Kinematic Ambiguity Resolution With a High Precision C/A Code Receiver

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ABSTRACT

Kinematic carrier phase ambiguity resolution, i.e., on the fly, which is the key to cm-level accuracy differential GPS positioning, is investigated using high precision, single frequency, 10-channel, C/A code receivers. The major characteristic of this unit is a narrow correlation spacing which improves code measuring accuracy to 10 cm and reduces code multipath interference. The high code accuracy enables the user to reduce the search area which contains the correct integer ambiguity solution. The principles of the least-squares search procedure used herein to obtain the correct ambiguity solution are described. Land kinematic test results are presented for the case of a benign multipath environment and that of a comparatively high multipath environment. For the benign multipath case, the correct ambiguities are found within 1 to 3 minutes with a high success rate, under a relatively good six-satellite geometry (GDOP $\approx$ 3) and a short monitor-remote separation (< 5 km). In the presence of carrier phase multipath caused by nearby trees, however, the success rate decreases to less than 50% and the correct ambiguity solutions are found only after a significantly longer observation period.

INTRODUCTION

GPS kinematic positioning at the cm accuracy level is feasible using carrier phase observables in double differencing mode, provided that the carrier phase ambiguities can be resolved to their correct integer values. Since the ambiguities remain constant when no loss of phase lock occurs, they can be estimated at the beginning of the mission using established static initialization methods. In such a case, both the monitor and the remote receivers must observe common satellites for at least a few minutes prior to setting the remote unit in motion (e.g., Cannon 1990). The method is constraining for two reasons, namely the difficulty associated with holding the remote fixed for any period of time, e.g., a ship, and losses of phase lock which occurs in kinematic mode due to signal masking and other reasons.

This is why much attention has recently been focused on ambiguity resolution methods without static initialization, i.e., on the fly (e.g., Hatch 1991, Remondi 1991). The use of such methods involves the resolution of the integer ambiguities using segments of kinematic data at the beginning of the mission and each time a loss of phase lock or cycle slip occurs. Although one epoch of measurements might in principle be sufficient, at least a few epochs are preferred to obtain redundant measurements and, as a consequence, a more reliable solution. The length of the cycle slip free data segment required to solve the ambiguities is a function of various parameters, including differential orbital and atmospheric errors, which are mostly a function of the distance between the monitor and remote units, the accuracy of the observations, the level of multipath and the type of data used, i.e., dual or single frequency. For monitor-remote separations of less than a few tens of km, the differential orbital and atmospheric errors are relatively small and will not generally prevent successful ambiguity resolution_ If dual frequency data is available, the widelaning technique can reduce the observation time span required to a few seconds (e.g., Lachapelle et al 1992b). Dual frequency receivers are however relatively expensive as compared to single frequency receivers. In addition, the fact that the dual frequency P code will be denied as of early 1994 further complicates the situation.

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Dual frequency codeless receivers which can operate effectively in the kinematic mode are only starting to appear on the market and their prices are relatively high. The use of single frequency receivers is therefore worthwhile exploring at this time, even if the observation segment length required is expected to be substantially longer.

METHODOLOGY

The procedure used for carrier phase ambiguity resolution without static initialization generally involves two steps. In the first step, differential code measurements are used to estimate an approximate position for the moving antenna to bound the potential number of integer ambiguity solutions to a manageable number. The accuracy of the differential code solution therefore plays an important role in reducing the processing effort, which is particularly important for real-time applications. In the second step, one of several techniques can be used to isolate the correct carrier phase integer ambiguity combination. The most well known techniques are the Ambiguity Function Method (e.g., Mader 1990) and the least-squares search method (e.g., Hatch 1991). Although both are mathematically equivalent (Lachapelle et al 1992a), they are implemented according to different schemes and they have different advantages and disadvantages (e.g., Erickson 1992). The least-squares search method was used herein.

Two properties of the least-squares search technique are used, namely (i) only three of the double difference carrier phase ambiguities are independent, and (ii) the estimated variance factor calculated using the adjusted carrier phase residuals should be minimum at the correct solution. The first property means that once three double difference phase ambiguities are known, the position of the moving receiver can be precisely determined, and therefore the ambiguities of the remaining satellites can be fixed. Four primary satellites are needed to generate an entire set of potential solutions which are computed based on different trials of double difference carrier phase ambiguities. Each potential solution, which corresponds to one specific three-ambiguity set of the primary satellites, is checked using observations from the redundant or secondary satellites. At the potentially correct solution, the computed observations for the secondary satellites should be very close to the corresponding measured observations. The agreement can be quantified using the estimated variance factor or sum of squares of residuals. A large disagreement between the computed and measured observations means that the solution tested is not the correct one and can be rejected. If more than one potential solution are passed through the agreement test at a certain epoch, the ambiguity sets corresponding to these potential solutions are retained and further tested at the following epochs. As more epochs are used, all the false ambiguity sets of the primary satellites are gradually rejected except the correct one. The more satellites available, the less the observation time required for resolving the ambiguities. Further details are given in Lachapelle et al. (1992c). The success of the method will depend, among others, on the satellite geometry, a better geometry resulting in faster convergence, and on the magnitude and distribution of the carrier phase residuals. Non gaussian phenomenae such as carrier phase multipath may bias the results and lead to the acceptance of incorrect solutions.

The high precision single frequency lo-channel CIA NovAtel GPSCard™ units used herein had a narrow correlation spacing capability to improves code measuring accuracy to 10 cm and reduces significantly code multipath interference (Fenton et al 1991, Cannon & Lachapelle 1992, Van Dierendonck et al 1992) In practice, the combined effect of receiver code noise and multipath limits the code accuracy to about 15 to 70 cm, as shown in Figure 1 for a relatively high and a relatively low satellite. The corresponding values for a standard C/A code receiver are 2 to 3 m. The level of performance shown in Figure 1 is similar to that of a P code receiver on either the Ll or L2 frequency. Of importance for the current test is the accuracy of the carrier phase measurements. Earlier tests confirmed an accuracy of about 1 mm which is consistent with that of receivers equipped with similar temperature compensated oscillators. This accuracy consists however only of internal receiver noise. For field measurements, the effect of carrier phase multipath, which is proportionally larger, has to be taken into account, as will be seen later.

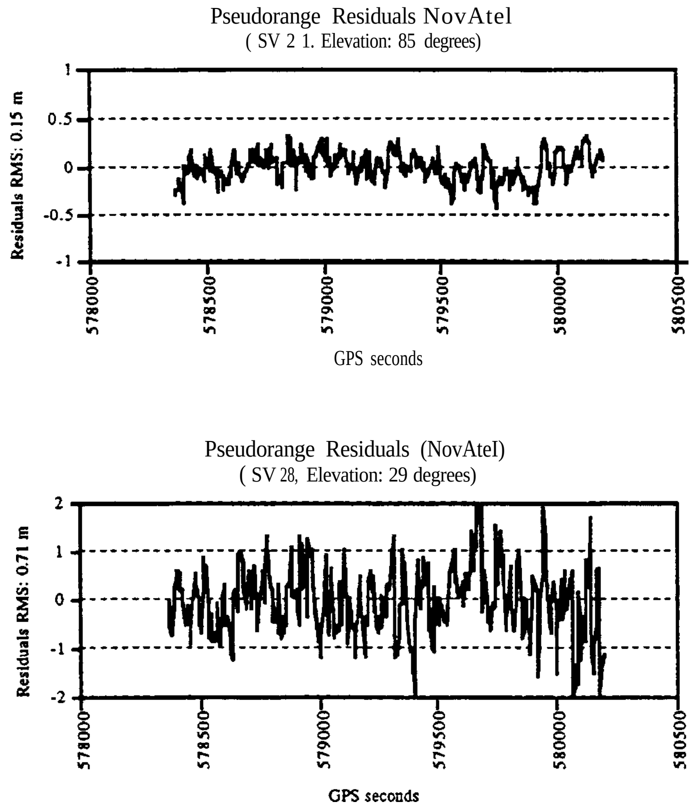

Figure 1: GPSCard™ Typical Combined C/A Code Receiver Noise and Multipath

FIELD TEST

A semikinematic test was conducted on June 15, 1992, on a portion of the Springbank test range west of Calgary. Only the kinematic portion of the test was used to investigate ambiguity resolution without static initialization. The static initialization was however used to provide a reference trajectory at the cm-accuracy level which became the benchmark solution in assessing whether the ambiguity on the fly solutions were correct. Two GPSCard™ units were used, one at the monitor and the other mounted on the roof of a mini-van. The receiver at the monitor location was a GPSCard™ operating with a tracking bandwidth of 5 Hz. The tracking bandwidth of the GPSCard™ in the vehicle was set at 5 Hz during the first run and at 10 Hz during the second run. This was done to test the effect of carrier phase noise on ambiguity resolution. Chokering ground planes were used at both the monitor and remote locations to reduce the effects of code and carrier phase multipath (e.g., Cannon & Lachapelle 1992, Lachapelle et al 1993). Both receivers collected data every second.

Figure 2 shows the monitor site as well as the vehicle trajectory during the tests. The static initialization was performed by observing Pillar 3 with the remote receiver for about four minutes at the beginning of each run. The vehicle then traveled to the east and then to the northern most point of the test range. This was done two times and, at the end of each run, Pillar 3 was re-observed for a short period with the remote antenna to ensure that a highly accurate and highly reliable reference trajectory was obtained in each case. As can be seen from Figure 2, there were numerous trees at the comer of the trajectory which were not however in the line of sight to the satellites. However, they caused carrier phase multipath as will be discussed in the following section. Each kinematic run lasted approximately five to eight minutes. Six satellites were observed throughout the entire test and the GDOP varied between 2.8 to 3.1. All six satellites were above 15 degrees elevation. The maximum distance between the monitor and the vehicle reached three km. The vehicle speed was typically between 15 and 22 m/s, i.e., 50 and 70 km/h.

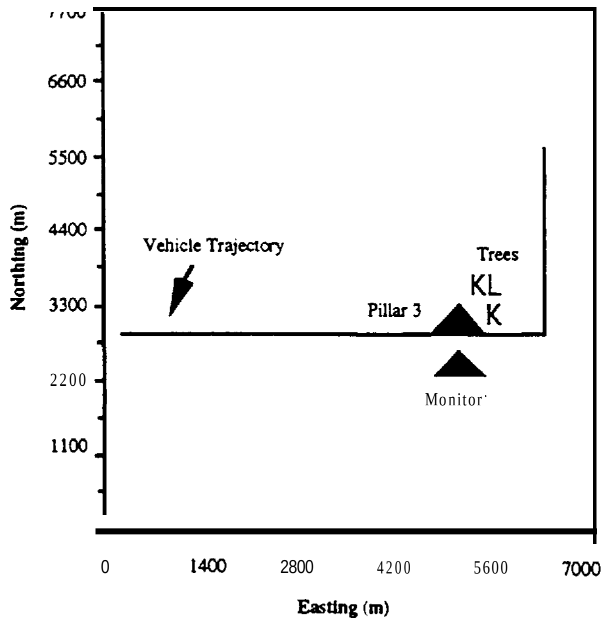

Figure 2: Vehicle Trajectory on the Springbank Baseline

ANALYSIS OF RESULTS

In order to assess the quality of the data before attempting to resolve the ambiguities without static initialization, the kinematic data was processed using a least-squares carrier phase difference model with the fixed integer ambiguities obtained using the data collected during the static initialization. Since redundant satellites were available, meaningful double difference carrier phase residuals could be calculated. These provides an indication of the carrier phase noise and multipath, which are the two main error sources in the case of a short monitor-remote separation. The residuals are shown in Figures 3 and 4. The residuals obtained along the comer section during the first run are not shown here because they were not used to solve the ambiguities on the fly. This was done to isolate the results obtained in the absence of carrier phase multipath caused by the trees. The absolute values of the double difference carrier phase residuals are generally below 5 mm for either bandwidth during the portion of the trajectory which is free from trees. No significant differences are apparent between the residuals obtained with the two bandwidth values in the clear section of the trajectory_ In Figure 4, the residuals obtained during the comer section, between 146400 s and 146650 s, are shown. They reach one cm due to the multipath caused by the trees. This will have a significant effect on the kinematic data span required to solve the ambiguities on the fly as will be seen below.

For ambiguity resolution without static initialization, an initial differential code solution was used to define the range in integer ambiguities for each double difference pair (using only the four primary satellites). This volume, which must contain the correct solution, is defined by the differential code solution and its estimated standard deviation, e.g. $\text{latitude}_{\text{dif code}} \pm 3\sigma_{\text{lat}}$ for a 95% probability level. In the present case, the cube size was approximately 2 m x 2 m x 2.5 m, which typically generates some 5000 integer ambiguity combinations. The goal is to isolate efficiently which of these 5000 integer combinations is the correct one. The data quality, in terms of noise and multipath, as well as the number and geometry of the satellites tracked, are critical factors for fast resolution. The advantage of the high precision GPSCard™ is its high precision C/A code which results in a smaller initial search volume and faster convergence from a computational aspect.

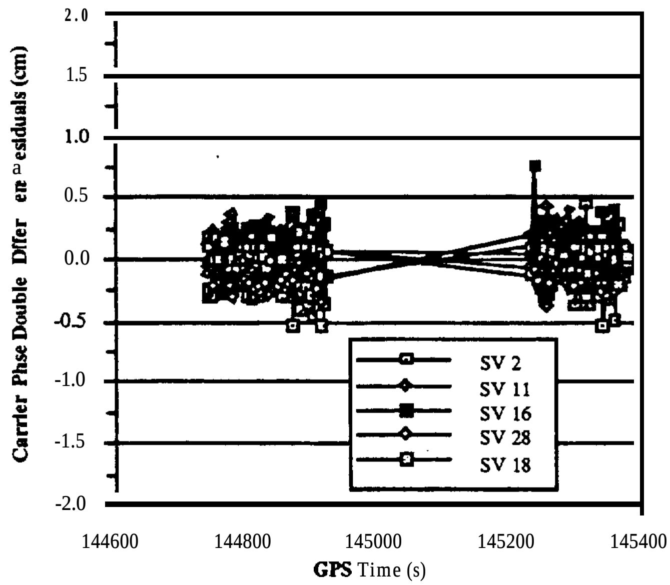

Figure 3: Carrier Phase Double Difference Residuals - 5 Hz Bandwidth

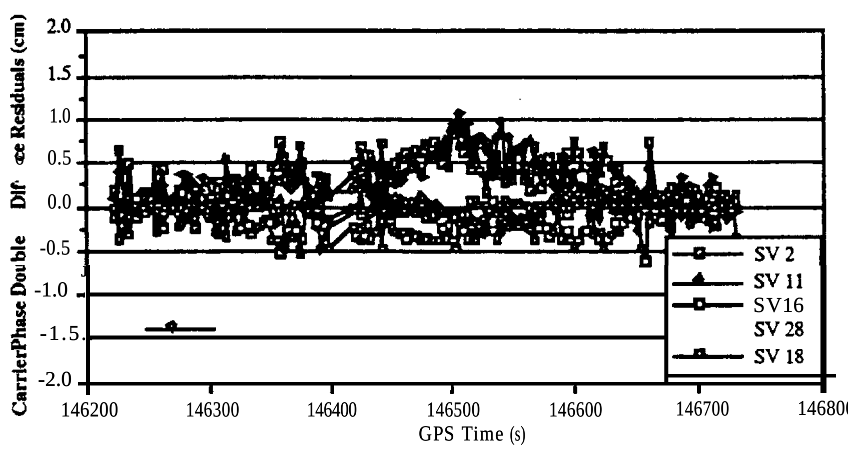

Figure 4: Carrier Phase Double Difference Residuals - 10 Hz Bandwidth

The data set for each test run was processed by starting at an initial kinematic epoch and determining how many subsequent epochs were required to obtain a unique integer ambiguity solution with a stated level of certainty. Once this was accomplished, the initial point was moved forward by 20 seconds to decorrelate receiver noise and multipath at the mobile unit. Several tests could therefore be made on each data set. The ***a priori*** standard deviations assigned to the double difference carrier phase measurements were 5 and 7 mm for the 5 and 10 Hz bandwidth data, respectively, as obtained in Figures 3 and 4. These values include the effect of receiver noise and carrier phase multipath. Table 1 summarizes the ambiguity resolution results without static initialization. Once a unique solution was obtained for the integer ambiguities, the corresponding three-dimensional coordinates were calculated and compared to those of the reference trajectory at the same epoch. If the differences were less than a few cm, the ambiguity solution was deemed to be correct_

From Table 1 it can be seen that ambiguity resolution using the 5 Hz data gathered during the clear section of the test range was highly successful. In all 16 trials, the integer ambiguities were determined correctly, using an average of 112 epochs. This means that in less than two minutes, cm-level positioning was achieved. The minimum amount of time to resolve integer ambiguities was 67 s. In the case of the 10 Hz data, which included the tree section of the test range, eight out of 19 trials were successful. In the other cases, there was not enough data to resolve the integer ambiguities or the correct solution was rejected. For the 8 successful trials, an average of 183 epochs were needed. The degradation in performance is mostly due to the inclusion of data along the tree section of the test range, as shown in Figure 2. In this section, the measurements are noisier due to a higher level of multipath as shown in Figure 4. The success rate could have been improved by increasing the a ***priori*** standard deviation of the phase observations (Lachapelle et al 1992b). The time to resolution however would have increased substantially. Successful ambiguity resolution is very sensitive to carrier phase noise, which includes multipath. Biased residuals may also result in the rejection of the correct ambiguity solution. See (Lachapelle et al 1992b) for further detail.

Table 1
Ambiguity Determination Results Without Static Initialization

Clear/Trees	Receiver Tracking Bandwidth	Nbr of Tests Performed	Nbr of Tests with Integer Ambiguities Resolved	Average Observation Time Required (rnin/max) in seconds
clear	5	16	16	112 (67/181)
clear + trees	10	19	**8**	**183 (1231248)**

Figure 5 shows a plot of the number of potential integer ambiguity solutions versus observation time for a typical run. At the initial epoch, there are approximately 5000 potential solutions to be tested, but this number quickly drops to less than 100 after a few seconds. The process is then fairly linear overtime until there are only three combinations remaining. It then requires an additional 40 seconds to isolate the correct solution.

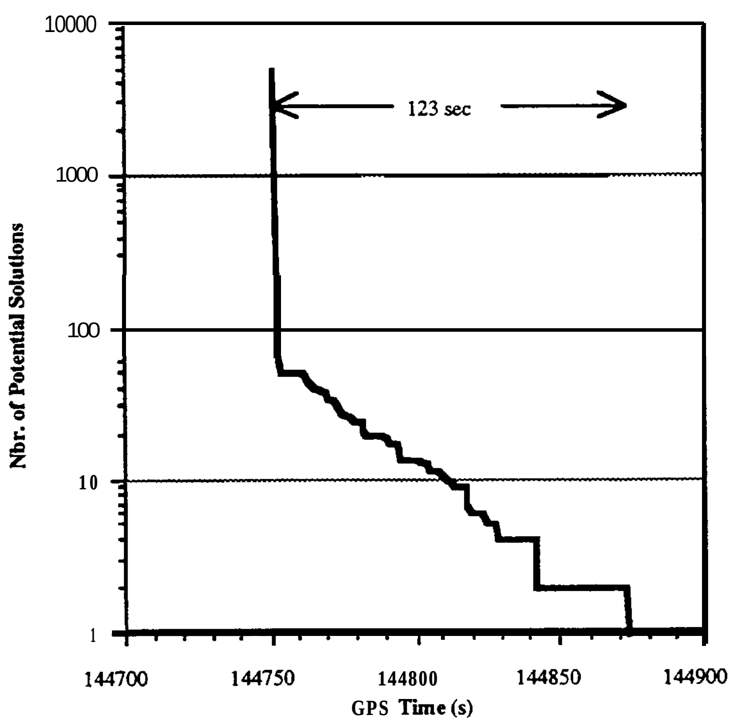

Figure 5: Number of Potential Integer Ambiguity Combinations Versus Time for a Representative Run

CONCLUSIONS

The feasibility of using high precision single frequency C/A code receivers for resolving the carrier phase integer ambiguities without static initialization was demonstrated using data collected in land kinematic mode at speeds of 50 to 70 km/h. Under benign multipath conditions, the ambiguities were resolved within one to three minutes. The method is however very sensitive to carrier phase noise, multipath being a major contributing cause. As a consequence, the reliability of single frequency data to resolve ambiguities on the fly in an operational environment is relatively low as compared to the use of dual frequency data (e.g., Lachapelle et al 1992b, 1993). Improving performance will be difficult, unless carrier phase multipath can be dealt with effectively. An alternative but operationally complex method would be to use dual-receiver systems both on the mobile and at the remote, to decorrelate and average out multipath. Early results suggest that a gain of 50% in terms of time to ambiguity resolution might be possible.

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