Integrated use of GPS and GLONASS in Support of the Redesign of Road Networks

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An integrated GPS/GLONASS system was employed in this study to support the re-design of road networks and the adjustment of traffic control. The system was used to update road maps, and to determine the velocity and acceleration of a test vehicle. The vehicle ran along the traffic stream at designated times of a day, for specific time spans, to identify traffic conditions in urban areas of uncontrolled intersections such as roundabouts. Issues addressed included: transformation of GLONASS satellite coordinates from PZ-90 to WGS-84, the presence of the receiver clock error in the GLONASS double-differenced measurements, and the impact of the carrier wavelength variation on the ambiguity resolution. Two tests were carried out in an urban environment using the combined GPS/GLONASS system. The first test included updating a road map of a test area by an RTK approach. Results were checked by comparing them with an accurate map of the area, previously determined by conventional methods. The second test comprised determining position, velocity and acceleration of a moving vehicle representing the traffic flow for a selected area. Different solution schemes were investigated, including: RTK, DGPS, and post-processing of phase measurements. The impact of GLONASS augmentation and the quality of GPS satellites on solution feasibility and accuracy were also examined. Test results showed the benefits of adopting the integrated approach. These included: improving productivity and economics of map production, and improving availability, integrity, and accuracy of determining the velocity and acceleration, linked to positions on the road networks.

KEY WORDS

1. GPS. 2. GLONASS. 3. Land. 4. Traffic Control

1. INTRODUCTION. Positions, velocity, and acceleration are valuable information for the design or redesign of road networks, and for evaluating and adjusting traffic control. Positioning is needed to update old maps of road networks, which constitutes a major time and cost consuming phase in road redesign. The use of fast positioning methods such as Real Time Kinematic (RTK) GPS is thus preferred, as it reduces fieldwork time and costs dramatically when compared to traditional methods, eliminating the need for the frequent instrument set-ups and traversing.

Determining velocity and acceleration, on the other hand, is important for monitoring traffic conditions in uncontrolled intersections such as roundabouts, which constitute the majority of the intersections in the small to medium size cities in the Arabian Gulf area. For instance, when using a test vehicle running along the traffic stream, at different times of a day (normal and peak), for different days (working days, weekends, and holidays), the velocity results when linked to different parts of the network would give precise details on the network traffic flow. Spatial linking of velocity and acceleration can be performed using the GPS-determined positions. This information, when stored in a database, is helpful for evaluating traffic flow, pointing to problematic spots, adjusting the traffic control system, defining the parts that need controlled intersections, the type of this control, and redesign of road networks based on actual demand.

Satellite visibility, however, is considered the main problem facing positioning and velocity determination by GPS in urban areas. For instance, in downtown areas, tall buildings obscure sky view. In residential areas, trees on roadsides form canopies that prevent continuous reception of the satellite signals. Integrating GPS and GLONASS represents an attractive approach for the resolution of this problem, since GLONASS increases the number of observable satellites. However, this integration has some problems related to the differences in the signal structure of the two systems, and the limited number of operational GLONASS satellites currently available.

2. AN INTEGRATED GPS/GLONASS SYSTEM.

A combined GPS/GLONASS system is more beneficial than GPS alone in mainly two cases. The first is in situations where less than four GPS satellites are being observed, such as in dense urban environments and under tree canopies. The second case was in using a point-positioning mode; since the trials were undertaken before Selective Availability on GPS was removed, GLONASS had pseudoranges of better accuracy. In addition, an integrated system has more speed and reliability in ambiguity fixing than the single frequency GPS (L1). Moreover, in cases where gaps exist due to ambiguity fixing failure, GLONASS augmentation resulted in faster recovery than GPS alone. Keong (1999) reported an improvement in availability by an amount of 8% when augmenting GPS by GLONASS measurements, but he also reported a small degradation of accuracy. He attributed this decrease in accuracy to a filter tuning problem or the additional noise in the GLONASS measurements. This is due to the fact that a much wider bandwidth is used in the channel design to receive the range of GLONASS frequencies. Another possibility for this cause is the temperature effects on frequency differences (Dodson *et al.*, 1998). In addition, the receiver measurement noise of the GLONASS L1 C/A code is found to be twice as noisy as that of GPS. This is in accordance with the fact that the wavelength of GLONASS code is double the length of that of GPS.

The process of integrating GPS with GLONASS has to take into account differences between the two systems. They differ in the time reference system, the coordinate reference frame and the signal multiplexing technique. GLONASS employs the technique of frequency division multiple access (FDMA) to distinguish the signals from different satellites versus the GPS technique of code division multiple access (CDMA). In addition, GLONASS has some minor problems – for instance, the presence of some anomalies in the broadcasted satellite navigation messages, such as inaccurate ephemerides, or faulty clock parameters. Fortunately, these errors can be detected by a simple [RAIM] algorithm (Misra *et al.*, 1996a). The following sections will describe the approach utilised in this study for processing GLONASS measurements with GPS, and treating the differences between the two systems.

2.1. *Transformation of GLONASS Satellite Coordinates into the WGS-84*.

Different models were developed to transform GLONASS satellite ephemerides from the GLONASS system frame (PZ-90) to the GPS frame (WGS-84). These models adopted a seven-parameter similarity transformation approach, employing: one scale, three rotations about the axes, and three shifts between the origins. The well-known models are given in Misra *et al.* (1996b), Rossbach *et al.* (1996), Spalding *et al.* (1997), and Bazlov *et al.* (1999). The first model determined the transformation parameters based on comparing synchronous GLONASS satellite ephemerides in both coordinate systems. However, these parameters lack accuracy since they were computed from GLONASS-broadcast ephemerides and not from the precise, post-processed ones. The last method, on the other hand, overcame this problem by using the straightforward approach of comparing absolute coordinates of ground-based, collocated stations, well determined in the GPS and GLONASS coordinate frames. These stations were only distributed within Russia and, therefore, the determined transformation parameters cannot be considered as global ones.

Differences in the computed satellite positions using the available transformation models are within the metre level (usually not exceeding 20 m). The impact of using any of these models, not necessarily the most accurate one, would only be visible in the single point-positioning mode. For the differential mode, the transformation errors are treated as orbital errors, which are almost eliminated in the differencing process. Thus, in practice, the differentially computed positions on the ground would differ by only a negligible fraction of a millimetre using either of these models. The transformation model adopted in this study was the one developed by Bazlov *et al.* (1999), as it is believed to be the most accurate. It is formulated as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{WGS\text{-}84} = \begin{bmatrix} -1{\cdot}1 \\ -0{\cdot}3 \\ -0{\cdot}9 \end{bmatrix} + (1 - 0{\cdot}12 \times 10^{-6}) \begin{bmatrix} 1 & -0{\cdot}82x10^{-6} & 0 \\ 0{\cdot}82x10^{-6} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{bmatrix}_{\mathrm{PZ-90}}, \quad (1)$$

where: $(\mathrm{X\ Y\ Z})^{\mathrm{T}}_{\mathrm{WGS\text{-}84}}$ is the position vector in the WGS-84 system, $(x\ y\ z)^{\mathrm{T}}_{\mathrm{PZ\text{-}90}}$ is the position vector in the PZ-90 system.

Unlike GPS, where the satellite ephemerides are defined by modified Kepler elements, GLONASS satellite coordinates are given in the form of position, velocity, and acceleration. Interpolation of the GLONASS satellite coordinates was thus carried out following the model described in the GLONASS Interface Control Document (ICD, 1995), using the Runge-Kutta method for numerical integration. A time interval of 15 minutes was employed as well as a one-second integration step width (following Habrich, 1998).

2.2. *Synchronising GPS/GLONASS Satellite Ephemerides and Measurements.* GLONASS uses the Soviet Union Universal Coordinated Time (UTC-SU) as its reference time frame, and broadcasts in its time standard GLONASS Time (GLONASST). The latter has an exact offset of three hours from the UTC-SU. The offset between the GLONASST and the UTC-SU is known to 50 nanoseconds, where the absolute difference between them is always less than one millisecond. The accuracy of the difference is known to the sub-microsecond level (Keong, 1999). The UTC-SU is, however, a discontinuous time scale, with leap seconds introduced as needed to follow the UTC. Thus, there is no integer-second difference between

GLONASST and UTC, keeping only the three hours shift (Misra *et al*., 1996a). The GPS system, on the other hand, uses the GPS time system, which leapt by 13 seconds from UTC (at the beginning of the year 2000). Therefore, when processing GLONASS data, epochs of GLONASS were transferred to GPS time frame by adding the integer number of seconds (+13).

2.3. *Carrier Phase Formulation and Ambiguity Resolution.* Each GLONASS satellite broadcasts using a different carrier frequency, and accordingly has its unique wavelength. The only exception is that the antipodal pair of satellites on 180 degrees difference of the argument of latitude share the same frequency. However, they cannot be simultaneously observed from the Earth's surface. Each of the GLONASS signals also experiences a different ionospheric delay, where these delays can be temperature-dependent according to the measuring conditions. The observation equation of GLONASS carrier phase measurements can be formulated as:

$$\phi_1^i = 1/\lambda^i \rho_1^i + 1/\lambda^i \mathrm{d}\rho_1^i + \mathrm{C}/\lambda^i (dT^i - dt_1) + N^i - 1/\lambda^i d_{ion} + 1/\lambda^i d_{trop} + \epsilon, \tag{2}$$

where:

ϕ_1^i is the carrier phase observation for the satellite (i) and station (1),
λ is the carrier phase wavelength,
ρ is the receiver-to-satellite range,
$\mathrm{d}\rho$ represents orbital errors,
C is the speed of light,
dT & dt are the satellite and receiver clock errors,
N^i is the carrier phase ambiguity (integer number),
d_{ion}, d_{trop} are the ionospheric and tropospheric errors,
ϵ is noise (including: multi-path, receiver noise, and any remaining errors)

The single difference equation, between two ground stations (1 & 2) and a common satellite *i*, can be written as:

$$\Delta\phi_{12}^i = 1/\lambda^i \Delta\rho_{12}^i + \mathrm{C}/\lambda^i (dt_1 - dt_2) + \Delta N_{12}^i - 1/\lambda^i \Delta d_{ion} + 1/\lambda^i \, \Delta d_{trop} + \Delta\epsilon. \tag{3}$$

The effect of ionospheric and tropospheric errors is reduced for short distances, where they can be modelled out. In this context, they will be neglected in the coming formulations as well as the noise term for the sake of simplicity. Accordingly, the double difference observation equation for the satellite pair (*i* & *j*) can be given as:

$$\nabla\Delta\phi_{12}^{ij} = 1/\lambda^j \Delta\rho_{12}^j - 1/\lambda^i \Delta\rho_{12}^i + C/\lambda^j (dt_1 - dt_2) - C/\lambda^i (dt_1 - dt_2) + \nabla\Delta N_{12}^{ij}, \tag{4}$$

which can be rewritten as:

$$\nabla\Delta\phi_{12}^{ij} = f^j/C\,\Delta\rho_{12}^j - f^i/C\,\Delta\rho_{12}^i + f^j(dt_1 - dt_2) - f^i(dt_1 - dt_2) + \nabla\Delta N_{12}^{ij}. \tag{5}$$

Thus, unlike GPS, the GLONASS receiver clock errors remain in the double differenced observation equation due to the different frequencies used by the GLONASS satellites. The receiver clock error can be eliminated when transforming the carrier phases to a mean frequency (f_m), which can be selected as the middle of the L1 GLONASS frequency band (Leick, 1998). It is assumed here that the terms (f_m/f^i) and (f_m/f^j) can be practically taken as unity. The double difference equation becomes:

$$\nabla\Delta\phi_{12}^{ij} \cong f_m/f^j\,\Delta\phi_{12}^j - f_m/f^i\,\Delta\phi_{12}^i =$$
$$f_m/C\,\nabla\Delta\rho_{12}^{ij} + f^j f_m/f^j(dt_1 - dt_2) - f^i f_m/f^i(dt_1 - dt_2) + f_m/f^j\,\Delta N_{12}^j - f_m/f^i\,\Delta N_{12}^i, \tag{6}$$

which yields:

$$\nabla\Delta\phi^{ij}_{12} \cong f_m/f^j\,\Delta\phi^j_{12} - f_m/f^i\,\Delta\phi^i_{12} = f_m/C\,\nabla\Delta\rho^{ij}_{12} + f_m/f^j\,\Delta N^j_{12} - f_m/f^i\,\Delta N^i_{12}. \tag{7}$$

The problem with this formula is that the integer nature of the ambiguities could not be preserved. The outcome solution is therefore similar to the GPS float solution, which is expected to give accuracy only at the deci-metre level. Alternatively, when scaling the phase observations from cycles to distance by multiplying each satellite single difference phase measurements by its wavelength, and substituting into equation (3), the receiver clock error cancels out, and the double difference equation can be written as:

$$\nabla\Delta\phi^{ij}_{12} = \lambda^j\Delta\phi^j_{12} - \lambda^i\,\Delta\phi^i_{12} = \nabla\Delta\rho^{ij}_{12} + (N^j_1 - N^j_2)\,\lambda^j - (N^i_1 - N^i_2)\,\lambda^i. \tag{8}$$

After some mathematical derivation, the ambiguity term can be formulated as (Habrich, 1998):

$$(N^j_1 - N^j_2)\,\lambda^j - (N^i_1 - N^i_2)\,\lambda^i = -(\Delta N^i_{12} - \Delta N^j_{12})\,\lambda^i - (N^j_1 - N^j_2)\,(\lambda^i - \lambda^j), \tag{9}$$

and the double difference equation becomes:

$$\lambda^j\Delta\phi^j_{12} - \lambda^i\Delta\phi^i_{12} = \nabla\Delta\rho^{ij}_{12} - (\Delta N^i_{12} - \Delta N^j_{12})\,\lambda^i - (N^j_1 - N^j_2)\,(\lambda^i - \lambda^j). \tag{10}$$

Finally:

$$\nabla\Delta\phi^{ij}_{12} = \nabla\Delta\rho^{ij}_{12} - \nabla\Delta N^{ij}_{12}\,\lambda^i - \Delta N^j_{12}(\lambda^i - \lambda^j) \tag{11}$$

Equation (11) represents the ambiguities in two terms, an integer part $\{\nabla\Delta N^{ij}_{12}\,\lambda^i\}$, which is similar to GPS, and an additional part $\{(N^j_1 - N^j_2)\ (\lambda^i - \lambda^j)\}$, which would change the integer nature of the whole ambiguity term. Thus, in order to determine the integer ambiguities, the latter term has to be resolved first. This approach was adopted in this study to process GLONASS measurements and to resolve the carrier phase ambiguities.

Two scenarios were set out in the adopted approach. The first one was to consider only GLONASS measurements (although it is a remote case due to the lack of a sufficient number of GLONASS satellites most of the time, and GLONASS measurements are basically needed as an augmentation to GPS). In this case, the float solution using equation (7), which transforms the carrier phases to a mean frequency, was initially applied to determine the unknown point position to the deci-metre level. This position was next used to reconstruct the approximate single difference ambiguities using equation (3), estimating also the receiver clock error as a nuisance parameter. Although the initial single difference ambiguities would be accurate only to a few cycles, when they were multiplied by the small value of the wavelength difference, they would give a good estimation of the last term in equation (10), usually accurate to less than 0·1 cycle. The integer ambiguity term can then easily be found. The ambiguities of satellite pairs with small wavelength differences were resolved first to reduce error possibility. An iterative approach was used to ensure convergence of results. On the other hand, in the general case of using GPS, GPS measurements can be added to find the float initial solution. Although this approach sounds computationally intensive, with the rapid increase in computer speed and technology, the method is in practice fast and reliable.

3. AVAILABILITY OF GLONASS SATELLITES.

The main problem currently facing the use of GLONASS is the low number of operational satellites available. For instance, there were only nine operational satellites at the beginning of the year 2000. This situation resulted in observing as few as two satellites for long periods, while observing three to six satellites was limited to only one to two hours. The problem was also magnified as the good satellite windows were moving in such a way that they were separated by as much as several hours between one day and the following one. For many days, the good window did not come during the working day. In other situations, there was only one visible satellite. Moreover, six out of the nine operational satellites were uploaded in 1995. This means that by the end of the year 2000 their service life would nearly be over, leaving only three operational satellites in space. There is a possibility however of launching more satellites by the end of the year 2000. If this happens, it would be a temporary relief for the system users.

4. TESTING OF THE INTEGRATED GPS/GLONASS SYSTEM.

Two tests were carried out to evaluate the performance of the integrated GPS/GLONASS system and software, and to assess its applicability for the proposed applications in an urban environment. The first test included updating a road map of a test area. The second test comprised determining velocity and acceleration of a test vehicle, linked to positions on a road network.

4.1. *Testing the Integrated System for Updating Road Maps.* In this test, a GPS/GLONASS system was used for updating a road map of an area of approximately 700 m by 1 100 m. Figure 1 shows the layout of the test area, which had been mapped before using a total station to provide a general reference for checking GPS/GLONASS results. The RTK positioning technique was utilised, and its computed positions were used to check the road map on site, and update it later in the office. The reference receiver occupied a second-order control station close to the test area. To accelerate mobility of the roving receiver during mapping of the road perimeter, the antenna was mounted on a telescopic arm fixed on a bicycle.

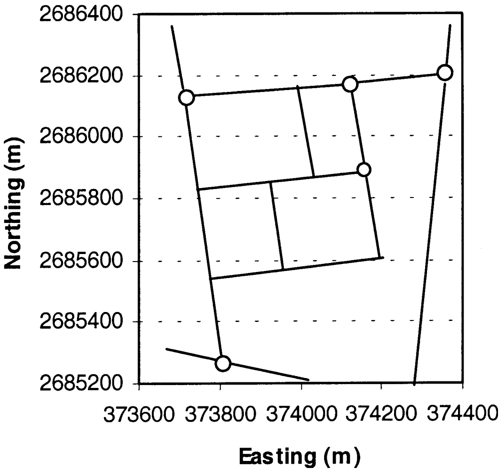

Figure 1. Layout of the test area.

The bicycle was provided with two small wheels attached to each of the front and back wheels to provide stability to the bicycle, and to prevent any sudden movement that could result in loss of signal lock. The telescopic arm was aligned in a horizontal direction, and was used to position the antenna above the hovered point on the road as the bicycle was moving on the sidewalk. The hand controller was fastened on the steering bar to ensure maximum comfort to the surveyor. A cheap laser pointer was mounted vertically beneath the antenna to point at its corresponding location on the ground. It was thus used to ensure that the recorded points were precisely positioned on the mapped roads.

An alternative approach was also tested to minimise possible vibration of the antenna due to swinging of the telescopic arm holding it. In this approach, the antenna was mounted directly on the bicycle using a rigid post (approximately one metre high). The telescopic arm was only used here to hold the vertical laser pointer. The telescopic arm was set to a constant value of 78 cm (which could be varied according to sidewalk conditions). An approximate azimuth using a magnetic compass was manually recorded at each point to translate the antenna position, using the known offset distance of the telescopic arm, to the road points that were selected using the vertical laser pointer.

The GPS/GLONASS equipment used in the test consisted of a pair of Sokkia GSR2400 receivers (manufactured by Ashtech Inc.), with a UHF radio modem with a power of 2 Watts. The GPS observables used were single frequency (L1). The data acquiring and processing rate was set to one second, but positions were stored by the observer whenever needed. A cut-off elevation mask angle of 10 degrees was implemented. The area was covered in less than a day, while with a traditional total station procedure it would need twice as much time. Traditional traversing was also eliminated since only one reference station was operating for the whole survey. In general, employing GPS for updating the existing map when compared to traditional methods resulted in significant reduction of labour, fieldwork time and cost, and increased productivity, with no traffic disturbance. The accuracy of the survey is given in Table 1 in the form of the standard deviations (SD) of the X, Y, and Z position components. As shown, the average SD for all components did not exceed 2 cm. This level of accuracy is very satisfactory, and no greater accuracy would be expected from the traditional methods (El-Mowafy, 1999)

Table 1. Standard Deviations of the GPS+GLONASS estimated point coordinates.

SD	Minimum (cm)	Maximum (cm)	Average (cm)
σ_X	0·20	4·51	1·28
σ_Y	0·10	2·80	1·16
σ_Z	0·30	3·72	1·75

GLONASS was fundamental to achieving the above results. For some parts of the road, particularly close to trees and large road signs, some GPS satellite signals were obscured. For instance, during the test, seven GPS satellites were generally available in clear areas, but this frequently dropped to four satellites under tree canopies or close to buildings. Without GLONASS, which added measurements from two to three satellites, RTK positioning was not possible. In some places, although five GPS satellites were observed, the PDOP was too high (reaching 12·5) to permit continuing with GPS alone. However, when supplemented by GLONASS satellites, the PDOP dropped to 4·7, allowing accurate positioning to resume.

Since the area had been previously mapped using a total station, a quick comparison of the map details showed that there were no large discrepancies between the GPS and the total station solutions. Direct comparison between the integrated GPS/GLONASS system and the total station was only possible at a few locations (seven temporary control points defined by nails fixed on the curb). The differences were generally less than 3 cm. These differences could be attributed to errors either in the GPS/GLONASS system, the total station, or both. However, these differences showed that both methods were compatible, within the degree of accuracy accepted for this application.

4.2. *Testing the Integrated System for Traffic Management.* In this test, the rover antenna was mounted on the roof of a car. Position, velocity and acceleration information were recorded for the purpose of monitoring traffic conditions in an area of uncontrolled intersections (roundabouts). The goal was to extend the application, and perform similar runs in a data campaign, running the test vehicle along the traffic stream, at different times of day (normal and peak), and on different types of days. The collected velocity and acceleration would be stored in a database and categorised according to time and value, and linked to their location on the network using the GPS positioning data. These data could then be related to certain directions of the intersections, as each one can be identified by a pre-defined extent along the east and north directions. The results would give precise details on the network traffic flow. Road and traffic network designers can then evaluate traffic flow graphically and numerically, identify problematic spots, adjust the traffic control system, define locations of required controlled intersections, and the type of control required.

4.3. *Test Description.* The test was carried out using RTK methods, storing both the phase and code measurements in the internal memory of the receivers. The objective was to perform an additional post-processed DGPS, as well as accurate positioning using phase measurements. The reference antenna was located less than 1·5 km from the farthest point of the vehicle route. Figure 2 shows the test area

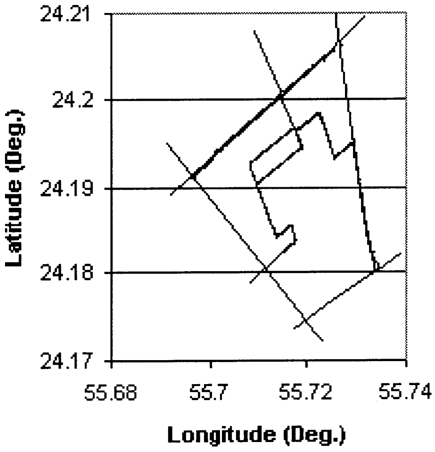

Figure 2. Test area.

Figure 3. The satellite window.

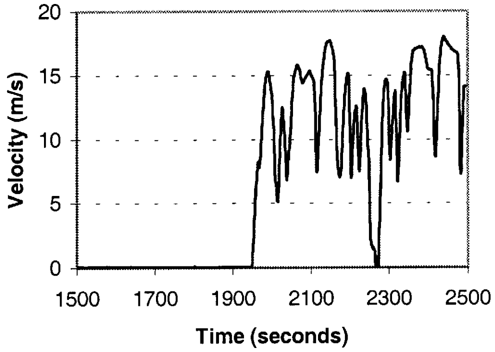

Figure 4. Velocity data.

selected in the city of Al-Ain. The area contains mostly one- or two-storey buildings. The satellite window during testing was good in general, giving an opportunity to observe a minimum of six GPS satellites in open sites, in addition to four GLONASS satellites. However, all roads in the test area have trees on both sides of the sidewalks. The trees vary in height, ranging between four and seven metres. This situation created major tree canopies for the moving vehicle, which resulted in several cycle slips. Figure 3 shows the satellite window of the test using a zero elevation cut-off angle at both the reference and rover antennas (shown by different grayscales). As depicted in the figure, most of the satellites having elevation of less than 50 degrees suffered from loss of signals for some periods, but they were restored after a short while. This situation resulted in the need to re-initialise the ambiguities regularly. In these cases, the vehicle had to stop in nearby locations with good satellite windows to re-initialise the ambiguities for the post-processed solution of phase measurements.

4.4. *Test Results.* The carrier phase ambiguities were determined using an On-The-Fly (OTF) approach, applied in agreement with the concepts given in Teunissen *et al.* (1997). GLONASS double difference measurements and ambiguities were treated using the approach based on equation (11). All ambiguity resolutions were successful. Figures 4 and 5 show an example of the velocity and acceleration output,

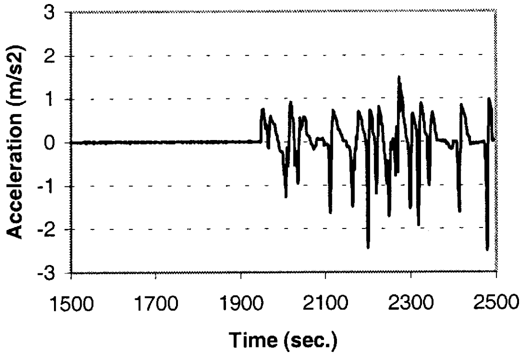

Figure 5. Acceleration data.

Table 2. Accuracy of RTK Method.

SD	Minimum (cm)	Maximum (cm)	Average (cm)
σ_E	0·20	1·18	0·94
σ_N	0·40	1·75	1·53
σ_h	0·60	7·82	2·35

respectively, for a part of the test, which was not interrupted by the need for the ambiguity re-initialisation. The velocity elements along the X, Y, and Z directions were determined as parameters in the state vector of the Kalman filtering solution. The acceleration was determined as the differential change of velocity with respect to time. The velocity results were satisfactory when compared to the recorded odometer results. Different dynamic phases can be shown from the Figures 4 and 5, including: accelerating, steady speed, decelerating, and stopping. All of these data were linked to the vehicle positions. They were later associated with the road intersections and categorised according to time and value at each direction of the intersections for further study of the traffic flow conditions.

Table 2 gives the positioning accuracy of the RTK processing. The standard deviations of the plane coordinates were generally less than 2 cm. However, as expected, the height accuracy was less than that, as its average standard deviation reached 2·35 cm. The results of the different passes of the vehicle through the same trajectory showed that the repeatability of the RTK was very good.

To test the performance of different GPS scenarios under the same test conditions, a post-processing differential code analysis was carried out. The rationale behind testing this scheme was that it is usually applicable when observing a limited number of satellites, where phase positioning and rigorous ambiguity resolution are not normally feasible. On the other hand, the sub-metre or the metre accuracy expected from this approach can be considered satisfactory for the major cases of the investigated application. Two separate runs were performed utilising the differential code approach; the first one used only GPS data, and the second one used combined GPS/GLONASS measurements. Statistics of this test are given in Table 3 in the form of the standard deviations of the X, Y, and Z coordinates, as extracted from the processing results. The table shows that, although the inclusion of GLONASS satellites improved the satellite geometry, as depicted by lowering the PDOP value of

Table 3. Comparison between DGPS by GPS and GPS/GLONASS separately.

SD (m)	DGPS (GPS)	DGPS (GPS + GLONASS)
σ_x	0·693	1·133
σ_y	0·406	0·692
σ_z	1·444	2·623
PDOP	1·840	1·470

Table 4. Statistics of the Phase and DGPS solution differences.

Difference	Minimum (m)	Maximum (m)	Average (m)	SD (m)
X	0·010	3·223	0·229	0·216
Y	0·005	2·880	0·626	0·292
Z	0·001	4·346	0·286	0·208

Table 5. Accuracy Comparison between GPS Standalone and GPS + GLONASS.

SD (cm)	GPS Alone	GPS + GLONASS
σ_{min}	0·241	0·506
σ_{max}	3·140	4·501
$\sigma_{average}$	1·141	2·315

the last row in the table, the GPS/GLONASS combined solution gave less accurate results for all position components compared to GPS standalone. The standard deviations of the combined solution ranged between 0·69 and 2·622 m, while with GPS it ranged between 0·41 and 1·44 m. This can be attributed to the noisy measurements of GLONASS. Similar results would be expected if a real-time DGPS approach was considered.

To assess differences in positioning by the differential code approach and the accurate phase solution, their computed positions were compared. The differences in the X, Y, and Z directions and their standard deviations are listed in Table 4. In general, the average differences ranged between 0·229 m and 0·626 m, with standard deviations of less than 0·3 m.

In another scheme, the phase measurements were first post-processed using only GPS measurements, and were then processed after being augmented by GLONASS measurements. The objective was to evaluate the impact of adding GLONASS data on the accuracy of the final solution. The minimum, maximum, and average position SD (computed as the square root of squared SD of the X, Y, and Z coordinates) are given in Table 5. As shown in the table, GPS data gave better results compared with the dual GPS/GLONASS measurements. This may be also attributed to the fact that the GLONASS phase measurements were noisier than the GPS data. This result agreed with previous tests carried out under different satellite configurations.

The importance of augmenting GPS by GLONASS was, however, proven when observing fewer satellites. For instance, assuming observing only four satellites, considering for example the satellites number (4, 16, 18, 19), which gave an average PDOP of 3·2. The ambiguity OTF search algorithm failed in determining the set of the correct integer ambiguities, and thus positioning was not possible. However, when as few as two GLONASS satellites were added to the data, ambiguity resolution occurred successfully. On the other hand, the distribution and quality of GPS satellites also played a vital role in achieving a successful solution. For instance, when eliminating satellite number 4 and including satellite number 27, the geometry improves (PDOP becomes 2·2 on average) and ambiguity resolution was possible, but in the post-processing mode.

Finally, although the positioning accuracy of the combined GPS/GLONASS system was at the centimetre level, which in practice was accepted for the purpose in hand, this might not be so for applications requiring millimetre accuracy, for instance, attitude determination, deformation analysis, and machine monitoring. More studies are needed to investigate this issue. Nevertheless, considering the results of this study, it is safe to say that GLONASS measurements are certainly very useful in situations whenever an insufficient number of GPS satellites are available either during ambiguity resolution or positioning. However, when there is a sufficient number of GPS satellites capable of doing either tasks, it is recommended to depend on GPS measurements solely, and neglect GLONASS.

5. CONCLUSIONS.

The results show the benefits of employing satellite-based systems in supporting the redesign of road networks and traffic management in urban areas. These benefits include: improved productivity and thus reduced cost for updating road maps and evaluating designated samples of the traffic flow. An integrated GPS/GLONASS system provides good availability and integrity when observing few GPS satellites in an urban environment. A reliable approach was presented to handle the problem of the existence of the receiver clock errors in the double differenced GLONASS measurements, and finding the correct integer phase ambiguities. The approach is applicable for real-time applications using the RTK method, and in post-mission analysis.

The accuracy of GPS measurements is better than using a dual GPS/GLONASS system. Therefore, use of GLONASS measurements is only recommended when observing an insufficient number of GPS satellites either during ambiguity resolution or positioning. When there is a sufficient number of GPS satellites to perform either task, it is recommended that only GPS is used. A major concern regarding GLONASS is the low number of operational satellites, and the possibility of this number decreasing substantially by the end of the year 2000, unless a major launch of new satellites takes place. In situations where few satellites are visible, the DGPS approach was, however, feasible in order to obtain positions at the decimetre level, which is sufficient for the proposed application.

ACKNOWLEDGEMENTS

The financial support of the Research Council of the United Arab Emirates University is gratefully acknowledged. Thanks are also extended to Mr. Rohit Anand and Sokkia Gulf Inc. for their help in providing some of the equipment used.

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