7-2003

Topographic Mapping Through Measurement of Vehicle Attitude

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Disciplines
Bioresource and Agricultural Engineering

Comments
ASAE Paper No. 031008

This is not a peer-reviewed article.

Paper Number: 031008
An ASAE Meeting Presentation

Topographic Mapping Through Measurement of Vehicle Attitude

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Written for presentation at the
2003 ASAE Annual International Meeting
Sponsored by ASAE
Riviera Hotel and Convention Center
Las Vegas, Nevada, USA
27- 30 July 2003

Abstract. *A self-propelled agricultural sprayer was equipped with four RTK DGPS receivers, and an Inertial Measurement Unit (IMU) to measure vehicle attitude and field elevation as the vehicle was driven across a field. Data was collected in a stop-and-go fashion at 3.05 m (10 ft) intervals, as well as in a continuous fashion at three different speed levels. Using ordinary kriging, surface grids were interpolated using only elevation measurement, as well as combinations of elevation and vehicle attitude measurements. The resulting surfaces were compared to each other to evaluate the effect of including attitude measurement on DEM (Digital Elevation Model) accuracy. At the widest row spacing, the DEMs generated with attitude measurements had lower RMSE than those DEMs generated without attitude measurements. Vehicle speed also affected DEM accuracy. Vehicle attitude measurements have the potential to improve DEM accuracy for larger swath widths in ordinary field operations.*

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Introduction

Field topography is an important factor in agricultural production. Topography influences soil characteristics, water flow, and crop yields. Improvements in sensing technologies and computers enable the development of digital representations of topography as a layer in geographic information systems. A digital elevation model (DEM) is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals. In agriculture, DEMs are valuable for modeling watersheds and hydrological flow (Renschler et al, 2002), evaluating erosion and environmental impact (Casasnovas, 2002), and explaining spatial yield variability for site-specific farming (Yang et al., 1998; Kaspar et al., 2003; Kravchenko and Bullock, 2000).

Topographic maps and DEMs can be generated using several methods. Traditionally, they were created via conventional surveying techniques. Currently, however, aircraft or satellite-based remote sensing techniques such as photogrammetry, synthetic aperture radar (SAR; Evans and Apel, 1995), and LiDAR are more often used for topographic development. Aerial survey techniques require less labor than typical ground-based surveys, but are more cost-effective only over large areas. Additionally, remote sensing methods can lose accuracy depending on the resolution of the images taken (Kavanaugh, 2003).

DEMs are available from a number of different sources. The U.S. Geological Survey (USGS) offers several different types of DEMs at varying levels of accuracy. DEMs are available in resolutions of 7.5-minute, 15-minute, 30-minute, and 1-degree. USGS 7.5-minute DEMs, with grid spacing of 10 m or 30 m, are the most accurate and have been produced from photogrammetric models and interpolation of elevation data digitized from contour maps. These DEMs are currently produced by interpolating elevations from vectors or digital line graph hypsographic and hydrographic data, and the other methods have been discontinued. DEM accuracy is dependent on the source data and its resolution. DEMs obtained from photogrammetric data have a desired vertical root-mean-squared error (RMSE) of 7 m or less, with 15 m as the maximum allowable vertical RMSE. Those produced from hypsographic and hydrographic data digitization must have an RMSE no greater than one-half the contour interval. (USGS, 2000). As noted by Clark and Lee (1998), for a 7.5-minute DEM with a 1:24000 scale and a 6.10 m (20 ft) contour interval, the acceptable level of error is 3.05 m for no more than 10% of the points tested. Aside from the USGS, DEMs are also available from commercial sites offering much the same information (Childs, 2002).

Several studies have investigated the use of GPS to generate DEMs. Clark and Lee (1998) developed DEMs by measuring elevation data with a variety of dual-frequency GPS receivers. They collected position measurements from a RTK GPS receiver mounted to the roof of a tractor cab, as well as with the antenna mounted on a tripod. The tripod was used to collect measurements with the most accurate antenna height, in a stop-and-go fashion. They generated DEMs for several fields and with multiple grid sizes, The DEM produced from stop-and-go measurements had elevation errors of 2-3 cm, and the DEM from the kinematic measurements had errors of 3-8 cm. They also determined that kinematic measurements can be used for validation points. These validation sets gave slightly higher errors, but the increase was minimal in light of the fact that the data is much easier to collect than stop-and-go validation points.

Yao and Clark (2000) used a single-frequency GPS receiver (Model PRO XRS, Trimble, Sunnyvale, CA) with differential correction (OmniStar, Houston, TX) to collect data from an all-terrain-vehicle every 2 s at 6-9 km/h. They collected 22 passes of data 3.3-5 m apart, and randomly selected 2, 5, 10, 15, 20, or 22 of the passes to generate topographic maps in either

5m or 10m grids. The effects of the number of passes and the data processing methods were investigated using statistical analyses. No significant differences between processing methods were detected. Maps created from ten or more passes, however, had lower mean elevation errors and standard deviations.

Bishop and McBratney (2002) examined different methods of interpolating digital elevation models from GPS data. Elevation data was collected using differential GPS receivers and was jackknifed into prediction and validation sets before the various interpolation techniques were applied. The TOPOGRID function of ArcGIS (ESRI, Redlands, CA) resulted in lower standard error than several other interpolation techniques. TOPOGRID is an iterative finite difference interpolation method based on the ANUDEM software package developed by Hutchinson (1989). For interpolations on a 5 m grid, the TOPOGRID method yielded RMSEs of 0.04 m to 0.12 m, while on a 10 m grid, it yielded RMSEs of 0.07 m to 0.19 m.

Wilson et al. (1998) examined the influence of the number and pattern of GPS input data on the resulting DEMs. They collected data on north-south and east-west patterns from a truck-mounted kinematic GPS receiver. They created DEMs using the full data set, reduced data sets in each direction, and from random points selected from grids of various sizes. They found that the magnitude and clustering of errors decreased as the sample size increased, as well as when the grid size decreased. They also found that small elevation differences at individual points can cause large differences in resultant slope values, and that the orientation of the vehicle routes can have a significant impact on the quality of the DEMs.

Inertial measurement units (IMUs) have been combined with GPS in the past. Guo et. al (2002) developed a sensor fusion system by combining low-cost GPS and an IMU with Kalman filtering to reduce bias error in the GPS and perform path smoothing for an off-road vehicle. Fiber-optic-gyros have been used to correct for GPS antenna inclination on off-road vehicles with RTK guidance systems (Nagasaka et. al, 2002, Noguchi et. al 2002). Kise et. al (2002) used an IMU to acquire vehicle heading on an experimental tractor with RTK GPS.

Since measurements from IMUs have shown utility in automatic guidance of vehicles to improve vehicle posture estimates, it is possible that these measurement may enable more accurate estimates of topography. This possibility led to the following objectives of this study:

1. To compare measurements of vehicle roll and pitch from two sources.
2. To develop a calibration technique for removing constant vehicle body pitch and roll biases due to unequal weight distributions on the vehicle.
3. To compare the accuracies of DEMs interpolated from data sets using different combinations of vehicle location and attitude measurements.

METHODS

Instrumentation

A John Deere self-propelled sprayer (Model 4710, Deere & Co., Moline, IL) was equipped with four experimental RTK GPS receivers (StarFire RTK, Deere & Co. Moline, IL) operating at 1 Hz. Although not commercially available at the time of this experiment, these GPS receivers had a vertical RMS error of less than 1.5 cm based on a Deere internal test report. The GPS receivers were mounted in diamond-shaped pattern on the vehicle, with receivers located at the front, rear, left and right sides of the vehicle (Figure 1). Front and rear receivers were 3.86 m (152 in.) apart, located along the vehicle centerline. Left and right receivers were 3.05 m (120 in.) apart, 1.63 m (64 in.) behind the front receiver. All GPS receivers were located at a height of 3.81 m (150 in.) off the ground. Correction signals were sent from a local base station via a radio link (Pacific Crest Corp., Santa Clara, CA). An IMU (Model VG600AA-201, Crossbow, Santa Clara, CA) capable of measuring pitch and roll angles; yaw, pitch, and roll angular rates; and x/y/z accelerations was also mounted on the vehicle. The pitch and roll angle measurements – all that were used in this study – had a static accuracy of ±0.5° and a dynamic accuracy of 2.5° rms dynamic based on the manufacturer literature (Crossbow, 2001).

The field used for this study was located near Ames, Iowa at 42° 00' N latitude and 93° 39' W longitude. The area of the field used for this research was approximately 2.3 ha. The field had been chisel-plowed after the previous corn crop had been harvested. Data collection took place November 19-22 and December 11-12, 2002. Data was collected in a stop-and-go fashion as well as in a continuous fashion at three different speeds. Using ArcView (Version 3.2; ESRI, Redlands, CA), a 3.05m (10 ft) grid pattern was established prior to the beginning of the study. The grid was oriented N-S and E-W, with intersections every 3.05 m. During the stop-and-go data collection, the sprayer was driven along a N-S path, stopping at each intersection point on the grid. After allowing the vehicle to come to steady-state, position measurements were collected from all four GPS receivers along with IMU data for approximately 15 seconds before stopping recording and moving to the next data point. In continuous (kinematic) data collection, the vehicle was driven along the N-S paths at three different speeds while continually recording data. The three speed levels chosen to investigate the effects of ground speed on DEM development were: 3.2-4.8 km/h (2-3 mph), 6.4-9.7 km/h (4-6 mph) and 12.9-16.1 km/h (8-10 mph). Data acquisition was performed with a personal computer with a 1.1 GHz Intel Celeron processor. GPS data and IMU measurements were brought into the computer through multiple serial ports and recorded at 1 Hz using a custom-written data logging program.

Data Analysis

Comparing Vehicle Attitude Measurements From Two Sources

The first step in evaluating the usefulness of the IMU data was to verify that the measurements recorded from it agreed with measurements from another source. Using the elevation measurements from the RTK receivers, pitch and roll angles were calculated and compared to pitch and roll angles from the IMU through regression analysis. Of particular interest was to determine how much the error between the two methods increased as vehicle speed increased. Regression analysis was used to evaluate the relationship between the two methods. RMSE was calculated for the four speed levels—three continuous speeds and stop-and-go.

Measurement and Calibration of Vehicle Suspension Bias

The test vehicle was fully suspended and therefore, the vehicle body could have pitch or roll angle biases relative to the slope of the terrain at the wheels. Any substantial biases could hinder the generation of DEMs that accurately represent the shape of the terrain. The estimation of these biases was based on a model: the change in slope (pitch and roll angles) between points on adjacent paths will be a combination of the terrain change plus any vehicle bias. The change in terrain was assumed to be normally distributed with zero mean. Thus, any systematic biases across the field could be estimated.

Each measured attitude angle will be a combination of the slope of the terrain and any bias that exists due to suspension difference or unequal weight distribution. If the bias angles are constant, then adjacent attitude measurements on two paths will be:

$$\theta_{MEAS1} = \theta_{BIAS} + \theta_{SLOPE1} \quad (1)$$

$$\theta_{MEAS2} = \theta_{BIAS} - \theta_{SLOPE2} \qquad (2)$$

where

θ_{MEAS1} and θ_{MEAS2} are attitude (either pitch or roll) measurements at nearest northings on two adjacent north-south paths,

θ_{BIAS} is the corresponding bias angle due to the vehicle suspension, and

θ_{SLOPE1} and θ_{SLOPE2} are the angle of the slope relative to the orientation of the vehicle. Note the sign change on θ_{SLOPE2} is due to a change in vehicle path direction from one path to the other.

When these two measurements are added together, we get:

$$\theta_{MEAS1} + \theta_{MEAS2} = 2\theta_{BIAS} + \Delta\theta_{SLOPE} \qquad (3)$$

where

$\Delta\theta_{SLOPE}$ is the change in slope from one path to the next.

Taking the expected value of Eqn 3 results in:

$$E[\theta_{MEAS1} + \theta_{MEAS2}] = 2\theta_{BIAS} + E[\Delta\theta_{SLOPE}] \qquad (4)$$

Since the change in slope from one path to another is a random variable and is assumed to have a zero mean, we can solve for the bias angle using:

$$\theta_{BIAS} = \frac{E[\theta_{MEAS1} + \theta_{MEAS2}]}{2} \qquad (5)$$

For each speed level, the mean of the sum of attitude was estimated.

Comparison of DEMs created from different position and attitude measurements

Pitch and roll measurements by the IMU, and GPS position measurement of the front GPS receiver were combined according to the vehicle geometry to estimate the locations of the right and left GPS receivers. Elevation points were estimated for each of the left and right receivers by subtracting the biases and using Eqns 6-11:

$$z_{right,pred} = z_{front,meas} - \frac{W}{2} * \sin(\theta - \theta_{bias}) - a * \sin(\phi - \phi_{bias}) \qquad (6)$$

$$N_{right,pred} = N_{front,meas} - a * \cos(\Psi) - (\frac{W}{2}) * \sin(\Psi) + (1 - \cos(\theta - \theta_{bias})) * \frac{W}{2} * \sin(\Psi) + (1 - \cos(\phi - \phi_{bias})) * a * \cos(\Psi) \qquad (7)$$

$$E_{right,pred} = E_{front,meas} - a * \sin(\Psi) + \frac{W}{2} * \cos(\Psi) + (1 - \cos(\phi - \phi_{bias})) * a * \sin(\Psi) - (1 - \cos(\theta - \theta_{bias})) * \frac{W}{2} * \cos(\Psi) \qquad (8)$$

$$z_{left,pred} = z_{front,meas} + \frac{W}{2} * \sin(\theta - \theta_{bias}) - a * \sin(\phi - \phi_{bias}) \qquad (9)$$

$$N_{left,pred} = N_{front,meas} - a * \cos(\Psi) + (\frac{W}{2}) * \sin(\Psi) - (1 - \cos(\theta - \theta_{bias})) * \frac{W}{2} * \sin(\Psi) + (1 - \cos(\phi - \phi_{bias})) * a * \cos(\Psi) \qquad (10)$$

$$E_{left,pred} = E_{front,meas} - a * \sin(\Psi) - \frac{W}{2} * \cos(\Psi) + (1 - \cos(\phi - \phi_{bias})) * a * \sin(\Psi) + (1 - \cos(\theta - \theta_{bias})) * \frac{W}{2} * \cos(\Psi) \qquad (11)$$

where :

a = distance along vehicle centerline from front GPS receiver to left and right receivers (m)

W = distance perpdendicular to vehicle centerline from left to right GPS receivers (m)

Ψ = vehicle heading angle, CCW from North (radians)

θ = roll angle (radians)

θ_{bias} = vehicle roll bias angle (radians)

ϕ = pitch angle

ϕ_{bias} = vehicle pitch bias angle (radians)

These calculations enabled easy comparisons between "virtual" elevation estimates using the attitude measurement from IMU and one elevation measurement and actual elevation measurements at those same locations where the GPS receivers were located.

The data was divided into one of three groups according to the types of measurements contained therein. Group 1 consisted of GPS measurements taken from the front RTK receiver only. Group 2 was the data set containing the front GPS position and the IMU attitude measurements to estimate 2 more virtual positions. Group 3 consisted of GPS measurements from each of the four RTK receivers mounted on the vehicle.

Collecting data on a 3.05 m grid is not very practical for real-world applications because the vehicle swath is typically wider. To simulate a more sparse data set than that collected at 3.05 m resolution, each group was jackknifed into separate sub-groups by skipping data along paths at regular intervals. This division of the data was used (1) to simulate the effect of driving the vehicle along swaths much farther apart than 3.05 m and (2) to produce calibration and validation sub-groups. The calibration sub-groups were used to interpolate surfaces, and the validation sub-groups were used to measure the quality of the interpolated surfaces (Bishop and McBratney, 2002). Three different sub-groups were generated by jackknifing out several rows of data at a time. The narrowest spacing consisted of every third row (skipped two rows) of elevation measurements, the next spacing was every fifth row (skipped four), and the widest spacing was every ninth row (skipped eight). This corresponds to swath widths of 9.15 m, 15.25 m, and 27.45 m respectively. This data became the calibration set, from which the DEMs were generated. The remaining data became the validation set against which the DEM was judged. For each swath width, one validation set was used to judge each of the different speed levels.

The calibration sub-groups representing the three swath widths for each measurement group and speed level were imported into ArcView to be compared with one another. The three measurement groups were compared to one another within the same level of jackknifing. There are a total of 36 cases in this study: 4 speed levels, 3 groups of data, and 3 levels of jackknifing. A kriging interpolation (Nieuwland Automatisering, Wageningen, The Netherlands, c 2003) extension was used in ArcView spatial analyst to interpolate the surface for the DEMs. Ordinary kriging was chosen to interpolate the data. Simple visual inspection of the data indicated no large trends, and ordinary kriging is known to be quite robust (Trangmar, 1985). The linear model was chosen with a fixed radius of 20 m and minimum of 12 data points. Data was interpolated to a 1 m grid.

To evaluate interpolations from each data group, the kriged surfaces interpolated from the calibration sub-groups within each data group were then compared to a single validation data set. This validation set came from the elevation measurements in the stop-and-go procedure at the same level of jackknifing as the kriged surface which was being evaluated. This was done in order to use a common data set which had not been used to interpolate the surface. Elevation errors were calculated by locating each validation point on the grid, and subtracting the grid elevation from the point elevation. Root mean square error (RMSE) is the normal way of stating the error of a DEM (Wise, 1998). The RMSE was calculated for each combination of speed level, measurement group, and swath width. The SAS (SAS Institute, Cary, N.C.) General Linear Model procedure (GLM) was used to test for significant differences in error variance using Tukey's Test across vehicle speed level and measurement group, for each swath width.

RESULTS

Comparing Measurement of Roll and Pitch From Two Sources

At each speed level, the IMU attitude measurements were highly correlated with those calculated from the location measurements of the four GPS receivers and exhibited a linear relationship with each other.

Biases existed, however, at all speed levels between the two types of measurements despite efforts to mount the IMU level and all GPS receivers at the same height. In the stop-and-go mode, the linear regression resulted in a coefficient of determination, R^2, of 0.989 and an RMSE of 0.286° for pitch (Table 1) and an R^2 of 0.989 and an RMSE of 0.206° for roll (Table 2). Increasing speed resulted in a decreasing R^2 – down to 0.758 for roll and 0.797 for pitch at the highest speed level—and corresponding increases in RMSE.   The slopes of the regression lines for pitch were all different than one at the 0.05 level of significance. The y-intercepts – which were the biases – were significantly different from zero at all speeds. Roll angle regression lines were all different than one at the 0.05 significance level. The y-intercepts-the biases-were significantly different from zero at all speeds (Figures 3-6,). These results show that the vehicle attitude measurements from the IMU closely match the attitude estimations from the GPS at speeds not exceeding 9.7 km/h, after accounting for the bias.

Measurement and Calibration of Vehicle Suspension Bias

Using the method described above, significant bias angles were found relating the vehicle body to the terrain using both IMU attitude measurements (Table 3) and those calculated from the location measurements of the four GPS receivers (Table 4). Additionally, when the IMU/terrain bias is subtracted from the GPS/terrain bias, it gives results very close to the GPS/IMU bias. The IMU to terrain bias angle estimates ranged from 0.242° to 0.876° for pitch and -0.660° to -1.727° for roll. No clear trends were observed in the angles or their variance with increasing speed levels. There were clear and substantial bias angles present between the terrain and the vehicle body; these angles however varied from one speed level to another. Possible causes of this variation in bias angles include: 1) differences in the mounting angle of the IMU relative to the vehicle – the IMU was remounted each day of data collection, 2) variations in the volume of fuel in the fuel tank leading to changes in weight distribution, 3) temperature variations causing changes in the stiffness of the air suspension system due to changes in the air pressure in or material properties of this system.

Comparison of DEMs created from different position and attitude measurements

As the row spacing increased, the RMSE for each mode of data collection increased. When two rows of data were jackknifed to form the calibration sub-set, the variation of the error was very close for all data sets. The error of Group 1 varied from 0.028 – 0.035 m across the different speed levels, Group 2 had error ranging from 0.023-0.065 m, and Group 3 had error of 0.026 – 0.118 m (Table 5). The measurements at the 3.2-4.8 km/h speed level are significantly worse than those at other speed levels. As can be noted from Tables 6 and 7, this was not an issue at the wider row spacings, despite the fact that the data for the wider swaths is also part of the data at the narrow spacing. This behavior is as yet unexplained and deserves further analysis.

At the next widest row spacing, the RMSE rose for all measurements (with the previous anomalies excepted). Group 1 had RMSEs ranging from 0.043 – 0.087 m (Table 6). Group 2 had RMSEs of 0.033 – 0.049 m. The errors of Group 3 were 0.038 -0.059 m across all speed levels.

At the widest row spacing, Group 1 had RMSE of 0.134 – 0.274 m (Table 7) across all speed levels, Group 2 had errors ranging from 0.065 – 0.157 m, and Group 3 had errors of 0.066 – 0.168 m. The additional attitude measurements of Groups 2 and 3 produced less error than Group 1 without the attitude measurements.

Attitude measurement was a significant factor in the DEM errors in this study. The GLM analysis also determined that vehicle speed is a significant factor in DEM error. Further studies may be necessary to recognize trends based on speed.

CONCLUSIONS

The addition of an IMU unit may aid in the interpolation of elevation measurements to create DEMs. In data sets with passes that are relatively close together, the additional measurement did not improve the accuracy of the DEM, and in fact made it slightly worse. At wider swath widths which would better represent practical field operations, the addition of IMU attitude measurements resulted in DEMs with lower RMSE and standard error for the DEM generated with attitude measurements. This may prove helpful while collecting data during regular field operations, particularly when using wide equipment.

This study has also shown that when taking multiple vehicle attitude measurements across a field, it is possible to measure any biases or mounting errors during post-processing, without lengthy calibrations in the field. These biases can be estimated and accounted for in subsequent analyses.

Acknowledgements

This journal paper of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 4003, was supported by Hatch Act and State of Iowa funds. The authors would like to thank Deere & Co. for their technical and financial support of this project.

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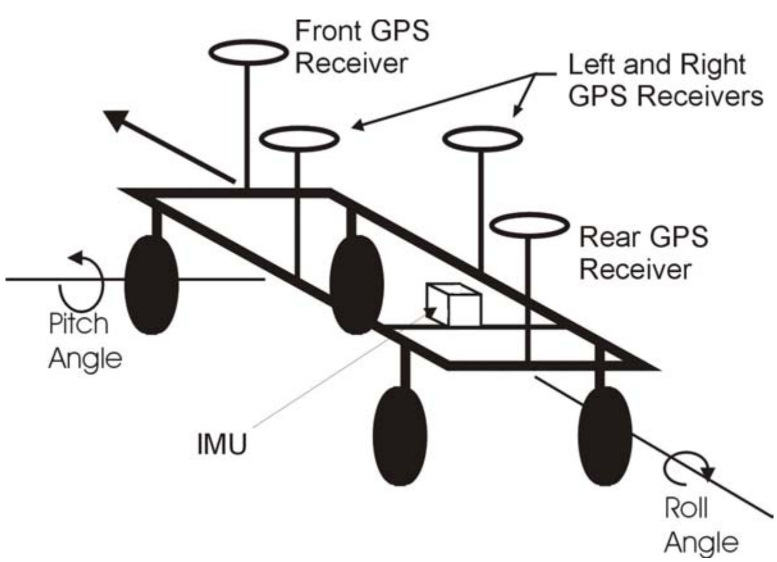

Figure 1. Diamond pattern of four GPS receivers on vehicle

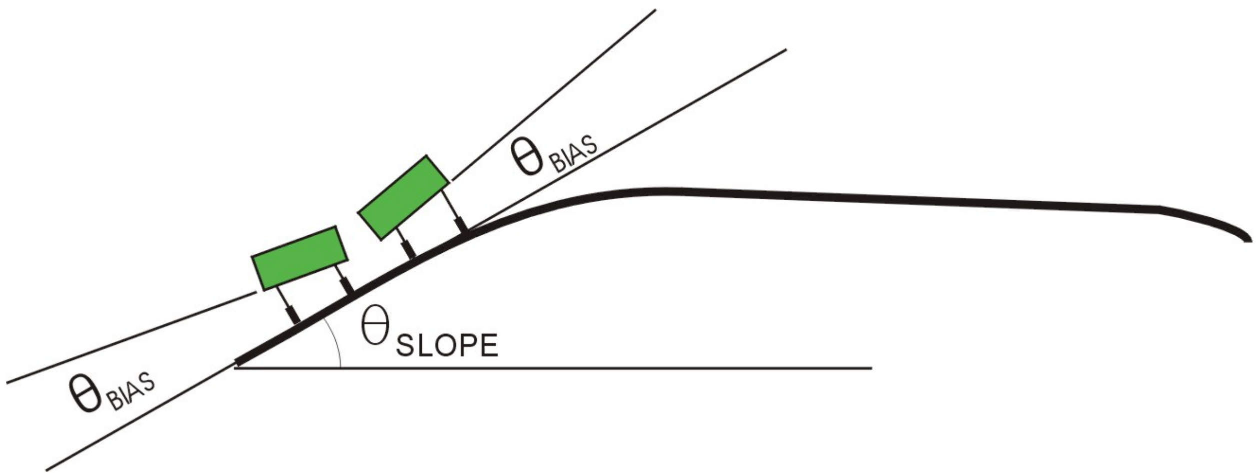

Figure 2. Roll angle bias (Δθ) for adjacent paths

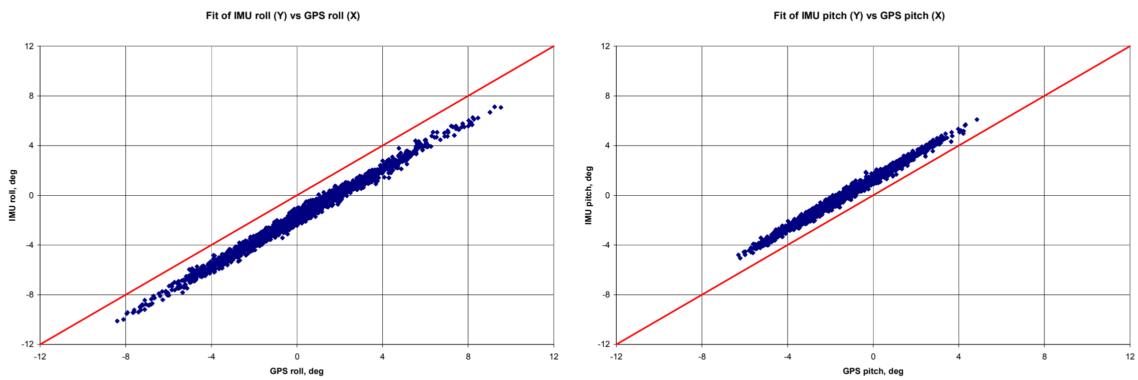

Figure 3. Fit of IMU angle vs GPS-calculated roll and pitch angles for stop-and-go

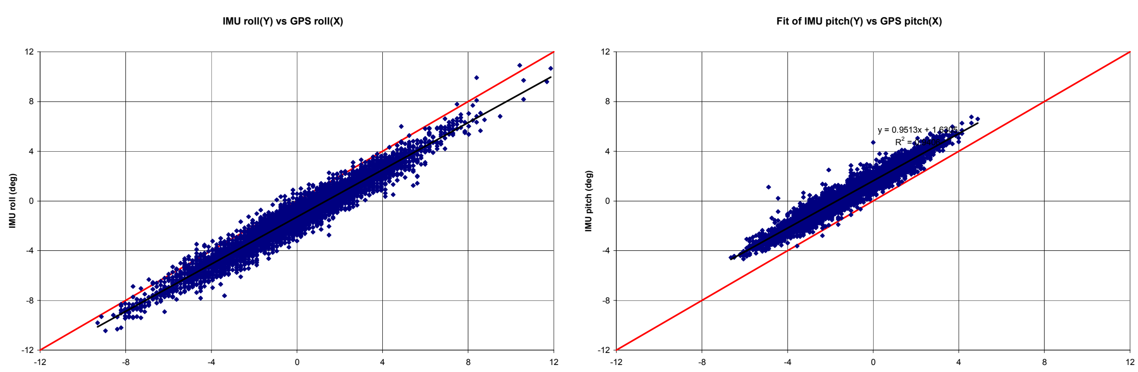

Figure 4. Fit of IMU angle vs GPS-calculated roll and pitch angles at 3.2-4.8 km/h

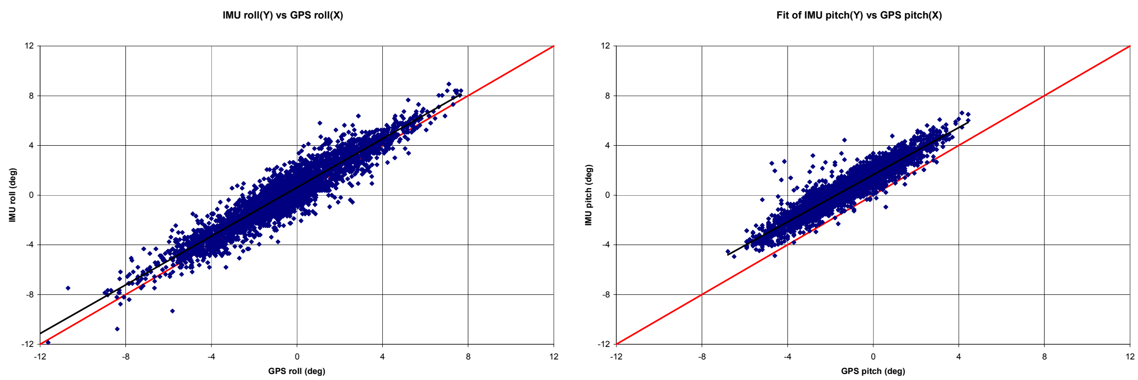

Figure 5. Fit of IMU angle vs GPS-calculated roll and pitch angles at 6.4-9.7 km/h

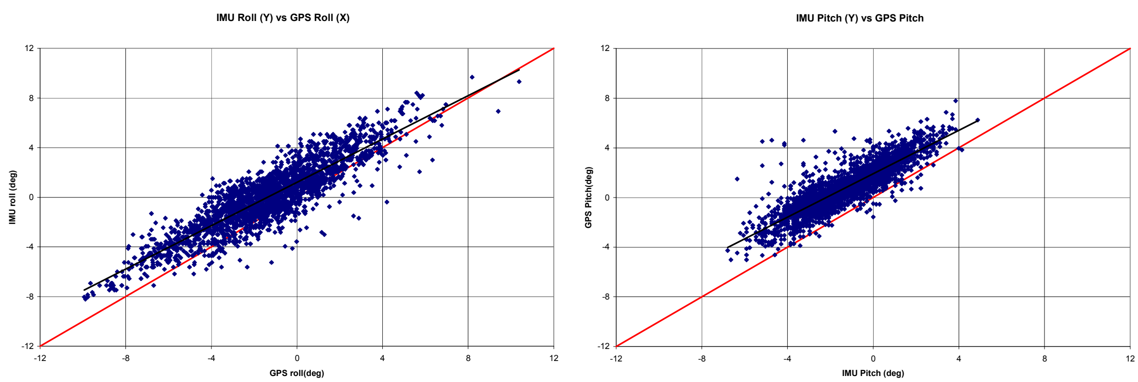

Figure 6. Fit of IMU angle vs GPS-calculated roll and pitch angles at 12.9-16.1 km/h

Table 1. Comparison of pitch angles measured by IMU to pitch angles calculated from GPS measurements

Speed	R^2	RMSE (degrees)	Bias (95% C.I.) (degrees)	Slope of Regression Line
Stop-and-go	0.989	0.206	1.307 +/- 0.010	0.994*
3.2-4.8 km/h	0.941	0.468	1.630 +/- 0.013	0.951*
6.4-9.7 km/h	0.890	0.637	1.639 +/- 0.024	0.949*
12.9-16.1 km/h	0.758	0.963	1.911 +/- 0.046	0.874*

[*] Indicates significant difference from 1 at the 0.05 level

Table 2. Comparison of roll angles measured by IMU to pitch angles calculated from GPS measurements

Speed	R^2	RMSE (degrees)	Bias (95% C.I.) (degrees)	Slope of Regression Line
Stop-and-go	0.989	0.286	-1.835 +/- 0.012	0.978*
3.2-4.8 km/h	0.943	0.646	-1.284 +/- 0.014	0.949*
6.4-9.7 km/h	0.893	0.846	-0.629 +/- 0.027	0.979*
12.9-16.1 km/h	0.797	1.270	-1.368 +/- 0.051	0.873*

[*] Indicates significant difference from 1 at the 0.05 level

Table 3. Estimated suspension bias angles for the IMU relative to the terrain

Speed	Pitch Bias (degrees)	Roll Bias (degrees)	No. Samples
Stop-and-go	0.2420 ± 0.017	-1.7174± 0.0262	2346
3.2-4.8 km/h	.5513 ± 0.0109	-1.3665± 0.0219	6037
6.4-9.7 km/h	0.4784 ± 0.0134	-0.6596 ± 0.0214	3305
12.9-16.1 km/h	.8763 ± 0.0365	-1.3572± 0.0524	1600

Table 4. Estimated suspension bias angles for the GPS relative to the terrain

Speed	Pitch Bias(degrees)	Roll Bias(degrees)	No. Samples
Stop-and-go	-1.1437± 0.0159	0.1590 ± 0.0552	2346
3.2-4.8 km/h	-1.1304± 0.0119	-0.1031±0.0209	6037
6.4-9.7 km/h	-1.2346± 0.0134	-.0459 ± 0.0216	3305
12.9-16.1 km/h	-1.2222± 0.0272	.0617±0.0617	1600

Table 5. Elevation error, 2 rows jackknifed. 9.15 m swath width

	RMSE (m)		
Speed Level	Group 1(1RTK)	Group 2(1RTK+IMU)	Group 3(4RTK)
Stop-and-go	0.029	0.023	0.063
3.2-4.8 km/h	0.028	0.065	0.118
6.4-9.7 km/h	0.030	0.025	0.028
12.9-16.1 km/h	0.035	0.035	0.026

Table 6. Elevation error, 4 rows jackknifed. 15.25 m swath width

	RMSE (m)		
Speed Level	Group 1(1RTK)	Group 2(1RTK+IMU)	Group 3(4RTK)
Stop-and-go	0.087	0.047	0.059
3.2-4.8 km/h	0.043	0.033	0.053
6.4-9.7 km/h	0.087	0.049	0.051
12.9-16.1 km/h	0.055	0.046	0.038

Table 7. Elevation error, 8 rows jackknifed. 27.45 m swath width

	RMSE (m)		
Speed Level	Group 1(1RTK)	Group 2(1RTK+IMU)	Group 3(4RTK)
Stop-and-go	0.225	0.157	0.168
3.2-4.8 km/h	0.274	0.121	0.116
6.4-9.7 km/h	0.134	0.065	0.066
12.9-16.1 km/h	0.219	0.140	0.137