DEVELOPMENT AND TESTING OF A REAL-TIME INTEGRATED INS/DGPS

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ABSTRACT

In this paper, the prototype development of a real-time georeferencing system is described. It consists of a navigation grade strapdown inertial system (INS) which is integrated with a receiver of the Global Positioning System operating in differential pseudo-range mode (DGPS) with a master station receiver. Such a system can be considered as the core of a real-time mapping system because it provides precise position and attitude as a function of time and, thus, allows the georeferencing of analogue and digital cameras and of multi-spectral scanners. After briefly discussing the constraints imposed on system design by the requirement for real-time operation, the chosen system configuration and its hardware and software implementation are outlined. To verify the system design and evaluate the accuracy achievable, a number of kinematic tests have been conducted. These test data are analyzed with respect to accuracy and operational reliability. In terms of accuracy, standard deviations are at the meter level for position and at the centimeter level for velocity. Since an independent attitude reference was not available, no definite statement on absolute attitude accuracy can be made. However, the relative accuracy compared to post-mission attitude results achieved with carrier phase data are at the level of 10 arcseconds for pitch and role and at the level of 5 arcminutes for azimuth. This indicates that pitch and roll are hardly affected by noisy position updates while the azimuth deteriorates by about one order of magnitude. In terms of reliability, results show that the integrated real-time data show error spikes which are not visible in the individual data sets. Some possible explanations for these spikes are given, but further investigations are needed to clarify this issue and eliminate these spikes by an appropriate real-time procedure.

1. INTRODUCTION

During the past five years, direct georeferencing of remote sensing devices by an integrated INS/ has been thoroughly tested and has resulted in exterior orientation parameters of high precision, see for instance Schwarz et al (1993), Schwarz (1995), El-Sheimy (1996), Scherzinger (1997), Toth (1997), Skaloud et al (1998). The position of a CCD camera on a moving vehicle, for instance, can be determined with a standard deviation of better than 0.1m, its pitch and roll with about 10 to 15 arcseconds, and its azimuth with about 30 arcseconds. Similar results are achievable in airborne mode, although positioning accuracy may be slightly worse. For many applications, direct georeferencing allows more flexibility because it does not require ground control nor a pattern of overlapping images. It will therefore be more efficient and more economical than standard procedures.Typically, INS/DGPS integration is done in post-mission mode and can therefore make use of precise GPS carrier phase data. For many remote sensing and mapping applications, this mode is preferable because there is no need for a real-time use of the data. Thus, high positioning accuracy can be achieved which, in turn, will result in tighter updates for the inertial data. In addition, data gaps and error spikes are more easily detected and resolved because of the possibility of combining a forward and a backward filter.

There are, however, some emerging applications, such as environmental monitoring, forest fire control, and right-of-way corridor mapping that would greatly benefit from real-time georeferencing. In most of these applications, operational reliability and fast turn-around times are more important than highest possible accuracy. Thus, GPS carrier phase data are not needed and can be replaced by differential pseudo-range measurements. This has the advantage that real-time ambiguity resolution is not necessary which will result in much higher operational reliability of the integrated system. The positioning accuracy achievable with such a system is at the level of 1-3 m.

This positioning accuracy has to be matched by a commensurate real-time attitude accuracy. Depending on flying height and sensor characteristics, the attitude accuracy required would typically be in the range of a 1-5 arcminutes, see Schwarz et al (1995) for details. The objective of this study is therefore the design, implementation, and testing of a real-time system with standard deviations of 1-3 m in position and 1-5 arcminutes in attitude. The following sections briefly describe the development and testing of such a system which is based on inertial strapdown technology and differential GPS. Testing of the prototype system has been done in a road vehicle. Tests in airborne mode are anticipated in the near future.

A system of this type can provide georeferencing information for a variety of remote sensors, such as analogue and digital cameras, multi-spectral systems, scanning lasers, or SAR. Typically, the information is obtained in digital form and can directly be used in real-time processing. It can also be used for sensor stabilization to avoid for instance image blurring. In such a case, the Inertial Measuring Unit (IMU) can be directly mounted on the remote sensor or its platform, and stabilization could be achieved by feedback loops.

2. SYSTEM DESIGN AND IMPLEMENTATION

2.1 Real-Time Requirements

Compared to post-mission integration of INS/DGPS data, there are additional constraints that have to be considered when implementing a real-time integration. They usually result in a more complex system structure and in reduced accuracy as compared to a post-mission approach. The additional design requirements can be subdivided into three major groups:

- Accurate time synchronization of all sensors
- Time-efficient and stable algorithms
- Real-time fault detection and quality control.

Time synchronization is usually done by using the GPS Pulse per Second signal (PPS) and slaving all other time signals to it. Although the PPS signal is very accurately defined, the time delays in and between systems are not and give rise to a number of errors. In addition, there may be time tagging delays due to the priority rating of the computer interrupt service routines (ISR) and real-time computer clock reading errors; for details, see Schwarz and El-Sheimy (1996). Most of these errors can be eliminated in static mode, and can be reduced in post-mission processing. In real-time mode, they will result in discrepancies between the INS and DGPS results and, thus, contribute directly to the error budget of the integrated system.

The integration of high rate DGPS and INS data via centralized or decentralized Kalman filters is a time-consuming process which usually has to be done within the period defined by the GPS data rate. The integration usually runs on the computer of the roving system and the demands for fast data communication and processing are very high. This also applies to the data transmission between the master and the roving receiver and the interpolation of time-delayed master station data. In addition, stability of the algorithm in extreme situations is more important than highest possible accuracy of the results. Thus, processing speed is not the only concern. Algorithm structure is at least as important and the selection of robust filter parameters is not far behind.. These problems are not critical in post-mission processing. They can therefore not be identified by processing logged data in 'real-time mode'.

Fault detection in a real-time system is extremely important because it can prevent disasters in the worst case and save considerable costs in the best case. In INS/DGPS integration, fault detection is usually not a problem because the output of the two independent subsystems can be directly compared. and any malfunction can be detected in real time. This is most easily done by running separate Kalman filters for each subsystem which interact from time to time. It is more difficult to design an effective real-time quality control process which issues a warning when the required system accuracy cannot be guaranteed any more with a prescribed level of confidence. In general, quality control requires a certain amount of expert knowledge built into the system which is combined with information on the measurement process to issue a warning to the operator. Again, this issue is not critical as long as data are logged and processed in post-mission mode.

In general, real-time systems operate under the maxim that there is no second chance if something goes wrong.. Thus, reliability is more important than accuracy. This principle has considerable consequences for system design and algorithmic structure.

2.2 System Configuration

The considerations discussed in the previous section influenced the system design shown in Figure 1. The hardware consists of two major components, the master station and the rover station. At the rover station, a Lunchbox 486/66 personal computer is used to collect GPS and INS raw measurements and GPS corrections from the master station, and perform DGPS and DGPS/INS integration computations. GPS raw measurements and the corrections are collected through RS232 serial communication ports (COMs). A SS1000 ARINC board is used to interface the IMU and the computer. The INS and GPS data streams are time-synchronized by Pulse Per Second (PPS) signals from the GPS receiver through a parallel communication port (LPT).

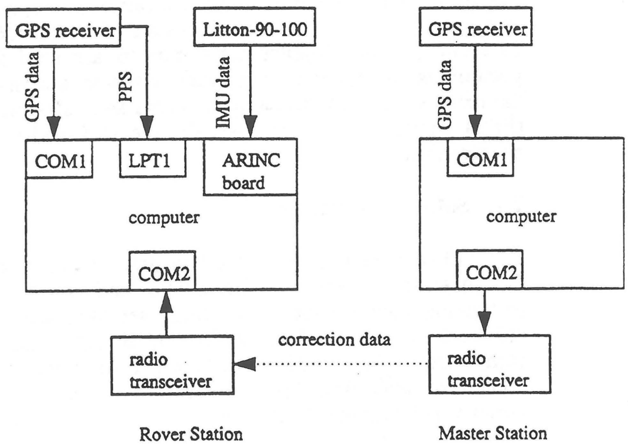

Figure 1: System Configuration

At the master station, a 486/66 personal computer is used to collect GPS raw data and to calculate the corrections to the C/A code pseudorange and Doppler measurements. The corrections are transmitted from master station to rover station by a Radio Data Link System (RDLS). The system consists of two antennas, two radio transceivers, a Base Station Data Link Control (BDLC), and a Mobile Radio Modem (MRM). The correction data is sent to the radio transceiver through a RS232 serial communication port with a Baud rate of 9600. The radio transceiver transmits the data modulated by BDLC at an UHF frequency with a power of 25 watts. At the rover station, the transmitted radio signals are received and demodulated by another radio transceiver and sent to the computer through a RS232 port with a Baud rate of 9600. The design of this configuration is described in more detail by Zhang (1995). It should be noted that the RDLS was used for convenience, i.e. it was available, rather than necessity. Its function could be taken over by any real-time DGPS service.

2.3 System Hardware

Inertial Measurement Unit (IMU)

One of the key hardware components of the real-time system is the Inertial Measurement Unit. An LTN-90-100 IMU is used as the INS. The LTN-90-100 is a medium accuracy inertial reference unit. The IMU sensor assembly consists of a precision mounting block with three Litton A-4 linear accelerometers in one triad module, one high voltage power supply, and three LG-8028B laser gyros (Litton, 1984). The IMU interface is in the industry ARINC 429 standard. It outputs navigation parameters or, as a specific feature of the 90-100 system, the raw measurements. Depending on the application, the medium accuracy system could be replaced by a low accuracy system; for details see Skaloud et al (1997).

SS1000 ARINC Board

To reduce the host computer burden, a special purpose board was designed which is inserted in a bus slot of the computer. The SS1000 ARINC board loads the data from the IMU and writes the data to its local dual port memory.

GPS Receivers

GPS receivers used throughout the tests are AshTech Z-XII receivers which are dual frequency, 12-channel receivers. This receiver outputs C/A code pseudorange, carrier phase and phase rate on L1, and P-code pseudorange, carrier phase, and phase rate on L2. In the real-time system, 0.5 Hz C/A code pseudorange and Doppler measurements are used for GPS positioning computation. In addition to raw measurement data, the receiver also outputs navigation data and Pulse Per Second (PPS) signals which are used for the INS and GPS data synchronization.

2.4 Software Structure

The software integration of the two data streams is done by decentralized filters for the DGPS and the DGPS/INS navigation computations, for details see Wei and Schwarz (1990). In the DGPS Kalman filter, three GPS position error components, three GPS velocity error components, and a relative receiver clock bias and drift are modeled in the state vector which is given by Equation 1.

$$x=\left(\delta x_r^e, \delta y_r^e, \delta z_r^e, \delta \dot{x}_r^e, \delta \dot{y}_r^e, \delta \dot{z}_r^e, \delta b_{clk}, \delta \dot{b}_{clk}\right) \quad (1)$$

where

x: the system state vector;

$\delta x_r^e, \delta y_r^e, \delta z_r^e$: rover station position errors in the e-frame;

$\delta \dot{x}_r^e, \delta \dot{y}_r^e, \delta \dot{z}_r^e$: rover station velocity errors in the e-frame;

δb_{clk}: receiver clock bias;

$\delta \dot{b}_{clk}$: receiver clock drift.

and the e-frame is WGS84.

The velocity errors and clock drift are modeled as first-order Gauss-Markov processes. Single differenced C/A code pseudorange and Doppler observations are used for positioning calculations.

In the master Kalman filter, INS position errors, INS velocity errors, misalignments, gyro drifts and accelerometer biases are modeled, see Zhang (1995). The 15 state model is shown in Equation 2.

$$x=\left(\varepsilon_x^e \varepsilon_y^e \varepsilon_z^e \delta x^e \delta y^e \delta z^e \delta v_x^e \delta v_y^e \delta v_z^e d_x^b d_y^b d_z^b b_x^b b_y^b b_z^b\right) \quad (2)$$

where

$\varepsilon_x^e \varepsilon_y^e \varepsilon_z^e$: three misalignment errors in the e-frame;

$\delta x^e \delta y^e \delta z^e$: three position errors in the e-frame;

$\delta v_x^e \delta v_y^e \delta v_z^e$: three velocity errors in the e-frame;

$d_x^b d_y^b d_z^b$: three gyro drifts in the b-frame;

$b_x^b b_y^b b_z^b$: three accelerometer biases in the b-frame.

where (b) is the body frame of the INS. Gyro drifts and accelerometer biases are modeled as first-order Gauss-Markov processes.

The actual measurements are the misclosures of the position and velocity between GPS and INS after the lever arm corrections have been made. For this configuration, the INS outputs high-rate navigation data to the master filter. GPS-derived position and velocity are fused into the integration filter periodically to update the estimated INS errors. This eliminates the long-term INS system errors effectively. Before the integration takes place, the GPS solution validity has to be checked.

3. TESTS AND RESULTS

3.1 Reference Solution

Both static and kinematic tests have been conducted to verify the system design and assess the system performance. To do this, a reference of superior accuracy is needed. This is easy to obtain for the positioning component by recording GPS carrier phase data during the test and by comparing the real-time results to the post-mission results obtained with carrier phase data. It is more difficult for the attitude data. An attitude reference of superior accuracy was not available. However, the GPS carrier phase solution will provide position and velocity updates of superior accuracy to the integration process which normally should result in an improvement of the attitude parameters. Thus, a comparison between the real-time results and the post-mission results achieved with carrier phase data in post-mission will provide a relative measure of attitude accuracy. It will also answer the question to what extent the use of carrier phase data will improve the accuracy of the real-time results.

During the tests, both GPS and IMU raw measurement data was recorded. In post-mission processing, GPS carrier phase data has been used for GPS positioning calculation. The derived position and velocity are integrated with INS. The KINGSPAD software used for post-mission processing was developed at the University of Calgary. For fixed ambiguities, the kinematic positioning accuracy is typically at the 10 cm level.

In the following, only selected results of these tests can be presented. For all details, reference is made to Sun (1998) where a more extensive documentation of the results is given.

3.2 Static Test

A number of static tests were conducted on the roof of the Engineering Building at the University of Calgary. Because of the limitations of a static test, system performance with respect to the real-time requirements, listed in Section 2.1, could not be assessed. Despite this limitation, such a test provides a first check on hardware and software performance and provides baseline statistics for a benign environment.

The antennas of both the master station and the rover station receivers were installed on pillars whose coordinates are well known. The LTN-90-100 IMU was put close to the pillar on which the rover station antenna was installed. The offset between the IMU center and the receiver antenna phase center was surveyed and put into the system. During the static test, 7 to 8 satellites were observed at all times. Thus, the PDOP varied only in a small range, from 1 to 1.8, indicating excellent receiver-satellite geometry. In such a situation, it can be expected that the position and velocity results will be dominated by the DGPS accuracy. Thus, there should be little difference between the DGPS solution and the integrated INS/DGPS solution.

That this is indeed the case can be seen from the statistics listed in Tables 1 to 3. In general, they are at the expected accuracy level. The bias terms are small for the horizontal positions (dm), the horizontal velocities (mm/s), and pitch and roll (0.1 arcsecond). Typically, the root mean square estimates (RMS) are an order of magnitude larger, i.e. m, cm/s, and arcsecond for the same parameters. When compared to the horizontal errors, the height error and the vertical velocity error are larger by a factor of two or three, again an expected result. The statistical results for the DGPS solution and the INS/DGPS solution are, in general, of the same order of magnitude. Similarly, when comparing the individual trajectories (position, velocity, attitude) for the two solutions, there are no significant discrepancies.

There are, however, two results that seem not to fit the pattern and need some discussion. First, the INS/DGPS results for latitude and height are considerably poorer than the DGPS-only results. This should not be the case. It was found that this was due to a weighting problem in the Kalman filter that was subsequently eliminated. Second, the azimuth drift of the system for the integrated solution is about double the size of the typical azimuth error of the INS-only solution for this system. Although puzzling at first, this can be explained by analyzing the update procedure during alignment. Azimuth accuracy during alignment is mainly affected by the quality of the velocity updates used. The DGPS velocity error shows considerable multipath and is in general larger than the INS velocity error in stationary mode which is normally used for the attitude estimate at alignment. This means that the azimuth drift is not as well estimated by DGPS velocity updates as by INS zero velocity updates.

Table 1: Position Error Statistics (Static Test)

Statistic	Mean (m)		RMS (m)	
Error in	DGPS	DGPS/INS	DGPS	DGPS/INS
Latitude	-0.09	0.08	0.63	1.03
Longitude	-0.16	-0.24	0.46	0.45
Height	0.76	0.72	1.86	2.42

Table 2: Velocity Error Statistics (Static Test)

Statistic	Mean (cm/s)		RMS (cm/s)	
Error in	DGPS	DGPS/INS	DGPS	DGPS/INS
East Velocity	-0.1	-0.1	0.5	0.4
North Velocity	0.1	0.2	1.0	1.4
Vertical Velocity	0.3	0.4	4.0	3.5

Table 3: Attitude Error Statistics (Static Test)

Error in / Statistic	Roll	Pitch	Azimuth
Mean (arcsec)	-0.1	0.1	201
RMS (arcsec)	1.4	0.4	268

3.3 Kinematic Tests

Two kinematic tests were performed on December 12, 1997 along major city roads in Calgary. In general, results of the two test are similar, although the statistics of the first test are somewhat better, due to a smaller PDOP, i.e. a better receiver-satellite configuration. The results of the second test are probably more typical and are presented in the following in some detail. During the test, the master station GPS receiver antenna was set up on one of the pillars on the roof of the Engineering Building. The radio antenna was mounted nearby to provide good conditions for signal transmission. The rover station GPS receiver antenna was installed on top of the IMU which was put in the trunk of a car which had the lid taken off. The radio antenna was mounted on the roof of the car; for details, see Figure 2. The GPS receiver, radio transceiver and the computer were put inside the car. The IMU, GPS receiver and radio transceiver were powered by 12V batteries.

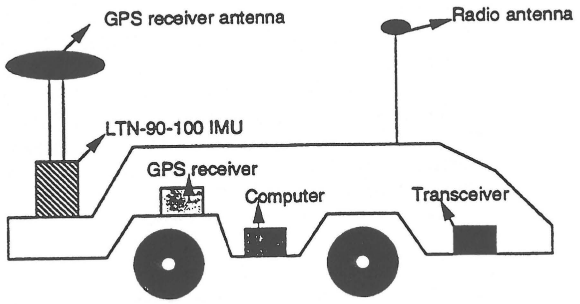

Figure 2: Hardware Installation

The car was driven along major city roads during day-time traffic. There were a number of overpasses along the route, one of them 20 m in length. The distance between master station and roving receiver changed between 0.5 km and 2.1 km. The total length of the test route was about 5 km and the course was run twice for each test. During the test, 5 to 7 satellites were observed. The PDOP factor varied between 1.8 and 3.7. Although loss of lock occurred on one or two satellites when passing under the overpasses, the number of satellites observed never dropped below 5 and the PDOP values always stayed in the given range. Before starting the test run, the system was operated in static mode for a period of about 20 minutes, followed by about 40 minutes in kinematic mode. The static period is needed for the INS initial alignment and, in this case, it is also used for post-mission GPS ambiguity resolution.

Because of the short distances between master and roving receiver, atmospheric errors and orbit errors will be small and can usually be neglected. Thus, the real-time DGPS positioning accuracy is determined by receiver noise, multipath, transmission latency, synchronization errors, vehicle-to-satellite geometry, and quality of the mathematical model and the estimation procedure. Receiver noise depends on the vehicle dynamics and is not a major concern in this case. Multipath will occur at the master station, but should not be larger than in the static case. Transmission latency of the master station corrections does not exceed 2 seconds and should therefore not be a problem because of the small time variations of these corrections. Synchronization errors will increase the error budget, especially during sharp turns. They are difficult to estimate in real time and may not be constant either. Vehicle-to-satellite geometry, as expressed by the PDOP factor, is poorer than in the static test. Looking at the PDOP range, standard deviation should increase by a factor of about two.. However, a closer scrutiny of the PDOD values shows that, for most of this run, they are hovering about 2 and that there are only three distinct periods where they are well above 3. Finally, large changes in the solution are possible with changes in the covariance and spectral density matrices of the Kalman filter. Since these matrices are usually determined empirically and are dynamics dependent, these errors are difficult to quantify.

In the following, selected results of this test will be discussed, using Figures 3 to 7, and Tables 4 to 6 for illustration. In Figure 3, a comparison of the DGPS solution and the INS/DGPS solution for the latitude parameter is shown. Even a very quick inspection of these figures shows that the integrated solution is much smoother and removes most of the spikes in the DGPS solution. This is confirmed by the statistics in Table 4 which indicate a reduction of about 40% in the RMS value between the DGPS solution and the integrated solution. The same general pattern is visible in the corresponding figures for longitude and height, of which the latter one is shown in Figure

4. The filter seems to work very well in removing large spikes in the DGPS data, see especially the three large spikes between 20.05 and 20.10 h local time. However, the solution still shows some sensitivity with respect to systematic DGPS errors sustained over a certain period. This effect could be further reduced by finetuning the weighting in the Kalman filter. In general, the results in Table 4 indicate that the integrated solution results in an improvement of the position accuracy by 40% to 45%. This result will vary with receiver-satellite geometry because spikes of this type will not occur so frequently for small PDOP numbers.

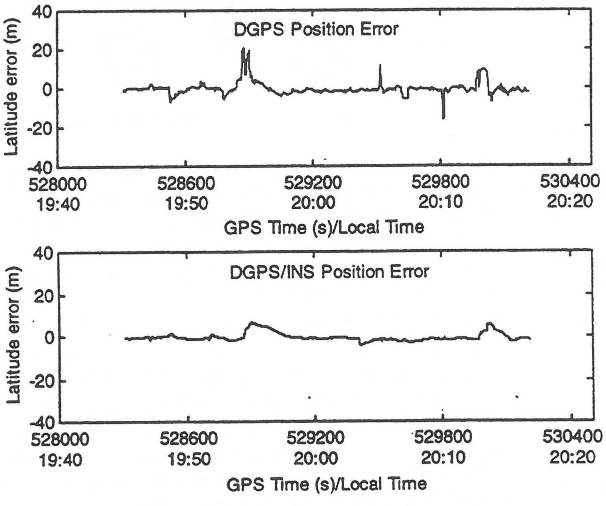

Figure 3: Latitude Errors (Kinematic Test)

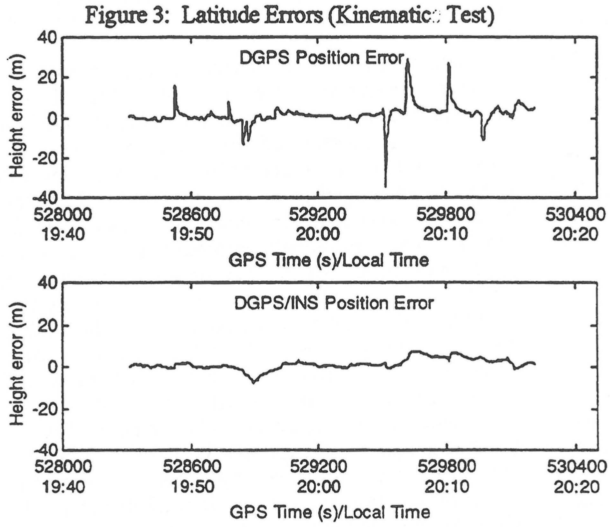

Table 4: Position Error Statistics (Kinematic Test)

Statistic / Error in	Mean (m) DGPS	Mean (m) DGPS/INS	RMS (m) DGPS	RMS (m) DGPS/INS
Latitude	-0.47	-0.57	3.40	2.15
Longitude	1.69	1.36	4.33	2.41
Height	1.65	1.28	5.04	2.95

Table 5: Velocity Error Statistics (Kinematic Test)

Statistic / Error in	Mean (cm/s) DGPS	Mean (cm/s) DGPS/INS	RMS (cm/s) DGPS	RMS (cm/s) DGPS/INS
East Velocity	0.1	-0.3	2.9	3.7
North Velocity	0.1	-0.1	2.8	3.9
Vertical Velocity	0.1	-0.3	8.2	5.2

Table 6: Attitude Error Statistics (Kinematic Test)

Error in / Statistic	Roll	Pitch	Azimuth
Mean (arcsec)	-3.9	-2.0	217
RMS (arcsec)	9.9	9.2	281

In Figure 5, a comparison of the DGPS solution and the INS/DGPS solution for the East velocity is shown. In this case, the DGPS results are smoother which is confirmed by the smaller RMS values in Table 5. The spikes in the DGPS velocities are only partially removed by the integration and new spikes appear in the integrated solution. Some of them are correlated with spikes in the DGPS position solution. The higher noise level of the integrated solution seems to indicate that the weighting between the DGPS velocity and the INS velocity needs improvement. This is indirectly confirmed by the results for the vertical velocity which is shown in Figure 6. In this case, the spike removal works very well and the noise after spike removal appears to be of the same size in both solutions. Since the vertical velocity noise in GPS is usually larger than the horizontal velocity noise, while it is about the same in INS, the problem may indeed be one of non-optimal weighting. However, this problem needs further investigation because there seems to be no consistent pattern in the velocity spikes of the integrated solution.

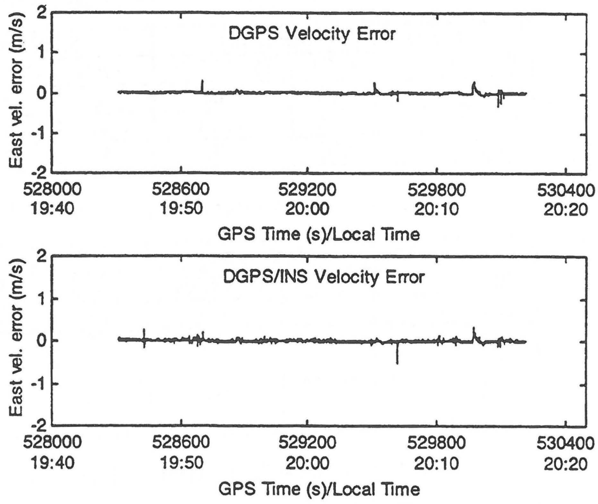

Figure 5: East Velocity Errors (Kinematic Test)

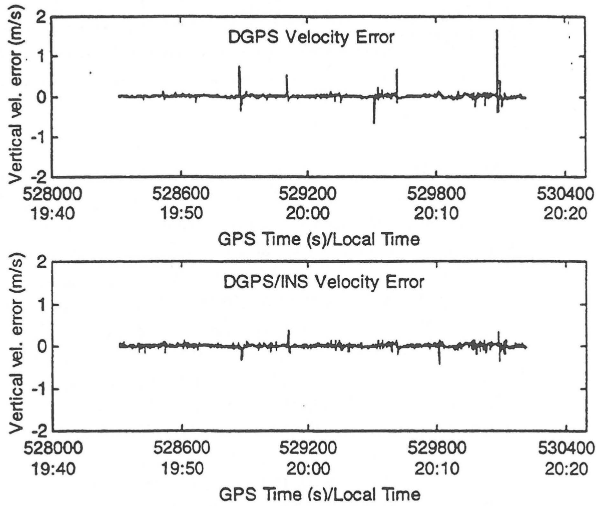

Figure 6: Vertical Velocity Errors (Kinematic Test)

In Figure 7, attitude errors of the integrated solution are shown. There is obviously no independent attitude solution from GPS. The errors simply indicate the difference between updating the INS with a differential pseudo-range solution in real time and updating it with a double difference carrier phase solution in post mission. The difference indicates how much the real-time attitude deviates from a post-mission attitude obtained by using carrier phase data for position and velocity. The difference does therefore not contain the attitude errors due to the INS. However, since the INS errors of an integrated INS/DGPS solution using GPS carrier phase data have been estimated with respect to an independent reference, see for instance Skaloud and Schwarz (1998), the accuracy of the real-time solution can be derived.

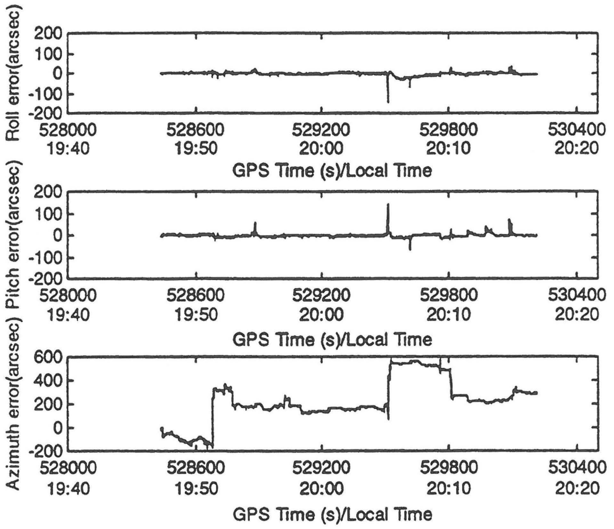

Figure 7: Relative Attitude Errors (Kinematics Test)

The errors in pitch and roll are quite small and show only a few spikes. The spikes occur essentially at the same times and are correlated with the spikes in the horizontal position errors in the DGPS solution. This would indicate that the attitude spikes are generated by errors in the DGPS solution. However, the pattern is not consistent, i.e. not all position error spikes result in corresponding pitch and roll spikes. This aspect needs further investigation. If the spikes can be removed, the standard deviations will be at the 5 arcsecond level. As can be seen from Figure 7, azimuth errors are much more erratic than pitch and roll errors and are much larger in size. There are several jumps of about 400 arcseconds in the data set of which the last two are correlated with major spikes in the DGPS position solution. None of them shows a correlation with spikes in the DGPS velocity solution. Since azimuth errors are not observable in a constant velocity environment, it appears that the position error spikes in conjunction with the Kalman filter generate a short-periodic acceleration which affects the azimuth error in a rather erratic way. Since it is possible to decouple azimuth errors from position errors in the state model, it should be possible to eliminate these jumps. In that case, the residual noise will be at a level of about 40 arcseconds.

In conclusion, the relative attitude accuracy of the real-time solution as compared to a post-mission solution with carrier phase data, is better than 10 arcseconds for pitch and roll and better than 5 arcminutes for azimuth. Taking into account the attitude accuracy of the INS, the corresponding absolute values are about 20 arcseconds for pitch and roll, and about 5 arcminutes for attitude. It appears possible that the latter standard deviation can be reduced to about one arcminute.

There are numerous applications which do not require orientation accuracies of an arcminute or better, but which can operate with accuracies of 5-10 arcminutes. In those cases, the medium accuracy INS can be replaced by a low-accuracy system. Such systems are commercially available and are much lower in costs than the navigation-grade system used in this study. For test results of such a system, see Skaloud et all (1997).

4. CONCLUSIONS AND RECOMMENDATIONS

The prototype development of a real-time INS/DGPS system has been presented in this paper. The objective of the development, to achieve standard deviations in position of 1-3 m and in attitude of 1-5 arcminutes in real-time kinematic mode, has been realized in vehicle tests. The following conclusions can be drawn from an analysis of the test results:

- The use of differential GPS pseudo-range data results in a robust system design. No loss of trajectory data was encountered in the two kinematic tests conducted.
- The integration of INS and DGPS provides spike removal in the DGPS position solution and considerably reduces the noise in the satellite data. The accuracy of the solution, measured by RMS, was improved by 40% to 45%.
- Biases in the DGPS position are not reduced by the integration.
- The real-time velocity solution showed error spikes which cannot be completely explained. They may be due to a weighting problem in the Kalman filter and need further investigation.
- The real-time attitude results in pitch and roll do not deteriorate very much by using a differential pseudo-range solution instead of a differenced carrier phase solution. The azimuth results are considerably worse, however, due to the large error spikes in the DGPS position data. An improvement is most likely possible by a change in the state vector model.
- The overall accuracy of the current system is about 2-3 m (RMS) in position for each coordinate, 20 arcseconds (RMS) in pitch and roll, and 5 arcminutes (RMS) in azimuth. The latter value can most likely be reduced to about 1 arcminute by a change in the mathematical model.
- For applications that do not require a high attitude accuracy, a low-cost inertial system can be used which would reduce overall cost of the system considerably.

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