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Adaptive Bandwidth Algorithm for Optimal Signal Tracking of DGPS Reference Receivers

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Abstract : *A narrow loop noise bandwidth method is desirable to reduce the error of raw measurements due to the thermal noise. However, it degrades the performance of GPS initial synchronization such as mean acquisition time. And it restricts the loop noise bandwidth to a fixed value determined by the lower bound of the allowable range of carrier-to-noise power ratio, so that it is difficult to optimally track GPS signal. In order to make up for the weak points of the fixed-type narrow loop noise bandwidth method and simultaneously minimize the error of code and carrier measurements, this paper proposes a stepwise-type adaptive bandwidth algorithm for DGPS reference receivers. In this paper, it is shown that the proposed adaptive bandwidth algorithm can provide more accurate measurements than those of the fixed-type narrow loop noise bandwidth method, in view of analyzing the simulation results between two signal tracking algorithms. This paper also carries out sensitivity analysis of the proposed adaptive bandwidth algorithm due to the estimation uncertainty of carrier-to-noise power ratio. Finally the analysis results are verified by the experiment using GPS simulator.*

Key words : *Adaptive bandwidth algorithm, Narrow loop noise bandwidth, Differential GPS, Raw measurements,* Carrier-to-noise power estimator

1. Introduction

To generate the accurate DGPS (Differential Global Positioning System) correction data, DGPS reference receivers should have capability to minimize the error of raw measurements, such as pseudorange and doppler, provided by delay and frequency lock loop. The reason is that the DGPS correction data generated by DGPS reference receiver include the error of raw measurements, which is one of the non-common errors incapable of elimination on differential technique. It is generally known that the accuracy of raw measurements is mainly affected by the carrier-to-noise power ratio (Ward et al., 2006). Particularly the accuracy of raw measurements is degraded by ground-based radio navigation signal and noise provoked by machines and communication equipment around DGPS reference receiver. Good examples of those are pseudolite using pulsing scheme and GPS near-band microwave link transmitter overcoming front-end filter of DGPS reference receiver (Clynch, 2002).

The methods to minimize the error of raw measurements are classified into pre-correlation approach and post-correlation approach. A narrow chip spacing correlator is the representative method of pre-correlation approach, which mitigates the error of raw measurements before correlating GPS signal with PRN (Pseudo Random Noise) code. And it is well known that a narrow loop noise bandwidth method and a carrier aided smoothing are the representative methods of post-correlation approach, which mitigates the error of raw measurements after correlating GPS signal with PRN code. Particularly the narrow loop noise bandwidth method is desirable to reduce the measurement error due to the thermal noise. However, unfortunately, we have known that no detail study on the narrow loop noise bandwidth method has been published for DGPS reference receivers. For this reason, this paper deals with the narrow loop noise bandwidth method for optimal signal tracking of DGPS reference receivers.

In this paper, the optimal narrow loop noise bandwidth is derived for minimizing the error of raw measurements provided by delay and frequency lock loop of DGPS reference receiver. And this paper shows that a fixed-type narrow loop noise bandwidth has some problems in view of initial synchronization and optimal GPS signal tracking. In order to make up for the above weak points of the fixed-type narrow loop noise bandwidth, a stepwise-type

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adaptive bandwidth algorithm is proposed. In this paper, it is shown that the proposed adaptive bandwidth algorithm can provide more accurate measurements than those of the fixed-type narrow loop noise bandwidth method in view of analyzing the simulation results between two signal tracking algorithms. This paper also carries out sensitivity analysis of the proposed adaptive bandwidth algorithm due to the estimation uncertainty of carrier-to-noise power ratio. Finally the analysis results are verified by the experiment using GPS simulator.

2. Optimal Narrow Loop Noise Bandwidth

The LOS (Line-Of-Sight) relative dynamics between the antenna of GPS receiver and the GPS SV (Space Vehicle) has a significant impact on the design of GPS signal tracking algorithm. In the static case such as DGPS reference receiver, the maximum LOS jerk dynamic is very small even if the LOS jerk dynamics is found. For this reason, the capability for minimizing the error of raw measurements of DGPS reference receiver is greatly affected by the loop noise bandwidth.

This paper assumes that the tracking loops of DGPS reference receiver are implemented into third-order DLL (Delay Lock Loop) and second-order FLL (Frequency Lock Loop) because the LOS jerk dynamic occurs as mentioned above. Various papers have been published on the signal tracking error of raw measurements over a long period time. Among these studies, the error analysis presented by Ward et al. (2006) is recognized as the significant result. If Ward's result is applied to the tracking loops of DGPS reference receiver, the error of raw measurements can be given by Eqs. (1) and (2). From Eqs. (1) and (2), the optimal narrow loop noise bandwidth is defined as Theorem 1.

$$\sigma_{DLL} = \frac{1}{T_c}\sqrt{\frac{B_{n_{DLL}}\int_{-B_{RF}/2}^{B_{RF}/2} S_s(f)\sin^2(\pi f D T_c)\,df}{(2\pi)^2 C/N_o\left(\int_{-B_{RF}/2}^{B_{RF}/2} f S_s(f)\sin^2(\pi f D T_c)\,df\right)^2}} \times \sqrt{1+\left(\frac{\int_{-B_{RF}/2}^{B_{RF}/2} S_s(f)\cos^2(\pi f D T_c)\,df}{T\,C/N_o\left(\int_{-B_{RF}/2}^{B_{RF}/2} S_s(f)\cos^2(\pi f D T_c)\,df\right)^2}\right)} + \left(\frac{0.0161}{B_{n_{DLL}}}\right)^3. \quad \text{(chip)} \quad (1)$$

$$\sigma_{FLL} = \frac{1}{2\pi T}\sqrt{\frac{4FB_{n_{FLL}}}{C/N_o}\left(1+\frac{1}{TC/N_o}\right)} + \left(\frac{0.0817\times10^{-3}}{B_{n_{FLL}}}\right)^2 . \text{(Hz)} \quad (2)$$

where σ_{DLL}: 1-sigma error of code measurement [chips], T_c : chip period [seconds], B_n : loop noise bandwidth, B_{RF} : double-sided RF front-end bandwidth [Hz], C/N_o : carrier to noise power expressed as a ratio [Hz], $S_s(f)$: power spectral density of signal, normalized to unit area over infinite bandwidth, T : predetection integration time [seconds], R : LOS range to the satellite [meters], D : correlator early-minus-late chip space [chips], σ_{FLL} : 1-sigma error of carrier frequency measurement [Hz], F : 1 at high C/N_o, and 2 near threshold.

Theorem 1: The optimal narrow loop noise bandwidth of code tracking loop ($B_{n\_\mathrm{DLL}}^{op}$) and the optimal narrow loop noise bandwidth of carrier tracking loop ($B_{n\_\mathrm{FLL}}^{op}$) for DGPS reference receivers are as follows:

$$B_{n\_\mathrm{DLL}}^{op} = \left(\frac{6\,k_1}{k_2}\right)^{2/7}, \quad (3)$$

$$B_{n\_\mathrm{FLL}}^{op} = \left(\frac{4\,h_1}{h_2}\right)^{2/5}, \quad (4)$$

where $k_1 = 0.0161^3$, $h_1 = (0.0817\times10^{-3})^2$, $R_c = 1/T_c$,

$$k_2 = \begin{cases} \sqrt{\dfrac{D}{2\,C/N_o}\left[1+\dfrac{2}{T\,C/N_o\,(2-D)}\right]} & ; D \geq \pi\dfrac{R_c}{B_{RF}} \\ \sqrt{\begin{array}{l}\dfrac{1}{2\,C/N_o} \\ \times\left[\begin{array}{l}\dfrac{1}{B_{RF}\,T_c}+\dfrac{B_{RF}\,T_c}{\pi-1} \\ \times\left(D-\dfrac{1}{B_{RF}T_c}\right)^2\end{array}\right] \\ \times\left[1+\dfrac{2}{T\,C/N_o\,(2-D)}\right]\end{array}} & ; \dfrac{R_c}{B_{RF}} < D < \pi\dfrac{R_c}{B_{RF}} \\ \sqrt{\dfrac{1}{2\,C/N_o\,B_{RF}\,T_c}\left[1+\dfrac{1}{T\,C/N_o}\right]} & ; \dfrac{R_c}{B_{RF}} \leq D \end{cases}, \quad (5)$$

$$h_2 = \frac{1}{2\pi T}\sqrt{\frac{4F}{C/N_o}\left(1+\frac{1}{T\,C/N_o}\right)}. \quad (6)$$

Fig. 1 and Fig. 2 show the pseudorange measurement error as a function of loop noise bandwidth with C/N_o as a running parameter, assuming that code tracking loop is an unaided third-order C/A code DLL with normalized early-minus-late discriminator, D=1 chip, T= 1 msec., and B_{RF}= 8×1.023 MHz. In Figure 1 and 2, the circle is the optimal narrow loop noise bandwidth at each C/N_o.

From these Figures, it can be known that the fixed-type narrow loop noise bandwidth method causes the increase in measurement noise at high C/N_o. The reason is that the optimal loop noise bandwidth ($B^{op}_{n\_\mathrm{DLL}}$) for the fixed-type narrow loop noise bandwidth method is determined by the lower value ($\mu_{c/n}$) of the dynamic range of carrier-to-noise power ratio allowed by DGPS reference receiver.

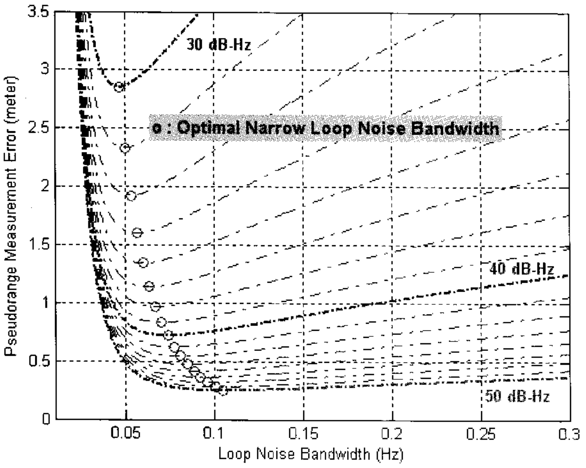


Fig. 1 The pseudorange measurement error as a function of loop noise bandwidth.

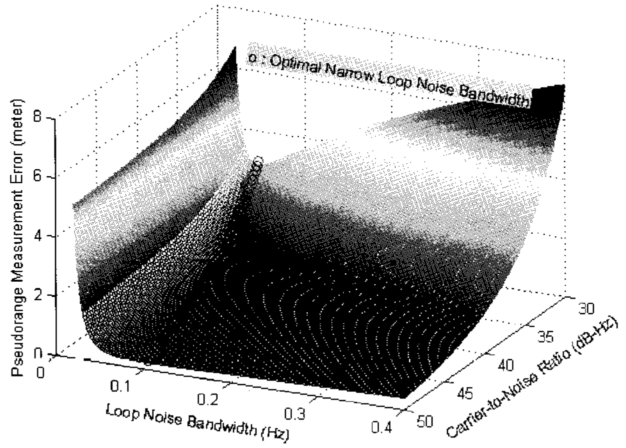


Fig. 2 The pseudorange measurement error with C/N_o as a function of loop noise bandwidth.

Table 1 The increment in measurement error by the change of incoming GPS signal strength.

	PR measurement error(m) / Increment in measurement noise(cm)		
C/N_o of incoming GPS signal / $\mu_{c/n}/B^{op}_{n\_\mathrm{DLL}}$	30 (dB-Hz)	40 (dB-Hz)	50 (dB-Hz)
30(dB-Hz) / 0.046(Hz)	2.85 / 0	0.91 / 19	0.56 / 31
40(dB-Hz) / 0.074(Hz)	3.19 / 34	0.72 / 0	0.28 / 3
50(dB-Hz) / 0.105(Hz)	3.71 / 86	0.77 / 5	0.25 / 0

Table 1 shows the increment in measurement error by the change of incoming GPS signal strength. And the fixed-type narrow loop noise bandwidth method causes the increase in the total number of search bins because the narrow loop noise bandwidth needs the short pull-in range and small search bin. Ultimately the initial synchronization performance such as mean acquisition time is degraded. Fig. 3 illustrates the phenomenon of the increase in the total number of search bins after applying the fixed-type narrow loop noise bandwidth to code tracking loop.

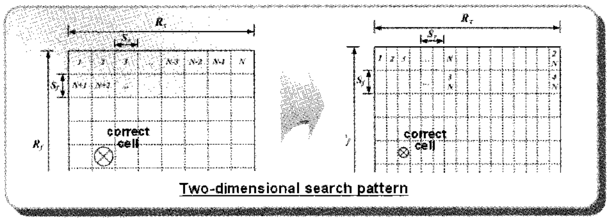


Fig. 3 The increase in the total number of search bins after applying the fixed-type narrow loop noise bandwidth.

3. Adaptive Bandwidth Algorithm

In order to solve the weak points of the fixed-type narrow loop noise bandwidth method and simultaneously minimize the error of code and carrier measurements, this paper proposes an stepwise-type adaptive bandwidth algorithm for DGPS reference receiver. The proposed adaptive bandwidth algorithm consists of incoming signal carrier-to-noise power estimator, signal dynamic estimator, and loop bandwidth adjuster. Fig. 4 and Fig. 5 show the GPS signal tracking scheme including adaptive bandwidth algorithm and the structure of adaptive bandwidth algorithm.

Over the past few years, several studies have been made on adaptive bandwidth algorithm (Jow, 2001; Legrand, 2000, 2001; Lian, 2005). In this paper, these previous results are modified to effectively apply to DGPS reference receiver. In contrast to previous studies, the proposed adaptive bandwidth algorithm uses the estimated properties of incoming signal, such as signal strength (C/N_o) and LOS range dynamics (d^3R/dt^3), to determine the optimal narrow loop noise bandwidth. Fig. 6 illustrates the procedure to determine the optimal narrow loop noise bandwidth of the proposed adaptive bandwidth algorithm. The procedure to determine the optimal loop noise bandwidth is divided in 2 phases by the following design criterion:

- Phase 1: Find the loop noise bandwidth (B_{n_η}) regarding the threshold of required measurement error,

- Phase 2: Find the loop noise bandwidth (B_{n_ω}) regarding the minimization of measurement error.

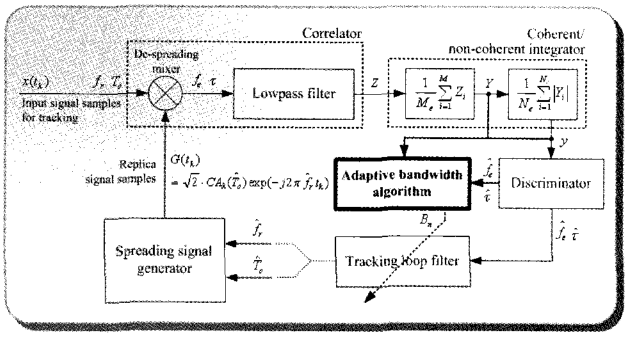


Fig. 4 The signal tracking scheme including adaptive bandwidth algorithm.

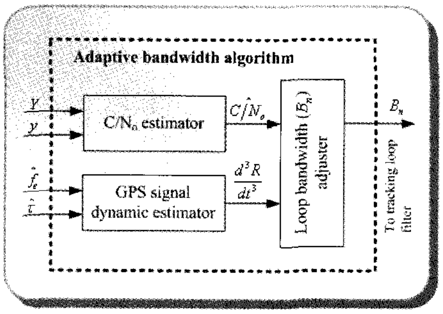


Fig. 5 The structure of adaptive bandwidth algorithm.

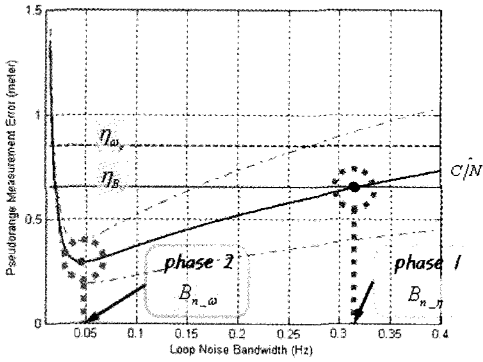


Fig. 6 The determination of loop noise bandwidth.

Assuming that code tracking loop is an unaided third-order C/A code DLL with normalized EML discriminator, D =0.2 chip, T=1 msec. B_{RF}=8×1.023 MHz, $\mu_{c/n}$=30 dB-Hz, the threshold of required measurement error $(\eta_{\omega p})$=1 meter, and the threshold of measurement error with design margin (η_{B_n})=0.85 meter, the theoretical pseudorange measurement error and the loop noise bandwidth of two narrow loop noise bandwidth algorithms are shown as Fig. 7. Table 2 and Table 3 summarize the theoretical results from Fig. 7. From these Tables, it can be found that the proposed adaptive bandwidth algorithm provides more accurate measurements than the fixed-type narrow loop noise bandwidth method. Furthermore, Table 2 shows that, through providing wider loop noise bandwidth than that of the fixed-type narrow loop noise bandwidth method at the initial tracking stage, the proposed adaptive bandwidth algorithm prevents the degradation of initial synchronization performance due to narrow loop noise bandwidth.

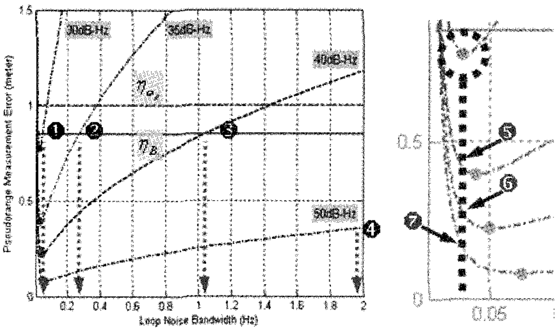


Fig. 7 The theoretical pseudorange measurement error and loop noise bandwidth

Table 2 The comparison of loop noise bandwidth between the fixed-type narrow loop noise bandwidth method and the proposed stepwise-type adaptive bandwidth algorithm.

		Loop noise bandwidth(Hz)			
C/N_o of incoming GPS signal		30 dB-Hz	35 dB-Hz	40 dB-Hz	50 dB-Hz
Fixed-type narrow loop noise bandwidth method		0.0317	0.0317	0.0317	0.0317
Proposed adaptive bandwidth algorithm	Phase 1	0.05(❶)	0.27(❷)	1.05(❸)	>2(❹)
	Phase 2	0.0317	0.0407	0.0502	0.0705
Ratio of code search bin size		1.6 : 1	8.5 : 1	33.1 : 1	> 63.1 : 1

Table 3 The theoretical pseudorange measurement error

	Pseudorange measurement error(cm)			
C/N_o of incoming GPS signal	30 dB-Hz	35 dB-Hz	40 dB-Hz	50 dB-Hz
Fixed-type narrow loop noise bandwidth method (A)	77.61	42.54(❺)	29.60(❻)	18.15(❼)
Proposed adaptive bandwidth algorithm (B)	77.61	38.08	21.93	7.85
Degree of improvement ((A-B)/A) [%]	-	8.1	25.9	56.7

The proposed adaptive bandwidth algorithm needs C/N_o estimator. This study uses the C/N_o estimator proposed by A.J. Van Dierendonck (Parkinson et al., 1996). The applied C/N_o estimator computes the incoming signal C/N_o using wide-band power and narrow band power for 1 second. The error in this estimate are shown in Figure 8 (Parkinson et al., 1996). This error shows that 1 second average is sufficient to estimate the incoming signal C/N_o. In this paper, the additional measurement error due to uncertainty of C/N_o estimate is analyzed. It can be found that the additional measurement error has the properties as follows:

- Additional measurement error at $C/N_o \geq 38$ dB-Hz
  : below 1.0cm,
- Additional measurement error at $C/N_o \geq 30$ dB-Hz
  : below 1.4cm.

From the above results, we can conclude that the uncertainty of C/N_o estimate has a little effect on the measurement error of adaptive bandwidth algorithm.

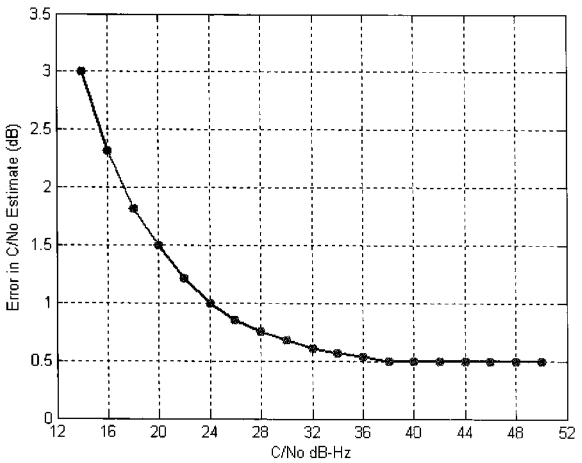


Fig. 8 The error in C/N_o estimate.

4. Performance Analysis

In order to verify the performance difference between the fixed-type narrow loop noise bandwidth method and the proposed adaptive bandwidth algorithm described in the previous Section, this paper performs the analysis of pseudorange measurement error after signal tracking. Firstly GPS IF data are collected with the signal strength of 50dB-Hz for the performance analysis, where $B_{RF}=$ 8MHz, IF frequency $(f_{IF})=$ 8.58MHz, and sampling frequency (f_s) =22MHz. And then the collected GPS IF data are provided to the input signal samples of software-defined receiver including the fixed-type narrow loop noise bandwidth method and the proposed adaptive bandwidth algorithm. Finally the near real-time processing is performed to obtain the raw measurement. Figure 9 shows GPS data collection and experiment setup. It is assumed that code tracking loop is an unaided third-order C/A code DLL with normalized EML discriminator, D =0.2 chip, T=1 msec., $B_{RF}=8\times1.023$ MHz, $\mu_{c/n}=30$ dB-Hz, $\eta_{\omega\rho}=1$ meter, and $\eta_{B_n}=0.85$ meter.

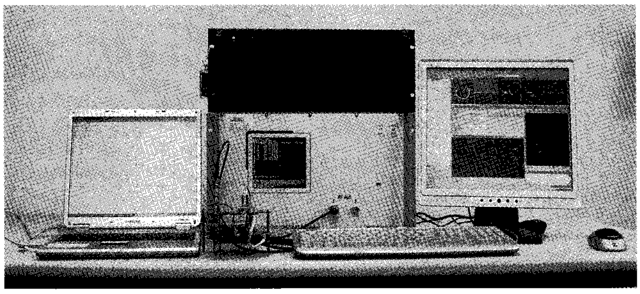
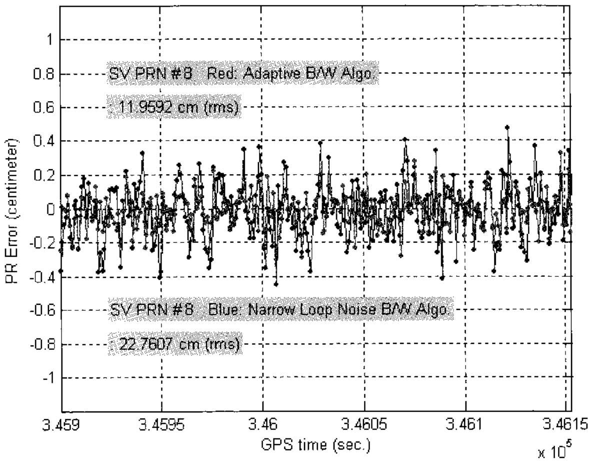
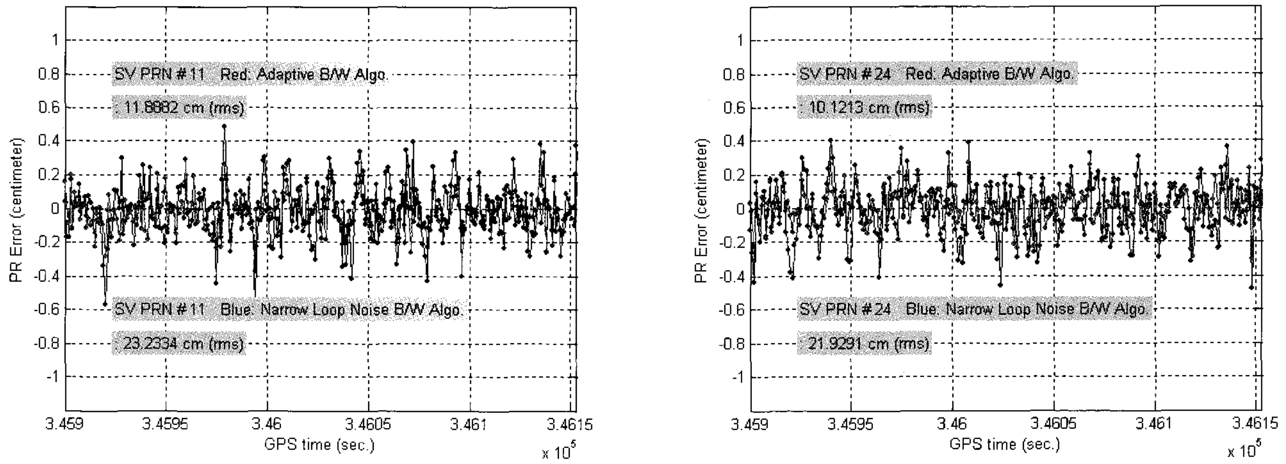


Fig. 9 GPS data collection and near real-time experiment setup for performance analysis.

Fig. 10 shows the pseudorange measurement error. From Fig. 10 and Table 4, it is seen that the measurement error variance of the proposed adaptive bandwidth algorithm is reduce to about 51% of the measurement error variance of the fixed-type narrow loop noise bandwidth algorithm. For reference, the theoretical expectation degree of improvement was 56.7% derived in the previous section. And it can be expected that the proposed adaptive bandwidth algorithm provides more accurate measurements than the fixed-type narrow loop noise bandwidth algorithm.

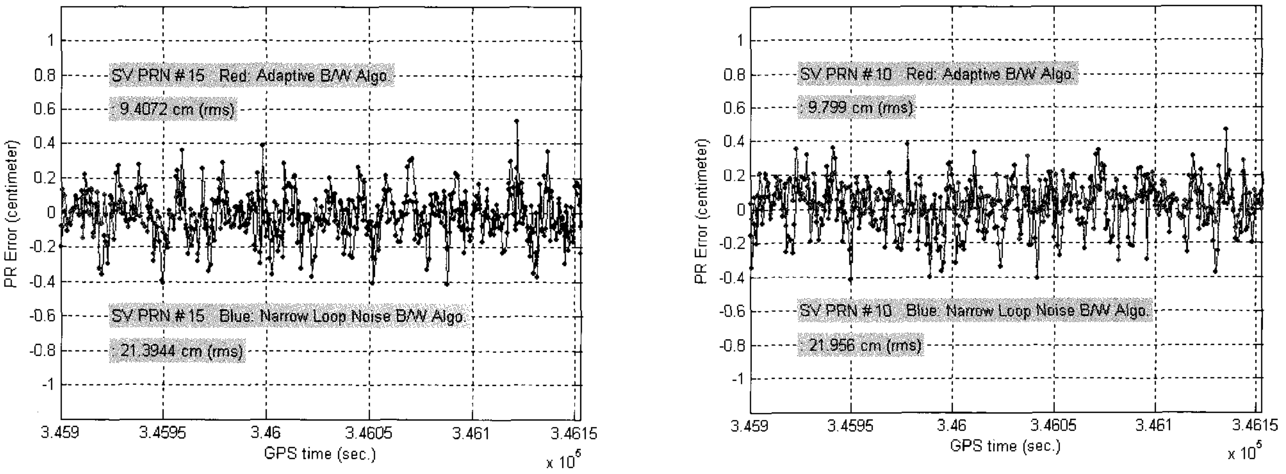


(a) Pseudorange measurement error (SV PRN #08)



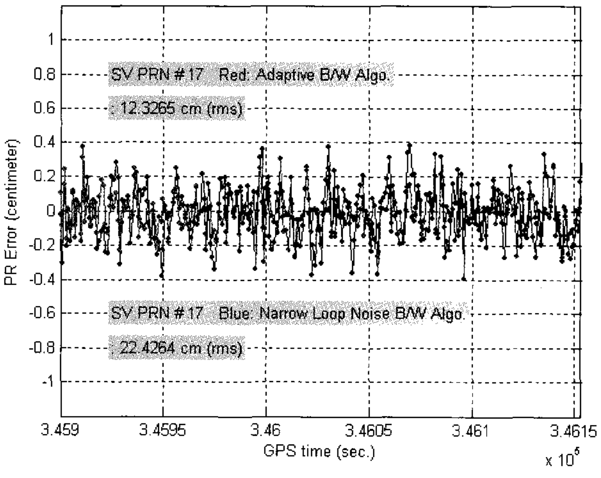
(b) Pseudorange measurement error (SV PRN #11)

(e) Pseudorange measurement error (SV PRN #24)



(c) Pseudorange measurement error (SV PRN #15)

(f) Pseudorange measurement error (SV PRN #10)



(d) Pseudorange measurement error (SV PRN #17)

Fig. 10 The experiment results for performance comparison.

Table 4 The experiment results for performance comparison

GPS SV PRN number	Pseudorange measurement error (cm)		Degree of improvement ((A-B)/A) [%]
	Fixed-type narrow loop noise bandwidth method (A)	Proposed adaptive bandwidth algorithm (B)	
08	22.76	11.96	45.5
11	23.23	11.89	48.8
15	21.39	9.41	56.0
17	22.43	12.33	45.0
24	21.93	10.12	53.9
10	21.96	9.80	55.4

5. CONCLUSION

This paper described the narrow loop noise bandwidth for DGPS reference receivers and showed that the fixed-type narrow loop noise bandwidth causes the increase in measurement noise at high C/N_0 and the degradation of initial synchronization performance. In this paper, it was proposed the stepwise-type adaptive bandwidth algorithm with 2 processing phases in order to make up for the weak points of the fixed-type narrow loop noise bandwidth method and simultaneously minimize the error of code and carrier measurements. From the theoretical analysis of pseudorange measurement error, it could be found that the proposed adaptive bandwidth algorithm enhances the accuracy of pseudorange measurement and furthermore provides more accurate measurements than the fixed-type narrow loop noise bandwidth algorithm. And this paper presented the sensitivity analysis results of the adaptive bandwidth algorithm due to the estimation uncertainty of GPS signal strength. Finally, it could be verified that the proposed adaptive bandwidth algorithm holds back the degradation of initial synchronization performance and that the proposed adaptive bandwidth algorithm is superior to the fixed-type narrow loop noise bandwidth method in raw measurement accuracy from the experiment for performance analysis. For further work, it is necessary to analyze the effect of DGPS reference receiver clock on the carrier phase measurement error and to make a study of C/N_0 estimation scheme under shorter averaging.

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