Precise Marine DGPS Positioning Using P Code and High Performance C/A Code Technologies

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ABSTRACT

The objective of this paper is to assess and compare the capability of P code and high performance C/A code receiver technologies for survey launch positioning at sea water to the sub-metre level. The receivers used to assess these technologies are the dual frequency Ashtech P-XII and the single frequency NovAtel GPSCard™. Sea trials were conducted at velocities of 10 to 15 knots using both receiver types simultaneously to collect the data necessary for the evaluation. Two data processing methods are analysed, namely ambiguity resolution on the fly and carrier phase smoothing of the code. The survey launch environment is relatively harsh with code and carrier phase multipath being a major error source. Ambiguity resolution on the fly is successful using the widelaning capability of the dual frequency P code. Ambiguity determination using single frequency data is also possible but the observation time required is substantially longer. In this case however, the use of a twin receiver system on the launch contributes in this case to improving the reliability of the solution. The effectiveness of chokering groundplanes to decrease the time to ambiguity resolution by reducing carrier phase multipath is demonstrated. DGPS P and high performance C/A code results in rrns accuracies are at the one metre level. A slight improvement is achieved using carrier phase smoothing of the code.

INTRODUCTION

GPS positioning in the marine environment is required for a variety of hydrographic and other applications. Precise positioning of a survey launch moving at cruising speeds of 10 to 15 knots is especially challenging due to the high dynamics of the antenna and the high reflectivity of the water. The use of carrier phase smoothing techniques with standard C/A code receivers has resulted in rms accuracies at the l-3 m level (e.g., Lachapelle et al 1988). In order to obtain accuracies at the sub-metre level, the receivers and/or the data processing techniques must be improved.

The two major objectives of this paper are (i) to assess and compare the performance of two receiver technologies for DGPS launch positioning, namely high performance single frequency C/A code and dual-frequency P code technologies, and (ii) to assess and compare two processing methods, namely carrier phase ambiguity resolution on the fly and carrier phase smoothing of the code. Carrier phase ambiguity resolution on the fly, i.e., without static initialization, delivers an accuracy at the centimetre level, provided the integer ambiguities can be resolved correctly. Various methods are available to resolve the ambiguities on the fly (e.g., Erickson 1992). The method selected here is the least-squares approach described by Lachapelle et al (1991), which is a variation of the method proposed by Hatch (1991). The level of success of any ambiguity resolution method is a function of several parameters, such as the type and quality of observables used, the multipath environment, the distance between the monitor and mobile receivers, and the satellite geometry. Since the presence of multipath around a survey launch operating at sea is typically greater than multipath in the land kinematic environment, ambiguity resolution on the fly is expected to be more difficult to achieve reliably in the marine case. The carrier phase smoothing of the code approach is more robust but less accurate. Carrier phase smoothing accuracies at the 25 - 100 cm level were achieved in the land kinematic environment using high performance C/A code technology (Cannon & Lachapelle 1992a, Lachapelle et al 1992). In the marine environment, accuracy degradation to the 50 - 100 cm level is expected due to the harsher multipath conditions.

EQUIPMENT SELECTION

The receivers selected for the sea trials are the same as those used previously for similar land kinematic tests (Lachapelle et al 1992) and consist of the NovAtel GPSCard™ and the Ashtech P-XII. The ambiguity resolution on the fly trials conducted earlier on land confirmed the capability of both technologies under benign multipath conditions. The GPSCard™ is a high performance lo-channel C/A code unit which has two unique characteristics, namely a 10-cm code noise and a narrow correlator spacing option to reduce code multipath interference (Fenton et al 1991, Van Dierendonck et al 1992). The P-XII is a 36-channel unit which measures carrier phase and C/A, P(L1), and P(L2) code simultaneously.

The C/A code noise of the P-XII is 100 cm while the corresponding P code noise is 10 cm. The phase noise is stated as 0.2 mm for the P-XII and 0.4 mm (differential channel) for the GPSCardTM. In practice, however, receiver noise and multipath cannot be separated and their combined effect becomes the prime error source in the resolution of the phase ambiguities on the fly. The estimated combined rms effect of receiver code noise and multipath for both receivers is given in Table 1. These figures can be considered pessimistic for the case of a normal kinematic environment since they were derived from a series of static experiments in a high multipath environment (Cannon & Lachapelle 1992b). The narrow correlator spacing on the code tracking loops of the GPSCardTM results in a combined rms effect of 70 cm, the same value as that of the P-XII P code. The corresponding P-XII C/A code rms effect of 300 cm is at the level anticipated for standard C/A technology. In both cases, the use of chokering ground planes results in a significant multipath reduction. Carrier phase multipath is also significant at the cm level. In kinematic mode, the combined phase receiver noise and multipath can vary from a few mm to a few cm. The impact of this effect on phase ambiguity resolution on the fly turns out to be very significant as will be shown later.

Table 1: GPSCard™ and P-XII Code Measurement Characteristics in a High Multipath Environment

Receiver & Obs. Type	Measuring Noise (rms)	Noise + Multipath (rms)
GPSCardTM	10cm	70cm
GPSCardTM with choke rings		30cm
P-XII C/A code	100 cm	300cm
P-XII P code	10 cm	70cm
P-XII C/A code with choke rings		200an
P-XII P code with choke rings		30cm

SEA TRIALS

A marine test was conducted by The University of Calgary and the Canadian Hydrographic Service (Pacific Region) in early September 1992 in the Sidney, B.C., area using a 12-m launch. The GPS observations used in this paper were collected on September 3 over a period of 40 minutes. The launch track observed is shown in Figure 1; the track length is 16 km. The speed ranged from 10 to 15 knots, i.e., from 18 to 27 km h^{-1}. The roll and pitch angles did not exceed 5'. The satellites observed, together with their azimuths and elevations, are listed in Table 2. The PDOP varied between 1.9 and 2.6. The differential mode was used and one GPSCard™ and one P-XII unit were used on-shore. The distance between these two monitor stations was 2.6 m. The distance between the shore units and the launch ranged from 10 to 24 km. A cursory analysis of single point residuals revealed that Selective Availability was either off or minimal during the trial.

The antenna configuration used on the launch is shown in Figure 2. Three GPScard™s and one P-XII unit were used. All code and carrier phase data were recorded at a data rate of two Hz using PC laptops. The three-GPSCard™ configuration was used to obtain redundant observations for the on the fly ambiguity resolution solutions and to estimate the attitude parameters of the launch. The results of the attitude parameter estimation experiment are reported by Lu et al (1993). The distances between the three GPSCard™ units were measured with an accuracy of about one cm, as shown in Figure 2. These distances will be used later to independently check the double difference carrier phase ambiguities estimated between the shore antenna and each one of the three launch-based GPSCard™ antennas.

All shore and launch-based **P-XII** and GPSCard™ antennas were equipped with chokering groundplanes except one GPScard™ antenna on the survey launch. The use of such groundplanes has proved effective, with both receiver types, in minimizing multipath effects during previous experiments (e.g., Cannon & Lachapelle 1992a, b). In this case, however, their use appears to make little difference on code ,multipath as can be seen by comparing Tables 3 and 4, which give statistics between double difference code and carrier phase measurements. These are results between the shore receiver, which was fitted with a chokering and two launch receivers, one of which was fitted with a chokering and the other, not. The rms values are similar for both pairs of receivers. It shall be shown in the next section, however, that the chokerings were effective in reducing carrier phase multipath. If one divides the rms values given in Tables 3 and 4 by $\sqrt{2}$, one obtains the combined effect of **code noise and multipath for a single code measurement. The effect ranges from 22 to 68 cm and agrees** well with the ***a priori*** values quoted in Table 1. Similar results were obtained with P-XII PLl and PL2 data. The P-XII C/A code results were substantially higher, as expected.

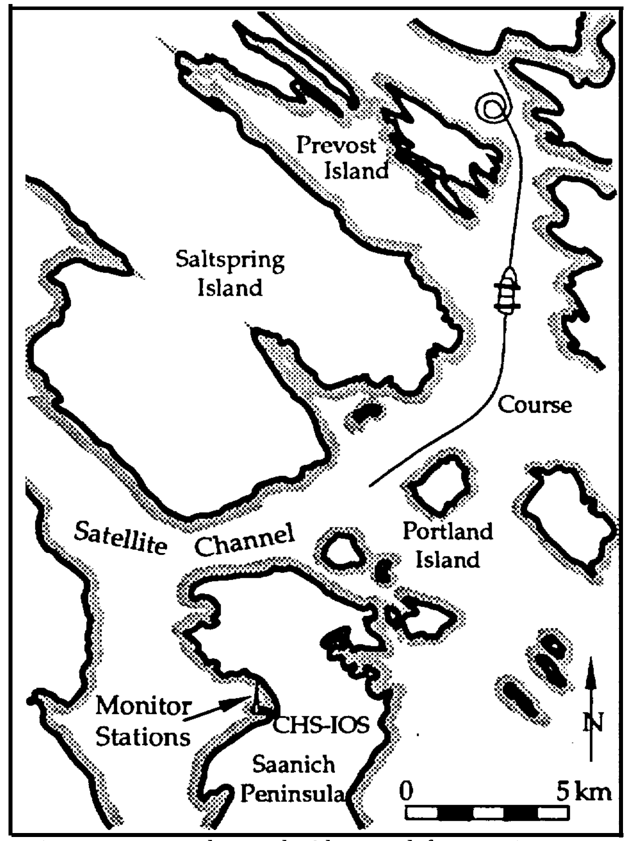

Figure 1: Launch Track Observed for Marine Test

Table 2:
SV Observed and their Azimuth and Elevation

SV	Azimuth	Elevation
03	130 - 143°	40 - 22°
17	68 - 92’	71 -55’
21	225 -235’	31-48’
23	204 - 108’	71- 86’
26	67 - 50°	35-28’
28	308 -295’	34-48’
PDOP = 2.6 - 1.9		

Table 3
Multipath Effects For GPScard™ Antenna 1
(With Chokering)

SV (Base SV: 23)	AV Code minus AV Carrier (m)			
	Max.	Min.	Mean	RMS
03	1.48	-1.14	025	0.58
17	1.16	-0.29	0.49	0.58
21	1.01	-2.28	-0.35	058
26	3.14	-1.16	0.89	1.15
28	1.43	-0.91	0.21	0.47

Table 4
Multipath Effects For GPScard™ Antenna 2
(Without Chokering)

SV (Base SV: 23)	Code ∆∇ minus Carrier ∆∇ (m)			
	Max.	Min.	Mean	RMS
03	2.07	-0.78	0.55	0.70
17	1.34	-0.39	0.53	0.62
21	1.08	-1.55	-0.05	0.43
26	2.81	-0.93	0.87	1.11
28	1.48	-1.16	0.37	0.51

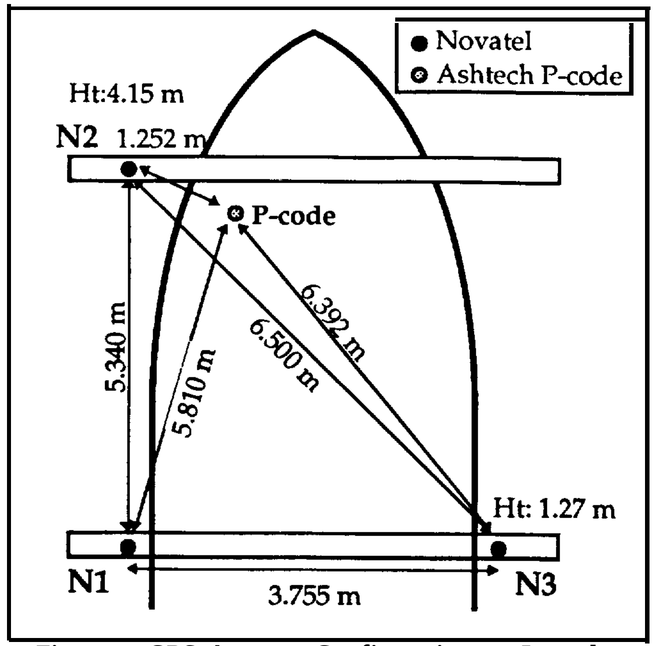

Figure 2: GPS Antenna Configuration on Launch

DATA REDUCTION AND ANALYSIS

Ambiguity Resolution On The Fly

The on the fly least squares ambiguity resolution method used herein is the same at that used by Lachapelle et al (1992) and involves two steps. Differential code measurements are first used to estimate an approximate position for the mobile receiver to limit the potential number of integer ambiguity solutions. The accuracy of the differential code solution therefore plays an important role in improving processing efficiency. Secondly, a least-squares search technique is used to isolate the correct integer ambiguity combination. Two properties of the least-squares search technique are used herein, 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 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, i.e. the residuals should be minimum. This implies that the estimated variance factor should also be a minimum. The estimated variance factor is computed as

$$\hat{\sigma}_o^2 = \frac{v^T C^{-1} v}{n-u} \qquad (1)$$

where $\hat{\sigma}_o^2$ is the estimated variance factor, v is the vector of measurement residuals, C^{-1} is the measurement covariance matrix, n is the number of double difference observations and u is the number of unknown parameters which is three in this case. For each integer ambiguity solution, the estimated variance factor is compared to the ***a priori*** variance factor using a χ^2 test. If the test fails for a particular integer ambiguity combination, this potential solution is rejected. Clearly from Eqn. (1), the magnitude of the estimated variance factor is a function of the measurement accuracy, i.e. C-1. For the double difference carrier phase measurement case, the combined effect of receiver noise and multipath must be taken into account. In the present case, the double difference carrier phase measurements were assigned ***a*** priori standard deviations of 20 mm W-XII L1-L2), 15 mm (P-XII Ll and L2) and 18 mm (GPSCard™). These values take in account phase receiver noise, multipath and residual differential atmospheric and orbital noise over the 10-24 km separation between monitor and launch.

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. In this case, a variance factor based on the previous carrier phase measurements is tested. This is called 'global' variance factor testing, since more than one epoch is considered. As more epochs are used, all the false ambiguity sets of the primary satellites will gradually be rejected except the correct one. The more satellites available, the less the observation time required for resolving the ambiguities. For more information on statistical testing criterion for on the fly ambiguity resolution, see Lachapelle et al (1991).

In order to accelerate the convergence time and reduce the effect of a possible bias on the ***a priori*** carrier phase variance $\sigma^2_{\nabla\Delta\phi}$, a ratio test is also used. When the number of potential solutions is reduced to a relatively low number after global testing, the ratio of the two smallest variance factors is computed. If the ratio is greater than a preset value (2 was used herein), the potential ambiguity solution with the smaller variance is selected as the correct ambiguity set.

In order to obtain several solutions for the carrier phase ambiguities and therefore improve reliability, several trials were conducted using a different starting point, shifted 10 seconds forward from the previous one. This lo-second shift is sufficient to decorrelate code and carrier receiver noise at both the monitor and the launch and to decorrelate the multipath at the launch. Several quasi-independent solutions are thus obtained for the ambiguities. The number of trials, number of identical ambiguity solutions, success rate (number of trials / number of identical solutions) and average observation period required for each type of solutions are given in Table 5.

The success rate is 100% in all cases, except for the P-XII L2 and widelane (L1-L2) cases. In the L2 case, a 100% success rate could have been obtained by increasing the ***a priori*** carrier phase standard deviation $\sigma_{\nabla\Delta\phi}$. This would have increased the period required for ambiguity resolution. In the widelane case, 69% of the solutions yielded identical sets of ambiguities. The remaining 31% produced different solutions. These incorrect solutions were often off by one cycle and this is due to a combination of the effects of multipath and satellite geometry. The time to convergence for the widelane case is very short, namely a few seconds. This is due to the favourable ratio between the carrier phase noise and the 86 cm wavelength of the widelane carrier. In the single frequency cases, the high success rate was obtained at the expense of a longer observation period. Such a high success rate is achieved by increasing the ***a priori*** standard deviation of the double difference carrier phase measurements (e.g. Lachapelle et al 1992). The average time required using a GPSCard™ with no chokering groundplane on the launch increases by some 60%. The reason is that the use of chokerings does reduce carrier phase multipath substantially, a fact which was not evident from Table 3 and 4.

Sample double difference carrier phase residuals obtained after integer ambiguity resolution are shown in Figure 3 to 5 for GPSCard™, P-XII Ll and P-XII widelane (Ll-L2) data, respectively. A comparison of the ***a posteriori rms*** residuals with the ***a priori*** standard deviations given in Table 5 shows that the latter have the correct order of magnitude,

TABLE 5: AMBIGUITY RESOLUTION ON THE FLY - PERFORMANCE STATISTICS

Receiver and Observation Type	$\sigma_{\Delta\nabla\phi}$	Nbr of trials	Nbr of Correct Trials	Success rate	Average Period Required
GPSCard™ No 1 (Chokerings)	18mm	9	9	100%	1032s
GPSCard™ No. 2 (Chokering at monitor only)	18 mm	7	7	100%	1825
GPSCard™ No 3 (Chokerings)	18 mm	7	7	100%	1146
P-XII (Chokerings)					
P1 and Φ	15mm	10	10	100%	a65
P2 and Φ	15 mm	29	27	93%	545
Widelane (Ll-L2)	2omm	58	40	69%	2

once **a safety factor of 2 is applied to increase the success rate. The time period required for ambiguity resolution using single frequency data is much longer** in this case than **for similar land kinematic tests conducted with the same equipment (Lachapelle et al 1992). The two likely reasons are (i) larger carrier phase multipath and (ii) much longer monitor-mobile distances, namely 10 - 24 km, in this case.**

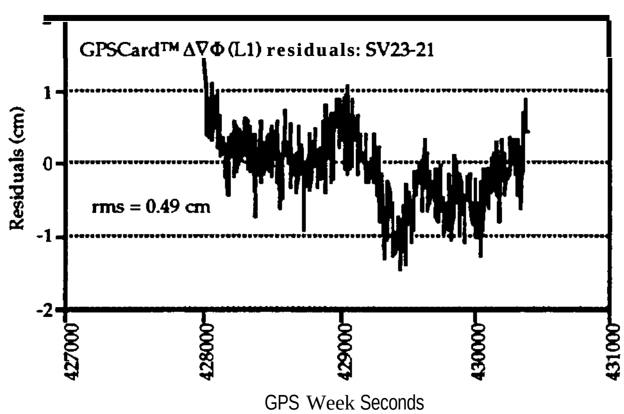

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figure 3: GPSCard™ Double Difference Carrier Phase Residuals for SV 23-21 (Chokering Groundplanes at both the Monitor and Launch)

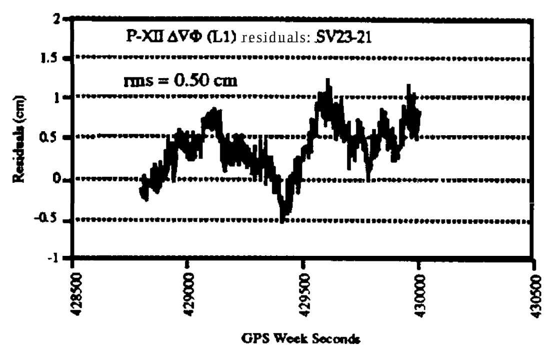

Figure 4: P-XII Ll Double Difference Carrier Phase Residuals for SV 23-21

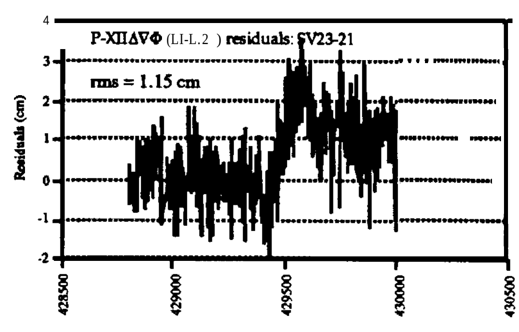

Figure 5: P-W Widelane (L1-L2) Double Difference Carrier Phase Residuals for SV 23-21

In order to independently verify that the P-XII **L1, L2** and **L1-L2** ambiguity solutions statistically identified as the correct ones are indeed correct, the following equation was used to test the double difference ambiguities obtained on L1, L2 and L1-L2 for each pair of satellites:

$$\Delta\nabla N_{L1\text{-}L2} = \Delta\nabla N_{L1} - \Delta\nabla N_{L2} \qquad (2)$$

where $\Delta\nabla N_{L1\text{-}L2}$ is the double difference ambiguity of the Ll-L2 observations and $\Delta\nabla N_{L1}$ and $\Delta\nabla N_{L2}$, the corresponding ambiguities on Ll and L2, respectively. In each case, the equation was satisfied, which confirmed that all ambiguities were correctly identified.

Eqn (2) cannot be used to verify the ambiguities determined with the GPSCard™ since only Ll observations are available in this case. However, three GPSCard™ units were recording data simultaneously on the launch, as shown in Figure 2. Since the distances between the antennas on the launch are short and known, the double difference ambiguities between these can be determined reliably with a few seconds of observations (e.g., Cannon et al 1992). For any two GPSCard™ units i and j on the launch and the monitor unit k, the following double difference ambiguity relation can be derived:

AVNi_j = AVNi_k - AVNi_k (3)

where the notation is self-explanatory. In each case, the equation was satisfied, which confirmed that all single frequency GPSCard™ ambiguities were also correctly identified. In order to illustrate the level of accuracy achieved for the launch track with fixed ambiguities, the distance between any two of the three GPSCard™ units was calculated at each epoch using the fixed ambiguity solution and compared to the corresponding measured distance shown in Figure 2. The differences between the measured and calculated distances are shown in Figure 6 and 7 for the GPSCard™ units 1 and 2, and 1 and 3, respectively. The rms differences are 1.5 and 0.5 cm, respectively. The smaller value in the latter case is due to the fact that chokering groundplanes were used both at the monitor and on the launch. These values are indicative of the level of positioning accuracy achievable using fixed ambiguities determined to their correct integer values.

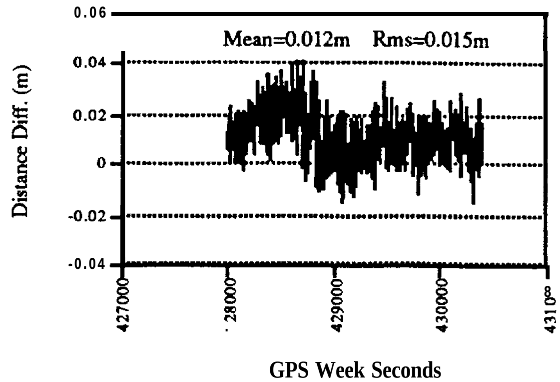

Figure 6: Distance Calculated Using Fixed Ambiguity Solutions Minus Measured Distance Between GPSCard™ 1 and 2 (No Chokering) on Launch

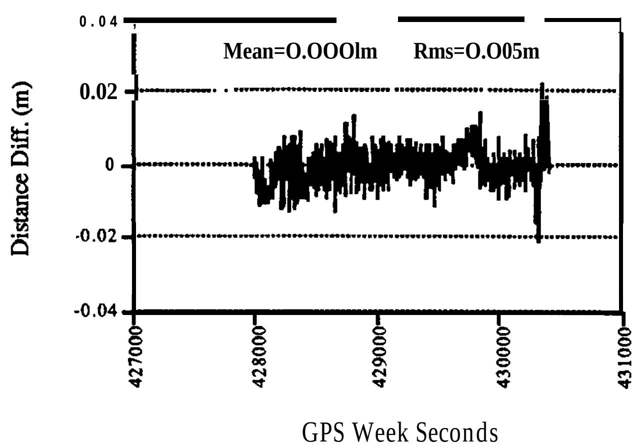

Figure 7: Distance Calculated Using Fixed Ambiguity Solutions Minus Measured Distance Between GPSCard™ 1 and 3 on Launch

An interesting question is the magnitude of the positioning biases which may result from an incorrect ambiguity solution. The magnitude of the biases will depend on the satellite affected, the satellite geometry and the number of cycles by which the ambiguity is incorrect. The case of an error of one cycle on a single satellite (SV3 in this case) is illustrated in Figure 8. The differences between the coordinates obtained using the correct ambiguity set and a set with the above error are plotted for a period of 20 minutes. The largest bias is 3 cm in longitude in this case. The biases increase with time due to the constantly changing satellite geometry. This shows that the ambiguities should be kept fixed only when they can be determined to their correct values with a high level of probability, an option which might not always be available in an operating environment due to a variety of factors. In such a case, the use of a less accurate carrier phase smoothing of the code approach might be preferable.

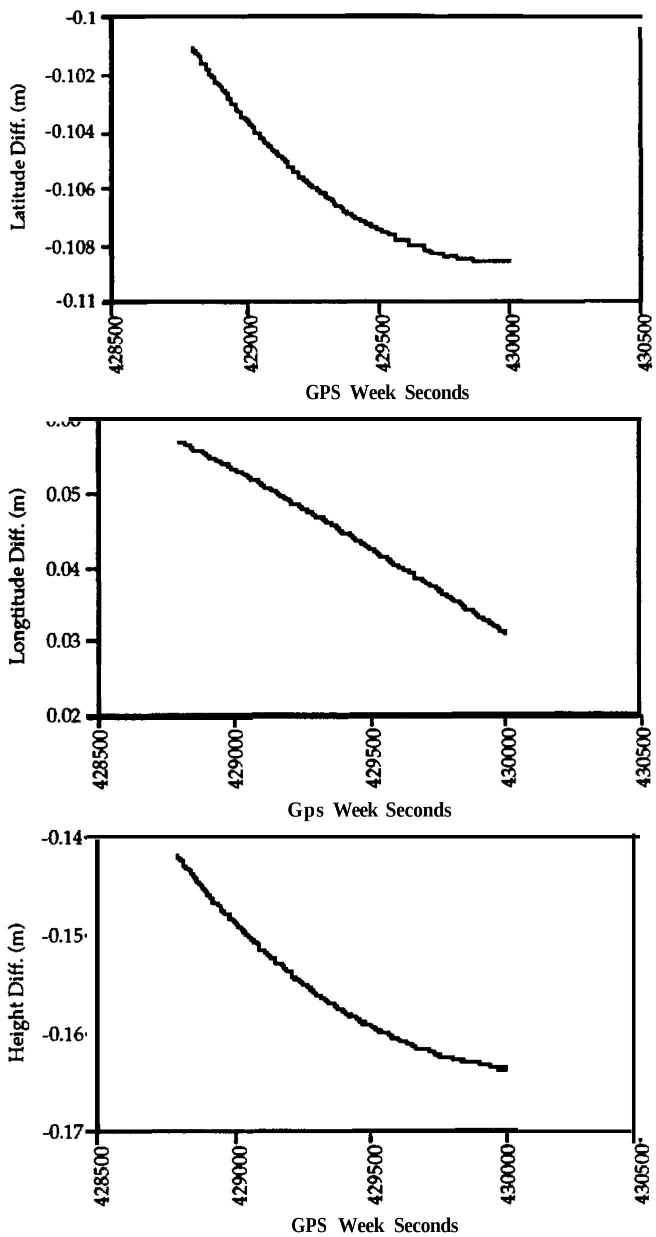

Figure 8: Effect of a One-Cycle Ambiguity Error on Coordinates

Code and Carrier Phase Smoothing of the Code Positioning

The kinematic positioning performance of the two receiver technologies used during the trial was also assessed using successively code only and carrier phase smoothed code measurements in between-receiver single difference mode. C^3N A V (Combination of Code and Carrier for Navigation), a software package developed at The University of Calgary (e.g., Cannon & Lachapelle 1992a), was used for this purpose. Although the computations were made in post mission, the algorithms can also be used in real-time. In C^3NAV, parallel filters are used to control code multipath and code/carrier divergence. These filters were reset at every 300 epochs in this case. The use of a different constant did not affect the results significantly.

Results are summarized in Table 6 in term of rms differences between coordinates estimated using successively code and carrier phase smoothed code, and coordinates calculated using fixed ambiguity solutions. The latter solutions are accurate to within a few cm as discussed earlier and the rms differences given in Table 6 represent the accuracy of the code or carrier phase smoothing solutions. The rms differences of the GPSCard™ code solutions are at the 0.5 - 1.1 m level, as compared to 2.3 - 6.0 m for the P-XII C/A code solution. The corresponding carrier phase smoothing solutions are the 0.4 - 0.9 m level for the GPSCard™ and 0.7 - 1.0 m level for the P-XII C/A code. The GPSCardTM code and carrier phase smoothed code solutions are at the same level as the P-XII Pl or P2 solutions. The GPSCard™ results presented here are slightly less accurate than those previously obtained in land kinematic mode, where rms differences of 25 - 75 cm were obtained. Again, this is due to the higher prevailing multipath conditions and longer monitor-mobile distances in the present case. These tests however confirm that a sub-metre accuracy can be obtained in the marine environment using high performance single frequency receiver technology.

TABLE 6: DGPS CODE AND CARRIER PHASE SMOOTHING POSITIONING - PERFORMANCE STATISTICS

Receiver	Observation Type	RMS Differences (m) Lat	Ion	Height
GPSCard™ No. 1 (Chokerings)	Code	0.8	0.5	1.0
	Code & carrier	0.7	0.5	0.7
GPSCard™ No 2 (Chokering at Monitor only)	Code	0.6	0.5	1.1
	Code & carrier	0.5	0.4	0.9
GPSCard™ No. 3(Chokerings)	Code	0.7	0.5	0.9
	Code & carrier	0.6	0.4	0.6
P-XII C/A (Chokerings)	Code	3.5	2.3	6.0
	Code & carrier	0.7	0.7	1.0
P-XII PL1 (Chokerings)	Code	0.6	0.6	0.8
	Code & carrier	0.3	0.2	0.4
P-XII PL2 (Chokerings)	Code	0.5	0.6	0.8
	Code & carrier	0.3	0.2	0.4

CONCLUSIONS

The results presented herein show that both P code and high performance single frequency C/A code receiver technologies have the same level of performance in terms of ambiguity resolution on the fly in a survey launch environment when single frequency P code data is used. The time to resolution is of the order of 10 to 20 minutes. As a consequence, the operational reliability drops considerably. In this case however, the use of a twin receiver system on the launch *is* however useful in maintaining a relatively high level of statistical reliability. The use of the full dual frequency capability of the P code technology, however, improves the results dramatically by reducing time to resolution to a few seconds. Although the statistical reliability of the solutions is lower in this case, the larger number of solutions possible makes up for this deficiency. Both receiver technologies are equally affected by carrier phase multipath, a major factor in ambiguity resolution on the fly. In this respect, the use of chokering groundplanes proved very effective in reducing carrier phase multipath. When ambiguity resolution on the fly is not operationally desirable or feasible, code or carrier phase smoothing methods remain an attractive alternative. The tests confirm that a sub-metre accuracy can be obtained in the marine environment using high performance single frequency C/A code receiver technology.

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