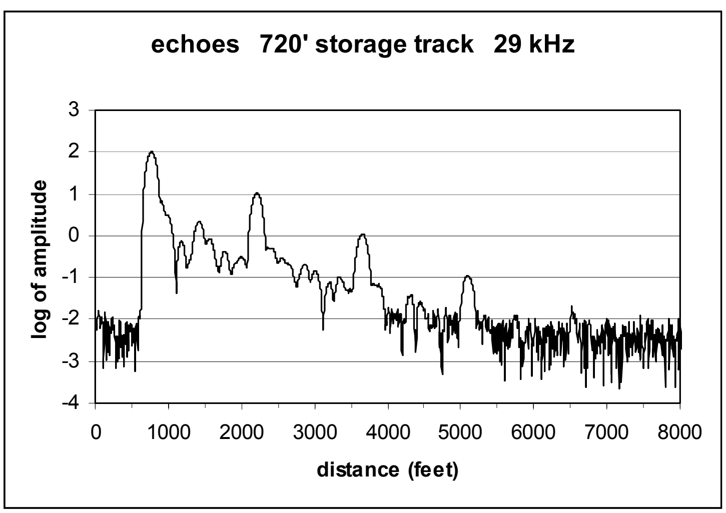



**Figure 25.** **Plot of the log of the amplitude of the 29 kHz recording from Figure 21.**

The vertical white bars in Figure 24 represent echoes. The data is normalized such that the brightness of the first echo in all of the recordings is always the same. In all recordings a large echo was received every 0.178 seconds. The distance traveled between echoes is 1440 feet, giving a wave speed of 8050 fps. This is on the order of the speed measured when a side mounted transducer was used, and just under half the speed of a longitudinal wave excited in free rail. The data recorded at 29 kHz (Figure 25) shows 5 echoes, representing a distance of 1.1 mile. The attenuation is calculated to be 74 dB/mile, which is 4.4 times the attenuation calculated for free rail. The broadband testing also implied that transverse waves have about 4 times the attenuation of longitudinal waves.

Longitudinal waves were not produced in this experiment, based on the low wave speed and high attenuation. The result was unexpected because it was assumed that a transmitter glued directly to the end of the rail would have the

highest probability of exciting longitudinal waves. Longitudinal waves were not produced in the 78’ free rail test in section 4.1 either. In both cases the results are puzzling. The spectral response seems very broad, on the order of 1 kHz, whereas the spectral response from the test track and 800 foot free rail tests were very peaky, with a bandwidth on the order of 10 Hz. The differences in these test results are unexpected and thus far unexplained.

# 6.0 FUTURE WORK

If any further investigation and development of this concept is undertaken, the following tasks would have to be considered.

## 6.1 RAIL JOINTS

When rail is found to be defective, a short length is often removed and a new rail segment is installed with a pair of temporary rail joints. It is unknown how well acoustic energy will pass through such joints. If the signal is reduced, but still present, then the system can continue to operate at a reduced data rate. If the signal does not get through at all, then a means of getting around the joint will need to be developed. A preferred method would be to develop a passive device that can be added to a rail joint that will allow the signal to pass through. If that is not possible then a field-deployable node may be developed. Such a device would have a controller with wires to transducers on both sides of the pair of joints that acts to re-transmit signals around the break.

## 6.2 NETWORK DESIGN

In this phase of the project the basic communication ability of sending text was developed. Future work would be required to build that ability into a robust network. A full system would have to operate over distances of many miles, which may require many hops to get information about distant rail segments back to the train control room. The communication protocol would need to be developed. This includes handshaking, error detection, retransmission of packets, and what to do when a node fails.

## 6.3 FAULT TOLERANCE, AND SAFETY CONCEPT

This system has the ability to greatly disrupt train traffic if it fails; therefore fault tolerant design is required to allow the system to operate even when nodes have failed. Fault tolerance may be achieved by having the nodes spaced such that every node can communicate with two nodes on either side. In that way messages can still get through in the event of a single node failure.

The cost of the system will be lower if the nodes are not failsafe. One possible scheme for allowing non-failsafe hardware is to have the main controller send a special binary code, or token through the network. A different token is selected every cycle. As the token hops from node to node via the acoustic network, each node will modify it in a way that only that node is capable of. The modification may be some combination of bit shifts, or other binary operations. By the time the message has returned to the main controller in the train control room it will have been modified a number of times. The main controller knows how each node is supposed to have modified the code, and will calculate what the message will look like when it finally returns. If the received message is different from the predicted message, then the main controller will declare a fault, and the system will switch over to a different mode of operation in order to determine where the fault lies. A scheme of this sort will be able to detect both hardware and software faults anywhere in the system.

# 7.0 CONCLUSIONS

The results of this research indicate that there are a number of technical issues that need to be addressed before a practical ultrasonic broken rail detection system can be built.

Any further development of this project would require:

1. Transducer mounting systems that can efficiently generate longitudinal waves in rail.
2. Determination of the cause and solution of the increase in attenuation due to wet rail conditions.
3. Cost-effective techniques for transmitting through or around bolted rail joints, insulated rail joints, turnouts and other special trackwork.

4. Fast, efficient algorithms for discriminating between acoustic reflections caused by rail breaks, and those caused by normal discontinuities such as rail joints and switches.

An important finding of this research is that high-powered piezoelectric transducers can be used as receivers, and that the optimal frequencies between two nodes are the same in each direction. This finding allowed a prototype bi-directional acoustic communication system between two nodes to be constructed. The prototype sends text messages between nodes over a range of 1.3 miles, and can form the underlying hardware in an acoustic network. This ability eliminates the need for an external communication system for transmitting broken rail status information. If the nodes could be powered by solar panels, there would be no need for wayside cabling.

## 8.0 INVESTIGATORS

The primary contact for this project,
Ken Schwartz, Senior Research and Development Engineer, Bay Area Rapid Transit District.

Additional personnel,
John Evans, Senior Research and Development Engineer, Bay Area Rapid Transit District.
David Lehrer, Senior Research and Development Engineer, Bay Area Rapid Transit District.
Dr. Ali Modjtahdzadeh, Senior Research and Development Engineer, Bay Area Rapid Transit District.
Eugene Nishinaga, Manager of the Research and Development Department, Bay Area Rapid Transit District.
Richard Lu, Senior Research and Development Analyst, Bay Area Rapid Transit District
Dr. Wei-Yang Lu, consultant, Sandia National Lab

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