Defence Research and Development Canada
Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

Analysis of MEMS IMU Motion Table Testing

Dale Arden

This work was completed in September 2004 and published in May 2007.

Defence R&D Canada – Ottawa
CONTRACT REPORT
DRDC Ottawa CR 2007-092
May 2007

Canada

Analysis of MEMS IMU Motion Table Testing

Dale Arden

Prepared By:

Dale Arden Consulting
RR3 Almonte ON K0A 1A0

DRDC Ottawa Contract W7714-010525
Contractor Document Number: DAC-0401

CSA: J. S. Bird, CNEW Section

This work was completed in September 2004 and published in May 2007

Defence R&D Canada – Ottawa

Contract Report

DRDC Ottawa CR 2007-092

May 2007

Table of Contents

List of Tables

1 INTRODUCTION

The Navigation Group of the Communications Electronic Warfare Section of Defence R&D Canada – Ottawa (DRDC Ottawa) is funding research to study and develop an integrated navigation system based on Inertial Measurement Units (IMUs) based on Micro-Electro-Mechanical Systems (MEMS) gyros and accelerometers and the Global Positioning System (GPS). Three MEMS IMUs were purchased under the terms of this contract. To better understand the error characteristics of MEMS inertial sensors and to gain familiarity with these instruments, a series of tests were designed (see the test plan in Reference [1]) and executed. The Inertial Test Lab owned and managed by DRDC Ottawa is equipped with two two-axis Contraves motion tables. One of these tables was used for these tests.

This report describes the results of analyses performed on data collected on a DRDC Ottawa motion table. Emphasis was placed on statistical characterization of individual gyro and accelerometer error behaviour with the aims of

1. Comparing real-life results with manufacturers' specifications,
2. Developing IMU error models that may be suitable for use in the MEMS/GPS Kalman filter integration processing,
3. Comparing the performance of the three IMUs under test.

References [2] (a description of inertial MEMS state-of-the-art), [3] (a description of the strapdown navigator algorithm), and [4] (a description of the Kalman filter processing) provide additional background information.

Chapters 2 , 3 and 4 provide descriptions of the test environment:

The IMUs being tested,

The laboratory set-up under which the tests were executed, and

The techniques used to level the IMUs on the motion table.

Chapters 5 , 6 and 6.2.1.3.4 contain results of four-position tests (used to try to separate earth rotation from gyro error terms), six-position tests (used to characterize accelerometer and gyro errors), and long-term drift tests.

Results are summarised in Chapters 8 and 9 .

Appendix A contains summaries of all the positions of all the runs in the six-position accelerometer testing.

2 THE MEMS IMUs TESTED

The Navigation Group at DRDC Ottawa has purchased three MEMS Inertial Measurement Units under the current contract. Based on manufacturers' specifications, the units can be broadly characterized as follows:

1. The Crossbow IMU400CB is a low accuracy unit (gyro biases of about 1 degree per second) marketed for navigation and control, marine dynamics, and vehicle testing applications.

2. The Inertial Science ISIS is a medium accuracy unit (turn-on to turn-on gyro biases of about 50 degree per hour, in-run stability of about 5 degrees per hour) marketed for use in AHRS, vertical reference systems, GPS/INS integration, or stabilization.

3. The BAE Systems SiIMU is another medium accuracy unit (turn-on to turn-on gyro biases of about 100 degree per hour, in-run stability of about 5 degrees per hour) marketed for vehicle navigation, guidance and stabilization, as well as tactical grade weapons and gun-launched guided projectiles.

These instruments have other important characteristics that are dramatically different from each other. A more detailed listing, presented in Table 1, was extracted from Table 1 of Reference [2].

3 LABORATORY SET UP

The IMUs under test were mounted on a two-axis Contraves motion table. The IMUs were physically attached to the motion table as follows:

> A round metallic base plate was mounted to the table itself.
>
> On the base plate is a breakout box that acts as a junction connecting all the electrical signals to and from the IMUs (power in, data out for the most part) with the table's slip rings.
>
> Also attached to the base plate is a rigid structure holding all three IMUs in a vertical "tower": the BAE SiIMU on the bottom, the Crossbow IMU400CB in the middle, and the Inertial Science ISIS on top.
>
> The y-axes of all IMUs are aligned with West when the table is in its home position (axis 1 at 90 degrees and axis 2 at 180 degrees).

Table 1: MEMS IMU Summary

Manufacturer	Model	Size (inches)	Weight (g)	Supply Voltage (VDC)	Input Power (W)	Gyro Range (°/sec)	Gyro Bias (°/hr)	Gyro Scale Factor Error (ppm)	Gyro Band-width (Hz)	Gyro Noise (°/sec)	Gyro Random Walk (°/hr$^{1/2)}$	Accel. Range (g)	Accel. Bias (mg)	Accel. Scale Factor Error (ppm)	Accel. Band-width (Hz)	Accel. Noise (mg)	Accel. Random Walk (m/s/ hr$^{1/2}$)	Cost ($US)
Crossbow	IMU 400CB	3.0 3.7 3.3	590	9 to 30	<3	200	<3600	$<10^4$	>10		<1.7	10	<12	$<10^4$	>75		<0.5	$4500
Inertial Sciences	ISIS	3.0 2.8 2.3	500	+28	5	300	5^S 50^R	2000	50		1	30	3^S 30^R	2000	50			9900
BAE	SiIMU	2.9 1.8	250	+5, +15	4 @ +5 VDC & 0.5 @ +15 VDC	1000(x) 540 (y,z)	5^S, 100^R	1500	75	1	0.75	50(x) 35 (y,z)	2^S 15^R	2000	75	8.4	1	16000

S = Stability

R = Repeatability

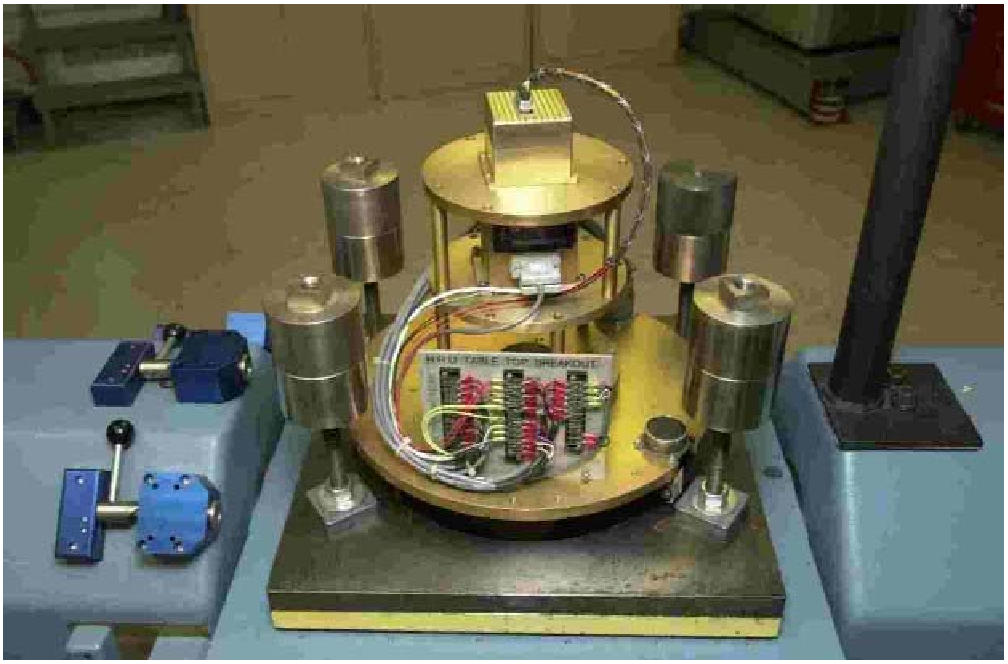

Figure 1: Motion Table Fixture Without BAE SiIMU

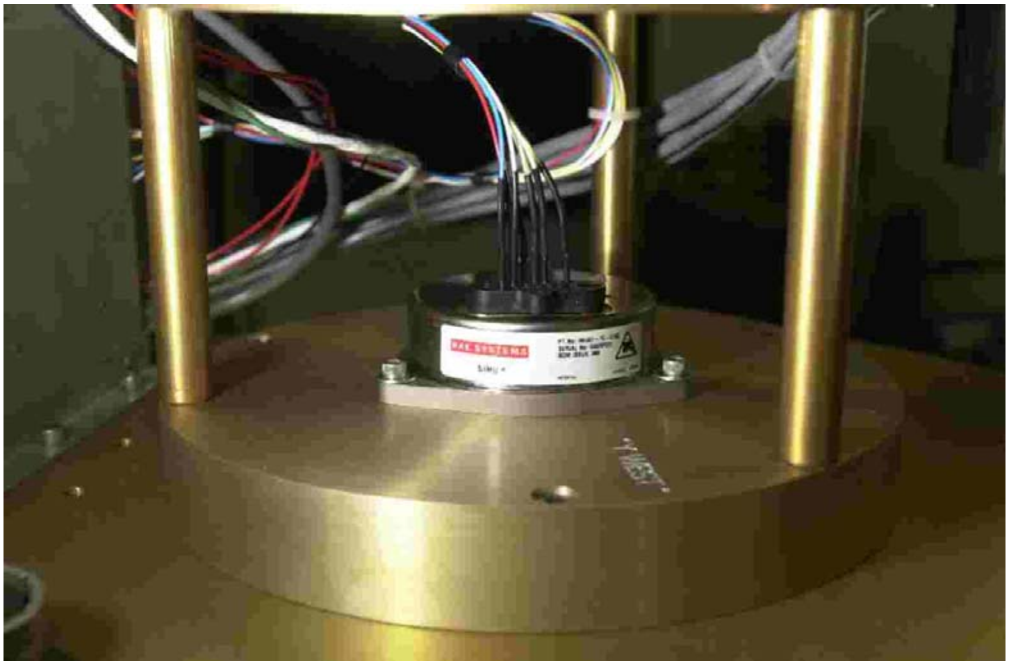

Figure 2: BAE SiIMU in the Fixture

Permanent cabling runs from the table's slip rings to a number of instrument racks nearby. One rack holds another breakout box. This configuration of the second breakout box matches that of the table exactly: a signal going into a particular pin on the table will exit the same pin on the rack. From the rack, cables ran to a series of power supplies and to a desktop computer ("SNOW" on the DRDC Ottawa network) where data was collected.

Figure 1 is a photograph of the custom fixture with the Inertial Science ISIS IMU on top and the Crossbow IMU400CB in the middle. All power and data cabling to and from the IMUs connects to the breakout panel, visible in the foreground. Just visible behind the panel is the hole where the BAE SiIMU was later mounted. (The BAE SiIMU had not yet been delivered at the time this photo was taken.) Figure 2, taken at a later date, shows the SiIMU in place on the fixture.

The motion table's Axis 1 is in the vertical position in Figure 1. Rotation about Axis 2, the trunion axis, would be into or out of the page.

Three separate software programs (on a single computer, as mentioned) collected the data from the three IMUs. Data collection software for the Crossbow IMU was supplied by Crossbow. It was modified for the purposes of these tests. The same source code was further modified to create the data collection programs for the BAE and Inertial Science units.

Data processing for the six-position tests was performed with custom software written specifically for that purpose. Four-position (earth rate) tests and drift tests were processed using a commercial spreadsheet program, Microsoft Excel .

4 IMU ALIGNMENT

As indicated above, all three IMUs under test are mounted on the test table at the same time. This is convenient from a testing point of view but complicates the alignment process.

All three IMUs were supplied with mounting instructions. The three-tiered assembly used to mount them to the test table was constructed on these bases. The mounting surface of each IMU is level, and each y-axis is aligned to West when the motion table is in its home position. Table 2 gives the axes orientation of the IMUs in the table's home position.

Table 2: Orientation of IMUs in Motion Table's Home Position

IMU	X-Axis	Y-Axis	Z-Axis
BAE SiIMU	Down	West	North
Inertial Science ISIS	South	West	Down
Crossbow	South	West	Down

IMU400CB			

The tabletop was levelled using accurate spirit levels placed on the mounting surfaces. The table was confirmed to be level along the trunion axis. Perpendicular to the trunion axis, level was determined to be at a table axis 2 reading of 179.9388 degrees (a tilt of +3.7 arc minutes with respect to the IMU y- or the table West-axes).

To determine the orientation of the table axis 1, the table was rotated by 90 degrees about the trunion axis to a position of 270 degrees. The IMUs were visibly off level about table axis 1. Axis 1 was rotated until the cases of the ISIS and Crossbow units were level (again using spirit levels as the reference). The SiIMU has a cylindrical case and could not be levelled using this technique. The average level was achieved with the table axis 1 at a reading of 87.52 degrees.

Confidence in the levelling of the table axis 1 was lower than that of axis 2. To confirm the spirit levelling results, simple levelling tests were conducted using accelerometer outputs and procedures developed for levelling an IMU prior to initialisation of strapdown navigation (see reference [3]).

As a reference, table level at the home position was tested. The process requires the collection of accelerometer data with two axes in a nominally level orientation. Data is collected at the first position (table home was used), then the IMU(s) is rotated about the vertical axis by 180 degrees. A second data set is collected at the new orientation. The averaged accelerometer outputs at each position are then used to estimate the tilts and biases of the horizontal accelerometers. The test was run twice from the table's home position. Tilt results are summarised in the following table.

Table 3: Tilts at Home Position

Tilt about Axis (all in arcmin)	BAE Z	BAE Y	ISIS X	ISIS Y	Xbow X	Xbow Y
Test 1	-1.7	-0.4	6.4	0.4	-1.1	-1.0
Test 2	-0.5	-1.7	-0.5	0.7	1.9	-0.2

Except for an outlier in the ISIS x-axis tilt from Test 1, these results indicate apparent random tilt errors on the order of 2 arc minutes. This is inline with sensor noise levels and the expected misalignments of this kind of sensor.

All results were generated from data sets …_8Jul03_1040(1047, 1335, 1339).

With the process confirmed to within a few arc minutes accuracy, the level of the table with the trunion axis 90 degrees off level was tested. A starting table position with axis 1 at 87.52 degrees and axis 2 at 269.9388 degrees was used.

The misalignments of the IMUs relative to table axis 1 can be estimated using the outputs from the y-accelerometers of all IMUs at the start position and a second position of 267.52, 269.9388 degrees. A second test was performed using the BAE z-accelerometer and the ISIS and Crossbow x-accelerometers at table positions (177.52, 269.9388) and (357.52, 269.9388) degrees.

Being a two-axis machine, the table cannot rotate about the vertical axis in this orientation. But, rotating by 180 degrees about the table axis 1 allows us to estimate the tilt about the y-axis of each sensor.

Table 4: Tilts About Table Axis 1

Tilt about Axis (all in arcmin)	BAE Y	BAE Z	ISIS Y	ISIS X	XBow Y	Xbow X
Test 1	-2.9 (-4.5)	N/A	9.2 (-3.4)	N/A	-2.1 (4.0)	N/A
Test 2	N/A	5.6 (4.0)	N/A	2.1 (1.0)	N/A	5.0

Note: the first results were generated from six-position data sets …_10Jul03_1118(1128, 1140, 1150)_auto. The results in brackets were generated from data sets …_9Jul03_1433 (1439, 1444, 1448) except for “Xbow X”. Crossbow data from (what should have been) XBOW_9Jul03_1444 was somehow lost. The first data set is comprised of 10-minute runs with every tenth data record saved. The second data set is comprised of 1-minute runs with every data record saved.

What can we conclude about table axis 1 tilts? The mean and standard deviation of the first set of results is 2.8 and 4.7 arc minutes, respectively; the mean and standard deviation of the second is just 0.2 and 4.0 arc minutes. These are certainly not statistically valid results, but they do give some indication of quality of the table levelling achieved: it is likely within a few arc minutes of being level. A tilt of 3.4 arc minutes (1 milli-radian) will introduce an accelerometer bias of 1 milli-g. The accelerometers in these IMUs random biases on the order of a few tens of milli-gs, stable to a few milli-gs. Tilt-induced biases of 1 milli-g will not have a significant impact on subsequent test results.

The many accelerometer and gyro six-position tests run subsequent to this alignment confirm the quality of the levelling process, albeit with accuracies below those predicted here.

5 FOUR-POSITION TESTS

The expected gyro bias errors of the MEMS IMUs under test are larger in magnitude than the earth's rotation rate: observation of earth rate using these instruments will be difficult or impossible. But, for the sake of completeness, attempts were made to evaluate this capability. A standard four-position test was used: the trunion axis of the motion table is maintained in its level position (table axis 1 at 180.0000 degrees) throughout; table axis 2 is rotated to the following four positions:

1. 90.0000 degrees,
2. 0.0000 degrees,
3. 270.0000 degrees,
4. 180.0000 degrees.

This orientation places a portion of the earth rate into two IMU axes – X and Y for the Inertial Science ISIS and Crossbow IMU400CB, Y and Z for the BAE SiIMU. The portion in each axis is latitude-dependent: at DRDC Ottawa, each gyro will see about 70% of earth rate, or about 10.5 degrees per hour.

The full earth rate signal (15 degrees per hour) can be concentrated in one IMU axis (the ISIS and Crossbow Z-axis and SiIMU X-axis) by tilting the table's trunion axis so the axis is parallel with the earth's spin axis. This is accomplished by rotating the trunion axis from 0 or 180 through an angle equal to the local latitude (about 45.35 degrees at DRDC Ottawa): the trunion axis should be set at either the 225.35 or 45.35-degree position.

The four-position test is designed to take the axes under test through plus and minus earth rate as well as two zero rate positions. This new configuration requires rotation about the trunion axis to:

1. 225.35 degrees (first gyro at plus earth rate),
2. 135.35 degrees (first gyro at null),
3. 45.35 degrees (first gyro at minus earth rate),
4. 315.35 degrees (first gyro at null).

By placing the table axis 1 at 0 or 90 degrees, a second gyro can be rotated through the required plus and minus earth rate and zero rate positions. Of course, the second gyro is 90 degrees out of phase with the first:

1. 225.35 degrees (second gyro at null),
2. 135.35 degrees (second gyro at plus earth rate),
3. 45.35 degrees (second gyro at null),
4. 315.35 degrees (second gyro at minus earth rate).

5.1 Results

The standard test (with the trunion axis level) was run with one-minute data collection intervals at each position. This process exercised the Y and Z gyros in the BAE SiIMU and the X and Y gyros in the other two units. The table below summarises the gyro averages for the four positions.

Table 5: Four-Position Test – Averaged Gyro Data

Position #	BAE Y Gyro (deg/s)	BAE Z Gyro (deg/s)	ISIS X Gyro (deg/s)	ISIS Y Gyro (deg/s)	XBow X Gyro (deg/s)	XBow Y Gyro (deg/s)
1	-0.010056	-0.010657	-0.010367	-0.024002	-0.106307	0.088785
2	-0.013806	-0.015943	-0.008216	-0.027862	-0.106536	0.083179
3	-0.011935	-0.020902	-0.004708	-0.026089	-0.106080	0.079553
4	-0.007325	-0.018653	-0.007865	-0.024941	-0.109230	0.078659

Each indicated gyro in these tests sees about 10.5 degrees per hour of earth rotation signal. This is equivalent to 0.002917 degrees per second. The next table shows the signal available to each gyro at each position.

Table 6: Four-Position Test – Earth Signal Visible to Each Gyro

Position #	BAE Y Gyro (deg/s)	BAE Z Gyro (deg/s)	ISIS X Gyro (deg/s)	ISIS Y Gyro (deg/s)	XBow X Gyro (deg/s)	XBow Y Gyro (deg/s)
1	0	0.002917	-0.002917	0	-0.002917	0
2	-0.002917	0	0	-0.002917	0	-0.002917

3	0	-0.002917	0.002917	0	0.002917	0
4	0.002917	0	0	0.002917	0	0.002917

One would be hard pressed to identify the earth rate signal from the results of Table 5. But, what if we estimate the gyro biases from the given data, and remove those biases from the calculated averages? The biases are the average of the four positions for each gyro. Results are presented in Table 7.

Table 7: Four-Position Test – Estimated Gyro Biases

BAE Y Gyro (deg/s)	BAE Z Gyro (deg/s)	ISIS X Gyro (deg/s)	ISIS Y Gyro (deg/s)	XBow X Gyro (deg/s)	XBow Y Gyro (deg/s)
-0.010779	-0.016539	-0.007789	-0.025724	-0.107038	0.082544

Table 8 shows the averaged gyro outputs with the computed bias removed.

Table 8: Four-Position Test – Averaged Gyro Data with Bias Removed

Position #	BAE Y Gyro (deg/s)	BAE Z Gyro (deg/s)	ISIS X Gyro (deg/s)	ISIS Y Gyro (deg/s)	XBow X Gyro (deg/s)	XBow Y Gyro (deg/s)
1	0.000723	0.005881	-0.002578	0.001722	0.000732	0.006241
2	-0.003026	0.000596	-0.000427	-0.002138	0.000502	0.000635
3	-0.001156	-0.004363	0.003081	-0.000365	0.000958	-0.002991
4	0.003455	-0.002114	-0.000076	0.000782	-0.002192	-0.003885

By comparing Table 6 (the true signal) with Table 8 (the measured, corrected signal), can we now say that any or all of the IMUs can detect earth rate? No, not all can:

The BAE SiIMU seems to do the best – earth rate can be identified in both axes.

The Inertial Science ISIS does very well in X-axis but very poorly in Y.

The Crossbow IMU400CB is pretty much oblivious to earth rate.

Is there the potential for automatic heading of a MEMS IMU using the earth's rotation? The potential is there for future units, but presently available MEMS IMUs will likely have to rely on external heading information. That said, the BAE and Inertial Science units did a better job of "gyro-compassing" than would have been expected.

6 SIX-POSITION TESTS

The six-position test used here to characterize the performance of the three IMUs under test is described in references [1] and [5]. In essence, each sensor (individual accelerometer or gyro) is placed into an orientation whereby it experiences the entire input signal and the other two sensors experience no signal. The sensor under test is then subjected to the negative of the first signal.

For example, one accelerometer would be placed parallel to the gravity vector, first reading positive gravity, then negative (the order is unimportant). Ideally, the other two accelerometers will see no component of gravity. The motion table is used, in this case, to precisely position the IMUs to bring the accelerometer under test into proper alignment and keep it there until the data collection is complete. Errors are introduced when the accelerometer is not precisely aligned to the gravity vector.

The gyros are tested by placing the instrument under test in an alignment that brings its sensitive axis into alignment with one of the moveable axes of the motion table. The input signal is provided by a constant rotation of the motion table about that axis. The negative signal is provided by the reverse rotation with the table in the same orientation. In this case, the motion table must provide a stable base by keeping one axis stationary and also provide the test signal by spinning the other axis at a constant rate. As with accelerometer testing, errors are introduced when the sensitive axis of the gyro is not precisely aligned with the table's spin axis.

A six-position test provides 18 observables (3 sensors at six positions) that are used to estimate up to 15 unknowns: 9 misalignment angles, 3 scale factors and 3 biases.

Note that all RMS values are calculated as the square root of the sum of the sample variance and square of the mean that are calculated as part of the six-position test.

6.1 Accelerometers

The table positions used for the six-position accelerometer tests are listed in the following tables.

Table 9: Table Positions for Six-Position Accelerometer Tests for July 9-10

Table Axis	#1 (degrees	#2 (degrees)

	)	
Position 1	90.0000	179.9388
Position 2	90.000	359.9388
Position 3	87.52	269.9388
Position 4	267.52	269.9388
Position 5	177.52	269.9388
Position 6	357.52	269.9388

Table 10: Table Positions for Six-Position Accelerometer Tests for July 14-15

Table Axis	#1 (degrees)	#2 (degrees)
Position 1	90.0000	179.9388
Position 2	90.000	359.9388
Position 3	87.52	269.9388
Position 4	177.52	269.9388
Position 5	177.52	89.9388
Position 6	87.52	89.9388

On July 15, 2003, a series of six-position tests were run. Between most runs, the power to the IMUs was cycled off and on. This was designed to provide information on the variation in IMU performance from turn-on to turn-on. All but one test was run for one minute at each position, followed by a transition to the next position and a 30 second settling interval. For the last data set collected on this day, each position was maintained for 10 minutes.

Individual runs made on July 9, 10 and 14 are included in the analysis.

The table was controlled by software. Data collection was performed manually: the data collection programs were typically started shortly after the settling time began and ended about 10 seconds before the one-minute run was finished.

File names have the conventions: BAE(ISIS, XBOW)_15Jul03_T2T_2(3..7)1(2..6). For example, BAE_15Jul03_T2T_41.asc is the data file collected from the BAE SiIMU on July 15, 2003 for turn-on to turn-on test number four, position number 1. Note that the first run used the other file naming convention, with the "T2T_xy" replaced with time of day (hhmm), e.g. BAE_15Jul03_0945.asc.

All runs were processed using the "Six_Pos_Test" program developed for these tests. This program reads an ASCII input file containing

1. A flag to indicate whether accelerometers or gyros are being tested,
2. A flag to indicate the model of the IMU being tested (currently supporting the BAE SiIMU, Inertial Science ISIS and Crossbow IMU400CB),
3. The decimation rate (fraction of available records that were saved) used during data collection,
4. A flag to indicate whether or not misalignments are to be estimated,
5. The minimum number of records to be read before outlier testing commences,
6. The maximum number of records to be processed from each data file,
7. The factor to be used to scale the standard deviation during outlier testing, and
8. The names of the six files containing the data collected at the six test positions.

The program then processes each data file, reading in all records and computing the means and standard deviations. The runs are then sorted, pairing the runs that will be used to compute misalignments and scale factors (biases are computed using all six runs). The sensor scale factors, biases and (optionally) misalignments are computed using the procedures described in reference [1]. A reprise of the input data, statistical results from each file, and the estimated sensor errors are saved in a new ASCII file. The output file is automatically assigned a name with the same prefix (all characters up to the first '.') as the input file's name. All characters after the first '.' are replaced by 'out' to complete the output file name.

6.1.1 Results

Runs 09Jul03, 15Jul03_1 to 15Jul03_6, and 25Jul03_All_In_One have 1 minute of data at each position with every data record collected; runs 10Jul03, 14Jul03 and 15Jul03_7 have 10 minutes of data at each position with every tenth data record collected. All files for a particular IMU will contain approximately the same number of records. The SiIMU outputs data at 200 Hz, the ISIS at 100 Hz, and the IMU400 at about 134 Hz: the size of the data files for the different IMUs will be proportionate to these data rates.

The IMUs had the power cycled between all runs except 15Jul03_3 and 15Jul03_4 and 15Jul03_5, 15Jul03_6 and 15Jul03_7.

The data analysis here has been designed to compute accelerometer scale factor errors, biases and misalignments so they can be compared with manufacturer's specifications. In addition, the turn-on to turn-on changes in sensor performance will be analysed (albeit with a very small sample size) by comparing overall standard deviations with the standard deviations from runs 5, 6 and 7 from July15 (run without a power cycle). A simple comparison of results from runs 3 and 4 from July 15 will be used in the analysis.

Note that scale factor errors are reported as (1 – scale_factor), where scale_factor is computed in the procedures described in reference [1]: a positive scale factor error indicates an estimated scale factor that is less than one; a negative scale factor error indicates an estimated scale factor that is greater than one. When mention is made of "global" scale factor errors (taking the results from all three channels together), the statistics have been computed using the absolute values of the individual results.

The means and standard deviations of the ten runs in the test are presented in the following tables. This not a statistically valid number of samples, but given the time required to make full six-position tests, ten runs should be adequate to at least give a good indication of size of the sensor errors.

6.1.1.1 BAE SiIMU

6.1.1.1.1 Accelerometer Scale Factors

Table 11: BAE Accelerometer Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
09Jul03	1302	2330	2060
10Jul03	2009	1583	1657
14Jul03	619	1497	1485
15Jul03_1	2441	3030	3200
15Jul03_2	972	2027	1830
15Jul03_3	1602	2230	2632
15Jul03_4	1841	1978	1647
15Jul03_5	1414	1644	1932

15Jul03_6	4200	4499	4533
15Jul03_7	1848	1823	1464
25Jul03_All_In_One	2025	1578	2084
Average (All)	1843	2202	2091
Std. Dev. (All)	936	882	923
Average (All except 15Jul03_6)	1581	1989	1876
Std. Dev. (All except 15Jul03_6)	567	494	543
Average (567)	2487	2655	2643
Std. Dev. (567)	1499	1599	1653
Average (57)	1631	1734	1698
Std. Dev. (57)	307	127	331

The global average scale factor error (computed for all axes and all runs) is about 2090 ppm, with a standard deviation of 900 ppm and RMS of 2275 ppm. The manufacturer's specification is 2000 ppm. These global statistics indicate that this unit is not quite meeting the specifications.

A two-sigma test appears to be the standard for manufacturer's acceptance tests. Note that the scale factor errors computed for 15Jul03_6 are significantly worse than other runs, failing the two-sigma (4000 ppm) test in all channels while all other runs easily pass the two-sigma test. If 15Jul03_6 is removed from the calculations, the global statistical summary becomes 1580 570 ppm, equivalent to an RMS of 1680 ppm. If the suspect run is considered an outlier, the unit meets the scale factor specifications.

Is there less variability between runs without power cycles? A first glance at Table 11 indicates more variability – an unexpected result. However, removing the suspect run (15Jul03_6) improves things significantly to bring them more in line with the expectations. Inspection of runs 15Jul03_3 and 15Jul03_4 adds little to the analysis.

6.1.1.1.2 Accelerometer Biases

Table 12: BAE Accelerometer Bias Estimates

Run I.D.	X (milli-gs)	Y (milli-gs)	Z (milli-gs)
09Jul03	-35.5	30.1	3.2
10Jul03	-35.4	30.2	3.5
14Jul03	-37.2	34.1	1.0
15Jul03_1	-37.3	35.1	2.2
15Jul03_2	-35.7	32.7	2.9
15Jul03_3	-36.7	33.2	1.4
15Jul03_4	-36.2	32.9	1.4
15Jul03_5	-37.0	34.7	0.7
15Jul03_6	-36.9	35.6	0.3
15Jul03_7	-37.3	36.2	0.5
25Jul03_All_In_One	-42.9	40.5	1.8
Average (All)	-37.1	34.1	1.7
Std. Dev. (All)	2.1	2.9	1.1
Average (567)	-37.1	35.5	0.5
Std. Dev. (567)	0.2	0.8	0.2

Here, results from run 15Jul03_6 are in good agreement with other results: this run will not be dealt with any differently from other runs in the following bias analysis.

The global average accelerometer bias (all accelerometers combined) for the SiIMU is –0.4 milli-gs with a standard deviation (and RMS) of 30 milli-gs. So, while the results for individual accelerometers are remarkably consistent from run to run (in the 1 to 2 milli-g one-sigma range), the global variation is somewhat larger than the manufacturer specified limit of 15 milli-gs bias repeatability.

Alternatively, while individual accelerometers may have large biases, the global average is very small. This small global value is a coincidence resulting from the similar magnitudes but opposite signs of the large X and Y averages.

The X- and Y-accelerometer results for every run fail the 30 milli-g two-sigma test. Once again, this result is attributable to the large X and Y biases.

The large bias, small standard deviation results from the X- and Y-accelerometers, as contrasted with the small bias, small standard deviation results from the Z-accelerometer, may be attributable to the skewed configuration of the accelerometers. The SiIMU accommodates higher acceleration inputs in the X-axis by mounting all accelerometers at a 54.74-degree angle to the Y-Z plane. In this way, input acceleration parallel to the X-axis is split into three equal measurements, allowing 30g accelerometers to measure 50 gs acceleration and 600 degree per second gyros to measure 1000-degree rotations along the X-axis. Therefore, what has been called the “X-accelerometer” (for example) is really the effective X-accelerometer comprised of measurements from all the real accelerometers. The six-position test is designed to put each accelerometer into plus and minus gravity, with one accelerometer parallel to and the other two perpendicular to the gravity vector at each position. In the case of the SiIMU, it is the effective accelerometers that are positioned and the error performance of the effective accelerometers that is estimated. It may be that the six-position test does not work well with this kind of IMU, skewing the bias estimates.

It would take some time to fully understand the implications of these issues. A cursory analysis has suggested that all sensors measurements are properly balanced (e.g. each real accelerometer goes through plus and minus the same fraction of gravity acceleration). Of course, the sensor skewing does reduce the magnitude of the input signal that is observable by the sensors. For example, if the IMU X-axis is aligned to the gravity vector, each of the three real accelerometers will see about 60% of the gravity signal (because $\cos(54.74\,\mathrm{deg}) = 0.57$ and $\cos^2(54.74\,\mathrm{deg}) = 0.333$). The inverse of these equations was used to derive the required angle: the angle required to get one third of the signal in the X-axis to each of the sensors is $\arccos\left(\sqrt{1/3}\right) = 54.74$.

Table 12 indicates reduced variability in the results for individual accelerometers with no power cycles (runs 5,6 and 7 from July 15). The global values for these runs are –0.4 31 milli-gs, in very close agreement with the results from all ten runs.

Inspection of runs 15Jul03_3 and 15Jul03_4 shows good consistency relative to overall standard deviations.

6.1.1.1.3 Accelerometer Misalignments

Table 13: BAE Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
09Jul03	-2.1	1.3	1.5
10Jul03	-0.7	0.9	1.6
14Jul03	-0.6	0.2	1.2
15Jul03_1	-0.3	0.6	1.2
15Jul03_2	-0.7	0.5	1.2
15Jul03_3	-1.5	0.8	1.3
15Jul03_4	-0.8	1.0	1.7
15Jul03_5	-1.4	0.2	1.4
15Jul03_6	-0.8	0.6	1.3
15Jul03_7	-0.5	0.3	1.6
25Jul03_All_In_One	-0.9	1.2	0.9
Average (All)	-0.9	0.7	1.4
Std. Dev. (All)	0.5	0.4	0.2

The misalignment results indicate that

1. The initial alignment procedures were very effective, leaving misalignments on the order of 1 milliradian;
2. The six-position tests are able to reliably estimate the misalignments.

Unlike the other errors being studied in this report, misalignments are expected to be constants, not varying from turn-on to turn-on.

6.1.1.1.4 Accelerometer Noise

The six-position software used to generate all these results calculates the standard deviations as well as the means of all the data used in each particular position. The mean values from each of the six positions are used to estimate the scale factors, biases and misalignments presented in this report. The standard deviations are not used directly but can be used as a measure of the noise in a particular accelerometer or gyro. See Appendix A for a listing of all accelerometer results.

The standard deviations of all the BAE SiIMU positions used in this analysis ranged from 0.8 to 1.7 milli-gs. This compares favourably to the manufacturer's 8.4 milli-g specification. An Allan variance analysis of sensor noise is underway.

6.1.1.2 Inertial Science ISIS

6.1.1.2.1 Accelerometer Scale Factor

Table 14: ISIS Accelerometer Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
09Jul03	-1527	447	-1802
10Jul03	-735	347	-1181
14Jul03	-1344	945	-1608
15Jul03_1	-231	986	-1246
15Jul03_2	-1005	848	-149
15Jul03_3	-1111	574	-1599
15Jul03_4	-1155	558	-1489
15Jul03_5	-705	676	-1483
15Jul03_6	-879	694	-1397
15Jul03_7	-1357	474	-1778
25Jul03_All_In_One	-1071	547	-1480

Average (All)	-1011	645	-1383
Std. Dev. (All)	364	207	451
Average (567)	-980	615	-1553
Std. Dev. (567)	338	122	199

The global average scale factor error (using the absolute values of negative errors) is about 1000 ppm, with a standard deviation of 365 ppm (RMS 1064 ppm). The manufacturer's specification is 2000 ppm. All individual runs and the statistical summary of all runs indicate that the ISIS is safely within its specified scale factor performance.

What about variability between runs without power cycles? Table 14 suggests that the scale factor is less variable when the power is not cycled: the standard deviations are smaller and inspection of results from individual runs shows good consistency, with the possible exception of Run 15Jul03_7.

6.1.1.2.2 Accelerometer Biases

Table 15: ISIS Accelerometer Bias Estimates

Run I.D.	X (milli-gs)	Y (milli-gs)	Z (milli-gs)
09Jul03	12.5	-2.6	13.3
10Jul03	10.5	-3.5	12.5
14Jul03	12.8	-3.4	13.6
15Jul03_1	9.2	-9.0	13.3
15Jul03_2	11.9	-0.7	13.2
15Jul03_3	12.7	-2.8	14.0
15Jul03_4	12.5	-3.9	14.2
15Jul03_5	11.3	-7.5	14.3
15Jul03_6	11.6	-6.3	14.4

15Jul03_7	12.4	-5.5	14.7
25Jul03_All_In_One	13.1	-3.3	15.8
Average (All)	11.9	-4.4	13.9
Std. Dev. (All)	1.2	2.4	0.9
Average (567)	11.8	-6.4	14.5
Std. Dev. (567)	0.6	1.0	0.2

The global average accelerometer bias for the ISIS is 7 milli-gs with a standard deviation of 8 and RMS of 11 milli-gs, falling well within the manufacturer's specification of 30 milli-gs.

Table 15 indicates reduced variability in the results for individual accelerometers with no power cycles (runs 5,6 and 7 from July 15). The global values for these runs are 7   10 milli-gs, in very close agreement with the results from all ten runs, with a small increase in standard deviation. On the other hand, standard deviations of individual accelerometers drop significantly when only these three runs are used.

Inspection of runs 15Jul03_3 and 15Jul03_4 again shows good consistency relative to overall standard deviations.

6.1.1.2.3 Accelerometer Misalignments

Table 16: ISIS Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
09Jul03	0.5	-1.0	0.8
10Jul03	1.0	-3.8	.07
14Jul03	0.8	-1.2	0.8
15Jul03_1	0.9	-3.5	0.7
15Jul03_2	0.7	-1.9	0.8

15Jul03_3	0.7	-1.5	0.8
15Jul03_4	0.7	-1.7	0.8
15Jul03_5	0.8	-2.1	0.8
15Jul03_6	0.8	-1.9	0.8
15Jul03_7	0.8	-1.3	0.9
25Jul03_All_In_One	0.9	-1.3	0.8
Average (All)	0.8	-1.9	0.7
Std. Dev. (All)	0.1	0.9	0.2

Again we find that the six-position accelerometer test is very effective at estimating sensor misalignments.

6.1.1.2.4 Accelerometer Noise

Appendix A can again be used to extract estimates of accelerometer noise from the standard deviations calculated for each position.

The standard deviations of all the positions used in this analysis ranged from 0.6 to 1.1 milli-gs. Inertial Science did not provide this kind of simple noise specification. These figures are slightly better than the corresponding BAE numbers.

6.1.1.3 Crossbow IMU400CB

6.1.1.3.1 Accelerometer Scale Factors

Table 17: Crossbow Accelerometer Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
09Jul03	N/A	N/A	N/A
10Jul03	-724	516	-786
14Jul03	-4894	1193	-515
15Jul03_1	-1011	831	-417

15Jul03_2	-1287	781	-593
15Jul03_3	-3707	951	-640
15Jul03_4	-3996	965	-661
15Jul03_5	-3332	1098	-561
15Jul03_6	-3500	977	-524
15Jul03_7	-4686	860	-700
25Jul03_All_In_One	-3137	954	-616
Average (All)	-3027	913	-601
Std. Dev. (All)	1504	185	104
Average (567)	-3839	978	-595
Std. Dev. (567)	738	119	93

The global average scale factor error (again using the absolute values of negative errors) is about 1490 ppm, with a standard deviation of 1605 ppm. The manufacturer's specification is 1% or 10,000 ppm. All individual runs and the statistical summary indicate that the IMU400CB is well within its specified scale factor performance. However, note that the X-accelerometer (with a large negative bias and much larger standard deviation) seems to perform significantly worse than its Y and Z counterparts.

The large averages and relatively small standard deviations suggest that these accelerometers could be better calibrated.

Table 17 suggests minor but consistent improvement in scale factor variability when the power was not cycled: the standard deviations are all smaller. Inspection of results from these three runs shows reasonable consistency.

6.1.1.3.2 Accelerometer Biases

Table 18: Crossbow Accelerometer Bias Estimates

Run I.D.	X (milli-gs)	Y (milli-gs)	Z (milli-gs)
09Jul03	N/A	N/A	N/A
10Jul03	-2.0	2.3	2.3
14Jul03	-8.3	8.2	-0.3
15Jul03_1	-1.1	2.3	2.4
15Jul03_2	-3.9	4.2	1.6
15Jul03_3	-6.8	6.7	0.0
15Jul03_4	-7.1	7.0	-0.3
15Jul03_5	-6.5	6.9	-0.4
15Jul03_6	-6.8	7.3	-0.6
15Jul03_7	-7.7	7.8	-0.8
25Jul03_All_In_One	-6.4	6.6	0.0
Average (All)	-5.7	5.9	0.4
Std. Dev. (All)	2.5	2.2	1.2
Average (567)	-7.0	7.3	-0.6
Std. Dev. (567)	0.6	0.5	0.2

The global average accelerometer bias for the IMU400CB is about 0.2 milli-gs with a standard deviation of 5.2 milli-gs (RMS of 5.2 milli-gs), well within the manufacturer's specification is 12 milli-gs.

Table 18 indicates reduced variability in the results for individual accelerometers with no power cycles (runs 5,6 and 7 from July 15). The global values for these runs are –0.1   6.2 milli-gs, in very close agreement with the results from all ten runs, with a small increase in standard deviation. However, comparison of individual accelerometers' results does show a significant improvement in variability when power is not cycled.

Inspection of runs 15Jul03_3 and 15Jul03_4 again shows good consistency relative to their standard deviations.

6.1.1.3.3 Accelerometer Misalignments

Table 19: Crossbow Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
09Jul03	N/A	N/A	N/A
10Jul03	-3.2	2.1	4.5
14Jul03	-4.2	3.0	3.7
15Jul03_1	-3.5	1.6	4.7
15Jul03_2	-4.5	2.1	4.4
15Jul03_3	-4.3	2.7	3.8
15Jul03_4	-4.2	2.6	3.8
15Jul03_5	-4.4	2.6	3.9
15Jul03_6	-4.4	2.6	4.0
15Jul03_7	-4.3	2.7	3.7
25Jul03_All_In_One	-4.5	2.7	3.9
Average (All)	-4.2	2.5	4.0
Std. Dev. (All)	0.4	0.4	0.4

The Crossbow sensors appear to have larger misalignments than the other IMUs. These larger misalignments have been well estimated by the six-position accelerometer test.

6.1.1.3.4 Accelerometer Noise

Using the standard deviations calculated for each position and listed in the tables of Appendix A, the Crossbow accelerometer noise can be estimated as 1.4 to 7.0 milli-gs. Again, Crossbow does not provide this kind of simple noise specification.

6.2 Gyroscopes

All runs were one minute in duration with data collected at the IMU data rates (without any decimation). The table control software would not accept input rates as being constant, so the table was manually operated from the console for all runs. IMUs were always powered off at the end of the day; various power cycling strategies were used during particular days' testing.

The table positions and rates used for the six-position gyroscope tests are listed in the following tables.

Table 20: Table Positions for Six-Position Gyro Tests for July 23

Table Axis	#1 Position (degrees)	#1 Rate (deg/sec)	#2 Position (degrees)	#2 Rate (deg/sec)
Position 1		+10 (50, 100)	180	
Position 2		-10 (50, 100)	180	
Position 3	90			+10 (50, 100)
Position 4	0			+10 (50, 100)
Position 5	0			-10 (50, 100)
Position 6	90			-10 (50, 100)

On July 23, 2003, three six-position tests were run at different table rates: 10, 50 and 100 degrees per second. IMU power was applied one hour before the start of the first test and was not cycled between the tests. This was designed to provide information on the variation in IMU performance as a function of input rate.

Note that the stable axis was aligned with table axes and not with level (as discussed in Chapter 4). As a result, when the table was spinning about its trunion axis, a component of the input rotation was sensed by the gyro nominally perpendicular to the trunion axis (a similar component being lost by the gyro nominally parallel to the trunion). The estimates from the six-position tests for this day should (and in fact do) reflect this 2.48-degree (or 43.3 milli-radian) misalignment.

Table 21: Table Positions for Six-Position Gyro Tests for July 24-25, August 12

Table Axis	#1 Position (degrees)	#1 Rate (deg/sec)	#2 Position (degrees)	#2 Rate (deg/sec)
Position 1		+10	180	
Position 2		-10	180	
Position 3	87.52			+20 (10, 50, 100)
Position 4	357.52			+20 (10, 50, 100)
Position 5	267.52			+20 (10, 50, 100)
Position 6	177.52			+20 (10, 50, 100)

On July 24, a single test at 10 degrees per second was executed. The IMUs were powered up one hour and 40 minutes before the test started.

On July 25, a number of different tests were run, all at 20 degrees per second. IMU power was applied almost two hours prior to commencement of the first test. The following runs were executed:

> The 10, 50, 100 degree per second multi-rate tests were repeated with the improved procedures and more accurate levelling of Table 21. Power to the IMUs was not

> cycled between multi-rate tests but was cycled before the next test started (power was off for one hour and 20 minutes).
>
> One run was made with data from all positions stored in the same data file to allow Kalman filter processing. There was no power cycle between this test and the next.
>
> Three turn-on-to-turn-on tests were run at 20 degrees per second. IMU power was off for 5 minutes between runs one and two and runs two and three.

On August 12, five turn-on-to-turn-on tests were run at 20 degrees per second. IMU power was applied 40 minutes before the start of Test 1 (the BAE had to be power cycled 8 minutes before testing started because the 5 volt power supply showed zero voltage).

> Between runs 1 and 2, IMU power was turned off for 30 minutes. Run 2 commenced after a 10-minute IMU warm-up period.
>
> Between runs 2 and 3, IMU power was turned off for 12 minutes. Run 3 commenced after a 14-minute IMU warm-up period.
>
> Between runs 3 and 4, IMU power was cycled off then on in the span of a few seconds.
>
> There was no power cycle between runs 4 and 5.

The tests were run with different IMU-off times to try to determine if this has any impact on performance changes from turn-on to turn-on.

File name conventions are different from those used for accelerometer data. Data from each day are stored in separate directories. The three different types of runs on July 25 are stored in separate subdirectories under the July 25 directory. The file name contains an IMU identifier, followed by the string "_1_Min" , and concluding with a rate or a run/position identifier. For example,

> "BAE_1_Min_100dps.asc" is the name of a one-minute data file from the BAE SiIMU with a 100 degree per second table rate.
>
> And, "ISIS_1_Min_35.asc" is the name of a one-minute data file from the Inertial Science ISIS from position five of the third run.

Again, all runs were processed using the "Six_Pos_Test" program. The ASCII input file for gyro processing contains all the information used for accelerometer processing plus an additional data item for the input table rate. Output files have the same naming convention and format as the accelerometer files.

6.2.1 Results

The results and subsequent analysis will focus on the scale factor errors and biases; misalignments will be discussed when significant results arise.

6.2.1.1 BAE SiIMU

6.2.1.1.1 Gyro Scale Factors

Table 22: BAE Gyro Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
23Jul03_10dps	-2946	-3118	-2977
23Jul03_50dps	-202	-323	-416
23Jul03_100dps	-290	-319	-674
24Jul03_10dps	-1830	-1997	-1599
25Jul03_Multi_Rate (10dps)	-3403	-3239	-2619
25Jul03_Multi_Rate (50dps)	2159	1874	1840
25Jul03_All_In_One (20dps)	-1797	-1834	-1251
25Jul03_T2T_1 (20dps)	-1747	-1937	-1167
25Jul03_T2T_2 (20dps)	-1343	-1810	-1200
25Jul03_T2T_3 (20dps)	-1611	-1585	-1225
12Aug03_T2T_1 (20dps)	-1627	-1683	-1365
12Aug03_T2T_2 (20dps)	-1703	-1985	-1586
12Aug03_T2T_3	-1611	-1803	-1624

(20dps)			
12Aug03_T2T_4 (20dps)	-1726	-1716	-1498
12Aug03_T2T_5 (20dps)	-1646	-1910	-1505
Average (All)	-1422	-1559	-1258
Std. Dev. (All)	1270	1224	1068
Average (20dps)	-1646	-1807	-1380
Std. Dev. (20dps)	131	129	177

Note that results for July 25 (multi-rate) at 100 degrees per second are not available because one data file was accidentally overwritten.

The global average scale factor error standard deviation (computed for all axes and all runs) is about 1400 ppm, with a standard deviation of 1170 ppm and RMS of 1825 ppm. These results are somewhat worse than the manufacturer's specification of 1500 ppm.

Using a two-sigma test of individual runs (based on the manufacturer's specification), the 10 degree per hour runs of July 23rd and 25th are identified as outliers, with all gyros near or exceeding the test limit. Removal of these runs produces a new global mean of –1160 ppm, standard deviation of 1040 ppm and RMS of 1525 ppm.

There appears to be an inverse relationship between the size of the scale factor error and the input rate. Also, note the consistency between runs at the same rate (especially the last nine runs at 20 degrees per second). When only the 20 degree-per-second runs are considered,

> The standard deviations for individual axes drops from a 1000 to 1300 ppm range to a 130 to 180 ppm range;
>
> The global standard deviation drops from 1170 to 228 ppm.

All other factors being constant, the scale factor may be more observable at higher rates: i.e. the magnitude of the error in the measured rate is proportional to the rate – the higher the rate, the larger the size of the scale factor induced error.

In addition, scale factor error most likely does change with rate. However, the magnitude seen here is much larger than would be expected.

Note further that the scale factor results for the ISIS IMU contradict the hypothesis (scale factors being quite consistent at different rates); but it is supported by the Crossbow results (where the 10 degree per second estimates are significantly larger than the higher rate estimates).

The question of variability with and without power cycles is complicated by this rate dependence. The following runs were made without intervening power cycles:

The multi-rate tests of July 23rd and 25th;

The all-in-one run and the first turn-on-to-turn-on run of July 25;

The fourth and fifth turn-on-to-turn-on runs of August 12.

The variability of the multi-rate tests seems to be dominated by the rate changes. Note the apparent lack of correlation between the 10 and 50 degree per second runs on July 23rd and 25th. However, there is good agreement between the 50 and 100 degree per second runs on July 23rd. Perhaps scale factor estimation is best done above some threshold rate (between 10 and 50 degrees per second). The lost 100 degree per second run for July 25 would have been useful in supporting this hypothesis.

6.2.1.1.2 Gyro Biases

Table 23: BAE Gyro Bias Estimates

Run I.D.	X (deg/hr)	Y (deg/hr)	Z (deg/hr)
23Jul03_10dps	-262	-103	-145
23Jul03_50dps	-270	-134	-133
23Jul03_100dps	-242	-120	-145
24Jul03_10dps	-223	-111	-151
25Jul03_Multi_Rate (10dps)	-178	-92	-148
25Jul03_Multi_Rate (50dps)	-188	-122	-127
25Jul03_All_In_One	-158	-74	-170

(20dps)			
25Jul03_T2T_1 (20dps)	-152	-86	-160
25Jul03_T2T_2 (20dps)	-93	-30	-49
25Jul03_T2T_3 (20dps)	-86	-41	-36
12Aug03_T2T_1 (20dps)	-250	-28	-48
12Aug03_T2T_2 (20dps)	-219	-33	-68
12Aug03_T2T_3 (20dps)	-195	-51	-71
12Aug03_T2T_4 (20dps)	-128	-33	-43
12Aug03_T2T_5 (20dps)	-158	-49	-104
Average (All)	-187	-74	-107
Std. Dev. (All)	58	38	49
RMS (All)	196	83	118

The global average gyro bias for the BAE SiIMU is –115 degrees per hour with a standard deviation of 71, and RMS of 135 degrees per hour. The manufacturer’s one-sigma specification published in Reference [8] is 100 degrees per hour, repeatability (taken to mean turn-on to turn-on). The standard deviations of all three gyros met the specification. Based on RMS values, the X-gyro is clearly not meeting specifications, the Z-gyro is marginal, and the Y-gyro is acceptable.

The manufacturer’s documents quote “1 ” values, implying a standard deviation (deviation about the mean). But a user is more interested in RMS values (deviation about zero). It is likely that the manufacturer does not distinguish between the two, assuming a zero mean.

It should be noted that this IMU was delivered with a known deficiency in the X-gyro performance (see Test Report, Reference [7]). The exact interpretation of this report is not completely clear. However, given the one-sigma specification of 100 degrees per hour, and a gyro test limit of 200 degrees per hour in Table 4-1 Rate Summary of Reference [7], we can deduce that BAE judges acceptable performance for a single run to be within the two-sigma specification. Six of the 15 X-gyro runs summarised in Table 23 failed on the basis of this criterion. The other two gyros passed this test in all runs.

How do results between runs without intervening power cycles compare to statistics for all runs? Table 23 shows that, for the most part, these runs are more consistent. Most are well within their respective overall one-sigma bound:

> The standard deviations calculated from the three multi-rate runs on July 23 are (14, 16, 7) degrees per hour for the X, Y and Z gyros, respectively;
>
> The two multi-rate runs on July 25 have standard deviations calculated as (7, 21, 15) degrees per hour;
>
> Runs 25Jul03_All_In_One and 25Jul03_T2T_1 have calculated standard deviations of (4, 8, 7) degrees per hour.
>
> Runs 12Aug03_T2T_4 and 12Aug03_T2T_5 have calculated standard deviations of (21, 11, 43) degrees per hour.

Only z-gyro standard deviation for the last set of runs appears to be anomalous:

> The Z-gyro difference between runs 4 and 5 of August 12 is at about 1.2 times the overall z-gyro sigma level;
>
> The Z-gyro standard deviation (43 deg/hr) is roughly the same as the overall z-gyro standard deviation (48 deg/hr).

Of course, statistics gleaned from two or three samples have to be used with great caution. Here they are just corroborating other conclusions.

6.2.1.1.3 Gyro Misalignments

Table 24: BAE Gyro Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
23Jul03_10dps	-1.1	-42.3	-42.2
23Jul03_50dps	-0.3	-42.5	-42.3

23Jul03_100dps	-0.2	-42.5	-42.4
24Jul03_10dps	-0.3	-1.1	-0.8
25Jul03_Multi_Rate (10dps)	-0.4	-1.2	-0.7
25Jul03_Multi_Rate (50dps)	-0.4	-1.2	-0.7
25Jul03_All_In_One (20dps)	-0.3	-1.1	-0.9
25Jul03_T2T_1 (20dps)	-0.2	-1.2	-0.7
25Jul03_T2T_2 (20dps)	-0.3	-1.0	-1.0
25Jul03_T2T_3 (20dps)	-0.2	-1.3	-0.9
12Aug03_T2T_1 (20dps)	-0.3	-1.1	-1.0
12Aug03_T2T_2 (20dps)	-0.3	-1.0	-1.0
12Aug03_T2T_3 (20dps)	-0.6	-0.9	-0.8
12Aug03_T2T_4 (20dps)	-0.4	-1.1	-0.9
12Aug03_T2T_5 (20dps)	-0.7	-0.9	-0.9
Average (All after July 25)	-0.4	-1.1	-0.9
Std. Dev. (All after July 25)	0.2	0.1	0.1

The 2.48-degree (43 milliradian) misalignment was intentionally re-introduced into the gyro tests of July 23rd. The results from that day clearly show that misalignments of this size are readily observable using this kind of six-position testing.

BAE does not provide misalignment specifications, but the values calculated above seem very good.

Recall that the misalignments estimated may be due to misalignment of the gyros relative to their case, or misalignment of the case relative to the average level.

Comparison with misalignments estimated from accelerometer data suggests that both components of misalignment are in play:

> Y and Z misalignments are similar in magnitude, but the differences are well outside the bounds predicted by their standard deviations;
>
> X misalignment differences fall within one-sigma bounds.

Common misalignments (as may be evidenced in the X axis results) can be attributed to misalignment of the case; non-common misalignments (like the Y and Z results) can be attributed to misalignments of individual sensors relative to the case.

6.2.1.1.4 Gyro Noise

The gyros in the SiIMU are expected to have large random errors (1.0 degree per second in the manufacturer’s specifications). The standard deviations estimated from all the data collected at individual positions are in the range 0.65 to 1.05 degrees per second, with a majority being consistently in the 0.8 degrees per second range.

6.2.1.2 Inertial Science ISIS

6.2.1.2.1 Gyro Scale Factors

Table 25: ISIS Gyro Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
23Jul03_10dps	3401	-3303	-3013
23Jul03_50dps	3438	-3363	-3431
23Jul03_100dps	3508	-2813	-2766
24Jul03_10dps	3166	-3772	-3745
25Jul03_Multi_Rate (10dps)	3091	-4163	-4029

25Jul03_Multi_Rate (50dps)	3326	-3806	-3713
25Jul03_All_In_One (20dps)	3041	-3787	-3458
25Jul03_T2T_1 (20dps)	3009	-3781	-3576
25Jul03_T2T_2 (20dps)	2744	-2812	-1246
25Jul03_T2T_3 (20dps)	2708	-2591	-1218
12Aug03_T2T_1 (20dps)	3605	-2578	-2470
12Aug03_T2T_2 (20dps)	3355	-1306	-662
12Aug03_T2T_3 (20dps)	3015	-2487	-2252
12Aug03_T2T_4 (20dps)	2559	-3243	-3427
12Aug03_T2T_5 (20dps)	2505	-3592	-3915
Average (All)	3098	-3160	-2861
Std. Dev. (All)	347	738	1076

The global average scale factor error is -975 ppm, with a standard deviation of 3010 ppm and RMS of 3164 ppm. These values seem to be outside the 2000 ppm manufacturer's specification.

The scale factors estimated for each gyro have large biases and small standard deviations, suggesting that scale factors could be better calibrated to bring them into line with specifications.

Only the Y- and Z-gyro results for the 10 degree per hour run on July 25 fail the 4000 ppm two-sigma test. Results from a number of other runs are close to the limit.

The statistics indicate poorer than expected scale factor performance in this IMU that may be improved by better calibration. The two-sigma tests of individual runs, on the other hand, suggest that this unit is performing at an acceptable level.

Table 25 suggests that the scale factor is less variable when the power was not cycled.

6.2.1.2.2 Gyro Biases

Table 26: ISIS Gyro Bias Estimates

Run I.D.	X (deg/hr)	Y (deg/hr)	Z (deg/hr)
23Jul03_10dps	-2	-198	-639
23Jul03_50dps	-19	-191	-675
23Jul03_100dps	-59	-164	-724
24Jul03_10dps	-7	-211	-643
25Jul03_Multi_Rate (10dps)	-8	-199	-652
25Jul03_Multi_Rate (50dps)	-30	-187	-677
25Jul03_All_In_One (20dps)	2	-196	-639
25Jul03_T2T_1 (20dps)	3	-192	-638
25Jul03_T2T_2 (20dps)	113	-234	-618
25Jul03_T2T_3 (20dps)	102	-238	-624
12Aug03_T2T_1 (20dps)	-52	-247	-1088
12Aug03_T2T_2	-25	-231	-1095

(20dps)			
12Aug03_T2T_3 (20dps)	-7	-287	-1075
12Aug03_T2T_4 (20dps)	107	-338	-1028
12Aug03_T2T_5 (20dps)	103	-337	-1025
Average (All)	15	-230	-789
Std. Dev. (All)	60	53	202

The global average gyro bias for the ISIS is –335 degrees per hour with a standard deviation of 360, and RMS of 490 degrees per hour. The manufacturer’s one-sigma specification is 50 degrees per hour, well below the results produced by these tests. The three gyros in this unit appear to have very different bias performance:

> The X-gyro performs the best, with a small bias and acceptable standard deviation; with four of fifteen runs failing the two-sigma test (100 degrees per hour).
>
> The Y-gyro has a large but fairly consistent mean, with all fifteen runs failing the two-sigma test.
>
> The Z-gyro has an even larger mean and a very large standard deviation; again with all fifteen runs failing the two-sigma test.

The Inertial Science acceptance tests seem to use a two-sigma criterion for individual runs just as BAE did.

On the other hand, the ISIS shows very consistent results between runs without a power cycle, especially if they are carried out with the same input rate.

One other feature of Table 26 should be noted. The Z-gyro bias estimates change suddenly between the last run on July 25 and the first run on August 12: the mean jumps from -650 to –1060 degrees per hour; and the standard deviations of the two sub-samples are both about 30 degrees per hour. Perhaps these gyros are aging; perhaps a discrete event caused the jump in bias. Another set of tests on or about August 30 may answer this question.

6.2.1.2.3 Gyro Misalignments

Table 27: ISIS Gyro Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
23Jul03_10dps	-43.8	-44.7	-0.4
23Jul03_50dps	-43.8	-44.6	-0.3
23Jul03_100dps	-43.8	-44.6	-0.3
24Jul03_10dps	-0.4	-1.4	-0.3
25Jul03_Multi_Rate (10dps)	-0.4	-1.4	-0.3
25Jul03_Multi_Rate (50dps)	-0.5	-1.4	-0.2
25Jul03_All_In_One (20dps)	-0.5	-1.4	-0.3
25Jul03_T2T_1 (20dps)	-0.5	-1.4	-0.4
25Jul03_T2T_2 (20dps)	0.5	-1.5	-0.3
25Jul03_T2T_3 (20dps)	0.6	-1.5	-0.3
12Aug03_T2T_1 (20dps)	-0.5	-1.5	-0.3
12Aug03_T2T_2 (20dps)	-0.5	-1.6	-0.3
12Aug03_T2T_3 (20dps)	-0.5	-1.6	-0.3
12Aug03_T2T_4 (20dps)	-0.5	-1.5	-0.3
12Aug03_T2T_5	0.5	-1.5	-0.3

(20dps)			
Average (All)	-0.5	-1.5	-0.3
Std. Dev. (All)	0.1	0.1	0.05

Note that results for July 25 (multi-rate) at 100 degrees per second are not available because one data file was accidentally overwritten.

The global average gyro misalignment for the ISIS is –0.7 milli-radians with a standard deviation of 0.5, and RMS of 0.9 milli-radians. The manufacturer’s one-sigma specification is 1 milliradian. The estimates include misalignments of the IMU relative to the motion table as well as the misalignments of the gyros relative to the IMU case. The manufacturer’s specifications include only the latter. Obviously, the ISIS misalignment is well within its performance bounds.

The two-sigma (2 milli-radian) for every test passes, confirming the good misalignment of the ISIS’ gyros.

The intentional 2.48-degree misalignment of July 23rd was again readily identified and estimated.

Comparison with misalignments estimated from accelerometer data suggests that both components of misalignment are in play:

> X and Z misalignments are similar in magnitude, but the differences are well outside the bounds predicted by their standard deviations;
>
> Y misalignment differences fall within one-sigma bounds.

Common misalignments (as may be evidenced in the Z axis results) can be attributed to misalignment of the case; non-common misalignments (like the X and Z results) can be attributed to misalignments of individual sensors relative to the case.

6.2.1.2.4 Gyro Noise

The standard deviations estimated from all the data collected at individual positions are in the range 0.05 to 0.63 degrees per second. The manufacturer does not provide a gyro noise specification. The observed values do seem reasonable, based on the 1 degree per second specification of the BAE SiIMU.

6.2.1.3 Crossbow IMU400CB

6.2.1.3.1 Gyro Scale Factors

Table 28: Crossbow Gyro Scale Factor Error Estimates

Run I.D.	X (ppm)	Y (ppm)	Z (ppm)
23Jul03_10dps	202,332	200,510	205,732
23Jul03_50dps	199,690	197,310	196,927
23Jul03_100dps	199,963	196,691	191,499
24Jul03_10dps	202,425	200,754	205,862
25Jul03_Multi_Rate (10dps)	202,109	200,386	205,015
25Jul03_Multi_Rate (50dps)	199,816	197,407	196,899
25Jul03_Multi_Rate (100dps)	199,926	196,762	191,558
25Jul03_All_In_One (20dps)	199,546	199,576	202,726
25Jul03_T2T_1 (20dps)	199,470	199,511	202,693
25Jul03_T2T_2 (20dps)	199,112	199,053	202,943
25Jul03_T2T_3 (20dps)	199,253	199,273	203,133
12Aug03_T2T_1 (20dps)	198,508	198,851	202,325
12Aug03_T2T_2 (20dps)	198,224	198,438	202,571
12Aug03_T2T_3 (20dps)	198,373	198,605	202,372

12Aug03_T2T_4 (20dps)	198,494	198,925	201,999
12Aug03_T2T_5 (20dps)	198,582	198,946	201,940
Average (All)	199,739	198,812	201,012
Std. Dev. (All)	1389	1255	4450
Average (20 dps)	198,840	199,020	200,127
Std. Dev. (20 dps)	504	382	403

The Crossbow scale factor errors are very large (about 20 percent !!). This was obvious as soon as the first gyro data was examined. Clearly, this is outside any reasonable bound. However, for completeness, the statistical summary is presented below.

The global average scale factor error is about 199,854 ppm with a standard deviation of 2875 and RMS of 199,973 ppm. The manufacturer's specification is 1% or 10,000 ppm. Of course, the global statistics and those from individual runs all confirm that this IMU's scale factors are well out of range.

However, the standard deviations show that the scale factors are fairly consistent. If the large biases could be removed, it is quite possible that the IMU could meet the 1% specification.

As with the BAE unit, any IMU400CB scale factors appear to be very dependent on rate. Runs at the same input rate but intervening power cycles consistently have very similar scale factor estimates. Table 28 includes statistics from all runs with 20 degrees per second input. Note the significant improvement in standard deviations.

This rate-dependence masks any possible improvement in scale factor variability when the power is not cycled between runs at different rates (July 23rd and 25th). But what about runs without intervening power cycles that have the same input rate? There are two examples in these tests - 25Jul03_All_In_One and 25Jul03_T2T_1, plus 12Aug03_T2T_4 and 12Aug03_T2T_5. These two sets show consistency that is even better than that found with runs at the same rate but with intervening power cycles.

6.2.1.3.2 Gyro Biases

Table 29: Crossbow Gyro Bias Estimates

Run I.D.	X (deg/hr)	Y (deg/hr)	Z (deg/hr)
23Jul03_10dps	-587	296	-119
23Jul03_50dps	-419	176	-76
23Jul03_100dps	-229	202	-14
24Jul03_10dps	-419	190	-61
25Jul03_Multi_Rate (10dps)	-433	251	42
25Jul03_Multi_Rate (50dps)	-305	177	60
25Jul03_Multi_Rate (100dps)	-213	202	117
25Jul03_All_In_One (20dps)	-280	139	106
25Jul03_T2T_1 (20dps)	-278	138	120
25Jul03_T2T_2 (20dps)	-481	278	301
25Jul03_T2T_3 (20dps)	-470	271	289
12Aug03_T2T_1 (20dps)	-649	174	-319
12Aug03_T2T_2 (20dps)	-702	251	-183
12Aug03_T2T_3 (20dps)	-640	184	-142
12Aug03_T2T_4	-614	137	-112

(20dps)			
12Aug03_T2T_5 (20dps)	-578	124	-104
Average (All)	-456	199	-6
Std. Dev. (All)	161	55	168
Average (20 dps)	-521	188	-5
Std. Dev. (20 dps)	157	62	217

The global average gyro bias for the Crossbow IMU is –88 degrees per hour with a standard deviation of 308, and RMS of 320 degrees per hour. The manufacturer's one-sigma specification is 1 degree per second, equivalent to 3600 degrees per hour. This appears to be a very conservative specification, easily exceeded by this unit.

Once again, rate dependence is evident in the results. However, the consistency between runs at the same rate is not as clear here as it was in other tests. For example, a statistical analysis of all the 20 degree per second runs, is no less variable (and may even be more variable) than the complete data set.

The rate dependence does act to mask consistency during the two multi-rate tests (with no power cycles). The improved consistency is seen in the two instances of back-to-back runs at the same input rate but with no intervening power cycle (25Jul03_All_In_One and 25Jul03_T2T_1, plus 12Aug03_T2T_4 and 12Aug03_T2T_5).

6.2.1.3.3 Gyro Misalignments

Table 30: Crossbow Gyro Misalignment Estimates

Run I.D.	X (millirad)	Y (millirad)	Z (millirad)
23Jul03_10dps	-40	45.5	-5.4
23Jul03_50dps	-37.8	47.4	-5.5
23Jul03_100dps	37.8	47.4	-5.5

24Jul03_10dps	-7.3	5.3	-5.3
25Jul03_Multi_Rate (10dps)	-7.1	5.5	5.2
25Jul03_Multi_Rate (50dps)	-5.7	5.0	5.6
25Jul03_Multi_Rate (100dps)	5.4	4.9	5.5
25Jul03_All_In_One (20dps)	-6.1	5.0	5.5
25Jul03_T2T_1 (20dps)	-6.4	5.0	5.5
25Jul03_T2T_2 (20dps)	-6.2	5.1	6.0
25Jul03_T2T_3 (20dps)	-6.2	5.0	6.0
12Aug03_T2T_1 (20dps)	-6.3	5.1	-5.6
12Aug03_T2T_2 (20dps)	-6.2	5.2	-5.8
12Aug03_T2T_3 (20dps)	-6.3	5.1	-5.5
12Aug03_T2T_4 (20dps)	-6.2	5.0	-5.6
12Aug03_T2T_5 (20dps)	-6.3	5.0	-5.6
Average (All)	-6.3	5.1	-5.6
Std. Dev. (All)	0.5	0.2	0.2

The global statistics give an average of –2.3 milli-radians with standard deviation of 5.3 and RMS of 5.8 mill-radians. Crossbow does not provide a misalignment specification. But, this performance is within the expected range.

The average misalignments for the Crossbow are in the 5 to 6 milli-radian range, suggesting that Crossbow gyros are misaligned relative to the average level determined at the start of testing. Misalignments of 1 to 2 milli-radians are typical for the other IMUs' gyros tested.

The intentional misalignment of July 23 is once again easily identified. However, the results for this day in Table 30 are skewed by the larger gyro misalignments: the X-axis misalignments are about 5 milli-radians too small, and the Y-axis misalignments are about 5 milli-radians too large, reflecting the combination of table tilts and gyro misalignments.

Comparison with misalignments estimated from accelerometer data suggests that both components of misalignment are in play:

> X and Y misalignments are similar in magnitude and sign, but the differences are well outside bounds predicted by their standard deviations;
>
> Z misalignments are similar in magnitude but have different signs.

Common misalignments (as may be evidenced in the X and Y axes) can be attributed to misalignment of the case; non-common misalignments (part of the X and Y misalignment and most or all of the Z misalignment) can be attributed to misalignments of individual sensors relative to the case.

6.2.1.3.4 Gyro Noise

The standard deviations estimated from all the data collected at individual positions are in the range 0.1 to 0.4 degrees per second. Again, the manufacturer does not provide a gyro noise specification, but the observed values do seem reasonable, based on the 1 degree per second specification of the BAE SiIMU.

7 DRIFT RATE TESTS

To characterize the long-term drift rates of the IMUs under test, a 15.5-hour test was run over the night of July 15th to 16th. Every 100th data record was collected from each IMU (a decimation rate of 100). Data was read into a Microsoft Excel spreadsheet and plotted. A best-fit line was computed, and the slopes of these lines are taken as a measure of instrument drift rate and presented in the following tables.

To be clear on terminology, a drift rate here means the rate of change of the sensor bias.

Note that all data sets had to be split into multiple plots (and multiple linear regression fits) because Excel does not allow more than about 32,000 data points in any one plot. Details are listed below.

The large files containing the full 55,630 seconds of data are split into subsets as follows.

BAE:

(1) 1 second to 16,000 seconds;

(2) 16,000 to 27,817 seconds;

(3) 27817 to 43817 seconds;

(4) 43817 to 55634 seconds.

ISIS:

(1) 1 to 27867 seconds;

(2) 27868 to 55633 seconds.

XBOW:

(1) 1 to 18543 seconds;

(2) 18543 to 37087 seconds;

(3) 37088 to 55631 seconds.

Data in the Excel files was plotted with the raw IMU output on the y-axis and elapsed time in seconds on the x-axis. To put the slopes (representing the drift rates) into more useful units, all accelerometer results were rescaled to milli-gs per hour and all gyro results were rescaled to degrees per hour per hour. The following scale factors were used:

BAE SiIMU accelerometer scale factor: Convert (metres per second per 0.005 seconds) per second to milli-gs per hour

$$1\,\frac{\frac{m/s}{0.005\,s}}{s} = \frac{\frac{1\,m/s}{0.005\,s}\times\frac{1000\,mg}{9.81\,m/s^2}}{s\times\frac{hr}{3600\,s}} = 73{,}394{,}495\,\frac{mg}{hr}$$

BAE SiIMU gyro scale factor: Convert (radians per 0.005 seconds) per second to degrees per hour per hour

$$1\,\frac{\frac{rad}{0.005\,s}}{s} = \frac{\frac{1\,rad}{0.005\,s}\times\frac{180\deg}{\pi\,rad}\times\frac{3600\,s}{hr}}{s\times\frac{hr}{3600\,s}} = 1.485106\,605\times 10^{11}\,\frac{\deg/hr}{hr}$$

ISIS and Crossbow accelerometer scale factor: Convert (metres per second per second) per second to milli-gs per hour

$$1\,\frac{m/s^2}{s} = \frac{1\,m/s^2 \times \dfrac{1000\,mg}{9.81\,m/s^2}}{s \times \dfrac{hr}{3600\,s}} = 366{,}972\,\frac{mg}{hr}$$

ISIS and Crossbow gyro scale factor: Convert (degrees per second) per second to (degrees per hour) per hour

$$1\,\frac{\frac{\deg}{s}}{s} = \frac{1\frac{\deg}{s} \times \dfrac{3600\,s}{hr}}{s \times \dfrac{hr}{3600\,s}} = 12{,}960{,}000\,\frac{\deg/hr}{hr}$$

Table 31: Accelerometer Drift Rates

	X (milli-g/hr)	Y (milli-g/hr)	Z (milli-g/hr)
BAE SiIMU (1)	-0.037	-0.231	0.140
BAE SiIMU (2)	-0.530	0.713	0.094
BAE SiIMU (3)	0.016	-0.300	-0.178
BAE SiIMU (4)	-0.142	0.043	-0.307
BAE SiIMU (All)	0.036	-0.084	-0.037
Inertial Science ISIS (1)	-0.002	-0.494	0.213
Inertial Science ISIS (2)	0.003	-0.193	0.140
Inertial Science ISIS (All)	-0.026	-0.352	0.137
Crossbow IMU400CB (1)	-0.404	0.256	-0.468
Crossbow IMU400CB (2)	-0.068	0.145	-0.291
Crossbow IMU400CB (3)	0.011	0.057	-0.146
Crossbow IMU400CB (All)	-0.151	0.125	-0.270

Table 32: Gyro Drift Rates

	X (deg/hr/hr)	Y (deg/hr/hr)	Z (deg/hr/hr)
BAE SiIMU (1)	15.874	-6.134	2.017
BAE SiIMU (2)	19.069	8.778	-9.225
BAE SiIMU (3)	2.983	-7.465	-11.489
BAE SiIMU (4)	18.421	-2.742	8.799
BAE SiIMU (All)	-0.090	1.293	4.459
Inertial Science ISIS (1)	-0.076	6.053	3.934
Inertial Science ISIS (2)	0.385	3.750	1.431
Inertial Science ISIS (All)	-0.412	5.470	3.039
Crossbow IMU400CB (1)	15.645	-5.593	20.398
Crossbow IMU400CB (2)	19.962	-4.413	4.647
Crossbow IMU400CB (3)	10.667	-2.980	-3.465
Crossbow IMU400CB (All)	19.125	-4.647	3.394

Drift rates are, for the most part, remarkably small.

Predicted accelerometer drifts will not reach the level of the manufacturers’ bias specifications (15 mg for BAE, 30 mg for Inertial Science, and 12 mg for Crossbow) for over 10 hours. Predicted accelerometer bias RMS (30, 11, 5 mg) would not be exceeded for at least 10 hours.

Predicted gyro drifts will not reach the level of the manufacturers’ bias specifications (100 deg/hr for BAE, 50 deg/hr for Inertial Science, and 3600 deg/hr for Crossbow) for at least 5 hours, typically more than 10. Predicted gyro bias standard deviations (135, 490, 320 deg/hr) will not be exceeded for at least 6 hours.

This analysis performed for this report is far from satisfactory: the data sets had to be split into 4, 2 and 3 subsets to enable the analysis, only linear fits for the subsets have been reported, and the best fit lines change considerably from one subset to another. It would be useful to more fully examine these drift rate data sets using more sophisticated software.

Autocorrelation functions and Allan variances based on these data sets are likely to provide a better understanding of sensor performance.

7.1 Autocorrelation Analysis of Drift Test Data

The long time span of the IMU drift tests provides a good basis for a more detailed analysis of sensor error behaviour.

7.1.1 A Brief Overview of the Autocorrelation Function

An autocorrelation function describes the correlation of one random process at two points of time. From reference [9], the generalized autocorrelation function is given as

$$\varphi_{xx}(t_1, t_2) = \mathrm{E}[x(t_1)x(t_2)]$$

Figure 2.2-4 in ibid. shows plots of the autocorrelation functions of several common random processes. Of particular interest for the present discussion is the first-order Gauss-Markov process. A continuous process is first-order Markov if its probability distribution

$$\mathrm{F}[x(t_k)|x(t_{k-1}), \ldots, x(t_1)] = \mathrm{F}[x(t_k)|x(t_{k-1})]$$

In words, this means that the probability distribution of a first-order Markov process is dependent only on the value at one point immediately in the past. If the probability density function is Gaussian, the process is a first-order Gauss-Markov process.

The statistics of a stationary first-order Gauss-Markov process are completely described by the autocorrelation function

$$\varphi_{xx}(\tau) = \sigma^2 e^{-\beta_1|\tau|^2}$$

which is in turn completely defined by its variance (σ^2) and correlation time, defined as the time at which the autocorrelation is $\left(1/e\right)$ the value at $\tau = 0$. The correlation time is equal to $\left(1/\beta_1\right)$.

The autocorrelations of many of many physical processes are well represented by this first-order Gauss-Markov model. More importantly, it is the model used in the Kalman filter used to process the IMU data.

7.1.2 Data Analysis

To characterize the error behaviour of individual IMU sensors (accelerometers and gyros), the long time span drift rate data sets were run through an autocorrelation program. The resulting autocorrelation functions were input into an Excel spreadsheet where they could be plotted and used to derive noise variance and first-order Gauss-Markov models of errors:

1) The noise (uncorrelated error) variance is taken as the difference between the autocorrelation value at $(\tau = 0)$ and the variance of the Gauss-Markov process.

2) The variance of the sample first-order Gauss-Markov is taken as the value of the autocorrelation function at $(\tau = 0)$. The correlation time is the value of where the function is $\left(1/e\right)$ times the variance. The variance and correlation time of each Gauss-Markov sample process is determined by fitting a curve to the autocorrelation function. The autocorrelation function is assumed to be that for a first-order Gauss-Markov process: it is the exponential given by the equation above. (Note that the BAE autocorrelation functions in no way resembled a first-order Gauss-Markov process: they will require further analysis.) The Excel spreadsheet program will fit data to an exponential only when all selected points are greater than zero. Six of the twelve ISIS and Crossbow data sets satisfied this limitation with little or no manipulation of the data (manipulation, when required, involved setting a few points below zero to a small positive number or cutting off the autocorrelation data set prematurely). To estimate the first-order Gauss-Markov parameters of the remaining six data sets, linear approximations were used:

   A) To best estimate the Gauss-Markov variance, a linear fit to the first few thousand data points was made. The y-intercept of the linear fit was taken as the process variance.

   B) To best estimate the correlation time, a linear fit to the full data set was made. The time at which the linear fit crossed the $\left(\sigma^2/e\right)$ value in the y-axis was taken as the process correlation time.

   C) The data sets with exponential fits were also processed using the linear fit procedure. Taking the exponential fit as true, the effectiveness of the linear fit procedure can be judged.

7.1.3 Summary of Results

The following tables list the experimental values derived for gyro and accelerometer uncorrelated noise standard deviations and first-order Gauss-Markov standard deviations and correlation times.

The autocorrelation functions for the BAE sensors indicated that their error behaviour could not be properly modelled as first-order Gauss-Markov – they appear to be periodic in nature.

This analysis will be performed at a later time. The noise standard deviations were computed under the (faulty) assumption that the errors are all uncorrelated. They are shown inside brackets to emphasise the approximation made.

The full noise and Gauss-Markov models for the ISIS and Crossbow IMUs are provided. Note that the ????

Table 33: Gyro Error Models

	Axis	Noise Std.Dev. (deg/hr)	G-M Std.Dev. (deg/hr)	G-M Correlation Time (s)	G-M Fit (Linear, Exponential)
BAE	X	(2443.6)	TBD		
	Y	(2307.1)			
	Z	(2578.2)			
ISIS	X	185.4 (185.4)	3.56	5,650	L
	Y	190.7 (192.28)	24.63	16,250	L
	Y		23.69	14,750	E
	Z	248.4 (248.8)	14.83	15,800	L
XBOW	X	522.9 (529.2)	81.51	13,450	L
	X		83.53	12,800	E
	Y	426.6 (427.1)	21.65	12,100	L
	Z	949.9 (950.3)	28.19	6,500	L

Table 34: Accelerometer Error Models

	Axis	Noise Std.Dev.	G-M Std.Dev.	G-M Correlation	G-M Fit (Linear or

		(mg)	(mg)	Time (s)	Exponential)
BAE	X	(1.812)	TBD		
	Y	(2.617)			
	Z	(2.325)			
ISIS	X	1.492 (1.500)	0.137	28,800	L
	Y	0.985 (1.907)	1.634	14,100	L
	Y		1.690	14,525	E
	Z	0.624 (0.887)	0.632	12,450	L
	Z		0.659	11,750	E
XBOW	X	3.562 (3.642)	0.763	10,200	L
	X		0.776	12,100	E
	Y	3.055 (3.105)	0.555	11,200	L
	Y		0.564	11,200	E
	Z	3.091 (3.305)	1.170	11,700	L
	Z		1.225	11,650	E

8 ERROR SUMMARIES AND IMU COMPARISONS

The preceding chapters have presented the results of analysis of three different IMUs more or less independently. In this chapter, much of that analysis will be condensed and presented in a way that will allow evaluation of the overall and relative performance of each IMU.

The number in brackets after the name of the IMU in the following tables is the manufacturer's specification for that error parameter. These specifications are normally compared to the test RMS (variation about zero) values. When the test averages are to be used to recalibrate the sensor in question, the specifications can be compared to test standard deviations (variation about the mean), keeping in mind that the standard deviations will be overly optimistic inmost cases.

Any accelerometer or gyro error that is estimated by an explicit Kalman filter state will be modelled as a first-order Gauss-Markov function, which is completely defined by its standard deviation and correlation time. Based on the results of the present analyses, the MEMS/GPS Kalman filter's IMU sensor error models will use either the manufacturer's specification or the present RMS (or standard deviation) estimates, whichever is larger. The correlation times are not addressed in this report: they can only be approximated on the basis of empirical evidence.

Past projects have used pre-packaged software to calculate autocorrelation functions that can then be used to provide measures of noise, standard deviation and correlation time. The software previously used is available only on a Sun workstation: data would have to be transferred from the PC for processing. Alternatively, software that will calculate autocorrelation functions on a PC could be used. Details of this procedure will not be examined here.

8.1 Accelerometer Error Summary

8.1.1 Scale Factor Errors

Table 35: Accelerometer Scale Factor Summary

IMU (manufacturer's specs)	X (ppm)	Y (ppm)	Z (ppm)
BAE SiIMU (2000 ppm)			
- Mean	1843	2202	2091
- Std Dev	936	882	923
- RMS	2067	2372	2286
Inertial Science ISIS (2000 ppm)			
- Mean	-1011	645	-1383

- Std Dev	364	207	451
- RMS	1075	677	1455
Crossbow IMU400CB (10,000 ppm)			
- Mean	-3027	913	-601
- Std Dev	1504	185	104
- RMS	3380	932	610

The test standard deviations are all well within the specified limits, with the SiIMU results at about 50%, the ISIS at 10-20%, and the Crossbow at 1-10%. (The Crossbow specifications seem to be very conservative.) When comparing RMS values to the specifications, the SiIMU results are up to 20% higher, while the ISIS and Crossbow results are comfortably lower.

The SiIMU shows consistent, but large, averages and standard deviations. The ISIS has less consistency between axes but smaller overall errors. The Crossbow misalignment error is dominated by a large average and standard deviation in the X-axis. The Crossbow Y- and Z-axes seem to perform at least as well as the ISIS and better than the SiIMU.

These results can be attributed to more careful selection of accelerometers (“cherry-picking”) for the more expensive BAE and Inertial Science units. Of course, this is speculation based on past experience.

Can the accelerometers in these IMUs be ranked on overall performance? Let’s start by taking the RMS of the RMS values as an indication:

The SiIMU has a value of 2245 ppm,

The ISIS is 1115 ppm, and

The Crossbow is 2055 ppm.

Using this crude global value, the ISIS appears to perform best in terms of scale factor errors. No clear preference can be identified between the other two units. The more detailed analysis presented above supports this conclusion.

Can these results be used to tune a Kalman filter error model? Scale factors will produce significant navigation errors when constant or long-duration acceleration is experienced by an accelerometer. For example, a scale factor error in an accelerometer under constant acceleration will produce a bias error; a scale factor error in an accelerometer under zero acceleration will produce no error; a scale factor error in an accelerometer under varying, zero-average acceleration will produce a varying, zero-average error.

This MEMS/GPS project is directed at two applications: a soldier-carried backpack and a light land vehicle.

A moving land vehicle will always be nominally level (at least over a long term average). The accelerometer sensing gravity will have a bias-like error due to this constant acceleration due to gravity; accelerometers perpendicular to gravity will have zero-average errors. A vehicle parked on level ground would exhibit scale factor error behaviour similar to a moving vehicle. However, a vehicle could also be parked for long periods with large tilts (on a steep hill for example), inducing scale factor errors in the accelerometers that are normally perpendicular to gravity.

A soldier is even more likely than a vehicle to position himself in orientations that expose any and all accelerometers to the effects of the gravity vector for extended periods of time.

So, the applications of primary interest can be expected to result in scale factor errors in any accelerometer. Does that mean that explicit Kalman filter scale factor states are required? The answer is: It depends. Additional states in a Kalman filter may improve performance but certainly increase computational loading. The MEMS/GPS Kalman filter software can model accelerometer scale factor errors with states, or if the errors are relatively small, they can be modelled as process noise, increasing the expected uncertainty of affected states. Further, adding states to a Kalman filter will provide useful benefits only if those states are observable. Let’s look at these issues separately.

Under the assumption that biases are the most significant error source and are modelled with explicit states, how large do scale factor errors have to be to warrant the use of scale factor states? Under the worst-case scenario, an unmodelled scale factor error would produce an apparent bias of the scale factor error multiplied by gravity. Based on the test RMS errors of about 1000-3000 ppm, maximum apparent acceleration biases of 1-3 milli-gs would be expected. Maximum apparent acceleration biases of 2-10 milli-gs would result from manufacturer’s specified limits of 2000 or 10,000 ppm. Expected bias errors are listed in Table 36. Based on the test RMS estimates and the manufacturer’s specifications (keeping in mind the worst case assumption), we can conclude that the SiIMU and the ISIS accelerometer scale factors can be adequately modelled in the process noise variance. The Crossbow has expected scale factors (especially the specification) that are large enough and expected biases that are small enough to justify the use of explicit states.

If the expected size of a particular error is large enough to warrant it own state, check further to see if the state is observable under the expected conditions.

Observability is a more complex issue: it depends primarily on the types of measurements available to the filter and the trajectory the IMU follows while the filter is running. What kinds of measurements are expected to most effectively cause accelerometer scale factors to be observable? Position and velocity measurements are available from GPS – they should be quite effective. Zero velocity measurements can be made when the IMU is stationary. Can stationary acceleration measurements be made at the same time? Would they add to state observability? The six-position test estimates scale factor errors by placing each accelerometer into a plus and minus gravity orientation. Could the six-position test "trajectory" or some variation be used to better estimate IMU errors? In theory, it certainly could be tested (in fact, "All-In-One" runs were made while collecting data for this report that can be post-processed through the Kalman filter to test the impact of trajectory on accelerometer state observability.

In the end, the observability of a state can be tested simply by including it the state vector and analysing the filter estimates of state accuracy. If accuracy improves (i.e. the standard deviation drops) as measurements are processed, the state would be judged observable. If accuracy does not improve, we can only say that the state was not observable under the specific conditions of the test. The test should be repeated with different measurements and trajectories. This is a brute force approach to state vector augmentation, but it is sometimes effective.

8.1.2 Bias Errors

Table 36: Accelerometer Bias Summary

IMU (manufacturer's specs)	X (mg)	Y (mg)	Z (mg)
BAE SiIMU (15 mg)			
- Mean	-37.1	34.1	1.7
- Std Dev	2.1	2.9	1.1
- RMS	37.2	34.2	2.0
Inertial Science ISIS (30 mg)			
- Mean	11.9	-4.4	13.9
- Std Dev	1.2	2.4	0.9
- RMS	12.0	5.0	13.9
Crossbow IMU400CB (12 mg)			
- Mean	-5.7	5.9	0.4
- Std Dev	2.5	2.2	1.2
- RMS	6.2	6.3	1.3

Conclusions on estimated accelerometer bias size versus specifications follow patterns similar to those found for scale factors. The test standard deviations are all well within the specified limits, with the SiIMU results at about 10-15%, the ISIS at 3-10%, and the Crossbow at 10-20%. But, when comparing RMS values to the specifications, the SiIMU suffers from large biases in the X and Y channels. The RMS values of the SiIMU Z-accelerometer and all ISIS and Crossbow axes perform very well relative to their respective specifications.

Standard deviations are remarkably consistent for all accelerometers in all IMUs, with all estimates in the 1-3 mg range). Averages are all less than 15 mg except for SiIMU X- and Y-axes at about 35 mg.

The RMS of the RMS values for the IMUs are:

29.2 mg for the SiIMU,

11.0 mg for the ISIS, and

5.2 mg for the Crossbow.

The SiIMU value is dominated by the large averages in the X- and Y-axes. The performance of the other two IMUs matches the respective specifications very well, with the Crossbow unit performing the best.

Accelerometer biases will always be modelled with explicit states in the MEMS/GPS Kalman filter. They will be modelled as described in the introduction to this chapter.

8.1.3 Misalignments

Table 37: Accelerometer Misalignment Summary

IMU (manufacturer's specs)	X (mrad)	Y (mrad)	Z (mrad)
BAE SiIMU			
- Mean	-0.9	0.7	1.4
- Std Dev	0.5	0.4	0.2
- RMS	1.0	0.8	1.4
Inertial Science ISIS (1 mrad)			
- Mean	0.8	-1.9	0.7
- Std Dev	0.1	0.9	0.2

- RMS	0.8	2.1	0.7
Crossbow IMU400CB			
- Mean	-4.2	2.5	4.0
- Std Dev	0.4	0.4	0.4
- RMS	4.2	2.5	4.0

Only Inertial Science provided a misalignment specification. The standard deviations of all units met the one milli-radian specification of the ISIS unit. The Z-axis RMS of the SiIMU, the Y-axis RMS of the ISIS and the RMS of all three axes of the Crossbow fall outside the limit. In each case, large biases (as opposed to large variations) can be blamed. Recall that the misalignment error estimates include the misalignment of the sensor relative to the case as well as the misalignment of the case relative to the motion table. It is not possible to separate the two effects using this data set. Thus, it is possible that the latter effect is dominating the averages.

The RMS of the misalignment RMS values for the IMUs are:

1.1 mrad for the SiIMU,

1.4 mrad for the ISIS, and

3.6 mrad for the Crossbow.

The Crossbow value is dominated by large averages. The performance of the other two IMUs meets expectations, with no real advantage between them.

As has been indicated previously, the estimated misalignments include those of each sensor relative to the case plus those of the case relative to the reference (north, east, down in the case of these tests). The MEMS/GPS Kalman filter will always have three states to estimate the latter, the attitude errors of the case relative to the reference (navigation) frame. The fact these two components are difficult to separate in a Kalman filter can be used to justify the use of a single set of misalignment states to estimate the combined misalignment errors.

8.1.4 Noise

Table 38: Accelerometer Noise Summary

IMU (manufacturer's specs)	Min (mg)	Max (mg)

BAE SiIMU (8.4 mg)	0.8	1.7
Inertial Science ISIS	0.6	1.1
Crossbow IMU400CB	1.4	7.0

Noise statistics are not provided by the six-position test results. Instead, they are taken from the standard deviation calculations made for each position of each run. Results can be found in Appendix A, Table 45 to Table 74. For the most part, these standard deviations are very consistent, thus justifying the simple minimum / maximum analysis in the above table.

Only BAE provided an accelerometer noise specification. All IMUs easily meet this (one-sigma) 8.4 milli-g limit.

The ISIS unit has the lowest accelerometer noise values, followed closely by the SiIMU. The Crossbow is somewhat noisier with larger variations between data sets.

8.1.5 Gauss-Markov Models

Table 39: Gauss-Markov Accelerometer Error Summary

	RMS Noise Std.Dev. (mg)	RMS G-M Std.Dev. (mg)	Min / Max Correlation Times (s)
ISIS	1.093	1.015	12,450 / 28,800
XBOW	3.244	0.868	10,200 / 12,100

The “RMS … Std. Dev.” values are the root mean square values of the standard deviations derived from the autocorrelation analysis for all three axes. For example, using Table 33, the RMS of the ISIS gyro noise is computed as

$$\text{RMS} = \sqrt{\left(1.492^2 + 0.985^2 + 0.624^2\right)/3} = 1.093\,\text{mg}$$

8.1.6 Overall

So what can we say about these accelerometers? First of all, as a general statement, overall errors (as measured by the RMS values) are dominated by biases (bias in this sense meaning a non-zero average). This holds across IMUs and across the different errors being characterized. This finding leads to the conclusion that performance might be improved by recalibrating the accelerometers using the averages calculated here.

All three IMUs have built-in calibration algorithms that are transparent to the user. If there is reason to believe that the manufacturers' built-in calibration parameters are suspect, the results of these tests can be used to correct the built-in values. It is a simple matter to apply these corrections in the MEMS/GPS strapdown navigator. Once some realistic field data has been collected, the suitability of recalibrating the accelerometers can be tested and evaluated.

However, since all the data in this report was collected under very homogeneous conditions – no dynamics, at the same temperature and so on – it is possible that the calculated averages are valid only under conditions similar to those present during testing. The manufacturers' calibration values, on the other hand, should be representative of a much larger range of conditions and may be the most appropriate even where significant biases were found in the present testing.

In essence,

> If there is evidence that the biases identified in these tests are the result of real changes in sensor performance, they should be applied in the strapdown navigator.
>
> But, if the biases can be attributed to differences between the specific conditions of these tests versus more general conditions used to generate the calibration parameters, no sensor recalibration should be contemplated.

Now, what conclusions can be drawn regarding the relative performance of the three IMUs under test? First of all, considering the differences in packaging, pricing, size, intended application and so on, these three units have remarkably similar performance. Where differences were identified:

> The Inertial Science ISIS had the best scale factor performance,
>
> The Crossbow IMU400CB had the lowest biases,
>
> The BAE SiIMU (closely followed by the ISIS) had the smallest misalignments, and
>
> The ISIS had the lowest noise.

Alternatively, relative performance can be judged the pointing out that SiIMU had larger biases, and the Crossbow had larger misalignments and noise.

If a winner were to be picked, the Inertial Science ISIS would have to be it. However, given the similarities in accelerometer performance, the decision to purchase one of these IMUs for a particular application would almost certainly be dominated by constraints of packaging, pricing, and size.

8.2 Gyro Error Summary

8.2.1 Scale Factor Errors

Table 40: Gyro Scale Factor Summary

	X (ppm)	Y (ppm)	Z (ppm)
BAE SiIMU (1500 ppm)			
- Mean	-1422	-1559	-1258
- Std Dev	1270	1224	1068
- RMS	1907	1982	1650
Inertial Science ISIS (2000 ppm)			
- Mean	3098	-3160	-2861
- Std Dev	347	738	1076
- RMS	3117	3245	3057
Crossbow IMU400CB (10,000 ppm)			
- Mean	199,739	198,812	201,012
- Std Dev	1389	1255	4450
- RMS	199,739	198,812	201,012

The SiIMU standard deviations are approaching but within the specified limits; the ISIS and Crossbow standard deviations are well within the limits. However, as was often the case with the accelerometer results, biases in the data lift the RMS values outside the specifications: the SiIMU RMS values are up to 10% to 30% higher; the ISIS 50% to 60% higher; and the Crossbow results are 2000% higher than the specified limit.

The Crossbow unit is clearly mis-calibrated. To use this unit for navigation, it is recommended that the large scale factor errors be corrected in the strapdown navigator using a correction of 200,000 ppm for all three gyros or else the means calculated for each gyro (199,739, 198,812 and 201,012 ppm, respectively).

The RMS of the RMS values will again be used as a measure of overall performance:

The SiIMU has a value of 1852 ppm,

The ISIS is 3140 ppm, and

The Crossbow is 199,856 ppm, or 2787 ppm using the RMS of the standard deviations.

Using this crude global value, the SiIMU appears to perform best in terms of scale factor errors. No clear preference can be identified between the other two units. The Crossbow value is likely optimistic since it assumes a zero mean scale factor error.

Scale factors will produce significant navigation errors, when a constant or long-duration angular rate is experienced by a gyro. When used in the intended backpack and land vehicle applications, these IMUs will not experience any such angular rate. The earth's rotation is a constant rate that influences all earth-based gyros. However, these gyros are not accurate enough to easily identify earth rate. Further, unless the IMU is stationary, the component earth rate seen by each gyro will be constantly changing. For these reasons, it is not likely that scale factor states will be required in the MEMS/GPS Kalman filter. The possible exception is the Crossbow unit: if the scale factors cannot be adequately calibrated, scale factor states may be required.

8.2.2 Bias Errors

Table 41: Gyro Bias Summary

	X (deg/hr)	Y (deg/hr)	Z (deg/hr)
BAE SiIMU (100 deg/hr)			
- Mean	-187	-74	-107
- Std Dev	58	38	49
- RMS	196	83	118
Inertial Science ISIS (50 deg/hr)			
- Mean	15	-230	-789
- Std Dev	60	53	202
- RMS	62	236	814
Crossbow IMU400CB (3600 deg/hr)			

- Mean	-456	199	-6
- Std Dev	161	55	168
- RMS	483	206	168

Conclusions on estimated gyro bias size versus specifications a familiar pattern: the test standard deviations are (mostly) well within the specified limits, but large means push the RMS values outside the required bounds. The exception in this instance is the ISIS, which does not meet specifications even on the basis of standard deviations. The ISIS Z-gyro in particular has a large mean and a large standard deviation, producing an RMS that is 16 times the 50 degree per hour limit. Once again, the Crossbow specification appears to be very conservative.

The RMS of the RMS values are:

140 deg/hr for the SiIMU,

491 deg/hr for the ISIS, and

318 deg/hr for the Crossbow.

The SiIMU exhibits the best performance on the basis of this overall RMS value. The ISIS would be comparable if the Z-gyro did perform so poorly. The Crossbow performs very well in light of its specified gyro bias limit.

Gyro biases will always be modelled with explicit first-order Gauss-Markov states in the MEMS/GPS Kalman filter.

8.2.3 Misalignments

Table 42: Gyro Misalignment Summary

	X (mrad)	Y (mrad)	Z (mrad)
BAE SiIMU			
- Mean	-0.4	-1.1	-0.9
- Std Dev	0.2	0.1	0.1
- RMS	0.4	1.1	0.9
Inertial Science ISIS (1 mrad)			

- Mean	-0.5	-1.5	-0.3
- Std Dev	0.1	0.1	0.05
- RMS	0.5	1.5	0.3
Crossbow IMU400CB			
- Mean	-6.3	5.1	-5.6
- Std Dev	0.5	0.2	0.2
- RMS	6.3	5.1	5.6

Only Inertial Science provided a misalignment specification. The standard deviations of all units met the one milli-radian specification of the ISIS unit. The Y-axis RMS of the ISIS and the RMS of all three axes of the Crossbow fall outside the limit.

The RMS of the misalignment RMS values for the IMUs are:

0.9 mrad for the SiIMU,

0.9 mrad for the ISIS, and

5.7 mrad for the Crossbow.

In all other regards, the comments made regarding accelerometer misalignments apply here.

8.2.4 Noise

Table 43: Gyro Noise Summary

	Min (deg/sec)	Max (deg/sec)
BAE SiIMU (1 deg/sec)	0.65	1.05
Inertial Science ISIS	0.05	0.63
Crossbow IMU400CB	0.10	0.40

As mentioned above, noise statistics are not provided by the six-position test results, but are taken from the standard deviation calculations made for each position of each run. Results of individual gyro runs are not included in this report. As with the accelerometers, the simple minimum / maximum analysis used here can be justified by the consistency of the standard deviations.

Only BAE provided a gyro noise specification. All IMUs are in good agreement with this (one-sigma) 1 degree per second limit.

The ISIS and Crossbow units have the lowest gyro noise values; the SiIMU noise is a bit higher.

8.2.5 Gauss-Markov Models

Table 44: Gyro Error Model Summary

	RMS Noise Std.Dev. (deg/hr)	RMS G-M Std.Dev. (deg/hr)	Min / Max Correlation Times (s)
ISIS	210.1	16.73	5,650 / 16,250
XBOW	672.7	51.34	6,500 / 13,450

8.2.6 Overall

Many of the comments made regarding accelerometers are again applicable here:

RMS values are for the most part dominated by biases (bias in this sense meaning a non-zero average)

- Performance might be improved by recalibrating the gyros using the calculated averages,
- But recalibration should be considered only if it can be shown that the new calibration estimates are more representative of all conditions under which the IMUs may operate.

The gyro performance of all three units is very similar.

If winners and losers were to be selected in each category,

- The BAE SiIMU had the best scale factor performance,
- The SiIMU also had the lowest biases,

  - The Crossbow had larger misalignments,
  - The SiIMU had the highest levels of gyro noise.

  A decision to purchase one of these IMUs for a particular application would almost certainly be dominated by constraints of packaging, pricing, and size rather than the results of these tests.

Overall, the BAE SiIMU could be selected as the unit with the best gyro performance.

9 SUMMARY

This report has documented experimental results from a large number of runs collected from three different IMUs simultaneously. All tests took place in a laboratory environment on a precision motion table: accelerometer tests required the table to maintain precise positions relative to the local gravity vector; gyro tests required the table to maintain precise rotation rates.

Three different kinds of test were executed:

1. Four-position gyro tests indicated that earth rate could not be directly measured with the current generation of MEMS gyro. However, when some extra data processing was performed (namely, the removal of calculated biases), the earth rate was visible in data from the BAE SiIMU and the Inertial Science ISIS units. Perhaps standard IMU course alignment algorithms can be modified to use this information and allow some level of gyro-compassing with MEMS IMUs. These results also suggest that gyro-compassing will become a reality with future MEMS gyros.

2. Drift rate tests showed that these sensors all have low drift rates relative to the sizes of other error terms.

3. Six-position test procedures were originally developed to provide estimates of accelerometer scale factors, biases and misalignments using gravity as a control input. Modifications to these procedures were implemented to provide estimates of gyro scale factors, biases and misalignments using constant angular rates. The bulk of the tests run and conclusions drawn were based on six-position tests. Surprisingly, all three IMUs, despite large differences in specifications, size, and cost, provided very similar performance. A notable exception was Crossbow gyro scale factors that were found to be about 20% - well beyond anything that would have been expected. It is expected that differences will be more readily apparent when the accelerometer and gyro data is integrated in a strapdown navigator algorithm.

As for the individual IMUs tested,

1. The BAE SiIMU had a small advantage in gyro performance relative to the other two IMUs even though it was delivered with a Z-gyro that failed one of its acceptance

tests. This unit, which can be installed in missiles and artillery shells, is expected to be very robust. However, on a number of occasions, the data being output from the SiIMU was nonsensical at start-up. A power cycle fixed the problem in every case. BIT status was not being monitored, so there is no way of knowing if BIT identified the problem. It is a situation that must be monitored when navigating with this unit. Fortunately, this problem arose only at start-up.

2. The Inertial Science ISIS had a small accelerometer performance advantage. It performed flawlessly throughout.

3. The Crossbow IMU400CB did not perform quite to the level of the other two units, but it did perform much better than expected. The exception was gyro scale factors that were consistently at about 20%. This greatly exceeds its 1% specification and the 0.2 to 0.3% results for the other IMUs. Clearly, a recalibration is required for these gyros. Other than the gyro scale factor, specifications for this unit were generally very conservative, leading to the pleasant surprise in overall performance.

The RMS error values from each suite of six-position tests should help in the often difficult task of tuning the IMU error models in a navigation integrating Kalman filter. As a general rule, the larger of the manufacturer’s specification and the RMS value will be taken as the initial standard deviation of first-order Gauss-Markov model. These tests do not help with identification of the appropriate correlation times for these models. That job will be left to, as yet unidentified, external software.

So, the testing is finished; the results are in; the goals were achieved. For the most part, all three IMUs met or exceeded expectations. From here, the “all-in-one” data sets will be run through the MEMS/GPS strapdown navigator – Kalman filter software to see how well the filter estimates of sensor errors agree with the results derived here. In the next few weeks, all IMUs will be mounted in a test van along with a GPS receiver and a digital compass for some dynamic testing. These data will be post-processed in the MEMS/GPS software. These dynamic data will be used to refine filter error modelling of all sensors. Then in a few months’ time, the MEMS/GPS software will be further expanded to allow real-time Kalman filter processing.

REFERENCES

[1] *Test Plan To Characterise MEMS IMU Errors On A Motion Table*, Dale Arden, Dale Arden Consulting, (under the current contract) 2003.

[2] *MEMS / GPS State of the Art*, Dale Arden, Dale Arden Consulting, (under the current contract) 2003.

[3] *The MEMS/GPS Strapdown Navigator*, Dale Arden, Dale Arden Consulting, (under the current contract) 2003.

[4] *MEMS/GPS Kalman Filter*, Dale Arden, Dale Arden Consulting, (under the current contract) 2003.

[5] *Alignment Determination and Error Characterisation of Inertial Components for Use in an Airborne Gravimeter*, Derek Hartl, M.Eng. Thesis, Carleton University, Ottawa, 1995.

[6] *MEMS/GPS Test Plan*, Dale Arden, Dale Arden Consulting, (under the current contract) 2003.

[7] *Test Report for Inertial Measurement Unit Serial Number 03SRP201, TR6941, Issue: 2*, BAE Systems, Plymouth, England, June 2003.

[8] *Product Specification for a Silicon Inertial Measurement Unit, SiIMU01 (PC Interface), Issue 3*, BAE Systems, Plymouth, England, January 2003.

[9] *Applied Optimal Estimation*, Arthur Gelb, ed., M.I.T. Press, Cambridge, Massachusetts, 1974.

APPENDIX A: ACCELEROMETER STATISTICS

Presentation of results will begin will a summary of the statistics computed for each position in every run. These can be found below in Table 45 to Table 74.

All units are milli-g.

Table 45: BAE Accelerometer Statistics for July 9, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev

1	11,880	-1,034.097	29.897	2.280	1.057	1.333	0.942
2	11,878	963.295	30.050	4.065	1.108	1.253	1.178
3	11,912	-37.782	32.259	-994.437	1.508	1.004	0.993
4	11,946	-33.619	29.669	1001.441	1.443	1.434	0.917
5	12,015	-35.158	-968.4313	1.783	1.508	1.140	1.336
6	13,683	-35.142	1026.907	4.120	1.464	1.229	1.289

Table 46: ISIS Accelerometer Statistics for July 9, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	5,885	12.159	-1.877	-988.808	0.771	1.069	0.628
2	5,870	12.960	-1.297	1014.796	0.830	0.893	0.609
3	5,921	1014.066	-3.852	13.020	0.775	1.153	0.947
4	5,927	-988.987	-1.878	13.899	0.774	1.116	0.964
5	5,991	12.162	-1002.975	14.117	1.102	0.840	0.973
6	6,772	12.727	996.130	12.817	1.066	0.846	0.947

Table 47: Crossbow Accelerometer Statistics for July 9, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	7,917	-3.517	13.817	-999.356	3.059	4.707	2.286
2	7,978	-11.050	6.102	1001.482	2.110	3.026	2.484
3	8,053	995.356	8.014	-3.152	2.209	5.908	3.431
4	7,993	-1012.113	5.661	-0.495	6.457	5.740	2.129

5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
6	9,058	-4.827	1005.319	3.915	2.686	3.463	3.693

Table 48: BAE Accelerometer Statistics for July 10, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	12,600	-1032.835	29.662	3.868	1.213	1.486	1.216
2	12,001	963.146	30.334	3.840	1.246	1.372	1.238
3	12,025	-36.581	31.801	-995.083	1.672	1.514	1.099
4	12,200	-34.946	-968.877	1.844	1.552	1.208	1.401
5	11,692	-35.334	30.121	1001.600	1.634	1.595	1.024
6	11,933	-35.649	1027.956	5.135	1.546	1.317	1.237

Table 49: ISIS Accelerometer Statistics for July 10, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	6,306	8.470	-10.954	-988.731	0.872	1.986	0.619
2	6,000	10.033	-5.531	1013.631	0.886	1.261	0.620
3	5,921	1011.650	-4.493	12.072	0.865	1.318	0.982
4	6,107	10.832	-1000.000	13.133	1.119	0.875	0.989
5	5,851	-989.819	0.859	13.002	0.837	1.171	0.972
6	5,969	12.043	999.292	11.971	1.188	1.037	0.977

Table 50: Crossbow Accelerometer Statistics for July 10, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	8,479	1.841	5.083	-997.373	4.233	7.209	2.642
2	8,034	-3.949	1.135	1004.179	4.114	8.879	2.770
3	8,044	998.075	1.988	0.228	2.881	7.511	4.008
4	8,181	-3.641	-997.025	-1.939	3.745	6.048	1.592
5	7,859	-1003.362	0.744	1.861	4.373	6.233	3.384
6	8,011	-0.743	1001.938	6.932	2.678	5.032	2.576

Table 51: BAE Accelerometer Statistics for July 14, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	851	-1037.121	34.266	0.744	1.079	1.238	0.924
2	1,452	961.640	34.683	1.864	1.159	1.358	1.087
3	1,367	-37.896	34.912	-997.669	1.380	1.264	0.945
4	1,463	-36.618	-965.487	-0.072	1.458	1.102	1.225
5	1,385	-36.847	1031.520	2.005	1.477	1.246	1.064
6	1,555	-36.615	34.643	999.360	1.459	1.334	0.968

Table 52: ISIS Accelerometer Statistics for July 14, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	498	11.998	-3.074	-988.084	0.752	0.870	0.603
2	617	13.092	-2.421	1015.131	0.751	0.802	0.593

3	763	1014.183	-4.837	13.3316	0.834	10.385	0.878
4	641	12.373	-1002.839	14.346	0.995	0.708	0.906
5	771	13.613	995.270	13.039	0.929	0.914	0.896
6	670	-988.503	-2.510	14.137	0.753	0.852	0.923

Table 53: Crossbow Accelerometer Statistics for July 14, 2003

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	606	-4.433	12.215	-999.680	2.562	2.450	2.231
2	880	-11.563	6.470	1001.335	1.668	1.483	1.934
3	959	994.890	8.917	-3.315	2.147	4.117	3.321
4	858	-9.195	-991.720	-3.454	2.686	3.278	2.377
5	975	-4.753	1005.885	3.584	2.390	2.489	3.325
6	954	-1014.881	7.488	-0.768	5.552	4.295	1.934

Table 54: BAE Accelerometer Statistics for July 15, 2003, Run 1

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	12,527	-1034.040	33.761	1.468	1.442	1.369	1.070
2	19,116	961.079	34.004	2.834	1.124	1.355	1.070
3	12,071	-37.744	36.350	-994.435	1.496	1.424	0.909
4	12,710	-37.200	-961.726	0.944	1.420	1.042	1.262
5	13,052	-36.889	1032.213	2.998	1.493	1.352	1.241
6	12,837	-38.172	35.082	999.163	1.575	1.328	0.897

Table 55: BAE Accelerometer Statistics for July 15, 2003, Run 2

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	15,000	-1034.513	32.574	2.332	1.102	1.371	1.061
2	11,000	963.543	33.100	3.301	1.072	1.410	0.950
3	16,000	-36.680	34.056	-995.544	1.506	1.389	0.978
4	14,001	-35.983	-966.568	2.083	1.399	1.149	1.243
5	15,000	-35.426	1029.378	4.211	1.543	1.155	1.196
6	18,001	-35.216	33.115	1000.795	1.516	1.347	0.930

Table 56: BAE Accelerometer Statistics for July 15, 2003, Run 3

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	12,927	-1035.267	32.831	0.945	1.211	1.362	1.083
2	14,326	-961.527	33.678	1.684	1.230	1.401	1.125
3	15,048	-38.086	34.182	-995.644	1.396	1.352	0.841
4	15,080	-36.936	-965.278	-0.053	1.454	1.175	1.255
5	15,327	-35.329	1030.262	2.377	1.463	1.214	1.155
6	15,298	-35.620	32.873	999.090	1.563	1.347	0.937

Table 57: BAE Accelerometer Statistics for July 15, 2003, Run 4

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	14,730	-1033.931	32.288	0.366	1.071	1.244	1.106

2	15,719	962.387	33.192	1.390	1.136	1.348	1.150
3	15,455	-37.270	34.338	-996.511	1.473	1.406	0.942
4	15,848	-36.375	-965.781	-0.130	1.481	1.150	1.248
5	15,976	-35.503	1030.262	3.159	1.448	1.114	1.211
6	15,880	-35.982	32.615	1000.192	1.500	1.454	0.991

Table 58: BAE Accelerometer Statistics for July 15, 2003, Run 5

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	15,778	-1035.335	34.299	0.545	1.204	1.541	1.101
2	15,300	961.835	34.298	0.911	1.174	1.396	1.164
3	15,334	-38.306	35.510	-997.279	1.473	1.615	0.946
4	15,153	-37.730	-963.975	-0.933	1.394	1.116	1.205
5	15,045	-36.381	1032.736	1.922	1.447	1.094	1.201
6	15,666	-35.919	35.029	998.854	1.434	1.366	1.003

Table 59: BAE Accelerometer Statistics for July 15, 2003, Run 6

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	17,289	-1032.995	36.061	-0.045	1.114	1.395	1.166
2	15,916	958.605	35.513	0.461	1.160	1.394	1.195
3	15,733	-38.095	36.959	-995.126	1.461	1.397	0.994
4	15,933	-36.245	-961.491	-0.974	1.267	1.005	1.116
5	15,479	-35.197	1029.511	1.519	1.456	1.151	1.167

6	12,616	-36.731	35.799	995.806	1.603	1.426	0.943

Table 60: BAE Accelerometer Statistics for July 15, 2003, Run 7

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	11,879	-1035.420	35.374	-0.127	1.272	1.553	1.148
2	11,957	960.884	35.940	0.522	1.538	1.460	1.176
3	11,863	-38.338	37.294	-997.622	1.647	1.493	0.953
4	11,970	-36.988	-962.704	-1.061	1.518	1.115	1.413
5	11,966	-36.405	1033.650	2.057	1.481	1.272	1.242
6	12,125	-37.444	37.240	999.447	1.517	1.600	1.050

Table 61: ISIS Accelerometer Statistics for July 15, 2003, Run 1

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	6,150	7.997	-13.292	-987.746	0.790	0.958	0.617
2	9,367	9.118	-10.362	1014.745	0.832	0.906	0.614
3	6,643	1009.563	-10.678	13.160	0.769	1.107	0.936
4	6,663	8.992	-1006.559	13.911	1.078	0.820	0.914
5	6,309	10.502	991.456	12.534	1.045	0.915	0.934
6	6,517	-990.898	-4.240	13.534	0.760	1.043	0.929

Table 62: ISIS Accelerometer Statistics for July 15, 2003, Run 2

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	6,403	11.357	-1.080	-988.374	0.809	0.900	0.599
2	5,500	12.028	-0.457	1014.607	0.841	0.913	0.607
3	7,999	1012.799	-2.423	12.803	0.830	1.147	0.944
4	7,053	11.615	-999.925	13.932	1.091	0.806	0.911
5	7,500	12.771	998.375	12.626	1.004	0.902	0.958
6	9,000	-989.210	1.229	13.751	0.764	1.034	0.937

Table 63: ISIS Accelerometer Statistics for July 15, 2003, Run 3

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	6,726	12.234	-2.790	-987.770	0.787	1.061	0.605
2	7,138	12.921	-2.150	1015.427	0.859	0.959	0.615
3	7,393	1013.789	-4.246	13.652	0.794	1.115	0.938
4	7,731	12.402	-1002.408	14.732	1.030	0.828	0.959
5	7,613	13.586	996.442	13.561	1.019	0.969	0.937
6	7,613	-988.433	-1.416	14.740	0.791	0.984	0.917

Table 64: ISIS Accelerometer Statistics for July 15, 2003, Run 4

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	7,300	11.899	-4.009	-987.367	0.817	0.944	0.614
2	7,880	12.564	-3.592	1015.610	0.862	0.922	0.606

3	7,629	1013.546	-5.488	13.824	0.795	1.142	0.954
4	7,830	12.209	-1003.536	14.861	1.063	0.841	0.948
5	7,864	13.351	995.345	13.695	0.996	0.877	0.943
6	7,892	-988.764	-2.214	14.859	0.762	0.997	0.943

Table 65: ISIS Accelerometer Statistics for July 15, 2003, Run 5

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	7,778	10.440	-8.651	-987.484	0.811	0.931	0.612
2	7,526	11.365	-7.532	1015.480	0.869	0.908	0.623
3	7,634	1012.054	-.062	13.924	0.828	1.116	0.941
4	7,424	11.140	-1006.533	15.024	1.069	0.795	0.941
5	7,611	12.356	992.110	13.892	0.937	0.800	0.942
6	7,782	-989.356	-5.071	15.081	0.745	0.954	0.933

Table 66: ISIS Accelerometer Statistics for July 15, 2003, Run 6

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	8,446	10.751	-7.261	-987.115	0.833	1.029	0.620
2	7,931	11.704	-6.301	1015.679	0.846	0.887	0.608
3	7,822	1012.540	-7.860	13.945	0.809	1.143	0.936
4	7,932	11.473	-1005.445	15.039	1.080	0.827	0.961
5	7,627	12.646	993.164	13.797	0.974	0.796	0.955
6	6,075	-989.218	-4.288	14.971	0.739	0.966	0.944

Table 67: ISIS Accelerometer Statistics for July 15, 2003, Run 7

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	5,929	11.541	-5.482	-987.306	0.792	0.947	0.613
2	5,967	12.749	-4.310	1016.250	0.883	0.972	0.618
3	5,924	1013.648	-6.864	14.309	0.806	1.117	0.938
4	5,960	12.101	-1005.302	15.430	1.035	0.885	0.951
5	5,963	13.274	993.748	14.086	1.025	1.013	0.928
6	6,037	-989.065	-4.534	15.436	0.841	1.197	0.935

Table 68: Crossbow Accelerometer Statistics for July 15, 2003, Run 1

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	7,454	1.897	6.313	-996.949	6.408	3.904	1.927
2	11,339	-3.868	3.423	1003.861	6.727	2.434	2.593
3	8,119	999.478	1.151	0.313	6.397	4.226	3.911
4	9,002	-2.633	-997.703	-2.061	4.526	2.400	1.438
5	8,306	1.334	1000.631	7.227	4.036	2.951	2.238
6	8,309	-1002.533	-0.220	1.868	3.841	4.408	3.302

Table 69: Crossbow Accelerometer Statistics for July 15, 2003, Run 2

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	8,212	-0.079	7.637	-997.728	2.266	6.997	2.164

2	7,363	-7.719	3.740	1003.439	3.689	6.403	2.621
3	10,694	996.898	3.960	-0.958	1.888	6.897	3.628
4	9,413	-5.716	-995.524	-2.339	3.248	5.839	1.746
5	10,044	-1.086	1002.910	6.295	2.557	6.020	2.946
6	12,055	-1005.657	2.540	0.918	5.095	6.769	3.132

Table 70: Crossbow Accelerometer Statistics for July 15, 2003, Run 3

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	9,441	-3.011	10.521	-999.499	3.206	4.620	2.340
2	9,498	-10.490	5.497	1001.766	2.741	2.911	2.265
3	9,878	995.757	7.325	-2.969	1.695	6.062	3.584
4	10,283	-8.072	-993.151	-3.092	3.169	4.161	2.360
5	10,082	-3.636	1004.939	4.149	2.760	4.204	3.662
6	10,131	-1011.640	5.308	-0.467	6.475	5.913	2.136

Table 71: Crossbow Accelerometer Statistics for July 15, 2003, Run 4

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	9,740	-3.506	10.740	-999.749	3.308	4.131	2.417
2	10,522	-10.731	5.708	1001.558	2.611	2.595	2.202
3	10,196	995.674	7.532	-3.356	1.750	5.819	3.594
4	10,514	-8.317	-992.891	-3.259	3.158	4.057	2.389
5	10,271	-3.811	1005.172	3.862	2.637	3.825	3.737

6	10,499	-1012.300	5.941	-0.605	6.447	5.690	2.039

Table 72: Crossbow Accelerometer Statistics for July 15, 2003, Run 5

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	10,256	-2.603	10.704	-999.704	3.006	3.919	2.414
2	10,079	-10.179	5.867	1001.404	2.771	2.202	2.116
3	10,138	995.816	7.642	-3.598	1.634	5.514	3.380
4	10,013	-7.880	-993.109	-3.467	2.901	3.820	2.464
5	10,137	-3.240	1004.688	3.756	2.499	3.194	3.732
6	10,380	-1010.828	5.744	-0.656	5.960	5.498	1.984

Table 73: Crossbow Accelerometer Statistics for July 15, 2003, Run 6

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev
1	11,100	-3.251	10.904	-999.752	3.132	3.422	2.369
2	10,521	-10.691	5.914	1001.280	2.342	1.951	2.196
3	10,456	995.643	8.018	-3.984	1.809	5.294	3.156
4	10,507	-8.083	992.688	-3.689	2.727	3.861	2.730
5	10,281	-3.481	1005.351	3.626	2.437	3.079	3.799
6	8,146	-1011.337	6.300	-0.829	5.847	5.415	1.878

Table 74: Crossbow Accelerometer Statistics for July 15, 2003, Run 7

Position	No. of Samples	X Mean	Y Mean	Z Mean	X Std Dev	Y Std Dev	Z Std Dev

1	7,928	-3.616	11.220	-1000.161	3.244	3.269	2.416
2	7,989	-11.018	5.971	1001.225	2.250	2.287	2.087
3	7,914	995.362	8.423	-3.975	2.077	5.343	3.506
4	7,987	-8.881	-992.202	-3.812	3.142	3.767	2.692
5	7,977	-4.546	1006.070	2.954	2.823	3.442	3.829
6	8,082	-1013.993	7.457	-1.042	6.495	5.375	1.739

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) Dale Arden Consulting R.R.. #3 Almonte, Ontario	2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable) UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

ANALYSIS OF MEMS IMU MOTION TABLE TESTING (U)

4. AUTHORS (Last name, first name, middle initial)

Arden, Dale A.G.

5. DATE OF PUBLICATION (month and year of publication of document) May 2007	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 88	6b. NO. OF REFS (total cited in document) 9

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contract Report

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

Defence R&D Canada - Ottawa, 3701 Carling Avenue, Ottawa, Ontario, K1A 0Z4

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written) W7714-010525/001/SV
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) DAC-0401	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor) DRDC Ottawa CR 2007-092

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(x) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; further distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

The Navigation Group of the Communications Electronic Warfare Section of Defence R&D Canada – Ottawa (DRDC Ottawa) is funding research to study and develop an integrated navigation system based on Inertial Measurement Units (IMUs) based on Micro-Electro-Mechanical Systems (MEMS) gyros and accelerometers and the Global Positioning System (GPS). Three MEMS IMUs were purchased under the terms of this contract. To better understand the error characteristics of MEMS inertial sensors and to gain familiarity with these instruments, a series of tests were carried out. The Inertial Test Lab owned and managed by DRDC Ottawa is equipped with two two-axis Contraves motion tables. One of these tables was used for these tests.

This report describes the results of analyses performed on data collected on a DRDC Ottawa motion table. Emphasis was placed on statistical characterization of individual gyro and accelerometer error behaviour with the aims of

1. Comparing real-life results with manufacturers' specifications,
2. Developing IMU error models that may be suitable for use in the MEMS/GPS Kalman filter integration processing,
3. Comparing the performance of the three IMUs under test.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Integrated navigation; Inertial Measurement Units (IMUs); Micro-Electro-Mechanical Systems (MEMS); Accelerometer; Gyroscope; Motion table; Error modelling