97-622

Motion Compensation Study

Task Two Report

Task 2 Contract #0405V.W7714-6-0010

March 27,1997

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1. Introduction

Tactical Technologies was contracted by DREO to investigate motion sensors which could be used to compensate for platform motion during ESM experiments (Contract No. 0405V.W7714-6-0010). At the conclusion of Task 1 of that investigation, a number of potentially suitable sensors had been identified and were described in the Task 1 final report. That report also included some preliminary recommendations for sensor selection.

This report summarizes the findings of Task 2, in which the performance of the previously identified sensors were compared using a custom-designed software model. As a result of this modeling and simulation activity, some revisions to the preliminary recommendations of Task 1 were made. These revised recommendations are included in this report.

2. Modeling Objective and Description

There were two related objectives to this modeling exercise. The first objective was to assess whether any of the systems identified in Task 1 were capable of inertial measurement to a bearing accuracy of 0.1°. The second objective was to compare the relative performance of the different systems.

For Task 2, a software model of an inertial measurement system was developed using the Matlab/Simulink[1] programming environment. The inertial model simulates a single-axis rate gyro's response to wave motion, so that actual platform heading may be compared to that measured inertially via the rate gyro. An idealized magnetic compass is also included in the model, to show the effect of periodically updating the inertial measurement with a non-inertial reference.

The Simulink model of the inertial measurement system is described in some detail in Annex A. The wave motion component of this model is based on recorded data from CFAV Endeavor. This wave motion data has been plotted and is presented in Annex B.

To facilitate the evaluation of the simulation run results, a user-configurable input menu or "dialog box" was set up for the rate gyro component. In this way the gyro could be quickly and easily configured to simulate each specific device under test, based on the manufacturer's specifications for that device. The dialog box accepted the following four input parameters:

---

[1] From The MathWorks Inc., 24 Prime Park Way, Natick, MA, 01760-1500

1. Angular rate limit
2. Random walk
3. Drift bias
4. Bandwidth

3. Assessment of Inertial Measurement Systems

Nine of the inertial measurement systems from the Task 1 report were selected for further analysis and evaluation in Task 2. These selected systems were:

Litton	LN-200
Honeywell	HG1700
Watson Industries	IMU-BA604
Watson Industries	AHRS-BA303
Boeing North American	Digital Quartz IMU (DQI)
SAGEM	30 MS 57
Andrew Corp.	Autogyro Navigator
KVH Industries	Azimuth Digital Gyro Compass (ADGC)
British Aerospace	FG314

For each system, the four gyro input parameters required by the Simulink model were determined (see Table 1). Values were either extracted directly from manufacturer's specifications or assessed based either on the technology used or on related manufacturer's specifications.

For example, in cases where the manufacturer supplied an RMS noise value in place of random walk, the random walk value was assessed to be equal to RMS noise divided by the square root of the bandwidth. Also, some resonator gyro systems did not have their drift bias specified. For these systems a drift bias of 10°/hour was assumed.

The following sections, 3.1 to 3.9, summarize TTI's assessment of the suitability of each of the above devices to DREO's motion compensation application. The devices have been ranked according to how well they were deemed to meet DREO's needs. The order in which the devices are addressed in the following sections is based on that ranking, with the most suitable devices discussed first.

In evaluating the inertial systems it was assumed that an IBM compatible PC would be used to receive and process the output from the ESM antenna, from the inertial measurement system and from a heading reference, to periodically re-calibrate the inertial system. Such a heading reference might come from a magnetic compass, a true north gyro compass, a GPS system, or an on-board inertial navigation system.

For those systems for which simulation runs were conducted, simulation results are shown.

The simulation results are presented as plots which show drift in the inertial measurement over a 15 minute time period. The desired goal was to achieve a total drift of less than 0.1°.

For each inertial system modeled, three drift plots were generated. The **Compensated Drift** result is generated assuming that an ideal magnetic compass updates the inertial system with a 32 second time constant. The **Uncompensated Drift** result is generated without the compass correction. And the **Uncompensated, No Bias** result is generated without the compass correction and with the drift bias set to zero. It was felt that this last result might be useful if it were possible to somehow measure and remove the drift bias through digital signal processing techniques.

Device	Angular Rate	Random Walk	Drift Bias	Bandwidth	Comment
Honeywell: HG1700	1,000°/s	0.125°/√hr	1.0°/hr	300 Hz	Bandwidth is estimated, based on one-half the maximum output data rate.
Litton: LN-200	1,000°/s	0.1°/√hr	1.0°/hr	500 Hz	
Watson: IMU-BA604 or AHRS-BA303	100°/s	0.2°/√hr	10°/hr	70 Hz	Drift bias is estimated, based on device type. These units include a magnetic fluxgate compass as a reference to prevent drift. Random walk is estimated, based on manufacturer's RMS noise and bandwidth specification.
Boeing: DQI	1,000°/s	0.03°/√hr	10°/hr	50 Hz	Random walk seems to be too good for a resonator gyro. Drift bias is estimated, based on manufacturer's repeatability specification.
KVH: ADGC	45°/s			20 Hz	The specifications for this device supplied by the manufacturer were not complete enough to accurately estimate either random walk or drift bias. The unit includes a gimballed magnetic compass as a reference to prevent drift.
Andrew: Autogyro Nav.	100°/s	0.33°/√hr	18°/hr	60 Hz	
Brit. Aero: FG314	100°/s	0.2°/√hr	50°/hr	125 Hz	Random walk is estimated, based on manufacturer's RMS noise and bandwidth spec.
SAGEM: 30 BM 61	120°/s	0.15°/√hr	10°/hr	100 Hz	Random walk is estimated, based on manufacturer's RMS noise and bandwidth spec.

Table 1. Gyro Model Input Parameter Values

3.1 Litton LN-200

The LN-200 is a six-axis inertial measurement unit which uses fiber optic gyros. It is designed mainly for military applications such as inertial navigation systems for military aircraft and inertial guidance systems for missiles.

The LN-200 is TTI's first choice for DREO's motion compensation system for a number of reasons:

i) The unit has the lowest uncompensated drift of any of the tested inertial systems. As can be seen from the Figure 1 plots, the uncompensated drift remains less than the desired 0.1 ° for up to six minutes.

ii) The unit is small enough and light enough to be attached directly to the ESM antenna.

iii) The unit may be purchased with special software such that attitude and heading are calculated internally from the normal IMU outputs: delta angle and delta velocity.

iv) Fiber optic gyros are not as affected by acceleration forces as resonator gyros or mechanical gyros. Acceleration at the top of a ship's mast in high sea states may reach 1 g.

v) Fiber optic gyros are not affected by any ferromagnetic effects due to the metallic structure of the platform.

vi) Fiber optic gyros are rugged and reliable.

On the negative side, at an estimated $30,000, the LN-200 is substantially more expensive than inertial systems using resonator gyros.

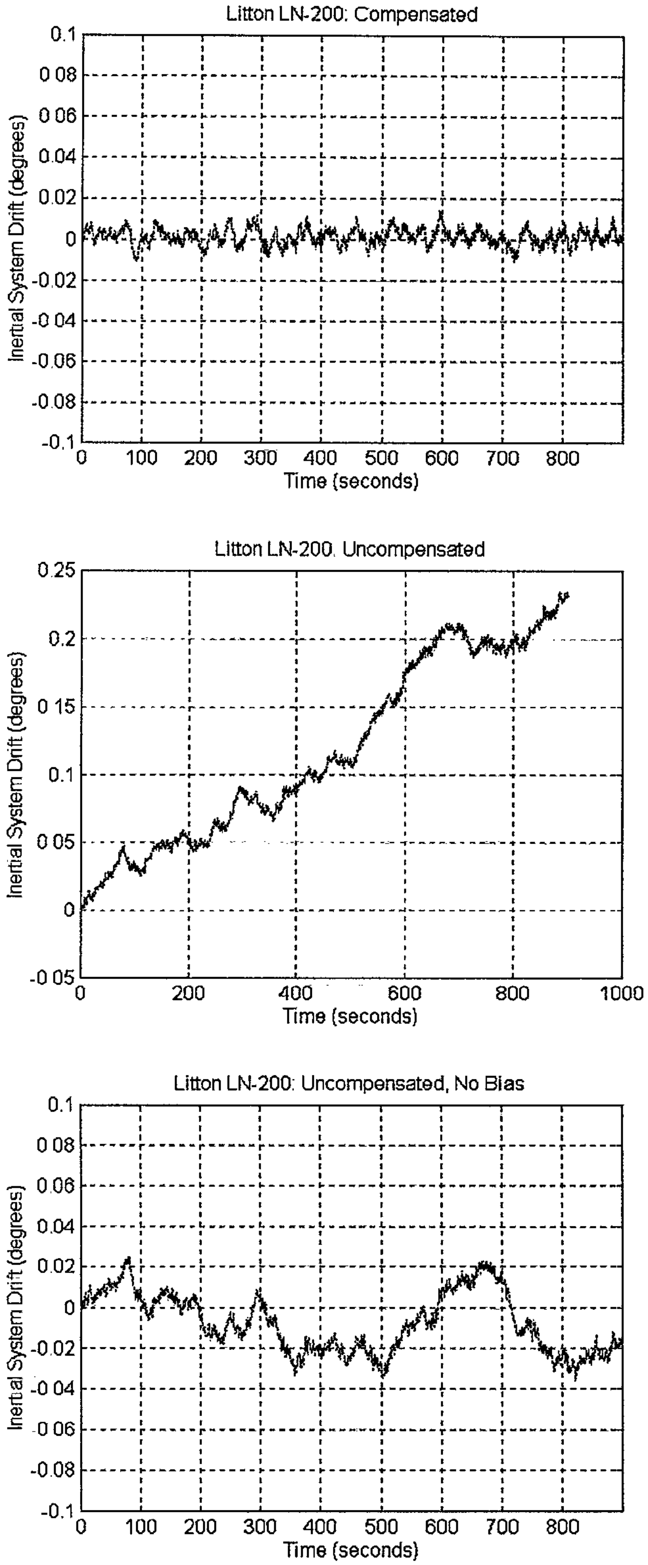


Figure 1 LN-200 Drift over 15 minutes

3.2 Honeywell HG1700

The HG1700 is a six-axis inertial measurement unit which uses ring laser gyros. It is designed mainly for military applications such as inertial navigation systems for military aircraft and inertial guidance systems for missiles.

This system shares many of the advantages of the LN-200: it is small, lightweight, rugged, and relatively immune to acceleration and ferromagnetic effects. The manufacturer's specifications for this system are comparable to those of the LN-200, and therefore a similar level of drift performance is expected.

However, there are two reasons this system is ranked second to the LN-200. Ring laser gyros are more expensive than fiber optic gyros, and it is expected that the HG1700 will cost twice as much as the LN-200. Also, TTI was unable to ascertain whether the HG1700 came with attitude and heading software. If it does not, software will have to be developed within the PC to perform this calculation.

3.3 Watson Industries IMU-BA604 and AHRS-BA303

The IMU-BA604 is a six-axis inertial measurement unit which uses resonator gyros. It is designed mainly for inertial navigation systems for commercial aircraft. As a motion compensation system for DREO, it has several advantages:

i) It is less than half the price of the LN-200;

ii) It has built-in non-inertial attitude and heading references;

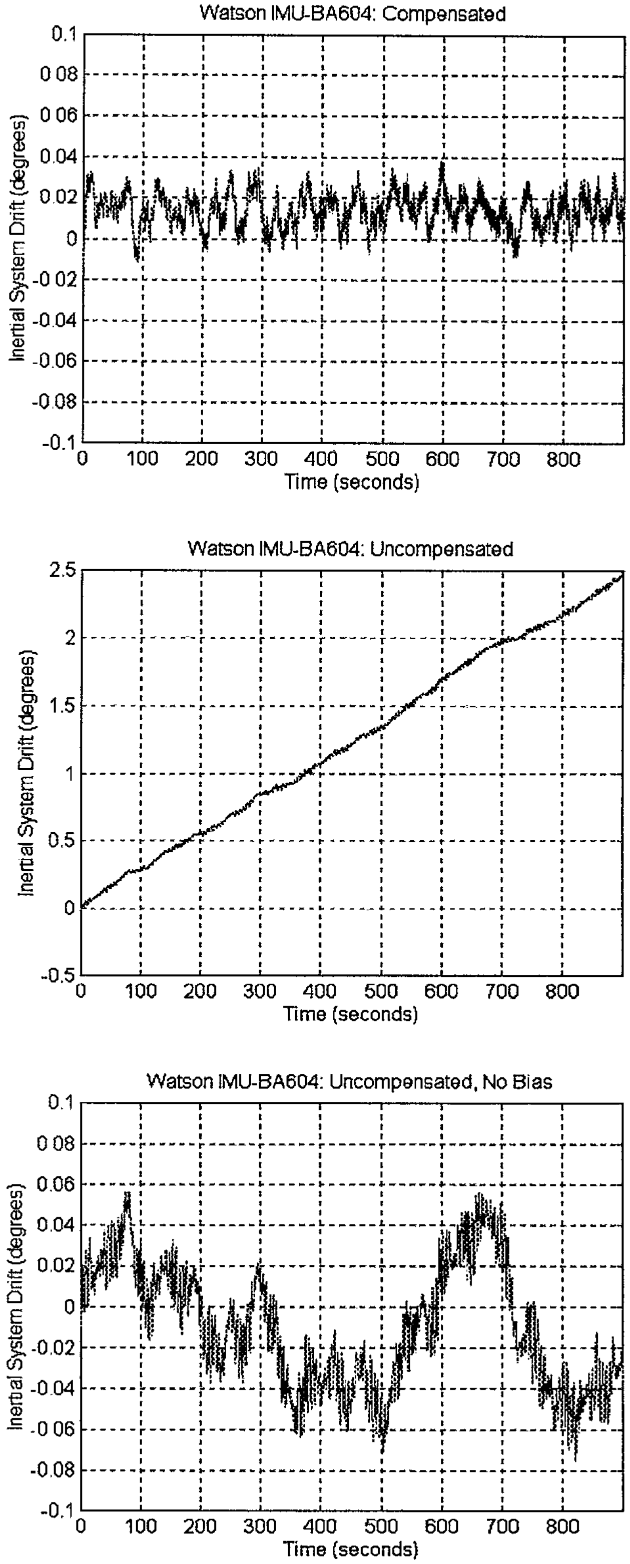
iii) It is designed specifically for use inside an aircraft;

iv) It is small enough to mount directly on the ESM antenna.

On the negative side, resonator gyro drift is substantially worse than that of either fiber optic gyros or ring laser gyros. It can be seen from Figure 2 that, without regular re-calibration, the heading measurement will drift by more than 0.1 ° in less than one minute.

To compensate for the drift, the BA604 includes a triaxial fluxgate compass and pendulous attitude references. With these devices as references, heading drift is probably limited to the repeatability specification of the magnetic fluxgate compass.

The manufacturer's specifications imply that the compass will measure with a repeatability of 0.2°, for a magnetic dip angle of 45° or less. Unfortunately, because of the location of the magnetic pole, the dip angle everywhere in Canada probably exceeds this value.


Watson IMU-BA604: Compensated

Watson IMU-BA604: Uncompensated

Watson IMU-BA604: Uncompensated, No Bias

Figure 2 BA604 Drift over 15 minutes

The AHRS-BA303 is a three-axis version of the BA604, containing rate gyros but no accelerometers. It is therefore a less expensive device. However, to compensate for centrifugal forces during platform manoeuvres, the BA303 requires a separate input which references the platform velocity.

3.4 Boeing North American Digital Quartz IMU (DQI)

The Digital Quartz IMU is a six-axis inertial measurement unit which uses resonator gyros. It is designed mainly for military applications such as inertial navigation systems for military aircraft and inertial guidance systems for missiles.

The DQI appears to have performance similar to the Watson devices, based on the plots of Figure 3, and is somewhat smaller in size. However, because it is more expensive and lacks the internal references, it is ranked below both the BA303 and BA604.

3.5 SAGEM 30 MS 57

The 30 MS 57 is a three-axis resonator gyro assembly. It is designed mainly for military applications such as inertial navigation systems for military aircraft and inertial guidance systems for missiles.

This unit is not really considered an option for DREO. Its performance is roughly comparable to that of the other resonator gyro systems, but it is larger and heavier. Also, its big disadvantage is that it does not provide the Euler angle processing required to convert the rotational rates to heading information. This processing would have to be developed at DREO to make this device useful.

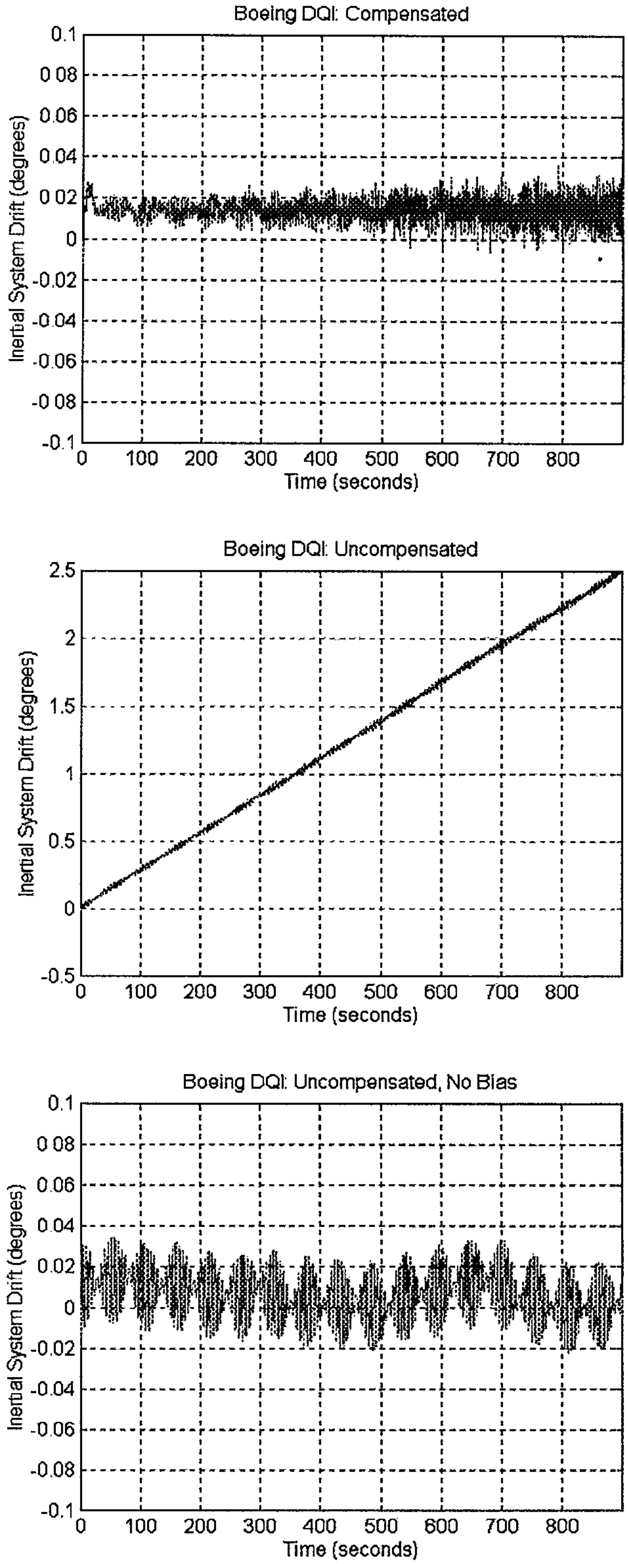


Figure 3 DQI Drift over 15 minutes

3.6 Andrew Corp. Autogyro Navigator

The Autogyro Navigator is a single axis fiber optic gyro. It is intended for use as part of an inertial navigation system for automobiles.

This unit is not really considered an option for DREO. The plots of Figure 4 show that this device has a large amount of drift. It would also require three of these devices and a significant programming effort to build a three-axis inertial measuring system.

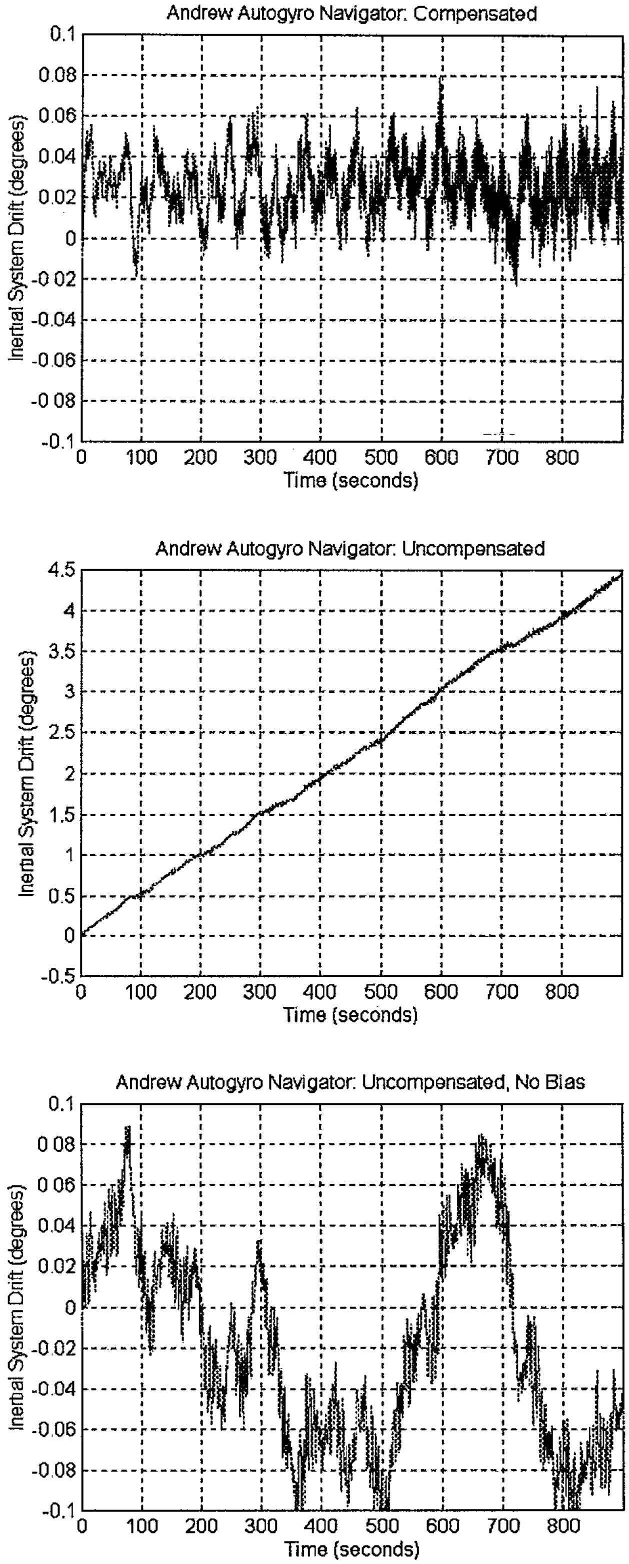


Figure 4 Autogyro Navigator Drift over 15 minutes

3.7 KVH Azimuth Digital Gyro Compass (ADGC)

The Azimuth Digital Gyro Compass is a three-axis mechanical gyro system referenced to a gimballed magnetic compass. It is intended for marine navigation.

It was originally felt that this system might be a good choice for DREO's motion compensation application, mainly because of its price ($3,000). However, further investigation has identified a number of serious problems with it. These are:

i) The stability of the device is not very good. Sitting undisturbed on a table, the heading readout will fluctuate by as much as 0.8°.

ii) The manufacturer strongly recommends against using the ADGC in an aircraft. The gimballed compass is not designed to respond well to aircraft motion, and the system will not calibrate properly in an aircraft.

iii) Because the compass is gimballed,

even on a ship calibration is not very accurate. As the ship pitches and rolls the orientation of the compass changes with respect to the metal structure of the ship, affecting calibration. This would not happen with a strap-down system such as the Watson Industries BA604.

iv) Because it is sensitive to acceleration forces, performance of the ADGC would probably degrade significantly if it were mounted anywhere on the mast of a ship.

The Azimuth Digital Gyro Compass is therefore no longer considered an option for DREO's motion compensation application.

3.8 British Aerospace FG314

The FG314 is a spinning wheel gyro assembly intended mainly for military applications. It is included in Table 1 as an example of a mechanical gyro system, and is not really considered an option for DREO's motion compensation application.

4. Conclusions

It is recommended that the Scientific Authority consider one of the following four systems for their motion compensation application. The four systems are (ranked according to their assessed suitability to the task):

1. Litton LN-200
2. Honeywell HG1700
3. Watson Industries IMU-BA604
4. Watson Industries AHRS-BA303

None of the inertial measurement systems investigated in this study were capable of maintaining a drift of less than 0.1° for 15 minutes. The best systems were the Litton LN-200 and the Honeywell HG1700, both of which held their drift to less than 0.1° over a six minute time period. Because it is probably less expensive and comes with AHRS processing, the LN-200 is recommended over the Honeywell HG1700.

Another two systems worth considering are the IMU-BA604 and the AHRS-BA303 from Watson Industries. If a drift of perhaps 0.5° is tolerable, then these two systems can offer a substantial cost savings. They also have the advantage of being somewhat more self-contained units in that they possess a fluxgate compass and pendulous references.

Simulink Model of an Inertial Measurement System

The Simulink model shown in Figure A1 was used to evaluate the available inertial measurement systems. The model consists of the following main components:

i) a wave motion simulator
ii) a gyro
iii) an integrator
iv) a compass reference

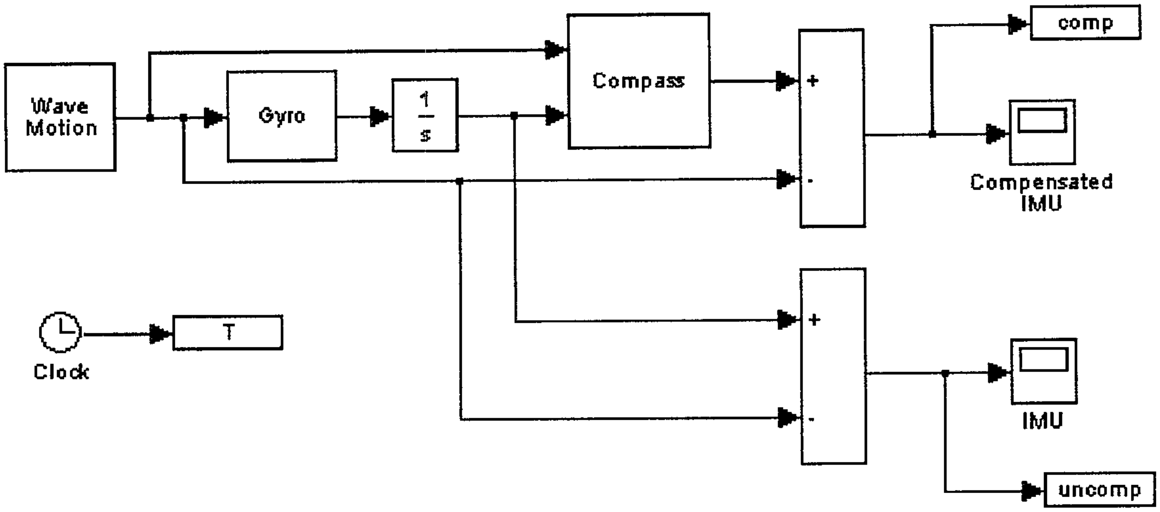


Figure A1 Simulink Model of Inertial Measurement

Wave Motion

The wave motion block models the dynamically changing heading (or roll, or pitch) of a ship in moderately rough seas. Its output is a modulated sine wave signal whose amplitude is measured in degrees. As a model for heading changes, the zero-amplitude reference may be interpreted as either magnetic North or true North. For roll or pitch, the zero-amplitude reference may be interpreted as perfectly horizontal.

The model is based on Sperry Mk-29 Mod 3 Inertial Navigation System data, recorded on CFAV Endeavor in May 1995, off the west coast. The INS data were recorded during a trip back to port and include segments in open ocean, in the Straits of Juan de Fuca, and finally continuing into

Esquimalt harbour. Plots of ship's motion based on this data are presented in Annex B.

The wave motion block, shown in expanded form in Figure A2, contains two sine wave generators. Each generator is configured with an appropriate period and amplitude such that their combined outputs approximates the roll, pitch and yaw based on the plots in Annex B.

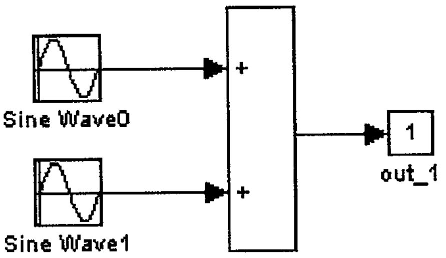


Figure A2 Wave Motion Model

The Annex B plots show an oscillatory motion in ship's attitude, with a period of approximately six to twelve seconds. In addition, a modulating period of the order of 50 seconds is also apparent. Worst case peak-to-peak motion during the high sea state is assessed to be six or seven degrees.

The parameter values in the wave motion model were selected to replicate the following characteristics: peak amplitude = +/- 3°; signal period = six seconds; amplitude modulation period = 50 seconds. A plot of this idealized ship's motion is shown in Figure A3.

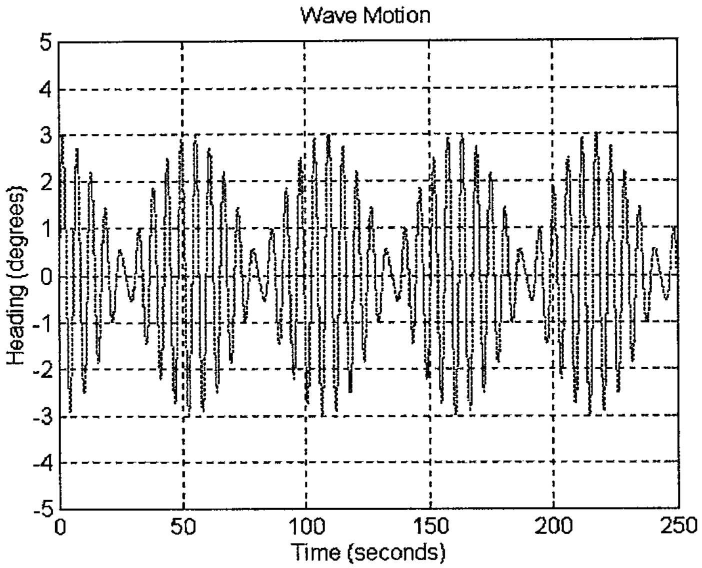


Figure A3 Simulated Wave Motion

Gyroscope Model

A rate gyro provides an output signal whose magnitude corresponds to rotational velocity, and this function is what is being modeled by the gyro block. The input to the gyro model is the changing ship's heading (or attitude) caused by the simulated wave motion. The output is a measure of the rate of change of that heading (or attitude).

An expanded view of the gyro model is shown in Figure A4. The model sums three components: the rate of change of the ship's heading; a white noise source to represent the gyro noise specification; and a constant to represent the gyro drift bias specification. The output is angle-rate limited and bandwidth-limited, again according to the gyro's specifications.

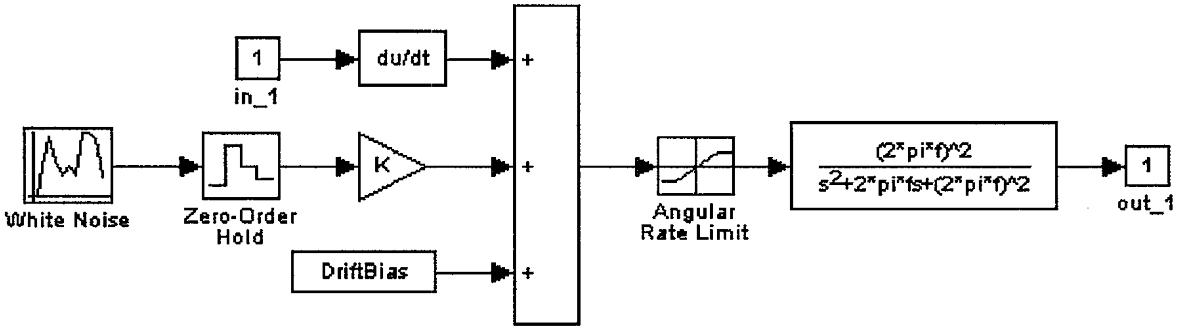
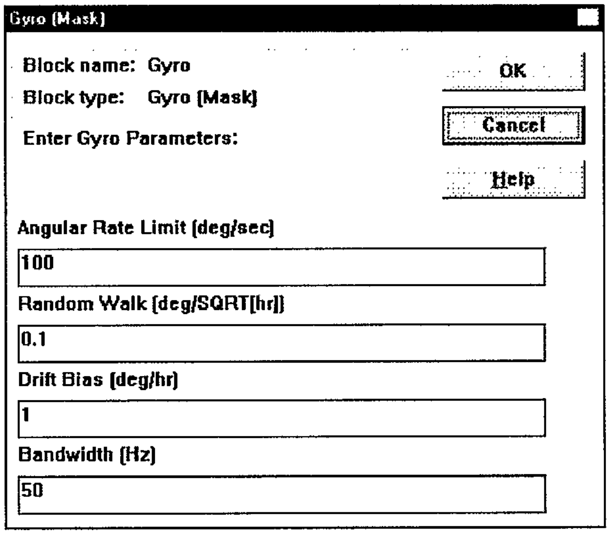


Figure A4 Rate Gyro Model

To make the gyro model somewhat user-friendly, a Simulink dialog box, shown in Figure A5, was set up. The values entered into this menu are passed to the underlying gyro model during simulation runs.

The parameters chosen for the menu were intended to match common manufacturers' specifications. For instance, gyro noise is entered as a random walk value (a standard specification). The gyro dialog box then calculates a noise power level based on the random walk specification. This is straightforward provided the noise is white.


Gyro (Mask)

Block name: Gyro

Block type: Gyro (Mask)

Enter Gyro Parameters:

Angular Rate Limit (deg/sec): 100

Random Walk (deg/SQRT(hr)): 0.1

Drift Bias (deg/hr): 1

Bandwidth (Hz): 50

Figure A5 Gyro Dialog Box

Integrator

The purpose of the integrator is to recover angular positional information from the rate gyro's output signal. This inertially-measured position may then be compared to actual position to note any degradation . Differences between the input position and the inertially-measured position are primarily a result of the gyro's noise and drift.

Compass Reference

Several commercially available inertial measurement systems have built-in non-inertial references, or are designed to accept external reference signals. A commonly used built-in reference is the north-seeking magnetic compass. A simple compass model was therefore included within the Simulink inertial measurement model.

The compass model is shown in Figure A6, and consists primarily of two low pass filters. The first filter is intended to have a bandwidth of one Hertz or less and represents the bandwidth-limited response of the compass to changes in heading. The second filter, called Update Time, is configured to gradually measure the difference between the compass heading and the inertially-derived heading. This difference is measured using a large filter time constant (30-60 seconds), and is subsequently applied as a correction factor to the inertial measurement.

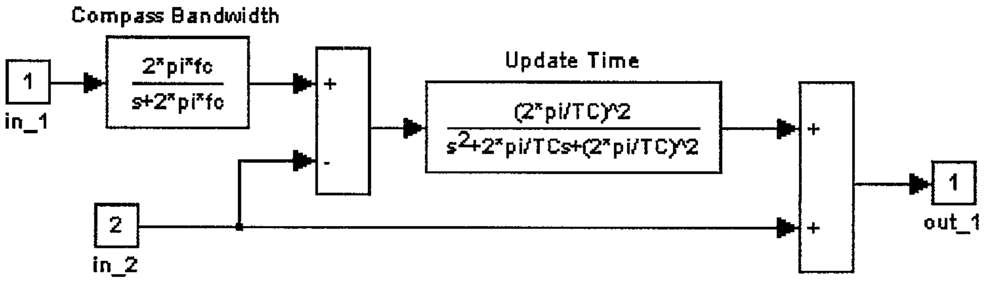
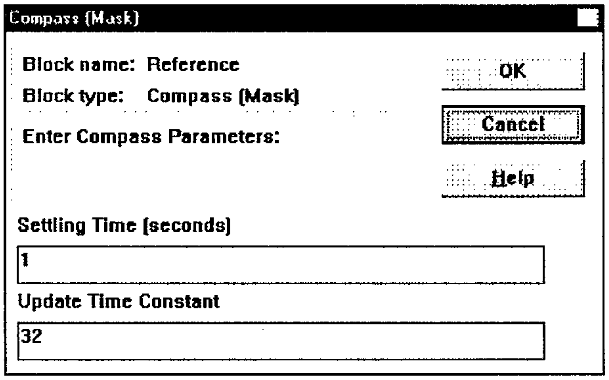


Figure A6 Magnetic Compass Model

A dialog box, shown in Figure A7, was also set up for the compass. Compass response, in the form of settling time, and update time constant may be entered from this menu, to note their effect on measurement accuracy.



Block name: Reference
Block type: Compass (Mask)
Enter Compass Parameters:
Settling Time (seconds)
1
Update Time Constant
32

Figure A7 Compass Dialog Box

The output from the compass reference represented an inertial measurement which had been compensated by the compass, and showed a decided improvement in accuracy over the uncompensated measurement taken directly from the gyro. However, it should be noted that the compass model was somewhat idealized in that it was assumed to measure magnetic north with absolute accuracy (within the constraints of its settling time). Real compasses appear to have an accuracy or repeatability limit of about 0.2°.

Ship's Motion from the CFAV Endeavor's INS Data

This Annex contains plots which show the effect of sea state on attitude, heading and speed of the CFAV Endeavor as it steamed back to port in May 1995. The plots are based on data generated by the ship's Sperry Mk-29 Mod 3 Inertial Navigation System. Three different segments of data were used to depict three different sea states: one segment was recorded in open ocean to represent a high sea state; one segment was recorded in the Straits of Juan de Fuca to represent a medium sea state; and finally one segment was recorded as the ship entered Esquimalt harbour to represent a low sea state.

A review of the plots shows that attitude (roll and pitch) varies cyclically with a time period of six to twelve seconds. Modulation of the roll and pitch amplitude is also apparent. The modulation is somewhat irregular, but appears to be occurring with a period roughly on the order of 50 seconds in the high sea state.

Heading can be seen to vary cyclically as well, with an apparent time period of from six seconds (for high sea state) to 50 seconds (for low sea state). The high sea state data also show a superimposed series of very low frequency cycles (time period = ~100 seconds; max amplitude ≤ 25° peak-to-peak), probably resulting from the settling time of a recently completed turn.

Finally, cyclical variations may be observed in the speed data in Figure B4, showing oscillation periods of six seconds (high sea state) to twelve seconds (medium sea state). During medium sea state, the speed is seen to oscillate at one point between six and nine knots. These low frequency oscillations in forward motion are sometimes termed *phugoid* oscillations.

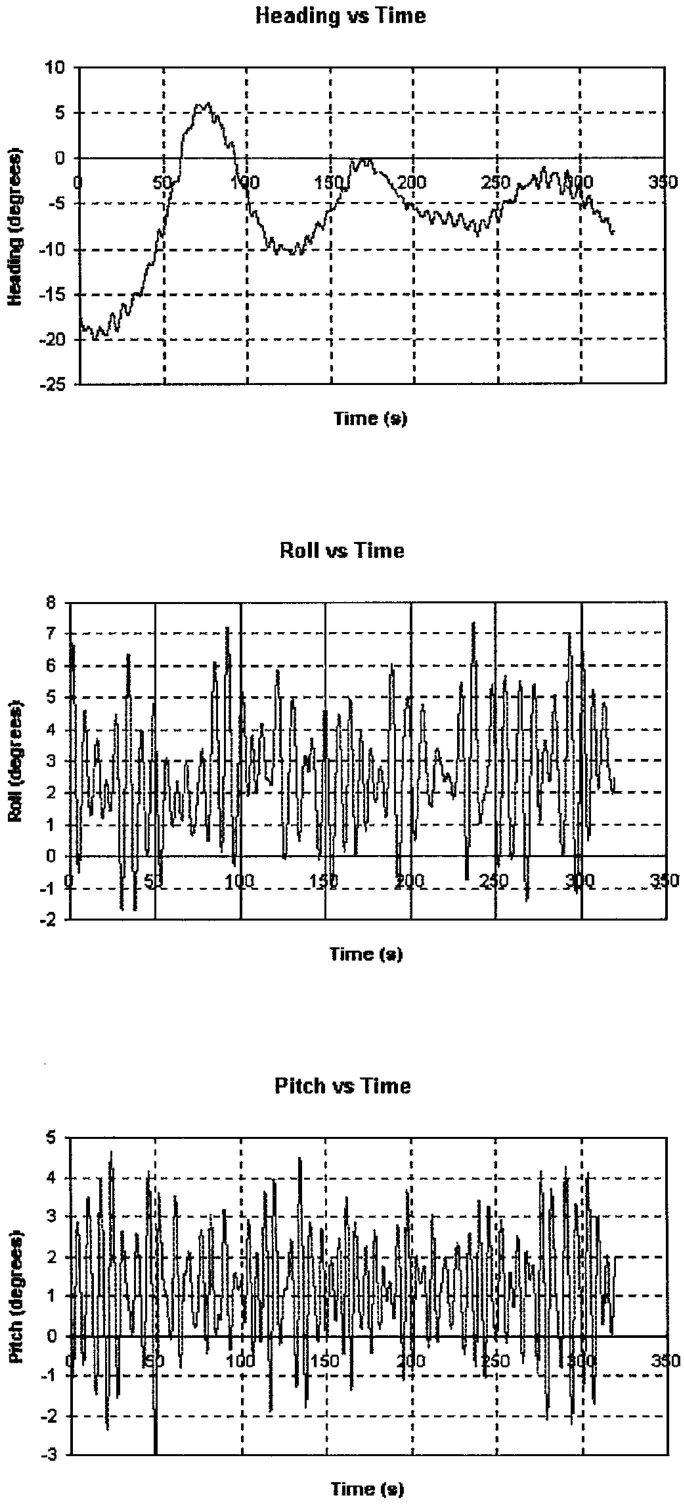
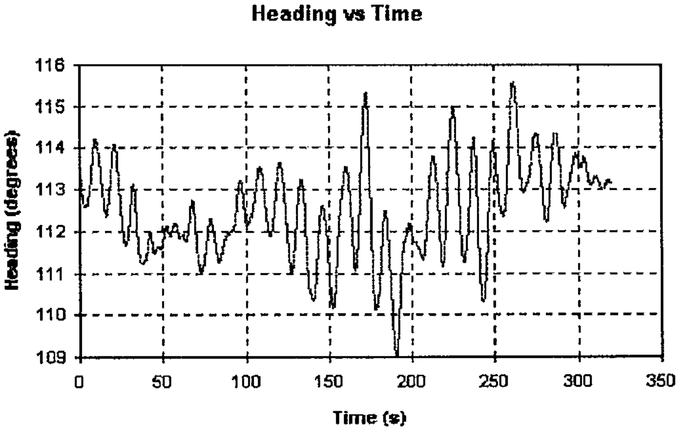
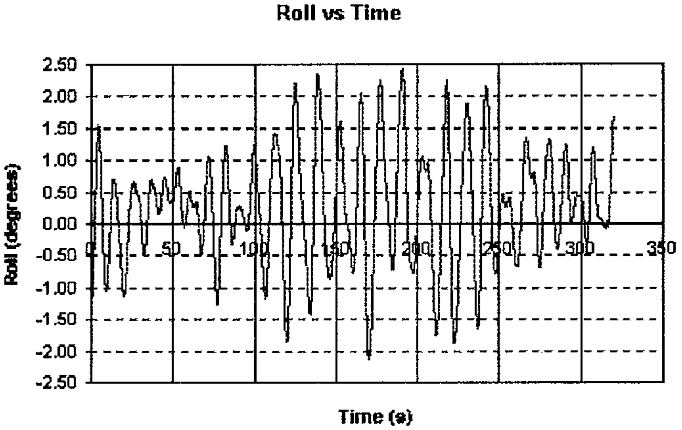


Figure B1 Attitude and Heading in High Sea State





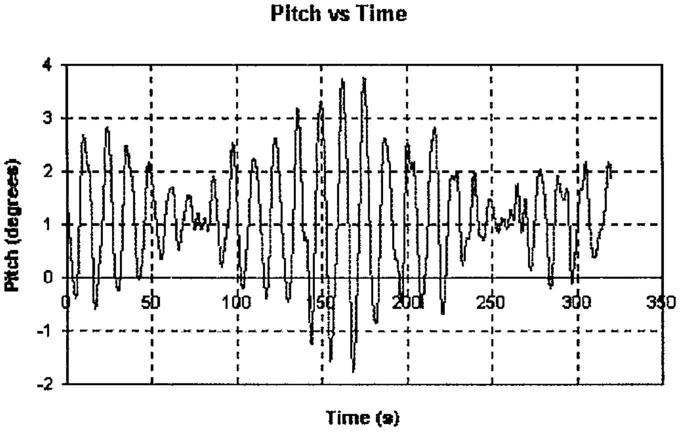


Figure B2 Attitude and Heading in Medium Sea State

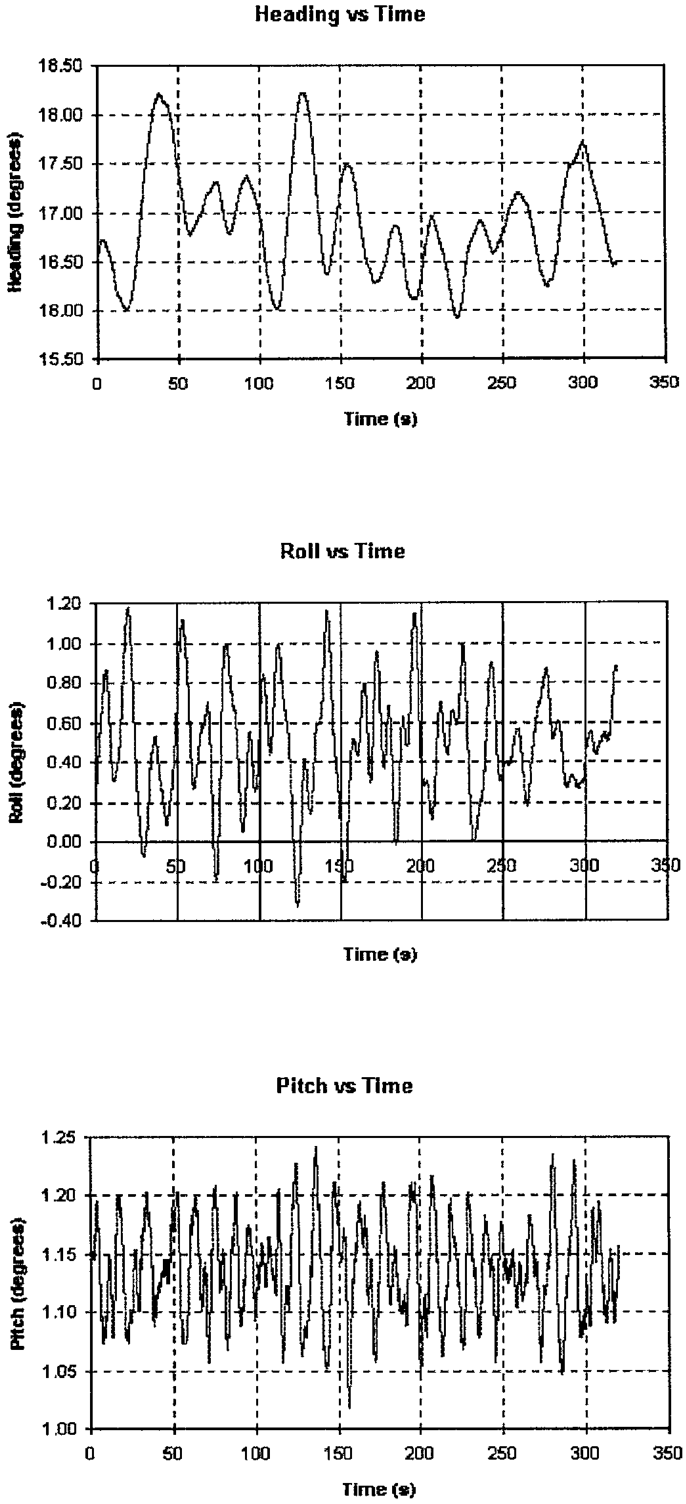
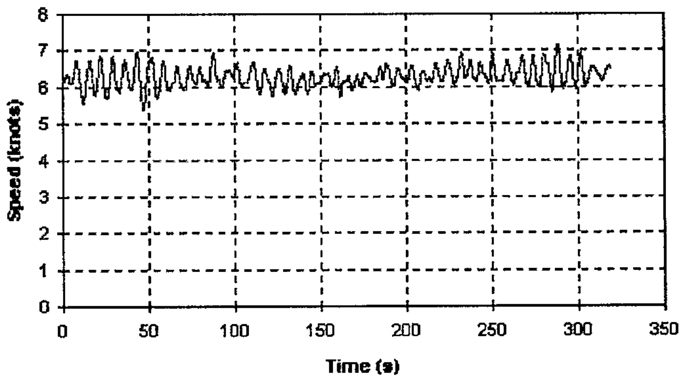
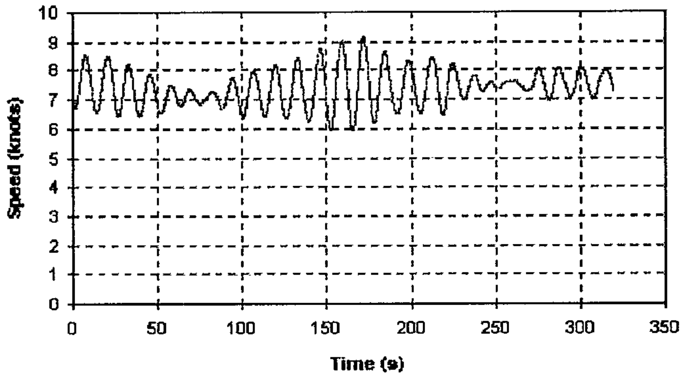


Figure B3 Attitude and Heading in Low Sea State

Ship's Speed: High Sea State



Ship's Speed: Medium Sea State



Ship's Speed: Low Sea State

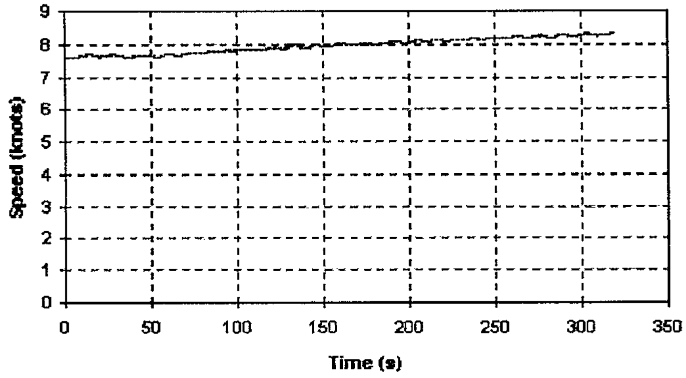


Figure B4 Effect of Sea State on Ship's Speed

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