Analysis of Multiple GPS Antennas for Multipath Mitigation in Vehicular Navigation

R. A. Nayak, M. E. Cannon
Department of Geomatics Engineering
University of Calgary, Calgary

C. Wilson, G. Zhang
DaimlerChrysler Research and Technology North America
Palo Alto, California

BIOGRAPHIES

Rakesh A. Nayak is a M.Sc student in Geomatics Engineering at the University of Calgary. He has a B.E. in Electronics engineering from Mangalore University, India. He has been involved in GPS research since 1994 in the area of receiver hardware and software development and low cost sensor integration.

Dr. M. Elizabeth Cannon is Professor of Geomatics Engineering at the University of Calgary. She has been involved in GPS research and development since 1984, and has worked extensively on the integration of GPS and inertial navigation systems for precise aircraft positioning. Dr. Cannon is a Past President of the ION.

Christopher Wilson is the Project Manager for Advanced Automotive Technology at DaimlerChrysler Research and Technology North America, Inc. His focus is on the development of position aware safety systems for road vehicle. He holds a BA in physics from Princeton University.

Gengsheng Zhang is currently a research scientist at DaimlerChrysler Research and Technology North America, Inc. He received his B.S. and M.S. in Automatic Control Engineering from Northwestern Polytechnical University, China. Mr. Zhang also holds a M.S. in Geomatics Engineering from the University of Calgary, Canada. His main research interests are in GPS, inertial navigation, and integrated navigation system.

ABSTRACT

The most important issue when using GPS for urban vehicular navigation is the position reliability which usually depends on the nature of the environment. In particular, the presence of urban canyons and foliage can cause significant degradation in satellite visibility as well as high multipath. Although GPS information tends to be integrated with other dead-reckoning sensors to increase position availability, it is often difficult to isolate satellites with significant multipath effects, which can then corrupt the integrated position solution. The objective of this paper is to assess the feasibility of using multiple antennas to isolate and detect multipath on pseudoranges so they can be rejected before they contaminate estimated vehicle positions. One of the properties of multipath is that it decorrelates rapidly as a function of distance, so antennas spaced at least 0.5 m apart may be subjected to different multipath conditions such that detection may be possible. Land tests were conducted with four antenna/receivers in Calgary under various environments including open sky, urban canyon and dense foliage conditions. The correlation of multipath between the antennas is analyzed for each of these environments, as is the overall satellite availability and multipath as a function of the environment. A multipath mitigation technique based on statistical reliability testing is presented.

INTRODUCTION

The Global Positioning System (GPS) has made land navigation applications affordable and dependable. However there are many situations where a GPS solution is either unavailable or unreliable. The first case occurs when GPS signals do not reach the antenna due to shading effects resulting from high rise buildings and underpasses present in an urban environment. The second situation arises from poor satellite geometry and the multiple reflection of signals. Although errors due to Selective Availability (SA), ionosphere, troposphere, multipath and receiver noise limit the achievable accuracy (Parkinson, 1994), the use of the differential GPS (DGPS) technique improves both accuracy and integrity although it does not reduce multipath (Parkinson and Enge, 1995).

Several multipath mitigation techniques have been developed such as Narrow Correlator™ (van Dierendonck et al., 1992) which has 0.1 chip spacing and a larger bandwidth at the IF and provides good long delay multipath mitigation. Similar technologies like MEDLL™ (van Nee, 1995), Edge Correlator™ (Garin et al, 1996), Strobe Correlator™ (Garin and Rousseau, 1997) use the correlator based approach to mitigate mulitpath. However, multipath errors can be as large as several tens of meters even with currently available state-of-the-art receiver technologies, and cannot be removed through differential positioning also due to its highly localized nature (Braasch, 1996).

Code multipath is typically the most significant error source for differential vehicular navigation applications, especially in urban and semi-urban areas with trees. The behaviour of code multipath in dynamic scenarios is very different from the static case. Cannon and Lachapelle (1992) did a detailed analysis of multipath in high performance receivers for kinematic applications. In static conditions the multipath source can be modeled as a single reflector, whereas in dynamic conditions, the position of various reflectors are changing rapidly and is difficult to model. One of the properties of multipath is that it decorrelates rapidly as a function of distance. Therefore, two antennas spaced at least 0.5 m apart, may be subjected to different multipath conditions even in a dynamic environment. Hence, a configuration of four antennas placed one meter apart from each other is used for the analysis.

An analysis of the effects of multipath on multiple antenna system in an urban environment is presented in this paper. To gain an insight into the code multipath in the four antennas, code minus carrier residuals are analyzed. The multipath correlation between the antennas is also investigated. Finally, a brief discussion of a proposed multipath mitigation technique is presented.

TEST DESCRIPTION

Data was collected on June 24, June 30 and September 9 1999 (herein referred to Days 1,2 and 3), from four GPS antenna/receiver systems mounted on a passenger vehicle and a fifth antenna on the roof of the Engineering Building at the University of Calgary (UofC). The four antennas on the vehicle were connected to four NovAtel MiLLennium™ GPS receivers. A NovAtel Beeline™ GPS receiver was mounted on a pre-surveyed pillar on the roof of the Engineering building to act as a reference station to generate differential corrections. Although the MiLLennium™ receivers are dual frequency units (whereas the Beeline™ is single frequency), only the L1 data was used during post-analysis. NovAtel's high performance active antenna (model 502) was used in the reference station and on the vehicle. Raw measurement and ephemeris records were logged from the vehicle and reference station receivers at a rate of 1 Hz.

Data from each receiver was independently post-processed in differential carrier smoothed mode using a cut-off elevation angle of 5º using C^3NAV™ (**C**ombined **C**ode and **C**arrier for GPS **NAV**igation, Cannon and Lachapelle, 1995) developed at the University of Calgary.

The location of the antennas on the roof of the vehicle is shown in Figure 1. The antennas were placed at least 0.5m apart from each other and are designated as Antennas A, B, C and D. Two of the antennas, labeled A and B, were mounted on ski racks and antennas C and D were mounted on magnetic mounts.

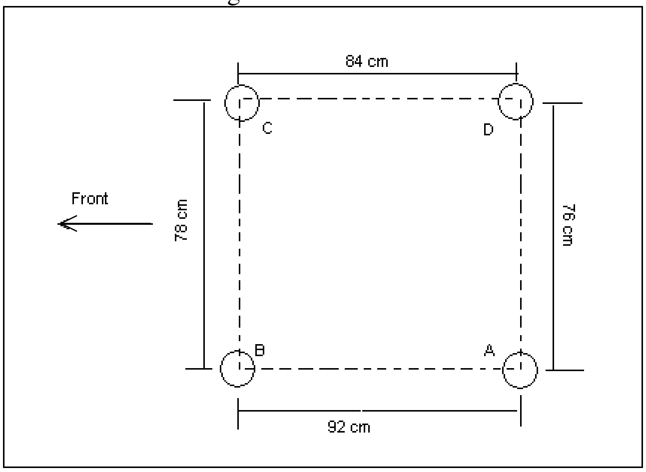

Figure 1: Antenna locations on vehicle roof

The complete antenna assembly of the four antennas on the roof of the car is shown in Figure 2 below.

Figure 2: Vehicle setup

Data from Antenna B on Day 1 was unusable due to a defective power connector. Consequently, only data collected on Days 2 and 3 are used in the analysis. For tests conducted on Days 1 and 2, a low cost inertial measurement unit (IMU) was mounted on the roof of the vehicle. Results of the IMU sensor are not addressed in this paper.

TEST ROUTE

A 30-km route in Calgary was chosen for the test, which encompasses four sections that can be classified as:

- Section 1: Open sky, which is free from obstacles for the entire section
- Section 2: Dense urban environment in downtown Calgary
- Section 3: Heavy foliage environment
- Section 4: Open sky in a semi-urban environment

A description of the four sections is given below.

Section 1 [open sky and suburban conditions]

The route traversed in Section 1 is shown in Figure 3 and has a very clear view of the sky, which is free from obstructions on both sides of the road. Crowchild Trail also has a very clear view of the sky with few underpasses.

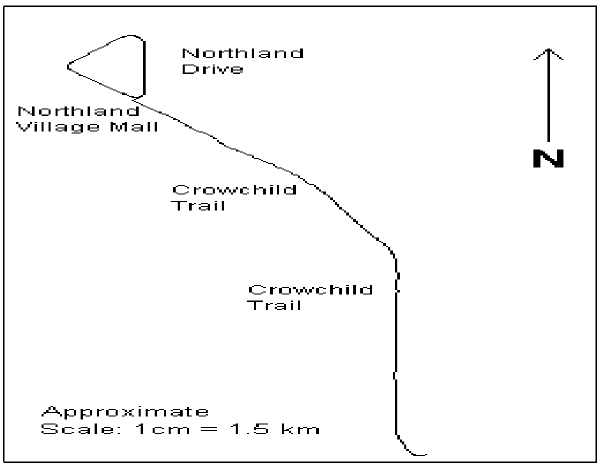

Figure 3: Section 1 route

Section 2 [Downtown section]

Section 2 of the test starts from Memorial Drive and passes through a rectangular block comprising 9th Avenue, Centre Street, 6th Avenue, 7th Street and 11th Street in the south west (SW) section of downtown Calgary. The dark line in Figure 4 shows the chosen route. Memorial Drive has mild foliage on the south side of the road whereas 9th Avenue has high rise buildings along the North side of the road and is fairly open on the south side. 6th Avenue has high rise buildings on both sides of the road and provides a very dense urban canyon scenario where satellites below elevation angles of 50 degrees are completely masked. Section 2 is approximately 9 km in length.

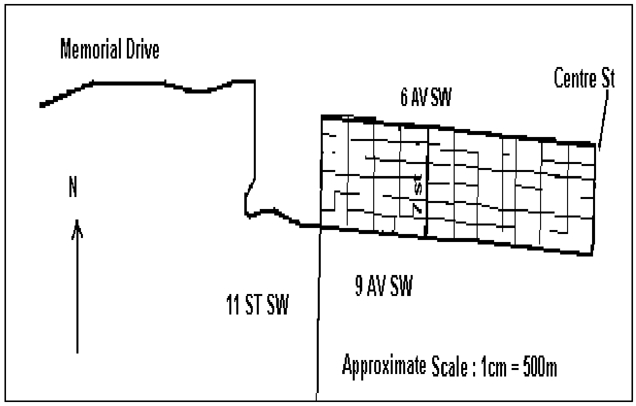

Figure 4: Section 2 route

Section 3 [foliage section]

A residential area in Calgary with sufficiently dense foliage was chosen for Section 3. The route has a variety of foliage characteristics and the majority of the 5.5km route has moderate to very dense foliage. The most densely covered section is along Montreal Avenue. Trees on both sides of the road branch out to cover the entire street providing very little line-of-sight capability. Satellite visibility is good along 10th Street, as there are no trees on either side of the road. Some sections, like Carleton Street and Montcalm Crescent, have few trees. The route shown in Figure 5 below provided a good variety of foliage attenuation.

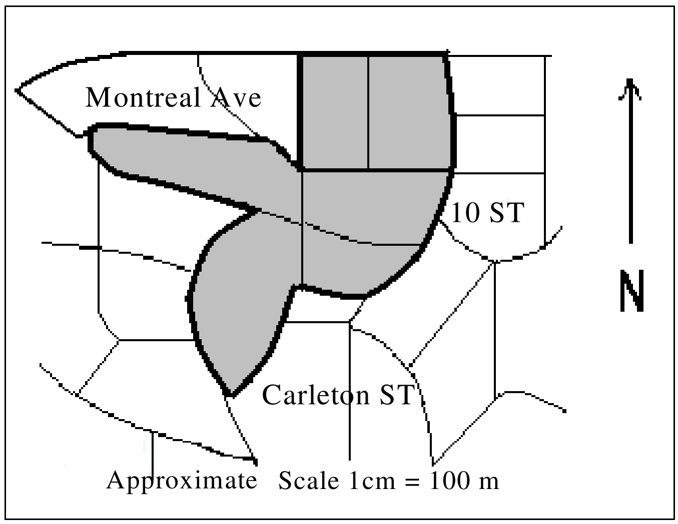

Figure 5: Section 3 route

Section 4 [open sky and suburban conditions]

Section 4 starts from downtown Calgary and ends at the University of Calgary and is mostly a retrace of Section 1. Satellite visibility varies from sparsely dense to open sky along this section. The route is comprised of 17th Avenue, Crowchild Trail and 32nd Avenue. 17th Avenue has low buildings on both sides whereas Crowchild Trail provides a clear and unobstructed view of the sky. The total distance in this section is approximately 8km.

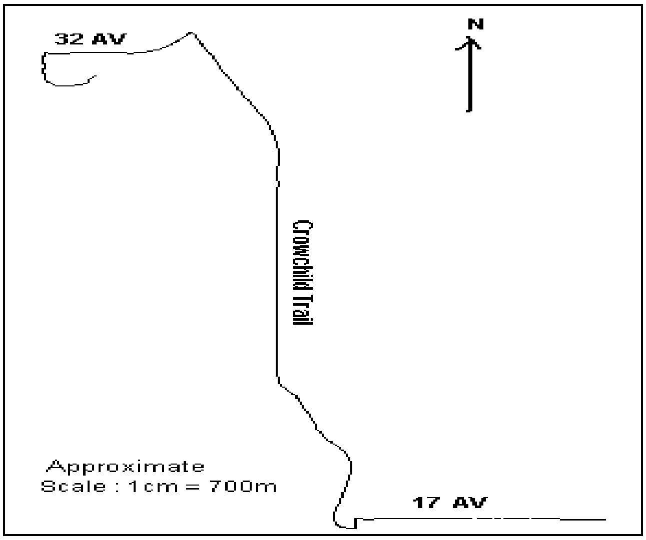

Figure 6: Section 4 route

DATA ANALYSIS APPROACHES

Measurement domain approach

Multipath analysis tends to be performed on the measurement residuals, which are output from an estimator (e.g. least squares adjustment). One of the problems that may occur however, is that the multipath on several antennas collecting data simultaneously may not be comparable due to differences in satellite availability (resulting from different levels of shading on the various antennas). This problem can be overcome if the exact location of each antenna is known from another source (e.g. from a carrier phase solution). However, this is not practical in the present case due to shading effects. For this reason, an approach using the code-carrier differences was implemented. This has been used extensively in the past and is also described by Braasch (1996).

The pseudorange and carrier phase observation equations can be formulated respectively as:

$$P = \rho + d\rho + c(dt - dT) + d_{ion} + d_{tropo} + \varepsilon(p) \quad (1.1)$$

$$\Phi = \rho + d\rho + c(dt - dT) + \lambda N - d_{ion} + d_{tropo} + \varepsilon(\varphi) \quad (1.2)$$

where
ρ is the geometric range between the satellite and the receiver antenna (m)
$d\rho$ is the orbital error (m)
dt is the satellite clock error (s)
dT is the receiver clock error (s)
d_{ion} is the ionospheric delay (m)
d_{tropo} is the tropospheric delay (m)
N is the integer cycle ambiguity (cycles)
$\varepsilon(p)$ is the code noise (receiver noise + multipath) (m), and
$\varepsilon(\varphi)$ is the carrier phase noise (receiver noise + multipath) (m).
C is the speed of light (m/s)
λ is the wavelength of L1 carrier (m)

By subtracting P-ϕ (code measurement – carrier phase measurement), this results in

$$r = 2d_{ion} - \lambda N + \varepsilon(p) + \varepsilon(\varphi) \quad (1.3)$$

Equation 1.3 contains the ionospheric error (actually twice the ionospheric error), the carrier phase ambiguity, code receiver noise and code multipath. Carrier receiver noise and multipath can be neglected since they are very small compared to the code values. The ambiguity term is a constant if there are no cycle slips whereas the ionospheric error generally varies slowly over time. A piece-wise linear regression model can therefore be implemented to remove terms due to the ionosphere and ambiguity. Since the ionospheric error changes with time, a regression model was implemented over predefined averaging intervals. An averaging interval of 6 minutes was chosen in the current model. The resulting code-carrier residual, r, will contain multipath and receiver noise and can be used for further analysis.

Subtracting out the mean removes not only the integer ambiguity, but also the bias components present in all of the remaining terms. Code multipath is a nonzero mean process (van Nee, 1992) and this technique only isolates relative multipath effects and not the absolute multipath because the regression process removes the portion of multipath with nonzero mean. (Braasch, 1994).

Position accuracy assessment

One of the important analyses is to compare the position results with some known reference. In this case the positions computed by C^3NAV™ are compared with a highly accurate digital road map of Calgary. The digital road map obtained from the city of Calgary is accurate to within a few centimeters, and was generated by airborne photogrammetric techniques. The UTM road coordinates are referenced to the center of the road. The road is divided into small straight-line segments and the two end co-ordinates of this segment are stored in the database.

ANALYSIS

Section 1

Although Section 1 has clear visibility there are some outages in the tracking performance due to underpasses present along the road. Most of the times these outages are correlated across antennas, which is a characteristic of complete signal masking. The tracking performance of the receiver gives an insight into the quality of the computed position. This can be analyzed by studying the Geometric Dilution of Precision (GDOP), which is a quality indicator of the geometry and is a function of the satellites tracked.

The average number of visible satellites and GDOP for Section 1 are shown in Table 1 below:

Table 1: Average satellite visibility and GDOP - Section 1

	Antenna A	Antenna B	Antenna C	Antenna D
Average GDOP	3.3	3.5	3.4	3.2
Average # of SVs	5.8	5.7	5.8	4.7

Antenna D has lower average number of satellites but has a better GDOP average than the rest of the antennas. The reason for this is for some portions of the test, antenna D lost lock on all satellites where as other antennas still had a few satellites, but with a poorer GDOP and for computing the average all the epochs in the section was considered.

To analyze multipath in all the four antennas code minus carrier differences were computed for all the satellites in each receiver. The result of only one satellite (SV 17) is shown in Figure 7.

Satellite 17 is at a fairly high elevation angle (68°) at the beginning of the test and slowly descends to 33° towards the end of the test.

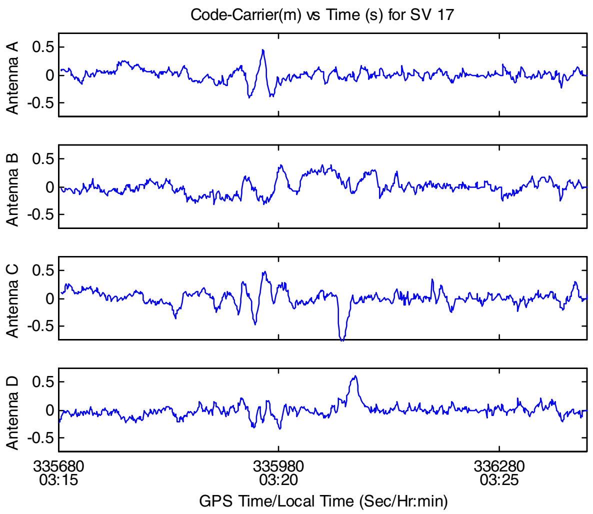

Figure 7: Code-carrier differences (SV – 17), Elevation (68° - 33°) – Section 1

The multipath between antennas, as seen from Figure 7, is not entirely uncorrelated but has some oscillations, which are not similar across the antennas. Multipath oscillations depend on the relative path delay between the direct and the reflected signal (Braasch, 1996).

Some of the multipath errors seen in Figure 7 above were a result of reflections from other vehicles when the car had stopped at lights. This was identified by analyzing velocity and position information of the vehicle and cross verifying with the intersections on the digital map.

The correlation of multipath between Antenna A and the three other antennas is computed for the entire duration in Section 1. The correlation coefficient results for satellite 17 is shown in the figure below.

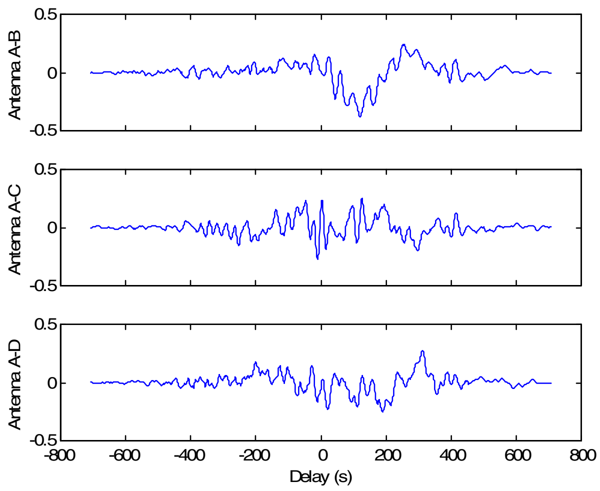

Figure 8: Cross correlation coefficient plots (SV – 17), Elevation (68° - 33°) – Section 1

If the code minus carrier differences between different antennas were unrelated then the correlation coefficient would be zero. The cross correlation plots above show oscillations, which decorrelate rapidly. This decorrelation can be used to identify and remove multipath.

The error between the GPS and the true reference is shown in Figure 9. This is the error as computed between the GPS and digital map co-ordinates. Comparisons are only done in 2D mode.

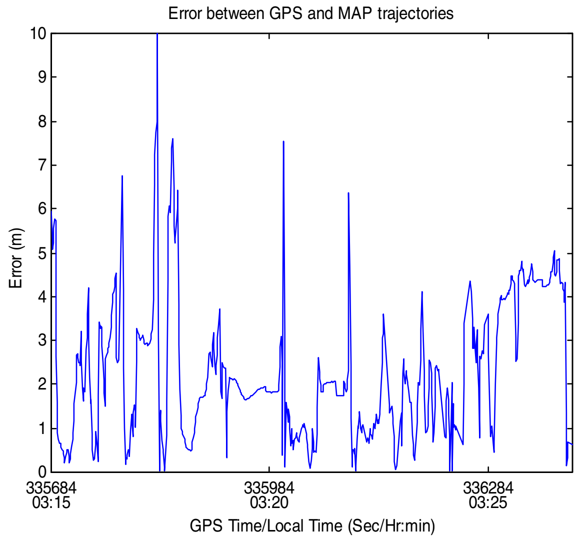

Figure 9: Error between the GPS and true trajectories – Section 1

The errors have a mean of 2.3m and RMS of 2.7m. This mean results from the fact that the digital road map corresponds to the center of the road, whereas the vehicle is moving in and out of the center of the road depending on whether the road is a single lane or a two lane road. This makes it practically impossible to estimate the distance from the center of the road to the vehicle and re-compute the errors. Some of the low frequency oscillations seen in could be attributed to this motion. There are some spikes in the graph, some of which are related to the change in geometry of the satellites and some oscillations related to multipath.

Section 2

The trajectory of Section 2 was chosen to test the effect of multipath in dense urban canyons. The total duration of the test was 25 minutes and the total distance covered was approximately 9km.

The continuous line in Figure 10 below represents the truth trajectory extracted from the digital map and the circles represent the co-ordinates computed from Antenna A on an epoch to epoch basis.

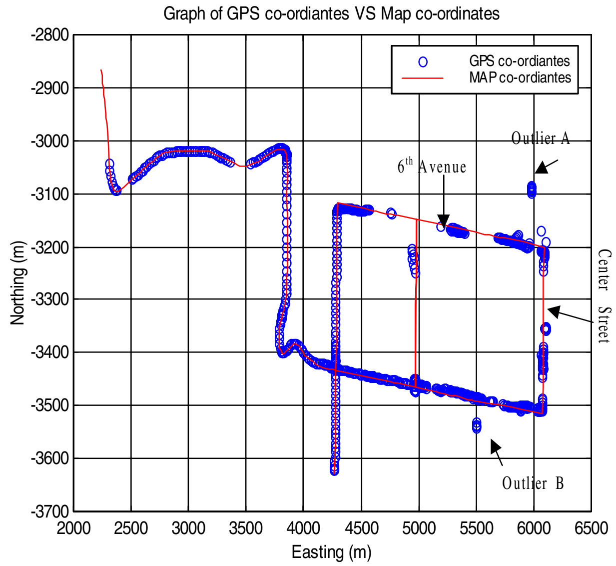

Figure 10: Comparison of GPS and digital map coordinates - Section 2

Two outliers (A and B) shown in the figure are some of the gross outliers clearly visible in Section 2. Outlier A is a result of very bad geometry (GDOP > 20) and outlier B is a gross multipath error. The position is erroneous by 100m and 60m at outliers A and B, respectively. Some error is also noticeable at the intersection of Center Street and 6th avenue.

Due to the harsh urban environment the satellite visibility is severely affected and the average number of visible satellites and the corresponding GDOP are shown in Table 2 below.

Table 2: Average satellite visibility and GDOP - Section 2

	Antenna A	Antenna B	Antenna C	Antenna D
Average GDOP	5.6	6.1	5.5	5.9
Average # of SVs	3.2	2.6	3.3	1.2

There is a severe decline in the average number of satellites in all four antennas compared to Section 1 and also the average GDOPs are larger compared to the values in Section 1. Once again Antenna D had complete loss of position more often than other antennas.

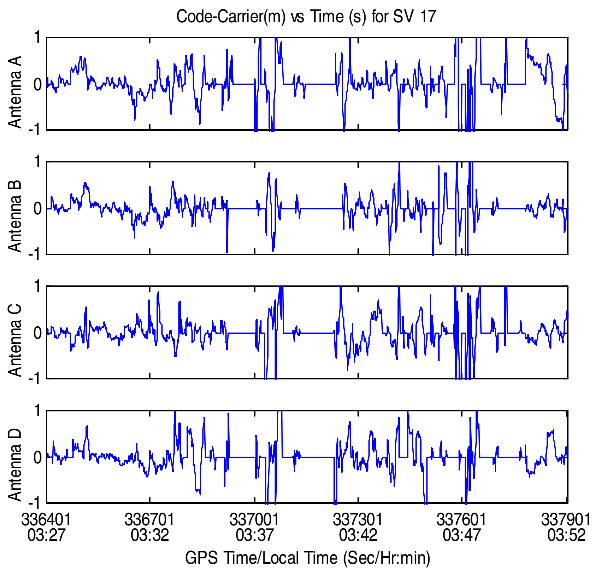

Figure 11: Code-carrier differences (SV - 17), Elevation (68° - 33°) – Section 2

The code minus carrier differences shown in Figure 11 have oscillations of up to 2 m, which can be attributed to multipath. In some instances, the differences are larger than 5 m which can introduce significant error into the estimated position. The code minus carrier differences for this section also have larger spikes compared to Section 1, which indicates larger gross multipath errors in an urban environment. Multipath errors for satellite 23 (not shown here) at an elevation angle of 75° had fewer gross errors compared to satellite 17 which is at a lower elevation angle. This is typical in urban environment. The correlation of multipath of Antenna A with the other three antennas is shown in Figure 12.

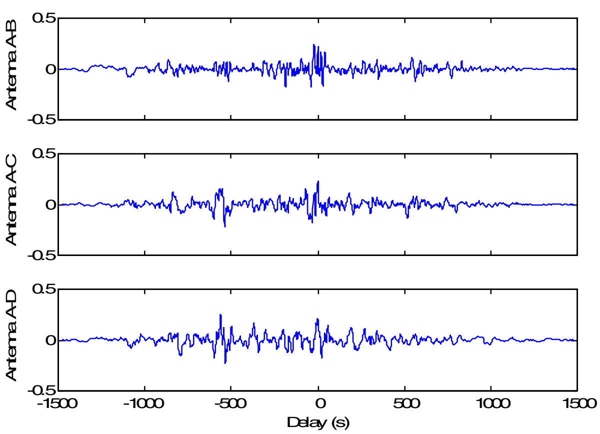

Figure 12: Cross correlation plots for SV 17, Elevation (68° - 33°)- Section 2

The cross correlation plots have a higher frequency component compared to Section 1, which means faster multipath decorrelation. High frequency multipath can be caused by reflections from objects at long distances such as buildings. Compared to Section 1 the multipath in this environment is large and has higher decorrelation, which can be exploited to detect multipath.

The error between the GPS and the true reference (digital map) for Section 2 is shown in the Figure 13.

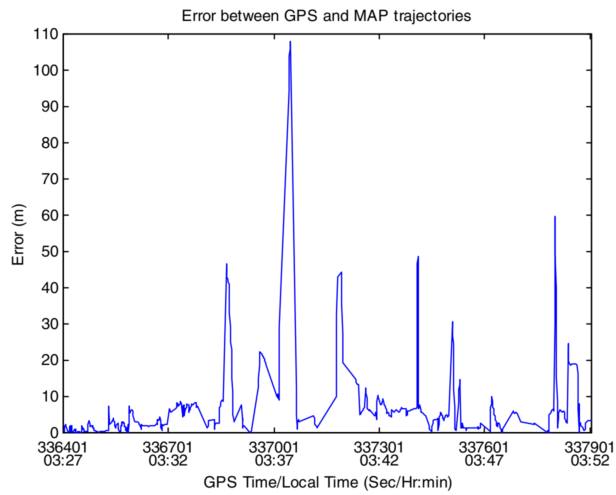

Figure 13: Error between the GPS and true map trajectory – Section 2

The mean and RMS values of the errors shown above are 7.1m and 13.4m respectively. The large RMS value clearly shows the degradation due to a severe multipath environment compared to Section 1. The large error of 100m in Figure 13 is due to bad geometry (GDOP > 20) and the remaining errors varying around 20m to 60m are due to multipath. As discussed in Section 1, these errors have a bias, which corresponds to the vehicle not moving on the center of the road.

Section 3

The trajectory of Section 3 was specifically chosen to test the effect of multipath in a dense foliage environment. Figure 14 below shows large discontinuities in the trajectory, which is a result of signal shading effects from the heavy foliage. The outages vary from 20 m to 200 m. The total duration of the run is 35 minutes and the total distance covered is approximately 5.5km. The visibility is very poor on Montcalm Crescent, Frontenac Avenue and Montreal Avenue where the foliage canopy completely covers the street whereas 10th Street has clear visibility on both sides of the road.

The continuous line in Figure 14 represents the truth trajectory extracted from the digital map and the circles represent the co-ordinates computed from Antenna A on an epoch to epoch basis.

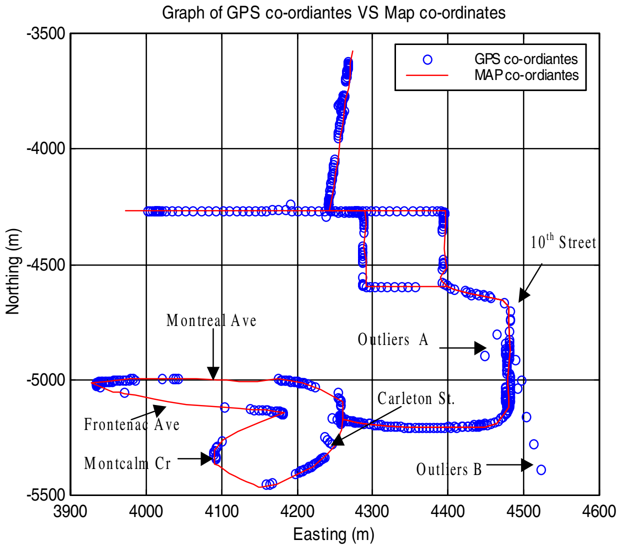

Figure 14: Comparison of GPS and digital map coordinates - Section 3

Two outliers A and B are shown in the figure above. Outlier A, which is a result of multipath, is erroneous by 50 m whereas outlier B is 175m from the reference trajectory and was due to very poor geometry (GDOP > 20). Some error is also noticeable along Carleton Street. The gross errors mentioned above are seen along 10th Street, where the visibility is better compared to other streets in this section. However, this multipath could be due to some of the buildings present along the street.

The trajectories computed from the other three antennas did not show an exactly similar pattern, but did have outliers at other places, which strongly supports the fact that multipath can be quite different at antennas placed short distances apart.

The average number of satellites and GDOP for this section is given in Table 3.

Table 3: Average satellite visibility and GDOP - Section 3

	Antenna A	Antenna B	Antenna C	Antenna D
Average GDOP	4.9	5.9	5.1	5.3
Average # of SVs	3.5	3.1	3.3	2.3

The poor visibility once again is a result of total masking by the thick foliage in the region. The effect of multipath due to this masking can be seen in Figure 15 below.

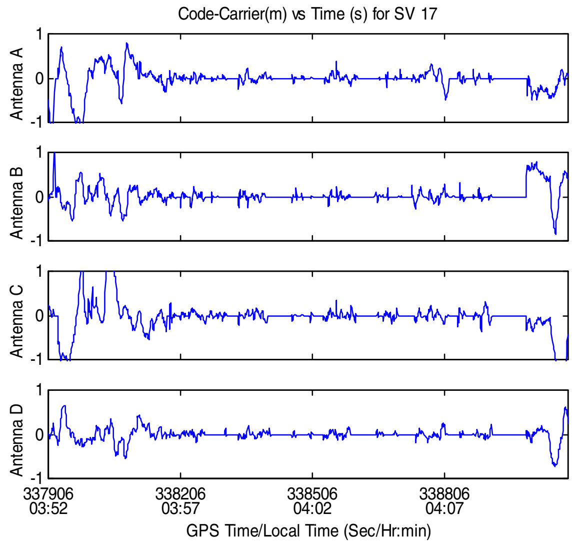

Figure 15: Code-carrier differences (SV - 17), Elevation (68° - 33°) – Section 3

The code minus carrier differences show multipath oscillations between GPS time 337906 and 338206 during which time the vehicle was travelling on 10th Street, where the satellite visibility is good. But later on, under heavy foliage sections on Montcalm Crescent and Frontenac Avenue, large outages can be seen in Figure 15 due to poor tracking. The absolute position error as compared with the digital map is shown in Figure 16.

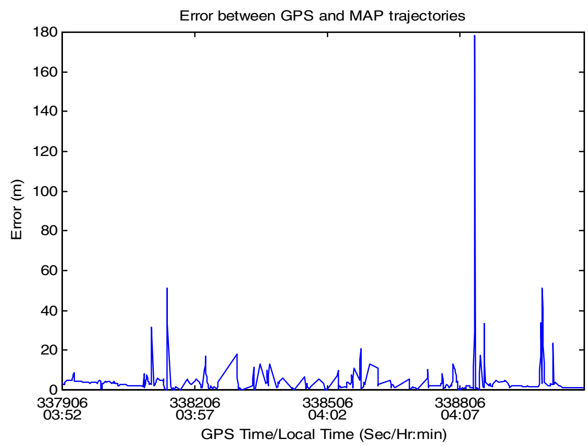

Figure 16: Error between the GPS and true trajectories - Section 3

The mean and the RMS values of the errors are 3.9m and 9.8m respectively. This indicates a less multipath-prone environment compared to section 2. Figure 16 clearly shows errors due to multipath and a gross error (175m) due to extremely poor geometry. There are fewer gross errors in Section 3 compared to Section 2 because foliage, rather than reflecting signals, provides a high degree of attenuation.

The analysis of Section 4 is not shown, as it is similar in nature to Section 1. The signal-to-noise ratio (SNR) has been successfully used to estimate carrier multipath for static applications (Axelrad, 1994). The SNR of each satellite was also analyzed to study the possibility of using it as an indicator of multipath. However, due to the dynamics of the vehicle and the constant change in the surrounding environment the SNR was affected more due to the shading effects than by multipath itself. Hence the SNR analysis provided inconclusive results.

Some of the results observed in the test are summarized in the Table 4.

Table 4: Average

	Sec 1 Suburban	Sec 2 Urban	Sec 3 Foliage	Sec 4 Suburban
Avg % visibility	93	44	45	95
Average GDOP	3.4	5.7	5.3	3.1
Multipath error (m)	+/- 0.5	+/- 2.0	+/- 1.0	+/- 1.0
Horizontal RMS error (m)	2.7	13.4	9.8	4.2

PROPOSED MITIGATION STRATEGY

The code-carrier differences clearly show the presence of multipath in the GPS code measurements. The approach being developed to mitigate multipath consists of the following steps:

- The differentially corrected position and velocity for each of the antennas will be computed independently at every epoch (t).
- A fixed distance constraint between the four antennas will be used in a least squares sense to obtain a best estimate of the position for all the four antennas at an epoch (t).
- The positions at epoch t+1 will be then computed using the *a priori* estimate. Reliability of the solution will be tested by comparing the normalized residuals against a conservative threshold.
- If any of the residuals fail the test, then smaller subsets with one satellite removed will be formed. The normalized residuals from each of the subsets will then be tested until the measurement corrupted by multipath is removed (Ryan et al., 1999).

The proposed methodology is reliable and easy to implement and it will never degrade the computed user's position and can eliminate measurements biased by multipath error.

The proposed method is similar to the RAIM algorithm proposed by Parkinson and Axelrad (1988).

CONCLUSIONS

A series of tests were conducted in Calgary whereby four antennas were mounted in vehicle and raw GPS data was collected over four sections of urban and suburban routes. The data from the four antennas was processed using the code minus carrier technique to analyze the presence of multipath and its correlation from one antenna to another. The estimated positions were also compared to an accurate digital road map to determine the overall position accuracy.

The code-carrier differences provide a good representation of the multipath error. From the code-carrier differences of Sections 1 and 2, the multipath error can be inferred to be dependent on the surroundings and dynamics of the vehicle. Inspite of the harsh multipath environments, gross multipath errors were observed only in a few cases. This could be due to the high performance Narrow Correlator™ technology employed in the Millennium™ receivers. The cross correlation results showed rapid decorrelation of multipath among antennas. Since multipath amplitude and phase change rapidly with the vehicle dynamics it is not possible to use the geometry information between the antenna to detect and mitigate multipath from the pseudorange measurements. Using the SNR to estimate multipath error is also not very effective in kinematic mode as SNR depends not only on the multipath but also on the vehicle dynamics, satellite elevation angles, and the surrounding environment.

One of the possible methods to improve the position accuracy in harsh urban environment has been proposed. The results of this technique will be compared with a highly accurate vector map of the city of Calgary to assess the improvement in position accuracy. Usually, even with a high performance correlator, mutipath errors of few meters (5 – 10 m) are quite common. Hence, the accuracy improvement that can be expected depends on successful identification and subsequent elimination of the multipath corrupted measurement.

ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support provided by Daimler Chrysler Research and Technology North America.

REFERENCES

Axelrad, P., C. Comp and P. MacDoran (1994), Use of Signal-To-Noise Ratio for Multipath Error Correction in GPS Differential Phase Measurements: Methodology and Experimental Results, Proceedings of ION GPS-94, Salt lake city, September 20-23, pp.655-666.

Braasch, M.S. (1994), Isolation of GPS Multipath and Receiver Tracking Errors, NAVIGATION: Journal of the Institute of Navigation, Vol. 41, No. 4, Winter, pp. 415-434.

Braasch, M.S. (1996), Multipath Effects, Global Positioning Systems: Theory and Applications, American Institute of Aeronautics and Astronautics, Vol. 1, Ch 14, pp. 547-568.

Cannon, M.E. and G. Lachapelle., (1992), Analysis of a High-Performance C/A-Code GPS Receiver in Kinematic Mode, NAVIGATION: Journal of The Institute of Navigation, Vol. 39, No. 3, Fall, pp. 285-300.

Cannon, M.E. and G. Lachapelle, (1995), C^3NAV™ Operating Manual, Department of Geomatics Engineering, The University of Calgary, 23 pp.

Garin, L., F. van Diggelen and J. Rousseau (1996), Strobe & Edge Correlator Multipath Mitigation for Code, Proceedings of ION GPS-96, Kansas City, September 17-20, pp. 657-664.

Garin L and J. Rousseau (1997), Enhanced Strobe Correlator Multipath Rejection for Code & Carrier, Proceedings of ION GPS-97, September 16-19, Kansas City, pp. 559-568.

Parkinson, W.B., and Axelrad, P., (1988), Autonomous GPS Integrity Monitoring Using the Pseudorange Residual, NAVIGATION: Journal of The Institute of Navigation, Vol. 35, N0. 2, pp. 255-274.

Parkinson, W.B (1994), Global Positioning System: Theory and Applications, American Institute of Aeronautics and Astronautics, Vol 1, Ch 11, pp. 469-483.

Parkinson, W.B and P.K.Enge (1995), Global Positioning System: Theory and Applications, American Institute of Aeronautics and Astronautics, Vol 2. Ch 1, pp 3-49.

Ryan. S, J. Stephen, and G. Lachapelle, (1999), Testing and Analysis of Reliability Measures for GNSS Receivers in the Marine Environment, Proceedings of ION NTM 99, San Diego CA, January 25-27, pp 505-514.

van Dierendonck, A. J., P. Fenton, T. Ford, (1992), Theory and Performance of Narrow Correlator Spacing in a GPS receiver, NAVIGATION : Journal of the Institute of Navigation, 39(3):265-283.

van Nee, R.D.J. (1992), Multipath Effects on GPS Code Phase Measurements, NAVIGATION: Journal of the Institute of Navigation, Vol. 39, No. 2, Summer, pp. 177-190.

van Nee, R.D.J. (1995), Multipath and Multi-Transmitter Interference in Spread-Spectrum Communication and Navigation Systems, Delft University Press, Delft, The Netherlands, 208 pp.