Attitude Determination with GPS-Aided Inertial Navigation Systems

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BIOGRAPHIES

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ABSTRACT

Precise attitude parameters are required in connection with numerous marine and airborne applications, including shipborne multi-beam echo sounding systems for sea floor mapping, and airborne laser and digital camera mapping. Multi-antenna GPS can deliver accuracies of better than several arcmins under good conditions. However this requires the use of a stable mounting system which can operationally be difficult to install and relate to the sensor that requires the attitude parameters in the first place. In addition, several of the above applications require accuracies that GPS may not achieve at this time due to the presence of carrier phase multipath. An alternative which has proven to be effective is the use of GPS-aided INS. For instance, the use of mid-range INS (e.g., LN200, HG1700) yields attitude accuracies sufficient for the most demanding multi-beam echo sounding systems. In this paper, an approach is presented to aid INS with GPS to derive attitude parameters. Two classes of inertial measuring units (IMU) are used, namely a MotionPak™ and a HG1700 unit. Performance analyses show how the attitude parameter accuracy varies as a function of the specific specifications of the IMU used and of the platform dynamics.

INTRODUCTION

Precise attitude parameters are required in connection with numerous marine and airborne applications, including shipborne multi-beam echo sounding systems for sea floor mapping, airborne laser and digital camera mapping. Multi-antenna GPS can deliver accuracies of better than several arcmins under good conditions. However this requires the use of a stable mounting system which can operationally be difficult to install and relate to the sensor that requires the attitude parameters in the first place. In addition, several of the above applications require accuracies that GPS may not achieve at this time due to the presence of carrier phase multipath.

The high cost of inertial devices is a main obstacle for the wider inclusion of these sensors to augment GPS in precision navigation and attitude systems. Therefore, the objective of this paper is to assess the feasibility of using the relatively low cost inertial sensor unit (MotionPak™) and a medium cost unit (HG1700), integrated with GPS, in order to achieve high accuracy attitude parameters. Field tests were conducted in an aircraft, for the case of the MotionPak™, and the performance was assessed by comparing the orientation parameters with a higher accuracy INS system. For the case of the HG170, tests were performed in a land vehicle, and the accuracy of the system was assessed through an indirect method. The methodology used to estimate navigation and attitude parameters in each case is presented along with the estimated accuracies.

SENSOR SYSTEM DESCRIPTION

The MotionPak™ 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 7.75x7.75x9.15 cm and it weighs less than 0.9 kg. The system is shown in Figure 1.

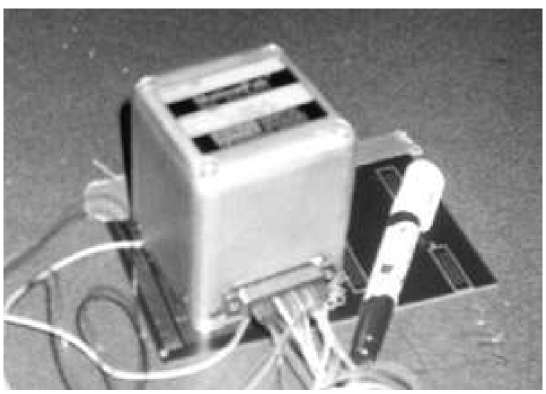

Figure 1: Systron Donner's MotionPak™

The nominal 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 to 300 s)	< 10 deg/h	< 50 deg/h

A medium-level accuracy inertial measurement unit (IMU) usually includes a rate gyro with an in-run bias stability of 0.5 to 1 deg./h and an accelerometer bias on the level of 10^{-3} to 10^{-4} g. Such an IMU can be used in stand-alone INS mode with a self-contained horizontal and azimuth alignment. However, the azimuth alignment accuracy is not high enough in this case and is expected to be on the level of 1 to 4 degrees.

The application of such an IMU for stand-alone navigation provides a poor position and attitude output accuracy. However, the integration of this unit with GPS provides a reasonable accuracy for the navigation parameters and is useful for a wide spectrum of applications. A good example of a medium class IMU is the Honeywell HG1700, see Figure 2. This unit contains laser gyros with a "run to run" bias stability of 0.5 to 1 deg/h and an "in-run" bias stability of within 0.3 to 0.8 deg/h.

Figure 2: Honeywell's HG1700

The following section describes the methodology used to process data from both systems integrated with GPS.

METHODOLOGY

Two basic approaches can be implemented in order to integrate the INS with GPS (or DGPS) information. The first one, named an *open loop*, deals with an estimation procedure which only includes the INS errors. In this particular scheme, the GPS calculations are performed external to the INS error estimation, and GPS positions and velocities are used to estimate the INS errors. The second approach, called a *closed loop*, provides for the correction of the GPS measurements within the calculation procedure as well as IMU sensor error compensation in the INS navigation mode.

In principle, the second approach may be more accurate, but the realization of this advantage depends on the application and on the stand-alone INS accuracy. The key lays in the high sensitivity of the state vector estimation accuracy which is dependent on the vehicle dynamics and the random part of the estimation components.

The open loop scheme operates with output error compensation, and as a result, it is more robust with respect to environment changes. The recommended approach can therefore be classified as an open loop scheme that guarantees an acceptable accuracy for different applications, and which has a low sensitivity to the hardware quality. The data from the two different inertial units used in this research were processed using an open loop scheme.

Low-cost System Methodology

From the specifications and test results given in Tables 1 and 2, the MotionPak™ cannot 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 nonlinear error behavior in stand-alone mode. In order to use this unit in an open loop integration scheme, a special damping error procedure is introduced using INS/DGPS measurements. The functional scheme of the low cost IMU/GPS integration is shown in Figure 3.

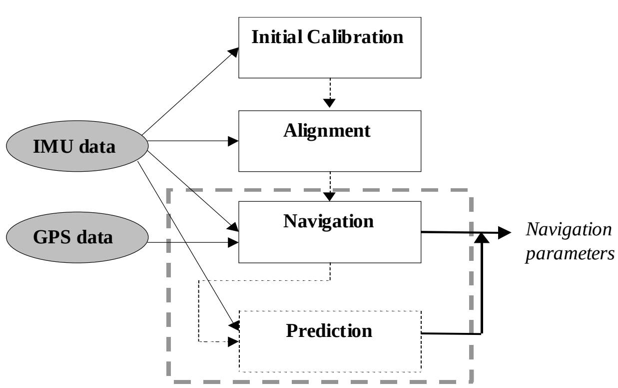

Figure 3: GAIN1™ operating modes

There are four steps in the process, namely (i) initial *calibration* of the run-to-run gyro drift rate bias, (ii) horizontal *alignment* based on the acceleration output, and azimuth *alignment* using a magnetic compass (or any external heading information), (iii) *navigation* mode which estimates errors after alignment, and (iv) *prediction* mode which estimates system errors when no external update information is available. All steps of the integration algorithm are implemented in GAIN1™ (GNSS-Aided Inertial Navigation 1), which is a software package co-developed by the Moscow State technical University's Laboratory of Inertial Geodetic Systems and the Department of Geomatics Engineering at the University of Calgary.

Medium Accuracy System Methodology

For the medium accuracy case, the initialization of the navigation process consists of horizontal alignment and azimuth alignment. Both of these alignment stages are developed in a closed loop manner (Salychev, 1998). The standard alignment in this particular case takes 10 minutes which is enough to smooth the random walk behavior of the gyros.

After alignment, the data processing program switches to navigation mode, and the following processes run in parallel (ibid):

- stand alone INS navigation ("Schuler loop")
- velocity correction
- roll and pitch correction
- heading correction
- INS error estimation for prediction (implemented during GPS outages)

These processes are shown in Figure 4.

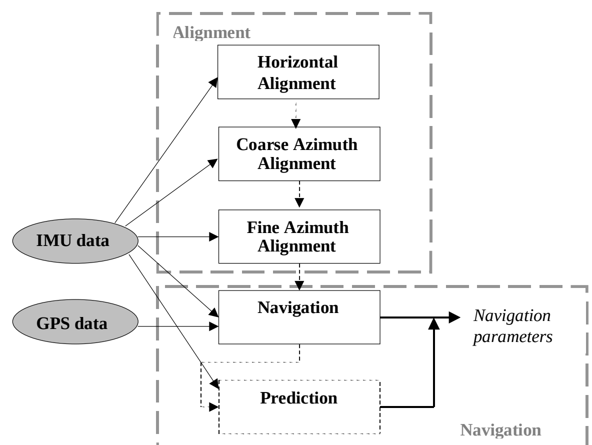

Figure 4: GAIN2™ operating modes

All the above steps are implemented in GAIN2™ which is a second software package also co-developed by same group as above. It is a flexible program for the integration of a medium class of IMUs with different types of GPS receivers. Only a minimal adjustment of the program options is required following from application and hardware. It is a variation of the GAIN1™ methodology described above (Salychev et al., 2000), and was modified to process a medium accuracy INS.

The stand-alone INS navigation algorithm and the correction loops are realized in parallel procedures which help to provide a predictable behavior of the estimated navigation errors. The suggested algorithms are designed for real time implementation, hence this system can be considered as a tool for a wide variety of applications. Note that the application algorithm provides the low frequency (Shuler frequency) error behavior, which leads to a good smoothing property of the estimation algorithm. Moreover, the Schuler behavior of the INS errors can be considered as a low-pass filter, which is able to strongly smooth the random noise of sensor errors.

MOTIONPAK™ TEST AND RESULTS

The MotionPak™ system was tested in airborne mode during flight tests performed in March, 1999 in Battle Mountain, Nevada, by the Newmont Gold Company (USA). The system was installed on top of an I-21, precise gimbal Russian INS, see Salychev (1995) for detailed performance information. Highly accurate aircraft attitude data was available from the I-21 for the entire flight and this was used to compare with the MotionPak™ attitude angles. A differential carrier phase solution from a Trimble 4000SSE was used to update the I-21 to maintain an accurate reference. A Cessna 206 aircraft was used over a total flight time of about one hour.

The accuracy of the I-21 attitude angles is estimated to be 0.1-0.2 arcmin for roll and pitch, and 3-6 arcmin 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 and removed from further data processed.

Figure 5 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 6. The agreement is generally within one degree and the RMS of the differences is about 25 arcmin, see Table 3.

The aircraft roll is illustrated in Figure 7 and is within a five degree range over the flight line. Differences between the two systems, and which represent the MotionPak™ error, are shown in Figure 8 and are within one degree, with the RMS being 22 arcmin. The pitch and roll accuracies are fully satisfactory considering the overall quality of the gyros used in the system.

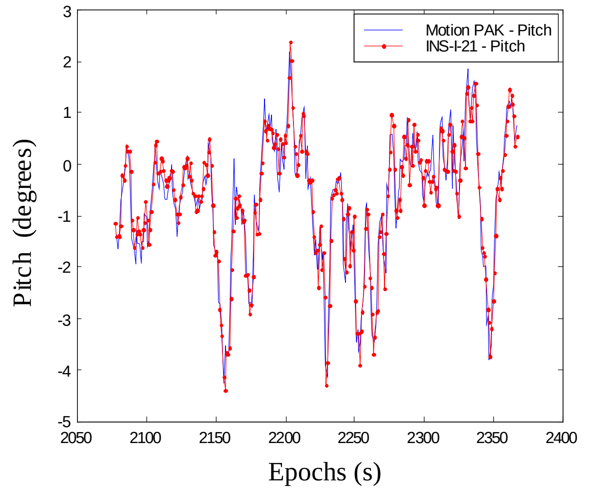

Figure 5: Comparison of pitch between the MotionPak™ and the I-21 INS

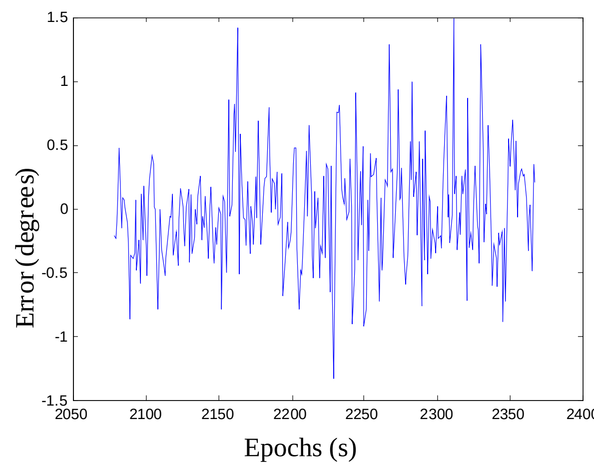

Figure 6: Pitch error (degrees)

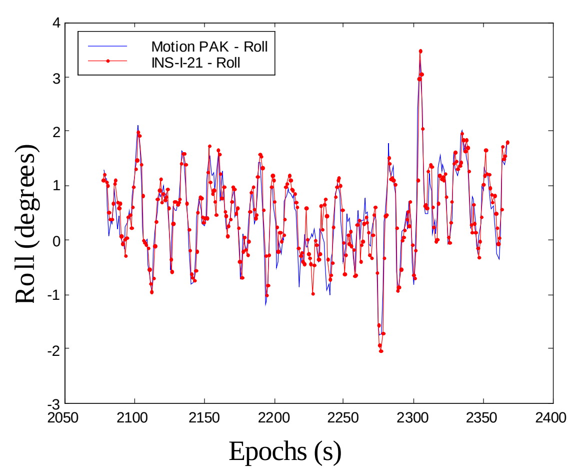

Figure 7: Comparison of roll between the MotionPak™ and the I-21 INS

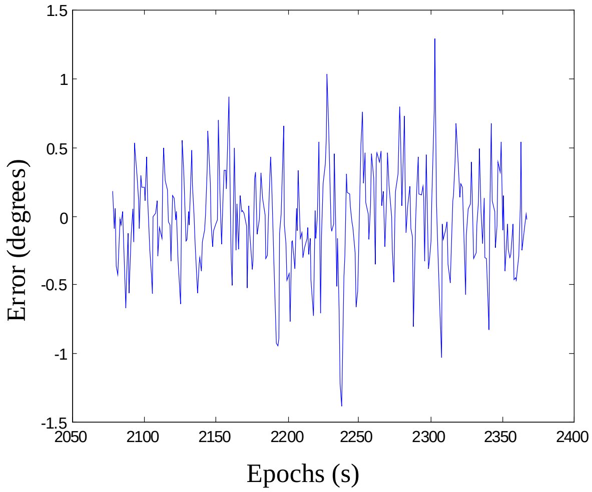

Figure 8: Roll error (degrees)

The aircraft heading is in Figure 9, and the MotionPak™ errors are in Figure 10. The RMS agreement is 44 arcmin, which is poorer than the roll and pitch performance due to the poor observability of the heading errors, as expected.

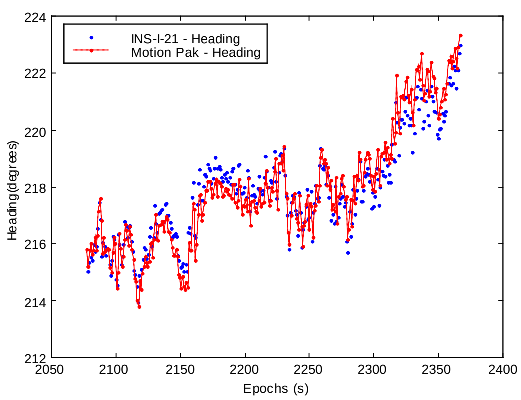

Figure 9: Comparison of heading between the MotionPak™ and the I-21 INS

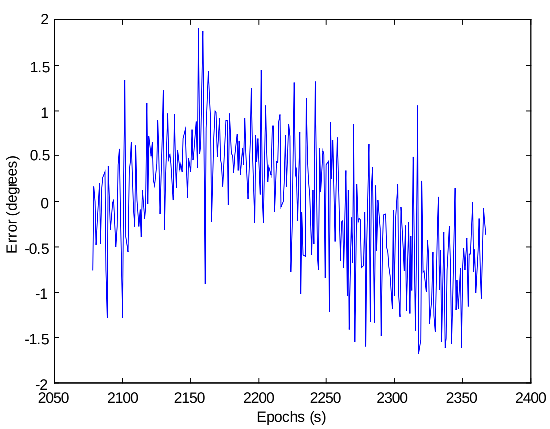

Figure 10: Heading error (degrees)

The differences between the GAIN1™ and I-21 attitude outputs, as summarized in Table 3, show the attitude errors of the MotionPak™/DGPS system. These results show a reasonable attitude accuracy with this low cost system.

Table 3: GAIN1™ attitude error statistics using the MotionPak™

	Pitch (arcmin)	Roll (arcmin)	Heading (arcmin)
RMS Error	25.1	22.4	43.7

HG1700 TEST AND RESULTS

In the case of the HG1700, test runs were carried out in Calgary, Alberta in August, 1999. The system was mounted on the roof of the test vehicle and the antenna was hard-mounted on the box containing the IMU. The test vehicle was driven on a 15.3 km L-shaped traverse as shown in Figure 11. The total duration of the test was 75 minutes. Raw measurements (RGEB) from a NovAtel OEM-3 receiver were logged at 1Hz and the raw angular rates and specific force data from the HG1700 was logged at a rate of 100 Hz.

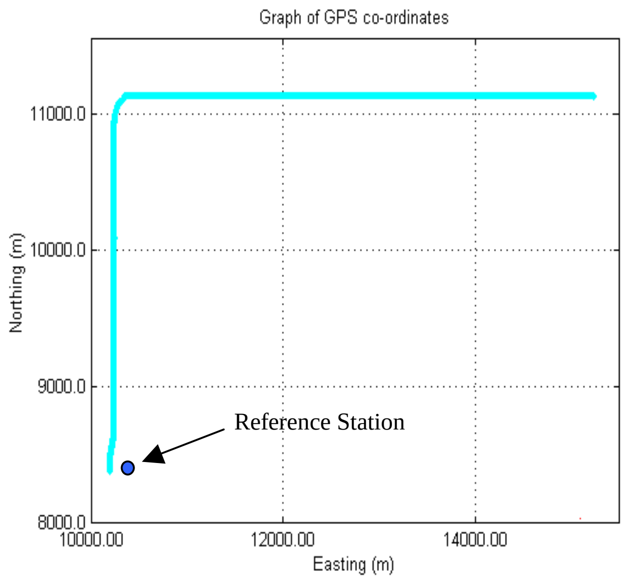

Figure 11: Complete GPS trajectory

The total number of satellites tracked during the test varied between four and nine, with a cut-off elevation of 10 degrees. Zero velocity updates (ZUPTs) were performed at approximately 5 minute intervals.

The particular HG1700 inertial unit used for this test has a run-to-run gyro bias on the level of 0.3 to 0.6 deg/hr which can be determined by the accuracy of the initial alignment. A self-contained horizontal and azimuth alignment has been realized through the GAIN2™ software, and the entire alignment procedure takes 10 minutes of data collected in static mode.

Heading Error Estimation

The GAIN2™ software was developed for the integration of a medium accuracy IMU with GPS (DGPS). In this case, carrier-derived positions (and Doppler derived velocities) were used as update information. A special procedure for heading error estimation was added as an additional estimation step. This procedure is based on the strong observability of the heading error when there is considerable vehicle acceleration (>0.2 to 0.3 m/s^2).

Figure 12 shows the INS velocity error in stand-alone mode (see 'before heading compensation'), and several jumps due to the azimuth error in the direction of the velocity of the vehicle are evident when the vehicle changes from a velocity of zero to the operating vehicle velocity. This jump can be explained by the influence of azimuth error according to the following model (Salychev, 1998)

$$\delta V_E \approx V_N \Phi_{up}$$
$$\delta V_N \approx -V_E \Phi_{up} \quad (1)$$

where V_N and V_E are the projections of the velocity on the local level frame, and Φ_{up} is the azimuth error (assumed to be constant within a restricted time).

For the case when the vehicle is stationary, the above errors are equal to zero, while after the vehicle accelerates, the influence of the azimuth error will quickly appear. In order to compensate for this effect, a heading estimate derived from GPS velocities was computed using the following

$$H = \tan^{-1}(V_E / V_N) \quad (2)$$

The newly estimated azimuth error was introduced into the navigation algorithm in order to recalculate the current velocity in the navigation frame. The heading error, δH, in this case is

$$\delta H = \frac{\sigma(DGPS)}{\sqrt{V_N^2 + V_E^2}} \ . \quad (3)$$

where σ(DGPS) is the standard deviation of the DGPS velocity estimates. As shown in equation (3), the accuracy of the DGPS-derived heading is inversely related to the horizontal velocity components. Therefore, in order to determine heading angles with acceptable accuracy, a minimum value of the velocity can be selected based on equation (1). A 10 m/s value was used in the tests described in this paper. If the speed is below this value, the GPS heading was not used.

Figure 12 shows the effect of the INS heading error compensation using DGPS data (see 'after heading error compensation'). The jumps which are evident before compensation were removed.

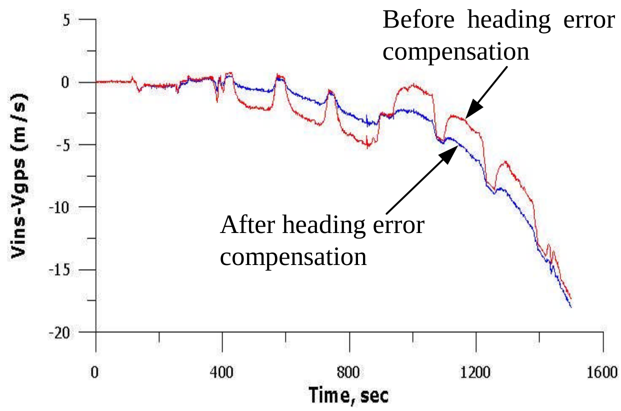

Figure 12: INS velocity errors before and after heading compensation

Horizontal Angle Accuracy Estimation Through Indirect Means

A precise INS (e.g. gyro drift rate is less than 0.005 to 0.01 deg/h) can be used as a reference to assess the attitude angle accuracy, as was shown in the case of the MotionPak™. In this case, such a unit was not available, so in order to estimate the GAIN2™ attitude accuracy, the following non-direct method was used. The simplified INS error model has a form (shown for the east channel) (Salychev, 1998)

$$\delta \dot{V}_E = -g\Phi_N + a_N \Phi_{up} + a_E \mu_E \quad (4)$$

where Φ_N is the horizontal angle error (misalignment angle),
a_N, a_E are the accelerations in the north and east directions,
Φ_{up} is the azimuth (heading) error, and
μ_E is the accelerometer scale factor.

The integration of above equation gives

$$\delta V_E = -\int_{t_0}^{t} g\Phi_N\, dt + \int_{t_0}^{t} a_N \Phi_{up} dt + \int_{t_0}^{t} a_E \mu_E dt \quad (5)$$

Under the condition of a constant vehicle speed, the following equation can be rewritten to give

$$\delta V_E \approx -g\Phi_N t \qquad (6a)$$

or

$$\Delta E = -g\Phi_N \frac{t^2}{2} \qquad (6b)$$

To assess the prediction accuracy of the system, the prediction error over a short time interval (10 to 20 s) can be approximately described as

$$\Delta\tilde{E} = -g\tilde{\Phi}_N(0)\frac{t_{pr}^2}{2} \qquad (7)$$

where $\Delta\tilde{E}$ is the position prediction error,
$\tilde{\Phi}_N(0)$ is the estimation error of horizontal misalignment angle at the beginning of prediction, and
t_{pr} is the prediction time interval.

In order to estimate the GAIN2™ accuracy for the prediction mode, a simulation of DGPS gaps was performed. Since the DGPS information is still available, it is possible to use it as a reference for the comparison with the GAIN2™ predicted values. The INS prediction accuracy based on test data when more then 20 gaps are simulated and the results are shown in Table 4.

Table 4: GAIN2™ prediction accuracy with the HG1700

Outage (s)	RMS Prediction Accuracy (m)
10	0.41
20	1.20

Using equation (7) and the prediction errors from Table 4, the approximate accuracy of the horizontal attitude angles can be estimated. Implementing this approach, the estimated accuracy of the horizontal attitude (roll, pitch) errors is at the level of 2 to 3 arcmin. Note that the above values are conservatively estimated, due to the neglected components in the error model which have additional influence on the output prediction accuracy.

CONCLUSIONS

The main purpose of this paper was to demonstrate the feasibility of using a low cost as well as a medium accuracy inertial unit integrated with DGPS to optimally process the data to achieve precise attitude parameters. Two methodologies were described and used to process test data, and each were implemented in software through GAIN1™ and GAIN2™.

Two inertial systems were tested, namely the MotionPak™ which is a low cost IMU. Tests were performed in airborne mode, whereby the IMU data was integrated with DGPS positions and velocities and the estimated attitude angles were compared to those from the highly accurate I-21 system. Once the misalignment between the two systems was accounted for, the agreement was on the order of 22 to 25 arcmin for roll and pitch, and about 44 arcmin for heading. In the case of the higher end, medium accuracy, HG1700, the achievable attitude accuracy is 2 to 3 arcmin for roll and pitch.

The tests demonstrate that the integrated systems show promising results, which makes possible the development of a cost effective navigation system to support a wide spectrum of applications requiring accurate attitude parameters. The cost of such a system makes it affordable for light general aviation airplanes, land vehicles and shipborne systems. In addition, the GAIN1™ and GAIN2™ software systems are robust with respect to a wide spectrum of hardware from low cost to medium accuracy and can be applied to different applications with minor adjustment.

Other low cost IMU systems, including the GNS Coremicro, will be tested in the near future.

ACKNOWLEDGEMENTS

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REFERENCES

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.

Salychev, O., V.V. Voronov, M.E. Cannon, R. Nayak and G. Lachapelle (2000), Low Cost INS/GPS Integration: Concepts and Testing, Proceedings of the ION National Technical Meeting, Anaheim, January 26-28, pp. 98-105.