Global Positioning System with an Attitude Method for Collecting Roadway Grade and Superelevation Data

ROBERT AWWUH-BAFFOUR, WAYNE SARASUA, KAREN K. DIXON, WILLIAM BACHMAN, AND RANDALL GUENSLER

The use of a specialized Global Positioning System (GPS) to conduct high-speed surveys of roadway alignment, grade, and cross-slope characteristics is discussed. The system uses a single GPS receiver that has 24 channels monitoring four separate antennas (six channels each). The collection of attitude (heading, pitch, and roll) is made possible through the relative orientation of the antennas. By mounting the system on a road surveillance vehicle, accurate grades, superelevation, and crown measurements can be made without differentially correcting the GPS data. However, to gather precise positional data that correspond to the roadway measurements, differential correction with a GPS base station at a fixed known point is required. The design and use of this attitude GPS unit are addressed. Accuracy specifications for static testing are provided along with techniques to maximize this accuracy. Kinematic data collection is depicted for a local road and a freeway off-ramp. The use of digital terrain modeling technology provides a promising graphic database representation of the roadway characteristics.

The ability of a department of transportation or local municipality to maintain an accurate database of roadway alignment, grade, and cross slope is essential to ensuring proper roadway maintenance and improvement evaluation. Similarly, FHWA requires state transportation departments to regularly report highway database features including road curvature and percent grade. Conventional field surveying and as-built certification require time-consuming data collection in which workers must physically measure the pavement surfaces. This standard surveying technique is costly and exposes the survey crew to dangerous conditions adjacent to active traffic. Lanes are often closed to minimize the risk of exposure to the surveyors, thereby adversely affecting traffic operations. An affordable tool that provides quick verification of site conditions while a vehicle progresses within the traffic stream would be an attractive alternative to traditional surveying techniques.

Researchers at the Georgia Institute of Technology (Georgia Tech) have combined the Global Positioning System (GPS) technology with kinematic vehicle operations to collect roadway alignment, grade, and cross-slope data simultaneously. Initial field studies with this system have produced promising results. Georgia Tech is using this system to obtain road characteristic data that are being used as input to a geographic information system–based mobile emissions model it is developing in conjunction with the Environmental Protection Agency. Other methods of obtaining these data were evaluated but were found to be cost prohibitive or lacked the accuracy needed for mobile emissions modeling. Although only grade and position are needed for the mobile emissions model, the system's ability to collect superelevation and roadway crown measurements simultaneously with grade makes it especially appealing for other applications.

ALTERNATIVE DATA COLLECTION TECHNIQUES

There are several methods for collecting grade and cross-slope data. Georgia Tech evaluated these methods in terms of their relative accuracy, their ability to collect both grade and cross-slope data simultaneously, cost, speed of collection, and safety considerations. The results of this evaluation are summarized in the following paragraphs.

Conventional survey techniques use manual methods to collect point coordinates and elevations. Surveyors use levels, rods, and electronic data collectors for site measurement. The point and elevation data collected are extremely accurate; however, the time required for data collection coupled with reduced safety and restricted traffic operations make this approach inflexible for large-scale database development. Furthermore, accurate grades can be achieved only if short distances between survey points are used.

Survey techniques in concert with hand-held GPS equipment again can provide accurate results, but they exhibit disadvantages similar to those of manual methods. Locating survey equipment in a static vehicle permits data collection with improved safety. The survey vehicle is typically positioned on the shoulder of the roadway, and with the aid of an electronic data collector, disto-meter, notebook computer, and GPS unit, accurate results can be obtained for the pavement cross section extending approximately 90 m (295 ft) beyond the front of the vehicle. This technique accommodates relatively quick database development; however, the required equipment is costly and the vehicle cannot be in motion during data collection.

The use of technology developed for the defense industry incorporates a gyroscope and accelerometer to provide a vehicle heading, pitch, and roll angle. The Michigan Department of Transportation developed a prototype, the PosNav System, in 1992 and has observed reasonably accurate results (1). The PosNav permits kinematic data collection so large quantities of data can be collected in a short period of time. The equipment is fairly expensive (estimated at $69,000 in 1992) and provides accuracy to within 0.1 percent of actual values.

Other jurisdictions have tested alternative inertial systems such as the VIASAT Mobile Highway Survey System that uses a GPS unit, camera cluster, and gyroscope (2). These inertial systems provide various levels of accuracy; however, the equipment expense is generally identified as the biggest disadvantage of these alternative methods.
Data extraction from as-built plans can be very accurate, especially if the plans were adjusted with field survey data to reflect the actual alignment after the road was constructed. The major disadvantage of the technique is that as-built plans are not always available, and it is very labor intensive to extract data from hard-copy as-built plans.

It is very easy to automate the collection of grade and crown-slope data from a digital terrain model such as U.S. Geologic Survey digital elevation data, but this method is not very accurate because most existing digital data sources that provide terrain data have a very low resolution because they were developed from high-altitude aerial photogrammetry surveys.

GEORGIA TECH ATTITUDE GPS TECHNIQUE

The proposed Georgia Tech method uses a specialized GPS unit with multiple antennas connected to a multichannel GPS receiver and a notebook computer. The self-contained unit is mounted to a fabricated roof frame on a passenger van and has been evaluated both statically and kinematically. Vehicle attitude is computed and postprocessed to determine grade and cross-slope data.

Determination of Attitude

Attitude is defined as the orientation of a land vehicle, ship, or aircraft (body-fixed frame) in a specific coordinate system with respect to a global or local coordinate system or reference frame. Three parameters are commonly used to define attitude: the Euler angles for roll, pitch, and yaw (heading). Gyroscopic devices such as those described earlier are capable of measuring attitude (bank and direction) in addition to grade. Another method for measuring attitude is by using a GPS attitude determination unit. GPS attitude determination units have origins in the aerospace industry. These units use multiple antennas connected to a single GPS receiver. A number of manufacturers of GPS equipment have developed attitude determination units that are specifically designed to be used on aircraft or seagoing vessels.

The orientation of the antennas is instrumental in the identification of the Euler angles that make up attitude. Some possible orientations of a four-antenna array are presented in Figure 1. An antenna configuration that maximizes baseline distances is critical in determining accurate angles because there is a fuzziness in the antenna positions as determined by the GPS. By spreading out the antennas, the adverse effects of this fuzziness on the angles are minimized. This is synonymous to two points defining a line. If there is any fuzziness in the position of the points, the variability of the direction of a line that goes through both points will be less as the distance between the points increases.

Figure 2 illustrates how Euler attitude angles are determined in a T configuration. The roll angle measures the rotation of the vehicle about the axis. In Figure 2 the vehicle is moving along the x-axis. The roll axis is defined by Antennas 1 and 2. Roll is determined by calculating the relationship between Antennas 3 and 4 and the roll axis. The pitch angle measures the rotation of the vehicle about the axis passing through Antenna 1 and parallel to the line defined by Antennas 2, 3, and 4. This is the rotation about the y-axis in Figure 2 and is also the zenith angle. The heading is a rotation about the vertical axis. This is also the azimuth of the vehicle. The system is configured such that if all three angles are zero, then the vehicle is moving straight and level and heading north.

A mathematical calculation is used to determine the Euler angles from the antennas’ positions. Let the baseline vector of the antennas’ relative positions be given by \( \Delta X \), which is a 3 x 3 matrix in the form

\[
\begin{bmatrix}
    dx_{12} & dx_{13} & dx_{14} \\
    dx_{23} & dx_{24} & dx_{34} \\
    dx_{23} & dx_{24} & dx_{34}
\end{bmatrix}
\]

The expression \( d_{kj} \) is equal to the \( k \) coordinate of antenna \( j \) minus the \( k \) coordinate of antenna \( i \). Two vectors are needed to calculate the Euler angles. The baseline body frame vector is made up of the antennas’ relative positions when the vehicle is absolutely level (pitch and roll equal to 0). The baseline local reference frame vector is made up of the antennas’ relative positions at a survey point. The relationship between the body frame vector and the local reference frame vector provides the Euler angles of the vehicle at the survey point. The angles are calculated by using the following mathematical expressions. If the body frame vector is given as \( \Delta X_b \) and the local reference frame vector is given as \( \Delta X_l \), the relationship between the vectors \( \Delta X_b \) and \( \Delta X_l \) may be described by a similarity transformation in the form

\[
\Delta X_l = R \Delta X_b
\]

(1)

where \( R \) is a rotation matrix composed of the Euler angles of rotation (roll, pitch, and heading). The rotation matrix \( R \) is determined by least squares as

\[
R = \frac{\Delta X_l (\Delta X_b)^T}{\Delta X_b (\Delta X_b)^T}
\]

(2)

where \((\Delta X_b)^T\) is the transpose of \( \Delta X_b \).

Configuring an Attitude Determination Unit for Land

On the project described here researchers from Georgia Tech have extended GPS-based attitude determination technology to ground vehicles. The attitude angles for pitch and roll that are determined by a GPS attitude determination unit can be directly translated to grade and superelevation/cross slope through simple trigonometry. Thus, the major task was to fit a system design for an aircraft or ship onto a land vehicle.

The Ashtech 3DF Attitude Determination Unit (ADU) was used as the base GPS platform (3). The unit uses an array of four antennas.
The dimensions of the platform that supports the antennas and the ability to reduce the errors due to multipath are critical elements of the device configuration. Multipath errors occur when the satellite signals are deflected before reaching a GPS antenna, which will make it appear that an antenna is farther from the satellite than it actually is. The multipath error can be significantly reduced by mounting the antennas on metal plates.

Three independent configurations were ultimately evaluated to determine the effect of the antenna separations on the accuracy of the vehicle's attitude. The initial orientation consisted of a square wooden vehicle rack with the antennas located at the frame corners. This configuration permitted a maximum separation of 1 m (3.3 ft) between antennas (Figure 1a). In this orientation, Antenna 1 was used to compute the position and velocity of the vehicle. Antennas 1 and 2 were used to determine the direction and the pitch angle of the vehicle, and all four antennas collectively were used for determination of the roll angle.

The second orientation was a wooden platform with the antennas positioned in a T formation as indicated in Figure 1b. This orientation provided better results than the square orientation because it allowed increase in the baseline distances between Antennas 1 and 2 to 2.5 m (8.2 ft). A problem that was encountered with the T orientation was that the effect of weather disfigured the wooden platform. Furthermore, the wooden platform was not very rigid, which made it vulnerable to wind-loaded deflections. The rear antenna also tended to bounce because of the short cantilever at the rear of the vehicle. To solve this problem, the entire platform was replaced with a much more rigid aluminum I-beam unit that is unaffected by weather. The rigidity of the aluminum provided the opportunity to increase the separation between antennas 1 and 2 to 3.5 m. By moving Antenna 2 forward, the new configuration became a cross (Figures 1c and 3). Antennas 3 and 4 were not moved forward to keep them over the mounting rack, which provided the greatest resistance to torsion forces. The 3DF ADU has one receiver that has four separate banks for each antenna, four microstrip antennas, four 9-m (30-ft) antenna cables, and a photogrammetry option that allows the surveyor to time tag data for control purposes. First, the cables are connected to the antennas and each antenna is connected to its corresponding bank; for example, Antenna 1 is connected to Bank 1 on the receiver. A wrong connection will result in erroneous attitude results. The receiver is then connected to a notebook computer and to a 12-V battery.

The orientation of satellites with respect to a position on earth is constantly changing. Therefore, it is important to perform mission planning to ensure maximum satellite coverage. Field surveys should be scheduled only when a desirable satellite orientation exists. Each antenna can track up to six satellites, but a minimum of four satellites are required for attitude computation. Thus, it is essential to verify that all antennas are functioning and are able to lock on to a minimum of four satellites. The researcher can verify position by using a serial communication link between the ADU and a laptop computer. Commercially available communications software is required for this purpose. The Georgia Tech system used Datastorm Technologies' PROCOM software. PROCOM can be used to check the status of the antennas, baud rate, data-receiving interval, and receiver update rate. Additionally, PROCOM can be used to submit commands and additional information.

FIGURE 3 Cross platform constructed with aluminum I beams.
to the ADU. The acceptable position dilution of precision and any additional parameters can be entered. The site location and other informational data can be entered so that they are stored with the attitude data.

System Calibration

The initial system calibration occurs during the static mode. For calibration purposes, data were collected at 5-sec intervals for three different data sets, each with a duration of approximately 1 hr. The final vectors for the three baseline vectors were obtained by processing the data obtained from the static survey.

The ADU creates three files during data collection, named files B, E, and A. The B file contains position information, the E file contains the satellite ephemeris data, and the A file identifies the three-dimensional instantaneous attitude of the vehicle at any epoch. During postprocessing, the B file is split into four files, each representing a corresponding antenna. The four B files were used to determine the orientation of the antennas and the antenna separation. All remaining files were processed and analyzed. The three data sets were compared with manual attitude measurements to ensure that the ADU provided reasonable and accurate results. Tests conducted at Georgia Tech indicated that the calibration process identifies the deflection angles of the baselines to greater than 0.05 percent. The exact accuracy is not easily established because of the errors associated with manual surveying techniques. Once the baseline vectors are established, they are entered into the receiver via PROCOM.

Static Survey Results

Initially, testing included data collected statically at four select locations. After inspection of the static data for reasonable and acceptable values, the next phase of the testing was implemented. Before data collection, the investigator verified adequate satellite coverage. The static survey included data collected at 0.5-sec intervals for 5 min and occurred at four separate locations of variable grade. The results of the static survey are presented in Tables 1 and 2 for two of the different antenna baseline separations.

As shown in Table 1, a variation of as much as 0.8 percent between the actual grade and the GPS-measured grade occurred by using the 1-m antenna baseline. Table 2 illustrates how increasing the length of the antenna separation results in an increase in the accuracy of the measurement. The maximum absolute deviation shown in Table 2 is approximately 0.4 percent. As stated earlier, multipath is one of the major sources of errors in the measurements. Multipath errors tend to accumulate, so the longer the vehicle remains at one location, the greater the observed errors. Thus, it was hypothesized that a kinematic survey will provide better accuracy than a static survey because it eliminates the error accumulation.

The static cross-slope measurements are presented in Table 3 for the T-platform antenna configuration. Antennas 3 and 4 were separated by 2.1 meters. The observed cross slope exhibited a maximum deviation of approximately 0.3 percent from values measured in the field.

Kinematic Survey Results

The researchers next initiated a kinematic survey of Tech Parkway, a 610-m (2,000-ft) section of roadway field surveyed previously. Tech Parkway is a lower-speed local road. Figure 4 presents actual grade values obtained by using conventional survey methods superimposed with the kinematic results collected by using the ADU on the same section of road. Variation in data between known and observed values resulted in a maximum grade deviation of approximately 0.4 percent. The deviation can be attributed to a number of factors including typical errors associated with GPS measurements, vehicle characteristics (especially the suspension and handling), and driver characteristics. Driver characteristics can contribute to error because gradual acceleration and deceleration of the vehicle are necessary to keep the vehicle parallel with the ground. The incorporation of a filtering process and a future data-smoothing algorithm promises greater accuracy for GPS-measured grade and cross slope as this research progresses. Smoothing is justifiable because roadway surfaces are continuous and the change in grade over a few feet is usually small. Variability in errors in the surveyed grade also can be expected. Manually surveyed grades are determined by measuring the change in x and the change in y between two discrete points. This assumes that grade is constant between the two points when, in reality, the grade is changing due to the undulations of the road.

<table>
<thead>
<tr>
<th>Location</th>
<th>GPS Grade (%)</th>
<th>Field Measured Grade (%)</th>
<th>Residuals in Grade (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>7.0</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
<td>5.0</td>
<td>-0.8</td>
</tr>
<tr>
<td>3</td>
<td>4.3</td>
<td>5.0</td>
<td>-0.7</td>
</tr>
<tr>
<td>4</td>
<td>-6.8</td>
<td>-6.0</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>GPS Grade (%)</th>
<th>Field Measured Grade (%)</th>
<th>Residuals in Grade (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.83</td>
<td>9.52</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>-0.58</td>
<td>-0.20</td>
<td>-0.38</td>
</tr>
<tr>
<td>3</td>
<td>-1.82</td>
<td>-1.50</td>
<td>-0.32</td>
</tr>
<tr>
<td>4</td>
<td>-7.14</td>
<td>-7.00</td>
<td>-0.14</td>
</tr>
</tbody>
</table>
TABLE 3  Comparison of Surveyed and Static GPS Cross Slope (2.5-m platform baseline)

<table>
<thead>
<tr>
<th>Location</th>
<th>GPS Grade (%)</th>
<th>Field Measured Grade (%)</th>
<th>Residuals in Grade (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.02</td>
<td>-0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>2</td>
<td>4.79</td>
<td>4.63</td>
<td>0.16</td>
</tr>
<tr>
<td>3</td>
<td>2.88</td>
<td>2.62</td>
<td>0.26</td>
</tr>
<tr>
<td>4</td>
<td>2.57</td>
<td>2.60</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

Variations can be minimized by establishing grades at short intervals (e.g., 3 m or 10 ft). Because the ADU collects grade and cross-slope data simultaneously, only one vehicle pass is necessary to collect enough information to create a digital terrain model (DTM) of the vehicle's path. Once this is accomplished, an as-built horizontal alignment, vertical profile, and pavement cross sections can be generated from the DTM. The Georgia Tech test vehicle traversed a major freeway on-ramp (access to Georgia 400, in Atlanta, Georgia) where operating speeds vary from 70 to 100 kph (approximately 45 to 65 mph). Figure 5 depicts the alignment (based on Antenna 1's positioning) and the profile of the off-ramp as developed by using DTM technology and the kinematic data described. Figure 6 depicts sample pavement cross sections derived from the DTM that was developed. The cross slope and grade change are depicted for six sample stations. This visual database option readily identifies possible sources of data error and levels of accuracy achieved in an easily understood graphic format.

The future evaluation of the Georgia Tech GPS technique will focus on calibration and validation of the kinematic survey methods for large data sets. The ultimate comparison of relative grades for an entire roadway segment can easily be accomplished by the DTM approach, and smoothing equations can be developed to ensure that observed values conform to known conditions.

CONCLUSION

The available expensive and time-consuming survey techniques lend support to the observation that a more affordable, kinematic attitude GPS system provides promise for agencies responsible for...
FIGURE 5  Georgia 400 on-ramp horizontal alignment and profile.

FIGURE 6  Georgia 400 on-ramp sample cross sections.
roadway database development. Since differential correction is required only for position identification, the GPS base station can be located a considerable distance from the rover unit without affecting the accuracy of the grade and cross-slope data. The selection of the T platform, which maximizes baseline distances between antennas, ensures minimum introduction of local error. The validation of the static system presented offers great promise and justifies continued efforts to smooth and validate kinematic data so that a specification can be developed. Another significant benefit of this system is that large volumes of data can be collected in a short period of time while a data collection vehicle travels in the traffic stream.

REFERENCES


Publication of this paper sponsored by Committee on Pavement Monitoring, Evaluation, and Data Storage.