A New Suggestion
for the DGPS Correction Message

INTRODUCTION

The DGPS infrastructure should contain a reference station, a data-link, and user applications. The reference station generates corrections by measured pseudo-range or carrier-range, calculated distance between reference station and each satellite, satellite clock bias, and estimated receiver clock bias, and then it broadcasts them to user application. The correction messages contain PRC (Pseudo Range Correction) for DGPS, CPC (Carrier Phase Correction) for CDGPS, and their time rates, RRC (Range Rate Correction).

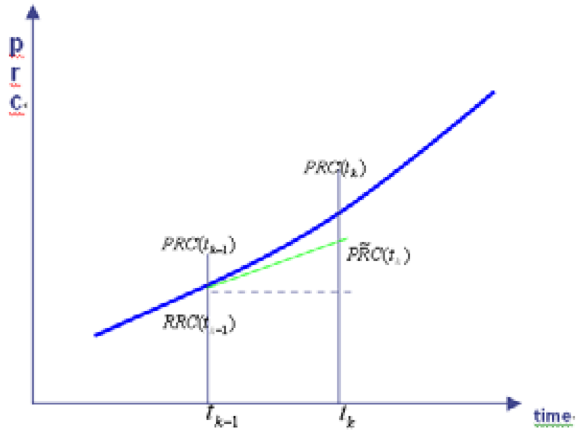
$$PRC = -(i + T + \delta R) = d - \rho - b + \hat{B} \qquad (1)$$

$$CPC = -(-i + T + \delta R + N\lambda) = d - \phi - b + \hat{B} \qquad (2)$$

ρ : psedo - range measurement
φ : carrier phase measurement$i$
λ : wavelength of the carrier phase
N : integer ambiguity
d : distance from the reference station to the satellite
b : satellite clock bias
$\hat{B}$: estimated clock bias of the Receiver
i : ionospheric delay
T : Troposheric delay
δR : Orbit error

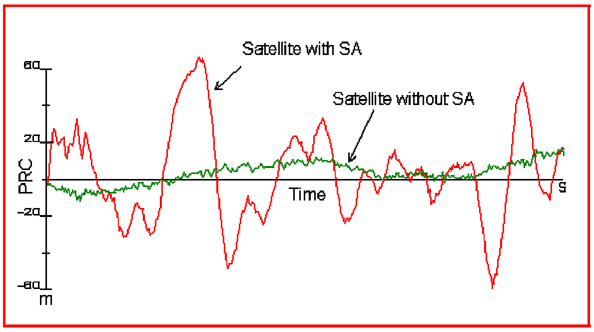
The user is generally apart from the reference station, so it should correct its measurement by old message. To reduce the problem caused by this time latency, the reference stations have generated and sent the corrections with RRC, and RRC have compensated PRC at old time, t_{k-1}, for the time-latency, $t_k - t_{k-1}$, linearly as shown in equation (3) and [Figure 1].

$$\widetilde{PRC}(t_k) \approx PRC(t_{k-1}) + RRC(t_{k-1}) \cdot \Delta t \qquad \text{where } \Delta t = (t_k - t_{k-1}) \qquad (3)$$



[Figure 1] Compensation PRC for the Time-latency

Before the removal of SA, Selective Availability, GPS signal has such a fluctuating error due to SA that DGPS users had to receive the PRC as frequently as possible at high rate. RRC has been useful in reducing this rate at which differential correction broadcast. Even though PRC did not vary linearly, the linear compensation by RRC was valid because the fast-moving SA effect on the PRC was so big that the nonlinearity of PRC or some errors in RRC were easily ignored. With SA removed, the temporal variation in PRC is now much smaller than before and primarily dependent on atmospheric variations, so we need to focus on the difference of its effect in various RRC generation techniques.



[Figure 2] PRC fluctuation with and without SA

The RRC is originally the time rate in PRC, but the raw PRC is too noisy to use directly. Now we can think out a number of RRC generation techniques, they are time difference of filtered PRC, that of CPC, and setting zero.

$$\begin{aligned} \delta PRC(t_k) &= PRC(t_k) - \tilde{PRC}(t_k) \\ &= PRC(t_k) - \{PRC(t_{k-1}) + RRC(t_{k-1}) \cdot (t_k - t_{k-1})\} \end{aligned} \tag{4}$$

When we use RRC to compensate for the time latency of PRC, bias and noise of estimated RRC and nonlinear property of PRC make error in time latency, $\delta PRC(t_k)$. The nonlinearity of RRC is not our matter of concern, and the best estimation of RRC should satisfy the conditions that the mean value of error should be zero, and it should minimize its variance. But in GPS signal case, it is generally hard to meet both conditions.

If we use CPC for generating RRC, its divergence problem $(2 \cdot |\dot{I}|)$ in ionosphere makes the PRC extrapolated in time latency with some bias, but it has very small noise, $\varepsilon_{C\dot{P}C}(std \cong 0.005 m/s)$, whose size is smaller than 1/100 of raw PRC's.

$$\delta PRC = (2 \cdot |\dot{I}| + \varepsilon_{C\dot{P}C}) \cdot \Delta t \tag{5}$$

The RRC, which is generated by the time-difference of filtered PRC, does not have significant bias, but the relatively big noise. The standard deviation of RRC generated by raw PRC is about 0.5m, and smoothing filter with averaging constant of 100 can reduce it to 0.05m/s. The filter should be a bias-free filter, i.e. divergence-free Hatch filter.

$$\delta PRC = \varepsilon_{P\hat{R}C} \cdot \Delta t \tag{6}$$

If we do not compensate the PRC, the rate of the ionospheric delay, tropospheric delay, and ephemeris error propagates into the RRC, but there is no additional noise. There is no SA, so the time rate in ephemeris error is almost zero.

$$\delta PRC = \left(\left|\dot{I} + \dot{T} + \delta\dot{R}\right|\right) \cdot \Delta t \approx \left(\left|\dot{I} + \dot{T}\right|\right) \cdot \Delta t \tag{7}$$

[Table 1] PRC Error of Each Generation Technique in Time-Delay

	δPRC	PRC Error(DRMS)
△PRC	$\left\|\varepsilon_{P\hat{R}C}\right\| \cdot \Delta t$	$\left\|\varepsilon_{P\hat{R}C}\right\| \cdot \Delta t$
△CPC	$(2 \cdot \|\dot{I}\| + \varepsilon_{C\dot{P}C}) \cdot \Delta t$	$\sqrt{(4 \cdot \|\dot{I}\|^2 + \|\varepsilon_{C\dot{P}C}\|^2)} \cdot \Delta t$
RRC=0	$(\|\dot{I} + \dot{T}\|) \cdot \Delta t$	$\sqrt{(\|\dot{I}\|^2 + \|\dot{T}\|^2)} \cdot \Delta t$

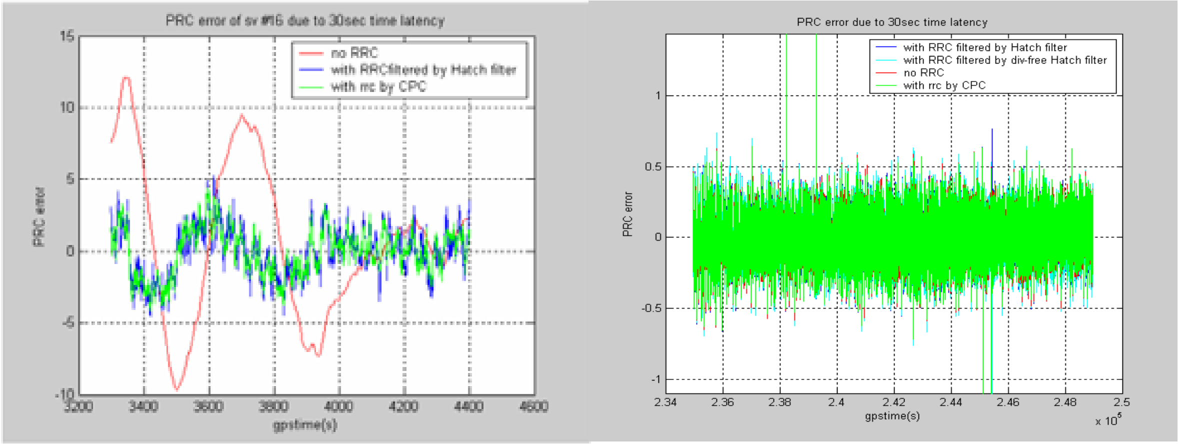
[Table 1] is the summary of PRC error for each RRC generation technique in time latency. We can find that the noise of the measurements is as important to the determination to the size of PRC error as the atmospheric error. It is obvious that if the common error moves very slowly, we don't need to compensate for the time delay. In other word, setting RRC zero makes no problem in DGPS system in case that the atmospheric variation in common error is small. Therefore, we focus on the maximum value of $\dot{I}$ and $\dot{T}$. The paper also provides the results that account for seasonal, diurnal, and regional differences in the atmosphere. Using the maximum value results, we simulate the DRMS error variation of each RRC generation technique, and the simulation includes the very low-lying satellites case. And then, the simulation results are supported by static and dynamic tests using commercial receivers and RTCM correction message.

GPS ERROR PROPAGATION INTO RRC

SA

Throughout the 1990s, the signals available for unrestricted use were purposefully degraded under the policy of SA by adding controlled errors in the measurements. These errors were significantly larger than the errors inherent to the system. The signal degradation was achieved by 'dithering' the satellite clock and broadcasting erroneous values of the ephemeris parameters.

SA was deactivated on 2 May 2000 in accordance with a President Decision. The design of the DGPS systems fielded in the 1990s was determined by SA, which introduced the largest and fastest-changing of the measurements errors. Before the removal of SA, GPS signal has such a fluctuating error due to SA that these systems typically computed new measurement corrections, PRC, each 5-10 seconds. In order to extend the life of a correction message and cut down on the data traffic, the correction messages generally transmit both the error size and its rate of change, RRC, observed at the reference station at the measurement epoch.



[Figure 3] The RRC Error in 30sec Time Latency with SA Turned On(left) and Off(right)

The PRC error in 30 sec time latency, δPRC , is up to 13m when we set RRC zero (red line in left graph of [Figure 3]). The 30 second delay is so big that the compensated PRC still has considerable additional error. Therefore, the reference station should have sent PRC with RRC as frequently as possible when SA was on. Now that the SA is off, and that the time rate of atmospheric delay is quite low, the PRC is by far robuster, so the error by latency is much smaller than before. The correction update interval and the usage of RRC, eventually, depend on the signal variation through atmosphere.

Ionospheric Delay

The ionosphere, existing from a height of about 50km to about 1000km above the earth, is a region of ionized gases. Within this region, free electrons influence electromagnetic wave propagation, including GPS signal. The slant ionospheric delay (I_s) can be denoted as a function of ionospheric zenith delay (I_z) and obliquity factor (Q).

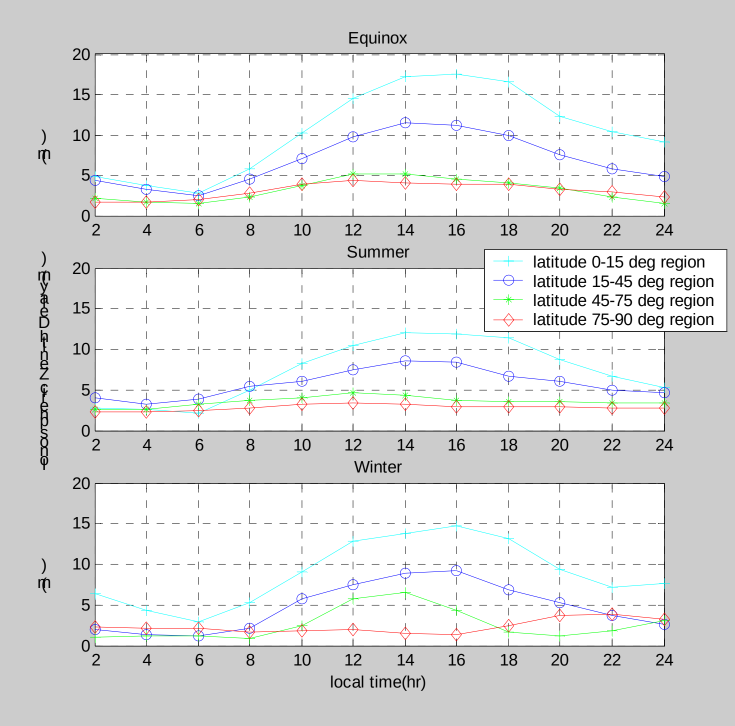
$$I_s(El) = I_v \cdot Q(El) \qquad (8)$$

The equation of time-rate of ionospheric delay ($\dot{I}_s$) can be obtained by differentiating the equation (8).

$$\dot{I}_s(El) = \dot{I}_v \cdot Q(El) + I_v \cdot \dot{Q}(El) \qquad (9)$$

To study the maximum value and variation of $\dot{I}_s$, we need to look up those of I_z and. $\dot{I}_z$

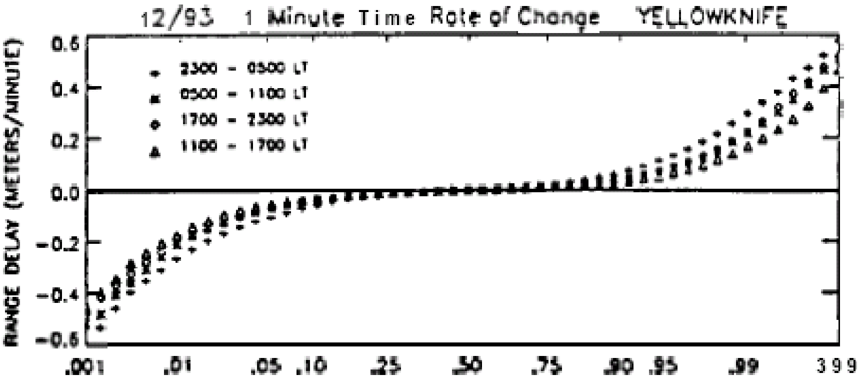
To search for the information about ionospheric zenith delay, we surveyed solar number and solar flux during the last 11-year solar cycle. The greatest solar number was found in 2000, and solar flux was maximized from 2000 to 2002. Therefore, we concluded the ionosphere activity was most vigorous between 2000 and 2001, and collected ionospheric zenith delay data from the IGS centers.



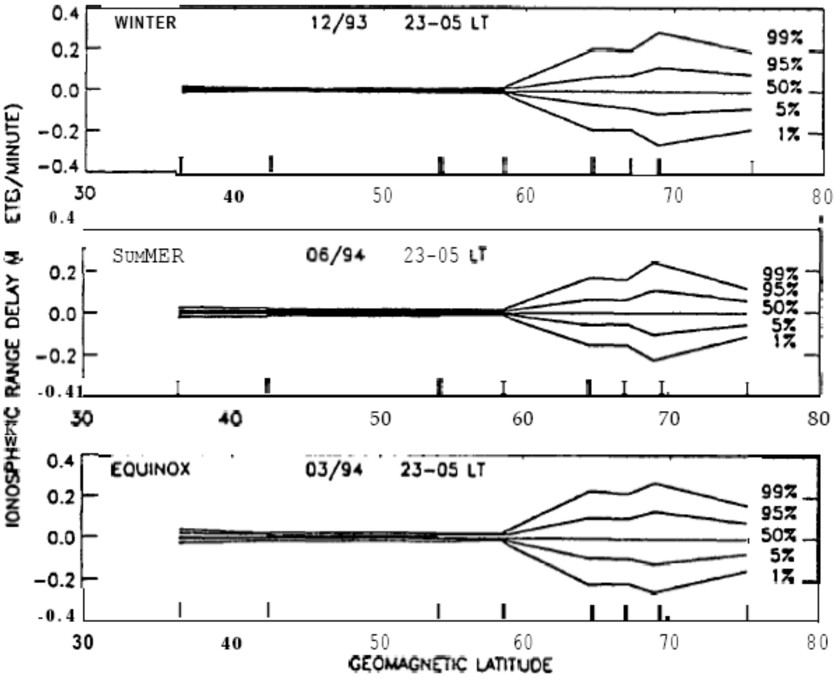
[Figure 4] Seasonal, Regional, and Diurnal Variation of Ionospheric Zenith Delay

From the results in [Figure 4], we found out that I_z is bigger in the cases of low latitude region, the afternoon, and Equinox or winter than in other ones.

Referring to the Doherty's statistical result, the largest short-term changes in ionospheric delays occur during the nighttime hours ([Figure 5] 23:00~05:00). [Figure 6] shows that the amount of time rate in ionospheric delay of the aurora zone at Equinox or in the winter reaches up to 0.4m/m (≅0.0067m/s).

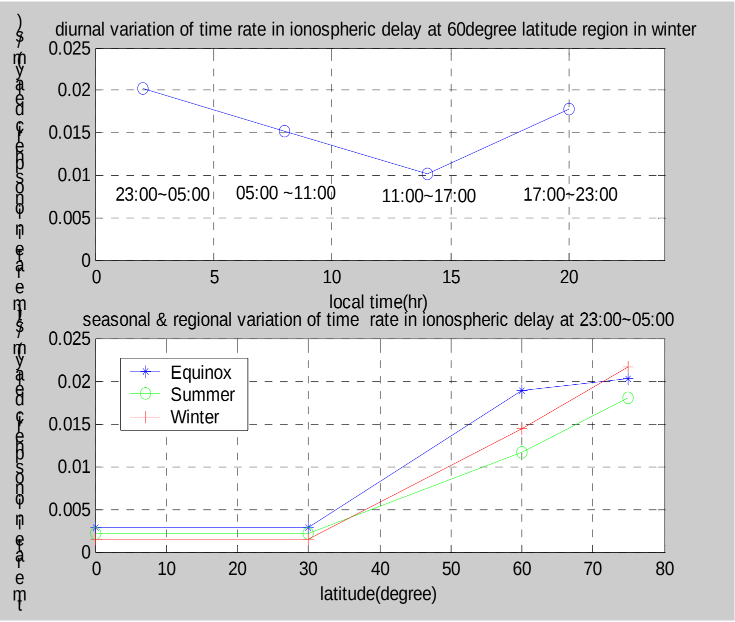


[Figure 5] Statistics of ionospheric delay variation for the daytime in 60-degree latitude region



[Figure 6] Summary of statistics of nighttime ionospheric delay variations for different seasons versus latitude

Equation (9) and result in Figure 4 to 6 make out the maximum value of time rate in ionospheric slant delay. The biggest speed of ionospheric slant delay variation is limited to 0.0203m/s at night (23:00~05:00), in high latitude region, in winter.



[Figure 7] Diurnal (up), Seasonal, and Regional (down) Variation of Ionospheric Slant Delay Rate

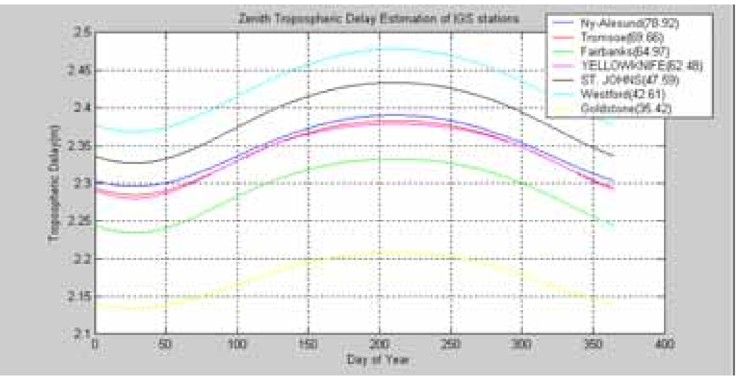
Tropospheric Delay

The troposphere is the lower part of the atmosphere composed of dry gases and water vapor. Unlike the ionosphere, troposphere is non-dispersive for GPS frequencies, so we generally use models to estimate the delay.

Similarly to the ionospheric slant delay equation, the tropospheric slant delay equation can be denoted as a function of the tropospheric zenith delay (T_v), time rate in tropospheric zenith delay ($\dot{T}_v$), mapping function ($m(El)$), and its change rate ($\dot{m}(El)$), so we need to observe the variation of T_v and $\dot{T}_v$

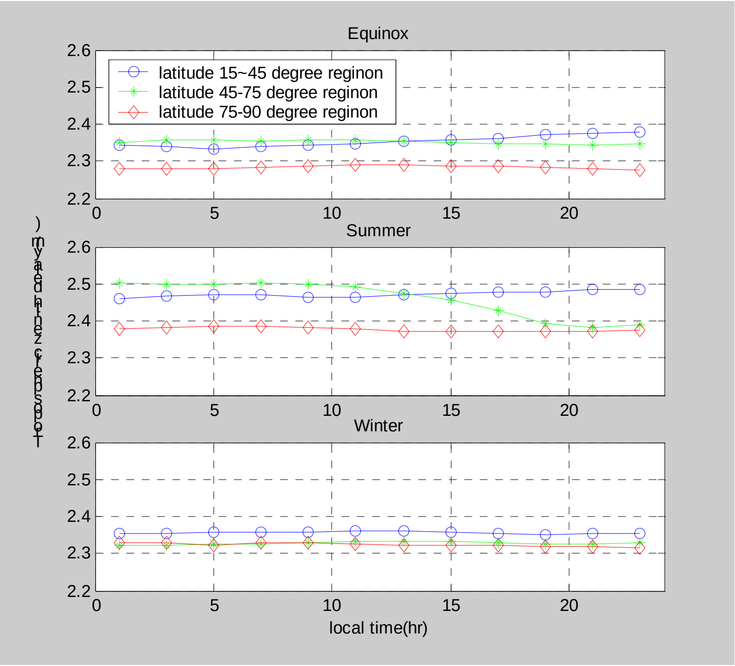
$$\dot{T}_s(El) = \dot{T}_v \cdot m(El) + T_v \cdot \dot{m}(El) \qquad (10)$$

To examine diurnal, seasonal and regional change of tropospheric zenith delay, we used data products of the tropospheric zenith path delay from IGS (International GPS Service). Unlike the ionosphere, the troposphere has little periodic tendency, and it is predicted with a few centimeters error. We used the WAAS tropospheric model to observe the seasonal and regional variation. The value of T_v is 2.15-2.5m, and it has the biggest value in summer and the smallest in winter.

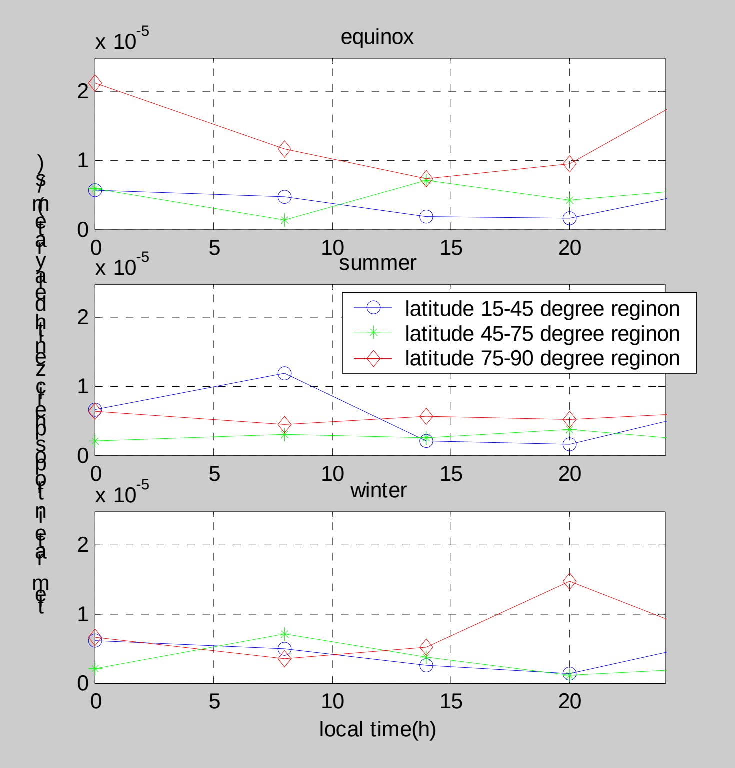


[Figure 8] Seasonal Variation of Tropospheric Zenith Delay

We took the data product of tropospheric zenith delay from the IGS to check up the diurnal variation, and we used meteorological data and Hopfield model to see the diurnal variation of the time-rate in tropospheric delay. The data of 15~45 latitude region was from Daejon station in Korea, that of 45~75 latitude from Churchill station in Canada, and that of 75~90 latitude from Thule Airbase station in Denmark. The graphs in [Figure 9] and [Figure 10] show that the diurnal change in troposphere is not so big.

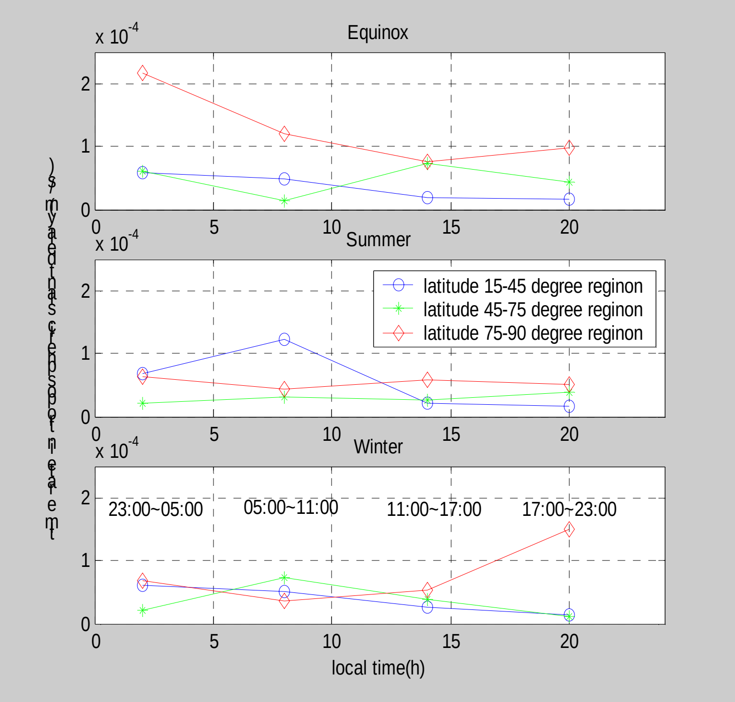


[Figure 9] Diurnal, Seasonal and Regional Variation of Tropospheric Zenith Delay



[Figure 9] Diurnal Variation of Tropospheric Zenith Delay Rate

From the equation (10) and result in Figure 8 to 10, the maximum value of time rate in tropospheric slant delay is calculated at $2.2\times10^{-4}\,m/s$. It was found at night (23:00~05:00), in high latitude region, in equinox.



[Figure 10] The Variation of Time-rate in Tropospheric Slant Delay

SIMULATION

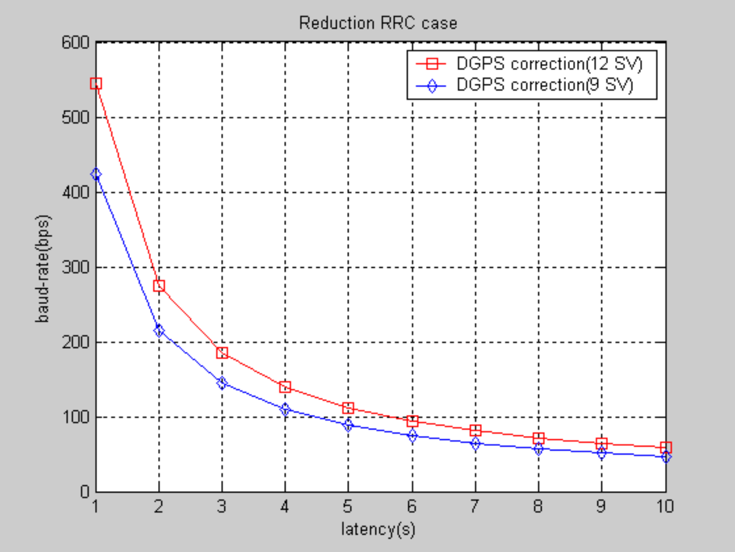
Summary of Simulation

For real-time users of DGPS, the resources required are establishment of a reference station and a radio link to transmit data to the users. The standard format of the broadcasted data developed by the Radio Technical Commission for Marine Services (RTCM) is in wide use, and RTCM has defined data messages and interface between the data link receiver and the DGPS receiver. Many providers of DGPS system broadcasts differential corrections in the RTCM SC-104 version 2.x formats from marine radio beacons at a modest data rate of 200bps, and they also plan to reduce the size to 50bps.

[Table 2] RTCM Message Type and Broadcast Schedule

RTCM Message Type	Interval(Schedule)
Type 1 Message (Correction Message)	As soon as possible
Type 3 Message (Reference Station Parameter)	every minute
Type 5 Message (Constellation Health)	every 15 minutes
Type 7 Message (DGPS Radio Beacon Almanac)	every 10 minutes

In general, the data stream is mainly made of message type 1 or 9 which consists of correction message such as PRC and RRC, while the broadcast of message types 3, 5, 7, and 16 will be rather infrequent. The following graph in [Figure 11] shows the relation between the baud rate and the time latency. We considered the real data size and sending message period of each type referring to the U.S. Coast Guard broadcasting schedule. Current DGPS system, which is 200bps for 9 satellites, has just 2 second delay in average, while the future system of 50bps for 12 satellites will have 10 second latency. Because the receiver uses old PRC till it receives the next one, and both of the reference and user have processing delay, the maximum latency that we experience is up to 6-9 second old PRC today and 22-25 second old one in a few years.



[Figure 11] Time Latency for Each Baud Rate

We did a simulation on the PRC error by the time latency using the equations in [Table 1]. The measurements noise statistics of Trimble 4000ssi receiver was used for this simulation. We considered seasonal, regional, and diurnal atmospheric variation results, and the time latency at current(200bps) and future(50bps) baud rate. We examined the results of not only a low-lying satellite (5 degree elevation angle) but also those of a satellite right above us (90 degree elevation angle).

[Table 3] All Cases of the Simulation on the PRC Error in Time latency

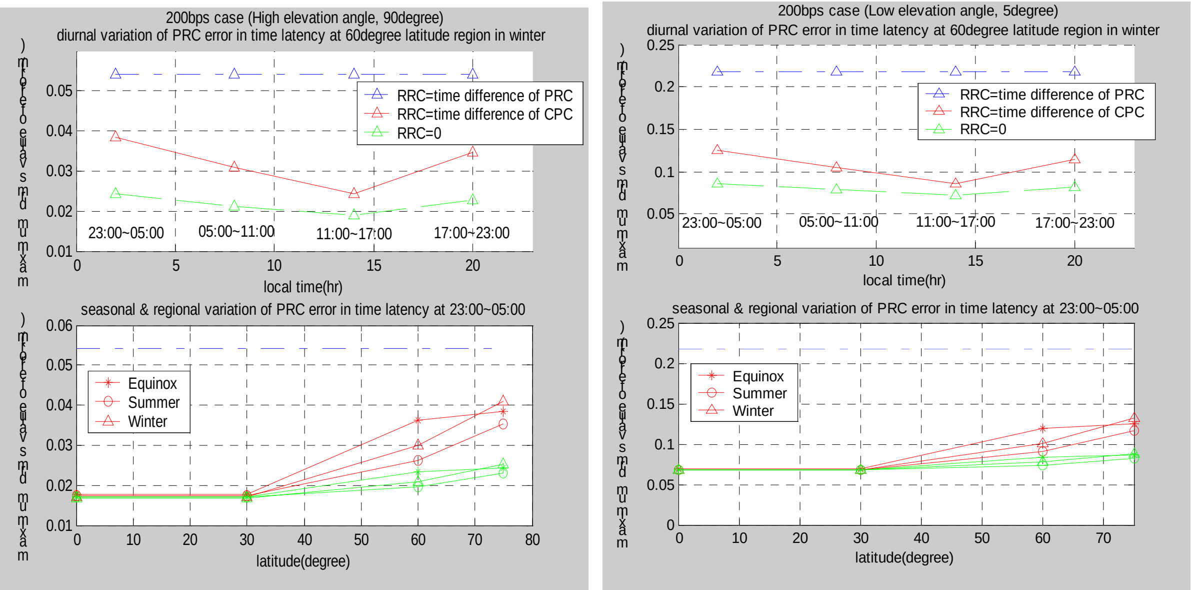
	Simulation Cases
Diurnal	23:00~05:00 // 05:00~11:00 // 11:00~17:00 // 17:00~23:00 //
Seasonal	Equinox // Summer // Winter
Regional	0~45 // 45~75 // 75~90 latitude
Satellite	5degree // 90degree elevation angle
Baud-rate	200bps // 50bps

Simulation Results

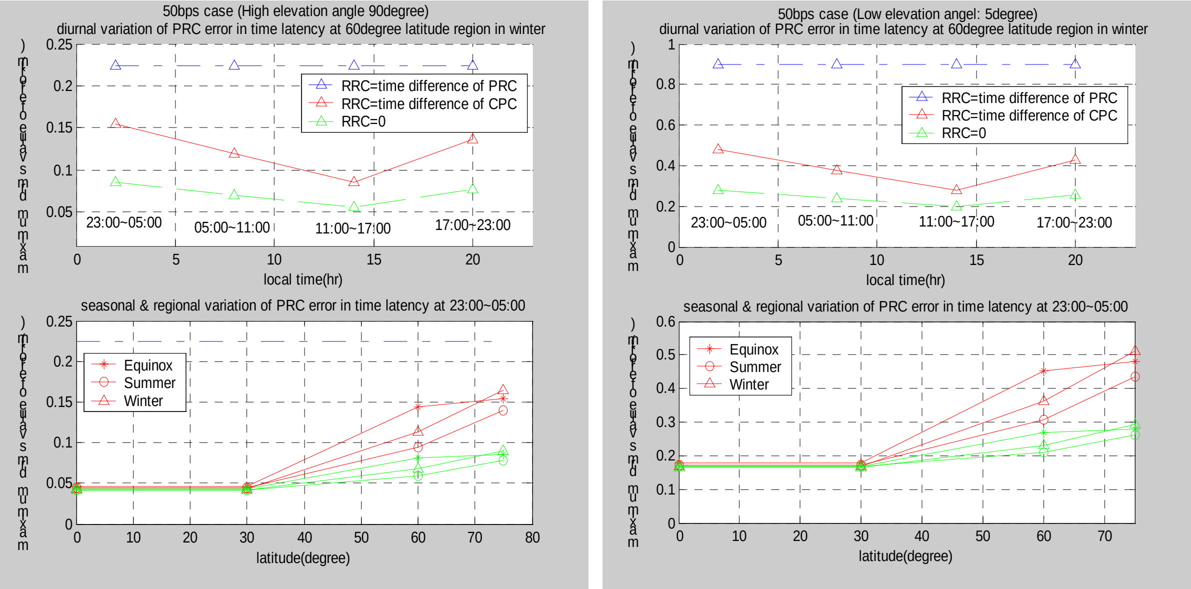
The simulation results are shown in the Figure 12 to 13 and [Table 4]. It is obvious that the error in 50bps of future system in [Figure 12] is far bigger than that in 200bps in [Figure 13]. And the error is enlarged by the low lying satellite. The tendency of the error in setting RRC zero and time difference of the CPC case are very similar to each other, and the results also coincide with the variation of ionospheric delay. That is to say, the time rate of it is the dominant factor of the PRC error in time latency. At daytime, the magnitude of ionospheric delay is large, but it stays still. Therefore, the time rate in ionospheric delay is not so big, neither is the PRC error by the time latency in the afternoon.

Let's turn to the result in time difference of the filtered PRC case. If we use it as RRC, there is no other error than the noise, so the error DRMS is dependent only on the satellite elevation angle. Using our results on the atmospheric delay, the RRC which is estimated correctly without measurement noise is smaller than 0.0203m/s (equation (11)), and it is far smaller than the noise of this generated RRC whose DRMS is 0.05~0.2m/s. Therefore it would be rather harmful to compensate the old PRC by it.

$$|RRC| = \left|-(\dot{i}+\dot{T})\right| \le \sqrt{0.0203^2 + 0.00022^2} = 0.02030 m/s \qquad (11)$$



[Figure 12]Diurnal(up), Regional, and Seasonal(down) Variation of PRC Error (DRMS) at 200bps : High(left) and Low(right) Elevation Angle Satellite Case.



[Figure 13]Diurnal(up), Regional, and Seasonal(down) Variation of PRC Error (DRMS) at 50bps : High(left) and Low(right) Elevation Angle Satellite Case

[Table 4] The Maximum PRC Error(DRMS, m) in Each Case

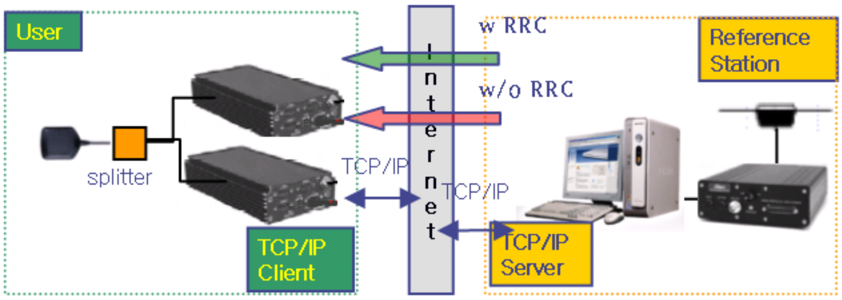
	200bps(current system)			50bps(future system)		
RRC	**△PRC**	**△CPC**	**RRC=0**	**△PRC**	**△CPC**	**RRC=0**
Equinox	0.217	0.125	0.086	0.899	0.481	0.280
Summer	0.217	0.116	0.082	0.899	0.436	0.261
Winter	0.217	0.132	0.088	0.899	0.512	0.293
0~45˚	0.217	0.069	0.068	0.899	0.178	0.169
45~75˚	0.217	0.119	0.083	0.899	0.451	0.267
75~90˚	0.217	0.132	0.088	0.899	0.512	0.293
23-05hr	0.217	0.119	0.083	0.899	0.451	0.267
05-11hr	0.217	0.104	0.079	0.899	0.377	0.237
11-17hr	0.217	0.087	0.073	0.899	0.280	0.200
17-23hr	0.217	0.114	0.082	0.899	0.429	0.258

Summarizing the result of this simulation, the additional error by setting RRC zero is far smaller for all the cases than those of other techniques. The RRC generated by PRC is too noisy to use, and that by CPC has big error especially in the winter, at high-latitude region, and in the morning.

EXPERIMENTAL TEST

Summary of Test

We organized an experiment test set, which proved our simulation results. It comprises a reference station, a transmission method, and a user application. The TCP/IP server in the reference station broadcasts RTCM message version 2 without any modification. Two receivers in the user application are connected to the same computer and receive the correction message simultaneously via internet after 30 second delay. According to the broadcast standard for the USCG DGPS, PRC Time out limit is 30 second, so we cannot delay longer than 30 second. The receiver used for reference station is Ashtech GG24 receiver, while those two for user application are Novatel 3151R receiver. They are different from each other, but there is no problem because the RTCM message is a standard format. A splitter enable the same GPS signal to flow into both receivers. The only difference in these two in one system is that one uses the RRC to compensate for the 30 second latency, and the other does not.



[Figure 14] Experimental System Construction

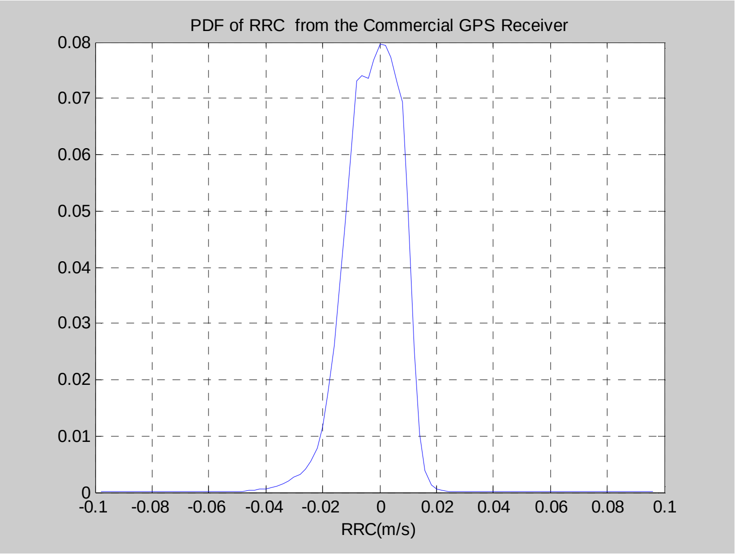
We did a zero-baseline static test for 24 hours long to show the diurnal variation and the persistency of the position accuracy improvement without using RRC. We set the elevation angle mask 5 degree as we did in the previous simulation. We also did a dynamic test using the moving automobile around the Seoul National University at night, because the simulation results indicate that the amount of the position error reduction is not so big at daytime.

[Table 5] Summary of the Static and Dynamic Test

Location	SNU, Seoul(37°26’58.903”N, 126°57’09.887”E, 281.925m)		
Date	Sep. 10, 2004 18:00~Sep. 11, 2004 18:00 (24hr, Static Test) Sep. 13, 2004 02:00~04:00 (Dynamic Test)		
GPS Receiver	Ashtech GG24(Reference) Novatel 3151R (User)		
Sampling Time	1 sec	Elevation Mask	5°
Time latency	30sec (Purposely introduced delay)		
Baud-rate	10.0Mbps(no additional time latency)		

Statistics of RRC

The [Figure 15] is the PDF, Probability Density Function, which is made by the statistics of RRC data. It was generated from Ashtech GG24 receiver and logged in the reference station computer during the 24hr-static test.

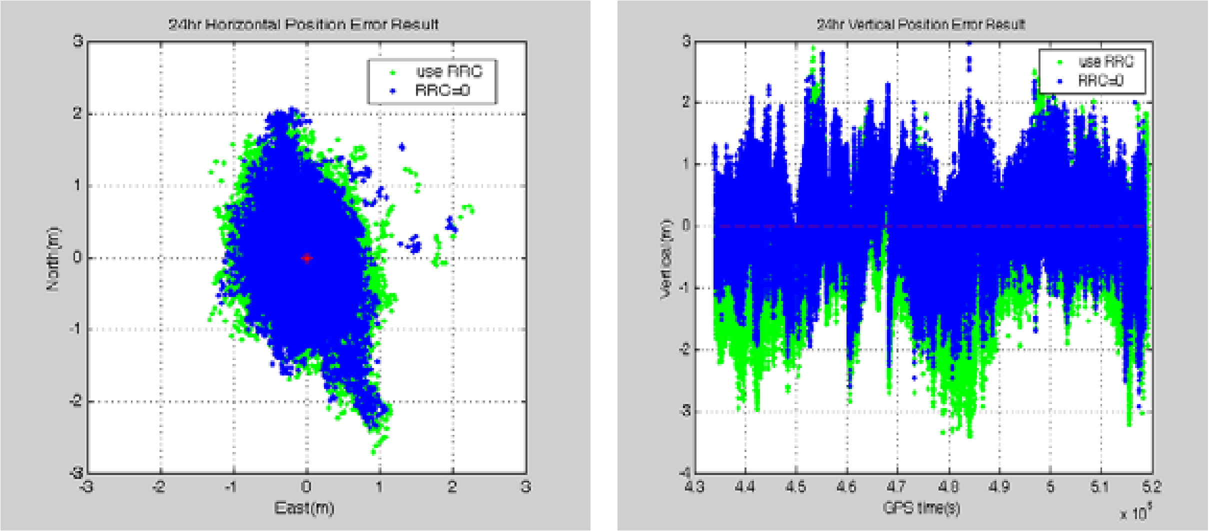


[Figure 15] The PDF of the RRC from a Commercial GPS Receiver

The mean value of this data was -0.0024m/s, and the standard deviation is 0.0093m/s. Most RRCs(99%) range between -0.034m/s and 0.016m/s. At the first glance this result seems not to support our simulation result that the magnitude of RRC would be smaller than 0.0203m/s (equation 11). Let’s recall the commercial receiver can not estimate RRC correctly because of the measurement noise and atmospheric bias. The fact that most RRCs are near 0m/s in spite of the noise and bias supports our simulation result.

Static Test Results

The zero-baseline static test results in 30 second latency is presented in [Figure 16] and [Table 6]. From the horizontal DGPS results, we found that the RRC make the position to be noisy and to jump far away from the origin. Moreover, the vertical result showed the position compensated by RRC has somehow bias.



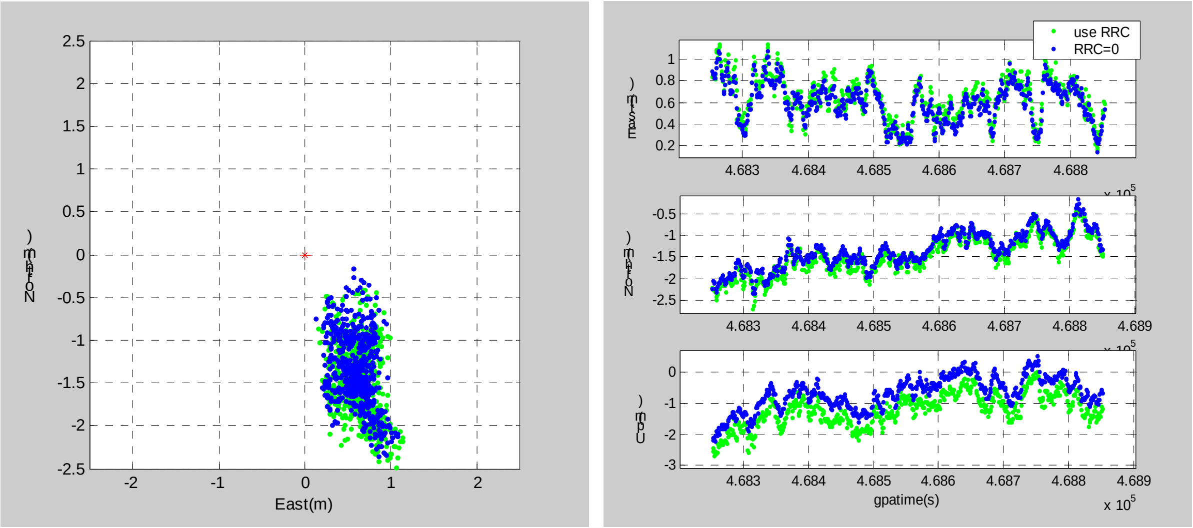
[Figure 16] 24hr Horizontal(left) and Vertical(right) Positioning Result

If we use RRC at future baud-rate(50bps), 95% horizontal position error is over 1m, and vertical error can be up to 3m. On the other hand, setting RRC zero can reduce these errors to 0.8m and 1.5m.

[Table 6] Position Error(DRMS) of 24hr processing

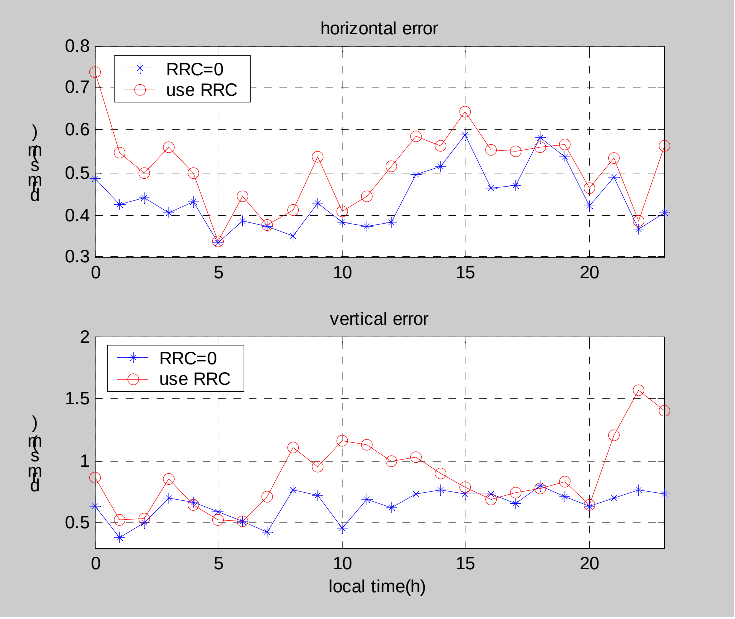
DRMS of Error	Horizontal	Vertical
Using RRC	0.5625m	1.4012m
Setting RRC zero	0.4056m	0.7297m

Let’s focus on the results for 600sec in [Figure 17]. The position jumped t 3m apart from the true one, and began to converge into the origin. At the time when the position jumped, the satellite of PRN number 19 started to rise. The elevation angle of it was 7 degree at 15:05, and the user used 30second-old PRC, so that of old PRC is 5degree. The RRC of a low-lying satellite contains large atmospheric divergence and measurement noise, and it moves nonlinearly. In this case, therefore, the error of PRC compensated by the wrong- or noisy-estimated RRC is far bigger than that of the old PRC, so the position by RRC was displayed much farther apart from the origin.

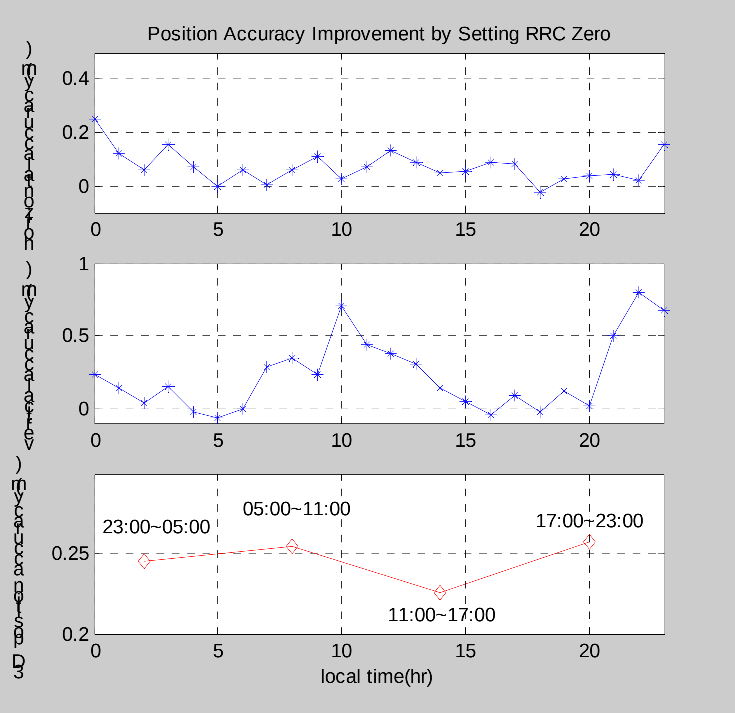


[Figure 17] Horizontal(left) and Vertical(right) Positioning Result for 17:05~17:15

[Figure 18] is the diurnal variation of the position error (DRMS) in using RRC and setting RRC zero cases. The changing tendency of using RRC is almost same to the other, but position accuracy is not so good as the other's. It is interesting that there is little accuracy improvement from 14:00 to 18:00, because the divergence effect of ionosphere in RRC is very small in the afternoon. During sun-rise or sun-set, the ionospheric delay grows longer or small steadily, so the divergence effect by RRC propagate directly into the error. Note that the last graph in [Figure 19] and diurnal variation of the ionospheric delay rate in [Figure 7] have similar trend, it supports our idea that the time rate in ionospheric delay is the dominant factor in the error by the time latency.



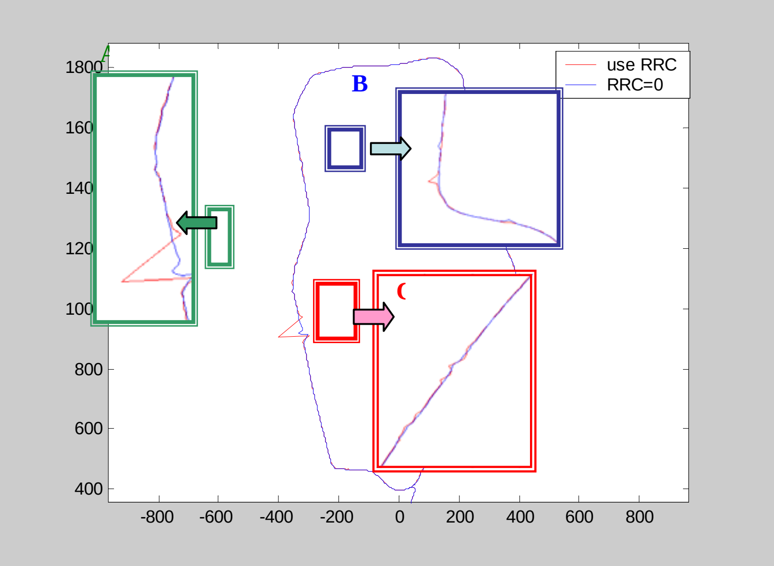
[Figure 18] Diurnal Variation of the Position Accuracy



[Figure 19] Position Improvement by Setting RRC Zero

Dynamic Test Results

[Figure 19] shows the trajectory of the car where the DGPS user application system was implemented. An antenna was mounted on the top of the automobile, and an internet service of a cellular phone was used for the datalink by which the two receivers got the correction message simultaneously. The user move around Seoul National University campus, the range between the user and reference station was from 400m to 1600m. The road was narrow, and many obstacles such as hills, trees and buildings blocked the signal.



[Figure 19] Dynamic Test Result

The buildings in the region zoomed in the window 'A' blocked GPS signal, so the observability was very bad. At the first jump, the position by both RRC and no RRC moved discretely, but the jumping amount by RRC was far bigger than the other. And after a big jump, the receiver with RRC did not work well for 5 second. Leaving aside the receiver problem, we found many jumping position in case of using RRC in the many parts of window 'A' and 'B'. Moreover, the result of using RRC was noisy in the part of 'C', while that without compensating had a very smooth trajectory.

CONCLUSIONS

There are many changes before and after SA-off. The magnitude of PRC became not only small but also robust to time latency. To examine the robustness of PRC in SA-off era, we studied on the time rates of atmospheric delay and ephemeris error, and the noise characteristics of the pseudorange and carrier phase. By many statistics of papers, data from IGS centers, many well-known atmospheric models, and simulation results, we made a conclusion that the RRC varies very slowly and linearly. In other words, the RRC is almost zero. Therefore, the noise in time difference of PRC and ionospheric divergence in that of CPC are dominant factors in latency error. The ionospheric divergence in CPC can also enlarge the error big in spite of the compensation for the time latency.

Experimental results demonstrate that this simulation results is true to the commercial receiver set. Setting RRC zero in 30 second delay makes the position more accurate by 0.32m in horizontal plane (95%, 24hr average) and 1.4m in vertical plane. This effect is shown obviously in the case of rising satellite and low observability.
The future DGPS system uses 50bps baud-rate, and the time delay would reach 30 second which is the same to that of our system. We can expect that if we setting RRC zero, the position accuracy will improve not only in normal case but also in extraordinary case. As the baud-rate becomes narrower, the improvement would be larger.

Compensating PRC using RRC has negative effect on DGPS positioning accuracy, while it increases the bandwidth of datalink. Removing RRC can reduce the amount of data about 20% and therefore reduce time latency and improve DGPS position accuracy. But the improvement will cause backward compatibility problem for DGPS legacy users. Therefore, we recommend DGPS correction provider to make RRC to be intentionally zero at reference station.

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