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CALIFORNIA PATH PROGRAM
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UNIVERSITY OF CALIFORNIA, BERKELEY

A System Review of Magnetic Sensing System for Ground Vehicle Control and Guidance

Ching-Yao Chan

**California PATH Research Report
UCB-ITS-PRR-2002-20**

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Final Report for MOU 396

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A System Review of Magnetic Sensing System for Ground Vehicle Control and Guidance

Ching-Yao Chan

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Abstract

This report contains research results of studies on magnetic marker systems that are used as a position reference system for Advanced Vehicle Control and Safety Systems. Effects of external objects and earth background fields on such systems are investigated with experimental measurements in Part I. The results show that signal processing techniques must be adopted in field applications to improve the accuracy and robustness of sensing algorithms. Part II of the report contains experimental results from an evaluation study of PATH marker system and 3M Tape system. The objective is to identify the characteristics of these two sensing systems and to offer a comparison of their distinct features. It was found that PATH marker systems offer a stronger signal-to-noise ratio and provides a more accurate position measurement.

Final Report for MOU396

PART I Effects of External Objects and Earth Fields on Magnetic marker Systems For Ground Vehicle Guidance and Control

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Executive Summary

In advanced vehicle control and safety systems, position measurement is an important link for the identification of vehicle locations, such as the lateral position within a lane. This report focuses on magnetic marker systems that are used as a position reference system. Effects of external objects and earth background fields on such systems are investigated with experimental measurements.

The magnetic fields from sample magnets are first measured to determine the characteristics of their patterns as the basis for detection and position identification. The effects of external objects, such as rebar or scrap metals on roadways, are then assessed with a selected list of potential objects. Tests are then conducted in a variety of infrastructure locations to observe the probable impacts from the earth fields. Observations from these data indicate that potential alteration or distortion of magnetic fields can be substantial from external objects and background field components. Therefore, the filtering of these external or background noises is a major task for signal processing.

It was found that for external objects near a marker:

- (1) Small external objects, such as those with sizes of hand tools, will impose negligible influences on the fields generated by the magnetic markers.
- (2) Large objects, such as those with a size of vehicle axle, will create considerable distortion of the magnetic fields from the markers. However, since such large objects constitute road hazards by their size alone, they will have to be removed for road maintenance reasons.
- (3) Objects with a size similar to reinforcement bars used in concrete structure, will present minimum effects if there is a single bar near the marker. If there are larger pieces of reinforcement elements or multiple re-bars, they can create significant effects. In those cases, a magnet marker with a stronger magnet will be preferred.

For earth magnetic fields, it was observed that

- (1) Variations in ambient magnetic fields in certain spots may be significant enough to distort magnetic field patterns generated by the markers.
- (2) Clear patterns of repetitive fluctuations are often associated with structural reinforcements in roadways and bridges.
- (3) Effects of ambient fields tend to be local and can usually be filtered with signal processing techniques or compensated by the use of stronger magnets.
- (4) Ambient data collection and verification after marker installation are required.

1.0 Background

In recent years, the California PATH program (Partners for Advanced Transit and Highways) has deployed the magnetic marker system in conjunction with its experimental vehicles in a number of international and national demonstrations [1,2,3,4]. In the positioning reference system demonstrated by PATH, magnetic markers with a size of 2-3 cm diameter and 10 cm long are installed just under the surface of roadway pavement. The magnetic fields generated by these markers are detected by magnetometers mounted under the bumpers of test vehicles.

In this report, the sensing concept is first illustrated in Section 2 by introducing the magnetic patterns produced by an exemplar marker. The effects of external objects and earth fields on the functioning of such systems are then examined in Section 3 and 4. Observations from these data indicate that potential alteration or distortion of magnetic fields can be substantial from external and background field components. Therefore, the filtering of these external or background noises is a major task for signal processing.

A considerable amount of measurements with external objects and earth fields was taken for this study. The exemplar data sets presented in Sections 3 and 4 are used to illustrate the observations. The remaining data were plotted and shown in separate files and attached as Appendices A and B.

2.0 Magnetic Patterns of Exemplar Markers

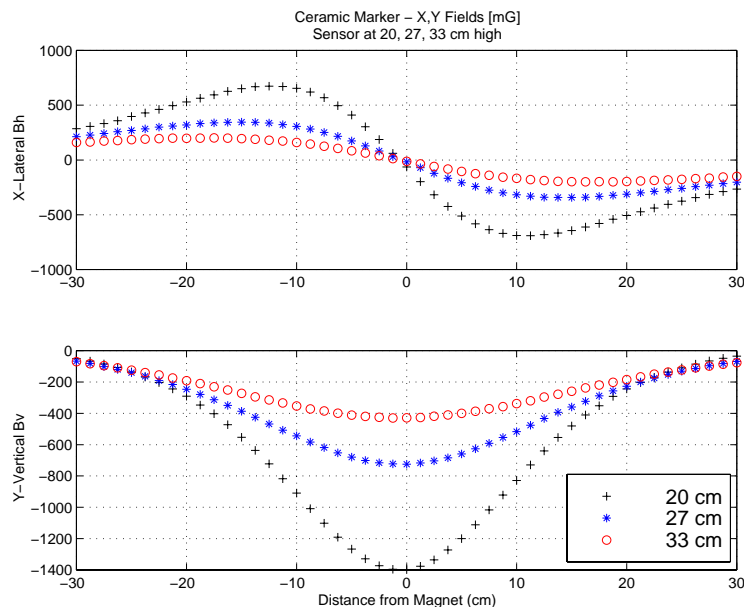


Figure 1. Lateral and Vertical Components of Magnetic Fields around a Sample Marker

In this section, the experimental data are presented for a comprehensive analysis of the magnetic fields. The data was collected from a static test on a bench table. The sample marker is made of ferrite (ceramic) material in a cylindrical shape with a diameter of 2.5 cm and a length of 10 cm. The long axis of the cylinder is placed perpendicular to the surface of the bench table. The

measurements took place with a magnetometer at several different heights from the surface of the table to acquire a representative map of the magnetic field.

Figure 1 shows the lateral and vertical fields generated by a sample marker at three different heights. The third axis is not shown since it is similar to the lateral direction, only in a different orientation. It should be noted that the magnetic field of the magnetic marker could be modeled as a cylindrical dipole. We use the experimental measurements for an actual representation.

In the three-dimensional space, the lateral field is opposite in sign and symmetric in magnitude on two sides of the marker. The lateral component rises from zero at the center of the marker and reaches its peak at a distance about 10-15 cm from the marker, then gradually weakens farther away from the marker. The vertical field is the strongest right at the top of the marker, and diminishes to zero at about 40 cm away from the marker. The longitudinal field makes a steep transition near the marker as it changes its sign. This steep transition becomes meaningful in interpreting the point at which a sensor passes through a marker location.

3.0 Effects of External Objects

Many different objects were tested, including steel blocks and plates of various sizes, a steel rebar, a vehicle wheel-hub cap, an aluminum bar, a bolt and nut combination, and a magnetized steel pipe. The magnetic marker tested was the same as the one shown in the Section 2. It was found that small size objects, such as a steel block of 2.5x6.5x7.5 cm or a rebar of 2.3 cm diameter, have limited effects on the field patterns of the exemplar magnet.

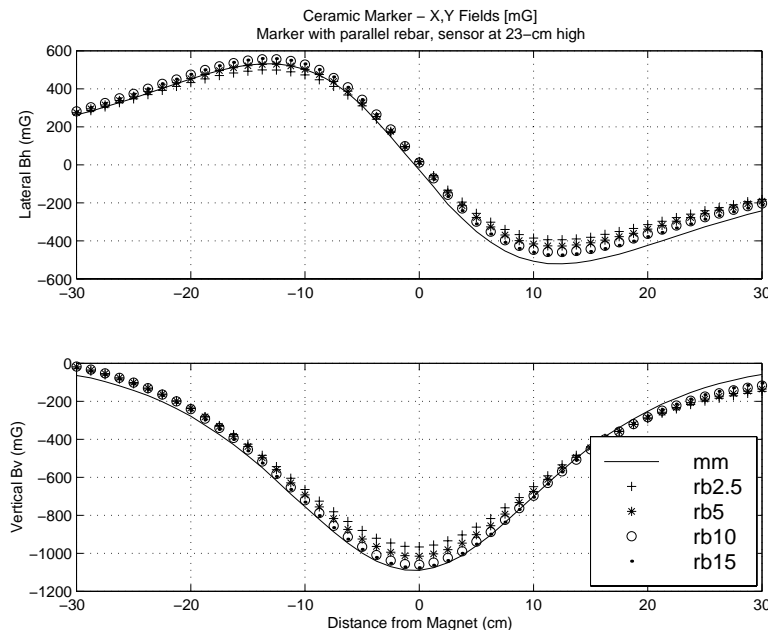


Figure 2. Magnetic Field Components with a Rebar and a magnetic Marker

Figure 2 shows the variation of lateral and vertical field components with a rebar, with a diameter of 1.6 cm and a length of 90 cm, placed at 2.5, 5, 10, and 15 cm offset from the

magnetic marker. The long axis of the rebar is oriented in a direction parallel to the longitudinal axis of measurement. It can be seen that the changes to the fields are only marginal. On the other hand, an object of considerable size, such as a steel plate of 1.3x15x90 cm, can result in significant alteration of the field strengths. Figure 3 depicts how the magnetic field strengths are reduced with the described plate placed at 9 and 15 cm from the magnet on either side. The numeric values in the legends of the plot indicate the offset distance of the centerline of the plate from the axis of measurement.

When a magnetically permeable object was placed near the magnet, the magnetic flux was naturally drawn to the object thus enhancing the strength in the vicinity of the object. Therefore, when the object is placed away from the magnet, the strength near the magnet will be reduced as seen in Figure 3.

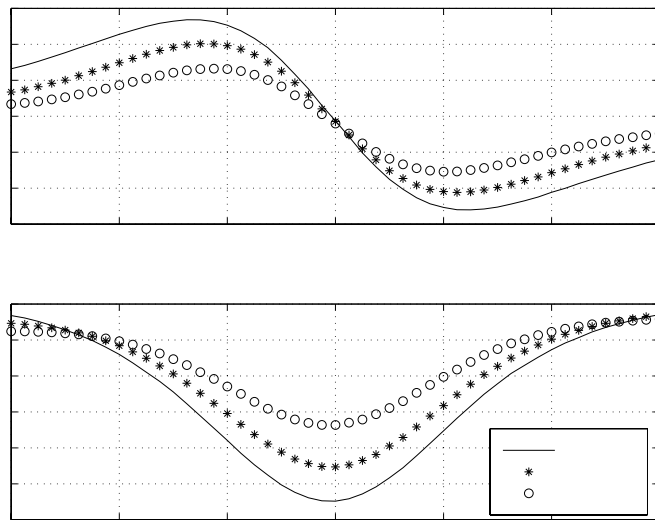


Figure 3. Magnetic Field Components with a Steel Plate and a magnetic Marker

Another tested object was a magnetized steel pipe. Figure 4 shows the data from the magnetic marker, the pipe, and their combination fields. The magnetic flux from the pipe is clearly shown when the pipe is reversed in direction. A magnetized object presents distortion or bias to the magnetic pattern and makes the detection more difficult, especially when the nature of the external object is unknown.

In summary, it is observed that small objects typically scattered on roadways have little impact on the overall system performance of the magnetic marker systems. There will certainly be situations when a single magnet is affected or blocked considerably by objects near its location; in this case, signal-processing algorithms should be able to “miss” one magnet while not causing a malfunction or breakdown of the operation. Moreover, if an object was large enough to affect a consecutive sequence of magnets, the roadway is likely obstructed so that the operation must be paused until the roadway is cleared out.

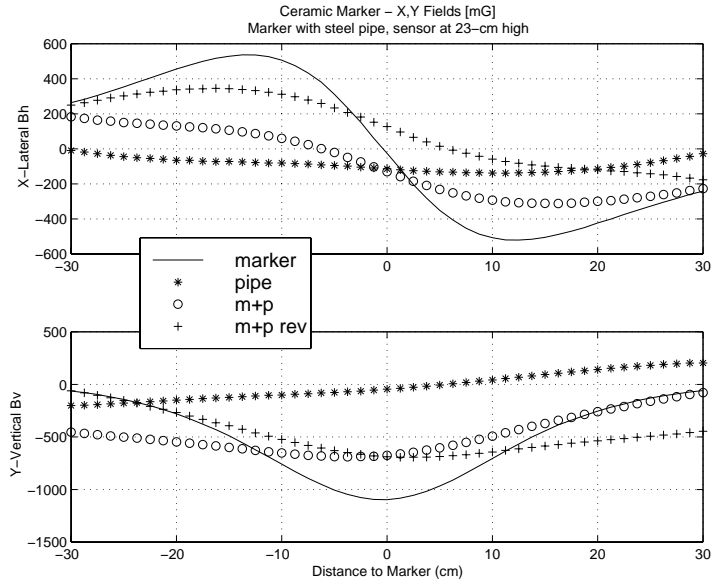


Figure 4. Magnetic Field Components with a magnetized Pipe and a magnetic Marker

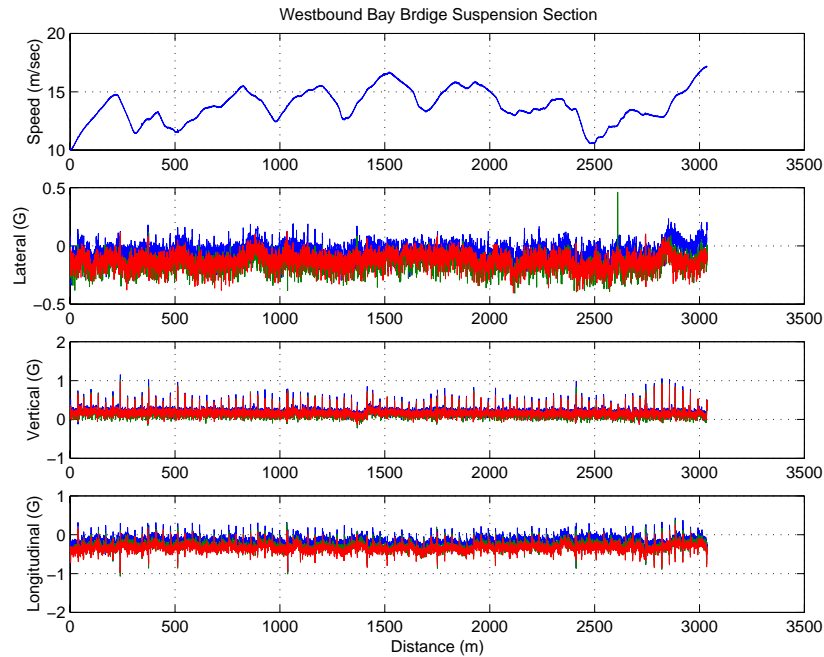


Figure 5. Ground Magnetic Fields in a Test Drive on the Bay Bridge in San Francisco, CA

4.0 Earth Magnetic Fields

The major concern in implementing a magnetic sensing system on roadways is the background earth fields in all areas. The earth field may be stable or varying, depending on the specific locations and the geological features. The phenomenon is further complicated by the roadway infrastructure, such as structural reinforcements. An experimental vehicle with associated sensor and data acquisition systems was used to acquire earth fields from a variety of locations. Three

sensors are mounted under the rear bumper of the test vehicle with a separation of 30 cm between them. The sensors are approximately 25 cm from the ground in a parked position.

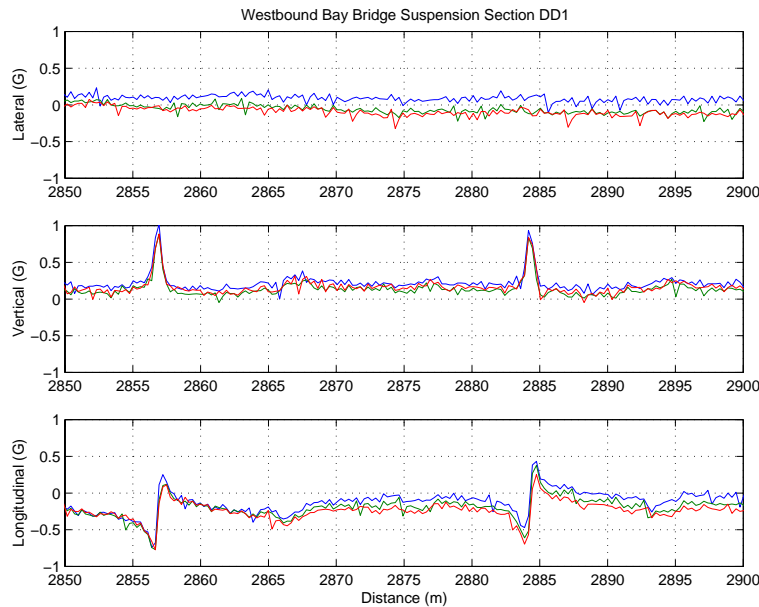


Figure 6. Ground Magnetic Fields in a Test Drive on the Bay Bridge (Portion of Figure 5)

Figure 5 depicts a sequence of data along a certain stretch on the Bay Bridge in San Francisco. The graph shows the vehicle speed and the three-axis components plotted against the traveled distance during the test. A “spiking” pattern is seen in the data set, especially in the vertical direction. Figure 6 shows a selected window of data from Figure 5 with details of the individual components. The vertical and longitudinal components of the ground magnetic fields possess an impulse type of patterns across the whole stretch of the bridge, which is likely to be associated with the structural members on the bridge. The pattern repeats at a spacing interval of just under 30 m.

Figure 7 shows a set of ground field data from a drive on Market Street in San Francisco, California. This is a stretch of roadway with rails on the surface for light-rail transit cars. It was found in these data sets that there are consistent fluctuations in the measurements with a few pronounced peaks and valleys, which are related to flat metal grids or ground covers found at those locations. The existence of rails or other magnetically permeable structures in the roadways can pose considerable problems for signal processing. Judging from the irregularity of data patterns in a number of data sets, it appears that a survey of the ground fields is essential for the identification of their characteristics and their effects on signal processing.

In summary, it was demonstrated by the sampled data sets that the ground or earth fields could produce variations of significant magnitude and irregular fluctuations. Certain repetitive patterns identified in infrastructure are probably associated with reinforcement elements. The verification of a candidate or installed track will be necessary to help understand the nature of background fields in specific locations.

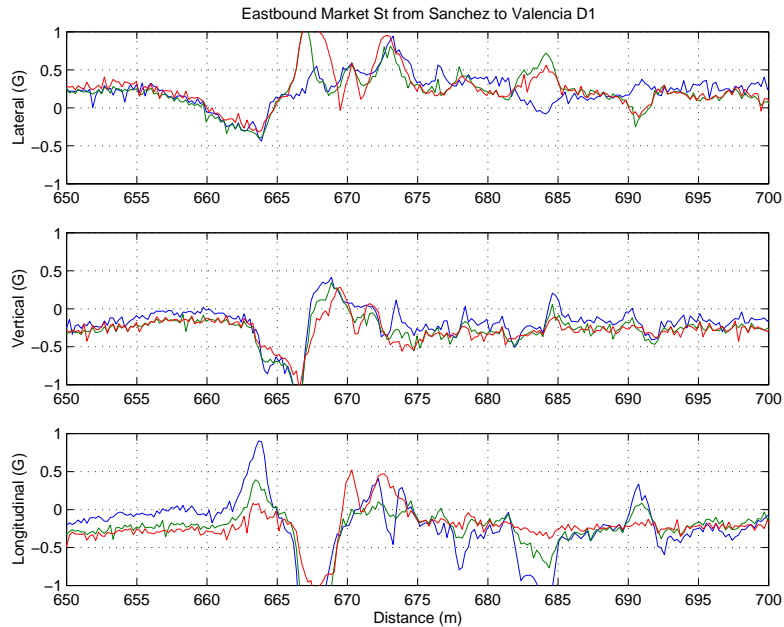


Figure 7. Ground Magnetic Fields in a Test Drive on Market Street in San Francisco, CA

5.0 Variations of Magnetic Field Measurements and Sensing Algorithms

In general, the signal processing for the described position measurement application involves two tasks: (1) the removal of background fields and noises, and (2) the mapping of processed signals to a position relative to the magnet.

There are several sources of measurement noise: earth magnetic field, AC-generated, and electrical fields. The largest source of external disturbances comes from the earth, as demonstrated in the previous section. The size of the disturbances varies with the coordinate axes of the sensor, which changes with the vehicle's attitude and orientation. A second source of noise comes from the alternating fields generated by various motors in the sensor's vicinity, such as alternator, compressor, pump, fan, and actuators. The knowledge of sensor installation plans and operating characteristics of nearby motors can help identify the nature of these noises. It is also possible to shield AC-generated disturbances by using materials with low magnetic reluctance. The other source of noise arises from electrical fields. They show up as fluctuations in the signals. A low-pass filter can be used to remove much of these noises.

The calculation of the earth field is not trivial. Since the earth field changes with the location as well as the vehicle orientation, it does require a real-time estimation. An error in the value of earth field can result in incorrect interpretation of the measured fields. Since sensing algorithms are based on the pattern of magnetic fields near the magnet, it is essential to take great caution in estimating the disturbances.

Several approaches have been suggested to rid the earth field off the measured signal, including (1) averaging, (2) peak-valley identification [5], and (3) differentials between dual sensor measurements [6]. The first method is based on an average of longitudinal data measurements

over a number of markers. This is based on the assumption that the longitudinal fields averaged from the magnets will approach zero, thus the remaining average represents the earth disturbance. While it is simple to implement, it is slow to respond to a quickly changing earth field. The second method utilizes the identification of valleys in the vertical field between magnets, thus reflecting the earth fields. An interpolation between the previous and the current valley values yields an updated earth field estimate. The last method uses two nearby sensors to eliminate the common background components by taking the differential between dual sensors. It is based on the assumption that the background fields are approximately the same at the two sensor locations.

Once the background disturbances are removed, the remaining portion of the signals represent the fields generated from the expected magnet. From these signals, the distance to the magnet must be determined. For example, the peak-mapping method looks for a peak since the strengths are strongest near or at the magnet. Once a peak is detected, the measured fields at that location are used to identify the distance to the marker. The transformation of the measured signals to the distance to the marker is based on a one-to-one mapping relationship.

Figure 8 shows contour maps of the measured field strengths at three different heights. The data points are produced with the data from Figure 1. Measurements from each height produce a unique oval contour without interfering with each other. These contours constitute a basis for position identification. The lines with labels of S1, S2, and S3 represent expected field values at different distances to the magnetic marker with the distances $S1 < S2 < S3$. In implementation, the contours as seen on the graph are tabulated in the signal-processing program. A pair of measured lateral and vertical field values near the detected peak can be compared to the tables and the position of the detected peak to the marker is estimated.

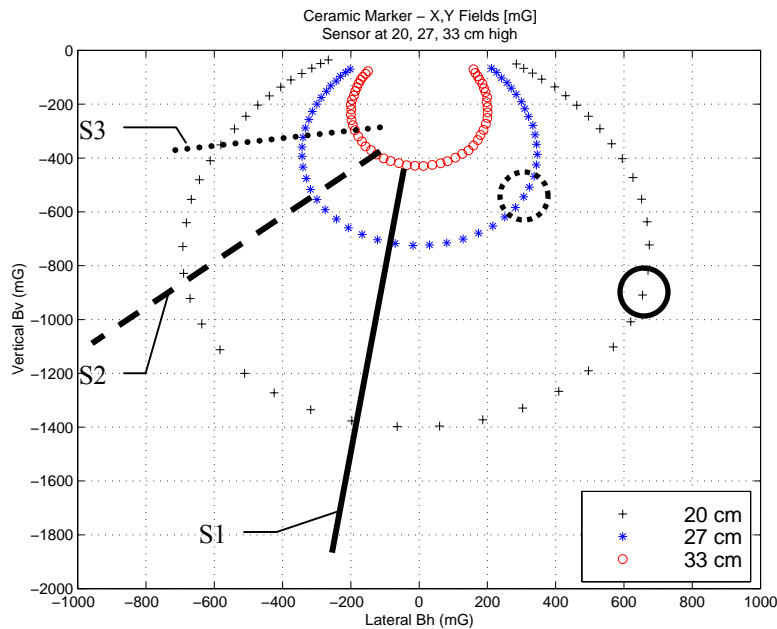


Figure 8. Contour Maps of Lateral and Vertical Magnetic Fields with Data in Figure 1

As can be seen from contour maps, the further away from the marker, the denser the data points are. Therefore, the accuracy of this approach deteriorates when the sensor is distant from the magnet. The robustness of the algorithms, when subject to measurement errors, can be determined by creating an error zone around each point on the contour, such as the two circles in the graph. When the measurement location is close to the marker, as indicated by the solid circle, errors in the lateral or vertical components lead to smaller deviations in estimated distance or height. A similar range of measurement errors at a farther location, as shown by the dashed circle, will result in much larger errors in position estimation.

6.0 CONCLUSION

In this report, we describe the data collection and observations for the magnetic marker system when external objects or ambient fields are present. The field patterns of sample magnetic markers were first measured to illustrate the basic characteristics of such systems. The effects of external objects and earth fields were then examined by conducting experiments with various objects and at different geographic locations. The observations from these experiments revealed that indeed there were potential complications that might be caused by external objects of considerable sizes and selected infrastructure locations. These effects must be handled carefully to ensure a robust sensing approach for correct identification of the target field patterns.

It was found that for external objects near a marker:

- (1) Small external objects, such as those with sizes of hand tools, will impose negligible influences on the fields generated by the magnetic markers.
- (2) Large objects, such as those with a size of vehicle axle, will create considerable distortion of the magnetic fields from the markers. However, since such large objects constitute road hazards by their size alone, they will have to be removed for road maintenance reasons.
- (3) Objects with a size similar to reinforcement bars used in concrete structure, will present minimum effects if there are a single bar near the marker. If there are larger pieces of reinforcement elements or multiple re-bars, they can create significant effects. In those cases, a magnet marker with a stronger magnet will be preferred.

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2. Patwardhan, S., Tan, H.-S. and Tomizuka, M., "Experimental Results of Tire Burst Controller for AHS," *IFAC Journal, Control Engineer Practice*, vol. 5, issue 11, Nov. 1997, pp. 1615-1622.
3. Tan, H.-S. and Bougler, B., "A Snowplow Steering Guidance System Using Roadway Markers - Problem Formulation and Solution Concept," *Vehicle System Dynamics*, vol. 32, no. 1, July 1999, pp. 3-22.
4. Suzuki, H., "Development of Lane Marker System in AHSRA," *Proceedings of the 6th World Congress on Intelligent Transport Systems*, Toronto, Canada, Nov. 1999.
5. Zhang, W.-B., Parsons, R., and West, T., "An Intelligent Roadway Reference System for Vehicle Lateral Guidance and Control," American Control Conference, San Diego, CA, June 1990.
6. Pham, H., Tomizuka, M., and Hedrick, J.K., "Integrated Maneuvering Control for Automated Highway Systems Based on a Magnetic Reference/Sensing system," PATH Research Report UCB-ITS-PRR-97-28, 1997.

Appendix A:

Effects of Roadway Objects on Magnet Marker Measurements

Effects of Roadway Objects on Magnet Marker Measurements

Ching-Yao Chan
California PATH



Experimental Setup

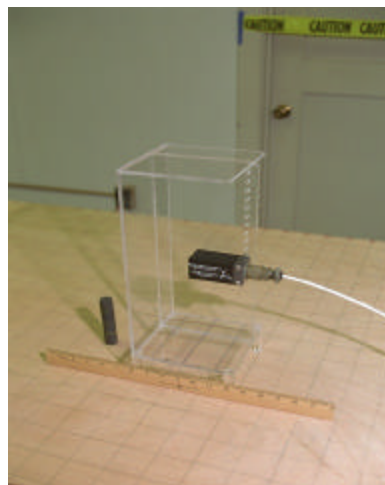
- **Test Bench**
 - Flat bench table with grids designating positions relative to marker
- **Marker**
 - Ceramic Marker, 7/8" diameter, 4" long
- **Sensor**
 - Applied Physics Magnetometer, mounted on a fixture movable on bench table



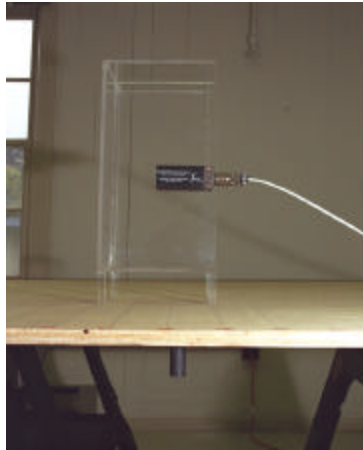
Test Bench



Magnetometer Setup



Marker and Magnetometer Position



Tested Objects

- **Rebar**
 - 5/8" diameter, 35" long, hexagonal cross-section
- **Steel blocks and plates**
 - 1"x1"x5"
 - 1"x2.5"x3"
 - 1/2"x6"x36"
 - 3/16"x13"x13"

Tested Objects

- **Miscellaneous**
 - Aluminum bar, 1/2"x1"x25"
 - Wheel hub cap from Lincoln Town Car, 16.25" diameter
 - Bolt and nut; 3/4"x12" bolt and 1" nut
 - Steel pipe, 1-7/8" diameter, 29" long, and 3/16" thick

Steel Block A



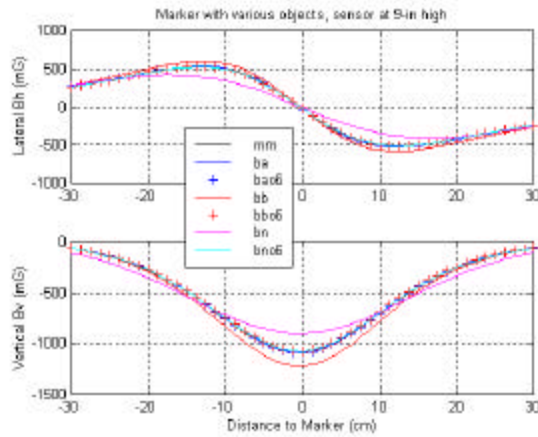
Steel Block B



Bolt and Nut

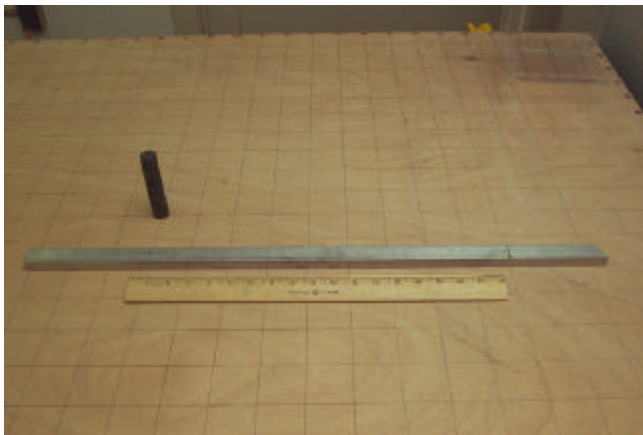


Blocks Bolt and Nut



mm: Marker
ba: Block A + mm
bao6: ba offset 6"
bb: Block B + mm
bbo6: bb offset 6"
bn: Bolt & Nut
bno6: bn offset 6"

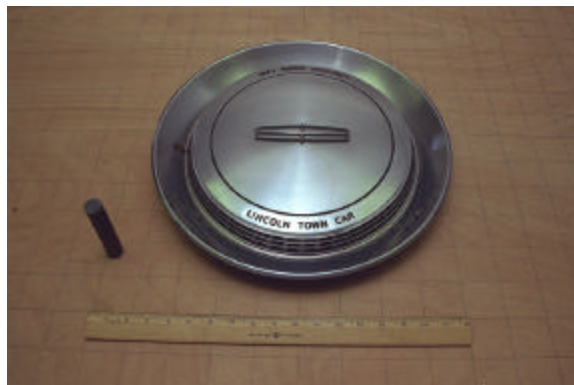
Aluminum Bar



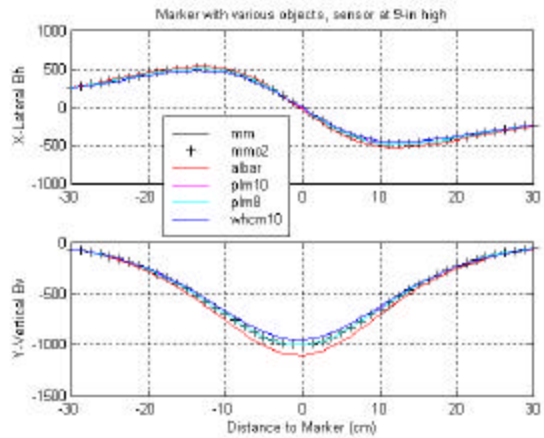
Steel Plate



Wheel Hub Cap

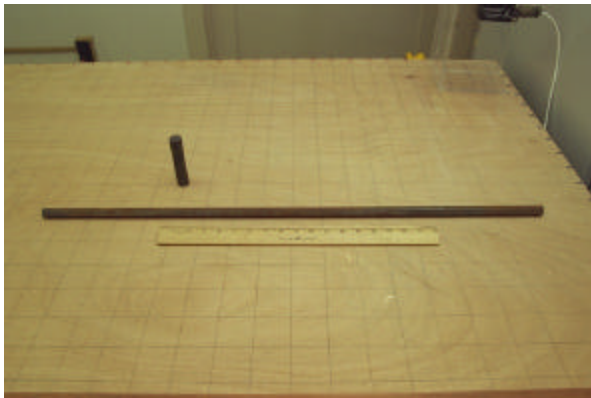


Miscellaneous Objects

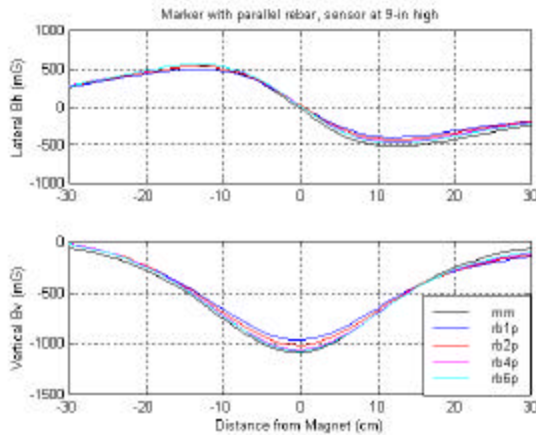


mm: Marker
mmo2: mm offset 2"
albar: aluminum bar
plm10: plate offset 10"
plm8: plate offset 8"
whcm10: whl offset 10"

Rebar

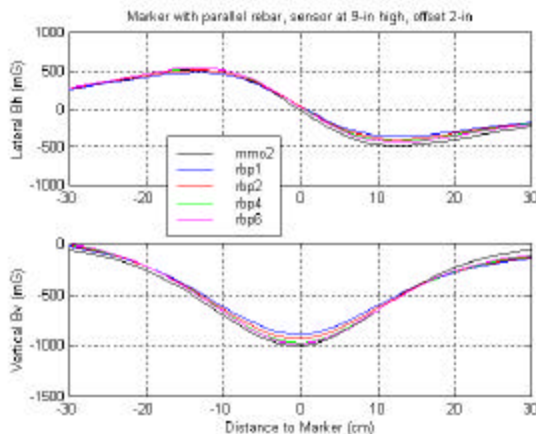


Rebar Parallel to Magnetometer Moving Axis



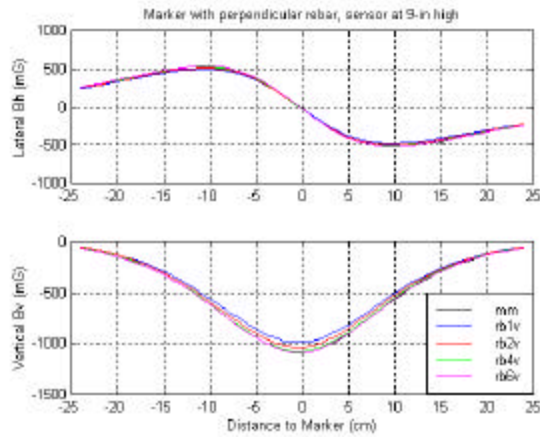
mm: Marker
 rb1p: rebar offset 1"
 rb2p: rebar offset 2"
 rb4p: rebar offset 4"
 rb6p: rebar offset 6"

Rebar Parallel to Magnetometer Moving Axis, which is offset from Marker by 2"



mmo2: Marker offset 2"
 rbp1: rebar offset 1"
 rbp2: rebar offset 2"
 rbp4: rebar offset 4"
 rbp6: rebar offset 6"

Rebar Perpendicular to Magnetometer Moving Axis

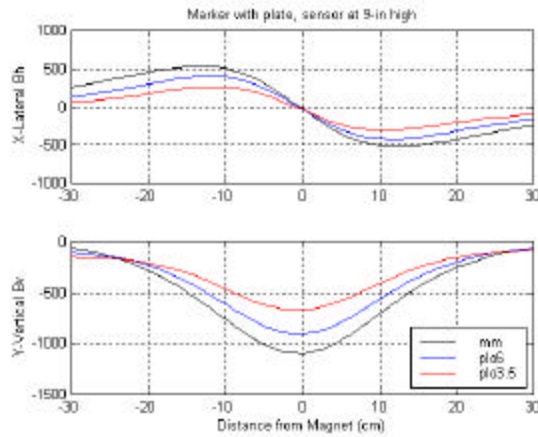


mm: Marker
rb1v: rebar offset 1"
rb2v: rebar offset 2"
rb4v: rebar offset 4"
rb6v: rebar offset 6"

Steel Plate

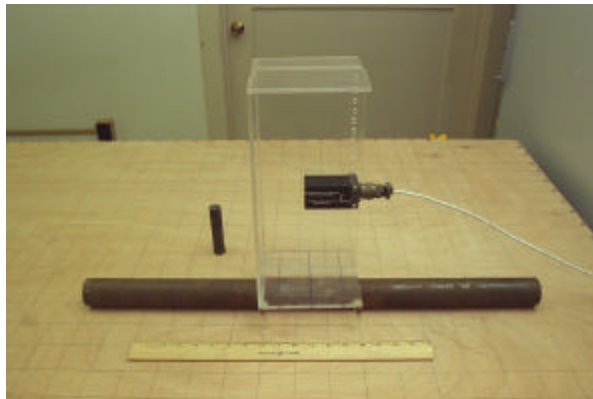


Marker and Plate

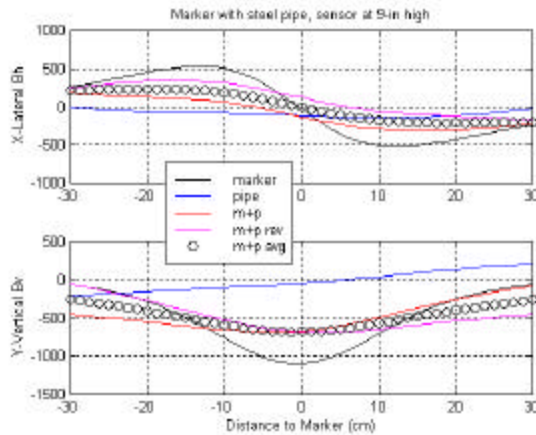


mm: Marker
plo6: plate offset 6"
plo3.5: plate offset 3.5"

Magnetized Pipe



Magnetized Pipe



----: Marker
pipe: pipe only
m+p: marker + pipe
m+p rev: marker + pipe
reverse direction
m+p avg: average of
the last two

Observations

- **Small-size objects and single rebar have limited effects on the magnetic field patterns generated by magnetic markers.**
- **Substantial objects can cause significant changes in magnetic field patterns.**
- **Magnetized objects result in biased or distorted patterns.**
- **Objects near markers tend to attract magnetic flux, thus enhancing the level of magnetic fields in the vicinity.**

Appendix B:

A Sampling of Ambient Magnetic Field Data

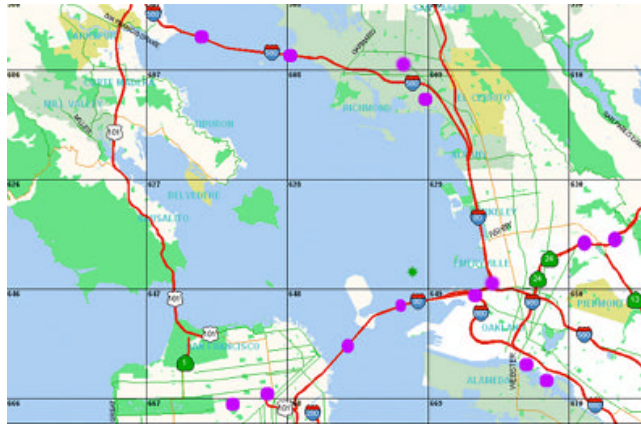
A Sampling of Ambient Magnetic Field Data

Ching-Yao Chan, Dave Nelson,
Paul Kretz, Benedicte Bougler

Bay Area Region



Bay Area Region



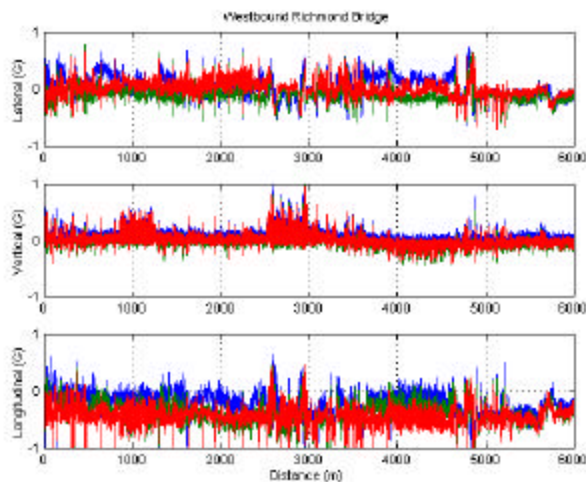
Locations of Data Sampling

- Bridges
- Highway Structures
- Tunnel
- Railroad Crossing
- Local Street with Streetcar Rail
- Roadway with Adjacent BART Track
- Roadway with Vehicle Detection Loop

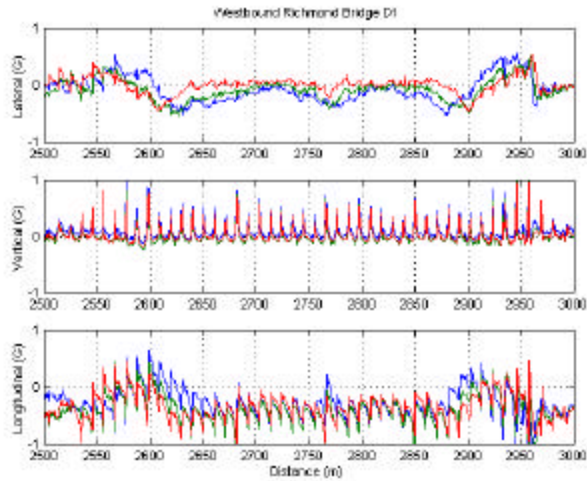
Locations of Data Sampling

- **Bridges**
 - Richmond - San Rafael
 - Bay
 - Hayward - San Mateo
 - Dumbarton
 - Alameda - Oakland at Fruitvale
 - Alameda - Oakland at Park Street

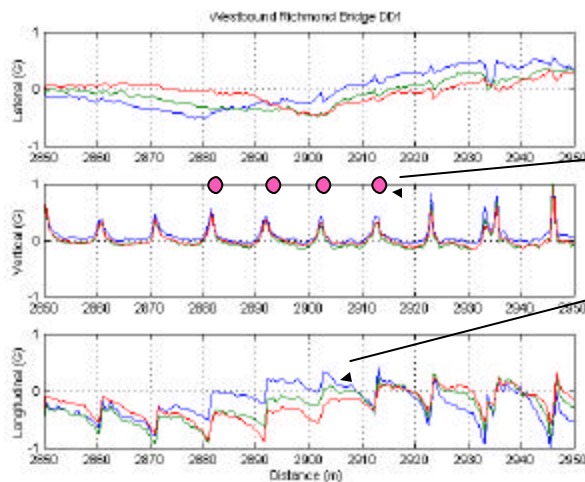
Richmond Bridge Westbound



Richmond Bridge Westbound



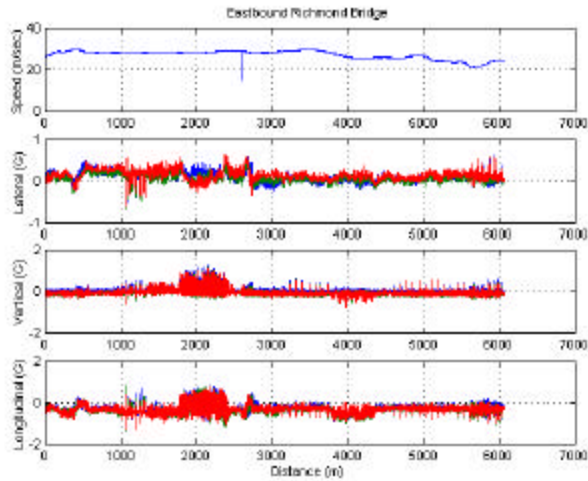
Richmond Bridge Westbound



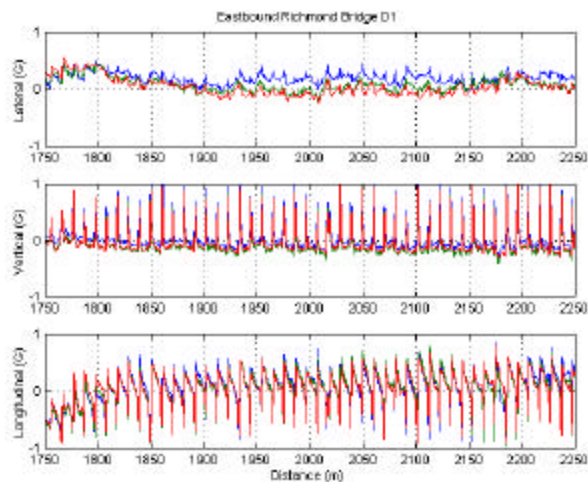
10 m Spacing
Spikes of $<1G$

Lane Change?

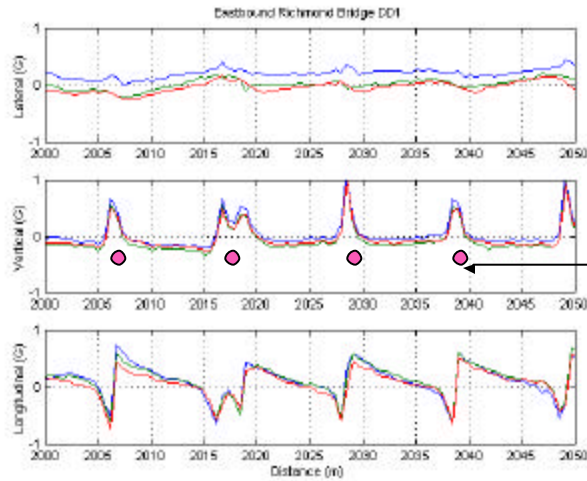
Richmond Bridge Eastbound



Richmond Bridge Eastbound

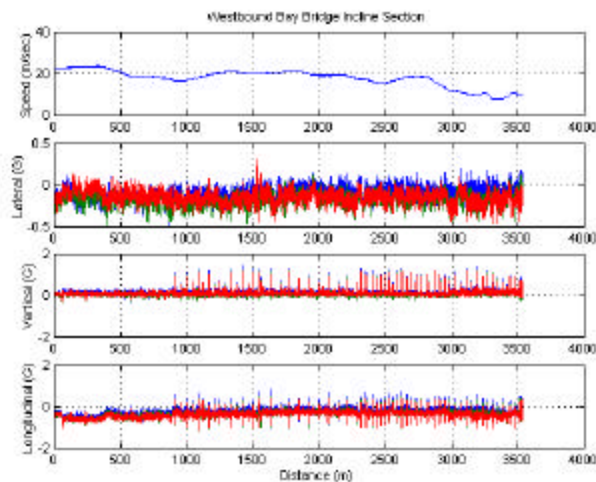


Richmond Bridge Eastbound

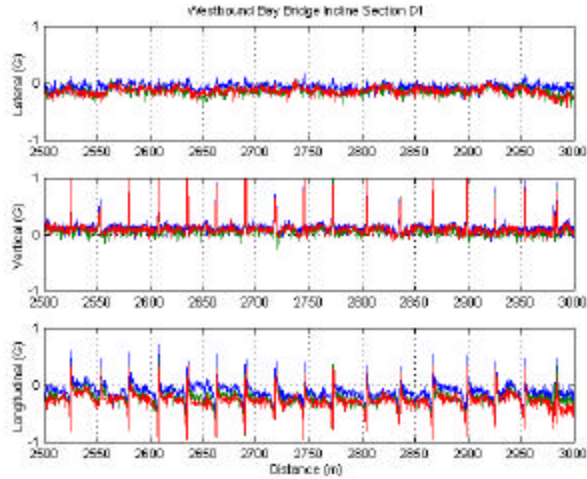


10 m Spacing
Spikes of ~1 G

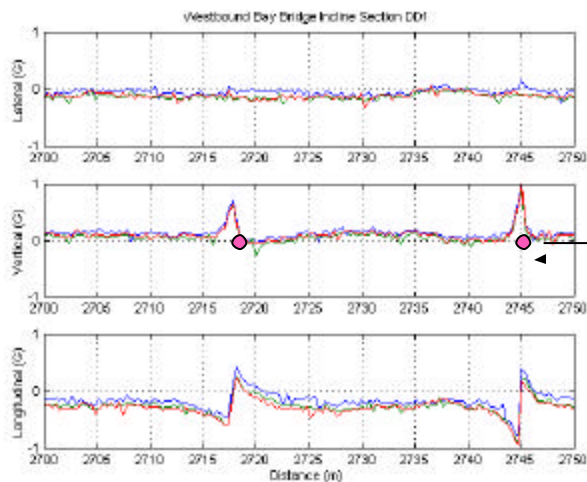
Bay Bridge Incline Section Westbound



Bay Bridge Incline Section Westbound

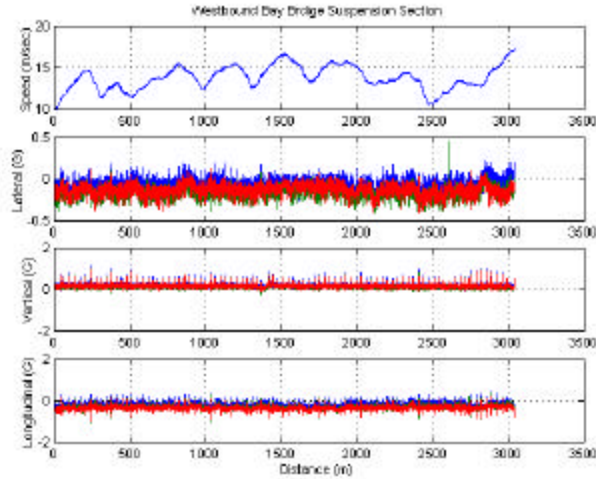


Bay Bridge Incline Section Westbound

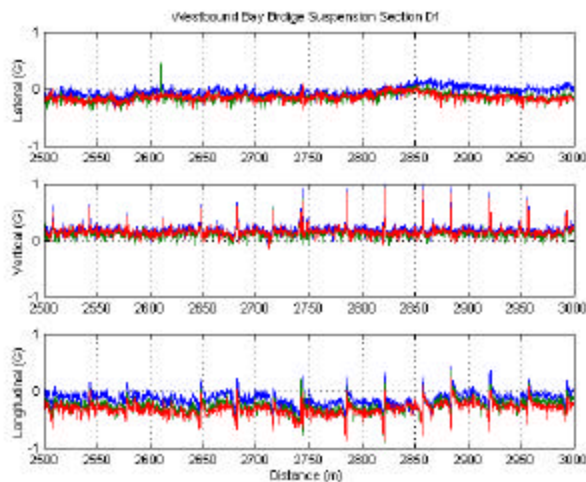


28 m Spacing
Spikes of ~1G

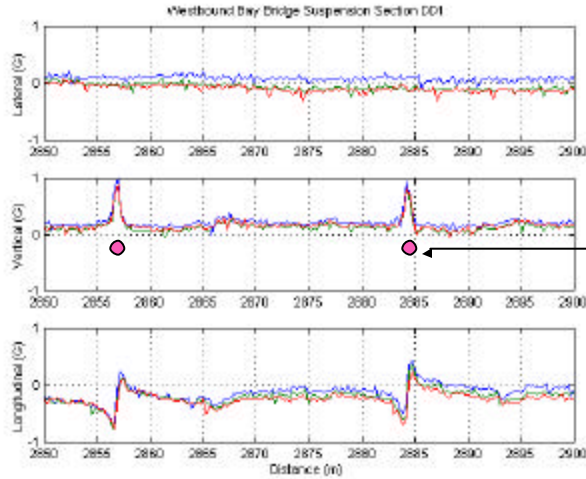
Bay Bridge Suspension Section Westbound



Bay Bridge Suspension Section Westbound

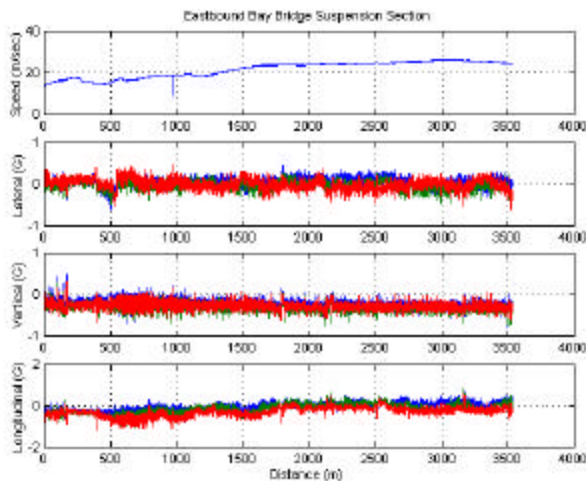


Bay Bridge Westbound Suspension

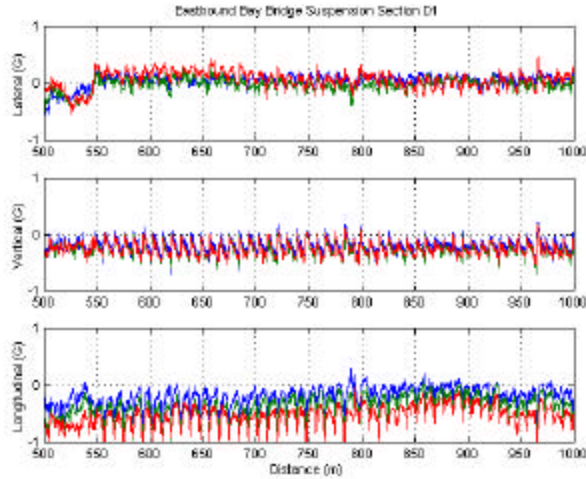


28 m Spacing
Spikes of <math><1G</math>

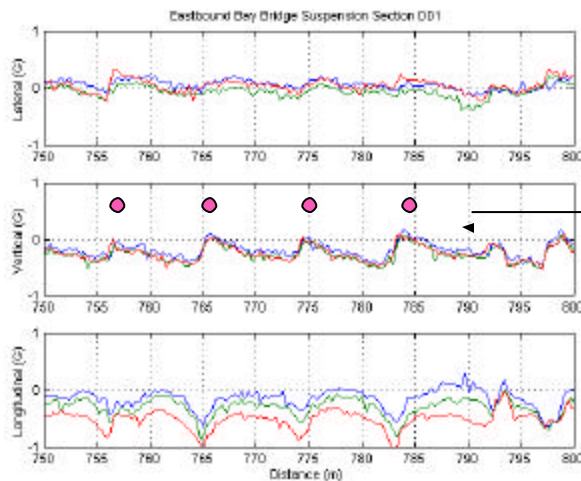
Bay Bridge Suspension Section Eastbound



Bay Bridge Suspension Section Eastbound

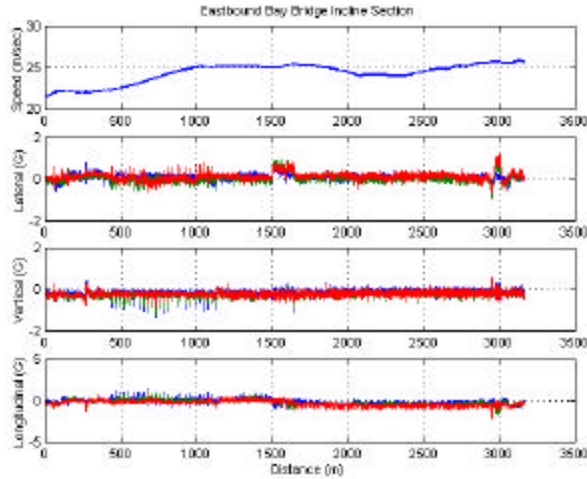


Bay Bridge Suspension Section Eastbound

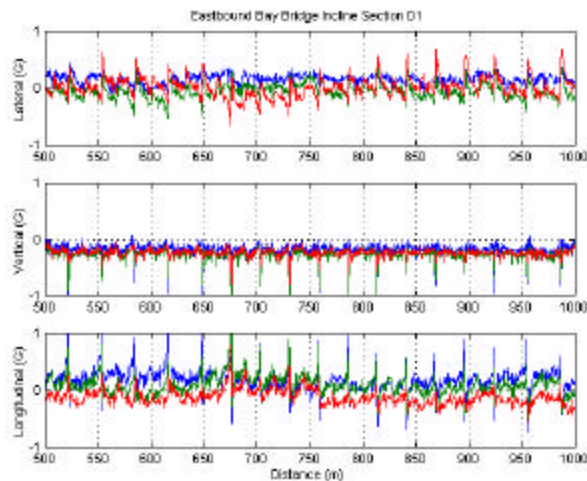


8 m Spacing
Bumps of ~0.5G

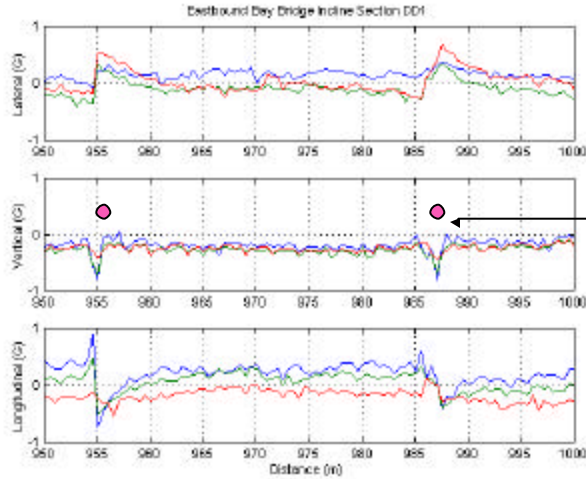
Bay Bridge Incline Section Eastbound



Bay Bridge Incline Section Eastbound

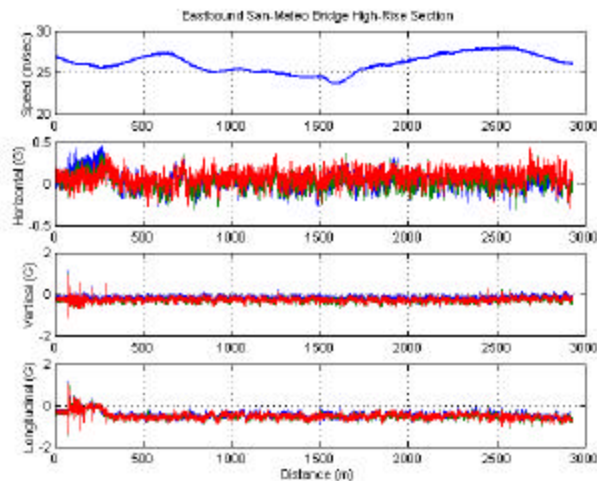


Bay Bridge Incline Section Eastbound

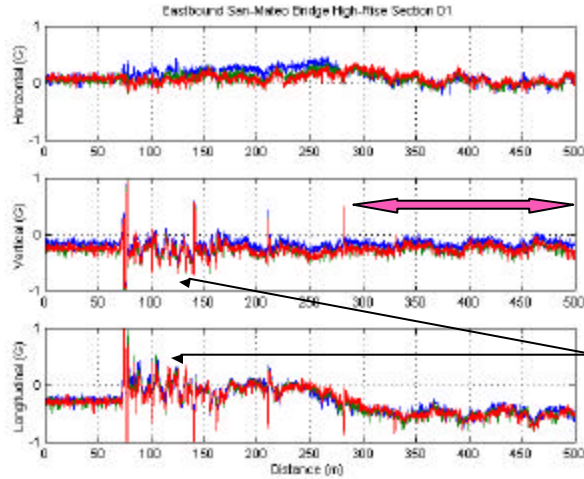


28 m Spacing
Spikes of <1G

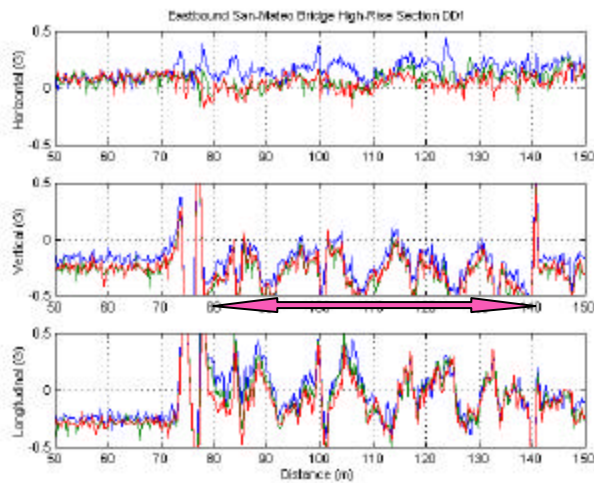
Hayward - San Mateo Bridge High-Rise Section Eastbound



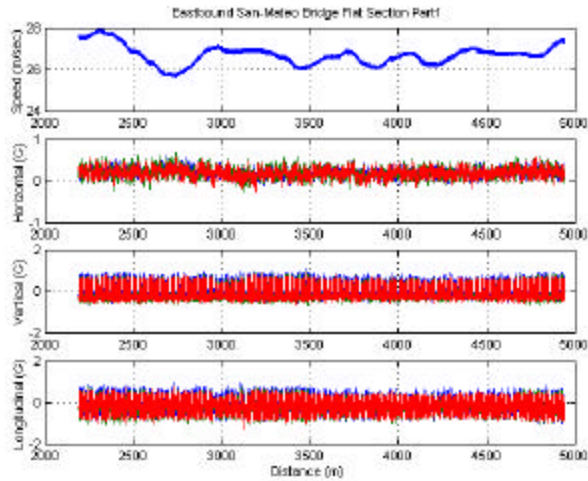
Hayward - San Mateo Bridge High-Rise Section Eastbound



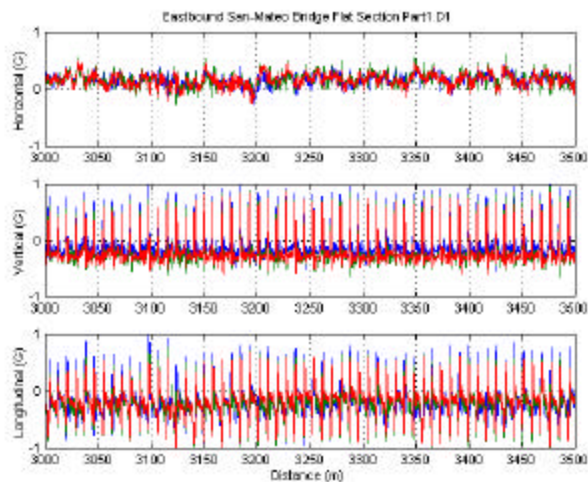
Hayward - San Mateo Bridge High-Rise Section Eastbound



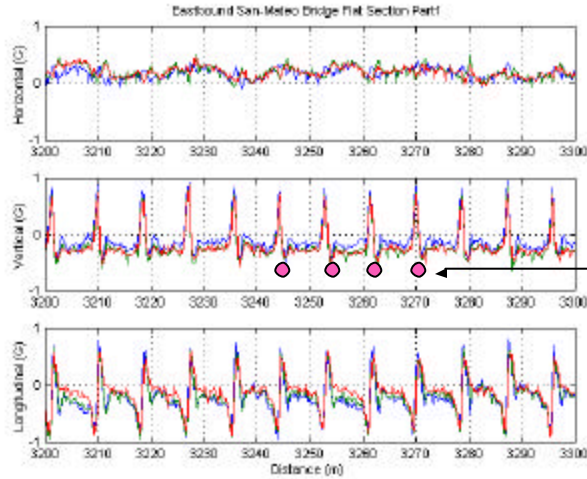
Hayward - San Mateo Bridge Flat Section Eastbound



Hayward - San Mateo Bridge Flat Section Eastbound

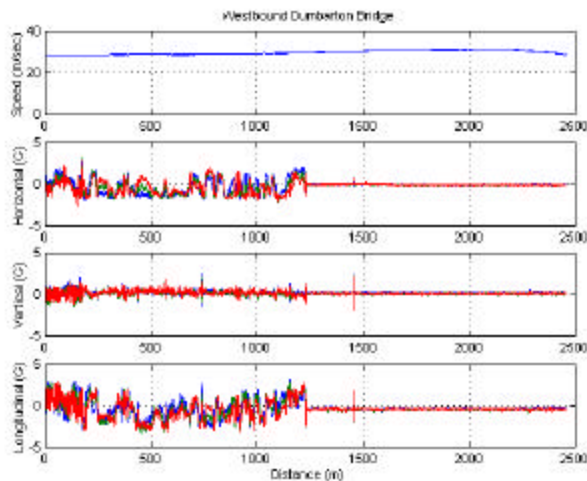


Hayward - San Mateo Bridge Flat Section Eastbound

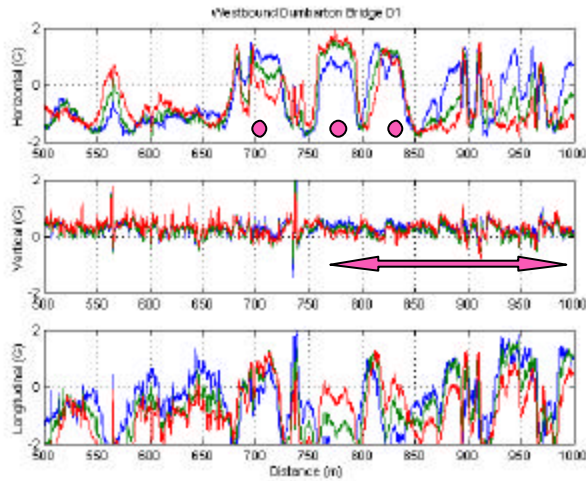


8 m Spacing
Bumps of >1G

Dumbarton Bridge Westbound



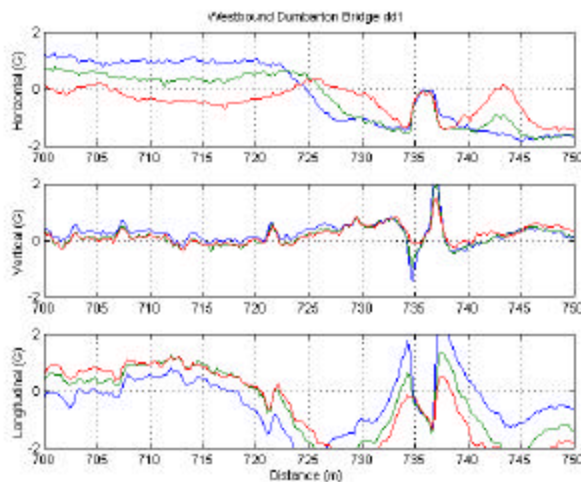
Dumbarton Bridge Westbound



Long-Span
Ambient Shift?

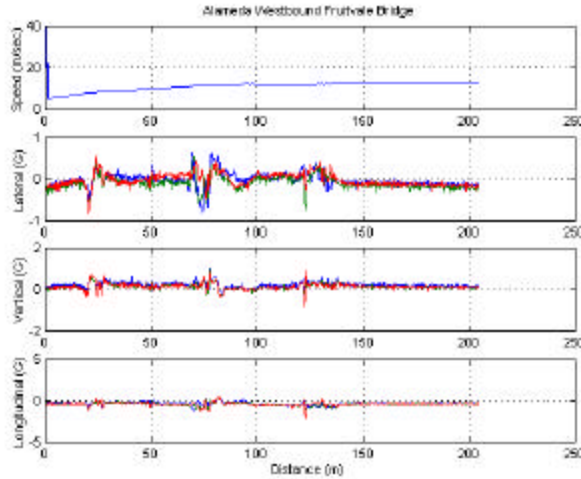
Relatively Stable
Vertical Fields

Dumbarton Bridge Westbound



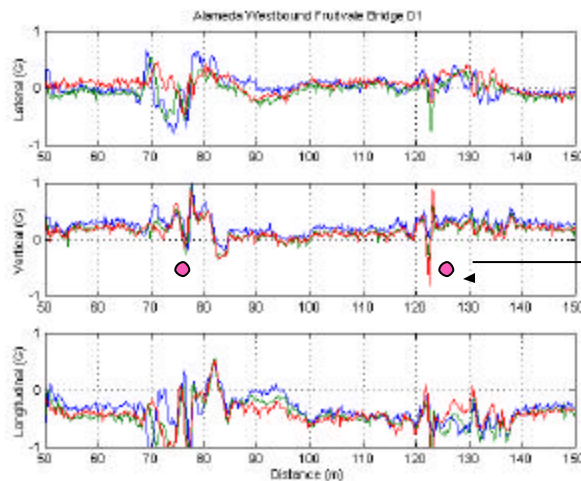
No Clear
Patterns except
Occasional Spikes

Fruitvale Alameda Westbound



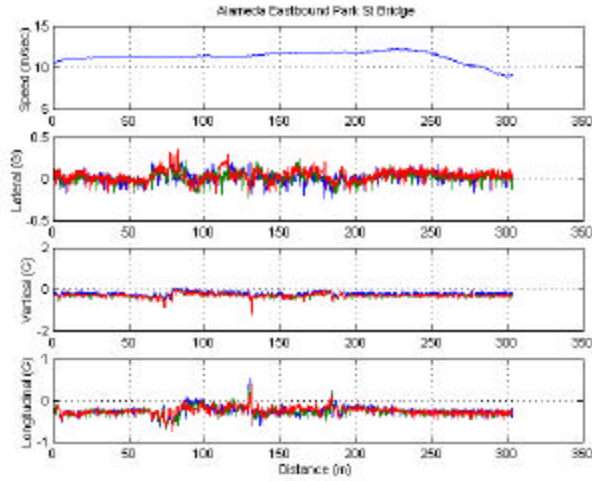
Bridge with
Concrete
Structure

Fruitvale Alameda Westbound



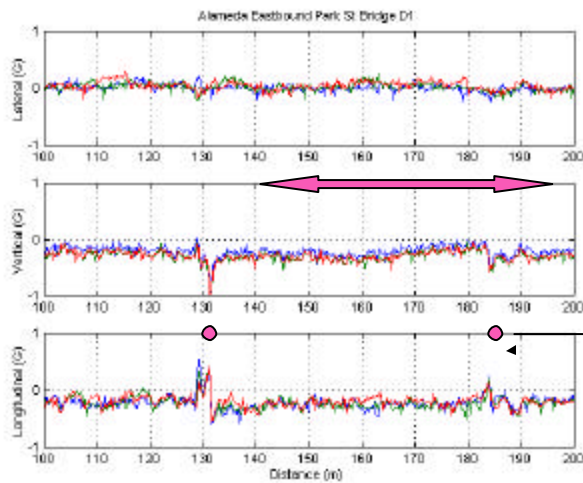
Bridge Support
Structure
50 m Apart?

Park St. Alameda Eastbound



**Draw Bridge
with Metallic
Structure**

Park St. Alameda Eastbound



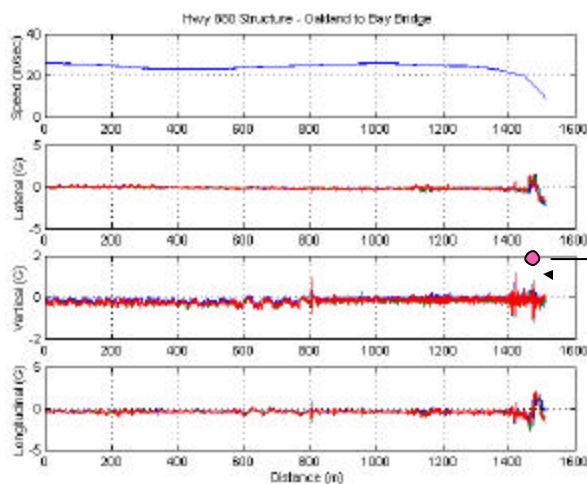
Relatively Flat

**Reinforcements
or Gaps in
Draw Bridge?**

Locations of Data Sampling

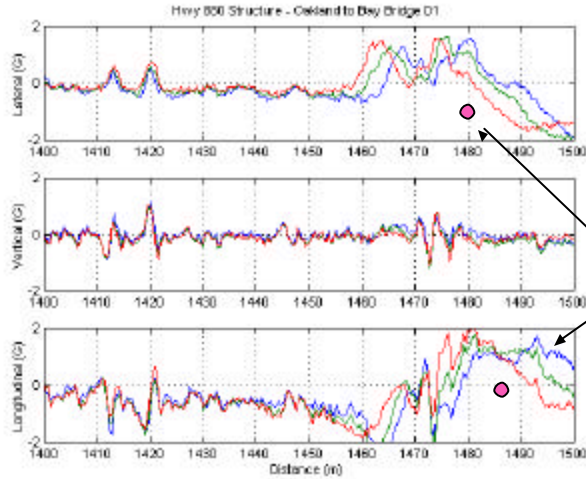
- **Highway Structures**
 - Highway 880, Oakland to Bay Bridge
 - Central Freeway, San Francisco, Van Ness to Fourth Street
 - Highway 80 to 580 Ramp
 - Highway 580 to 80 Ramp

Hwy 880 Northbound Grand to the Maze



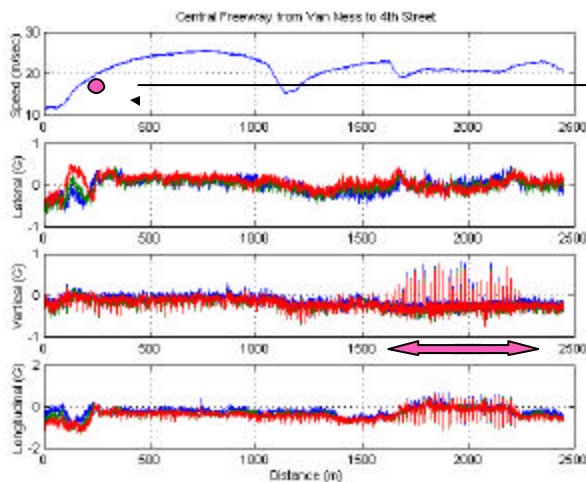
Near end of
High-Rise
Structure

Hwy 880 Northbound Grand to the Maze



Shift of >2G
within 30 m

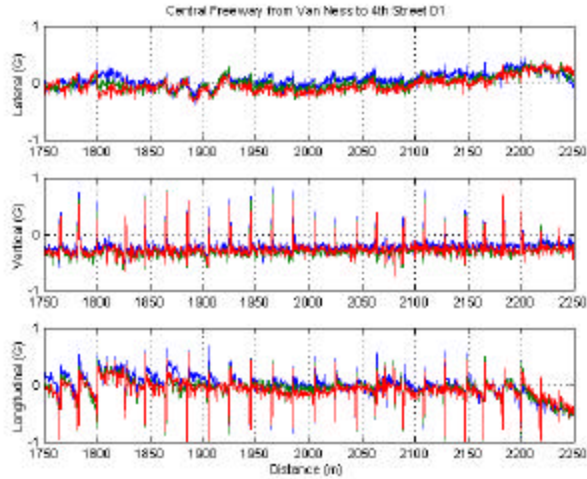
Central Freeway Van Ness to 4th



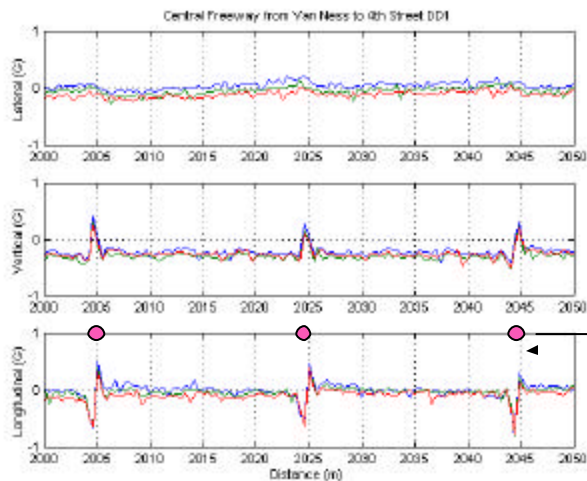
Ramp Entrance

Different
Structures?

Central Freeway Van Ness to 4th

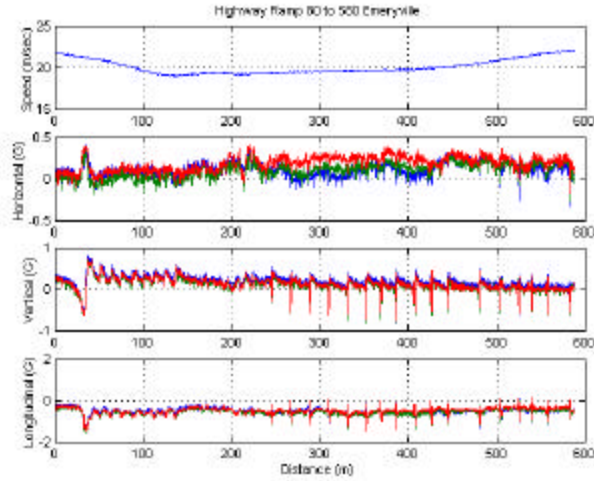


Central Freeway Van Ness to 4th

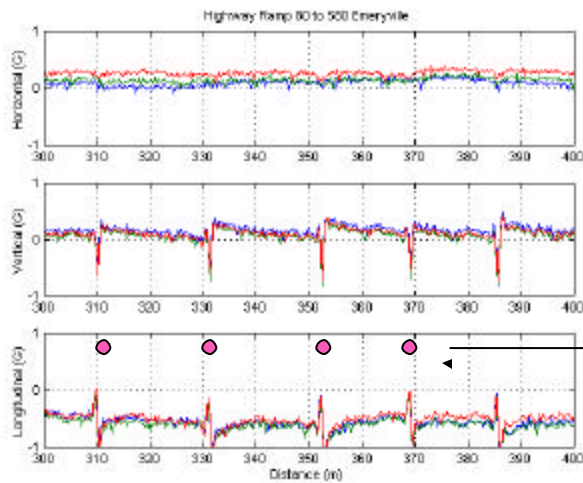


20 m Spacing
Spikes of ~1G

Hwy 80 to 580 Ramp

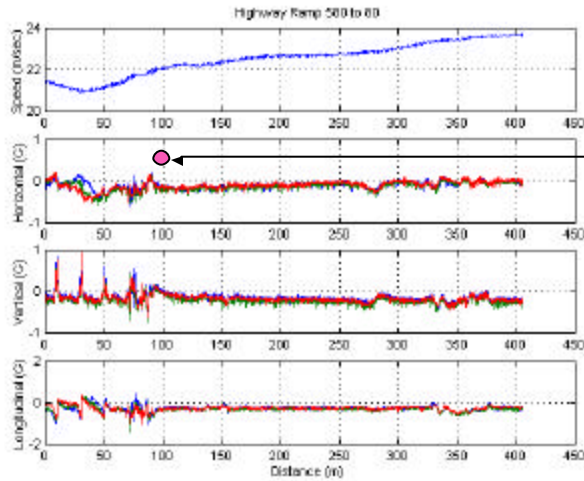


Hwy 80 to 580 Ramp

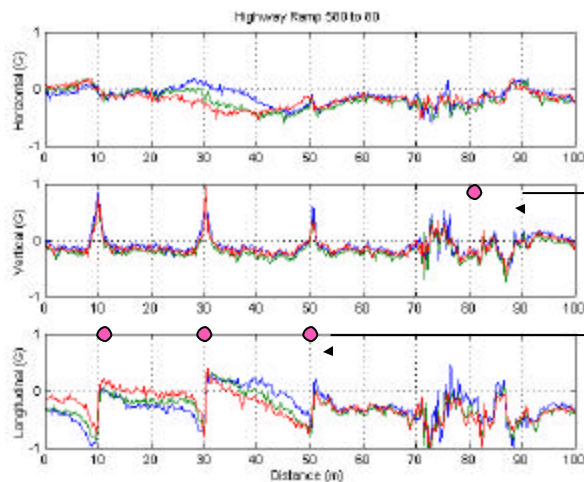


16-20 m Spacing
Bumps of ~1.0G

Hwy 580 to 80 Ramp



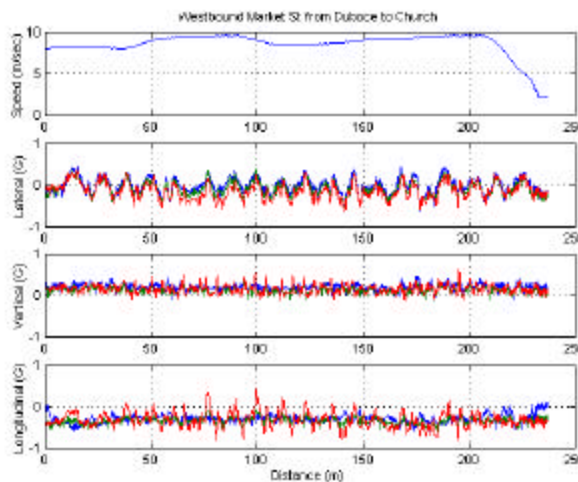
Hwy 580 to 80 Ramp



Locations of Data Sampling

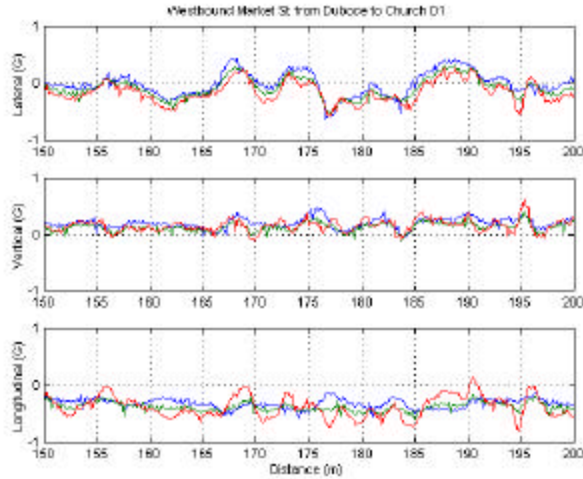
- Local Streets with Streetcar Rails
 - Market Street, San Francisco
- Roadways with BART Tracks nearby
 - Highway 24, Oakland
 - Highway 580, Castro Valley to Pleasanton
- Roadway with Vehicle Detection Loop
 - Highway 580 near RFS

Market St. Westbound Duboce to Church



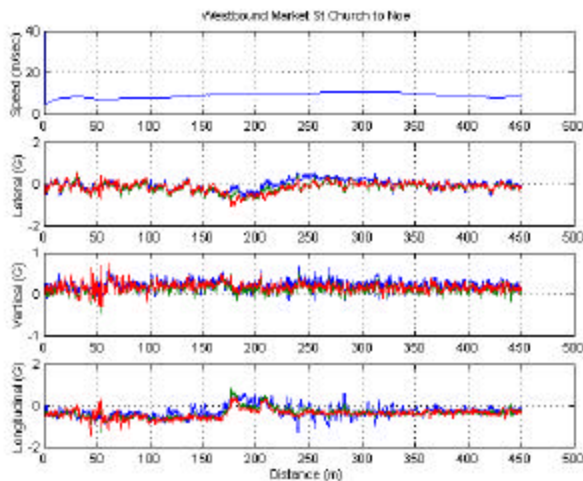
Fluctuations
exist in
all three axes

Market St. Westbound Duboce to Church

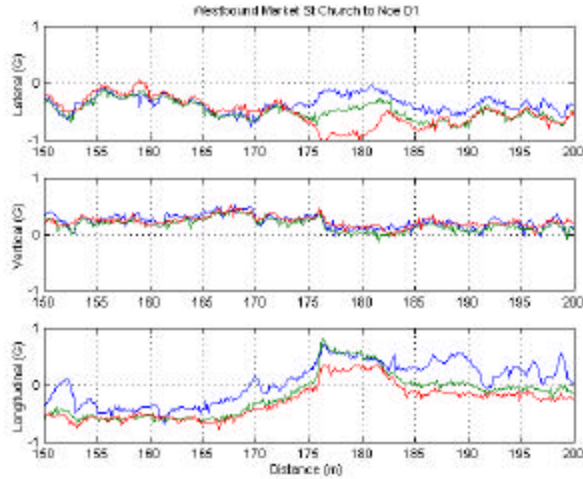


Fluctuations
due to
Relative positions
of surface rails?

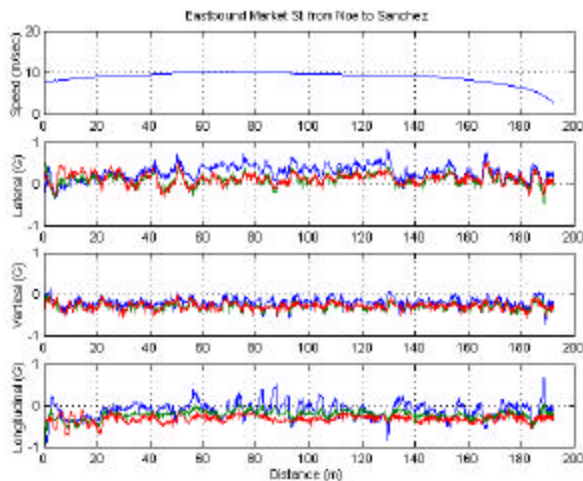
Market St. Westbound Church to Noe



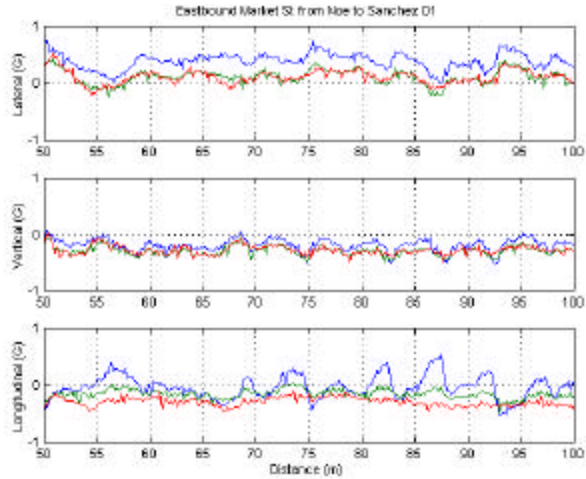
Market St. Westbound Church to Noe



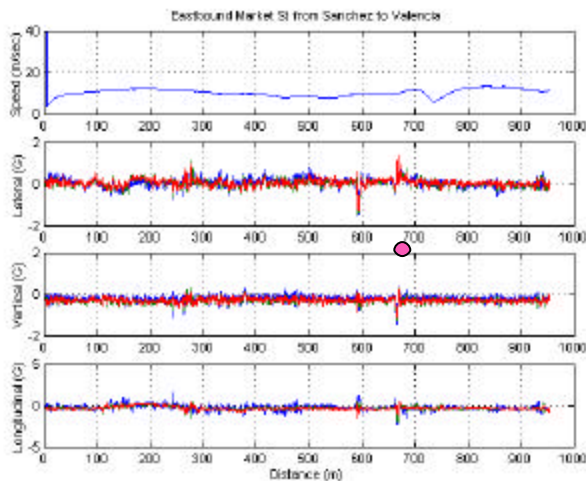
Market St. Eastbound Noe to Sanchez



Market St. Eastbound Noe to Sanchez

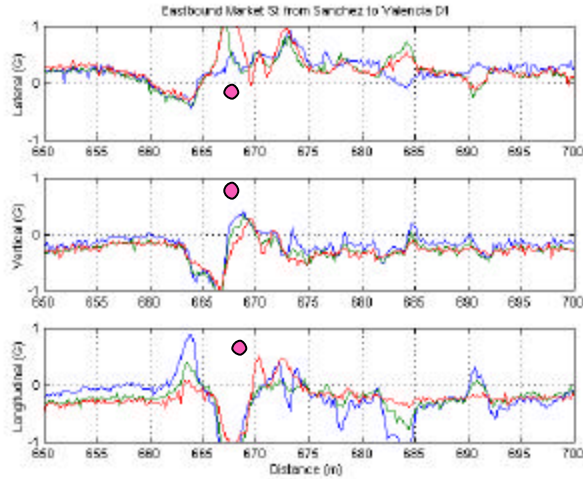


Market St. Eastbound Sanchez to Valencia



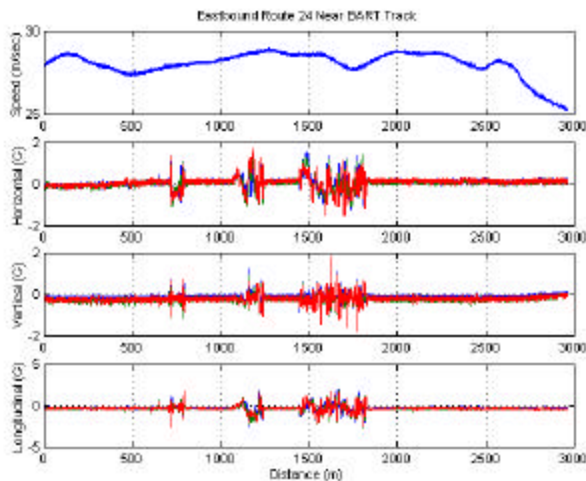
Larger Spikes

Market St. Eastbound Sanchez to Valencia



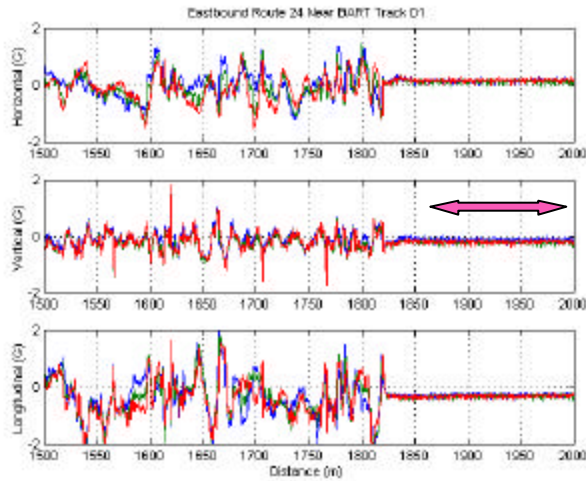
**Metallic Grids
on Surface or
Underground
Structure?**

Highway 24 near Rockridge Station



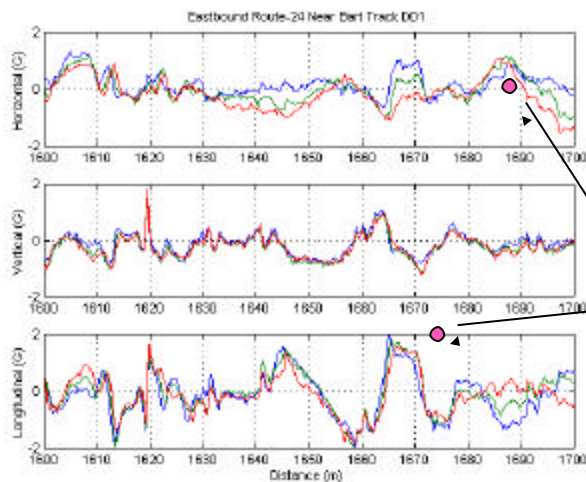
**Computer
Terminal
Experiences
Noises near
BART Station**

Highway 24 near Rockridge Station



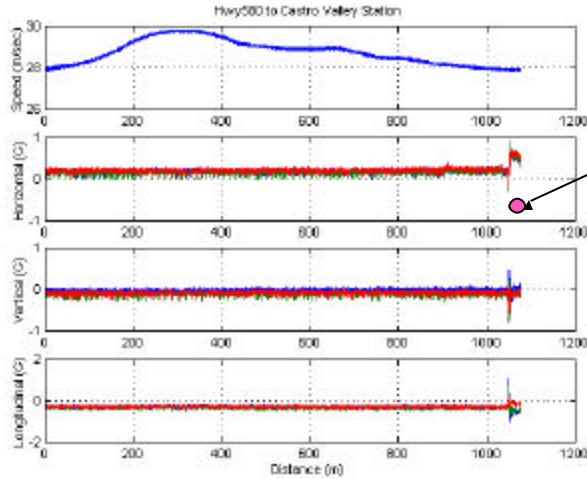
Flat Signals
in Remainder
of Highway 24

Highway 24 near Rockridge Station



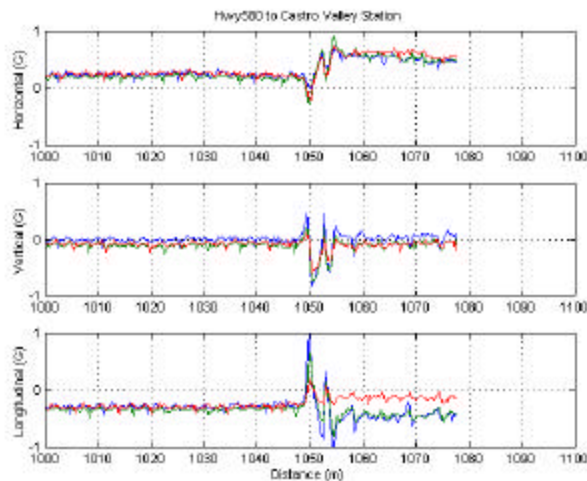
Fluctuation or
Shift $>2G$
within 10 m

Highway 580 Eastbound near Castro Valley Station

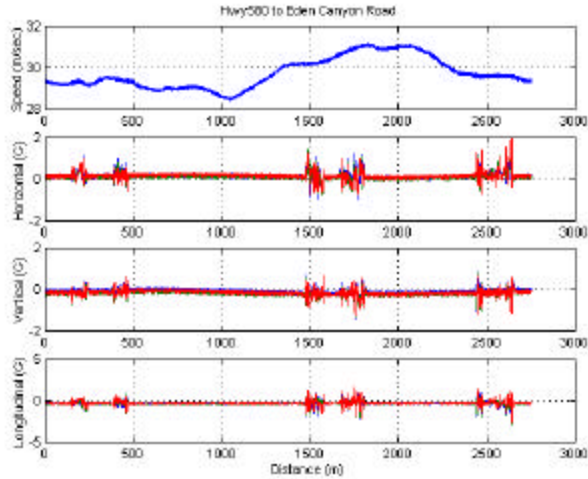


Ends near
BART station

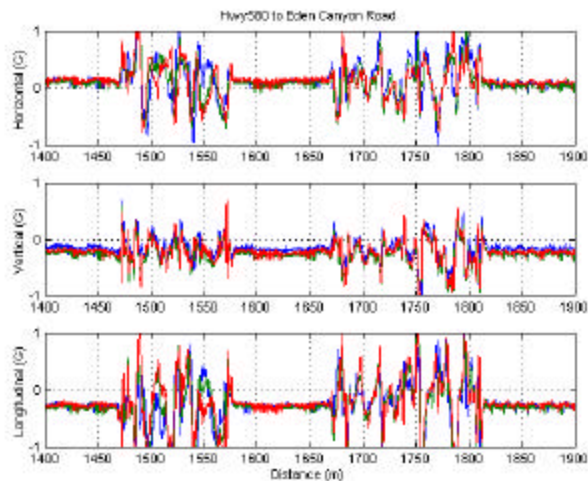
Highway 580 Eastbound near Castro Valley Station



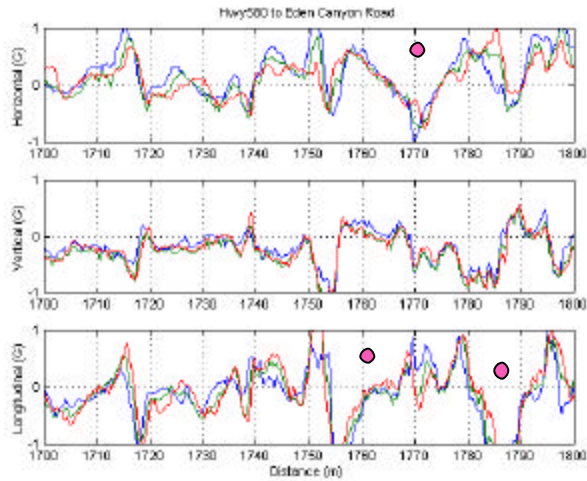
Highway 580 Eastbound near Eden Valley Road Exit



Highway 580 Eastbound near Eden Valley Road Exit

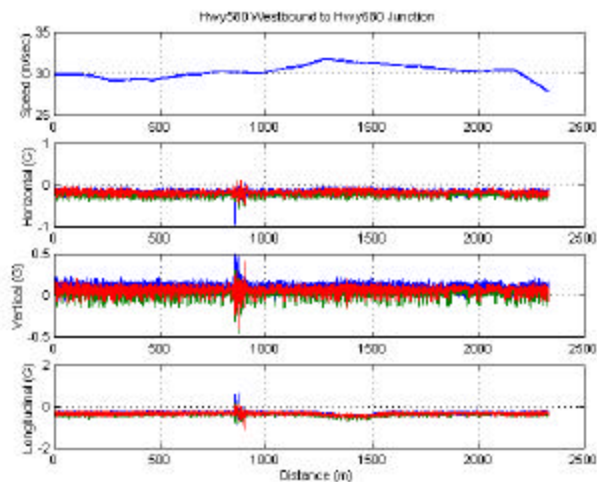


Highway 580 Eastbound near Eden Valley Road Exit

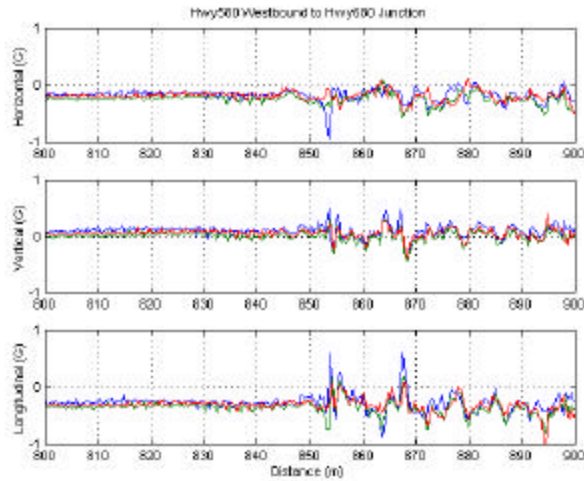


Significant shift
No clear pattern

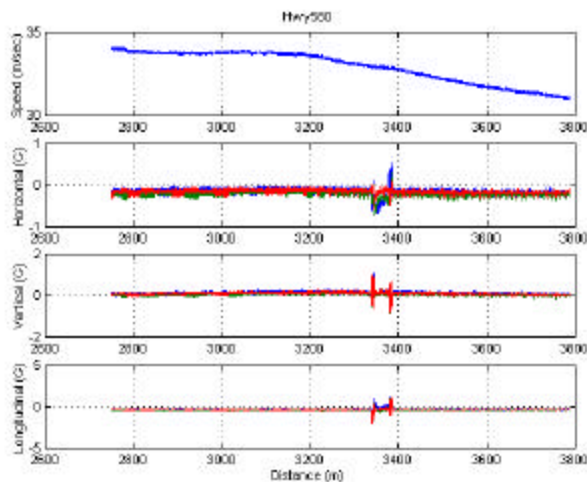
Highway 580 Westbound near Hwy680 Junction



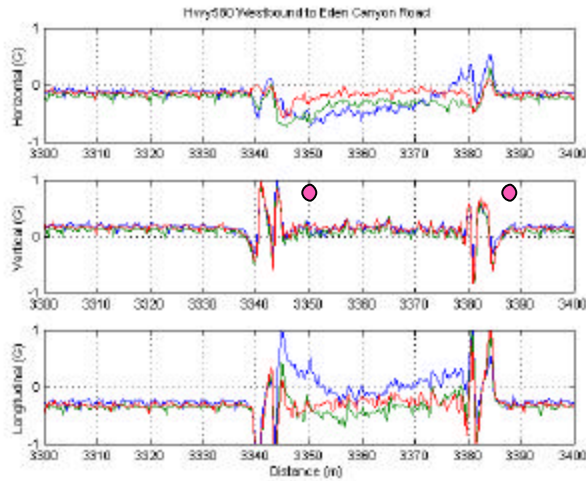
Highway 580 Westbound near Hwy680 Junction



Highway 580 Westbound near Eden Canyon Road Exit

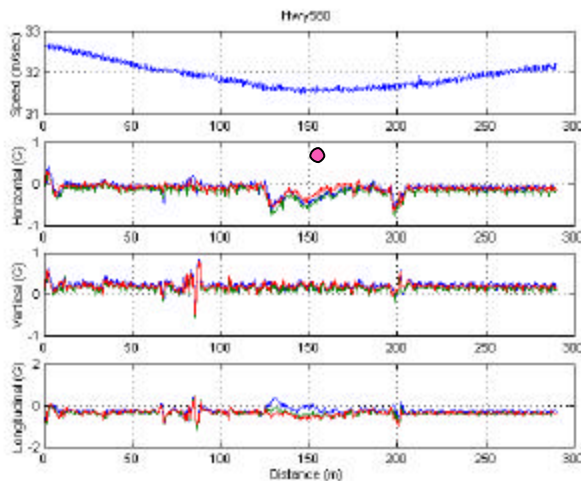


Highway 580 Westbound near Eden Canyon Road Exit



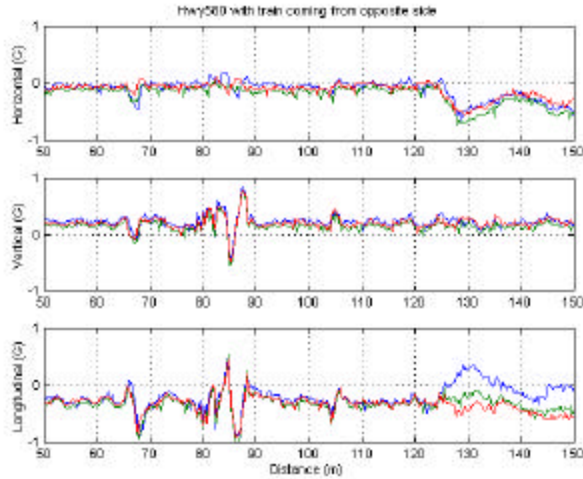
Significant spike
Yet different
from opposite
side of highway

Highway 580 Westbound with BART train passing

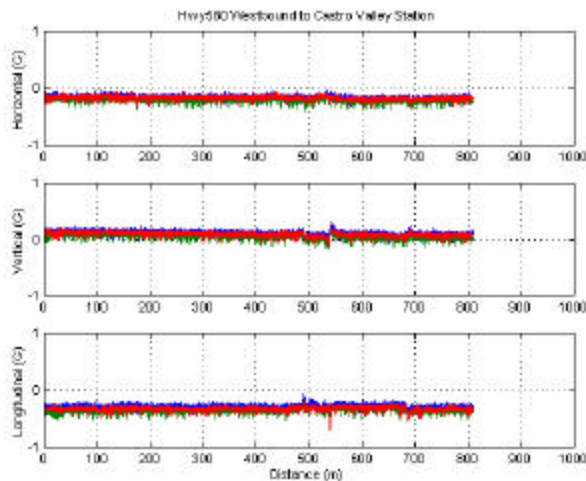


Train Passing?

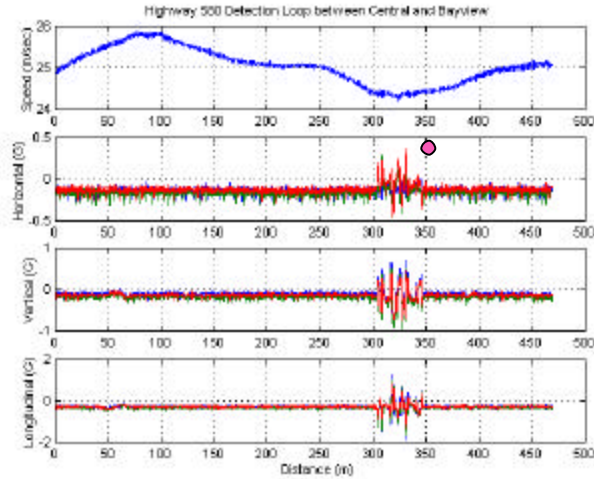
Highway 580 Westbound with BART train passing



Highway 580 Westbound near Castro Valley Station

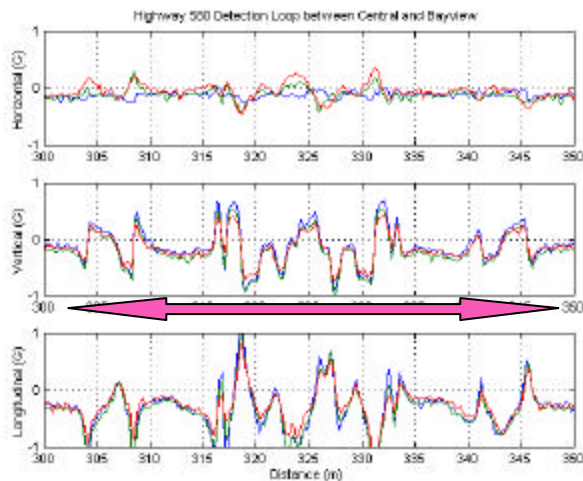


Highway 580 Westbound Vehicle Detection Loop near RFS



Detection Loop?

Highway 580 Westbound Vehicle Detection Loop near RFS

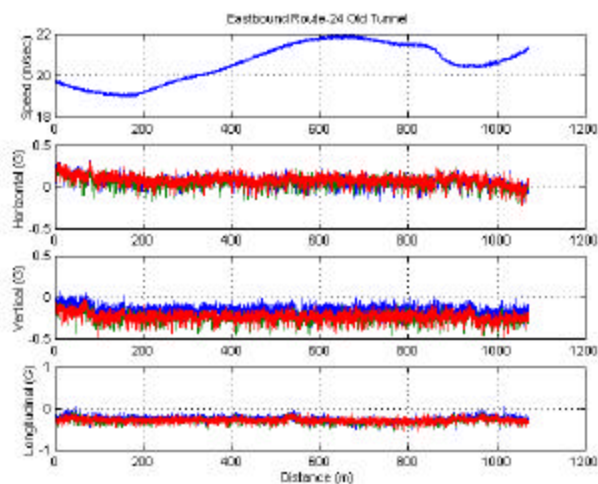


Other structures
besides detection
loop?

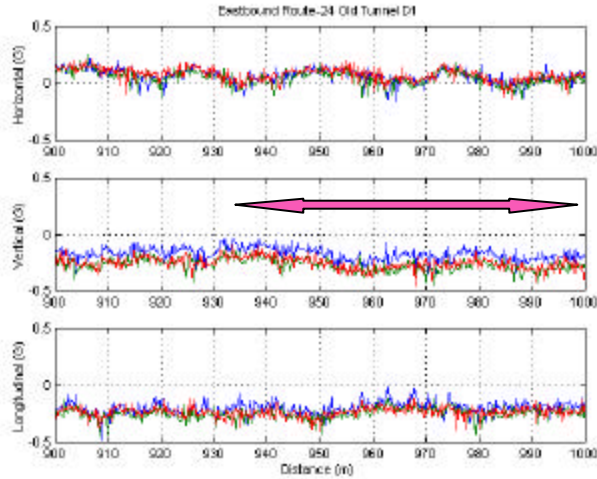
Locations of Data Sampling

- **Tunnel**
 - Highway 24, Caldecott, Oakland - Orinda

Caldecott Old Tunnel Eastbound

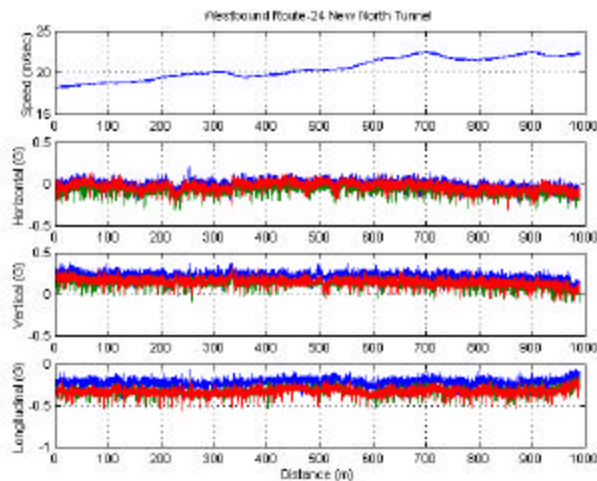


Caldecott Old Tunnel Eastbound

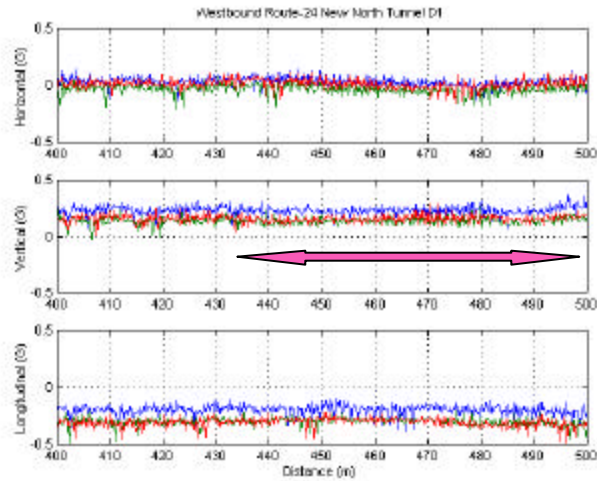


Relatively Flat

Caldecott New Tunnel Westbound



Caldecott New Tunnel Westbound

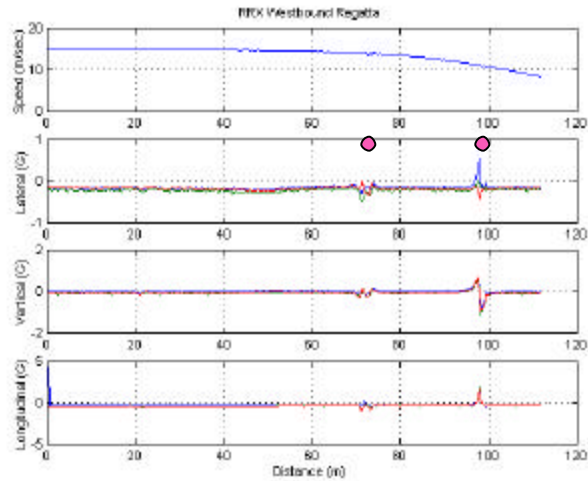


Relatively Flat

Locations of Data Sampling

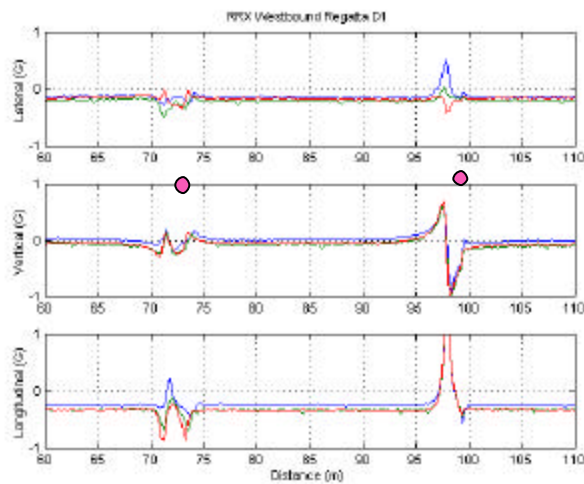
- **Railroad Crossing**
 - Regatta at Mead, Richmond near RFS
 - Cutting at Carlson

RRX Regatta Westbound



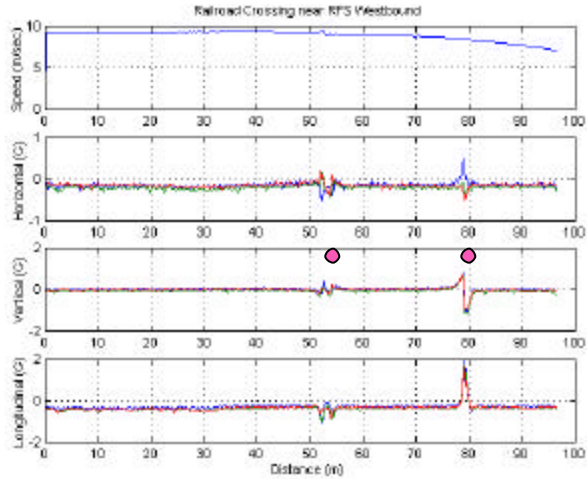
Double
Railroad
Crossing

RRX Regatta Westbound



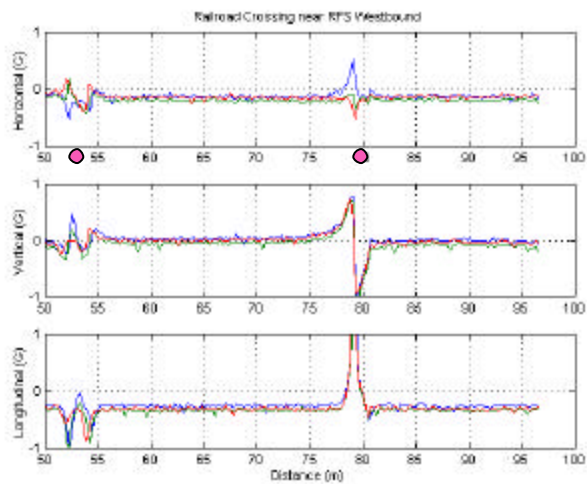
Uneven
Sizes
of Spikes

RRX Regatta Westbound



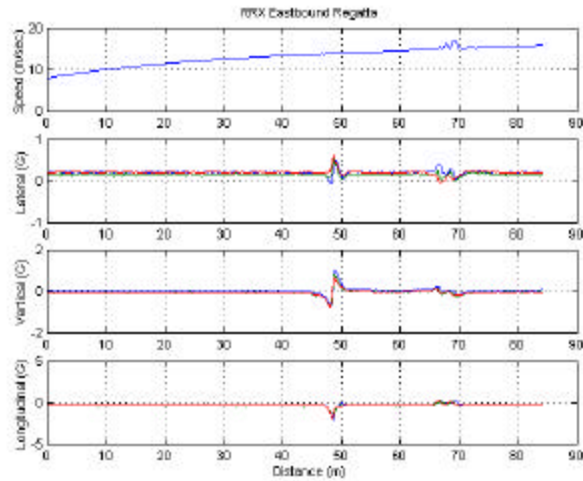
Double
Railroad
Crossing

RRX Regatta Westbound

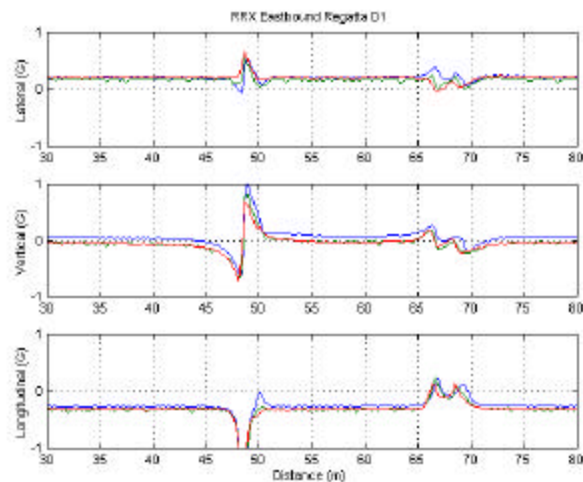


Uneven
Sizes
of Spikes

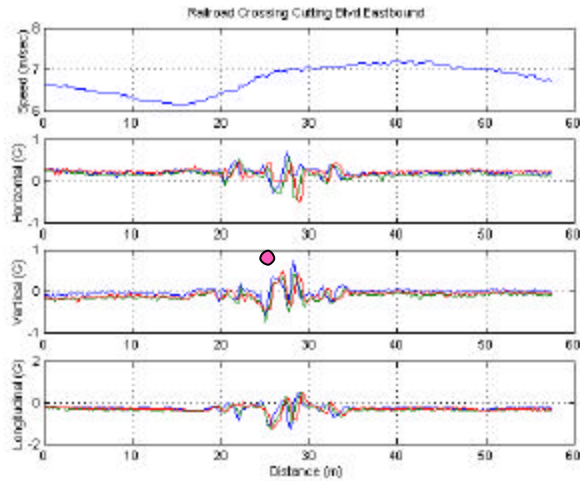
RRX Regatta Eastbound



RRX Regatta Eastbound

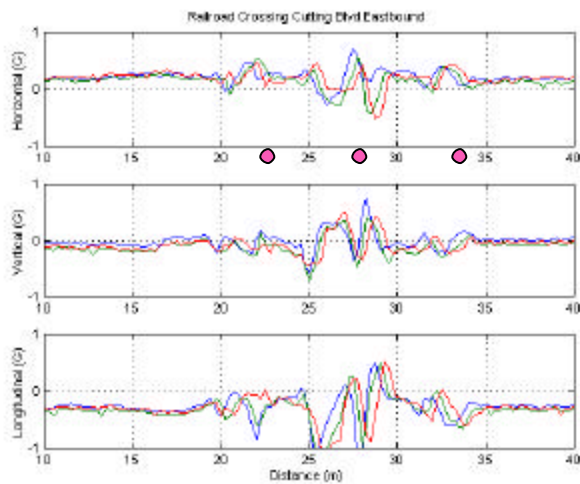


RRX Cutting Eastbound



Triple
Railroad
Crossing

RRX Regatta Eastbound



Triple
Railroad
Crossing

Concluding Remarks

- Ambient magnetic field data is like “a box of chocolate; you never know what you are gonna get.”
- Variations in ambient magnetic fields appear to be of significant magnitudes in local spots to be considered for signal processing purposes.
- Clear patterns of fluctuations in certain locations may be closely associated with structural reinforcements in roadways and bridges.
- Actual effects of ambient fields need to be evaluated after magnets are installed.

Concluding Remarks

- Abnormal fluctuations are mostly local phenomena which are limited to 1-5 meters.
- Some locations have a longer span of irregular patterns that may cover 10-30 meters.
- Local abnormality can probably be tolerated by the robust design features in sensing and control algorithms, such as with the aid of dead reckoning.
- Irregularities existing in a long stretch of roadways will likely need special selection of magnets or particular measures.
- Significant distortions from the ambient fields will also impose constraints on magnet coding.

Final Report for MOU396

PART II

Characterization of Magnetic Tape and Magnetic Markers as a Position Sensing System for Vehicle Guidance and Control

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University of California, Berkeley
Institute of Transportation Studies
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EXECUTIVE SUMMARY

In the studies of advanced vehicle control and safety systems, position measurement is an important link that provides essential information for the identification of vehicle locations. One type of critical information used by vehicle control systems is the measurement of lateral position relative to a lane or a desired trajectory. Among the technologies that have been developed for such purposes are electrically powered wire, computer vision, magnetic sensing, optical sensing, inertial navigation and global positioning systems. This paper focuses on two types of magnetic systems that have been experimentally demonstrated in recent years. The objective is to identify the characteristics of these two sensing systems and to offer a comparison of their distinct features.

Experimental data from the measurement of the magnetic fields around tape and marker systems are shown to illustrate their characteristics and functioning principles. The magnetic markers are implemented by a series of magnetic pieces installed under the road surface at a specified spacing along the subject trajectory. The magnetic tape embeds magnetic materials in a thin and narrow strip, which is laid on or under the surface of a roadway. The two systems exhibit distinct features in their field patterns, yet they possess similar properties that can be identified with sensing algorithms.

Magnetic sensing has been proven to be an effective positioning sensing system. Magnetic markers and magnetic tape, although different in their construction and characteristics, have both been demonstrated for selected AVCSS applications. Based on the measurements and evaluation tests as shown in this report, it is found that the magnetic marker systems offer better performances and more desirable features than the 3M tape system with its current setting and design.

To provide enhanced performance of the magnetic sensing systems, improvements may be sought in several areas, such as physical construction, signal processing, and costs. Considerations in physical construction involve the automation of installation and inspection, as well as the optimization of magnetic strength and layout design. Robustness and accuracy enhancements in signal processing are desirable. To promote the use of these technologies, it is essential to explore means to reduce material and sensing system costs in addition to the overall infrastructure investments.

1.0 BACKGROUND

Magnetic sensing is one promising technology that has been developed for the purposes of position measurement and guidance, especially notable for applications in advanced vehicle control and safety systems (AVCSS). In recent years, the California PATH program (Partners for Advanced Transit and Highways) has deployed the magnetic marker system in conjunction with its experimental vehicles in a number of international and national demonstrations [1,2]. These experiments successfully illustrated the potentials of this fundamental element for advanced transportation systems in activities such as the 1997 National Automated Highway System Consortium (NAHSC) Demo and the 1998-1999 Snowplow projects in California and Arizona. [3]

3M Corporation, headquartered in Minneapolis, Minnesota, has also carried out several demonstrative projects based on a proprietary product, 3m Magnetic Smart Tape [4,5]. The magnetic tape, made in the same form as those used as pavement marking tapes, is embedded with magnetizable materials. Besides the use of the magnetic tape as a lateral position guidance system for special vehicles, such as snowplows, 3M has also explored other applications, such as lane departure warning systems.

Despite the distinct features of magnetic markers and tapes, the essential concept of utilizing the measurement of magnetic fields to help identify positions is unequivocally similar. With the increasing deployment of magnetic sensing systems, California PATH and 3M initiated cooperative efforts to further explore the usage of such technologies. 3M donated several segments of tape samples and helped install these tapes in a PATH facility. Work conducted at PATH on these tape segments allowed a preliminary evaluation of the magnetic tape. Through this work and future collaborative efforts, an assessment of magnetic sensing systems was carried out.

2.0 COMPARISON OF MAGNETIC FIELDS

In this section, the data collected from magnetic tape and marker tests are presented for a comparative analysis of the magnetic fields.

2.1 Data from a Magnetic Tape

The conducted experiments include static and dynamic measurements of the magnetic fields from sample tapes.

2.1.1 Experimental Setup

For the dynamic tests, three 60-meter tapes were donated by 3M and installed at a RFS roadway in January 1999. The three tapes are made with different magnetization schemes. The first tape is made with the magnetic field alternating its direction in the vertical direction every one meter. In other words, one meter of tape with magnetic flux pointing outward from the tape surface is followed by one meter of tape with flux pointing inward. The second tape is also made with one-meter switching interval, but one meter of tape possessing magnetic properties is followed by one blank tape with no magnetization. The third tape is made of uneven lengths of magnetized and un-magnetized sections with 1.3 meters of magnetized tape followed by 0.7 meters of un-magnetized tape. The tapes were laid flat and glued to the surface of a roadway, situated behind Bldg. 280 at RFS.

Another sample tape was received from 3M. This tape has a magnetization scheme similar to the first tape mentioned above. This tape is used in static experiments for the identification of field characteristics around a magnetic tape. The static measurement is set up with a tape laid flat on a long, (5cm x 15cm x 240 cm) wood board. The tape along with the wood is then positioned under a large flat (120 cm x 240 cm) plywood board with the point of field-switching located at the center of a grid drawn on the plywood board. This setup allows the tape to be extended in a flat manner beyond the edges of the plywood. The plywood is placed on a 90-cm high bench to minimize signal interference from the ground. A three-axis magnetometer, made by Applied Physics, is attached to a plastic bracket, which can be manually positioned at selected points along the grid on the plywood. The height of the sensor is adjusted by the mounting positions on the bracket.

The actual measurements took place with the sensor at a height of 20, 27, and 33 cm from the surface of the tape. The sensor bracket was moved in a grid of 21x21 points with a step size of 5 cm. Each set of data at a certain sensor height therefore allowed data sampling in an area of 100 cm x 100 cm on top of the tape. Since the magnetic field switches location at the center of the grid and the tape has a wavelength of about 2 meters, the sampling of this grid area was representative of a repetitive segment along the tape that includes 0.5 meters of “north” and “south” fields each.

For each sensor height, the measurements were taken with and without the tape in place. The background earth field did not vary much at the three sensor heights. However, since the experiments were set up inside a room with steel cabinets, carts, and computers nearby, the fields did experience variations on certain sections of the grid. The “actual” field data generated by the tape was obtained by subtracting the background field data from the composite field data.

2.1.2 Magnetic Field Features of 3M Tape

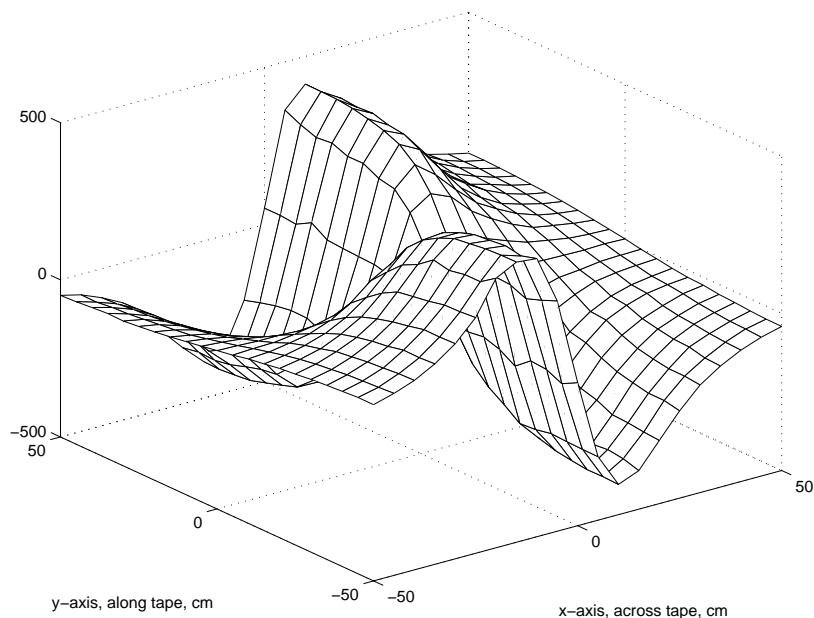


Figure 1. Tape Data, Lateral in mG, Sensor Height 20 cm.

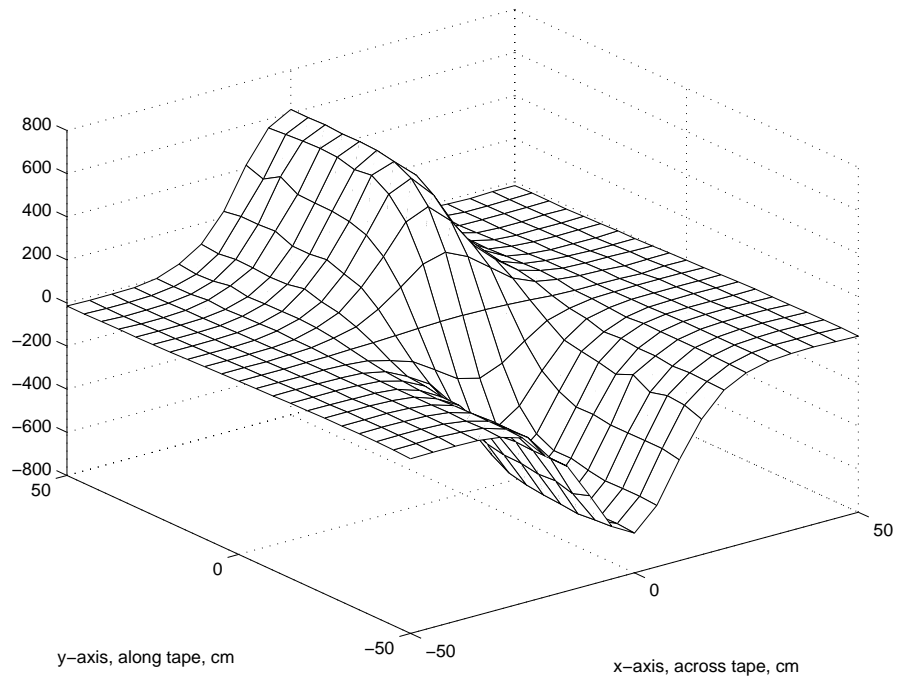


Figure 2. Tape Data, Vertical in mG, Sensor Height 20 cm.

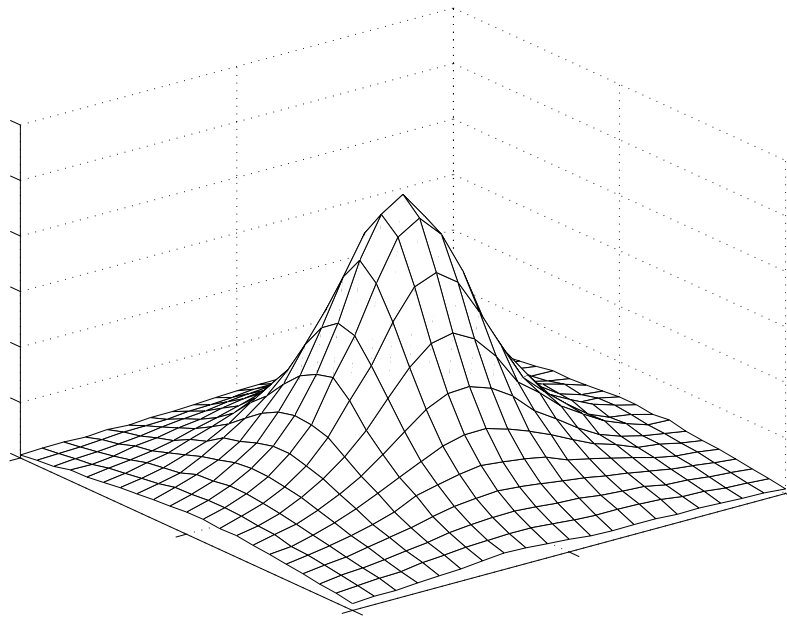


Figure 3. Tape Data, Longitudinal in mG, Sensor Height 20 cm.

Figures 1 to 3 are the three-dimensional plots for each component in three orthogonal axes with the sensor at a height of 20 cm from the tape. The longitudinal axis is parallel to the tape, the vertical axis perpendicular to the tape surface, and the lateral axis perpendicular to the other two axes. The tape is

centered along the zero position along the x-axis and the magnetic field switches its direction at the zero position along the y-axis.

Notice how the three components change over space. The lateral field is opposite in sign and symmetric in magnitude on two sides of the tape. The lateral component rises from zero at the center of the tape and reaches its peak at a distance about 10 cm from the tape, then gradually weakens farther away from the tape. The peak value for the data set in Figure 1 is about 400 milli-Gauss (mG). The pattern of lateral measurements across the tape at any cross-section remains the same, but the peak magnitude varies along the tape and becomes zero near the field-switching point on the tape.

The vertical field is the strongest right at the top of the tape, and diminishes to zero at about 25 cm away from the tape. The peak value is about 600 mG for the data set in Figure 2. The peak quickly drops near the field-switching point and the vertical field becomes totally flat at zero value right near the switching point. The longitudinal component becomes strong and reaches its peak at the field-switching point. The peak value for this data set is about 550 mG. The longitudinal field becomes weaker as the measurement point is farther away from the tape.

The distribution of magnetic strength near the tape can be envisioned by considering the fact that the tape consists of an infinite number of small segments along the direction of the tape. Each segment radiates magnetic flux from its surface. As these segments of the same polarity are assembled together, fluxes from adjacent segments dispel each other in the longitudinal direction and augment in the lateral and vertical directions. However, the situation is reversed when it gets closer to the switching point, where segments have opposite polarity. The fields in the lateral and vertical directions are cancelled out while the longitudinal direction sees attraction and strengthening. This results in the strongest longitudinal field near the switching point, but total elimination in the other two directions.

2.1.3 Dynamic Measurement of Tape on Pavement

Dynamic tests were conducted by driving a Buick LeSabre along the track where the magnetic tapes are installed. The data were collected with 3 magnetometers under the front bumper and 3 magnetometers under the rear bumper. The height of the sensors to the ground was estimated to be about 20-23 cm. The test run was conducted over the three tape samples, with a fraction of the data presented here.

The data in Figures 4 are those collected in a run with the vehicle going at approximately 9 m/sec (20 mph). They show how the three field components measured the front and rear sensors vary when the vehicle center, also the position of the center sensor, is kept close to the tape. Figures 5 show data taken in a run when the vehicle swerves back and forth in a S-maneuver over the tape. The horizontal axes in these plots indicate the number of data points taken at a frequency of 500 Hz.

Notice in Figure 5 that the back-and-forth fluctuation of the three components clearly indicates when the vehicle is crossing over the tape at various points during the test run. On the other hand, the curves in Figure 4 show that the vehicle is maintaining its center position relatively close to the tape with the left and right sensors detecting a weaker signal than the center sensor. The fluctuation in these components only indicates how the vector strength varies due to the magnetization patterns in the tape.

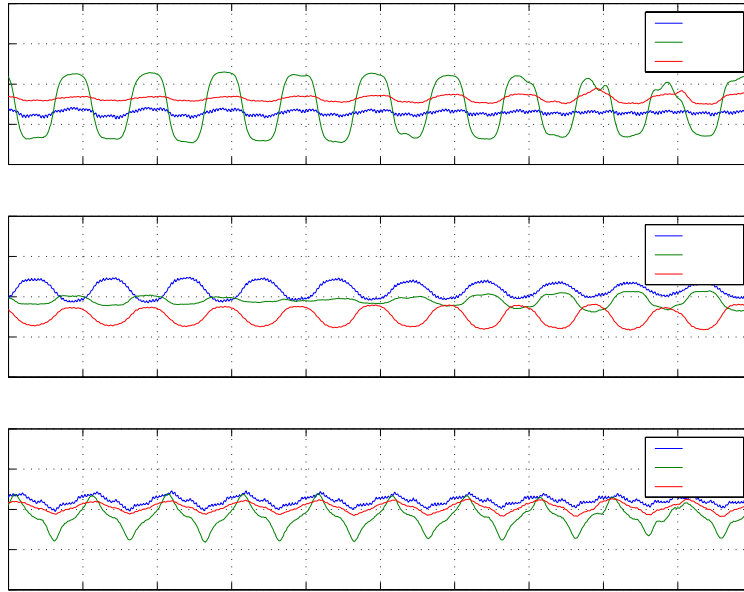


Figure 4. Dynamic Test Data, Sensors straight over Tape

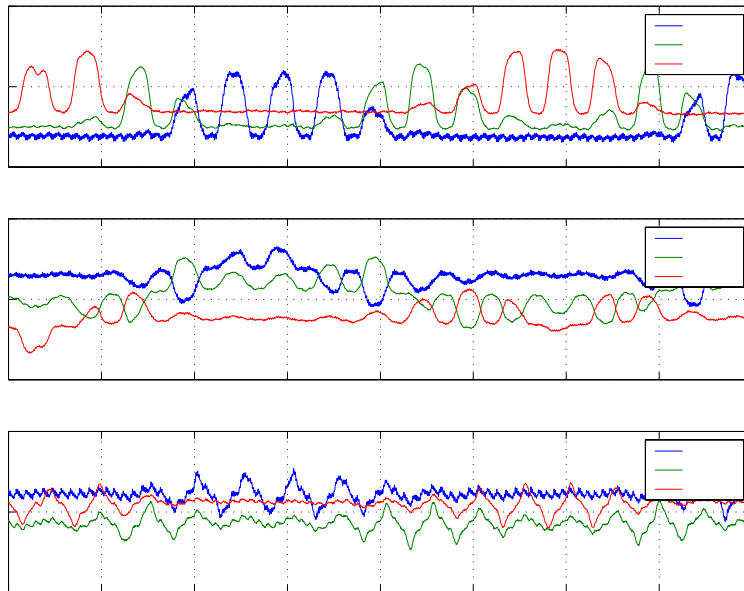


Figure 5. Dynamic Test Data, Sensors swerving across Tape back and forth

In a dynamic test with the vehicle maintaining its center position relatively close to the tape, the center sensor detects a much stronger signal than the side sensors. Fluctuation in all sensed signals is present due to the magnetization patterns in the tape. When the vehicle is swerving back and forth over the tape, the fluctuation in signals also reveals the instants when the vehicle is crossing over the tape during the test run.

2.2 Data from a Magnetic Marker

Similar experiments were conducted with a magnetic marker. The marker measured is a typical ceramic unit used in various PATH demonstrations. The unit is of a cylindrical shape with a diameter of 2.5 cm and length of 10 cm. Figure 6 shows the magnetic flux direction around a dipole created by the marker. The magnetic field intensifies near the top of the dipole, but diminishes when it is far away from the marker.

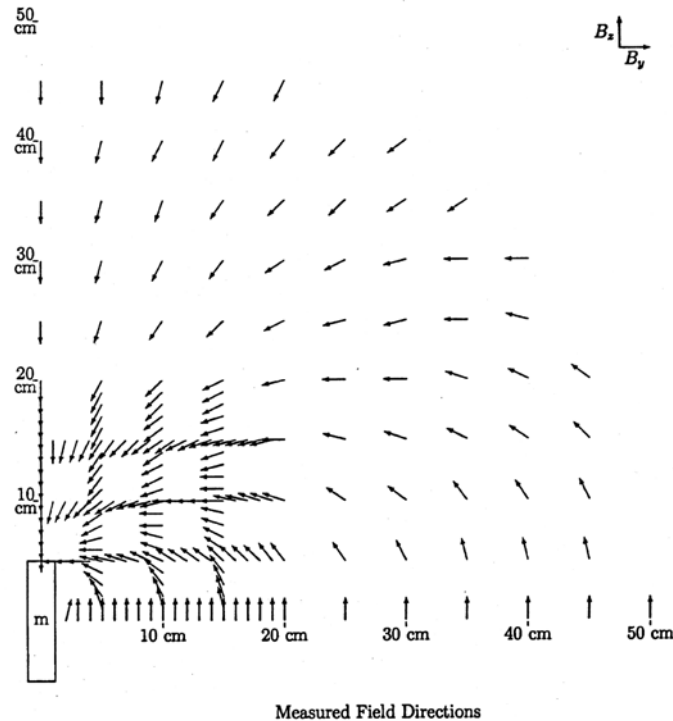


Figure 6. Magnetic Flux near a Dipole

A data set is shown in Figures 7 to 9 with the magnetometer placed at a height of 20 cm. The signal strengths generated by the sample marker were much stronger than those measured from the sample tape. The maps or patterns of the three field components are also distinctly different. This implies that the sensing schemes for two systems will probably require different approaches.

One visible difference between the magnetic tape and the magnetic marker lies in the alternating patterns among the three components. Note that in a magnetic marker system, the longitudinal field switches direction as the sensor moves across the top of the marker. The switching takes place with a steep change across zero level. This steep variation can be used to help identify the peak generated by the marker, although it is not mathematically required. In the case of the magnetic tape, however, the longitudinal field peaks when the other two components drop to near zero. On the other hand, the longitudinal component drops to near zero when the other two are peaking. Therefore, the longitudinal component is not as useful in identifying the peak as in the case of the magnetic marker. It should be noted, however, that the alternating features of the magnetic tape change when the magnetization schemes are different.

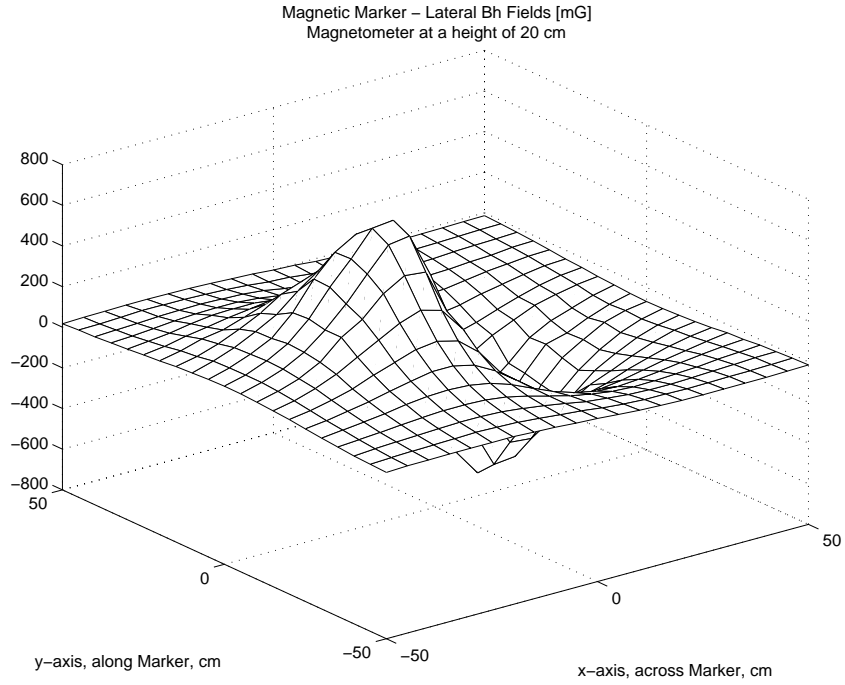


Figure 7. Marker Data, Lateral in mG, Sensor Height 20 cm.

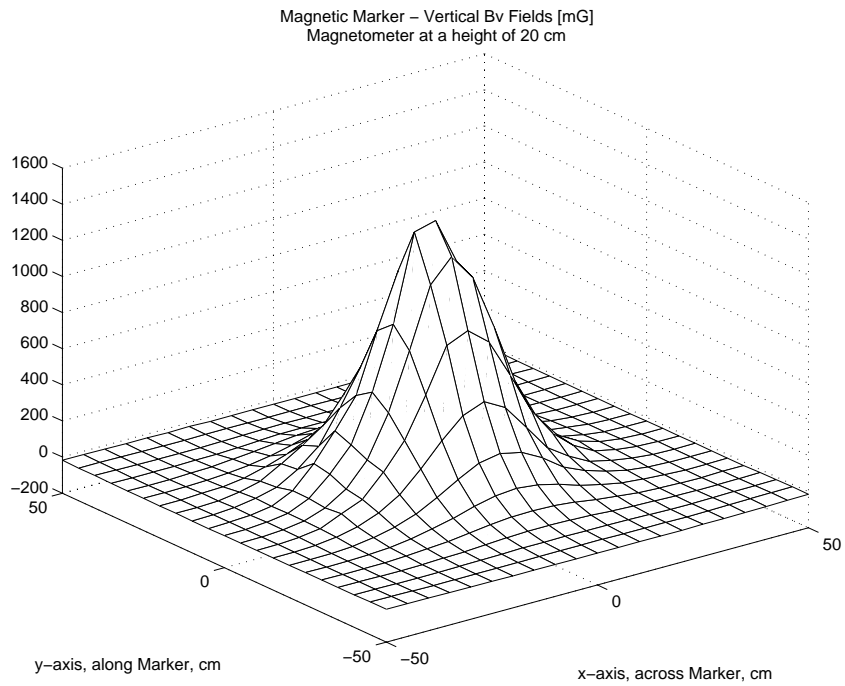


Figure 8. Marker Data, Vertical in mG, Sensor Height 20 cm.

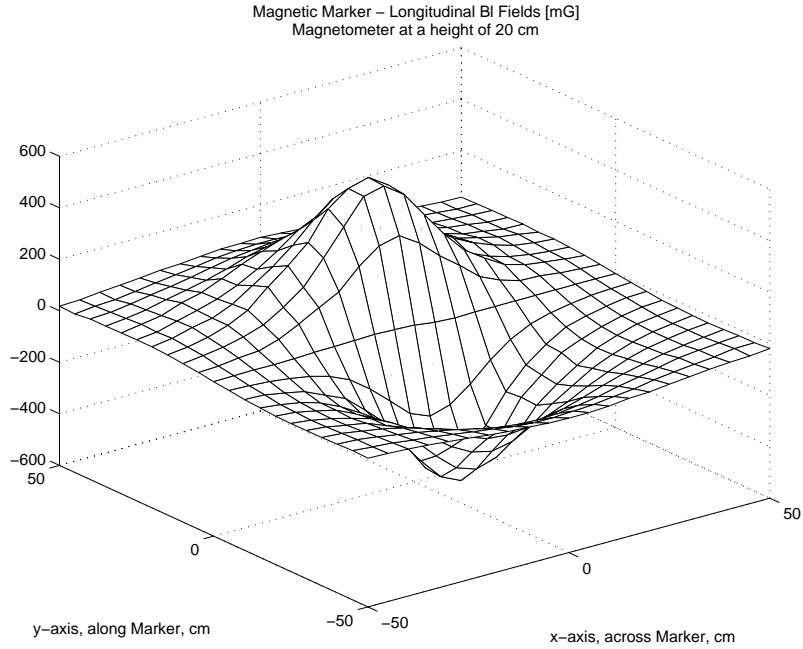


Figure 9. Marker Data, Longitudinal in mG, Sensor Height 20 cm

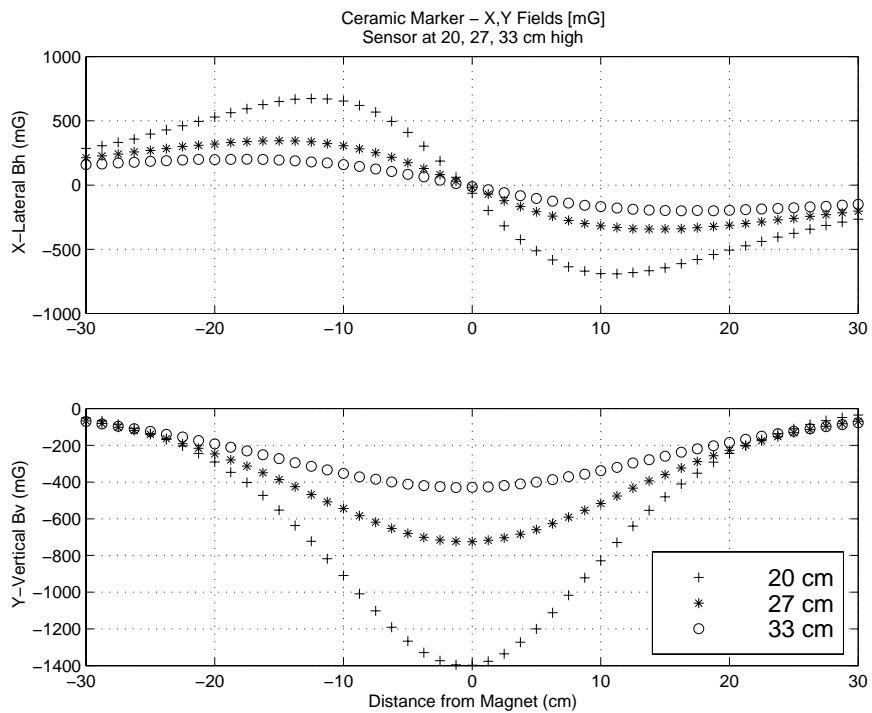


Figure 10. Lateral and Vertical Components of Marker Data at 3 different heights

3.0 DATA COMPARISON

This section compares the magnetic fields around a marker and a tape to offer certain observations on the potential performance in a vehicle guidance and control application.

3.1 Data Comparison from Static Testing of Magnetic Marker and Tape Systems

This set of data was obtained by placing a magnetometer at a certain height from the marker or the tape to capture the magnetic fields. The following data plots show the net field after the ground field is subtracted.

3.1.1 Magnetic Marker and Tape Data

Figure 10 and 11 shows the magnetic fields (lateral and vertical components) around a typical 10-cm long ceramic marker and a sample 3M tape.

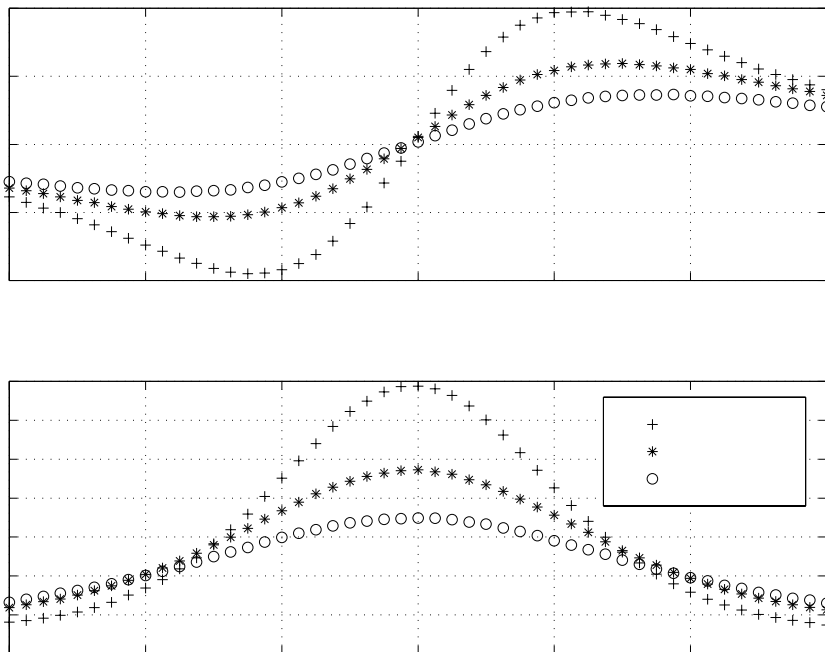


Figure 11. Lateral and Vertical Components of Tape Data at 3 different heights

3.1.2 Observations

As seen above, the magnetic field generated by the tape is much weaker than those by the marker. A significant consequence from that comparison is that the signal-to-noise ratio will be smaller in field applications when using the tape. In particular, for applications where sensors on a vehicle may be placed higher from the ground, it can result in the deterioration of performances.

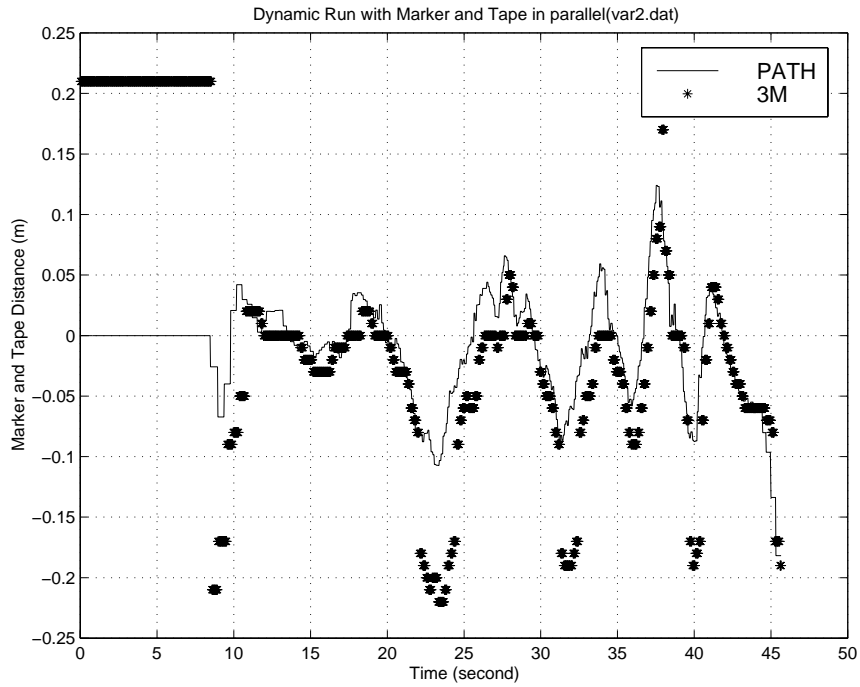


Figure 12. Estimated Position given by 3M and PATH Sensing Systems with Sensor Assembly Placed slightly to the left of Tape Center

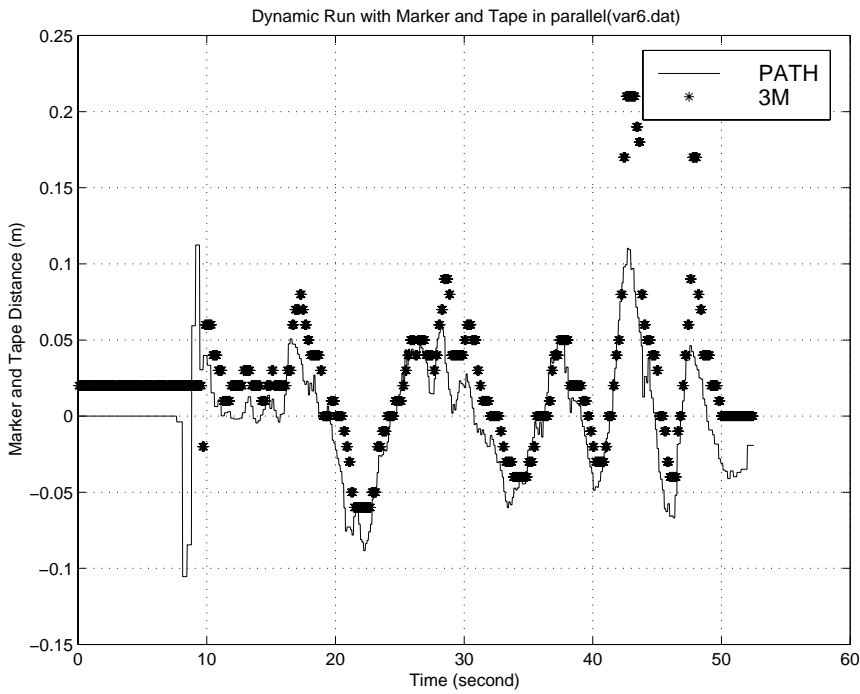


Figure 12. Estimated Position given by 3M and PATH Sensing Systems with Sensor Assembly Placed slightly to the right of Tape Center

3.2 Data Comparison from Dynamic Testing of Magnetic Marker and Tape Systems

The following set of data was obtained by running dynamic tests along a test track in PATH Richmond Field Station. The test track has a stretch of 3M tape installed at about 120 cm in parallel to an existing magnetic marker track. A 3M sensor-assembly was mounted at the front bumper of a PATH experimental vehicle and protruded to the side so that the sensor assembly was positioned on top of the tape. The experimental vehicle was controlled by the PATH guiding system to follow the marker track automatically.

3.2.1 Dynamic Test Data with Estimated Position given by 3M and PATH Sensing Systems

Figures 12 and 13 show the calculated position relative to the marker and the tape, as indicated by the two systems respectively. Since the placement of the 3M sensor-assembly to the side of the vehicle is not exactly precise, the plots show one set is slightly positioned to the right and the other is slightly to the left of the tape center.

3.2.3 Observation

The first 10 seconds or so of the data in each plot should be disregarded since the 3M sensor-assembly uses a quality indicator to reflect the readiness of the sensing function. It will require the vehicle speed to reach a threshold before the data is considered valid. The ideal speed of operation was said to be around 9 m/sec (20 mph).

The two data plots above show that the position estimation produced by the two systems are comparable. There are two noticeable features:

- (1) The 3M tape data show spikes and much larger measurement errors when the position is more than 10 cm from the tape.
- (2) There is a time lag in the 3M signal when compared to the marker system. This is mainly due to the fact that the 3M system uses time averages in signal processing and only generates an update every 0.1 second or so.

Both of these features may have significant complications in applications where deviations in precision and time delays are not tolerable. These complications also reduce the predictive ability of the system to produce "future information" that is needed either for higher speed operation, or stable steering to reduce driver workload.

4.0 COMPARATIVE ASSESSMENT

Besides the technical evaluation of magnetic fields and corresponding algorithms, an assessment of these systems for real-world applications is not complete without a more in-depth understanding of all related costs and complications. A thorough study is necessary, especially for a large-scale adaptation of these systems. For example, in a study by Japanese Advanced Cruise-Assist Highway System Research Association (AHSRA) [6], considerable efforts were carried out in assessing magnetic marker, tape and other systems. The evaluation criteria should at least include the following measures: accuracy, reliability, durability, cost, and applicability, which are described in more detail below.

(1) Accuracy

The achievable accuracy is affected by the sensing algorithms and the noises present in the operating environment. In recent years, the PATH magnetic markers and associated sensing algorithms have proven to be accurate within 5 mm near the markers and 2-3 cm at 30 cm from the marker. The magnetic tape and its sensing systems setup in recent demonstrations were used to indicate the vicinity of the tape with an accuracy of 5-8 cm reportedly. One major factor in the achievable accuracy is the signal to noise ratio in these two sensing systems. It is preferably to have a strong signal to noise ratio as in magnetic markers. The discrete nature of magnetic markers also allows the flexible use of various sizes or magnetic strength at specific locations.

(2) Coding capability

The discrete nature of marker systems offers another feature, which is the ability to arrange the magnet polarity in a particular sequence to embed coding information on the roadway. As a vehicle travels along the magnets, a code is conveyed to the vehicle for various types of information, such as milepost, entry, exit, direction of travel, and other control information.

(3) Reliability

The usefulness of a system depends on the consistency and robustness of its operation in a wide range of operating conditions and under a variety of disturbances. Both the magnetic marker system and the magnetic tape have been studied to overcome these problems with the use of signal processing techniques. As with regard to weather, the magnetic marker and tape systems have been shown to work reliably in rainy and snowy conditions.

(4) Durability

Durability is a major concern especially for large-scale implementation. The durability of magnetic marker and tape systems is tied into the life cycle of roadway surface because they are installed on or near the surface of pavement. The replacement cycle of pavement must be considered along with the integrity of marker or tape systems under a long period of usage.

(5) Cost

In calculation of the total cost of magnetic sensing system, it is important to consider material, survey, installation, maintenance, repair, and life cycle. The process of survey and installation can be fully automated potentially for both systems to minimize the costs. The maintenance expenses and life cycles need to be further evaluated.

(6) Applicability

Although the technical feasibility of a sensing system can be evaluated independently, its performance requirements are strongly related to its application. The magnetic marker system has been demonstrated by PATH over the years with outstanding accuracy and reliability. It is suitable for a variety of applications, such as lateral control at highway speeds, precision docking, and driver assistance for specialty vehicles. The magnetic tape system has been demonstrated to be a valid candidate for driving guidance for specialty vehicles. Due to the current limitation in position accuracy, it has not been deployed for precision or high-speed automated control.

5.0 CONCLUSION

Magnetic sensing has been proven to be an effective positioning sensing system. Magnetic markers and magnetic tape, although different in their construction and characteristics, have both been demonstrated for selected AVCSS applications. Based on the measurements and evaluation tests as shown in this report, it is found that the magnetic marker systems offer better performances and more desirable features than the 3M system with its current setting and design.

To provide enhanced performance of the magnetic sensing systems, improvements may be sought in several areas, such as physical construction, signal processing, and costs. Considerations in physical construction involve the automation of installation and inspection, as well as the optimization of magnetic strength and layout design. Robustness and accuracy enhancements in signal processing are desirable. To promote the use of these technologies, it is essential to explore means to reduce material and sensing system costs in addition to the overall infrastructure investments.

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