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Sea Motion Characterization of the Mobile Aerial Target Support System (MATSS) for the Stabilized High-Accuracy Optical Tracking System (SHOTS)

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ADMINISTRATIVE INFORMATION

The work described in this report was performed for the Office of Naval Research by the Advanced Technology Branch (D853) SSC San Diego.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

SCOPE/OBJECTIVE

The objective of this study was to conduct ship motion characterization to identify stabilization problems that could affect the operation of the Stabilized High-Accuracy Optical System (SHOTS) while onboard the Mobile Aerial Target Support System (MATSS).

REQUIREMENTS

As a missile tracking system, SHOTS must be stabilized to maintain its tracking capabilities. Successful operation of SHOTS requires extensive knowledge and characterization of environmental conditions that could possibly be encountered under normal operations. These conditions may change, depending on location, time, and additional sensors that may disturb SHOTS.

ACCOMPLISHMENTS

Angular amplitudes and rates, and linear accelerations were measured with a six-axis-gyroscope. High-frequency vibrations were characterized with a triaxial accelerometer. Additional measurements from an onboard gyroscope with better resolution were used as a correlation factor between the two gyroscope systems. Fourier analysis of angular amplitudes and linear accelerations determined relevant frequencies for the system. Sources of error for the gyroscope system such as temperature drift and axes misalignment were identified and characterized.

RECOMMENDATIONS

This report identifies the importance of conducting more measurements at different locations on MATSS, characterizing sea conditions and other sensors on MATSS more carefully, and analyzing measurements in more detail. Corrective measures should be developed and implemented to minimize systemic errors.

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INTRODUCTION

The linear and angular ship-motion measurements in this report were taken during the Mobile Aerial Target Support System (MATSS) Acceptance Plan: Phase II—Near-Shore Sea Trial on 15 April 1999. Yard tugs and a commercial tow ship transferred MATSS from the Navy Inactive Ship Maintenance Facility (NISMF) Pier to the mouth of Pearl Harbor, Hawaii, and from Pearl Harbor, Hawaii, to the test site, approximately 8 nautical miles offshore. During this phase, communication exercises, emergency drills, and helo-hovers were conducted along with evaluation of sea-worthiness and ship-motion characterization. This trial will transition to Phase III of the Acceptance Plan (Target Launch Demonstration Trial).

MATSS provides a stable BQM-74 and BQM-34 launcher platform for deployment in the open ocean to support Pacific Missile Range Facility (PMRF) training and test and evaluation (T&E) exercises. Platform remoteness removes PMRF and the Kauai, Hawaii, facility from the missile harm area. Appendix A briefly describes platform capabilities and physical characteristics of the MATSS system. MATSS will also host various auxiliary sensors that will support PMRF functions. Ship motion will have a profound effect on the operation and performance of most of these sensors. The Stabilized High-Accuracy Optical Tracking System (SHOTS) will be one system that is most sensitive to ship motion. It is essential to characterize the environmental conditions that SHOTS may encounter during normal operations and to incorporate these results in the final system design.

SHOTS is an optical missile tracking system for the PMRF in Kauai, HI. Textron, the prime contractor, will build two systems and the controllers. Each proposed system would have a 40-inch aperture, 200-inch focal length telescope with mid-wavelength infrared (MWIR) and visible cameras mounted on a stabilized mount for shipboard applications. The final accepted design might include modifications to the dimensions provided in this report. When completed, the system will track missiles from a sea-going platform using radar pointing, stored pre-flight nominal trajectory, and orientation from a global positioning system (GPS) augmented by the Inertial Navigation System (INS).

SHOTS must be stabilized to maintain target track capability and to ensure sufficient mechanical structural strength to allow operation without loading failures. With SHOTS on the open deck, maximum pitch accelerations would occur with the system located at the extreme ends of the MATSS platform. Maximum roll accelerations would occur with the system located on the extreme port or starboard laterals. The forces will increase on the SHOTS structure as the system mounts raise the elevation of the optical sensors above the deck. Therefore, it is important to realize that forces on SHOTS will necessarily be greater than report data that represent information taken at the motion sensors.

Report data were collected at the predetermined location on the MATTS chosen for the SHOTS system (Figure 1). Alternate locations have been identified for the SHOTS system and additional testing must be conducted at the new locations. The Crossbow® Six-Axis DMU-VGX gyroscope measured angular amplitudes and rates, and linear accelerations. A Crossbow® Triaxial Accelerometer CXL10HF3 characterized higher frequency vibrations. This report also presents data from the Seatex® MATSS MRU H gyroscope, permanently onboard MATSS. Although placed at a different location, data from this latter sensor provide an excellent correlation factor with slightly better resolution. This report also characterizes possible sources of error such as temperature drift and axes misalignment.

EXPERIMENTAL RESULTS

ANGULAR AMPLITUDE MEASUREMENTS MADE WITH CROSSBOW® DMU-VGX GYROSCOPE

The Crossbow®DMU-VGX gyroscope used in this experiment is a six-axis system that uses three angular rate gyroscopes and three accelerometers, and is designed for very accurate acceleration and angular measurements in dynamic environments. This device is ideal for platform stabilization analysis. According to the manufacturer, the DMU-VGX provides stabilized roll-and-pitch angles through sophisticated signal processing of the rate and acceleration sensors. Standard tilt sensors use the earth's gravitational field to measure angle. Consequently, they only measure tilt accurately when the object being measured is not accelerating. In dynamic environments, conventional sensors do not distinguish between tilt and acceleration. The DMU-VGX gyroscope uses the angular rate and acceleration signals to calculate the roll-and-pitch amplitudes by integrating the angular rate outputs and using the accelerometer outputs to correct for errors caused by angular rate sensor drift.

All six sensor elements are Microelectromechanical Systems (MEMS). The three angular rate gyroscopes are made out of vibrating ceramic plates that use the Coriolis force to compute angular rates independently of linear acceleration. The three accelerometers are MEMS silicon-based devices that use differential capacitance to detect acceleration. Table 1 shows manufacturer calibration data for all six sensors. The coordinate system is right-handed.

Table 1. DMU-VGX gyroscope calibration data.

Gyroscope Calibration Data	Range (deg/s)	Sensitivity (deg/s/V)	Null Offset (V)
X-Axis	50.00	25.38	2.48
Y-Axis	50.00	25.27	2.50
Z-Axis	50.00	25.32	2.52
Accelerometer Calibration Data	**Range (G)**	**Sensitivity (G/V)**	**Null Offset (V)**
X-Axis	2.00	1.03	2.50
Y-Axis	2.00	0.96	2.55
Z-Axis	2.00	1.02	2.49

The DMU-VGX gyroscope is easily installed with the Crossbow®-provided National Instruments®LabView format data acquisition application. Special applications can be incorporated using LabView programming. The gyro provided the following parameters (in analog format) for this experiment: roll-and-pitch amplitudes; roll, pitch, and yaw rates; and x, y, and z accelerations. Data analysis was performed with the help of Mathworks® MATLAB™ and Microsoft® Excel software packages.

The Crossbow® motion sensors were placed as close as possible to the predetermined location for SHOTS. Figure 2 and 3 shows the location and layout of the data acquisition sensors. The sensor package coordinates are 222 ft, measured from bow to stern, and 5 ft, measured from the edge of the stern–port side. Two steel angles were welded to the MATSS surface to provide better coupling between the sensors and the surface of the ship, and to provide support for the sensors. An aluminum plate was secured to the steel angles using C-clamps, and both sensors were mounted on the plate (Figure 2). The data acquisition and other electronic equipment used to acquire and store sensor information was protected from the environment by placing it inside a plastic hut secured to the rails (Figure 3). Figure 4 shows ship-motion parameters and relative orientation of the sensors with respect to the ship.

Figures 5 shows a time-domain display of roll measurements obtained over approximately 30 minutes. Figure 6 shows a zoom-in view of the data for a 200-second time span. The maximum amplitude for the roll was ±5.9 degrees (after correcting for the offset), with an average value of ±2.9 degrees. Table 2 provides relevant information regarding location, direction, speed, and environmental conditions under which the data were obtained. Appendix B gives a brief explanation of the criteria for determining sea state. Frequency content was extracted from the roll data by using Fast Fourier Transform (FFT) algorithms in MATLAB™. Figures 7 and 8 show the results. Different windows were used for the FFT analysis without much effect on the outcome. The results were obtained by windowing the data stream using a Kaiser (1815,20) window. The central roll frequency was at 0.198 Hz, corresponding to approximately 5 seconds/cycle. The power spectrums show other relevant frequencies at 0.201 and 0.213 Hz. Figures 7 and 8 show power spectrums with relative magnitudes in normal and db scales, respectively.

Figure 9 shows a time-domain display of pitch and Figure 10 provides a zoom-in view of the data. The maximum value for the pitch was ±1.5 degrees, with an average value of ±0.29 degrees. Table 3 contains the same relevant information provided in Table 2. Frequency content was extracted from the pitch data by using the same FFT algorithms, and Figures 11 and 12 show the results. The central frequency was at 0.195 Hz. Correlation between roll-and-pitch motion is an important issue that should be considered in SHOTS. When maximum roll-and-pitch amplitudes are added, the combined amplitude compensation required from the tracking system increases. Figure 13 shows the delay time between roll-and-pitch peaks. The bar graph in this figure shows that 40.7% of the time, both peaks happen without delay; 9.5% of the time, a 1-second delay occurs; 33.3% of the time, a 2-second delay occurs; 15.1% of the time, a 3-second delay occurs; and 1.4% of the time, the delay is greater than 3 seconds.

The combined maximum angular amplitude in this experiment was as follows:

Maximum Amplitude of Roll = A_r = 5.9 degrees
Maximum Amplitude of Pitch = A_p = 1.5 degrees
Combined Angular Amplitude = $A_c = (5.9^2 + 1.5^2)^{1/2} = \pm 6.1$ degrees.

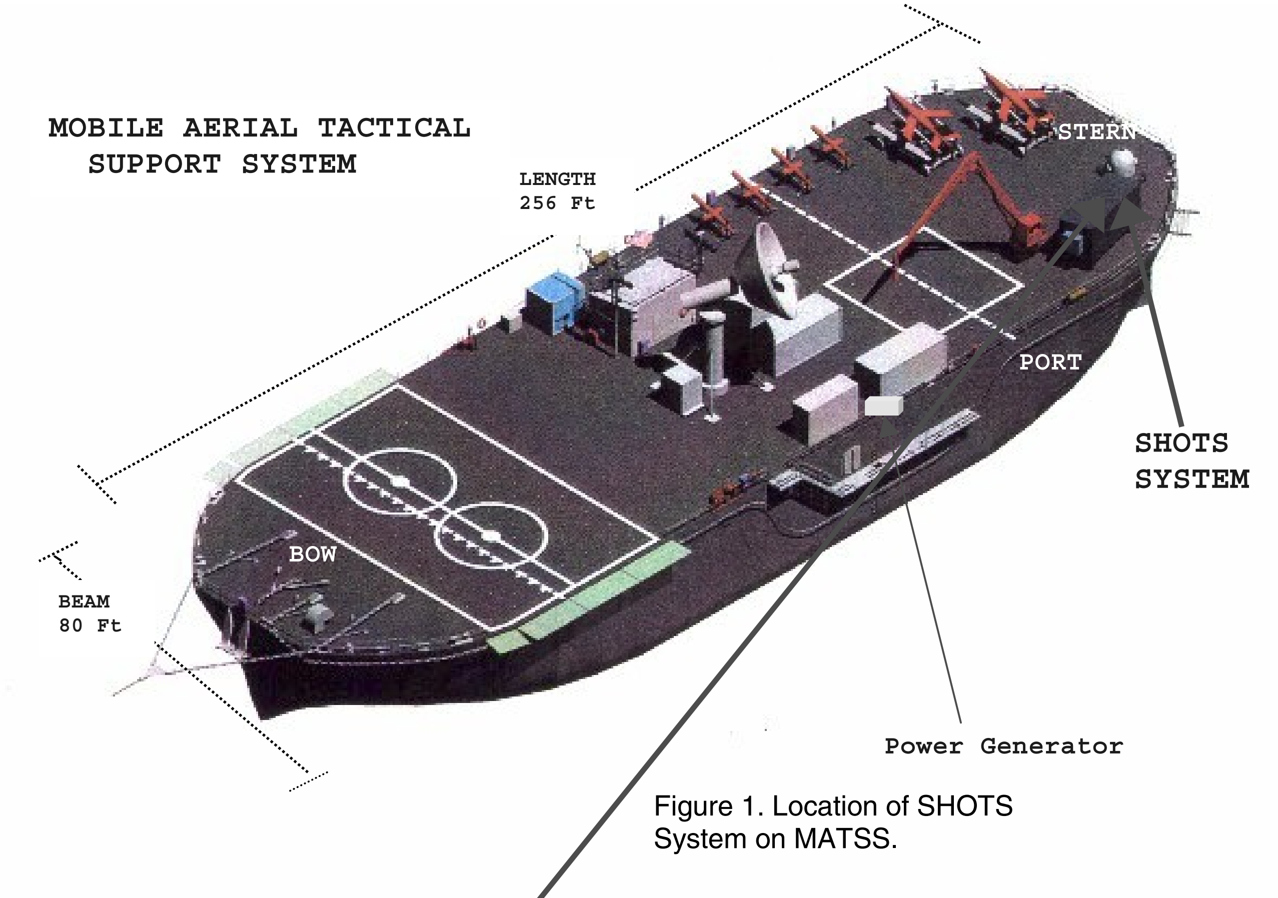
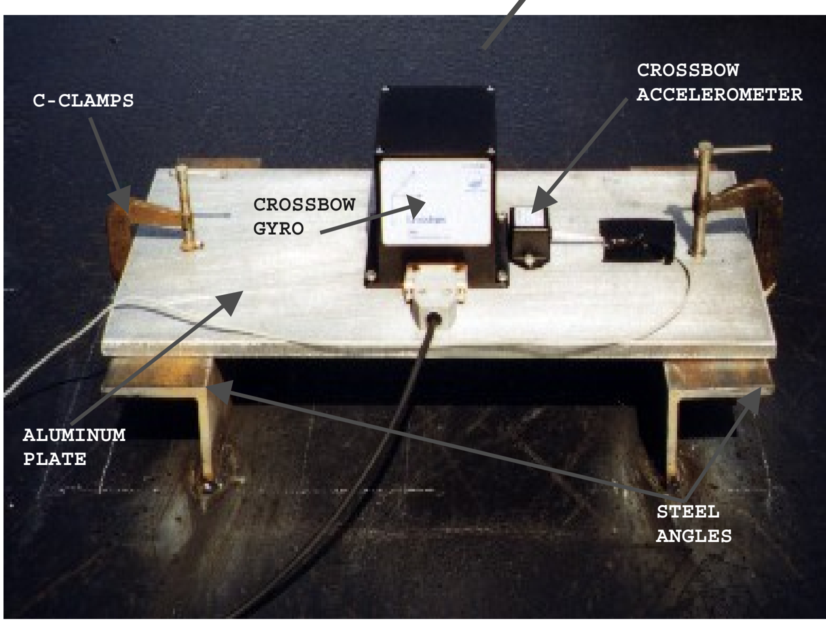


Figure 1. Location of SHOTS System on MATSS.



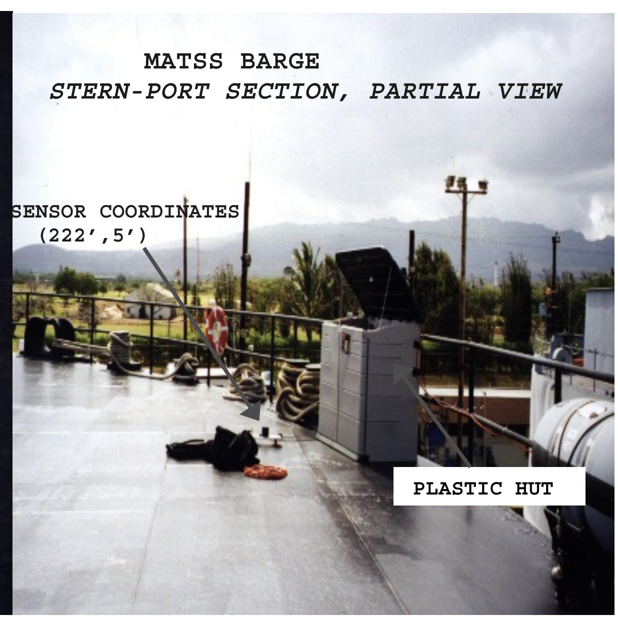


Figure 2. Sensor and secured mounting plate.

Figure 3. Protective plastic hut secured to rail.

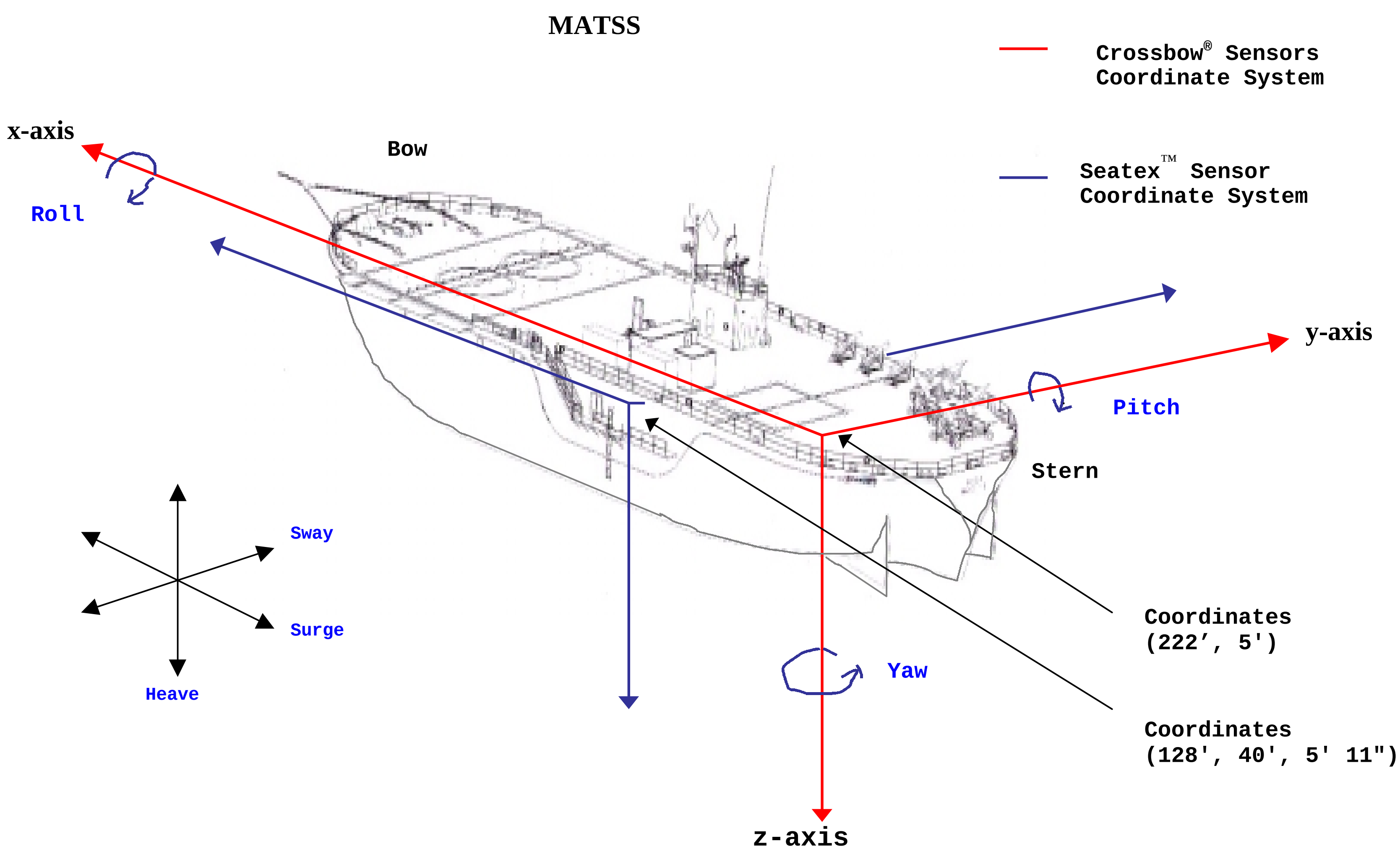


Figure 4. Ship-motion parameters and relative orientation of sensors.

Table 2. Relevant parameters during collection roll.

File Name	Time (UTC)	Latitude (deg)	Longitude (deg)	Heading (deg)	Tow Speed (kn)	Wind Speed (kn/dir)	Sea State	Max. Roll Avg. Roll (±deg)	Peak Roll Frequency (Hz)
MATSS0415#5	20:25	21.0	158.0	157.9	2.85	23/-82	SS4 Ave. SS5 Max.	5.9 2.1	.198 SR = 1 Hz

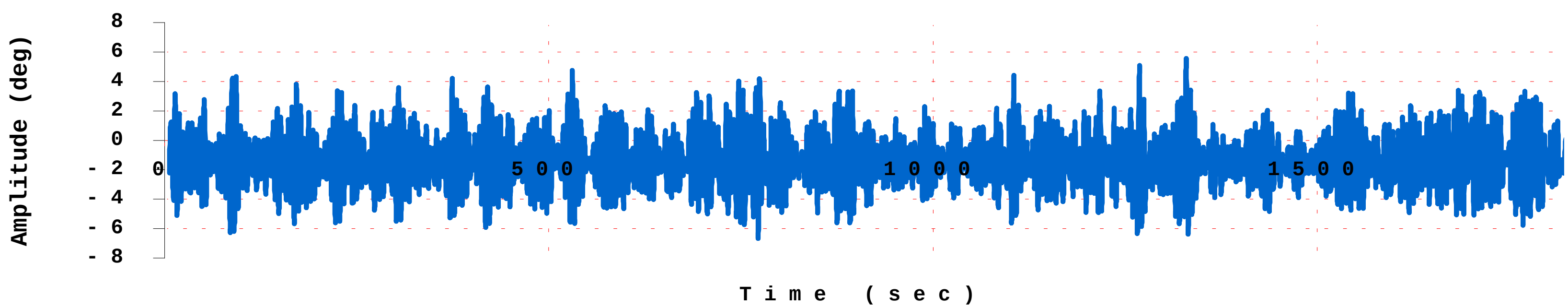


Figure 5. Amplitude of roll signal versus time.

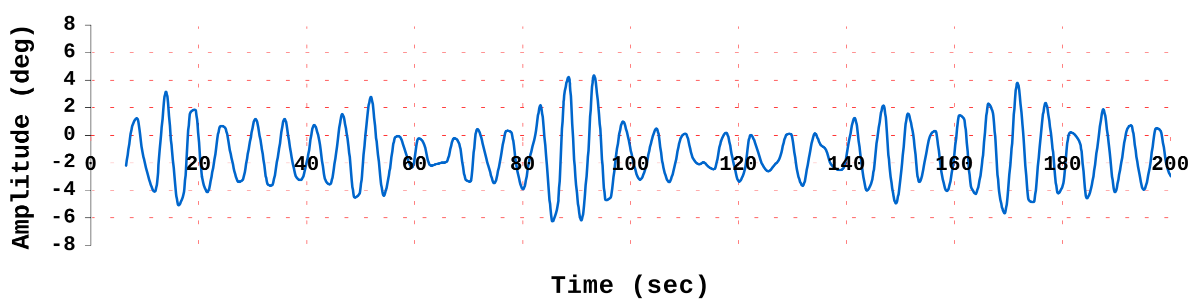


Figure 6. Zoom-in view of 200 seconds of roll data from Figure 5.

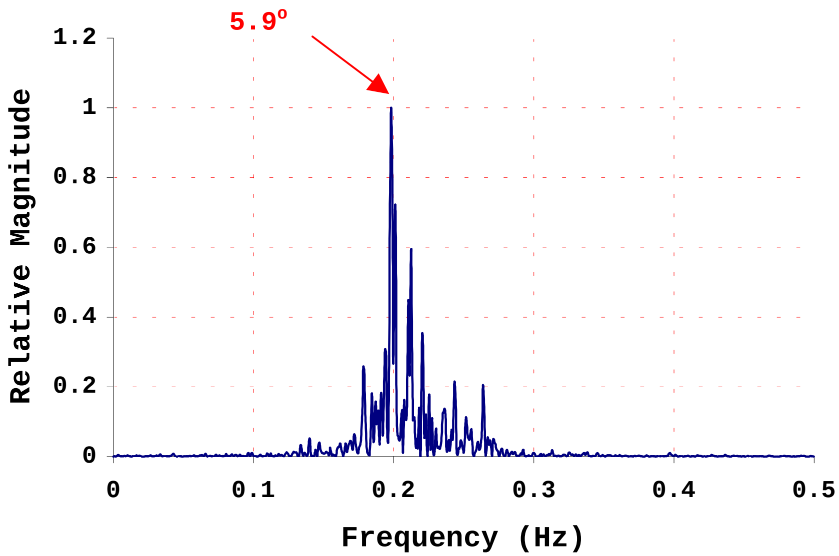


Figure 7. Roll power spectrum-window: Kaiser (1815,20). Maximum amplitude of roll spectrum output is ±5.9° and is represented by 1.0 in arbitrary units. Dominant peak frequency is 0.198 Hz.

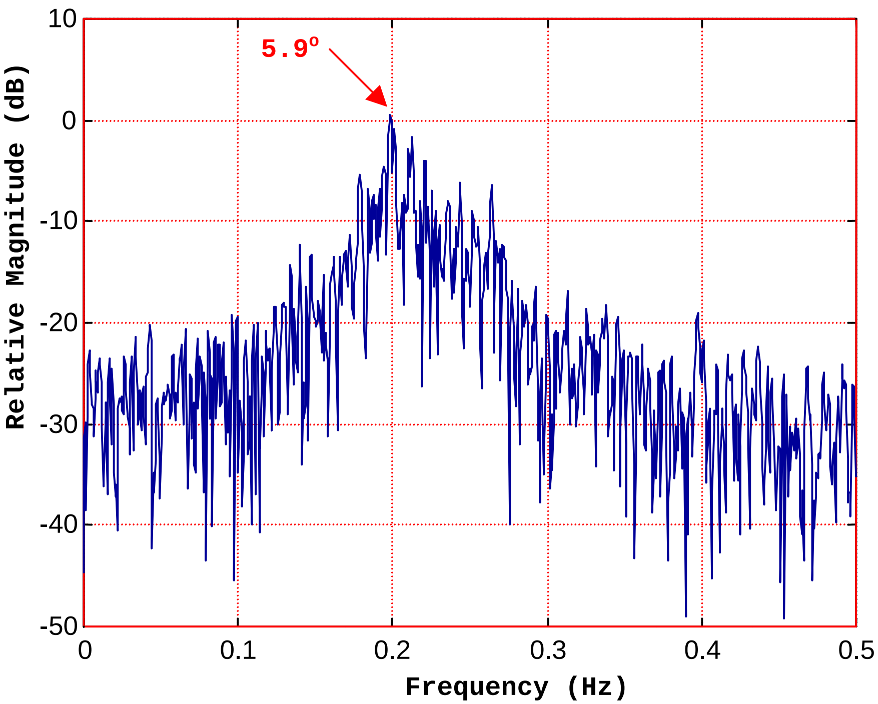


Figure 8. Roll power spectrum. Maximum amplitude of roll spectrum output is ±5.9° and is represented by 0.0 in db scale. Dominant peak frequency is 0.198 Hz.

Table 3. Pitch data.

File Name	Time (UTC)	Latitude (deg)	Longitude (deg)	Heading (deg)	Tow Speed (kn)	Wind Speed (kn/dir)	Sea State	Max. Pitch Avg. Pitch (±deg)	Peak Pitch Frequency (Hz)
MATSS0415#5	20:25	21.0	158.0	157.9	2.85	23/-82	SS4 Ave. SS5 Max.	1.5 .32	.195

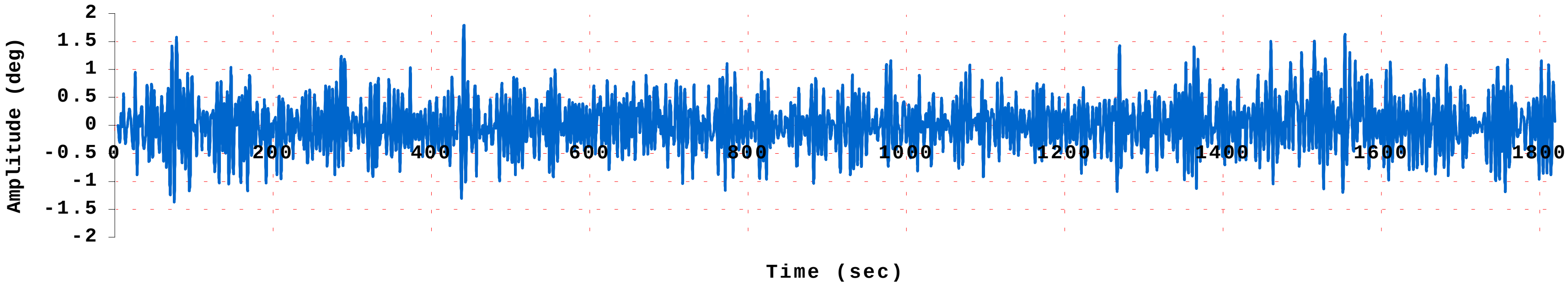


Figure 9. Amplitude of pitch signal versus time.

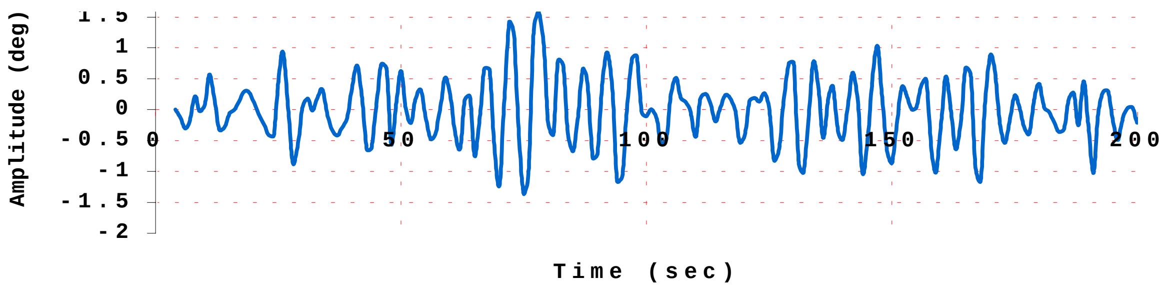


Figure 10. Zoom-in view of 200 seconds of pitch data from Figure 9.

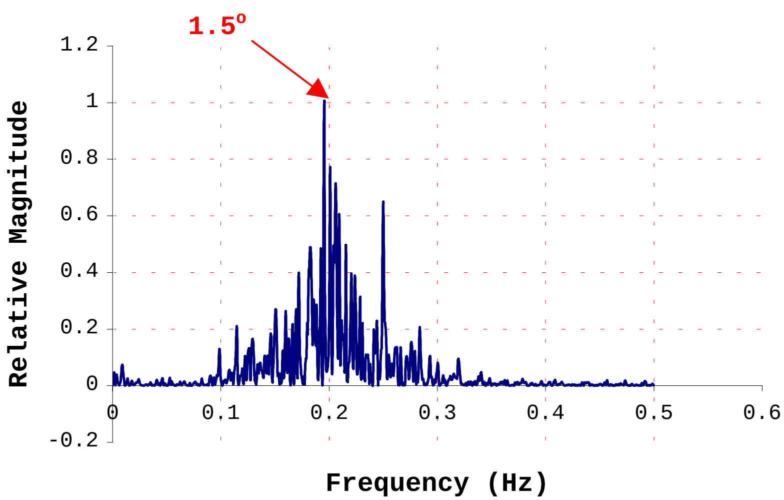


Figure 11. Pitch power spectrum-window: Kaiser (1815,15). Maximum amplitude of pitch spectrum output is ±1.5° and is represented by 1.0 in arbitrary units. Dominant peak frequency is 0.195 Hz.

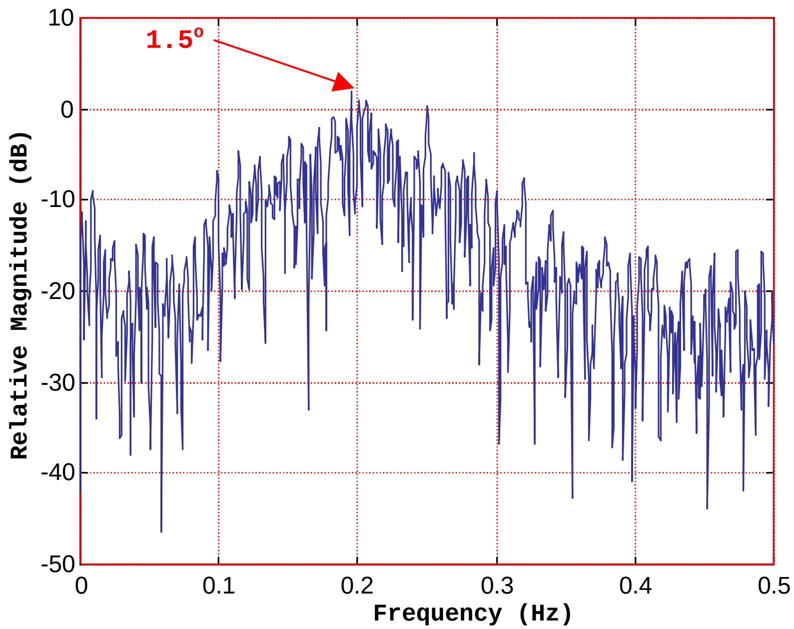


Figure 12. Pitch power spectrum. Maximum amplitude of pitch spectrum output is ±1.5° and is represented by 0.0 in db scale. Dominant peak frequency is 0.195 Hz.

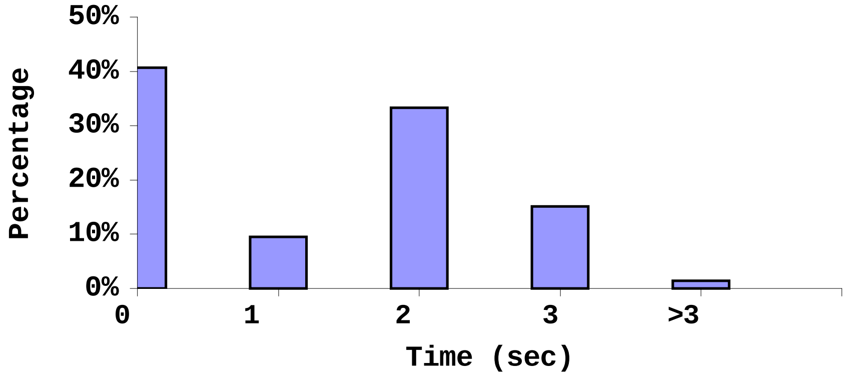


Figure 13. Time delay between roll and pitch peaks.

ANGULAR RATE MEASUREMENTS MADE WITH DMU-VGX GYROSCOPE

The Crossbow® DMU-VGX gyroscope measured roll, pitch, and yaw rates values. Figure 14 shows only a portion of the time-domain data stream for all three rates. Nevertheless, the maximum and minimum values for these rates were obtained after analyzing the entire data stream. Table 4 shows a maximum roll rate of 5.86 degrees per second, a maximum pitch rate of 2.64 degrees per second, and a maximum yaw rate of 0.5 degrees per second. The combined maximum angular rate for the obtained values was as follows:

Maximum Roll Rate = R_r = 5.86 degrees per second
Maximum Pitch Rate = R_p = 2.64 degrees per second
Maximum Yaw Rate = R_y = 0.50 degree per second

Combined Angular Amplitude Rate = $R_c = (5.86^2 + 2.64^2 + 0.5^2)^{1/2} = 6.45$ degrees per second

LINEAR ACCELERATION MEASUREMENTS MADE WITH DMU-VGX GYROSCOPE

The Crossbow® DMU-VGX gyroscope also measured linear accelerations in the x, y, and z directions. As in the angular rates, Figure 15 shows only a portion of the time-domain data. Table 4 shows a maximum x-acceleration of 0.025 g, a maximum y-acceleration of 0.079 g, and a maximum z-acceleration of 1.130 g. The combined maximum linear acceleration for the obtained values was as follows:

Maximum x-acc. = a_x = 0.025 g
Maximum y-acc. = a_y = 0.079 g
Maximum z-acc. = a_z = 1.130 g

Combined Linear Acceleration = $A_{xyz} = (.025^2 + .079^2 + 1.13^2)^{1/2} = 1.133$ g

The frequency contents of the angular rates and the linear accelerations were identical to those in the angular amplitude data. Results presented here are only for the roll rate and the linear acceleration in the z direction, but all three rates and all three linear accelerations were verified to contain the same frequency information. Figures 16 and 17 show that the peak frequency is at 0.198 Hz for both sets of data.

Table 4. Angular rates and linear acceleration data.

File Name	Roll Rate (deg/s)	Pitch Rate (deg/s)	Yaw Rate (deg/s)	x-acceleration (g)	y-acceleration (g)	z-acceleration (g)	Temp (C°)
MATSS0415#5	5.860 Max. -5.480 Min. 1.620 Mean	2.640 Max. -0.980 Min. 0.790 Mean	0.500 Max. -0.830 Min. 0.220 Mean	0.025 Max. -0.023 Min. 0.0061 Mean	0.079 Max. -0.130 Min. 0.039 Mean	1.130 Max. 0.820 Min. 1.000 Mean	26.8

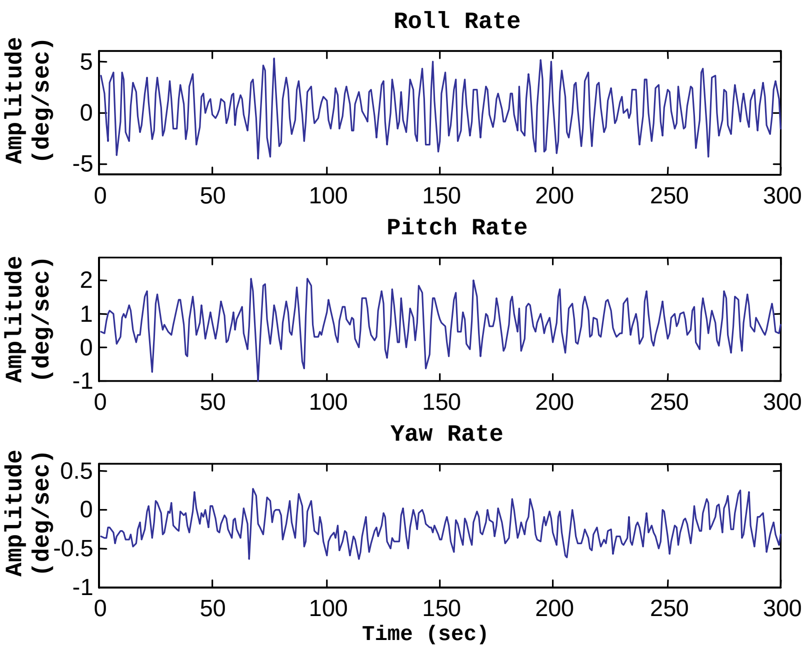


Figure 14. A 5-minute time evolution data stream for amplitude of roll, pitch, and yaw rates.

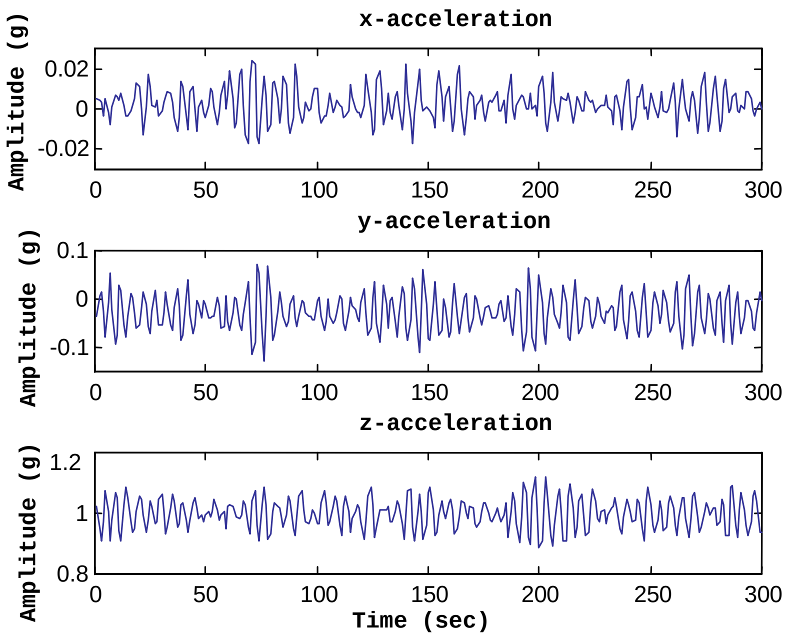


Figure 15. A 5-minute time evolution for amplitude of linear accelerations in x, y, and z directions.

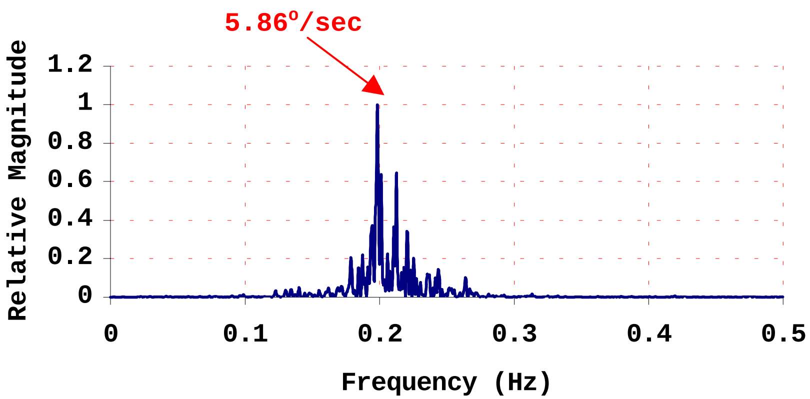


Figure 16. Roll rate power spectrum-window: Kaiser (1815,20). Maximum value of roll rate is 5.86°/s and is represented by 1.0 in arbitrary units. Dominant peak frequency is 0.198 Hz.

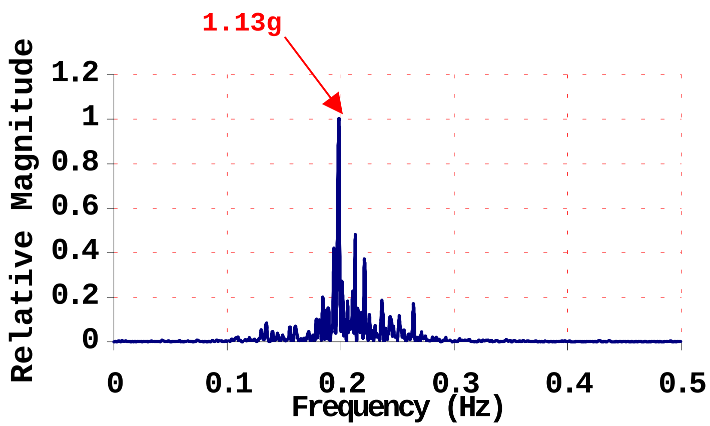


Figure 17. Z-acceleration power spectrum. Maximum acceleration in z direction is 1.13 g and is represented by 1.0 in arbitrary units. Dominant peak frequency is 0.198 Hz.

VIBRATION MEASUREMENTS MADE WITH CROSSBOW® CXLHF3

The Crossbow® CXLHF3 Triaxial accelerometer detects and characterizes higher frequency sources such as generators, motors, and other electromechanical systems. These accelerometers are precision vibration sensors made of piezoelectric material integrated with signal conditioning. The CXLHF3 was connected to a computer through the DAQ 700, a data acquisition card from National Instruments™. The data were acquired using LabVIEW™ programming and analyzed using MATLAB™ and Microsoft® Excel. Table 5 shows manufacturer sensor calibration data taken at room temperature.

Table 5. CXLHF3 accelerometer calibration data.

Vibration Accelerometer Calibration Data	Zero-g Voltage	Sensitivity (mV/g)
x-axis	3.500	94
y-axis	3.300	97
z-axis	3.400	100

Table 6 shows vibration results for all three directions, but this report discusses only the z-direction vibration results. Small vibrations were detected with a maximum amplitude of less than 10 mV in the z direction, and much lower amplitudes, about 2 mV, in the x and y directions. Sensitivity in the z direction was 100 mV/g, which resulted in a maximum amplitude of approximately 0.1 g. The frequency information in the z direction was maxima at frequencies of 140, 171, 125, and 4 Hz, in decreasing order of amplitude (Figures 18 and 19), which represent the power spectrums with relative magnitudes in normal and db scales, respectively.

The mechanical vibrations detected probably originated at the power generator and were used during the trial. Figure 1 indicates that the generator is about 75 ft from the SHOTS sensor. As indicated in the Table 6 results, most of the vibration was felt in the z direction. As more systems are added to MATSS, the mechanical vibration spectrum will require re-evaluation. More specifically, all instruments that will be active during SHOTS operation and in close proximity should be evaluated and their full effect on system stability characterized.

Table 6. Vibration data.

File Name	x-acceleration Max. Amplitude (g)	y-acceleration Max. Amplitude (g)	z-acceleration Max. Amplitude (g)	x-frequency Content (Hz)	y-frequency Content (Hz)	z-frequency Content (Hz)
MATSSACC4	0.02	0.02	0.10	Peak Frequency 255	Peak Frequencies 195, 270	Peak Frequency 140

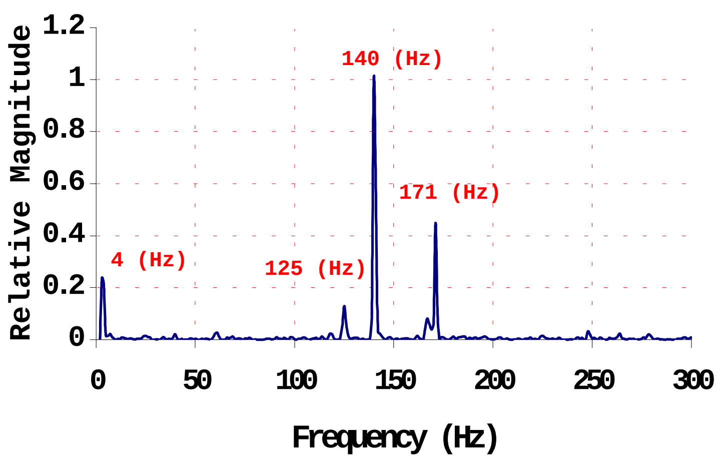


Figure 18. Vibration power spectrum-window Kaiser (1815,20). Dominant vibrational frequency modes with maximum vibration frequency of 140 Hz in the z-direction are represented by 1.0 in arbitrary units.

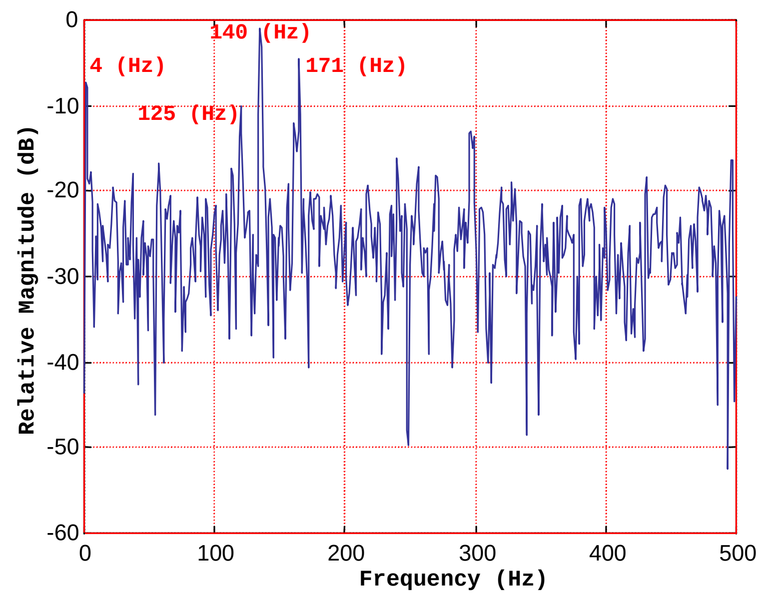


Figure 19. Z-vibrations power spectrum. Dominant vibrational frequency modes with maximum vibration frequency of 140 Hz in z-direction in dB scale.

STATIC MEASUREMENTS MADE WITH DMU-VGX GYROSCOPE

A set of measurements was taken 1 day before the MATSS sea trial. These measurements indicate the angular amplitudes and rates experienced by MATSS during the time it was on deck in a *static* environment. Table 7 shows the values obtained during this experiment and Figures 20, 21, 22, 23, and 24 show the time-domain display of these measurements.

The combined maximum angular amplitude was as follows:

Maximum Amplitude of Static Roll = A_{rs} = 0.209/2 = 0.105 degree
Maximum Amplitude of Static Pitch = A_{ps} = 0.220/2 = 0.110 degree
Combined Angular Static Amplitude = $A_{cs} = (0.105^2 + 0.11^2)^{1/2} = \pm0.152$ degree

The combined maximum angular amplitude rate was as follows:

Maximum Static Roll Rate = R_{rs} = 0.341/2 = 0.171 degree
Maximum Static Pitch Rate = R_{ps} = 0.249/2 = 0.125 degree
Maximum Static Yaw Rate = R_{ys} = 0.360/2 = 0.180 degree

Combined Angular Rate = $R_{cs} = (0.171^2 + 0.125^2 + 0.180^2)^{1/2} = 0.278$ degree per second

Table 7. Static measurements.

File Name	Roll (deg)	Pitch (deg)	Roll Rate (deg/s)	Pitch Rate (deg/s)	Yaw Rate (deg/s)
MATSS0414#1	2.109 Max. 1.890 Min. 0.209 Total	0.269 Max. 0.049 Min. 0.220 Total	0.398 Max. 0.057 Min. 0.341 Total	0.476 Max. 0.227 Min. 0.249 Total	0.758 Max. 0.398 Min. 0.360 Total

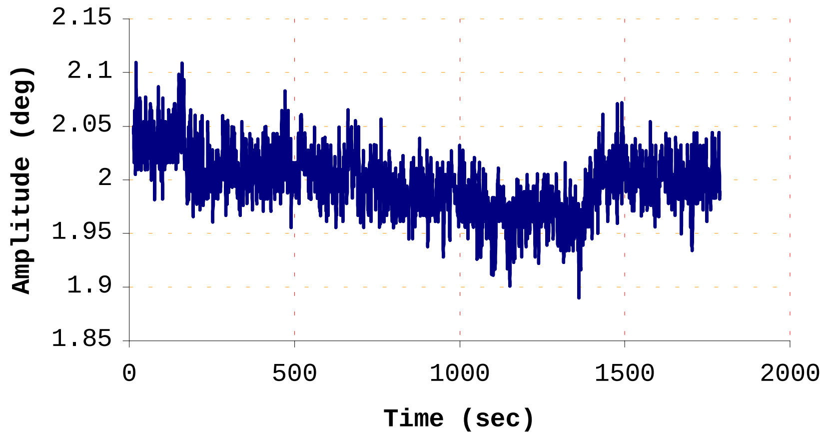


Figure 20. Roll measurements under static conditions.

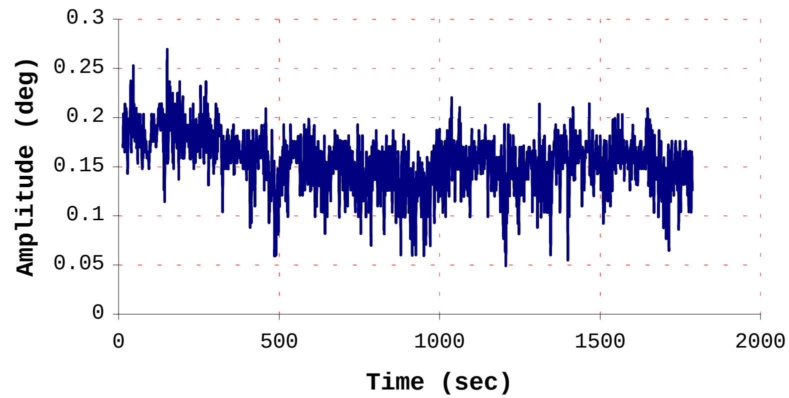


Figure 21. Pitch measurements under static conditions.

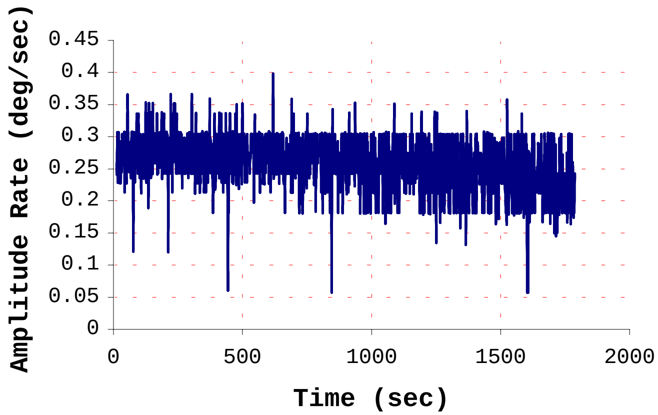


Figure 22. Roll rate measurements under static conditions.

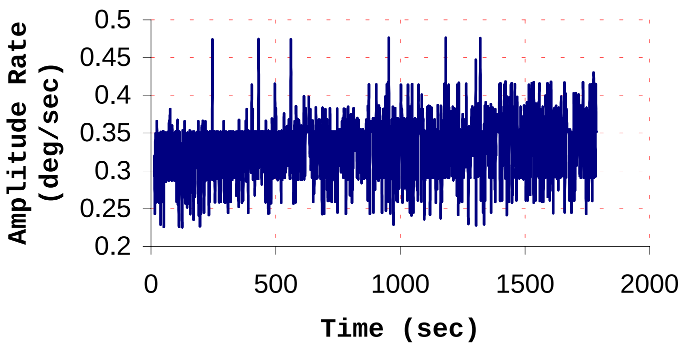


Figure 23. Pitch rate measurements under static conditions.

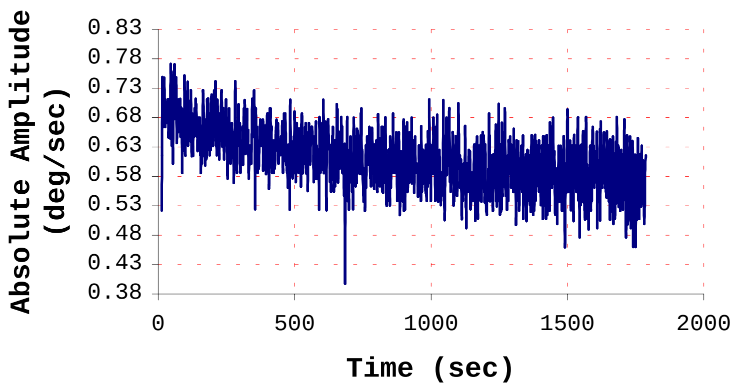


Figure 24. Yaw rate measurements under static conditions.

SYSTEMIC ERRORS FOR CROSSBOW® DMU-VGX GYROSCOPE

The intrinsic errors of the Crossbow® gyroscope were characterized for short-term and long-term effects in a controlled laboratory environment. Table 8 shows the maximum errors found during several laboratory bench trials of approximately 1 hour each, taken on 7 July 1999. This length of time is comparable to the length of the test files during the sea trial. The results are absolute values and the total angular amplitudes and rates are expressed as a plus or minus number after correcting for the offset. Figures 25, 26, 27, 28, and 29 show the time-domain display of these measurements. The linear accelerations contained an error of approximately 0.015 g in all three directions for the same 1-hour period. The intent was not to compensate for the errors, but to give a quantitative assessment for the actual errors expected in field use.

The combined maximum angular amplitude was as follows:

Maximum Error for Short-Term Roll = EA_{rs} = .099/2 = 0.0495 degree
Maximum Error for Short-Term Pitch = EA_{ps} = .093/2 = 0.0465 degree
Combined Angular Error = $EA_{cs} = (.0495^2 + 0.0465^2)^{1/2} = \pm 0.07$ degree

The combined maximum angular amplitude rate was as follows:

Max. Error Roll Rate = ER_{rs} = 0.114/2 = 0.057 degree per second
Max. Error Pitch Rate = ER_{ps} = 0.096/2 = 0.048 degree per second
Max. Error Yaw Rate = ER_{ys} = 0.046/2 = 0.023 degree per second

Combined Angular Rate Error = $ER_{cs} = (.057^2 + .048^2 + .023^2)^{1/2} = \pm 0.08$ degree per second

The combined maximum linear acceleration was as follows:

Maximum Error x-acceleration = EA_x = 0.015 g
Maximum Error y-acceleration = EA_y = 0.014 g
Maximum Error z-acceleration = EA_z = 0.015 g

Combined Linear Acceleration Error = $EA_{xyz} = (.015^2 + .014^2 + .015^2)^{1/2} = 0.025$ g

Figure 30 shows long-term errors for roll data. These measurements were made over 24 hours. This figure represents data taken on 7 July 1999 at 1600 to 8 July 1999 at 1700. The total roll drift for this experiment was recorded at about 0.5 degree for a temperature change of about 11°C. This graph shows a correlation between the roll drift and temperature. Temperature drifts were approximated as linear. Similar results, not included in this report, were obtained for pitch data.

Table 8. Short-Term systemic errors.

File Name	Roll (deg)	Pitch (deg)	Roll Rate (deg/s)	Pitch Rate (deg/s)	Yaw Rate (deg/s)
LABREF0209	.511 Max. .412 Min. .099 Total	.472 Max. .379 Min. .093 Total	.238 Max. .124 Min. .114 Total	.428 Max. .332 Min. .096 Total	1.48 Max. 1.02 Min. .046 Total

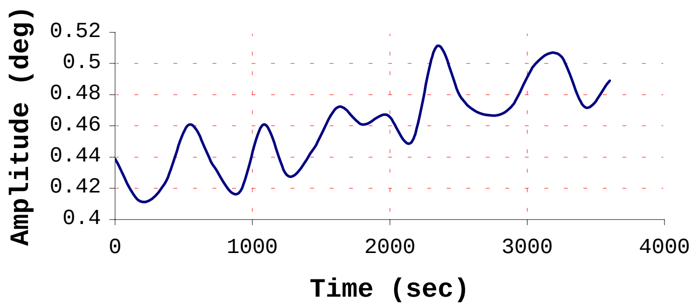


Figure 25. Typical roll systemic error for 1-hour laboratory bench trial.

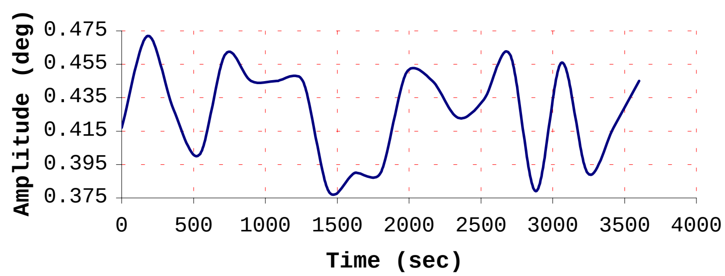


Figure 26. Typical pitch systemic error for 1-hour laboratory bench trial.

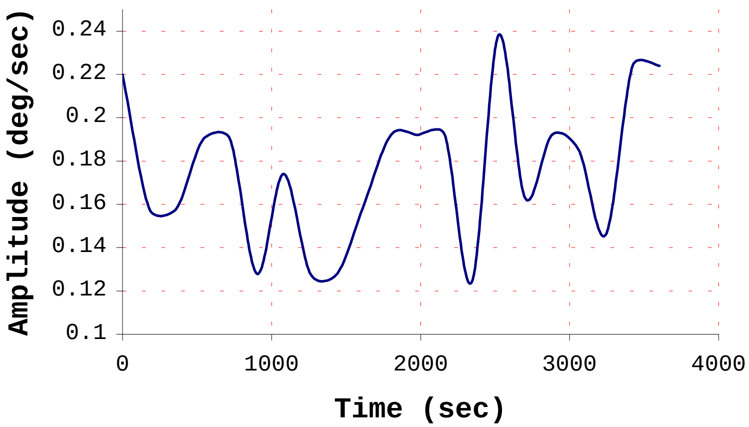


Figure 27. Typical roll rate systemic error for 1-hour laboratory bench trial.

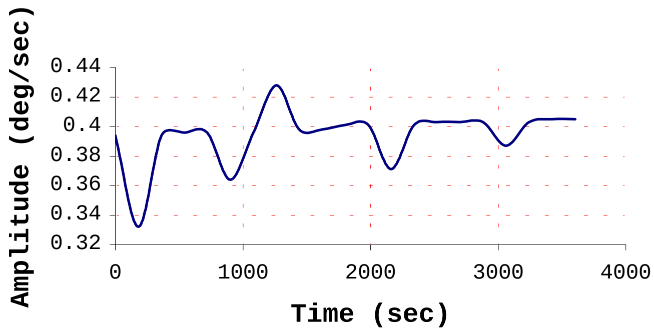


Figure 28. Typical pitch rate systemic error for 1-hour laboratory bench trial.

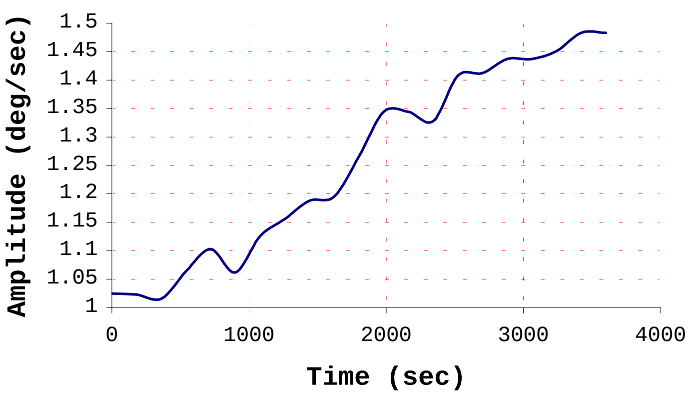


Figure 29. Typical yaw rate systemic error for 1-hour laboratory bench trial.

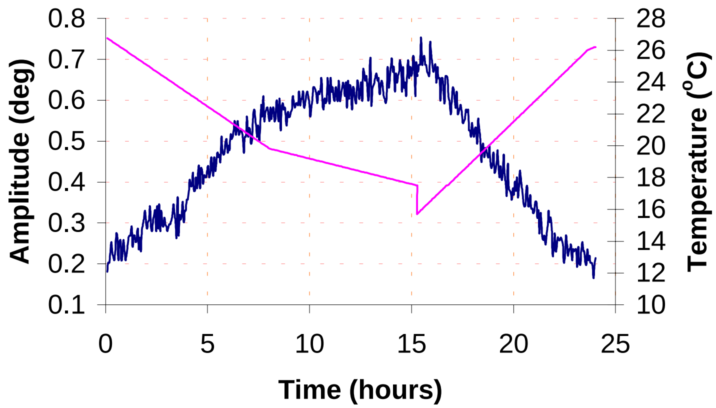


Figure 30. Typical long-term temperature effects on roll data.

ANGULAR AMPLITUDE MEASUREMENTS MADE WITH SEATEX™ MRU H GYROSCOPE

The Seatex™ motion sensor was placed as close as possible to the MATSS center of mass. Figure 30 indicates sensor location by coordinates at 128 ft, measured from bow to stern; 40 ft, measured from the port side (centerline); and 5 ft, 11 inches, measured from the keel. Figure 31 shows a time-domain display of roll measurements obtained over approximately 40 minutes. Figure 32 provides a zoom-in view of the data for a 300-second time span. The maximum value for the roll was ±6.46 degrees (after correcting for the offset). Table 9 provides relevant information regarding location, direction, speed, and environmental conditions under which the data were obtained. The central roll frequency was at 0.17 Hz, corresponding to approximately 5.8 seconds/cycle. Figures 33 and 34 show power spectrums with relative magnitudes in normal and db scales, respectively. Figure 35 shows a time domain display of pitch. Figure 36 provides a zoom-in view of the data. The maximum value for the pitch was ±2.03 degrees. Table 10 contains the same relevant information provided in Table 9 for pitch. Frequency content for pitch data was the same as in the roll data.

Table 9. Environmental conditions under which data for roll were obtained.

File Name	Time COMEX/FINEX	Latitude (deg)	Longitude (deg)	Heading (deg)	Tow Speed (kn)	Wind Speed (kn/dir)	Sea State	Max. Roll (±deg)	Peak Roll Frequency (Hz)
Seatex™#11	21:56:20	21.0	158.0	161.1	3.21	23/-90	SS4 Ave. SS5 Max.	6.46	0.17

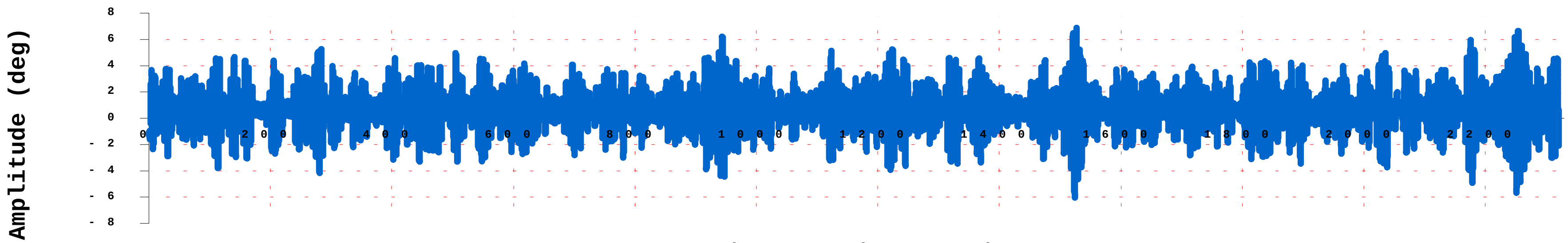


Figure 31. Amplitude of roll signal versus time taken with Seatex™ MRU H gyroscope.

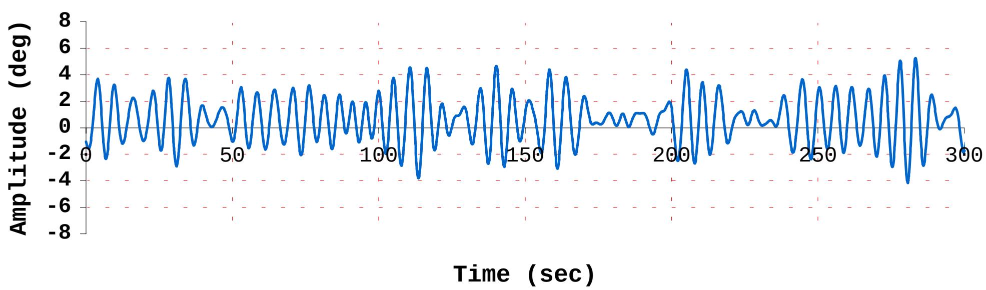


Figure 32. Zoom-in view of 300 seconds of roll data from Figure 31.

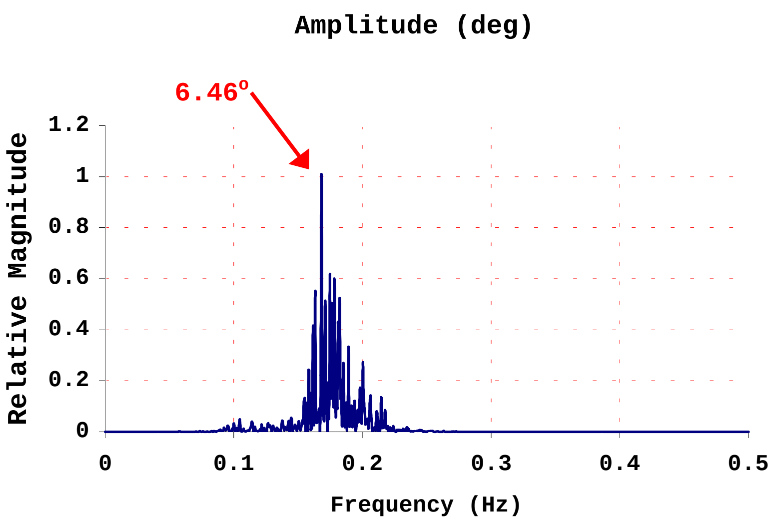


Figure 33. Roll power spectrum-window: Kaiser (1815,15). Maximum amplitude of roll spectrum output is ±6.46° and is represented by 1.0 in arbitrary units. Dominant peak frequency is 0.17 Hz.

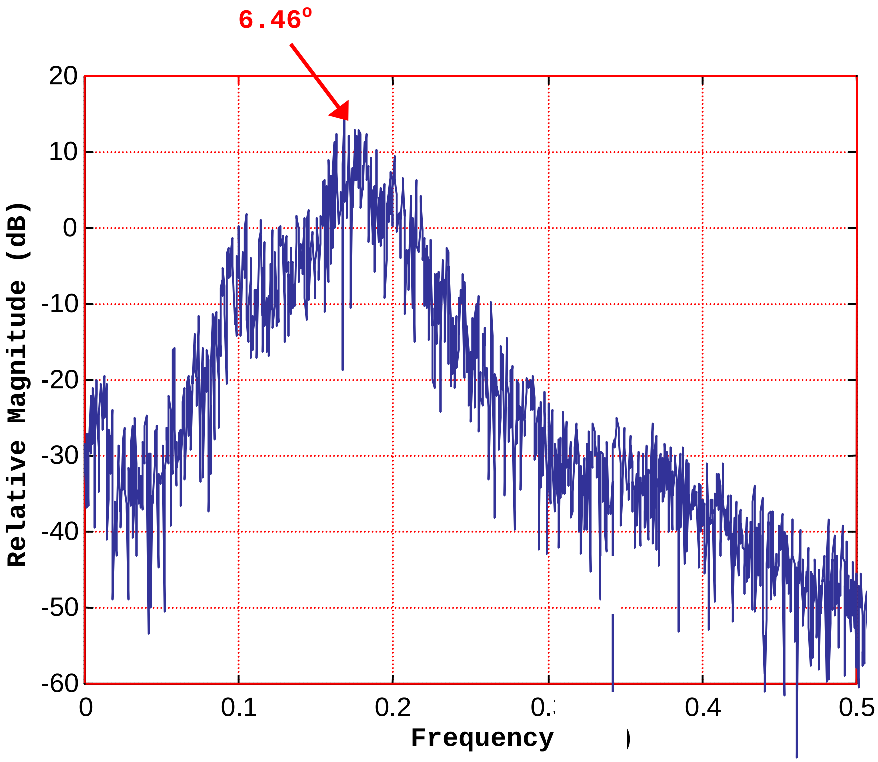


Figure 34. Roll power spectrum. Maximum amplitude of pitch spectrum output is ±6.46° and is represented by 0.0 in db scale. Dominant peak frequency is 0.17 Hz.

Table 10. Environmental conditions under which data for pitch were obtained.

File Name	Time COMEX/FINEX	Latitude (deg)	Longitude (deg)	Heading (deg)	Tow Speed (kn)	Wind Speed (kn/dir)	Sea State	Max. Pitch (±deg)	Peak Pitch Frequency (Hz)
Seatex#11	21:56:20	21.0	158.0	161.1	3.21	23/-90	SS4 Ave. SS5 Max.	2.03	0.17

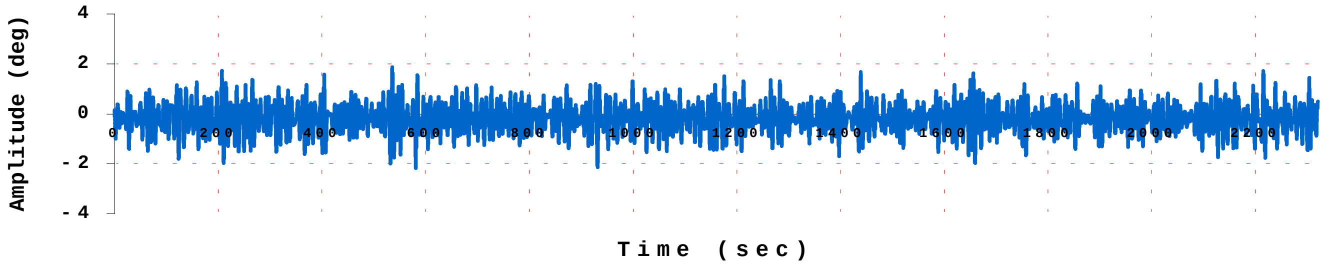


Figure 35. Amplitude of pitch signal versus time taken with Seatex® MRU H gyroscope.

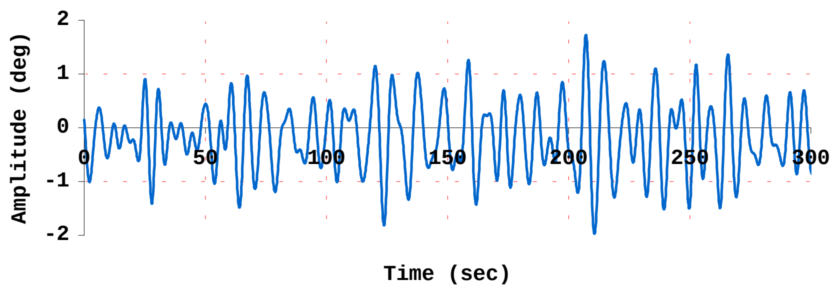


Figure 36. Zoom-in view of 300 seconds of data from Figure 35.

SUMMARY OF RESULTS

The measurements obtained with the Crossbow® gyroscope were compared with those obtained with the Seatex™ gyroscope and with information provided by the U.S. National Oceanographic Data Center (NODC) from Buoy 5100 (Table 11). One file (Seatex™ #11) was recorded during helicopter approach exercises, which could explain the slight difference in the magnitude of the angular measurements. Peak frequencies vary by about 10% between the Crossbow® and the Seatex™ data. The NODC roll-frequency data were very close to the data obtained with the Crossbow® gyroscope.

Table 11. NODC data from Buoy 5100.

Sensor	Maximum Roll	Roll Peak Frequency/Period	Maximum Pitch	Pitch Peak Frequency/Period
Crossbow®	±5.9	0.198/5.1	±1.50	0.195/5.1
Seatex®	±6.4	0.17/5.8	±2.03	0.17/5.8
NODC		0.192/5.2		

To fully characterize motion effects on SHOTS, more measurements must be made at the final location for the system. The full effect of other sensors and equipment must also be considered and analyzed. Full characterization of the environment under which SHOTS will be operating is essential, and will allow for corrections to be implemented. Corrective measures will minimize some of the errors addressed in this report.

APPENDIX A

DESCRIPTION OF THE MOBILE AERIAL TARGET SUPPORT SYSTEM (MATSS IX-524)

PLATFORM CAPABILITIES

- Open ocean operations
- Launch targets in an SS3
- Survive an SS6
- 7-knot tow in SS3, 5-knot tow in SS4
- Targets launched in favorable wind conditions
- Withstand a target explosion with minimum damage
- Transit water depths of <20 feet (5-foot draft)

CHARACTERISTICS

Dimensions		**Stability**
Length:	256 ft	2064-tons Displacement
Beam:	80 ft	42-tons/inch Immersion
Draft:	5 ft	3,300 LT-ft to heel 1 Deg.
Freeboard:	23 ft	Metacentric Height = 91 ft
Deck Space:	20,000 ft^2	Survive SS6

APPENDIX B

DETERMINATION OF SEA STATE

The National Oceanographic Data Center (NODC) provided information regarding sea-state conditions encountered by MATSS during the sea trial. Buoy 51003 collected the data in this report at the following location:

Latitude = 19^0 10' 17"N
Longitude = 160^0 43' 47"W

Buoy51003 was the closest buoy to MATSS when data were collected. The scale used to characterize sea state is known as the Beaufort scale (B-1), which provides a sea disturbance number ranging from 0 to 9 and is associated with wave height and wind speed. The average wind speed reported by the buoy for 15 April, between 2000 and 2200 Universal Time Code (UTC) was 8.75 m/s, and the average wave height was reported as 1.9 m, with an average period of 5.2 cycles/s and a maximum period of 10 cycles/s. Onboard MATSS, the average wind speed was measured as 21 kn (kn = 0.515 m/s), or about 10.8 m/s. Given those values, Table 12 indicates an average sea-state disturbance number 4. The MATSS encountered stronger winds than those reported by the buoy and waves, possibly with heights larger than the 1.9 m reported by the buoy. It is possible that MATSS encountered an occasional sea-state disturbance number 5 during the trial.

Table B-1. Beaufort wind force scale.

Sea State	Wave Height Average (m)	Wind Speed (m/s)
0	0	0.3 to 1.5
1	0 to 0.3	1.6 to 3.3
2	0.3 to 0.6	3.4 to 5.4
3	0.6 to 1.2	5.5 to 7.9
4	1.2 to 2.4	8.0 to 10.7
5	2.4 to 4	10.8 to 13.8
6	4 to 6	13.9 to 24.4
7	6 to 9	24.5 to 28.4
8	9 to 14	28.5 to 32.6
9	>14	>32.7

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