LOW COST INS/GPS INTEGRATION: CONCEPTS AND TESTING

O.S. Salychev, V.V. Voronov
Laboratory of Inertial Geodetic Systems
Bauman Moscow State Technical University
Russia

M.E. Cannon, R. Nayak, G. Lachapelle
Department of Geomatics Engineering
University of Calgary
Canada

BIOGRAPHIES

Dr. Oleg S. Salychev is Professor of Gyro Sensors and Navigation Systems at Bauman Moscow State Technical University, and Adjunct Professor in the Department of Geomatics Engineering at the University of Calgary. He has been involved in INS design and development since 1977 and has developed a number of algorithms for different INS applications.

Dr. Vladimir V. Voronov is Senior Scientist of the Laboratory of Inertial Geodetic Systems at Bauman Moscow State Technical University. He has a Ph.D. in Gyro Devices and Systems. He has been involved in the INS/GPS integration software design and implementation since 1988.

Dr. M. Elizabeth Cannon is Professor of Geomatics Engineering at the University of Calgary. She has been involved in GPS research and development since 1984, and has worked extensively on the integration of GPS and inertial navigation systems for precise aircraft positioning. Dr. Cannon is a Past President of the ION.

Rakesh A. Nayak is an M.Sc student in Geomatics Engineering at the University of Calgary. He has a B.E. in Electronics Engineering from Mangalore University, India. He has been involved in GPS research since 1994 in the area of receiver hardware and software development and low cost sensor integration.

Dr. Gérard Lachapelle is Professor and Head of the Department of Geomatics Engineering where he is responsible for teaching and research related to positioning, navigation, and hydrography. He has been involved with GPS developments and applications since 1980.

ABSTRACT

The high cost of inertial units is the main obstacle for their inclusion in precision navigation systems to support a variety of application areas. Standard inertial navigation systems (INS) use precise gyro and accelerometer sensors, however, newer inertial devices with compact, lower precision sensors, have become available in recent years. This group of instruments is called motion sensors. Given their weak stand-alone accuracy and poor run-to-run stability, such devices are not usable as sole navigation systems. Even the integration of a motion sensor into a navigation system as a supporting device requires the development of non-traditional approaches and algorithms. The objective of this paper is to assess the feasibility of using a motion sensor, specifically the MotionPak™, integrated with GPS and DGPS information, to provide the navigation capability to bridge GPS outages for tens of seconds. The motion sensor has three orthogonally mounted "solid-state" micromachined quartz angular rate sensors, and three high performance linear servo accelerometers mounted in a compact, rugged package. Advanced algorithms are used to integrate the GPS and motion sensor data. These include INS error damping, calculated platform corrections using GPS (or DGPS) output, velocity correction, attitude correction and error model estimation for prediction. This multi-loop algorithm structure is very robust, which guarantees a high level of software reliability. Vehicular and aircraft test trials were conducted with the system in land vehicle mode and the results are discussed. Simulated outages in GPS availability were made to assess the bridging accuracy of the system. Results show that a bridging accuracy of up to 3 m after 10 seconds in vehicular mode and a corresponding accuracy of 15 m after 60 seconds in aircraft mode can be obtained, depending on vehicle dynamics and the specific MotionPak™ unit used.

INTRODUCTION

The need to augment GPS (and GLONASS) with other navigation sensors to mitigate the line-of-sight issues inherent in satellite-based systems has been researched for a number of years (e.g. Hayashi, 1996, Cannon et al., 1999). The high cost of inertial units is the main obstacle for wider inclusion of these sensors to augment GPS in precision navigation systems. Standard inertial navigation systems (INS) use precise gyro and accelerometer sensors, however, newer inertial devices with compact, lower precision sensors, are currently available. This group of instruments is called motion sensors. Given the weak stand-alone accuracy and poor run-to-run stability, such devices are not applicable as sole navigation systems. Even the integration of a motion sensor into a navigation system as a supporting device demands the development of non-traditional approaches and algorithms.

The objective of this paper is to assess the feasibility of using a motion sensor, specifically the MotionPak™, integrated with GPS and GLONASS information, to provide a precise navigation capability. The algorithm that is used to process the motion sensor data is described. It is based on a multi-loop process which is robust in an operational environment and which can be implemented on various platforms. Several field test results have been conducted with the integrated system, in both land and airborne modes and results are presented. The paper introduces the newly developed technology which is aimed at achieving high accuracy results with a low cost inertial unit.

CONCEPTS

A good example of a low cost inertial unit is the Systron Donner's series of inertial sensors. Systron Donner's MotionPak™ is a "solid-state" six degree of freedom inertial sensing system used for measuring linear accelerations and angular rates in instrumentation and control applications. The unit is shown in Figure 1.

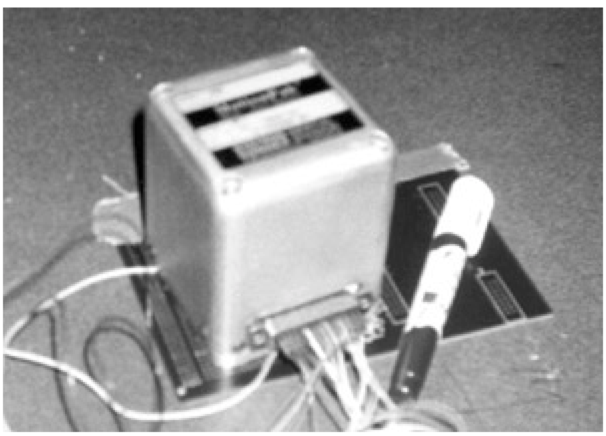

Figure 1: Systron Donner's MotionPak™

This is a highly reliable, compact and fully self-contained motion measurement package. It uses three orthogonally mounted "solid-state" micromachined quartz angular rate sensors, and three high performance linear servo accelerometers mounted in a compact, rugged package, with internal power regulation and signal conditioning electronics. Its dimensions are 7.75x7.75x9.15 cm and it weighs less than 0.9 kg.

The parameter specifications of the MotionPak™ sensors are shown in Table 1. It is important to note that the equipment accuracy varies from one unit to another even if they have the same factory specifications. A laboratory test was conducted on a particular unit and Table 2 shows the best and worst case gyro accuracies that were observed.

Table 1: MotionPak™ parameter specifications

Performance	Rate Channels	Acceleration Channels
Range	± 100 deg/sec	5 G
Bias	<2 deg/sec	<12.5 mG
Alignment to base	<1°	<1°
Resolution	<14 deg /hrs	<10 G

Table 2: Gyro accuracies from lab tests

Gyro Accuracy Parameter	Best Case	Worst Case
day to day (run to run) drift rate bias	< 100 deg/h	< 360 deg/h
drift rate bias in run (averaged within 20 s)	< 60 deg/h	< 180 deg/h
drift rate bias in run (averaged within 250…300 sec)	< 10 deg/h	< 50 deg/h

From the specifications and test results, the above unit could not be directly used as an inertial measurement unit (IMU) for a stand alone INS. Firstly, the gyros are not sensitive enough to sense the Earth rate, which means that a self-contained azimuth alignment procedure cannot be used. Secondly, the run-to-run gyro bias has a large magnitude that leads to large INS output errors in stand alone mode. Therefore in order to fully exploit the IMU data, a method of operating and processing the data was developed and is explained in the following section.

METHODOLOGY

In order to use the MotionPak™ integrated with GPS (or GPS/GLONASS), several preliminary procedures have been developed and implemented, and these include:

- horizontal alignment based on the acceleration output;
- stored azimuth alignment using a magnetic compass or any external heading information;
- calibration of the run-to-run gyro drift rate bias.

All these procedures can be realized in real-time and take 15 minutes. After that, the data processing program switches to navigation mode which includes the following correction loops:

- INS error damping;
- "calculated platform" correction using real time GPS output;
- velocity correction;
- attitude correction;
- error model estimation for prediction mode.

All steps are implemented in GAIN™ (GNSS-Aided Inertial Navigation, which is a software package co-developed between the Laboratory of Inertial Geodetic Systems and the University of Calgary. It is robust with respect to inertial sensor accuracy variation and is therefore a flexible program for the integration of the low accuracy inertial sensors (i.e. with the specifications given above) and different types of GPS receivers. It requires minimal adjustment and can be used on different vehicle platforms. Figure 2 gives the overall configuration of the algorithm. It is currently implemented in post-mission and is being extended for real-time use.

The integration scheme provides the capability to output the navigation parameters after each correction stage. This helps in obtaining accurate prediction of the attitude angles, velocity and position in case of GPS outages, as well as a convenient form of the real-time error compensation. In addition, this multi-loop algorithm structure is very robust, which guarantees a high level of software reliability. The algorithms are designed for real-time implementation, hence this system can be considered as a tool for a wide variety of applications.

The algorithms discussed above are original in the sphere of strapdown inertial technology (Salychev, 1998), such that a new category in inertial terminology can be defined: the 'Integrated Inertial Instrument Technology' (I.I.I. or simply "Triple I") which is implemented in GAIN™. It is a combination of an inexpensive motion sensor, which has a poor stand-alone performance, and advanced algorithms which are implemented in software to provide a powerful integration tool of a motion sensor with GPS information to obtain high accuracy position and angular attitude information. Figure 3 shows the software layout.

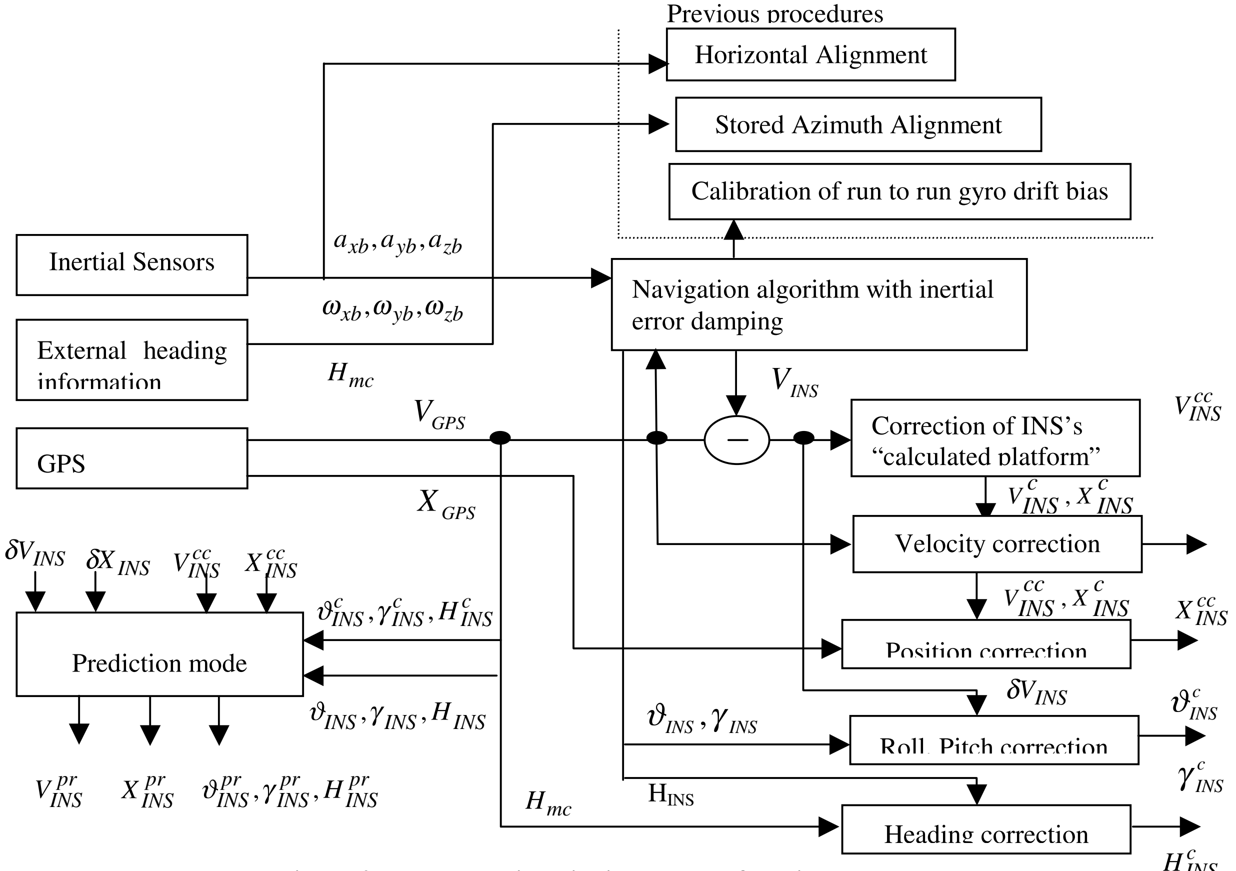

Figure 2: Integrated inertial instrument functional scheme

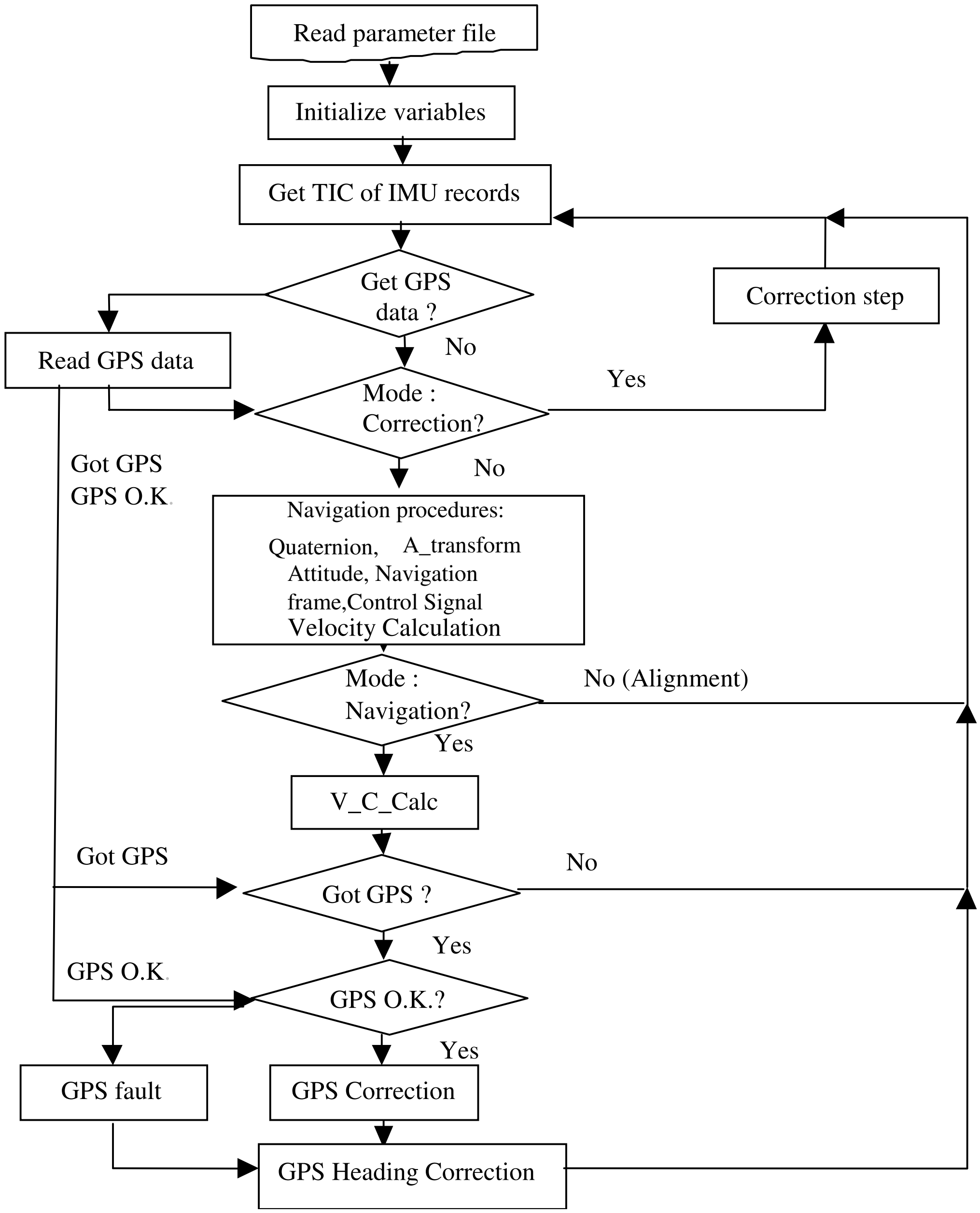

Figure 3: Software algorithm of GAIN™

TEST DESCRIPTIONS AND RESULTS

In order to demonstrate the accuracy of the system, a series of tests were conducted in both a land vehicle and aircraft modes. The test procedures and results are described below.

Land Vehicle Tests

Test runs were carried out in Calgary, Alberta in August, 1999. The MotionPak™ and Ashtech's GG24 GPS/GLONASS receiver were installed in a passenger vehicle and driven throughout suburban areas. The test trajectory is shown in Figure 4 and was approximately 24 km in length which required about 50 minutes to complete one run. A second GG24 unit was installed on the roof of the Engineering Building at the University of Calgary to provide differential corrections. The maximum distance between the test vehicle and the reference station was 8.85 km.

Seven runs were conducted over a three day period. One of the runs was selected for further discussion in this paper, however, the results from the other runs were used to generate outage statistics as discussed below.

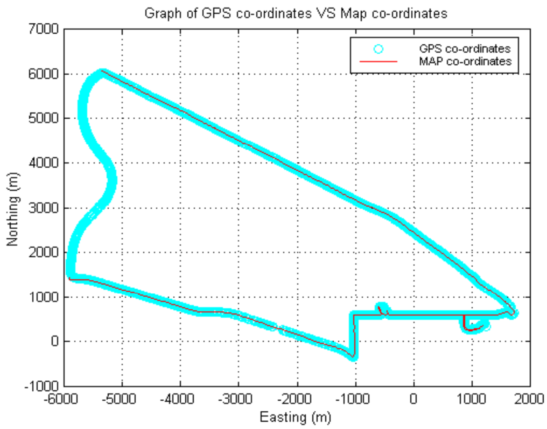

Figure 4: Calgary test trajectory

The GG24 was configured to output raw GPS and GLONASS data at 1 Hz with satellites being tracked above a 5° cutoff angle. The number of satellites tracked ranged from 0 to 12 and is shown in Figure 5 along with the GDOP (the GDOP is set to zero when no satellites are tracked). As can be seen there were several periods of poor coverage and no solution was possible for 11.5% of the time. Outages typically occurred when the vehicle went under overpasses. IMU data was recorded at 46 Hz.

The GPS and GLONASS data was first post-processed using the C^{3}NAVG^2™ software, developed at the University of Calgary, to produce position and velocity estimates (C^{3}NAVG^2™, 1999). This software processes the pseudorange data in differential mode using a standard least squares algorithm. Position accuracies are generally on the order of a 1 to 2 meters under good geometry.

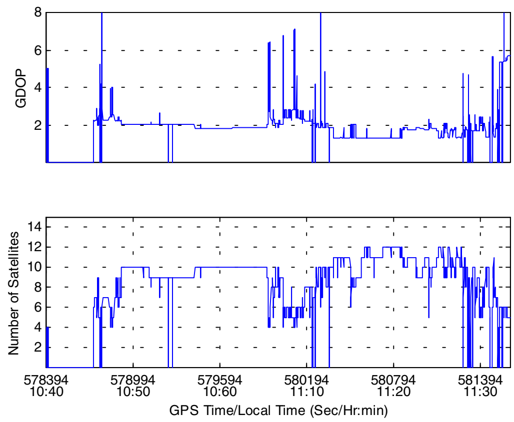

Figure 5: Satellite geometry and availability

The particular inertial unit used in this test had a rather poor accuracy, and the estimated long term gyro biases were at a level of 40 to 50 deg/h. Even though, a reasonable accuracy was achieved using GAIN™. Figure 6 shows the differences between the independently-computed DGPS/DGLONASS velocities and the integrated values, while Table 3 gives statistics of the differences.

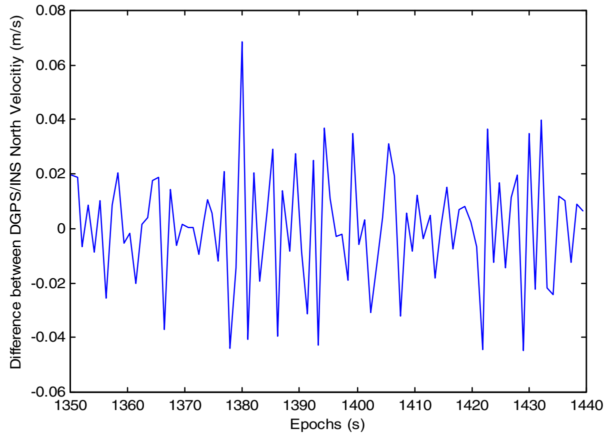

Figure 6: Differences between DGPS-DGLONASS and GAIN™ north velocity

Table 3: Statistics of the differences between DGPS/DGLONASS and GAIN™ north velocity

Mean (m/s)	Standard deviation (m/s)
0.001	0.022

GAIN™ also provides pitch, roll and heading information. For the heading correction, the DGPS measurements were used along with a constraint on the nominal vehicle velocity during movement.

One of the advantages of using an INS is during GPS/GLONASS outages. From an operational point of view, it is desired that there is no significant degradation in performance during the outage and that the INS can accurately predict positions during this time. In order to assess the prediction capability of GAIN™, DGPS/DGLONASS measurement gaps were simulated in the data set during two time periods. Since the DGPS/DGLONASS information was still available, it could be used as a reference for comparison with the INS-predicted values.

The INS prediction accuracy based on test data collected over the seven runs is shown in Table 4. As seen in the table, the results are sub-divided into two categories: (1) for periods when the vehicle was traveling at a constant speed before and during the outage, and (2) for periods when the vehicle underwent acceleration during the outage, hence the vehicle dynamics changed.

Table 4: GAIN™ RMS position prediction accuracy

Outage (s)	Constant dynamics during prediction	Acceleration during prediction
10	3 m	10 m
20	10 m	23 m

The INS prediction accuracy is strongly dependent on changes in the vehicle dynamics during the DGPS/DGLONASS gap. When the vehicle acceleration changes within the prediction interval, the prediction accuracy is 10 m over 10 seconds, whereas when the vehicle dynamics are constant, the results improve to 3 m over 10 seconds. For a 20 second outage, the prediction accuracy degrades to 10 m and 23 m for the two cases. This can be explained by the fact that the behavior of the nonstationary inertial error components (i.e. azimuth misalignment, accelerometer scale factors, nonorthogonality of installation errors) strongly depends on the dynamics within the prediction period. This is well illustrated by an example shown in Figure 7, where GAIN™ predicted positions and DGPS/DGLONASS positions are compared for two 20 second outage periods.

Overall however, the results are very good since the position accuracy is maintained to within a few meters after a 20 second gap in DGPS/DGLONASS coverage when the vehicle is travelling under benign conditions. This would represent, for example, the performance that could be achieved after a vehicle passes through a 160 m tunnel when travelling 60 km/h.

Airborne Tests

More tests were conducted thanks to the Newmont Gold Company (USA) using a different MotionPak™ unit with the same factory specifications as described above. This unit has much better gyro bias stability (<10 deg/h within 200 to 300 s and <60 deg/h within 20-30 s). These tests were performed in both land vehicle and airborne modes. For the brief discussion herein, only the flight test results are discussed.

Flight tests were performed in March, 1999 in Nevada, USA (Battle Mountain). For this test, the system was installed beside an I-21, precise gimbal Russian INS, see Salychev (1995) for detailed performance information of this system. Highly accurate aircraft attitude data was available for the entire flight. Two Trimble 4000SSE receivers provided double differenced GPS carrier phase data that was used as a position and velocity reference. In this case, the carrier phase solution was used to update the INS.

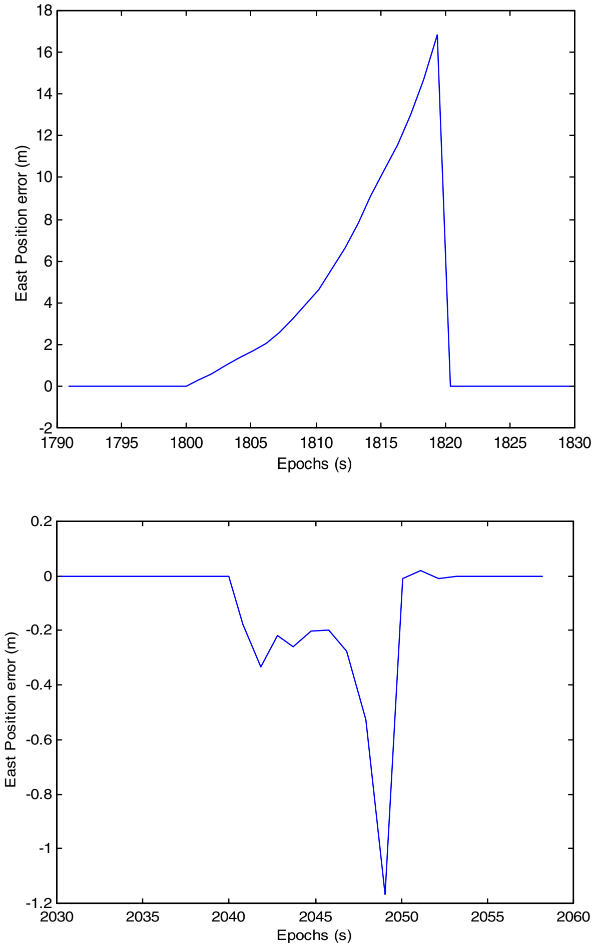

Figure 7: Position error between the GAIN™ predicted position and DGPS/DGLONASS position

After the first correction step (i.e. platform correction), the velocity accuracy improved to 0.7 m/s (RMS), and is shown in Figure 8. The final correction gave errors of 0.1 m/s and 0.2 m for velocity (Figure 9) and position (Figure 10), respectively. The RMS position agreement between the two solutions is given in Table 5 and is about 6 cm.

Table 5: GAIN™ position error statistics

Component	Mean (m)	RMS (m)
North	0.002	0.064
East	-0.001	0.059

As discussed previously, an important task of an INS in the overall navigation system concerns its prediction capability during DGPS data losses. The results of a 20 second simulated GPS outage are shown in Figure 11 for the north velocity while Figure 12 shows the north position error. The coordinate error during this gap does not exceed 6 m. For short term GPS measurement losses (e.g. 10 seconds), an accuracy of 1 to 1.5 m was achieved.

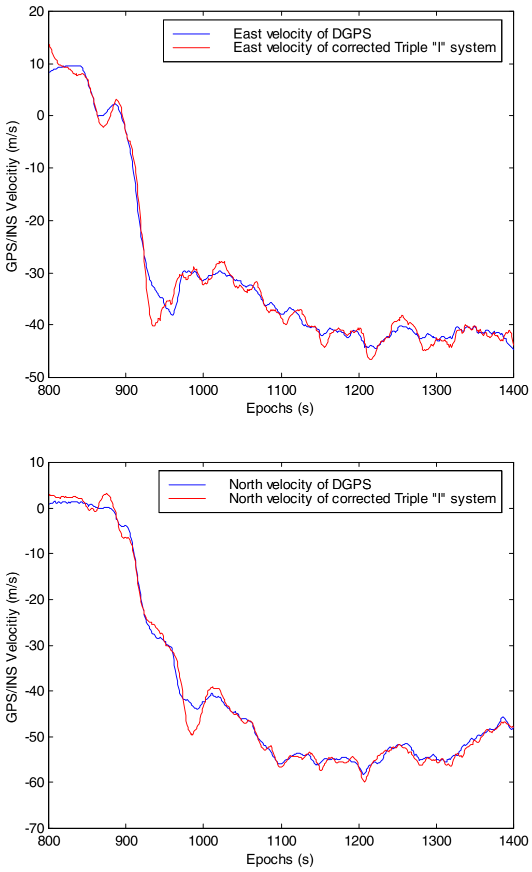

Figure 8. Airborne DGPS and DGPS/INS velocities after the first correction step

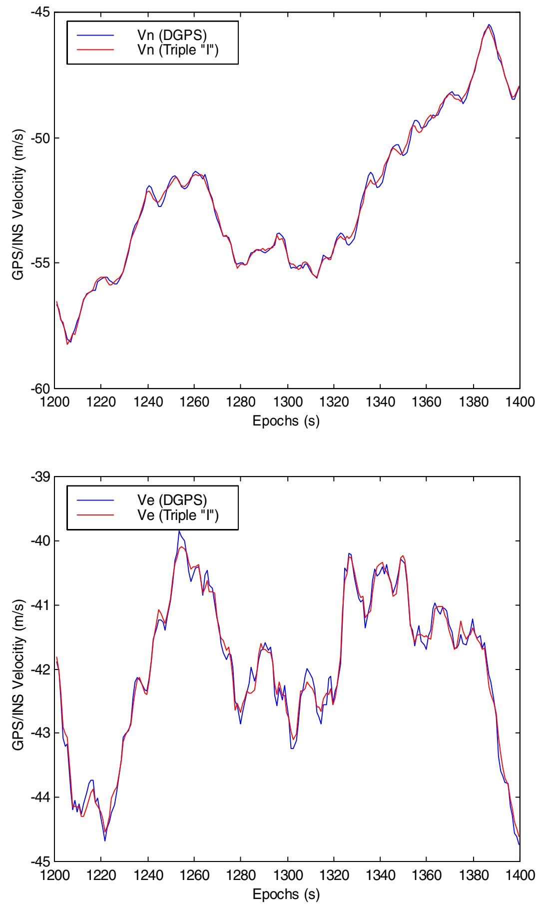

Figure 9: Airborne DGPS and DGPS/INS velocities after the final correction step

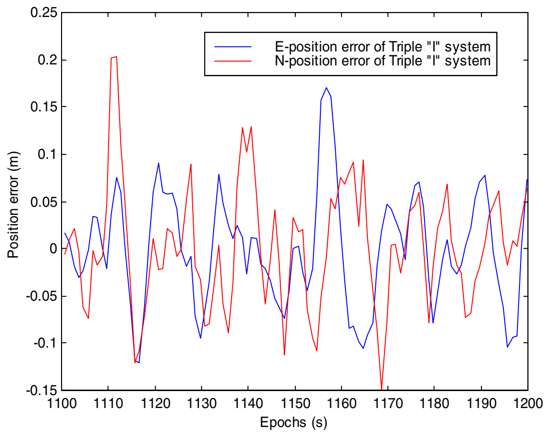

Figure 10: Airborne DGPS and DGPS/INS positions after the first correction step

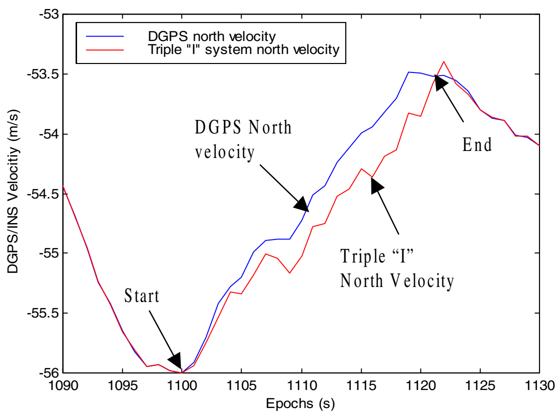

Figure 11: GPS outage recovery by the integrated system

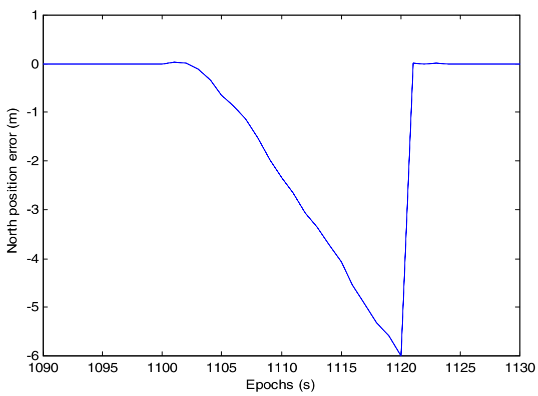

Figure 12: GPS outage recovery by the integrated system in position domain

The good prediction capability, as well as attitude accuracy, can be explained by two reasons. Firstly, in these tests a MotionPak™ with a more stable gyro was used in comparison with the Calgary tests. Secondly, there were more stable dynamics during the airborne tests. In addition, there were carrier phase-derived solution updates to the INS in this case.

CONCLUSIONS

The main purpose of this paper was to demonstrate the feasibility of using a low cost motion sensor system integrated with DGPS, along with new algorithms, to optimally process the data to achieve high position and velocity accuracies. The tests demonstrate that the integrated system shows promising results for accurate navigation using low cost inertial hardware, which allows the development of a cost-effective navigation system to support a wide spectrum of applications. The cost of such a system makes it affordable for light general aviation airplanes, land vehicles, and ships. The GAIN™ software is hardware independent, so it may be applied to any type of motion sensor with minimal adjustment.

REFERENCES

Cannon, M.E., G. Lachapelle, H. Sun, T. Fletcher, R. Caballero and I. Hawes (1999), Development and Testing of an Integrated INS/GPS Cross-linked System for Sub-meter Positioning of a CF-188 Jet Fighter, Proceedings of ION Annual Meeting, Cambridge, June 28-30, pp. 463-474.

C^{3}NAVG$^{2\text{TM}}$ (1999), Combined Code and Carrier for Navigation with GPS and GLONASS, Operating Manual, Version 2, Geomatics Engineering, July 1999, 31 pp.

Hayashi, N. (1996), Augmentation of GPS with a Barometer and a Heading Rate Gyroscope for Urban Navigation, UCGE Report Number 20098, Geomatics Engineering, University of Calgary.

Salychev O.S. (1995), Inertial Surveying: ITC Ltd. Experience, Bauman MSTU Press.

Salychev O.S. (1998), Inertial Systems in Navigation and Geophysics, Bauman MSTU Press.