Development and Test Results of a Cost Effective Inverse DGPS System

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BIOGRAPHIES

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ABSTRACT

An Inverse Differential GPS (IDGPS) system is developed to achieve better GPS accuracy and significant cost savings on the air radio traffic charges by not broadcasting direct RTCM messages to the vehicles. The system consists of a Reference Station and up to two-hundred and fifty In-Vehicle Equipment (IVE) fitted in cars. Each IVE has a low cost GPS receiver and a communication link to send data to a Control Station, which also receives RTCM data from the Reference Station through a leased line. The IDGPS is implemented in the measurement domain. The accuracy of the IVE position is calculated before and after the range correction to evaluate the performance achievable by this system. Initial results show that the corrected solution is significantly better compared to the uncorrected case, reducing the standard deviation of the position error from more than 10 m to less than 2 m.

INTRODUCTION

Prior to May 2, 2000, Selective Availability (SA) was the major source of measurement error in standalone GPS receiver. By using differential technique the Selective Availability error could be removed almost completely except for the spatially decorrelated part of the error. Therefore, DGPS was the only way to achieve acceptable accuracy for various Intelligent Transportation System (ITS).

After the SA was turned off on May 1-2, 2000, the standalone GPS receiver accuracy improved dramatically obviating the need for differential GPS for many applications which were earlier using the differential technique for improved position accuracy.

However, even without SA, the accuracy from the standalone GPS receiver falls short compared to the differentially corrected GPS receiver. The major remaining error sources in stand alone receiver is atomospheric delay error and residual ephemeris error. These errors together with receiver noise and multipath makes the position error bad enough for some ITS applications. Also, there is no guaranty that SA will not be turned on in a future date.

This paper addresses a differential GPS system used for fleet management. The use of standalone GPS was overruled due to the accuracy requirements of the system, which could not be fulfilled by standalone GPS. An inverse DGPS based network was developed instead of a standard DGPS based network due to the cost implication and suitability. The improvement in accuracy of the Inverse DGPS system with respect to a stand alone system is analyzed and demonstrated through static and mobile field trials.

INVERSE DGPS THEORY

Differental Global Positioning System (DGPS) is a technique whereby a GPS receiver uses information from another GPS receiver to improve the accuracy and integrity of its solution. A conventional DGPS has reference stations placed at surveyed locations, which simultanously track the GPS satellites and generate range, phase and/or range rate corrections. These corrections are broadcast to the DGPS users using a convenient communication link. The DGPS users are often mobile receivers, which apply those corrections to obtain more accurate position, velocity, time solutions.

As the name suggests, the Inverse DGPS concept is the opposite of DGPS, whereby the mobile receivers send raw range, phase and/or range rate measurements or the computed position to the reference stations. The reference staions, which simultanously track the satellites apply correction to the data from the mobile receivers to obtain high accuracy position and velocity of the mobile receiver. Unlike DGPS system, accurate position of the mobile receiver is known only at the reference station. The mobile receiver does not have the accurate position information. Therefore, this has applications in vehicle tracking, fleet management, emergency messaging applications.

The following sections breifly describe GPS raw measurements and various error sources in the meaurements. It then give a brief description of using code measurements and position information from a mobile receiver to compute Inverse DGPS position at the reference station.

GPS Measurements

The range measurement from a receiver contains various other small error components and is given by (Wells, 1987):

$$P = \rho + d\rho + c(dt - dT) + d_{ion} + d_{trop} + d_{hw} + \varepsilon_p + \varepsilon_{Mp} \quad (1)$$

where

P	is the measured code range (m)
ρ	is the geometric range between the satellite and receiver antennas (m)
$d\rho$	is the orbital error, nominal and SA (m)
c	is the velocity of light (m/s)
dt	is the satellite clock error with respect to GPS time, nominal and SA (s)
dT	is the receiver clock error with respect to GPS time (s)
d_{ion}	is the ionospheric delay error (m)
d_{trop}	is the troptospheric delay error (m)
d_{hw}	is the hardware delay in the satellite and in the receiver (m)
ε_{Mp}	is the code range multipath error (m), and
ε_P	is the receiver code noise (m).

Inverse DGPS Using Pseudorange

Many of the errors in the observation Equation are spatially correlated between receivers tracking a satellite simultaneously. This is because those errors are satellite dependent, or caused by atmospheric propagation and therefore common for two receivers on earth separated by a short distance. Often the degree of correlation between errors at two receivers is a function of the baseline length.

The errors that are correlated in measurements from two receivers simultaneously tracking a satellite, can be reduced by taking the single difference of the range observation equations for a single satellite and two receivers. This is shown in Figure 1 and is given by:

$$\Delta P = \Delta\rho + \Delta d\rho + c\Delta dT + \Delta d_{ion} + \Delta d_{trop} + \Delta d_{hw} + \Delta\varepsilon_p + \Delta\varepsilon_{Mp} \quad (2)$$

where Δ represents a *between-receiver single difference*.

In Equation 2 the satellite clock error term has disappeared, as it is the same for the two receivers at a particular time epoch. Other errors have now become the difference of errors in the two receivers. As a result, a high degree of correlation of errors in the two receivers results in cancellation of the error in the differenced equation. For a short baseline, the orbital error, ionospheric delay error and the tropospheric delay error are highly correlated, so the residual error can be assumed to be very small. The receiver clock bias, multipath and receiver noise, however, do not cancel. The hardware delay error, which is completely receiver dependent, is likely to be cancelled if both the receivers are of the same type, and from the same manufacturer. Under these circumstances, multipath error is the most dominant source of error in the single differenced measurements. For a long baseline, however, the residual orbital, ionospheric, and tropospheric errors become more significant compared to multipath errors.

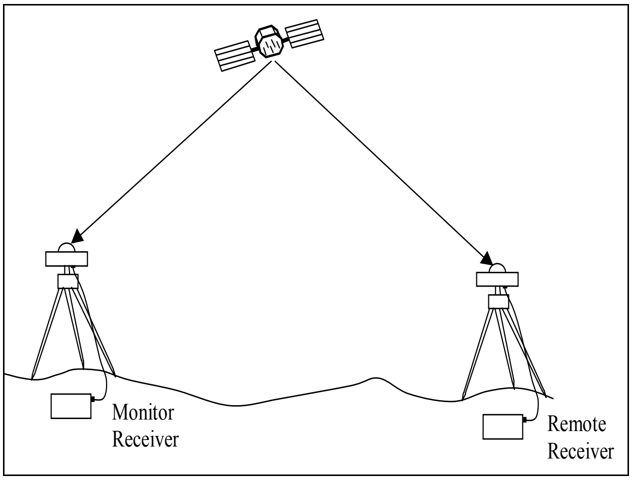

Figure 1: Between-receiver single differencing

If the mobile receiver sends raw pseudorange measurements to the reference station, the reference station uses Equation 2 to generate differential observations. It may then determines the differential position of the mobile receiver using weighted least square as shown in the following expression:

$$\Delta x = \left(H_P^T R_P H_P\right)^T H_P^T R_P^{-1} \Delta P \quad (3)$$

where,

Δx is the position and clock bias error vector

H_P is the dynamic matrix or direction cosine matrix

R_P is the measurement error covariance matrix

The position and clock bias vector has elements corresponding to 2D or 3D position error, either in Cartesian co-ordinate system or curvilinear co-ordinate system. In the curvilinear co-ordinate system, it is given by:

$$\Delta x = [\Delta\varphi \; \Delta\lambda \; \Delta h \; \Delta T]^T \tag{4}$$

where,

$\Delta\varphi$ is the latitude error (m)

$\Delta\lambda$ is the longitude error (m)

Δh is the height error (m), and

ΔT is the clock bias error (m).

These position error when added to the reference station position, gives the position of the mobile receiver.

Then the design matrix for *i* number of common satellites between the mobile and the reference receiver is given by the following expression:

$$H_P = \begin{bmatrix} \frac{\delta\Delta P_0}{\delta\Delta\varphi} & \frac{\delta\Delta P_0}{\delta\Delta\lambda} & \frac{\delta\Delta P_0}{\delta\Delta h} & \frac{\delta\Delta P_0}{\delta\Delta T} \\ & & & \\ \frac{\delta\Delta P_i}{\delta\Delta\varphi} & \frac{\delta\Delta P_i}{\delta\Delta\lambda} & \frac{\delta\Delta P_i}{\delta\Delta h} & \frac{\delta\Delta P_i}{\delta\Delta T} \end{bmatrix} \tag{5}$$

The measurement covariance matrix (R_P) is generally a function of the satellite elevation angle.

Inverse DGPS Using Raw Position

The raw position of the mobile receiver may be sent to the reference station, instead of raw measurements. It is then necessary to send the satellite numbers that were used to compute that raw position. If a position filter was used at the mobile receiver, then the weight or coeffecient of the filter also needs to be sent to the reference station. In addition, if the mobile receiver uses a ionosphereic or tropospheric model for correction, then the reference station needs to have the knowledge of which model was used at the mobile receiver.

As the reference station is generally established in a location with good satellite visibility, generally the reference station has measurements from all the satellites that were used in the position computation at the mobile receiver. If, however, the reference receiver does not have measurement from a satellite that was used to determine the position at the mobile receiver, then it is better not to correct the position at that particular epoch.

Due to the above mentioned constraints, Pseudorange based Inverse DGPS was the preferred technique used for this Inverse DGPS System.

INVERSE DGPS ARCHITECTURE

CET Technologies Pte Ltd and Accord have jointly developed this IDGPS System for vehicle tracking in Singapore. The system consists of a Reference Station and up to two-hundred and fifty In-Vehicle Equipment (IVE) fitted in cars. In addition to that a Control Station was set up where the Inverse GPS and fleet management software was installed. If the Control Station was on a high rise building with open sky, then the reference station could have been installed on the roof top of the same building. But, here, this was not the case. Therefore, the Reference Station was set up on a different building which is moderately high rise and at around 10 miles from the Control Station. A Leica MX9250 receiver was set up as the Reference Station. The antenna with choke ring was placed at the highest point of the building at the top of a shaft to maximize visibility and minimize multipath effects. The data from the Reference Station was connected to a Modem which was sending the data through a dedicated telephone line at a fixed 9.6K baud rate. The other side of the dedicated telephone line was connected to another Modem in the Control Station. The output of the Modem was connected to the PC hosting the Inverse DGPS software. Figure 2 shows a block diagram of the set up.

The mobile IVE has a low cost GPS receiver and a communication link to send data to a Control Station. In the current configuration no dead reckoning sensor was used in the IVE. The IVE sends the data to the Control Station using Mobitex Network^{TM}. Mobitex™ is a packet switched network for mobile data communication. Data transmission over the Mobitex™ is both secure and efficient compared to a circuit switched network. A Mobitex radio modem is used at both the mobile receiver and the Control Station to communicate over the network.

The Reference Station sends corrections for the satellite measurements in RTCM format. The IVE sends raw pseudorange measurements and receiver derived position in a predefined format at a nominal adjustable rate of once in 30 sec. The IDGPS is implemented in the measurement domain, wherein in the corrections for satellite range measurements are extracted from the Reference Station data and applied to the range measurements from the IVEs. As a result the common errors between the Reference Receiver measurements and the Remote Receiver measurements are cancelled out to give more accurate measurements. The accuracy of the IVE position is calculated before and after the range correction to evaluate the performance achievable by this system.

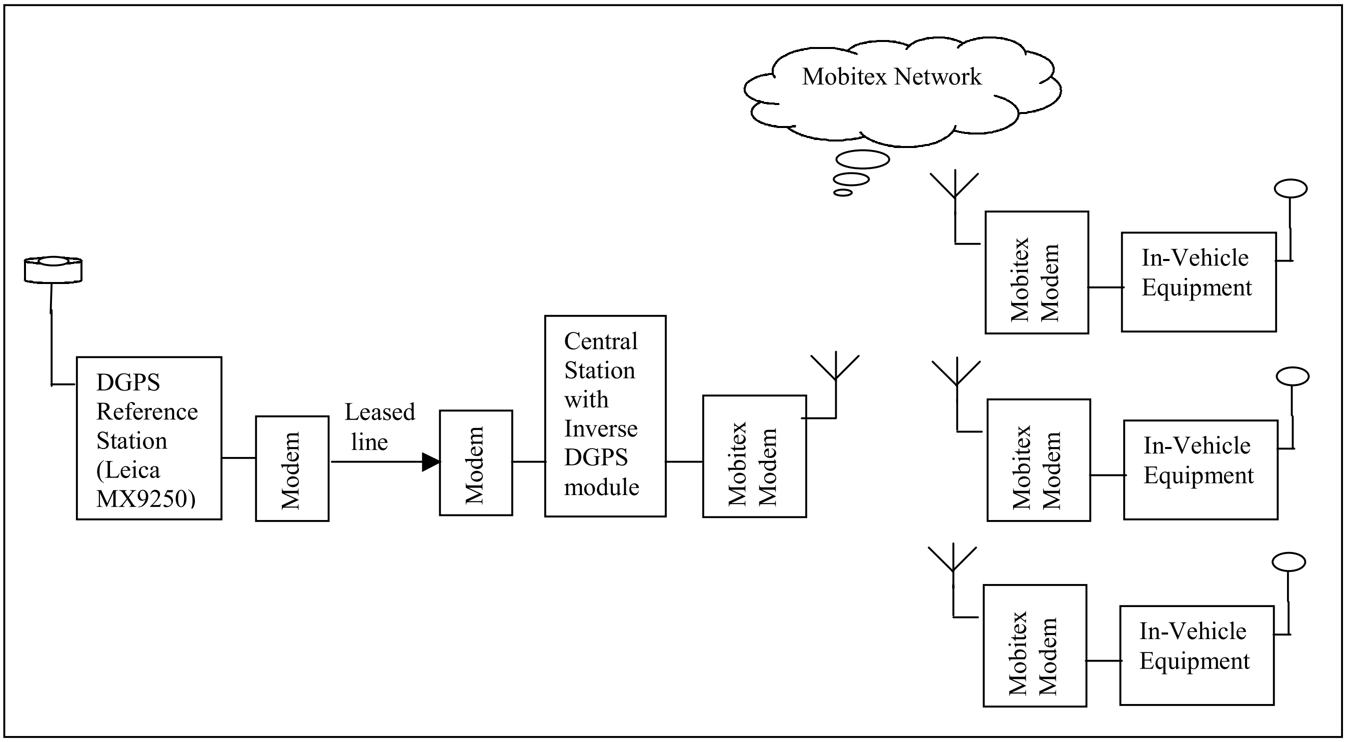

Figure 2: Inverse DGPS System architecture

INVERSE DGPS DATA FLOW

The Leica MX9250 is configured in Reference Station mode to transmit RTCM Type 1 messages and satellite ephemeris data at the baud rate of 9600 bps. RTCM Type 1 message contains PRC (pseudo-range), RRC (range-rate corrections), IODE (issue of data ephemeris) used to generate the corrections, for all the tracked satellites.

The data from the mobile receiver is received in a format called Vehicle Movement Information (VMI). VMI includes the following information:

- Vehicle ID (identified by the MAN ID of the Mobitex modem)
- Vehicle position (latitude, longitude and altitude and GPS time of fix)
- Satellite ID and pseudorange for all tracking satellites

The differential corrections from the reference station are applied to the pseudorange data from the IVEs using the Waypoint™ Inverse DGPS DLL. The data from the mobile unit and the reference station is *aligned in time* before it is fed to the DLL using the following.

$$PRC(t) = PRC(t_0) + RRC*(t - t_0) \qquad (6)$$

Where,

t is the time of measurement of mobile data (sec), and

t_0 is the time of measurement of reference station data (sec).

Figure 3 shows the data flow diagram of the Inverse DGPS system.

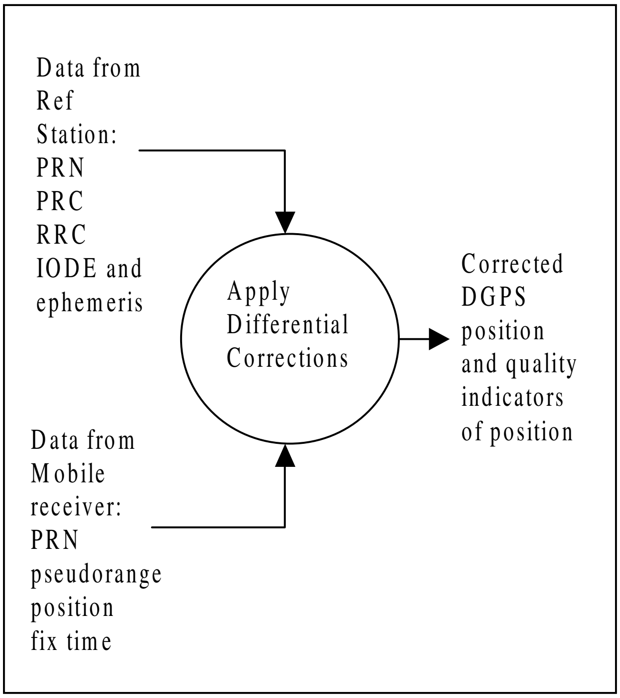

Figure 3: Inverse DGPS data flow diagram

The IDGPS system is implemented using Microsoft™ Visual C++ 5.0. The system consists of three threads: the first, to handle user interface events, the second reads raw bytes from the serial port in real time and stores into a circular buffer, and the third to extract the useful data from the raw stream of bytes stored in the circular buffer. The data from the mobile receiver is received, through a socket connection, from a different module, which is a part of the fleet management system. The user interface displays the status of the corrections made by the IDGPS system to the GPS data from the mobile units. The number of corrections made hourly and the reasons for non availability of IDGPS system are also displayed.

TEST DESCRIPTION

Static and mobile tests were conducted to assess the performance of the system. The following describe various results and statistics that were obtained from the tests.

Static Tests

During the Static test, the IVE was placed on the top of the CET building and data was continuously sent through the network. The position of the IVE was known with fairly good accuracy by averaging the GPS derived position for approximately 1 day duration. The Vehicle Movement Information (VMI) data from a IVE was sent at an approximate rate of 2 solution /minute. Inverse differential correction was applied at the Control Station using the data from the Reference Station. The test was carried out on September 14 and 15, 2000.

Figures 4 shows the x-y plot of latitude vs. longitude error ***before*** IDGPS correction for the data collected on September 14. The latitude error (φ_e) and longitude error (λ_e) were computed by subtracting the Mean of latitude and longitude from each sample of the incoming data. The plot shows that the latitude and longitude errors are generally clustered between –15 m and + 15 m. However, there are some large position error spikes which are due to large measurement errors probably caused by mulitpath and/or bad geometries. Similar observations can be made for the uncorrected input data collected on September 15 as shown in Figure 5.

Figure 6 shows the x-y plot of latitude vs. longitude error ***after*** IDGPS correction for the data collected on September 14. Figure 7 shows similar plots for the data collected on September 15. From both these plot it can be seen that the position errors are much smaller compared to the uncorrected data and restricted to –5 m and +5 m most of the cases. The spreads of the latitude and longitude errors as well as the maximum horizontal error are well below the uncorrected case with all the large spikes removed.

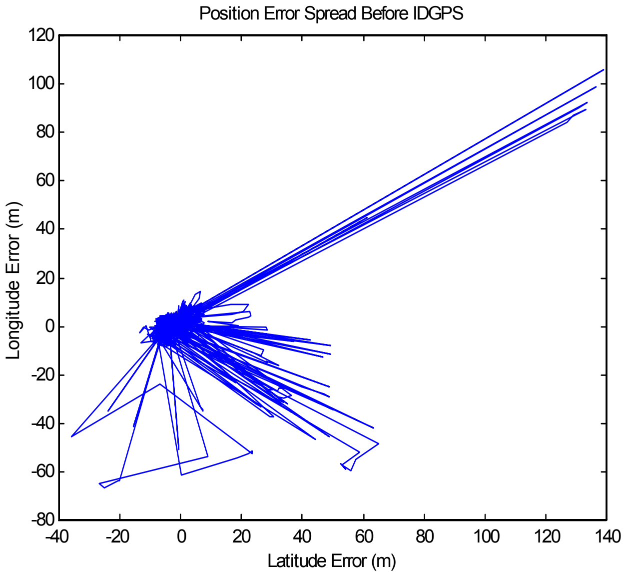

Figure 4: Latitude vs. Longitude errors before IDGPS correction (September 14)

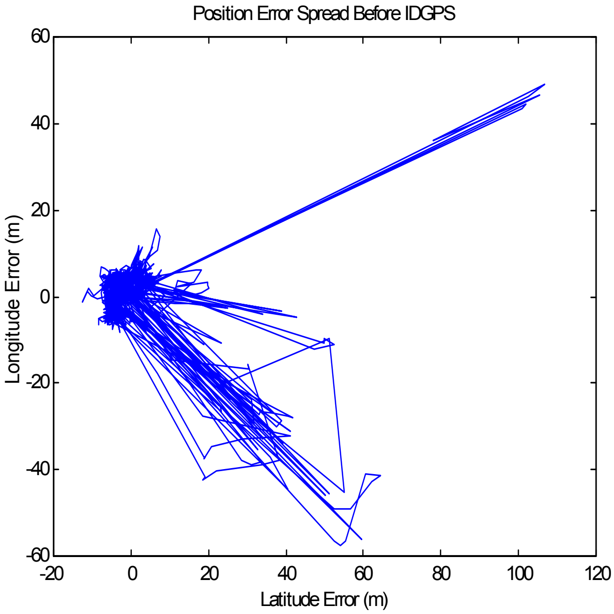

Figure 5: Latitude vs. Longitude errors before IDGPS correction (September 15)

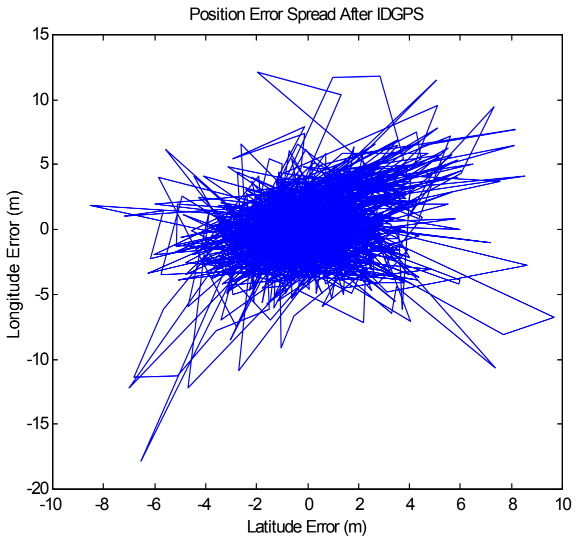

Figure 6: Latitude vs. Longitude errors after IDGPS correction (September 14)

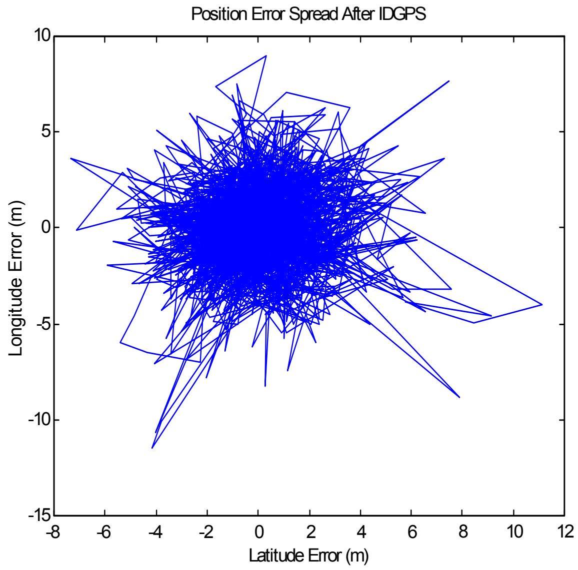

Figure 7: Latitude vs. Longitude errors after IDGPS correction (September 15)

Figures 8 and 9 show the histogram of the horizontal position error ***before*** IDGPS correction for the data collected on September 14 and 15 respectively. The horizontal position error is computed using the following:

$$\text{Horizontal position error} = \sqrt{\varphi_e^2 + \lambda_e^2} \qquad (7)$$

where,

φ_e is the latitude error (m), and
λ_e is the longitude error (m)

The X axis represents the horizontal position error and the Y axis represents the number of samples for a particular error. From the figures it is evident that the errors can be as large as over 100 m. It is also clear that the largest number of samples have an error of around 5 m. The statistics computed from these histograms show that the number of samples having less than 5 m of horizontal position error is less than 50 percent. The standard deviation of the position error is above 10 m.

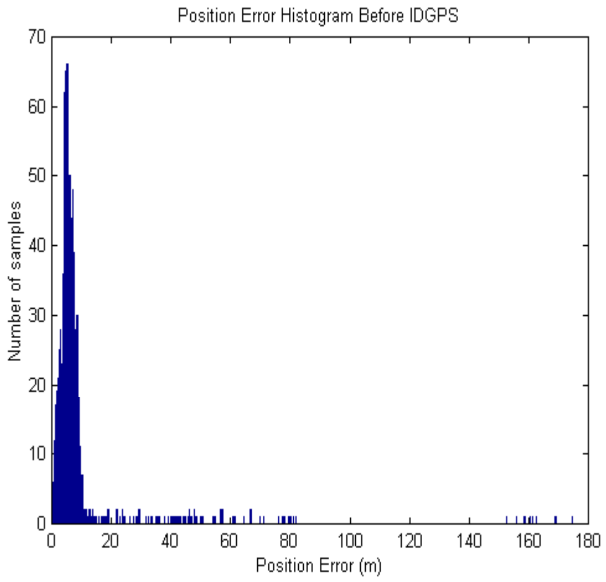

Figure 8: Hor. position error histogram before IDGPS correction (September 14)

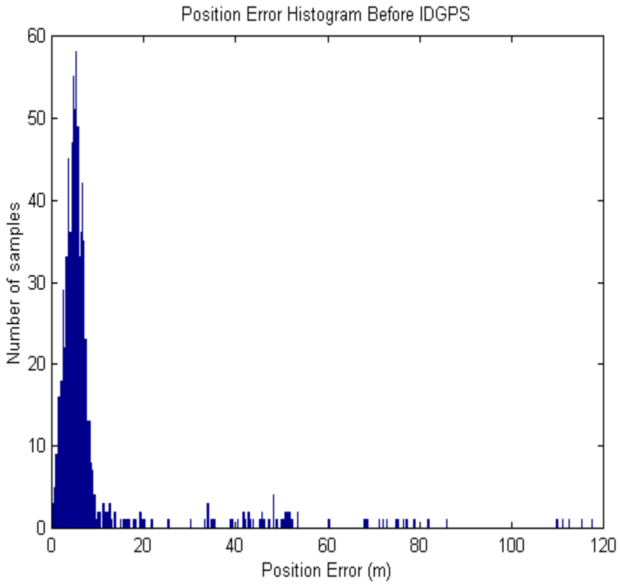

Figure 9: Hor. position error histogram before IDGPS correction (September 15)

Figure 10 and 11 show the histogram of the horizontal position error ***after*** IDGPS correction for the data collected on September 14 and 15 respectively. From the figures it is clear that the largest number of samples have an error of around 2 m. The statistics computed from these histograms show that over 90 percent of the samples have horizontal position error less than 5 m. The standard deviation of the position error is below 2 m. These statistics are well within the desirable error limits expected out of the IDGPS system. This clearly indicates the effectiveness of the IDGPS system in correcting the errors from the raw measurements.

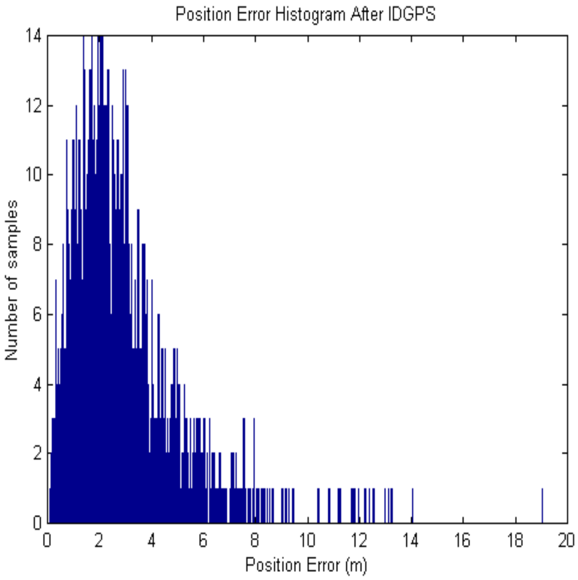

Figure 10: Hor. position error histogram after IDGPS correction (September 14)

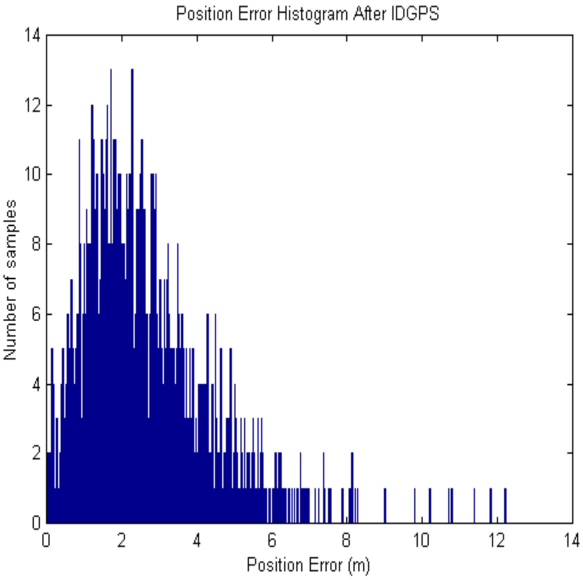

Figure 11: Hor. position error histogram after IDGPS correction (September 15)

Figure 12 shows the corrections sent by the reference station for various satellites based on the data collected on September 14.

It can be seen that the range errors can be as large as 20 m in some cases. These errors are mainly due to atmospheric delay i.e. ionospheric and tropospheric delays and have slow variations. The high frequency components of the errors, which are very small, are due to ionospheric scintillation, multipath at the reference site and receiver noise. These atmospheric errors are common to the reference receiver and any receiver within a short distance (say up to 50-100 KM). Such large errors in range would introduce large position errors, if remained uncorrected. The IDGPS system effectively corrects these common errors and improves the performance of the system significantly as evident from the above analysis.

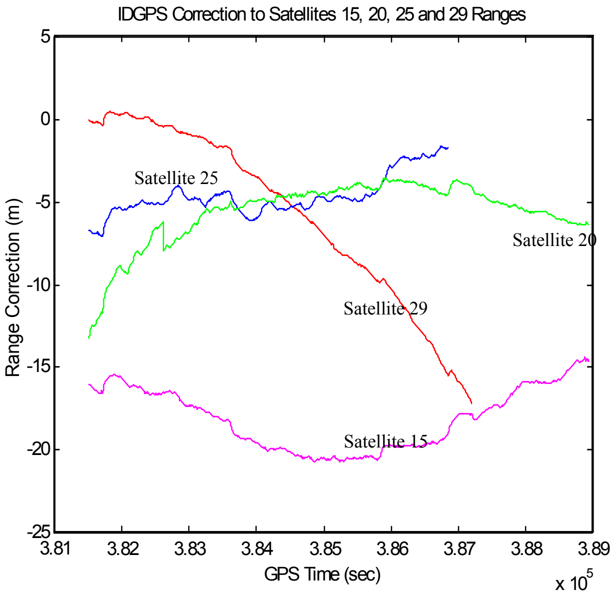

Figure 12: Range error corrections from the reference station (September 14)

Table 1 shows the improvement that was achieved by applying IDGPS correction to the uncorrected GPS data. It is evident from the Table that Inverse DGPS has improved the accuracy of the solution substantially.

The availability of the IDGPS solution is less than 100 percent due to large DOP in some cases. The large DOP is due to less number of common satellites between the reference station and remote receivers. The IDGPS applies correction only to those satellites, which are common in the reference and remote receivers. The reference station is set to have a cut-off elevation angle of 10 degrees to avoid large errors in the range measurements from the low elevation satellites. The remote receiver however, tracks some of those low elevation satellites. As a result sometimes the number of common satellites between the reference and remote receivers remains less, even when the remote tracks more satellites. To overcome this problem, the cut-off angle of the reference receiver is to be set to 5 degree or lower. This would improve the availability. But the IDGPS accuracy may deteriorate to some extent in that case.

Table 1: Performance improvement due to the use of IDGPS correction in static tests

Item	September 14, 2000		September 15, 2000	
	Before IDGPS	***After IDGPS***	***Before IDGPS***	***After IDGPS***
Duration	15 hours	15 hours	15.8 hours	15.8 hours
No. of samples	1744 (100%)	1681 (96.4%)	1819 (100%)	1801 (99.0%)
Sample frequency	30 sec/sample	30 sec/sample	30 sec/sample	30 sec/sample
Standard Deviation of Horizontal Position Error	14.3 m	1.9 m	10.7 m	1.6 m
Samples With Horizontal Position Error Less Than 5 m	38%	90%	49%	92%
Spread in Latitude	175.8 m	18.2 m	119.4 m	18.5 m
Spread in Longitude	172.3 m	29.9 m	106.6 m	20.5 m
Maximum horizontal error	174.8 m	19.0 m	117.6 m	12.2 m

Further static tests were carried out with the IDGPS system after tuning various thresholds. The performance of the IDGPS system repeated by reducing the spreads in latitude, longitude and the maximum horizontal error before correction. The availability of the IDGPS was also improved.

Mobile Test

A mobile test was carried out in the downtown of Singapore on September 20, 2000. A car, fitted with an IVE was driven in the city. Data was collected for approximately half an hour at a rate of 10 sec per sample. The IDGPS corrected the raw data from the mobile IVE. The map matching software used the corrected solution, whenever it was available and uncorrected solution, when corrected solution was not available. Table 2 shows the results of the mobile test.

Table 2: Mobile test results

Item	September 20, 2000	
	Before IDGPS	***After IDGPS***
Duration	1/2 hour	1/2 hour
No. of samples	70 (100%)	59 (84.3%)
Sample frequency	10 sec/sample	10 sec/sample
Position difference before and after IDGPS	12.89 m	

The table does not contain statistics about the absolute accuracy of the solution before and after IDGPS correction, as the true position of the IVE was not known. The positions were eventually matched on to a map, but the accuracy of the map itself is approximately 7 m. In addition, the map may correspond to the center of the road, whereas the car might have been driven on the side-lane of the road. Therefore, true position of the IVE at the instant of GPS and IDGPS solution time was not available. Therefore the analysis is done based upon the level of consistency of the solution before and after IDGPS.

From the table it can be seen that IDGPS was able to correct 84 percent of the solutions sent by the mobile receiver. The cause of not correcting in the remaining cases is mainly due to poor DOP. The standard deviation of the position solution before and after IDGPS correction for only those samples for which correction was made is about 13 m.

Figure 13 shows the trace of the field trial. The blue trace (dark shade) is before IDGPS correction and the green trace (light shade) is after IDGPS correction. The '*' symbol indicates the GPS or IDGPS derived position. The starting point of the field trial is assumed to be origin of the X-Y plot. The X axis of the plot shows the East-West spread of the trace the Y axis of the plot shows the North-South spread of the trace.

From the figure it could be seen that the trace is quite well defined by the GPS and IDGPS solutions. The IDGPS solutions are close to the GPS solutions most, but a few cases. As during the static cases it was proven that the IDGPS position is quite accurate, the difference between the GPS and IDGPS position can be considered to be the error in the GPS position.

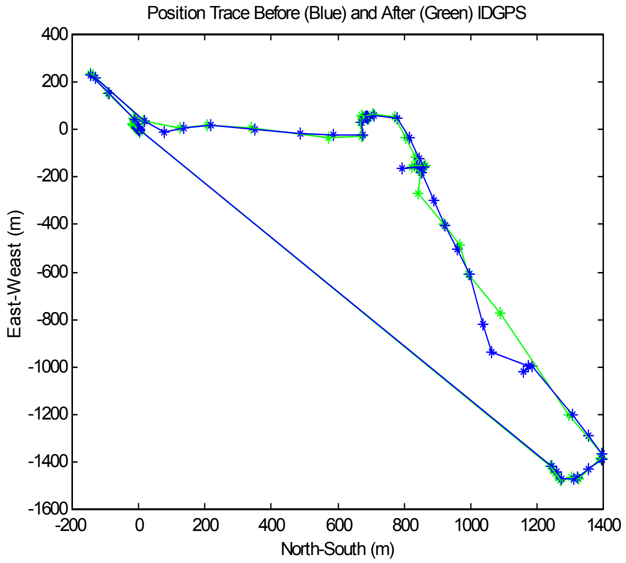

Figure 13: Position trace before and after IDGPS correction during the mobile test on September 20.

Figure 14 shows the difference between the GPS and the IDGPS position during the test.

The X-axis of the plot shows the GPS time, whereas the Y axis shows the difference. It can be seen that the difference between the two solution is less than 20 m most of the cases. However, in some cases the difference could be as large as 60 m. This is also evident in the traces in Figure 14. This indicates that the GPS position has such large errors in some cases and the IDGPS is able to correct them. This confirms the effectiveness of the IDGPS system in mobile condition as well.

CONCLUSIONS

An Inverse DGPS system was developed which showed signification improvement in accuracy compared to stand alone GPS receiver. The IDGPS solution was found to be less than 5 m in over 90% of the times compared to less than 50% times in case of stand alone GPS. This has also reduced the standard deviation of the horizontal position error from over 10 m before correction to less approximately 2 m after correction. These test results suggest that there is still a need for differential correction even in the absence of SA error, if the required accuracy from the system is to be good.

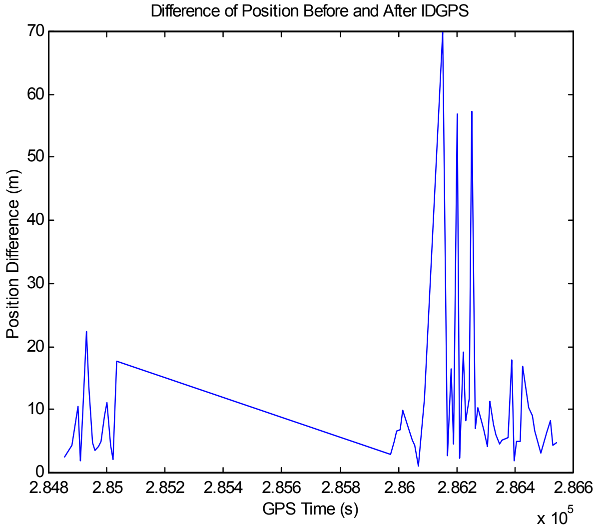

Figure 14: Position error differences between solutions before and after IDGPS correction during the mobile test

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