Low-Cost INS/GPS Integration: Concepts and Testing

M. E. Cannon, R. Nayak and G. Lachapelle

(*University of Calgary*)

O. S. Salychev, V. V. Voronov

(*Bauman Moscow State Technical University*)

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, called motion sensors, is six to eight times less costly than a standard INS. 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 DGPS and DGLONASS information, to provide accurate position and attitude information, and to assess its capability to bridge satellite outages for up to 20 seconds. The motion sensor has three orthogonally mounted 'solid-state' micro-machined 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 DGPS (or DGPS/DGLONASS) 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 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 6 m after 20 seconds in aircraft mode can be obtained, depending on vehicle dynamics and the specific MotionPak™ unit used. The attitude accuracy was on the order of 22 to 25 arcmin for roll and pitch, and about 44 arcmin for heading.

KEY WORDS

1. GPS. 2. INS. 3. Integration

1. 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 (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, called motion sensors, is six to eight times less costly than a standard

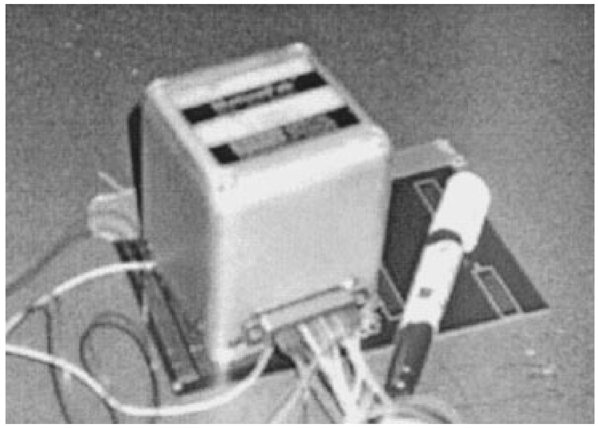

Figure 1. Systron Donner's MotionPak™.

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/h	< 10 G

INS. 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 DGPS and DGLONASS information, to provide a precise navigation and attitude capability. The algorithm that is used to process the motion sensor data is described. It is based on a multi-loop process that is robust in an operational environment and that can be implemented on various platforms. Several field tests have been conducted with the integrated system, in both land and airborne modes, and results are presented. The paper introduces the newly developed technology aimed at achieving high-accuracy results with a low-cost inertial unit. The unit used in this case cost less than US$10,000 in low quantities at the time of purchase.

2. 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. This is a highly reliable, compact and fully self-contained motion measurement package. It uses three orthogonally-mounted 'solid-state' micro-machined 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 $7{\cdot}75 \times 7{\cdot}75 \times 9{\cdot}15$ cm and it weighs less than 0·9 kg.

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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 2. Gyro accuracies from lab tests.

Gyro accuracy parameter	Best case	Worts 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 s)	< 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 exploit fully the IMU data, a method of operating and processing the data was developed and is explained in the following section.

3. METHODOLOGY.

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

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

All these procedures can be done in real time in 15 minutes, after which, the data processing programme switches to navigation mode and includes the following correction loops:

(a) INS error damping: damps the INS errors using the differences between the INS and GPS accelerations;
(b) 'Calculated platform' correction (first correction loop): estimates the angular errors between the calculated platform and the *true* navigation frames (the navigation frame is actually realised in the onboard computer using the real sensor output). It recalculates the specific forces from the platform frame to the navigation frame;
(c) Velocity correction (second correction loop): estimates velocity errors based on a Kalman filter;
(d) Position correction (third correction loop): estimates the position errors based on a Kalman filter;
(e) Roll and Pitch correction (fourth correction loop): uses the estimates of the attitude errors to correct the direction cosine matrix between the body and navigation frames;

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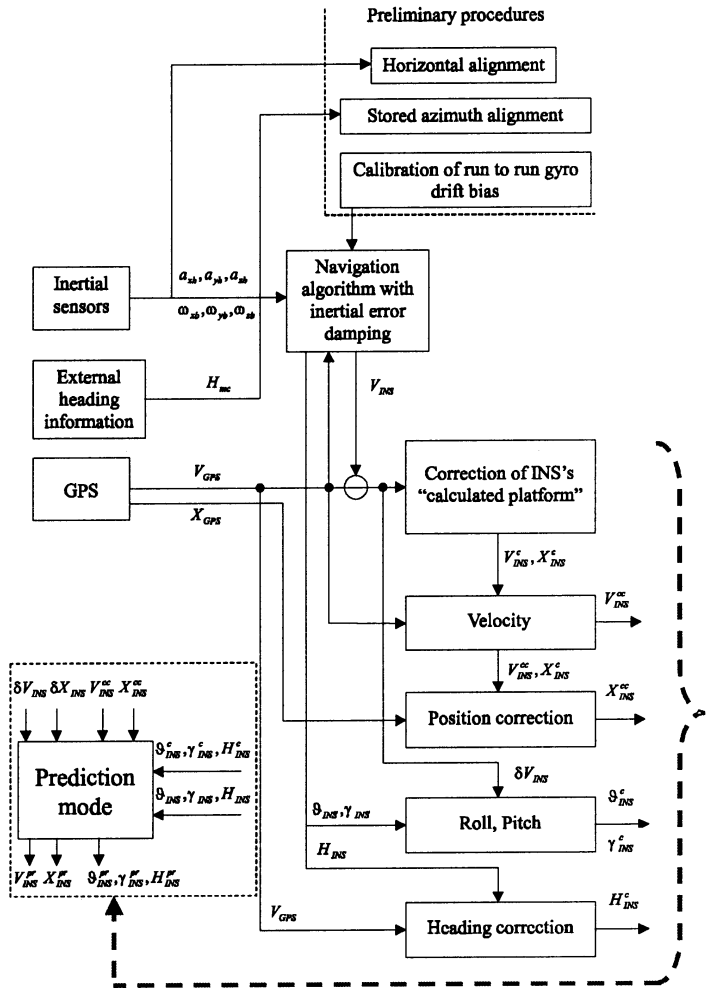

Figure 2. Integrated inertial instrument functional scheme.

(f) Heading correction (fifth and final correction loop): uses the difference between the INS and GPS heading calculations to correct the heading estimate;
(g) Error model estimation for prediction mode: the estimate of the INS errors play a role in the initial conditions for the 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 programme 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 strap-down 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 that 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.

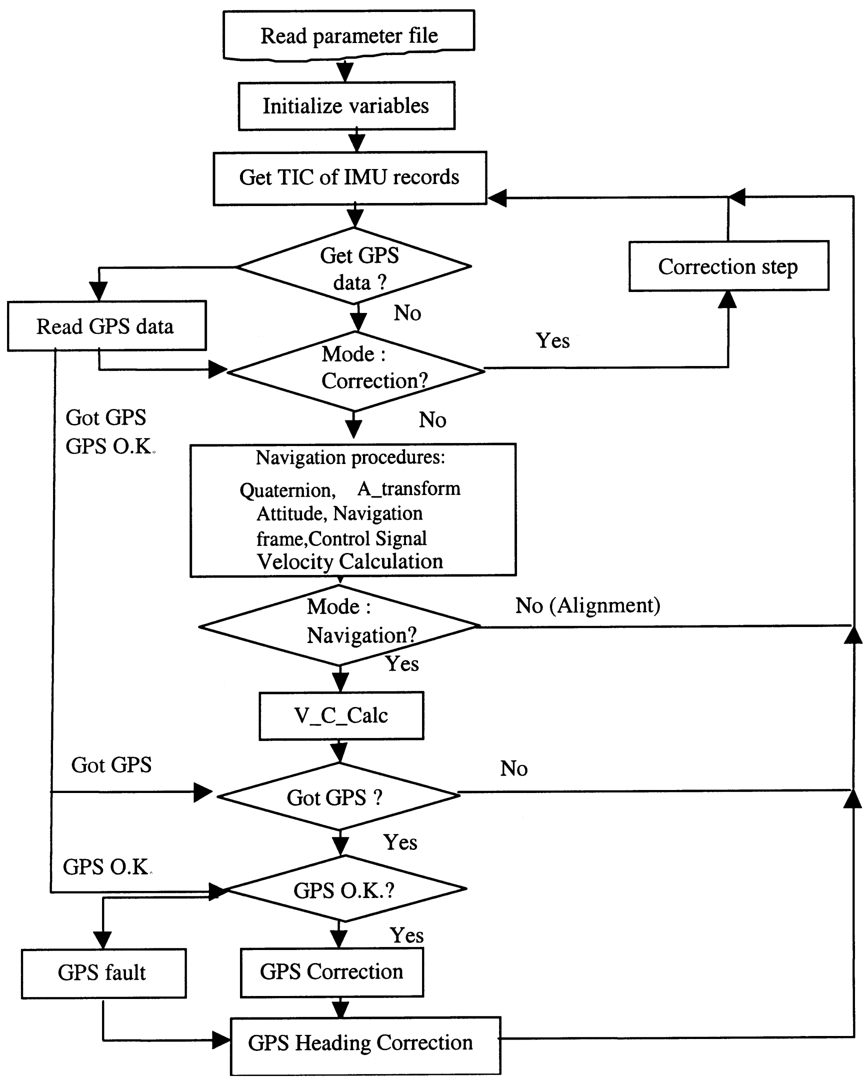

Figure 3. Software algorithm of GAIN™.

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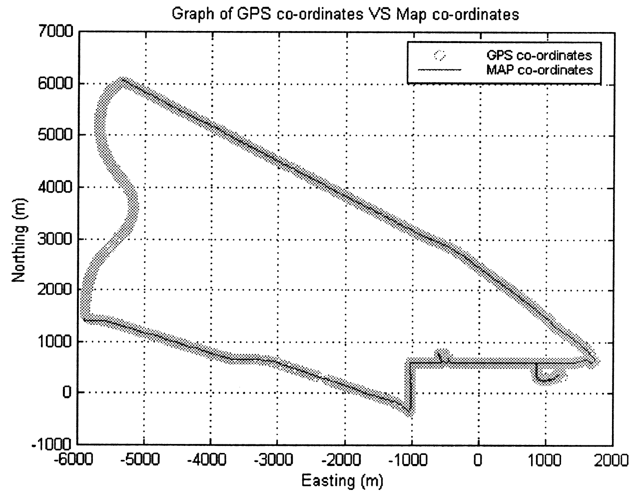

Figure 4. Calgary test trajectory.

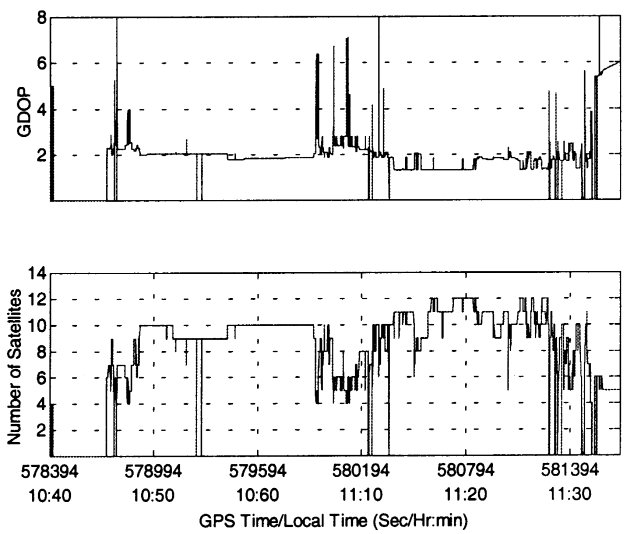

Figure 5. Satellite geometry and availability.

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

4.1. *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 and 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 less than 9 km.

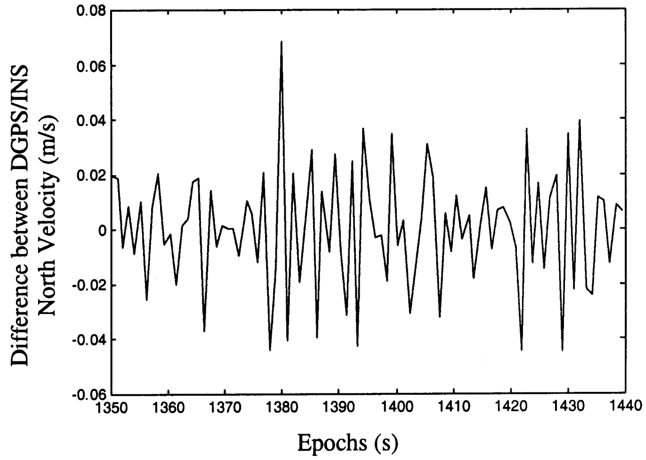

Figure 6. Differences between DGPS-DGLONASS and GAIN™ north velocity.

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

Mean (m/s)	Standard deviation (m/s)
0·001	0·022

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.

The GG24 was configured to output raw GPS and GLONASS data at 1 Hz with satellites being tracked above a 5° cut-off angle. The total number of satellites tracked ranged from 0 to 12 as 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 about 12% of the time. Outages typically occurred when the vehicle went under overpasses. IMU data was recorded at 46 Hz with the maximum output rate being 200 Hz.

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

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 40–50 deg/h. A reasonable accuracy was, however, 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. A comparison of the DGPS/DGLONASS velocity and position with the integrated system shows that the integrated solution is slightly better when there is sufficient satellite information (i.e.

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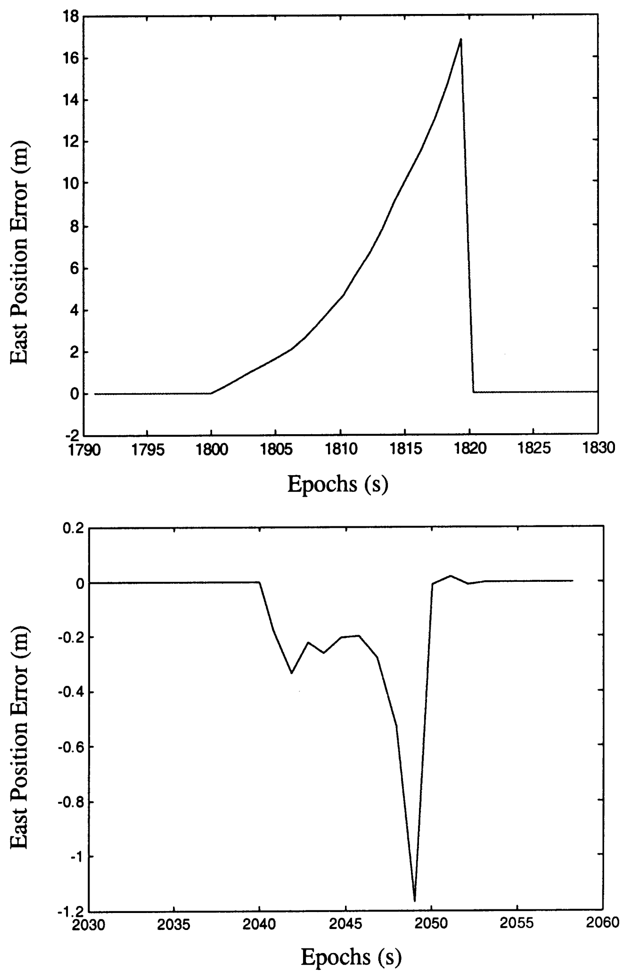

Figure 7. Position error between the GAIN™ predicted position and DGPS/DGLONASS position.

at least four satellites in good geometry). However, the main advantage of the integrated system is when there are DGPS measurement gaps, as will be shown later. 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.

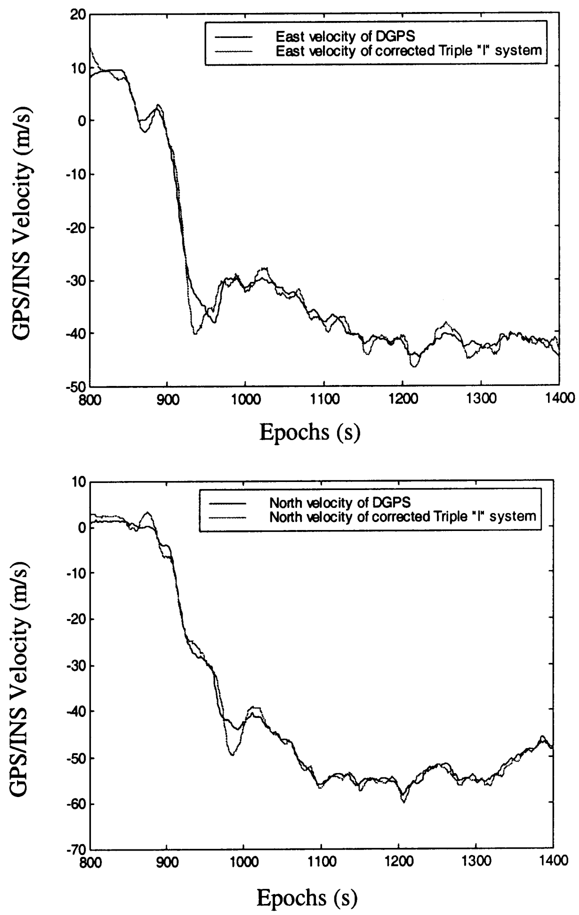

Figure 8. Airborne DGPS and DGPS/INS velocities after the first correction step.

Table 4. GAIN™ RMS position prediction accuracy.

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

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 travelling 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.

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 s, whereas when the vehicle dynamics are constant, the results improve to 3 m over 10 s.

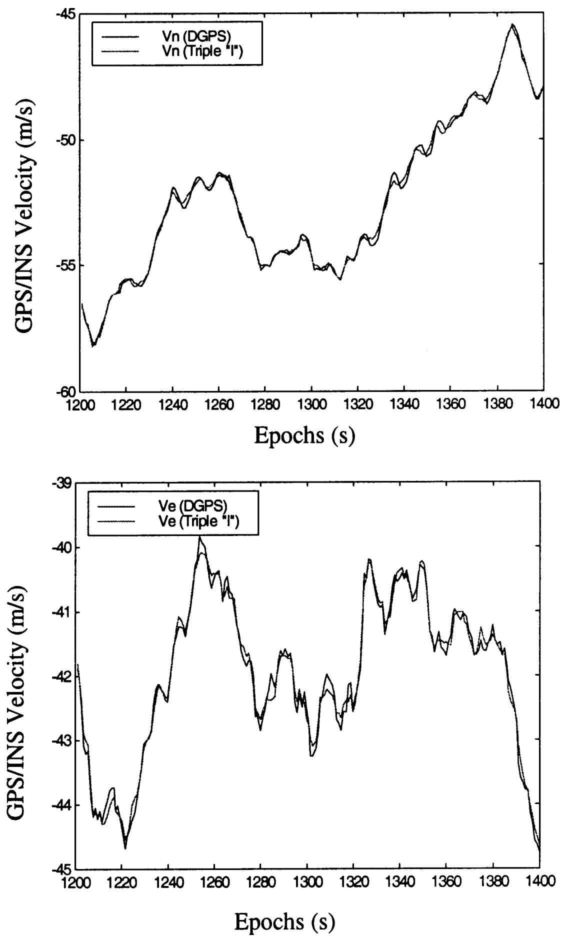

Figure 9. Airborne DGPS and DGPS/INS velocities after the final correction step.

For a 20-s outage, the prediction accuracy degrades to 10 and 23 m for the two cases. This can be explained by the fact that the behaviour of the non-stationary inertial error components (i.e. azimuth misalignment, accelerometer scale factors, non-orthogonality 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-s outage periods.

Overall however, the results are very good since the position accuracy is maintained to within a few metres after a 20-s 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.

4.2. *Airborne Tests.* More tests were conducted thanks to 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

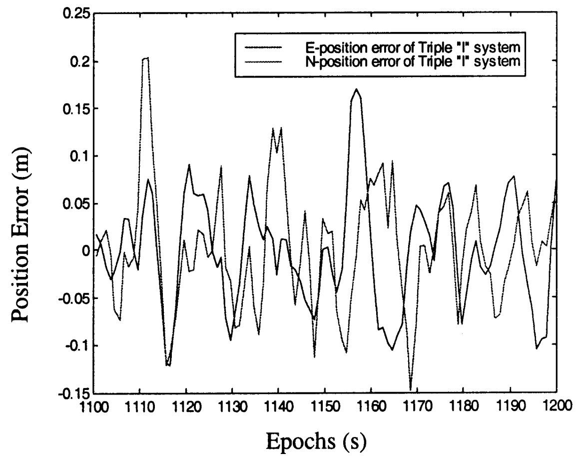

Figure 10. Airborne DGPS and DGPS/INS positions after the first correction step.

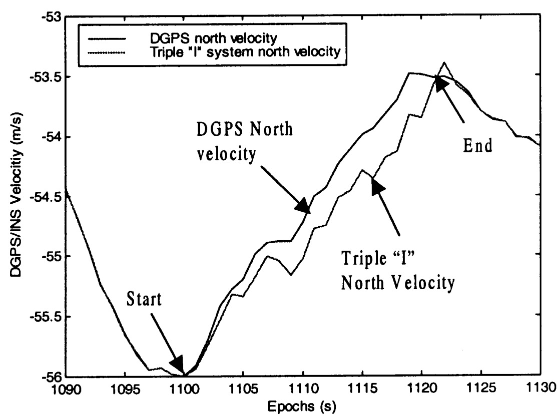

Figure 11. GPS outage recovery by the integrated system.

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.

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.

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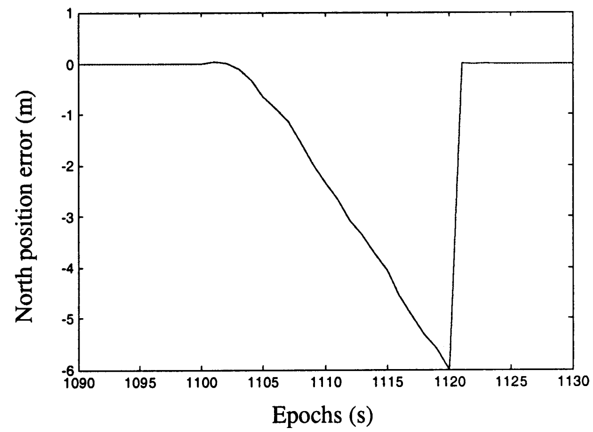

Figure 12. GPS outage recovery by the integrated system in position domain.

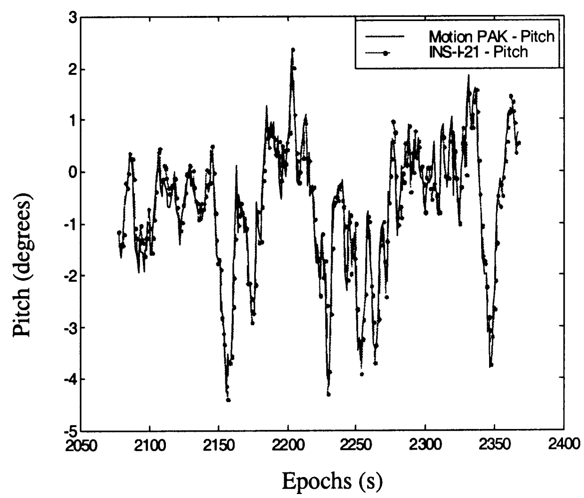

Figure 13. Aircraft pitch computed by the MotionPak™ and I-21.

Table 5. GAIN™ position error statistics.

Component	Mean (m)	RMS (m)
North	0·001	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-s 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 s), an accuracy of 1 to 1·5 m was achieved.

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

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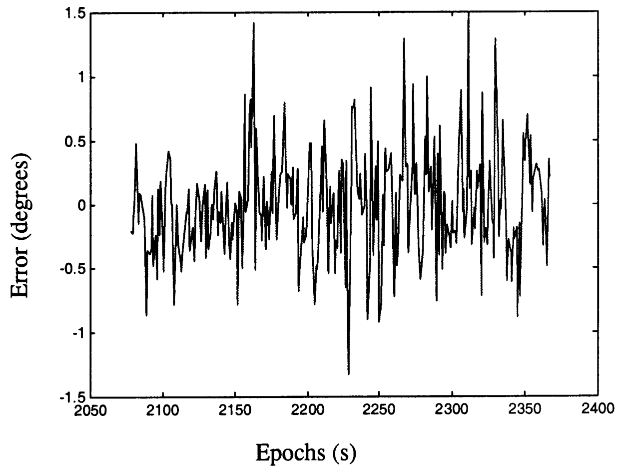

Figure 14. MotionPak™ pitch error.

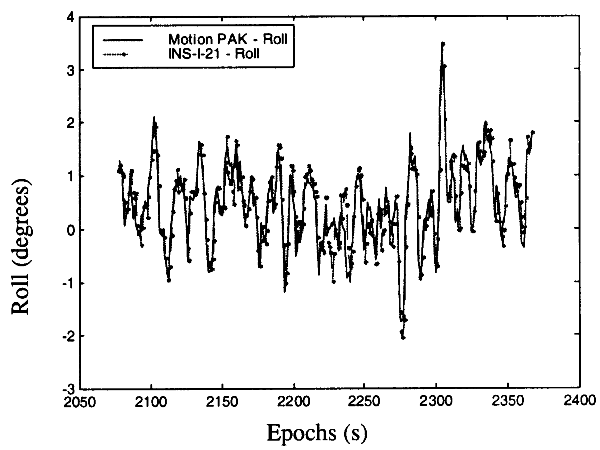

Figure 15. Aircraft roll computed by the MotionPak™ and I-21.

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.

The performance of the integrated system to determine attitude parameters was assessed through a comparison with the I-21 system. The accuracy of the attitude angles of the I-21 are estimated to be 0·1–0·2 arcmin for roll and pitch, and 3–6 arcminutes for azimuth. In order to account for the misalignment between the MotionPak™ and I-21, one flight line was chosen and the offset between the two systems was estimated.

Figure 13 shows the aircraft pitch as estimated by the MotionPak™ and I-21 systems. As can be seen, the pitch variation is within seven degrees and the agreement between the two systems is good. The MotionPak pitch error, using the I-21 as a reference, is shown in Figure 14. The agreement is generally within one degree and the RMS of the differences is about 25 arcmin, as shown in Table 6.

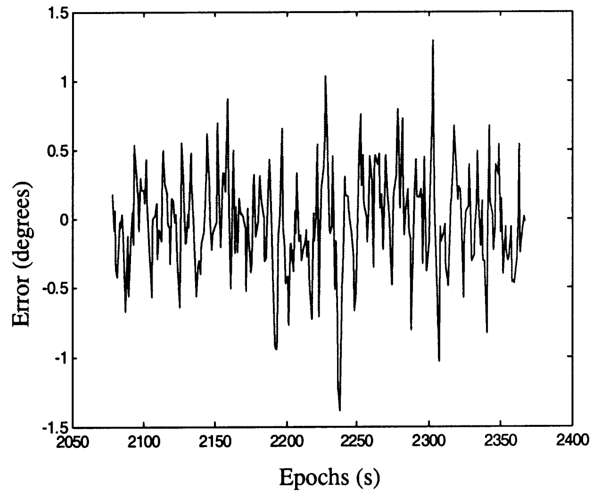

Figure 16. MotionPak™ roll error.

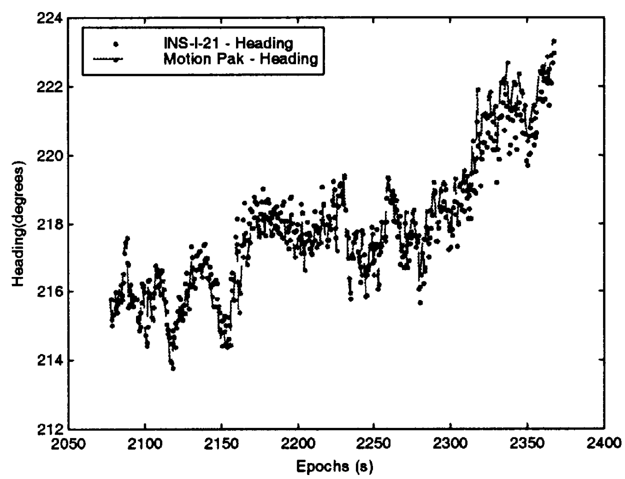

Figure 17. Aircraft heading computed by the MotionPak™ and I-21.

Table 6. GAIN™ attitude error RMS statistics.

	Pitch (arcmin)	Roll (arcmin)	Heading (arcmin)
Error	25·1	22·4	43·7

The aircraft roll is illustrated in Figure 15 and within a five-degree range over the flight line. Differences between the two systems, and which represent the MotionPak™ error, are shown in Figure 16 and are within one degree, with the RMS being 22 arcminutes (see Table 6). The pitch and roll accuracies with the MotionPak™ can be considered very good considering the overall quality of the gyros used in the

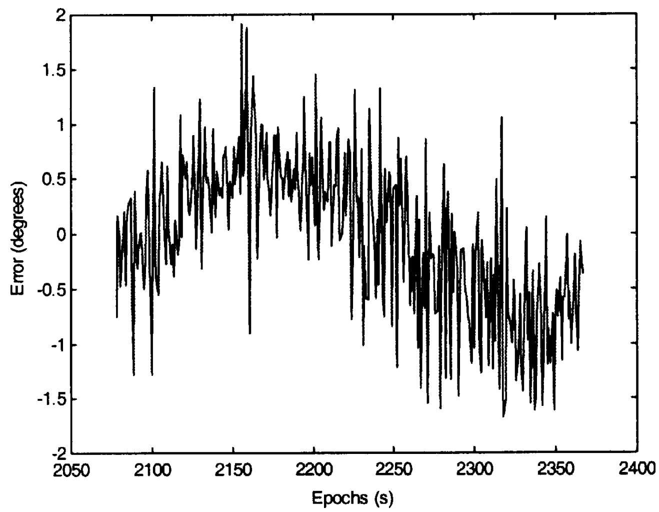

Figure 18. MotionPak™ heading error.

system. The aircraft heading is given in Figure 17, and the MotionPak errors are shown in Figure 18. The RMS agreement is about 44 arcmin, which is poorer than the roll and pitch performance due to the poor observability of the heading errors.

5. 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 process the data optimally to achieve high position and velocity accuracies.

For the case when the land vehicle was travelling under benign conditions, prediction accuracies of the MotionPak™ were shown to be on the order of 3 m over a 10-s GPS/GLONASS outage, and 10 m over a 20-s outage. For outages when the vehicle was accelerating, the prediction accuracy was on the order of 10 and 23 m for the 10 and 20 s cases, respectively. For the aircraft environment, the prediction accuracies were 1–1·5 m over 10 s and less than 6 m over 20 s. This improved performance in the flight tests was mainly due to the fact that a different MotionPak™ unit was used that had better performance characteristics compared to the one used in the land tests.

The ability of the MotionPak to provide accurate attitude angles was shown through comparisons with the Russian I-21 gimballed system. The agreement between the two systems was on the order of 22 to 25 arcmin for roll and pitch, and about 44 arcmin for heading. The land and airborne 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.

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