DETERMINING RAIL TRACK MOVEMENT TRAJECTORIES
AND ALIGNMENT USING HADGPS

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ABSTRACT

High Accuracy Differential Global Positioning System (HADGPS) was employed to conduct repeated track position surveys, at different speeds, over a 1,400 ft section of track. A parametric curve fitting best-fit Splines (B-Splines) algorithm was used to smooth the real-time kinematic (RTK) GPS data and optimize track position accuracy. The data generated from surveys employing HADGPS positioned atop a hy-rail vehicle yielded a baseline average horizontal and vertical accuracies of 1.2 cm (0.47 ins) and 2.2 cm (0.87 ins) respectively. Accurate position data is provided for track alignment and track displacement trajectory determination. The coordinates also provide location data for track superstructure and substructure anomalies identified during track monitoring.

INTRODUCTION

The project objective is to determine the accuracy of the HADGPS for routine surveying of track in a simplified set-up (platform), collect accurate track position data at different surveying speeds. Track surveying data is stored in a GIS database and will be used for track alignment and track movement monitoring, especially in areas of considerable ground movement. The data can also be processed applying a statistical model to calculate horizontal and vertical displacement, and including the time factor, the rate of displacement which may be indicative of substructure or geological anomaly.

Significant technological advances have been made in Mobile Multi-Sensor Systems (MMS) that accurately inventory geometric data along transportation routes such as roads, rivers and railways (1). Global positioning systems (GPS) is becoming more of a precise and inexpensive surveying tool that is readily integrated with other sensors to provide three position and three orientation parameters to describe the position of the track and vehicle trajectory. The HADGPS is a key component of a multi-sensor platform that is being developed to measure rail track movement and monitor subsurface maintenance and stability features in real-time. Initial trials were conducted with the HADGPS rover both located on a lightweight sensor platform towed behind a hy-rail, and attached to the hy-rail roof. Besides the high-tech hardware being configured, fusing data from multi-sensors in real-time requires efficient software to collect, store and interpret the data.

Accurate coordinates from the HADGPS provide location data to correct track misalignment and monitor movement, in real-time kinetic (RTK) mode. As the sampling rate of the GPS is constant, surveying at a higher speed will result in a lower density of data collected. For example, the HADGPS (Trimble 5700) samples every second and sampling at 30 mph collects a data point every 44 feet, at 10 mph about every 15 feet. Traditional surveying practices are labor intensive and have produced mixed results especially when
used in areas on significant ground movement, which often results in the continuous movement of the surveying monuments.

The HADGPS requires base-stations be setup at strategic intervals to achieve signal continuity and sufficient number of satellites within the appropriate geometric limits. Presently there are no other technologies that can compete in provide such location accuracies economically. However, in areas where the satellite signal is interrupted the GPS has to be integrated with other sensors such as Inertial Navigation Systems (INS) or vision-based systems (digital cameras) (2). The GPS-derived positions can act as an excellent external up-date for the INS and the INS can provide precision position data for the GPS during signal acquisition interruptions. This redundancy improves the reliability of the system. Similar to other hi-tech products, the unit price of GPS has dropped dramatically this past decade, for the 300 feet to the 0.4 ins accuracy range.

Wildi (3) developed a modular platform for kinematic track surveying (GPS-RTK) at speed up to 3 mph. An 11 mile section of railway line was surveyed with back and forth runs of the GPS platform. In sections without signal interruptions an accuracy of 0.6 ins horizontal and 1.0 ins vertical was reported. Using GPS to measure or survey the three dimensional coordinates of track geometry kinematically, with high accuracy, has been a significant recent trend. From 1993 to 1995, the Technical University Graz and the Research and Testing Department of Plasser Theurer studied the use of GPS for track surveying (4). The study showed that GPS yielded surveying accuracies of +/- 0.24 ins horizontal and +/- 0.4 ins vertical, traveling at a speeds of 1 to 2 mph. Zywiel (5) describes a GPS-supported electronic track surveying device (EM-SAT) used to complement an automatic leveling, alignment and tamping machine that can smooth existing track errors. Using a computer-assisted laser (chord measuring) technology, level accuracies of 1 mm (0.04 ins can be achieved. For this high precision it is necessary to have fixed GPS base-stations 6 to 12 miles apart. Ebersohn (6) used a profile geometry roughness factor ($R^2$) as an indicator of track service ability, based on 62.3 ft (19 m) chord geometry measurements. Munsen (7) has been developing GPS algorithms to precisely monitor rail position, then combine track survey and rail temperature data to infer contained rail stress to permit a prediction of some types of rail buckling.

**HADGPS SYSTEM PERFORMANCE AND APPLICATIONS**

High accuracy, RTK GPS surveying requires three modes of space vehicle (SV) signal reception and correction. Basic GPS location requires reception of the Course Acquisition Code (C/A phase). This provides a single point accuracy of less than 15 meters (47 ft). Using a second base station to calculate differential corrections and transmit them to a rover provides sub-meter accuracy in real-time. Operation of a real time differential station transmitter requires FCC licensing. One centimeter (0.4 ins) accuracy uses the SV carrier signal emissions. Carrier phase techniques count the number of wavelengths in the L1 and L2 band SV transmission to refine the position to within one centimeter horizontal and 2.0 cm (0.08 ins) vertical accuracy.

RTK surveying performance is influenced by several site-related factors. Most significant is a blocked horizon. The GPS antenna must have a clear line-of-site to the SVs. Hills, track below roadway grade, foliage, and structures all present difficulties for RTK surveying. Significantly, in the Appalachia region the dense foliage surrounding the track
quite easily blocks the low power SV carrier signals, resulting in a loss of initialization and data dropout.

**GPS TRACK SURVEYS**

To initiate HADGPS data collection the base station is established, see Figure 1. The antenna is placed on the hy-rail rack and aligned with the inside edge of the rail using a theodolite. The GPS RTK data is collected while the hy-rail is traveling at a specific speed. Firstly, a baseline was established, then data was collected traveling at speeds of 5, 10 and 15 mph and statistically compared to the base line to determine measurement accuracy. An accurate baseline for the track, or more specifically rail, is established by collecting high density of data from the HADGPS traveling less than 3 mph and stored in a GIS database. Conducting additional surveys periodically will generate new data sets.

**MOBILE PLATFORMS DESIGNS**

The initial platforms initially considered to support the HADPS and other sensors are inexpensive and robust. Two towed GPS platforms were constructed and tested. The first platform, designated Type I, was constructed using a Nolan model TD-3 track dolly (three wheel) as the base instrument stage, weighing 108 lbs. The Nolan TD-3 proved to have unacceptably low ground clearance. The dolly bottomed and lifted at crossings. Further, the dual flanged wheels did not negotiate switches and frogs without being manual lifted. Vibration due to the lack of wheel cushioning or suspension loosened fasteners on some instruments. However, the TD-3 dolly is small, light and easy to transport in the back of a small station wagon. The Type I base was replaced by a Type II platform employing a Nolan model TS-1 track cart a base of weight 175 lbs. Both platforms meandered between gauge-side rails exhibiting a side-to-side movement of approximately 1 to 3 ins. A spring loaded swing arm arrangement engages the gage side of the rail, the GPS antenna and pick-up to which are directly mounted. The assembly was able to navigate all grade crossings and pass through switches and frogs without manual intervention. Measurements were collected at velocities of 3 to 15 mph. However, due to damage to the GPS takeoff arm on bolted rails; reduced sky visible to the GPS antenna; and site assembly/disassembly requirements, mounting the GPS antenna directly to a hy-rail vehicle was explored.

**HY-RAIL PLATFORM**

The GPS receiving antenna and UHF differential receiving antenna were mounted to a rack attached to the roof of the hy-rail equipped vehicle. This orientation maximizes the sky visible to the GPS antenna and reducing data dropouts. Alignment of the GPS antenna location on the rack is accomplished with the use of a theodolite, set up on the gage side of the rail. The center of the GPS mount is aligned with the inside flange of the hy-rail vehicle. A standard differential level circuit is used to determine the elevation offset from the top-of-railway to the bottom of the antenna mount. Entering the elevation offset into the survey controller corrects elevation for data collected during a survey.

Several error sources in this method are apparent. Using a fixed antenna mount, the out-of-plumb error due to grade and cross-level are shown in Figure 2. More subtle errors stem from the vehicle ‘wandering’ between the gauge side of the rail. Vehicle speed has an influence on wandering. Testing confirms that at low speed the vehicle ‘falls’ to the inside of
a super-elevated curve. These errors can be accounted for and a correction to the data made in real time.

**TRACK MODELING ALGORITHMS**

As previously indicated, sets of data was collected with the HADGPS atop a hy-rail traveling at speeds of 5, 10, 15 mph. Initially baseline was established with GPS data form a survey speed of less than 3 mph. The HADGPS rover was then moved along the hy-rail rack, perpendicular to the line of the track, to a fixed a distance of 139.33 cm (54.9 ins), an arbitrary number. The above process was repeated with GPS RTK data sets collected at speeds of 5, 10 and 15 mph. If the fixed sample rate of the GPS is one data point per second then at 5, 10 and 15 mph data points will be collected every 7.3 ft, 14.7 ft and 22 ft respectively. A parametric curve fitting B-Splines algorithm was used to fit the baseline data, generated at a survey speed of less than 3 mph. Then two methods were used to determine the accuracy of the collected data sets compared with the fixed distance the rover was moved on the hy-rail rack.

1. The shortest distances of each point in the monitoring data sets (5, 10, 15 mph) (normal) to the baseline (B-Spline) curve is calculated, each set representing the position of the rail. Subtracting the fixed distance between the rovers 139.33 cm (54.9 ins) from the distance of the points of the monitoring data set to be baseline curve and plotted an error (Gaussian noise) distribution is generated, see Figure 3.

2. The curve fitting algorithm is applied the each monitoring data set and the shortest distance between the two curves (baseline and new curve) can be determined.

Track monitoring surveys conducted periodically will generate GPS data sets to be compared to baseline data, utilizing a GIS database. Tables 1 and 2 present position data repeatability or accuracy, which is mean of the horizontal and vertical differences, respectively, of each 5, 10 and 15 mph speed data sets, to the baseline, surveyed with the rover in the same position. The other values shown in Table 1 are the mean of the horizontal distance between the points generated by the rover moved a distance of 139.33 cm (54.9 ins) and the baseline created by rover in initial position; and the last column, the mean distance between the B-Splines created from the data set generated by the rover in the second position, and the baseline.

**DISCUSSION**

From Tables 1 and 2 present the horizontal and vertical components of GPS data from repeated runs over a 1,400 ft section of track with the simple hy-rail set-up. The data generated yielded average accuracies of 1.2 cm (0.47 ins) horizontal and 2.2 cm (0.87 ins) vertical for speeds of 5, 10 and 15 mph. As expected, the vertical component accuracy of the GPS data is less than the corresponding horizontal component. Figure 4 presents a graph of the elevation data for the track position data surveys along the 1,400 ft track, for speeds 5, 10, 15 mph. The vertical axis is marked in 10 cm (3.9 ins) intervals to demonstrate the narrow range of data collected using the HADGPS. Although the density of data collect decreases with increase in speed, the vertical and horizontal component accuracies are similar, for the GPS system (one data set) and using the data set differences using the B-Splines algorithm. From the two GPS surveys with the rover positions at a fixed distance
apart yielded: average accuracies from the two methods to calculate the rover separation using the B-Splines algorithm of effectively 0.2 cm (0.08 ins) and 0.4 cm (0.16 ins) respectively. However, the usefulness of HADGPS for track alignment and displacement monitoring will depend on the application system errors: DGPS station accuracy, environmental (weather, obstructions) and platform/sensor set-up. Thus system errors would probably increase significantly when the HADGPS is applied for larger scale track surveys.

Locating rover on the hy-rail is very practical but not the most precise for definitive rail or track position data. An inexpensive inclinometer or gyroscope could quite easily be configured to compensate the data for change in track super-elevation. System errors could be reduced by locating the rover closer and directly over the rail: A double flange wheel to reduce lateral movement relative to the rail.

The GPS/INS configurations can provide continuous accurate data, but is expensive. There are other lower-cost systems, and less accurate, such as employing a Kalman Filter algorithm to integrate GPS and Dead-Reckoning (DR) data, using an odometer (measuring wheel) and digital compass, for example. There has been a continuous improvement in other applicable technologies both in price and capability and have potential to enhance or compliment GPS technology, such as micro-electro-mechanical systems (MEMS).

Multi-sensors are being configured and efficient software developed to collect and store track position and track quality data on a GIS database. For the purpose of track alignment and displacement the stored data can be retrieved at any time and processed to produce valuable data for track maintenance operations. Incorporating the time period between surveys, the rate of track movement can easily determined at any point along the surveyed track, which can be a useful indicator of track superstructure, substructure or geological anomalies.

CONCLUSIONS

This small-scale study has shown the usefulness of HADGPS for railway track superstructure and substructure monitoring. Accurate track position collected with a relatively inexpensive GPS platform set-up and employing a data smoothing algorithm (B-Spline) the speed of data collection (5 to 15 mph) did not unduly influence data accuracy. However, these surveys were conducted on a short section of track (1,400 ft) without the need to compensate the data for change in super-elevation and GPS signal interruption. Therefore, there is considerable research effort required to apply this technology (sensor) for large-scale monitoring operations. Future research will involve refining the data smoothing algorithms and developing efficient software to collect, store and process the data. The geometric data needs to be presented in a format suitable for engineers engaged in track alignment and maintenance operations.

ACKNOWLEDGMENTS

The authors acknowledge the funding provided by the Federal Rail Administration and West Virginia Department of Transportation. Resources and administrative assistance from the Nick J. Rahall Transportation Institute, Marshall University; and the CSX and Norfolk Southern railway companies for their generous assistance in providing resources and rail track sites for investigation.
REFERENCES

TABLE 1: Horizontal Component of GPS Data

<table>
<thead>
<tr>
<th>Speed of Hy-Rail GPS Survey</th>
<th>Data Repeatability (Accuracy) cm</th>
<th>New Survey Point to Baseline Distance</th>
<th>New Survey Line to Baseline Distance</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean cm</td>
<td>From Initial 139.33 cm</td>
<td>Mean cm</td>
</tr>
<tr>
<td>5 mph</td>
<td>1.37 (0.54 ins)</td>
<td>139.15</td>
<td>0.18 cm (0.39 ins)</td>
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<tr>
<td>10 mph</td>
<td>0.77 (0.38 ins)</td>
<td>139.27</td>
<td>0.06 cm (0.02 ins)</td>
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<tr>
<td>15 mph</td>
<td>1.35 (0.53 ins)</td>
<td>139.06</td>
<td>0.27 cm (0.11 cm)</td>
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<tr>
<td>Average</td>
<td>1.16 cm (0.46 ins)</td>
<td>0.7 cm (0.07 ins)</td>
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</table>

TABLE 2: Vertical Component of GPS Data

<table>
<thead>
<tr>
<th>Speed of Hy-Rail GPS Survey</th>
<th>Data Repeatability (Accuracy) cm</th>
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</thead>
<tbody>
<tr>
<td>5 mph</td>
<td>1.93 cm (0.76 ins)</td>
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<tr>
<td>10 mph</td>
<td>2.42 cm (0.95 ins)</td>
</tr>
<tr>
<td>15 mph</td>
<td>2.19 ins (0.86)</td>
</tr>
<tr>
<td>Average</td>
<td>2.18 cm (0.89 ins)</td>
</tr>
</tbody>
</table>
Figure 1: Photo of HADGPS and Hy-Rail Setup

Figure 2: Error Due to Super Elevation of Track
Figure 3: Error (Gaussian) Distribution Curve for New Survey Point To Baseline GPS Data

Figure 4: Elevation Data from GPS Surveys, Traveling at Speeds 5, 10, 15 mph.
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Table 2: Vertical Component of GPS Data

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