GPS/MEMS Inertial Integration Methodology and Results

Tom Ford, NovAtel Inc.
Jason Hamilton, NovAtel Inc.
Mike Bobye, NovAtel Inc.
Dr. Laurence Day, BAE Systems Inc.

BIOGRAPHY

Tom Ford is a GPS specialist at NovAtel Inc.. He has a BMath degree from the University of Waterloo (1975) and a BSc in survey science from the University of Toronto (1981). He became involved with inertial and GPS technologies at Sheltech and Nortech surveys in 1981. He is a member of the original group of GPS receiver developers at NovAtel Inc., where he has helped develop many of the core tracking, positioning and attitude determination technologies used there. His current focus is the integration of GPS other supplementary systems, especially INS.

Jason Hamilton has been a Geomatics EIT at NovAtel Inc. since he graduated with a BSc in Geomatics Engineering from the University of Calgary in 1998. He has worked in the test and OEM development group until 2001, when he became a member of the research team at NovAtel Inc. He is focusing his efforts on GPS/INS integration and the use of phase measurements to enhance the GPS position.

Mike Bobye has been a Geomatics EIT at NovAtel Inc. since he graduated with a BSc in Geomatics Engineering from the University of Calgary in 1999. He worked in customer support until the fall of 2000, when he became a member of the research group assisting with the development of GPS/INS integration.

Laurence Day has a BSc (1974) and PhD (1978) in Applied Mathematics from the University of Wales (Swansea). He joined BAE Systems in 1979 and first got involved in the use of Kalman filters for the integration of navigation sensors in 1980 during the formative years of the TERPROM® terrain referenced navigation system. Since then he has led a number of teams in the development of integrated navigation systems, particularly involving inertial sensors, on a variety of projects within BAE. He is currently a Senior Consultant Engineer at BAE Systems, Plymouth, UK.

ABSTRACT

GPS and inertial systems (INS) provide an obvious synergy whereby low frequency errors in the inertial system are controlled with GPS measurements and at the same time, irregularities in GPS are smoothed or supplemented by continuously available inertial measurements. This technology is well known, and such integrations have been documented since the inception of GPS more than 25 years ago. In that time, inertial systems have evolved from stabilized platforms with spinning mass gyros, to strapdown systems that measure angular change with ring laser or fiber optic gyros to today's strapdown micro-electrical mechanical systems (MEMS). The MEMS inertial measurement unit (IMU) integrated with GPS, promises to provide a cost effective, low power, low volume position, velocity and attitude system for a myriad of navigation applications.

Typical performance for a tactical grade ring laser gyro IMU is 1 deg/hr gyro bias and 1 mg accelerometer bias. The best available MEMS unit currently provides 5 to 10 degrees gyro stability with an industry goal of 1 deg/hr in five years. Other IMU system parameters associated with MEMS are proportionally less certain than those associated with ring laser or fiber optic tactical systems. Therefore, the performance possible with MEMS integrated systems will be proportionally worse than that available from the more mature tactical systems. The system integrator must go to greater lengths to achieve acceptable performance with the MEMS IMUs currently available.

This paper describes NovAtel's experiences in integrating a MEMS IMU (the BAE SiIMU01) with its OEM4-G2 GPS receiver. The performance objective of the system is to provide accuracy over a ten second full or partial outage such that the resulting position at the end of the outage interval can be used to help the GPS carrier positioning software instantly regain carrier ambiguities. The challenge associated with this task is significant and various modeling approaches were used in order to achieve this performance. These approaches are described

along with the performance achieved with each of the different modeling methods. In addition, the performance is described during intervals in which only partial satellite coverage is available.

INTRODUCTION

BAE Systems is a leading provider of inertial sensors and systems, including silicon-MEMS inertial based products to automotive, commercial and military markets.

NovAtel Inc. is a leading provider of precise global positioning and Real Time Kinematic (RTK) augmentation technologies to commercial customers. Both companies have extensive expertise in GPS/INS system integration and have entered into a collaborative program of phased development to produce dependable, accurate and increasingly affordable MEMS-based GPS/INS products for all commercial markets.

An early step in this development is a loose integration of the SiIMU01® and the OEM4-G2. This provides a platform upon which different modeling scenarios can be investigated. The integration approach generally followed the one taken in [5] and [6], in which a 15 state filter modeled position, velocity, attitude and 6 bias states. The system errors were observed and damped with GPS position measurements. Double difference phase measurements (across satellites and time) provide error damping in some, but not all, directions when partial GPS (2 or 3 satellites) coverage is available. Wheel pickoff information can also be used to restrict error growth in the along track direction. The advantages of including the supplementary measurements (double differences and wheel pickoff) are quantified.

In order to identify additional modeling states that could be used to increase the accuracy and consistency of the system, error analysis based on the specified and measured sensor characteristics of the SiIMU01® was carried out. This analysis indicated that including modeling for the z gyro scaling and the x and y gyro non-orthogonalities with respect to the z axis would be advantageous for this system. Test results are included that quantify the increase in accuracy associated with the inclusion of these states.

The SiIMU01® is a MEMS IMU with a bias repeatability of 100 deg/hr (turn on uncertainty). With a gyro bias as large as this the heading is not observable with earth rate. Instead, heading is computed in the presence of motion by the Kalman filter. The heading is an element in the Kalman filter transition matrix and so non-linearities associated with the typically large initial heading error cause the system to take a long time to converge to a steady state solution. Modeling accommodations have been made to alleviate this problem, and results are presented that indicate the effectiveness of this approach.

BAE Systems and NovAtel Inc. have collaborated to produce the first of many integrated systems. This paper describes the components and the integration approach taken. It also identifies some design tradeoffs and quantifies the advantages of the various choices. It also quantifies the performance of the system under various GPS observation scenarios.

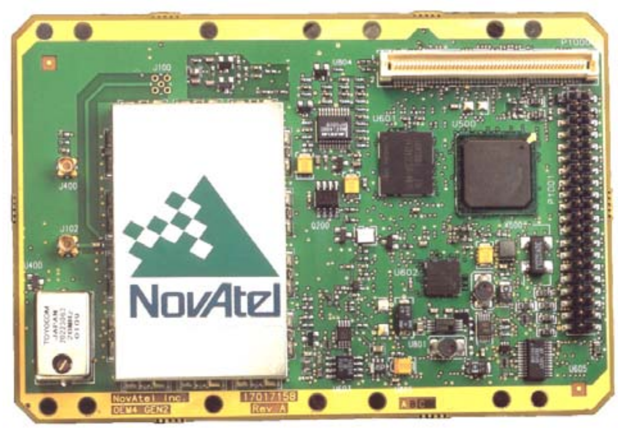
EQUIPMENT DESCRIPTION

The current integrated system is a combination of the NovAtel Inc. OEM4-G2 GPS receiver and the BAE SiIMU01® Inertial Measurement Unit.

NOVATEL OEM4-G2 GPS RECEIVER

The OEM4-G2 is the second generation of the original OEM4 GPS receiver. It is a single printed circuit board with integrated radio frequency (RF) and digital sections. It is a low power, high performance receiver that has been designed for flexibility of integration and configuration.

PHOTO 1:OEM4-G2



This is 61% of the actual size of the OEM4-G2.

Some of the notable features of the OEM4-G2 are the following.

Features:

- 24 channel “all-in-view” parallel tracking
- Pulse Aperture Correlator (PAC) technology
- 20 Hz raw data and position output rates
- Three serial ports, one of which is user-selectable for RS-232 or RS-422
- USB support (with firmware version 2.100 or higher)
- L1/L2 plus RT-2

The physical and performance characteristics are noted below.

Physical characteristics:

Size: 85mm x 125mm with connectors

Weight: 85 grams

Input Voltage: +4.5 to +18.0 VDC

Power consumption: 2.2 W (typical)

The performance characteristics of the OEM4-G2 depend on the enabling mode selected. Depending on the purchase price, different modes, and therefore different levels of performance are available.

TABLE 1: OEM4-G2 PERFORMANCE

Mode	**Accuracy**
L1 only	1.8 m CEP
L1/L2: 1.5 m CEP	1.5 m CEP
WAAS with L1 only	1.2 m CEP
WAAS with L1/L2	0.8 m CEP
Code Differential	0.45 m CEP
RT-20	0.20 m CEP
RT-2	0.01 m + 1 ppm CEP
Time Accuracy *****	20 ns RMS
Velocity Accuracy	0.03 m/s RMS

* Time accuracy does not include biases due to RF or antenna delay.

BAE SiIMU01® INERTIAL MEASUREMENT UNIT

SiIMU01® is an all-MEMS system, which provides fully compensated 6-DOF angular rate and linear acceleration measurements suitable for platform navigation, guidance and stabilization. Miniature high performance silicon accelerometers (Colibrys MS8000 series) and BAE SYSTEMS' highly successful SiVSG angular rate sensors are combined in a modular design. This allows price/performance optimization of the SiIMU01® to meet specific customer requirements.

Features:

Angular Measurement Range

x,y axis: ±600 deg/sec

z axis: ±1000 deg/sec

Linear Measurement Range: ±50g

Data rate: 100 Hz

PHOTO 2: SiIMU01®

The physical and performance characteristics are noted below.

Physical characteristics:

Size: 45.5mm x 80mm circular footprint

Weight: 250 grams

Input Voltage: +/-15V DC and 5V DC

Power consumption: 5 VA

Operating Temperature: -40 deg C to +75 deg C

Relative Humidity: 100%

Vibration (operational): 18 g rms (20 Hz to 2 kHz)

Shock: 250 g

The performance characteristics of the SiIMU01® are noted in Table 1 below.

TABLE 2: SiIMU01® PERFORMANCE

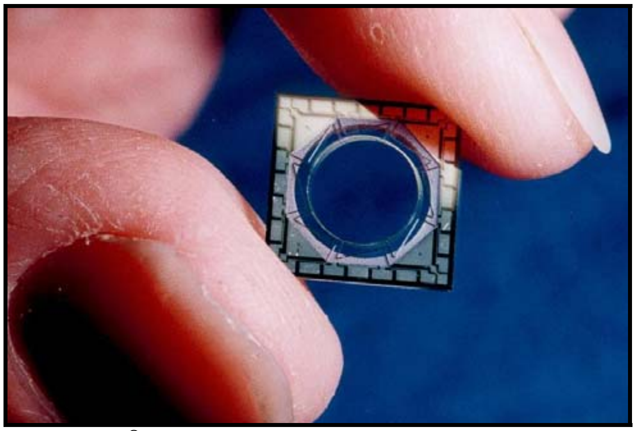
Characteristic	**Gyro**	**Accelerometer**
Bias Repeatability	100 deg/hr	10 mg
Bias Instability	5 deg/hr	0.5 mg
Random Walk	1 deg/rt-hr	1 m/sec/rt-hr
g Sensitivity	1 deg/hr/g	-

GYRO TECHNOLOGY

The Silicon Vibrating Structure Gyroscope (SiVSG®) technology is the culmination of more than 80 years of BAE SYSTEMS experience in the gyroscope business and over 15 years in the development and production of robust solid-state rate sensors. The key element is a vibrating ring resonator, the vibration mode of which changes (due to coriolis forces) when the device is subject to a rate of turn.

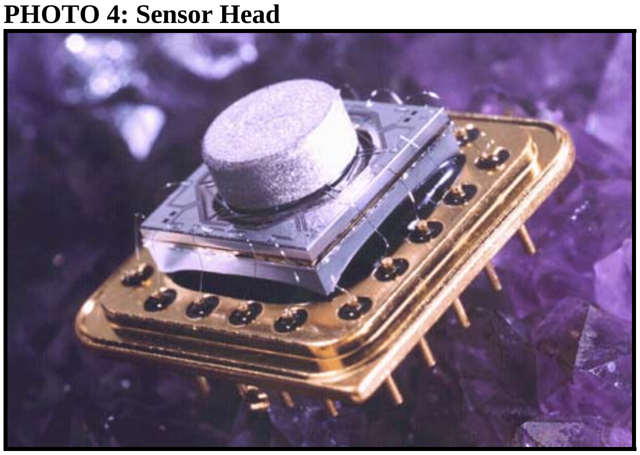
Originally a ceramic cup, then a metal ring, the use of crystalline silicon and micro-machining techniques has now shrunk the ring resonator to 6mm in diameter. A central miniature magnet provides the basis for the electromagnetic resonance, current being fed into the ring via metalised tracks deposited on its supporting 'dog-legs'. The complete packaged sensor head is in high volume production and sensor products using this device coupled with custom ASIC-based control circuitry are in use world-wide.

PHOTO 3: SiVSG® VIBRATING ELEMENT



The SiVSG® silicon element

PHOTO 4: Sensor Head



SiVSG® is the only known VSG technology to use closed-loop excitation, which provides excellent scale factor and performance stability over wide rate ranges. Over 80 patents have been filed or are pending. In addition, the particular vibration and the use of high technology adhesives ensure that the ring resonator has extremely high resistance to shock, giving a unique product advantage in both the automotive and defense markets.

ACCELEROMETER TECHNOLOGY

The Colibrys MS8000 series accelerometers are MEMS capacitive sensors, based upon a bulk micro-machined silicon element, a low power ASIC for signal conditioning, a micro-controller for storage of compensation values and a temperature sensor.

The core of the accelerometer is the capacitive bulk micro-machined silicon sensor. This element consists of three silicon wafers, bonded together by fusion bonding. The middle plate contains a seismic mass attached at one end by a beam. Under acceleration or tilt, the inertia makes it move between the upper and lower plates and change the values of the capacitors. This differential variation of the sensing capacitors is measured by the interface circuit, which uses a self-balancing capacitor bridge to translate the signal into a calibrated voltage output. The compensation parameters of the offset and gain and the correction of the remaining non-linearity are finally stored in the micro-controller.

INS ERROR ANALYSIS

In this section a prediction of the position and attitude errors on the integrated system after a 10 second GPS outage is made based on the noise and stability characteristics of the SiIMU01®. Tables 3 and 4 below show the error propagations of the gyro and accelerometer elements that dominate the position error budget [4]. In the first column of both tables are the expected errors of the dominating system error parameters for the SiIMU01®. An assumption associated with the effect of axis misalignment is that the bulk of the angular change will be about the vertical axis. This is valid on a road vehicle with the z-axis mounted vertically. Therefore heading change is the only angular factor included in the position error calculation based on axis misalignment. Also of note is the absence of any contribution from either gyro or accelerometer bias. Although these can be significant (especially the gyro bias), it is assumed that the filter is able to estimate these parameters to the level of the bias instabilities noted in the tables below.

TABLE 3

Gyro Error Parameter	Pos. Error after t seconds
Bias Instability Bias = 5°/hr D = 2.4e-5rad/sec	$g*D*t^3/6$
Scale Factor (Acc) Sf = 1500ppm	$Sin(Sf*dH)*t^2*Acc/2$
Noise ARW = 0.75°/√hr	$[g*ARW/(60*57.29)] *t^{5/2}/\sqrt{(20)}$
Axis misalign mis = 0.001 rad	$mis*dH*g*t^2/2$

Note: g = acceleration from gravity

Acc = Acceleration during heading change
dH = Heading change

TABLE 4

Accelerometer Error Parameter	Pos. Error after t seconds
Bias Instability Bias = 2 mg	$Bias*t^2/2$
Scale Factor Sf = 2000 ppm	Acc*Sf*T*t
Noise VRW = 1m/s/√hr	$(VRW/60)* t^{3/2}/\sqrt{(6)}$
Axis misalign mis = 1 mrad	-

Note: Acc = Acceleration, T = time of acceleration, t is the outage time

The errors in the following tables 5 and 6 are based on either the system specification or measured values from the SiIMU01® units tested. The parameter values used in the calculations are shown in the left hand column. The errors are computed for times of 10 and 30 seconds.

TABLE 5

Gyro Error Parameter	Pos. Error after 10 seconds	Pos. Error after 30 seconds
Bias Instability Bias = 5°/hr	0.04m	1.07m
Scale Factor (i) Sf = 1500ppm	0.47m	
Noise (ii) ARW = 0.3°/√hr	0.07m	1.13m
Axis misalign (iii) mis = 1 mrad	1.54m	13.87m

Note: (i) assume a 180 degree turn during which there are no satellites and an acceleration of 2 m/sec^2 for 10 seconds
(ii) Based on raw data collected
(iii) assume a 180-degree turn with no satellites followed by either 10 or 30 additional seconds with no satellites.

TABLE 6

Accel. Error Parameter	Pos. Error after 10 seconds	Pos. Error after 30 seconds
Bias Instability Bias = 0.5 mg *	0.25m	2.21m
Scale Factor ** Sf = 2000 ppm	0.49m	4.42m
Noise VRW = 1m/s/√hr	0.21m	1.11m
Axis misalign (1 mrad)	-	-

Note: * Based on collected sets of raw data
** assume an acceleration of 0.5 m/sec2 for 10 seconds, followed by an outage time of 10 or 30 seconds.
Acc = Acceleration, T = time of acceleration, t is the outage time

Based on this analysis, a ranking on importance of modeling the various sensor errors can be made. Under the selected maneuvers, horizontal axis misalignments have the larges effects, followed by accelerometer scaling and gyro scaling errors. Accelerometer noise and bias instability are next. Gyro bias and noise effects are small by comparison.

INTEGRATION DESCRIPTION

The OEM4-G2, power supply board and PCMCIA data collector module is housed in a NovAtel Inc. DL-4*plus*, shown in PHOTO 5 below.

PHOTO 5: DL-4*plus*

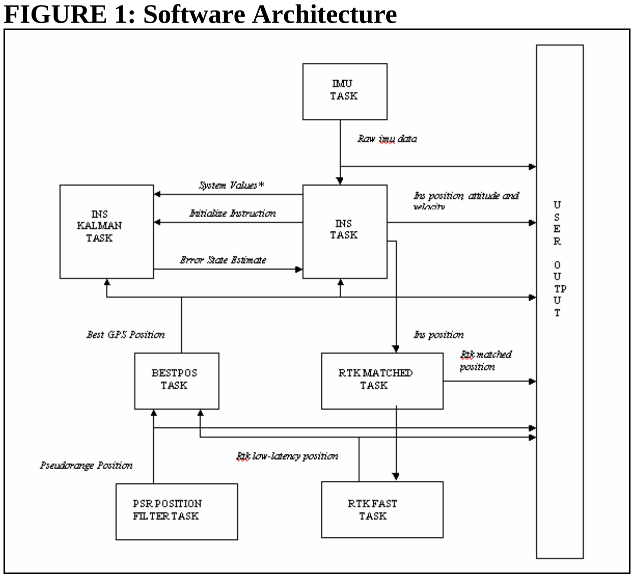
The SiIMU-01 is housed in a 16 by 16 by 10 cm aluminum case shown in the following PHOTO 6.

PHOTO 6: IMU Housing

The SiIMU-01 is connected to the OEM4-G2 via an RS-232 serial interface. Serial messages are transmitted at a 100 Hz rate from the IMU to the OEM4-G2. The first byte in each serial message triggers an interrupt serviced by a timing function tightly bound to the receiver's correlator chip. The time tag generated is accurate to 10 microseconds. The time tag is buffered while the rest of the 10 msec serial message is accumulated.

The OEM4-G2 software runs on a multitasking operating system that supports different priority levels for different classes of tasks. In general, interfacing tasks have the highest priority and low frequency computationally intensive tasks have low priority. Examples of the latter are the GPS positioning tasks, the RTK ambiguity resolution tasks and the inertial Kalman filter tasks. High frequency tasks with relatively limited computational demands (i.e. tracking and inertial processing – running at 50 or 100 Hz) have priority levels somewhere in between. Figure 1 below shows the software architecture used in the integration.

FIGURE 1: Software Architecture



With reference to Figure 1, the main inertial task elements include an IMU task (interfacing), an INS task (100 Hz position generation), and an INS Kalman filter task (1 Hz filter). The IMU task feeds the body frame measurements to the INS task, which in turn maintains the IMU attitude parameters, transforms the delta velocities to the ECEF frame, removes gravity and coriolis accelerations and integrates the remainder once for velocity and again for position. As the even second boundary is crossed, the position, velocity and attitude are propagated to the even second mark with a fractional portion of the raw data. The even second system data is transferred to the INS Kalman filter task to be used in the position update logic once a GPS position becomes available. When an update is completed the system corrections are propagated to the current time (typically 30 msec past the even second mark) and transferred back to the INS task for modification of its' system parameters.

The GPS tasks provide position, velocity, pseudorange and carrier data to the INS Kalman filter task. It can use velocity in the alignment process, and carrier data to update the INS system errors. The carrier data is used to constrain the change in position, as described in [8]. The means to do this includes differencing pairs of carrier measurement for specific satellites across time, and differencing pairs of these to remove the effect of a changing receiver clock to provide a double difference measurement that equates to a position change defined by the relative user/satellite geometries. This observation is incorporated into the filter via the addition of position error states associated with the appropriate previous time on which the position change constraint can be applied.

The basic Kalman filter has 15 basic states including nine for position, velocity, and attitude and six to model gyro and accelerometer biases. Additional states representing z axis (up) gyro scaling and x and y non-orthogonalities with respect to the z axis are included in the filter. It is appropriate to model these rather than all the scaling and non-orthogonalities, because the bulk of the system rotation occurs about the z-axis of the system.

CHALLENGES

The SiIMU01® gyro bias turnoff to turn on uncertainty is upwards of 100 deg/hr. This means that the usual gyro compassing used to determine rough heading with tactical and navigation grade IMUs will not work. This integrated system does not have an independent heading reference, so must rely on the pullin characteristics of the Kalman filter in the presence of vehicle dynamics to observe heading. If the biases are estimated before the heading is known, it is possible to insert non-linear effects via the transition matrix that cause significant delay in the computation of a valid alignment. In order to overcome this difficulty, the number of filter states is reduced to 9 until heading is estimated and validated. The validation criteria includes a history of measurement/system consistency and if possible an agreement between GPS velocity direction and system heading. Once the heading has been validated, the biases and additional states can be estimated without injecting hysterisis into the system.

According to the error analysis included above, the gyro axis non-orthogonalities and gyro scaling can cause significant maneuver dependent errors. This being the case, it should be possible to estimate these system elements and thereby remove their effects. But the estimation process is hampered somewhat by the sensor noise on the IMU. Over time, sensor noise can corrupt the system and reduce the observability of those elements that only affect the system during maneuvers. Given the size of the bias instability and gyro angular random walks, it is not clear if adding states to represent the z axis scaling or the x,y axis misalignments to z will help reduce system error or not. This will be the subject of some of the tests to follow.

RESULTS

The function of an INS is to provide attitude, velocity and position to the system's user in a timely and continuous fashion. A series of tests are designed to evaluate the accuracy and availability of the system's position and attitude under different operational conditions. The accuracy of the position is quantified during 10 second GPS outages while the system is in steady state. Position accuracy is also quantified when partial GPS coverage is available, and if a wheel pickoff is present. The effect of the inclusion of gyro misalignment and scaling states is evaluated. The attitude accuracy is determined when GPS is continuously available. Finally, the time it takes the system to reach steady states using two different alignment procedures is compared.

POSITION

Position errors after 10 seconds with no GPS, with either 2 or 3 satellites, with and without wheel pickoff are given. Data is collected in an area with good satellite coverage where precise carrier differential positioning is continuously possible. This provides both continuous control and complete flexibility in the choice of outage interval. By passing through the data multiple times, an outage interval can be induced to slide across the entire data set, one second at a time. In this way statistics can be generated that show the effect of a 10 second (for example) GPS outage at every epoch of a particular data set. We call this a sweep test, and it is repeated for various choices of observations available and methods of processing.

The trajectory used to generate test results has a significant impact on performance during ten second outages. The two trajectories selected for the test varied. A low dynamics trajectory had turns of 90 degrees or more every 2 minutes (approximately), while a "high" dynamics trajectory incorporated turns every 30 seconds or so. The positioning results are shown for the low and high dynamics cases. An example of the 10 seconds errors seen in the low dynamics case is shown in Figures 2, 3 and 4 below. The red lines representing the 1-sigma position error bounds reported by the system in general bound the irregular dark lines representing the 10-second position errors.

Figure 2: North Position Error No satellites for 10 sec

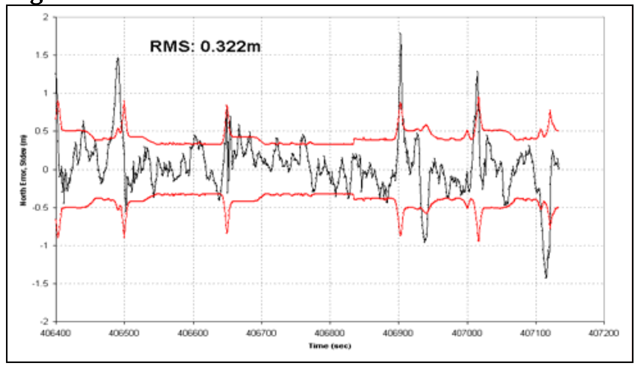


Figure 3: East Position Error No satellites for 10 sec

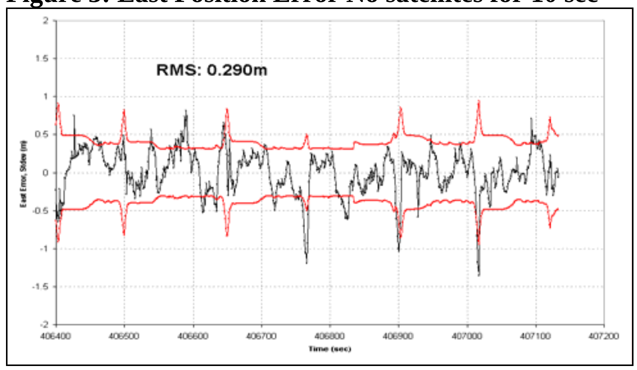
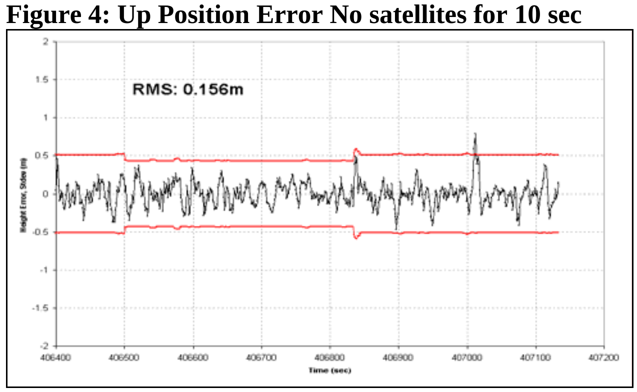


Figure 4: Up Position Error No satellites for 10 sec



This particular set of outage data was generated with a basic 15 state filter consisting of position, velocity, attitude, gyro biases and accelerometer biases. The RMS of the position errors were 0.32m, 0.29m and 0.16m for north, east and up respectively. These results can be compared favorably with those shown in Figures 5, 6 and 7 below that were generated from a more dynamic trajectory that had turns every 30 seconds.

Figure 5: North Position Error No satellites for 10 sec No Misalignment or Scaling Estimates

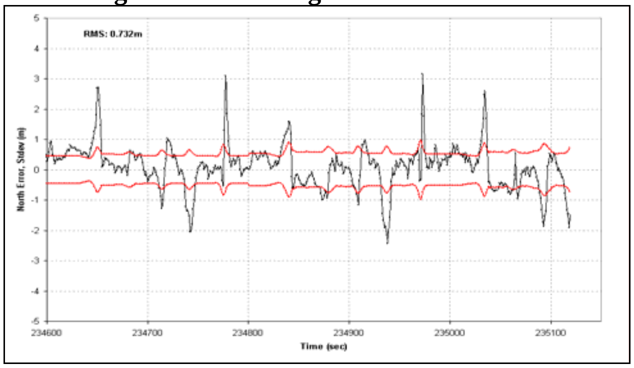


Figure 6: East Position Error No satellites for 10 sec No Misalignment or Scaling Estimates

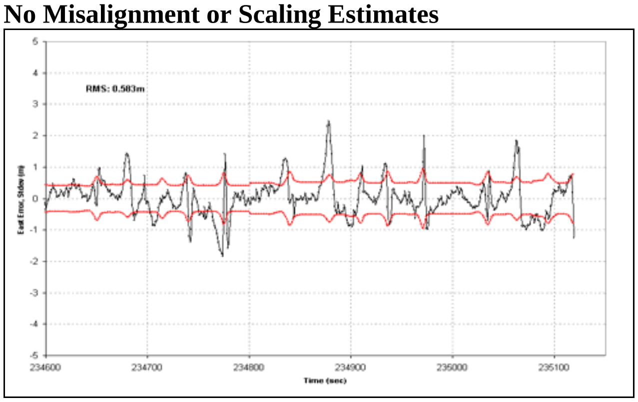
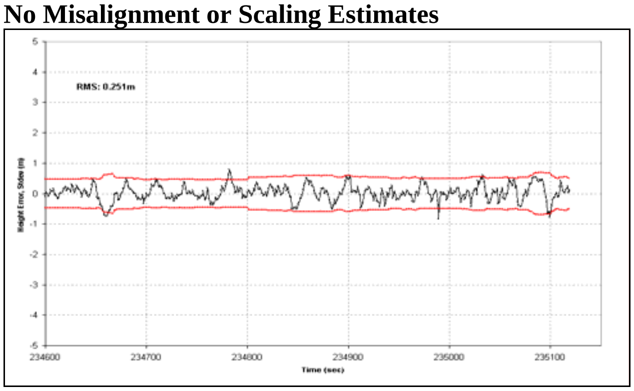


Figure 7: Up Position Error No satellites for 10 sec No Misalignment or Scaling Estimates



The RMS position errors for north, east and up for the data in Figures 5, 6 and 7 are 0.73m, 0.58m and 0.25m respectively. The addition of x into z and y into z misalignment states and a z gyro scaling state reduces the errors somewhat. For this data set, the RMS position errors reduce to 0.48m, 0.43m and 0.22m for north, east and up respectively when these three states are estimated. The 10-second position errors are shown in Figures 8, 9 and 10 below.

Figure 8: North Position Error No satellites for 10 sec With Misalignment and Scaling Estimates

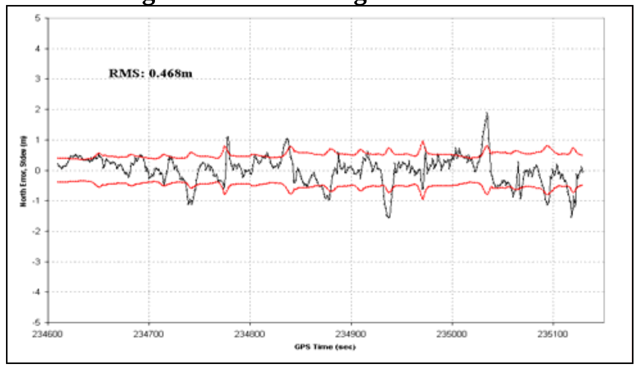


Figure 9: East Position Error No satellites for 10 sec With Misalignment and Scaling Estimates

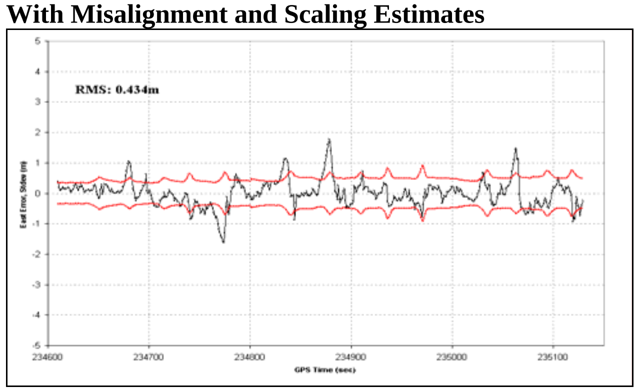


Figure 10: Up Position Error No satellites for 10 sec With Misalignment and Scaling Estimates

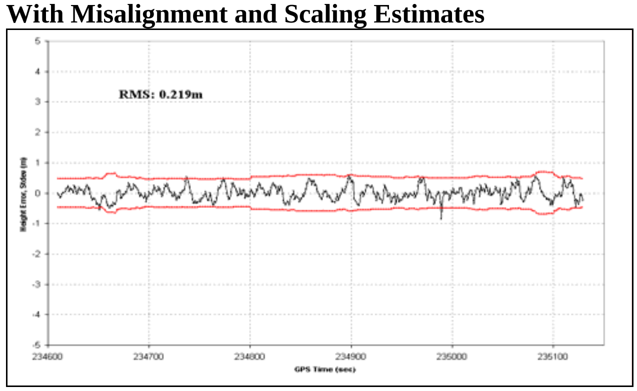


Table 7 below summarizes the complete satellite outage results when misalignments and scalings are not estimated. The north, east and up columns show the RMS of the position errors for the various position components. The Horizontal Peak to Peak error is also included because it shows an interesting contrast to the case in which the misalignments and z scaling are estimated.

TABLE 7: Complete Satellite Outage Results (No Misalignments or Scaling Estimated)

Run	North (m)	East (m)	Up (m)	HptoP (m)
1:MD	0.648	0.431	0.209	4.499
2:MD	0.473	0.437	0.267	3.250
3:MD	0.633	0.342	0.195	4.988
4:MD	0.549	0.464	0.248	3.910
5:LD	0.294	0.283	0.160	2.772
6:LD	0.299	0.296	0.153	2.851
All	0.483	0.376	0.205	3.712

Note: MD is medium dynamics, LD is Low Dynamics, HptoP is Horizontal Error Peak to Peak

The same data was reprocessed with the misalignments of the x and y gyro axis into z and the z-axis gyro scaling estimated. The results are shown below in Table 8.

TABLE 8: Complete Satellite Outage Results (With Misalignments and Scaling Estimated)

Run	North (m)	East (m)	Up (m)	HptoP (m)
1:MD	0.470	0.333	0.224	3.898
2:MD	0.362	0.404	0.248	2.027
3:MD	0.603	0.333	0.242	4.706
4:MD	0.468	0.435	0.233	3.443
5:LD	0.294	0.296	0.154	2.623
6:LD	0.279	0.282	0.154	2.840
	0.428	0.351	0.213	3.256

The additional 3 states cause the system performance to improve horizontally (in 11 of 12 cases) in an RMS sense, but not vertically. The improvement is most pronounced in the medium dynamics cases. The low dynamics cases improve marginally or not at all.

In many applications, partial GPS coverage is available. A test was devised to evaluate the performance of the integrated system when 2 or 3 satellites were available. As in the case where no satellites were available, some, but not all satellites were removed from the solution for 10 seconds, and the position error at the end of the outage interval was recorded. The time of the outage interval was then shifted and the process repeated. Errors for every epoch were generated in this way. The satellites were selected for partial outage availability on the basis of highest signal to noise. Wheel pickoff information can also help fill in the outages that occur when GPS is unavailable. The reduction in position error when a wheel pickoff is available is shown with the partial outage data below in Table 9. A summary statistic associated with a complete ten-second outage in all the data is included for comparison.

TABLE 9: Partial Satellite Outage Results (With Misalignments and Scaling Estimated)

SVS	North (m)	East (m)	Up (m)	HptoP (m)
0	0.466	0.373	0.296	3.256
2	0.317	0.208	0.190	2.750
3	0.204	0.121	0.153	1.5715
WP	0.309	0.263	0.211	2.446
2+WP	0.185	0.123	0.167	1.7105
3+WP	0.139	0.098	0.145	1.305

The two-satellite partial coverage case reduces the horizontal error by 36% over the complete outage case. The three-satellite case shows an improvement of 60%. A wheel pickoff is roughly equivalent to a pair of satellites (one satellite observation), while two satellites plus a wheel pickoff is more or less equivalent to two satellites. Three satellites and a wheel pickoff give the same number of observations as four satellites but the precision of the observations may not be as good, and the geometrical strength will not be as good as a full constellation. Therefore, combination of three-satellites and a wheel pickoff give the best partial coverage performance, but still have errors in the 10 to 15 cm range.

In order to see the effect of the additional sensors, a series of figures (11 to 15) are included to show the effects of different levels of partial coverage (2 or 3 svs) and the effect of a wheel pickoff. The same data set is used as in Figures 5 to 10 (see Fig 9 for a direct comparison).

Figure 11: East Position Error 2 satellites for 10 sec

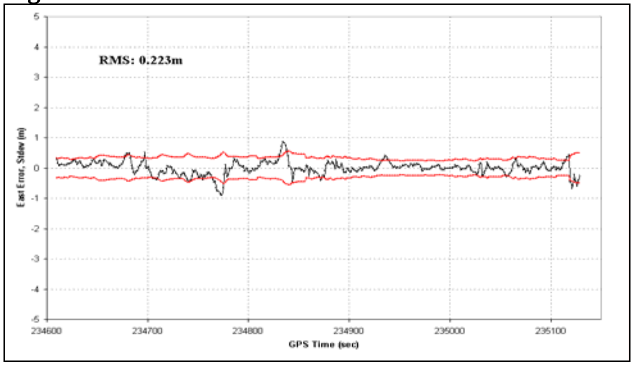


Figure 12: East Position Error 3 satellites for 10 sec

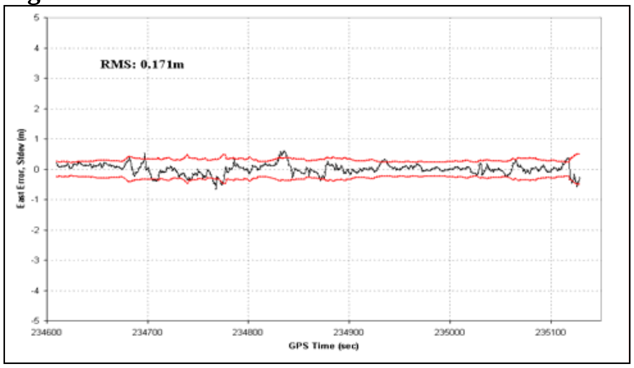


Figure 13: East Position Error 0 satellites but wheel pickoff for 10 sec

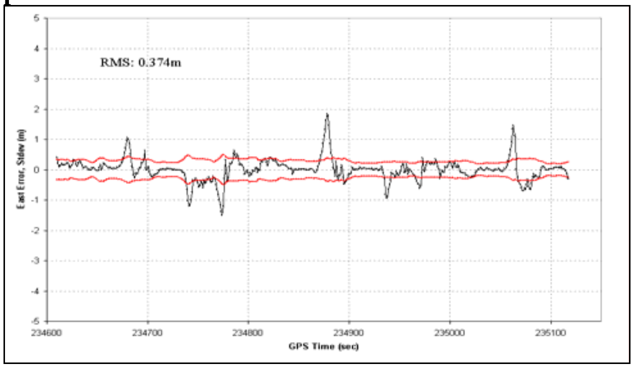


Figure 14: East Position Error 2 satellites and wheel pickoff for 10 sec

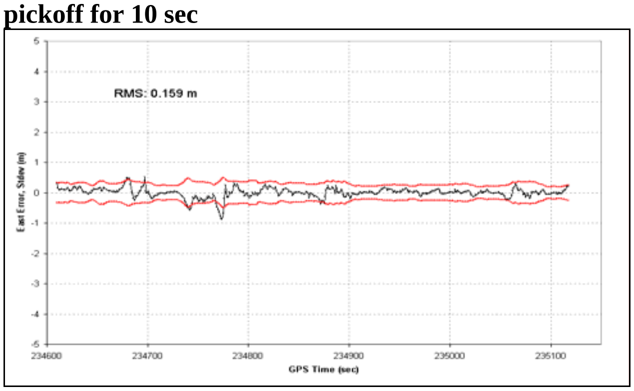
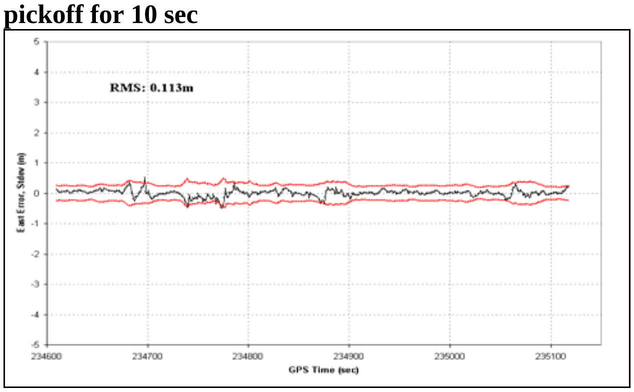


Figure 15: East Position Error 3 satellites and wheel pickoff for 10 sec



The wheel pickoff helps in the along track direction, but not cross-track. Consequently, for the trajectory being considered the east component improves about ½ the time, and stays the same the other half.

ATTITUDE

The attitude test consists of an attitude comparison of the SiIMU01® system with the HG1700 system when the full GPS constellation is continuously available. The HG1700 (AG11) is a Honeywell IMU that has a 1 deg/hr gyro bias and when integrated with the NovAtel Inc. OEM4-G2 can provide roll, pitch and heading accurate to 0.015 deg, 0.015 deg and 0.05 deg respectively. The variation of the BAE/NovAtel Inc. integrated system indicates a lower bound on the attitude accuracy of the system. In this test the BAE/NovAtel Inc. system attitude is differenced from the HG1700 system attitude. The angular offset is removed to account for mounting alignment differences and the RMS of the residual difference is computed. The data set on which the comparison was made had continuous GPS coverage, and both systems had reached steady state. The standard deviations of the difference in the attitude between the HG1700 system and the SiIMU01 system are shown in Table 10 below.

TABLE 10: Attitude Comparisons (Stdev of attitude differences between HG1700 and SiIMU01)

Run	Roll (deg)	Pitch (deg)	Yaw (deg)
1:MD	0.070	0.088	0.116
2:MD	0.093	0.089	0.156
3:MD	0.110	0.054	0.218
4:MD	0.060	0.044	0.112
5:LD	0.037	0.046	0.253
6:LD	0.039	0.040	0.161
All	0.073	0.064	0.177

Based on these results, it can be said that the average error in attitude for the SiIMU01 system is 0.075 degrees for roll and pitch and 0.20 degrees for heading.

ALIGNMENT

In this test a comparison is made of the position errors that occur while the system is aligning first when all the states are estimated during the alignment and second when just the nine primary states are estimated. During this test 6 different alignments were attempted. Four of the alignments had dynamics reflective of turns every 30 seconds or so. Two of the runs experienced turns every 150 seconds. The time to steady state (TTSS shown in the following table) is measured from the time of first motion to the time at which the agreement between GPS derived heading from velocity and inertial heading is within 2 degrees for 10 consecutive measurements.

TABLE 11: Dependence of Time To Steady State (TTSS) on filter size

Alignment Number *	15 State TTSS (sec)	9 State TTSS (Sec)
1:MD	537	157
2:MD	460	181
3:MD	443	47
4:MD	30	30
5:LD	846	351
6:LD	885	346
All	533	183

* MD is Medium Dynamics, LD is Low Dynamics, TTSS is Time To Steady State

The average time to steady state reduces from 533 to 183 seconds. This is an improvement of 60%. Clearly the number of states in the filter has an impact on the time to steady state, as does the dynamics experienced by the system. This is a result of the non-linearities in the filter that result from an initial random heading error of up to 180 degrees. The non-linearities cause pull-in delays via incorrectly estimated gyro and accelerometer biases. These are initially estimated with upwards of 4000 deg/hr error for the gyros, and 2 m/sec^2 for the accelerometer biases.

CONCLUSIONS

BAE Systems and NovAtel Inc. have collaborated to produce an integrated system consisting of the SiIMU01®.MEMS IMU and the OEM4-G2 GPS receiver.

Results show that attitude accuracy of 0.1 deg in roll and pitch and 0.20 deg in heading can be achieved with this system.

Results show that the position error grows to 0.39 metres horizontally and 0.21 metres vertically after 10 seconds without GPS.

The error growth can be significantly reduced (by 36% with two satellites, by 60% with 3 satellites) if partial coverage GPS is available.

The time to steady state of this system can be reduced by 60% if a partial state estimation is used during the initial heading pullin.

The addition of misalignment and scaling states improve the horizontal but not vertical performance of the system in the medium dynamics case. The improvement in the low dynamics case is marginal or imaginary.

ACKNOWLEDGMENTS

Thanks to Dervila Adams for providing a compatible data sheet for the OEM4-G2.

REFERENCES

[1] BAE Systems, “SiIMU01 Reference Manual”, 2004

[2] NovAtel Inc., “OEM4-G2 Reference Manual”, 2004

[3] NATO Lecture Partridge (BAE) “Description of wine glass gyro” (I’ll look up specifics)

[4] E. Levinson, “Laser Gyro Strapdown Inertial System Applications”, AGARD Lecture Series 95, June, 1978.

[5] T. Ford, J. Neumann, M. Bobye, “OEM4 Inertial: An Inertial/GPS Navigation System on the OEM4 Receiver”, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS), Banff, Alberta, Sept. 2001

[6] T. Ford, J. Neumann, M. Bobye, P. Fenton, “OEM4 Inertial: A Tightly Integrated Decentralised Inertial/GPS Navigation System”, Proceedings of ION GPS ‘01, Salt Lake City, Utah., Sept. 17-20, 2001, The Institute of Navigation, Washington, D.C.

[7] T. Ford, J. Hamilton, M. Bobye, J. Morrison, B. Kolak, “MEMS Inertial on an RTK GPS Receiver: Integration Options and Test Results”, Proceedings of ION NTM ‘03, Anaheim, California, Jan. 22-24, 2003.

[8] T. Ford, J. Hamilton, “A New Positioning Filter: Phase Smoothing in the Position Domain”, NAVIGATION, Journal of the Institute of Navigation, Vol. 50, Number 3, Summer 2003