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TITLE

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SUMMARY:

This paper describes the rational behind the selection of the storage and export system for the COHASSET/PANUKE Offshore Development off Nova Scotia. In addition, an evaluation of the thruster assisted positioning system on the floating storage and offloading tanker 'NORDIC APOLLO' is described and a safe operating envelope rationalized based on a statistical analysis of data compiled over a seven month period.

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EVALUATION OF THE THRUSTER ASSISTED POSITIONING SYSTEM ON THE LASMO STORAGE TANKER 'NORDIC APOLLO'

D. Cumming[1], S. Barkhouse[2], D. Molyneux[1]

INTRODUCTION

LASMO Nova Scotia Ltd. has completed the first production phase year of the Cohasset/Panuke offshore oil development, located 41 km southwest of Sable Island, off Nova Scotia. As acting operator of the project, LASMO has a 50% interest, as does its partner, Nova Scotia Resources (Ventures) Ltd., a provincial crown corporation based in Halifax.

After a detailed study conducted by LASMO to evaluate various options to store and export the oil from the site, a 127,000 DWT Floating Storage and Offloading (FSO) tanker was moored to a Catenary Anchor Leg Mooring (CALM) buoy, using a single hawser. To help maintain the FSO on the buoy, a sophisticated Thruster Assisted Positioning (TAP) System was also fitted to the tanker. This system was used to maintain the tanker at an optimum position and heading angle relative to the buoy for the given prevalent environmental conditions, as well as to reduce hawser tension and wear. The condensate is loaded via a single floating hose which extends from the CALM buoy to the bow section of the tanker. A schematic of the entire Cohasset/Panuke loading configuration for the first production year is given in Figure 1, with further information on the project provided in References 1 and 2.

The Institute for Marine Dynamics (IMD) of the National Research Council was requested by LASMO to evaluate the performance of the TAP system on the tanker used as an intermediate storage facility for this field. The purpose of the evaluation was to define the safe environmental envelope for pumping oil into the storage facility. A Personal Computer (PC) based data acquisition system was installed on the tanker by IMD and interfaced with the existing TAP system console on the bridge. All signals measured in this study were derived from existing sensors required for the operation of the TAP system.

This paper describes the reasoning behind the selection of the storage and export system as well as the results of the evaluation carried out using data

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acquired from June to December 1992. A safe operating envelope is rationalized using a statistical analysis of the data compiled over the seven month period.

SELECTION OF THE STORAGE AND EXPORT SYSTEM

The storage and export system options available for the Cohasset/Panuke development were defined by the following six factors:

- the water depth available (approximately 40m)
- the severe weather experienced in the area during the winter months
- the relatively short time span between project concept and production start-up (two years)
- the economically marginal size of the field
- the projected production rate
- the expected market to be served

The relatively shallow water depth in this part of the Scotia Shelf limits the types of mooring and storage system which can be used. Based on studies of a number of schemes, the following three favourable options were considered further:

1) a self moored storage and offloading vessel;
2) a CALM buoy with a soft moored storage vessel; and
3) a fully dynamic positioned storage tanker without mooring buoy.

The nature of the field and the production processing equipment is such that production shut downs had to be avoided wherever possible. Thus it was not feasible to have a single loading point serviced by two delivery tankers. That would have required a shut down between completion of one loading and initiating the next.

The possibility of using two loading points was evaluated, but was found to be uneconomic. Also, unless both vessels were larger than those which normally trade into the US coast ports, the loading time for one ship would not permit enough time for the other shuttle to make a delivery to the Gulf Coast ports and return.

The environmental conditions on the Scotian Shelf are historically reasonably benign for seven months of the year, marginal for another two, and frequently hostile from December through February. During the more environmentally difficult period, it was decided to discontinue production operations until satisfactorily operating experience had been gained, thus enabling the production operating period to be safely extended.

While consideration of the water depth and the environment resulted in the selection of the storage vessel soft moored to a CALM buoy, the expanded life of the field did not justify the building of new vessels. Thus there was a requirement to charter and modify a suitable FSO and shuttle tankers. A dedicated shuttle tanker is needed to minimize the potential for field shut-down due to no vessel being available.

DEVELOPMENT OF THE TANKER SELECTION CRITERIA

Using the proposed initial production rate of 30,000 barrels per day (with the possibility of peaking at 40,000 bopd), and the furthest destination for the shuttle tanker being Rotterdam, the appropriate deadweight size of the shuttle tanker was calculated to be between 70,000 and 80,000 tons. To minimize the chance of production shut-downs due to later return of the shuttle or high production rates, a FSO/shuttle size ratio of two was used.

The next question was whether a 160,000 DWT tanker could be moored on the Scotia Shelf. A mooring study was conducted to evaluate the conditions with tankers up to 200,000 DWT and concluded this task could be successfully accomplished using six 4 1/4" mooring chains combined with a buoy robust enough to sustain a 400 tonne maximum mooring load. Ultimately, to keep the single hawser size reasonable, and to use a standard 3" chafe chain connection to the FSO, a 240 tonne tension limit was established for the mooring force.

After reviewing a number of offshore FSO operations and other buoy loading arrangements, it was decided to pattern the facilities on the North Sea design, with a bow loading and bow mooring facilities for both the FSO and shuttle tanker. The shuttle tanker offloads the storage tanker by tandem mooring astern of the FSO and connecting to a 16" offloading hose from the stern of the FSO.

Based on these criteria, a search for a suitable vessel resulted in the seasonal charter of the former LNG carrier "JADE PHOENIX". This 12 year old vessel was found to be in excellent shape. The engine room and accommodations had been in de-humidified layup for the past five years. The candidate had several features not found on any other FSO candidate including:

- a 5000 kW generator capacity
- 1500 kW bow thruster
- bow traction winch and messenger storage reel
- numerous hydraulic power packs
- class A-60 exterior bulkheads on the accommodation and internal structural fire protection to current standards
- very high quality construction and equipment, including primarily US made machinery and electrical components.

The principal particulars of this vessel, renamed 'NORDIC APOLLO', are provided in Table 1.

MODIFICATIONS MADE TO THE 'NORDIC APOLLO':

The following modifications were made to the 'NORDIC APOLLO' for use on the Cohasset/Panuke field:

- a retractable azimuthing stern thruster
- a 300 tonne capacity hydraulic bow mooring bracket
- six inch, articulated loading manifold with dry-break coupling
- loading leak detection meter
- bow watch station and equipment control room
- hydro-acoustic position reference system
- ground-lock Doppler speed log
- helipad on main deck
- expanded fire fighting foam and water deluge systems
- stern oil discharge line, manifold, and floating hose
- stern mooring point, hawser, messenger, and retrieval equipment
- stern utility crane
- vapour detection system
- produced water treatment system
- utility boat davit
- intra-field communications system
- improved cargo control and inventory systems
- dynamic assist station keeping system

Recognizing that the FSO connected to the CALM buoy represents the only means of storing the production of the project and that the maximum forces permitted on the mooring hawser were limited to 240 tonnes, a thruster assisted positioning system was installed that controlled the bow tunnel and stern azimuth thruster outputs. The thrusters were employed to retain the optimum position and heading angle of the FSO with respect to the CALM buoy and to minimize tension and wear of the hawser.

THRUSTER CONTROL SYSTEM

The thruster system was designed after conducting a study of the motions and variables controlling the tanker motion. Proven North Sea technology was selected for the control system for the thrusters. Vessels motions were controlled using inputs from a wide variety of sensors based on a complex algorithm derived by the manufacturer of the control system.

Information from forward and aft draft sensors was used to adjust the mathematical model. A local position reference relative to the mooring buoy was provided by a hydro-acoustic position reference system based on the supershort baseline principle. This system consisted of three bottom mounted transponders fitted 45m away from the mean position of the CALM buoy in an equilateral triangle communicating with a ship mounted transceiver. The transceiver measures the direction and distance to each transponder, computed the position of the transponders and compensates for the roll and pitch motion of the tanker. The final position output was then corrected to the location of the ship's nominal center of gravity. Other inputs to the control system included signals from a directional anemometer, ship's gyro compass, vertical reference package providing pitch and roll angle and the hawser tension load cell. A detailed description of the motion studies carried out prior to the selection of the thruster control system is provided in Reference 3. A description of the positioning strategy around a CALM buoy adopted by the manufacturer of the thruster control system is given in Reference 4.

EVALUATION OF THE THRUSTER ASSISTED POSITIONING SYSTEM

In order to assess the effectiveness of the thruster assisted positioning system, an evaluation was carried out using data collected over a period of seven months from June 1992 through to December 1992. Production licences applied to the Cohasset/Panuke project by the regulatory authorities restrict the transfer of oil to the FSO. Transfer operations must cease and the flow line must be disconnected if any one of the following environmental conditions prevail:

- significant wave heights greater than 4.5m,
- wind speed greater than 50 knots or,
- current speed greater than 1.5 knots

due to unacceptably high risk of hawser failure. FSO tanker cannot resume loading until the weather permits reconnection of the flow line. This commonly entails a production delay of up to 24 hours. The purpose of the evaluation was to investigate the possibility of extending the safe operating envelop for pumping oil into the FSO. If oil can be transferred at low risk beyond the environmental constraints given above, the cost effectiveness of the entire operation is improved.

To accomplish this, a PC based data acquisition system interfaced with the thruster control system was installed on the bridge of the FSO and data was communicated via a standard RS-232 serial port at a nominal digital sampling rate of 1 Hz. All signals were obtained from existing sensors required for operation of the TAP system with the exception of a triaxial accelerometer package installed on by IMD on the bow near the hawser termination. A schematic of the data acquisition arrangement on the 'Nordic Apollo' is given in Figure 2.

A user friendly data acquisition routine was coded in Basic Language by IMD programmers. Data could be monitored in real time by ship's bridge watchkeeping personnel. Binary data was downloaded onto floppy discs for transfer every two weeks to IMD for analysis. IMD personnel could thus monitor the integrity of the data during the course of the study.

Environmental data for this project was collected from the following sources:

Wave information was derived from a directional wave rider buoy moored adjacent to the jack-up rig located 11 km from the CALM buoy. The following data was available every hour:

SWELL - significant height (m) - resolution = 0.5m
- period (s) - resolution = 1s
- direction (degrees TRUE) - resolution = 10 degrees

WIND WAVES - significant height (m) - resolution = 0.5m
- period (s) - resolution = 1s

The combined sea significant wave height is calculated from this data:

$$\text{COMBINED SEA} = ((\text{SWELL HEIGHT})^2 + (\text{WIND WAVE HEIGHT})^2)^{1/2}$$

It is the combined sea significant wave height that is used in all analysis carried out by IMD.

The following tidal induced current information was estimated using prediction software for the rough position of the jack-up rig (Latitude 43 48, Longitude 60 46):

- current speed (knots) - resolution = 0.1 knots
- current direction (degrees TRUE) clockwise from true north toward which the tide is running - resolution = 1 degree

Note that the prediction includes only the tidal induced component of the current and neglects the influence of the Gulf Stream and the Labrador Current. The FSO tanker is located close to where these two currents intersect and thus significant error is possible in this current prediction.

Wind data was available from two sources - a directional anemometer located on the jack-up rig 70m above the mean waterline and from one of two directional anemometers fitted atop the main mast of the 'Nordic Apollo' some 47m above the design waterline. The following wind information is available every hour from the rig:

- wind speed (knots) - resolution = 1 knot
- direction (degrees TRUE) with the wind - resolution = 1 degree.

Wind speed and direction relative to the ship data from one of the two adjacent anemometers (the optimal signal is selected depending on wind direction), designated 1 and 2, is fed to the TAP system where it was corrected to degrees TRUE and recorded by IMD. The following wind information was available:

- wind speed (knots)
- wind direction (degrees TRUE) with the wind
- directional anemometer in use (1 or 2)

Data Acquisition Procedure

Data collected over a wide range of environmental conditions from June 1st until the end of December, 1992 was downloaded onto floppy disk and sent to IMD where the data were inspected and a preliminary analysis carried out.

The general FSO mooring strategy adopted by LASMO involved maintaining an optimum heading and position relative to the CALM buoy for the prevalent environmental conditions. The vessel bow was directed towards the buoy and the yaw oscillations excited by the single point mooring were controlled by the efficient use of the bow thruster through the TAP controller. The stern azimuth thruster within this mode thrusts towards the stern and is used to maintain a small constant tension on the hawser. The main propulsion system was not used in this mode due to the inherently poor response time of the steam propulsion system.

DATA ANALYSIS PROCEDURE & DISCUSSION OF RESULTS

The data were plotted and inspected in the time domain to confirm its integrity throughout the data acquisition period. The following preliminary analysis was carried out:

- time series plots for each day of data
- basic statistics for each day including minimum value, maximum value, mean (average) value, standard deviation, and root mean square (RMS) value.

The basic analysis consisted of dividing the data into half hour segments commencing 15 minutes before an available environmental datum point. This half hour run duration was deemed long enough to acquire a meaningful statistical average while short enough to assume that the prevalent environmental conditions remain constant. Basic statistics including for a total of 363 half hour segments were analyzed.

Three distinct modes were observed from reviewing the data in the operation of the thrusters:

1) thruster off - zero command signal
2) thruster on manual TAP - this means that the thruster was operated at a constant output - perhaps adjusted occasionally by the FSO tanker operators.
3) thruster on auto - output from the thruster is fluctuating - controlled using an algorithm with inputs from shipboard sensors.

In addition, TAP control was lost during severe weather on October 19/20th due to a failure of the positioning system. The thrusters were controlled by the FSO tanker operators from another console during this period thus there are statistics for output (feedback) signals from the thrústers but no statistics for thruster command signals.

On completion of the data acquisition and the basic analysis, the following detailed analysis was carried out to investigate the behaviour of the moored FSO tanker and to further define the operating envelop for safely loading cargo:

Time Domain Analysis

Time series plots were generated to illustrate the behaviour of the moored FSO tanker controlled using different thruster configurations:

a) Typical Moored Condition

After reviewing the data for the seven month period, a typical run illustrating the moored condition in moderate environmental conditions was selected. Several channels of time series data are plotted in Figure 3.

wind:	25 knots acting on the stern quarter
current:	0.7 knots acting on the stern quarter
waves:	2m significant wave height

The bow thruster is off and the stern thruster is generating a constant thrust to maintain a small constant hawser tension. The magnitude of the stern thrust is occasionally adjusted between 50 to 60% of available power.

The vessel was riding comfortably in the swell with less than +/- 20 degrees of low frequency heading angle variation. The stern thruster is used to preserve a low average hawser tension of 10 to 15 tonnes. The peak hawser load is generally less than 25 tonnes. Thus the normal mooring strategy involves maintaining a minimum hawser load to prevent the hawser from going slack.

b) Effect of Bow Thruster Turned On

The influence of the bow thruster on vessel motion and hawser load is illustrated in Figure 4. Moderate environmental conditions prevailed:

wind:	27 knots acting on stern quarter
current:	0.7 knots acting on stern
waves:	1.5m significant wave height

Prior to turning on the bow thruster, the tanker is fishtailing at the end of the hawser resulting in high peak hawser loads (almost 25 tonnes) relative to the average load (6 tonnes). This is a common phenomenon for single point mooring bow loaders (see Reference 4) that can be triggered even by low amplitude waves. The bow thruster is turned on auto mode at about 2200s into the run. The yaw angle oscillations were immediately damped out and the peak hawser load was significantly reduced. Thus the bow thruster can be deployed even in light sea conditions to reduce hawser wear.

c) Effect of Turning Both Thrusters On

The effect of turning both thrusters on in turn is illustrated in Figures 5 and 6 recorded in rough seas on October 12th:

wind:	30 to 35 knots acting on stern quarter
current:	0.5 knots acting on port beam
waves:	3m significant wave height

Figure 5 shows the behaviour of the tanker in rough weather with no thrusters on. The tanker is fishtailing at the end of the hawser and the hawser load often reached well over 40 tonnes. Sometime between 1000 and 1100 hours, the bow thruster was switched on auto mode (this event was not recorded). The yaw angle oscillations were effectively damped out (see Figure 6), however, the peak hawser loads remain high. At about 5300s into the run, the stern thruster was activated on auto mode and quickly settled at nominally 100% of available power directed towards the bow. The average hawser load increased, however, the amplitude of the peak hawser loads were reduced.

d) FSO Tanker on Manual Control

On October 19/20th, the area south of Sable Island was subject to very severe seas. The instrumentation used to measure local position of the FSO tanker failed during the storm and TAP control was lost. Several data channels are plotted in Figures 7 and 8 illustrating the behaviour of the FSO tanker when the thrusters were controlled manually by the operators from a separate console.

wind: 10 to 20 knots acting on port beam
current: 3 to 4 knots acting on the bow
waves: 6m significant wave height

Figure 7 shows the erratic thruster control as the operators attempted to reduce hawser load. Both thrusters were active and the stern thrust was generally directed towards the stern. This period was the only time main propulsion system activity was noted during the seven month loading period. A review of the data revealed that the Master of the 'Nordic Apollo' prudently ordered the main propulsion system be put on standby in the event of hawser failure was then used intermittently to reduce hawser load. It was not used in normal circumstances since the response time of the steam turbine system was considered too slow to be of value.

Figure 8 shows that the strategy adopted by the operators could have resulted in hawser failure. The operators attempted to move the FSO tanker towards the CALM buoy to reduce hawser tension. Thus the hawser became slack (note the periods of zero load). The next sequence of high waves would then move the partially loaded vessel back onto the hawser. Thus virtually the entire inertia of the tanker was absorbed by the hawser resulting in very high peak loads. In retrospect, it may have been better to try to maintain a hawser load of 20 to 40 tonnes to prevent the cable going slack.

Frequency Domain Analysis

A frequency domain analysis was carried out to assess the influence of ship motion on hawser load. Power spectra of the primary oscillatory motions of the moored tanker including surge acceleration, heave acceleration, roll and pitch angle were reviewed. The energy for each of the motions is concentrated at its natural frequency - a value that will vary somewhat with loading condition. A typical frequency domain plot for pitch motion is provided in Figure 9. A spectral plot of the hawser load is provided in Figure 10. The corresponding time series plot for each of these channels is provided in Figure 11.

Generally the FSO tanker motions can be separated as follows:

i) first order high frequency oscillatory motions corresponding to the vessel natural frequency induced by incident wave action.

ii) second order surge, sway, and yaw motions originating from slowly varying environmental excitation, influence of the mooring system and thruster operation.

The analysis indicated that the natural period of the 'Nordic Apollo' motions ranges from 8 to 13 seconds which is typical for a tanker of this size. The primary energy for hawser tension, however, is very low frequency corresponding to a period over 300s with low level energy apparent in the frequency range of first order ship motions. A cross correlation of hawser load with the vessel first order motions carried out by IMD indicated low coherence (generally less than 0.5 where 1.0 is total dependence and 0.0 represents two signals that are independent) thus it can be assumed that the hawser load is less dependant on first order ship motions.

The time series plot of ship motions and hawser load (Figure 11) indicates that the high frequency components are superimposed on the very low frequency component. These low frequency motions are illustrated by reviewing the varying ship position signals and heading angle data in Figure 3.

Since it would be very difficult to actively reduce the first order motions of a large moored tanker, efforts could be concentrated on attenuating these motions using a tension-compensation device such as a constant tension winch fitted on the bow of the FSO tanker. Second order motions can be reduced using the existing thrusters controlled by an effective TAP algorithm. Results described in Reference 5 show that the most effective Single Point Mooring (SPM) hawser load reduction was achieved using a combination of these two methods.

Thruster Demand Analysis

To gain some insight into the demand on the bow and stern thrusters while the TAP system is operated on auto control, the percent of time the thruster pitch angle was over +/- 95% was determined for each run. This information is plotted in Figures 12 and 13 for bow thruster and stern thruster respectively. Different symbols were used on the bow thruster use plot to indicate when the stern thruster was also on auto. Note that the stern thruster was never on auto control without the bow thruster also on auto.

The plots indicate the percent of time during a given run when the thruster pitch angle was greater than +/- 95% for a given wave height. The bow thruster pitch was never over 95% for more than 50% of any given run up to 5m wave height. The stern thruster pitch was generally less than 95% for 60% of the time up to 3.5m wave height. The data implies that the TAP system is far from saturated. Generally the demand on each thruster increases with increasing wave height, however, there is a wide range of demand for any given wave condition.

Trend Analysis

A trend analysis was carried out to assess the relative influence of wind, wave, current and thruster use has on the operation of the FSO tanker.

Histograms of wind and current direction relative to ship's heading are provided in Figures 14 and 15. The histograms are divided into 45 degree intervals starting with midpoint the first interval at zero degrees, where zero degrees is a head sea. The ship has been treated as a symmetric system with all data folded into the interval from zero to 180 degrees. It is obvious from these plots that the FSO tanker was generally stern to the wind with the current more evenly distributed with respect to heading angle.

Peak hawser load is the key parameter of interest in defining the FSO tanker loading operational envelope. Scatter plots of peak hawser load versus significant wave height, wind speed and current speed for the wind acting on the stern are presented in Figures 16 to 18 respectively. The different thruster configurations used are also noted on these plots where:

none	=	neither bow nor stern thruster on
both	=	both bow and stern thruster on
stern	=	stern thruster on only
bow	=	bow thruster on only
manual	=	thrusters off TAP control and are controlled manually by the FSO tanker operators from a separate console

Examination of these scatter plots indicates that the variable with the most influence on the hawser load was wave height. Multiple linear regression identified a statistically significant trend (at 99% confidence) between hawser load and wind speed after allowing for waveheight, however this value was small in engineering terms. Current speed was found to have no predictable effect on hawser load. Studies carried out on tankers moored in the North Sea have yielded similar results (Reference 6).

Since the wave height had the most significant effect on hawser load, it was decided to plot all the data together regardless of wind direction (Figure 19). This procedure also avoided the potential problems caused by the high degree of collinearity between wind speed and wave height, which can make regression models unstable as predictors. The highest hawser loads occurred when the thrusters were being operated manually by the bridge crew. Operating the thrusters manually resulted in hawser loads some 30% higher than when the thrusters were operated on TAP. This trend is clearly illustrated in Figure 20.

Long Term Statistical Analysis

Data displayed in Figure 21 provides a good indication of the hawser loads that can be expected up to the present operating limit of 4.5m significant wave height. No peak hawser loads over 150 tonnes were noted up to this wave height during the seven month interval. Reviewing the data collected up to 4.5m significant wave height, it is considered highly unlikely that loads reaching 240 tonnes would be reached if the TAP system is operating correctly.

Since very little data was collected while the TAP system was operating and the wave height was greater than 4.5m, it was impossible to extrapolate the data set with confidence. Based on the worst cases observed, however, it would appear that the FSO tanker could be moored successfully with low risk of hawser failure up to 6.0m significant wave height with the TAP system operating.

CONCLUSIONS

Based on the data collected over the seven month period from June to December 1992, the following conclusions can be made:

1) Primary TAP input parameters were successfully collected on the FSO tanker over the seven month period. Local environmental data was provided by LASMO for this period. Little data was collected above a significant wave height of 4.5m, however.

2) Normal mooring strategy during moderate weather conditions (< 3.0m significant wave height) involves operating the TAP system with only the stern thruster operating. A small stern thrust is generated to maintain a small average tension on the hawser. The wind is generally acting on the ship's stern while there is no discernable trend with respect to relative current direction.

3) The bow thruster can be used effectively to reduce hawser wear even in light (< 2m significant wave height) seas by damping out second order yaw motion.

4) The bow and stern thruster can be used together in high seas (> 3.0m significant wave height) to effectively reduce hawser loads.

5) Operation of the thrusters on manual (ie: operated by the bridge staff) in severe seas (> 4.0m significant wave height) resulted in unacceptably high hawser loads and increased risk of hawser failure.

6) Existing thruster capacity does not appear to be close to saturation in seas up to 4.5m significant wave height.

7) The primary influence on hawser tension is wave height. Wind speed is correlated to hawser load to a lesser extent while little correlation between current speed and hawser tension was noted.

8) Peak hawser loads greater than 150 tonnes are unlikely up to 4.5m significant wave height if the TAP system is operating normally. Applying a worst case regression to the data, a hawser load of 240 tonnes would be sustained at a significant wave height of 7.2m

9) The TAP system as installed appears to be somewhat unreliable above a significant wave height of 5.0m.

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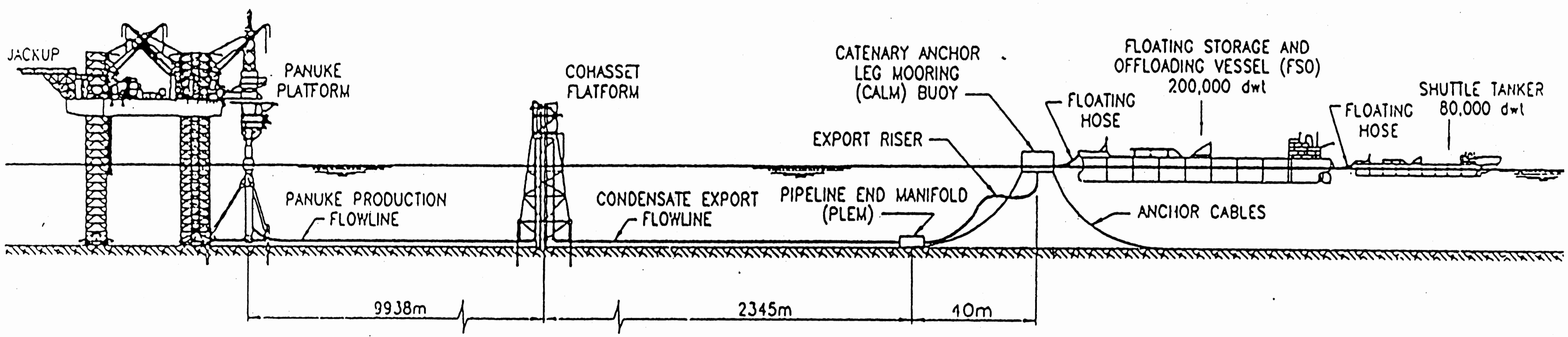
PRINCIPAL PARTICULARS OF THE "NORDIC APOLLO"

Length Overall	283.92 m
Length Between Perpendiculars	271.32 m
Breadth Moulded	42.82 m
Depth Moulded @ Centerline	28.96 m
Depth Moulded @ Side	28.65 m
Depth to Freeboard Deck	24.08 m
Draft - Design Waterline	17.37 m
Draft - Light	11.28 m
Deadweight	127,200 tonnes
Number of Cargo Tanks (including slop tanks)	11
Total Capacity	931,525 barrels
Built	Avondale, USA - 1978
Flag	Liberian
Forward Speed	12.5 knots
Main Propulsion Machinery	DeLaval Steam Turbine 10,000 kW single screw, fixed pitch single centerline rudder
Electrical Service	440/110 Volts AC 5,000 kW
Stern Azimuth Thruster	Ka-Me-Wa 750 kW variable pitch
Bow Tunnel Thruster	Bird Johnson (Ka-Me-Wa licensee) 1500 kW variable pitch
Thruster Assisted Positioning System	Simrad Albatross 701



PROFILE

Fig. 1

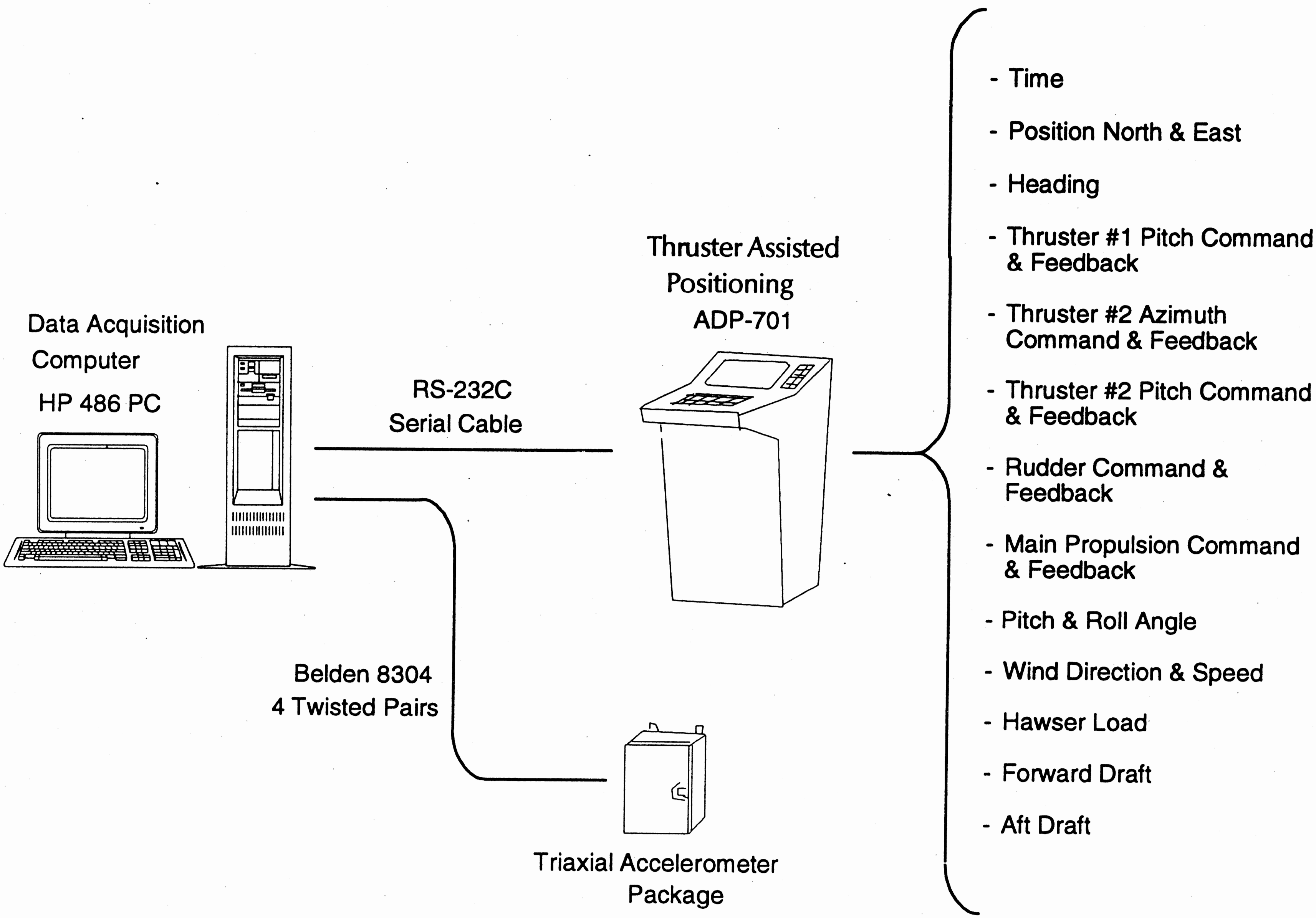
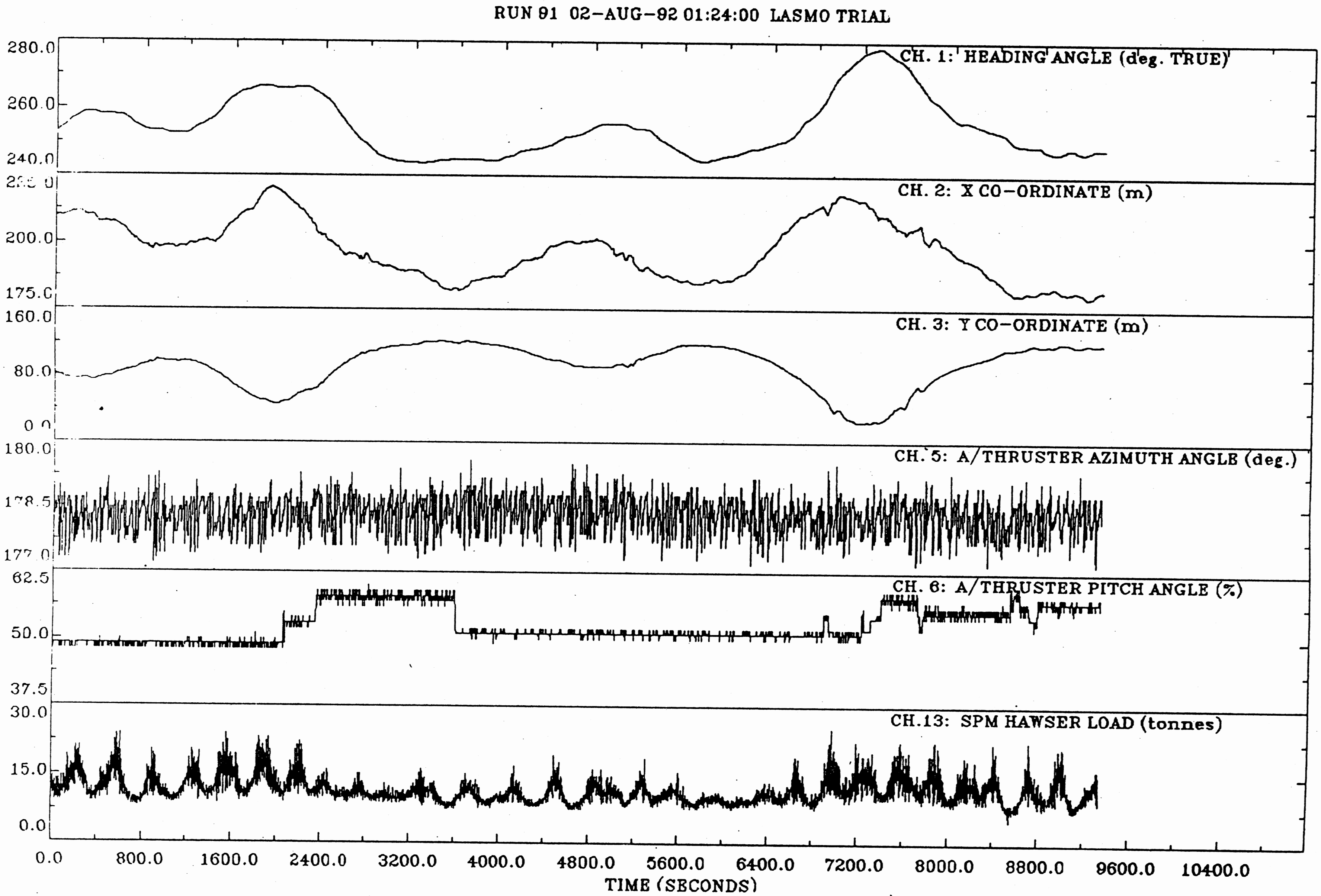


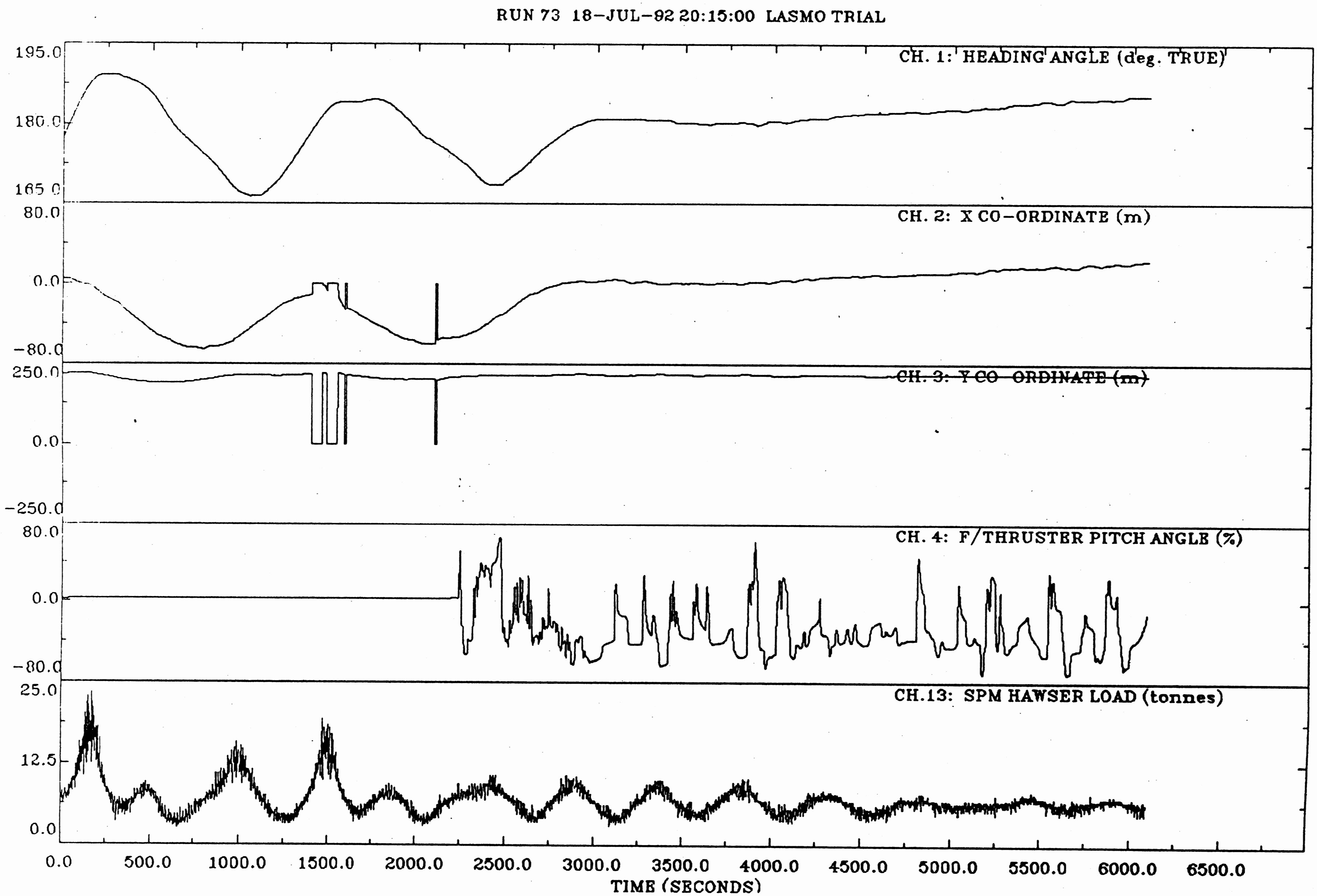
Fig. 2

DATA ACQUISITION ARRANGEMENT ON 'NORDIC APOLLO'



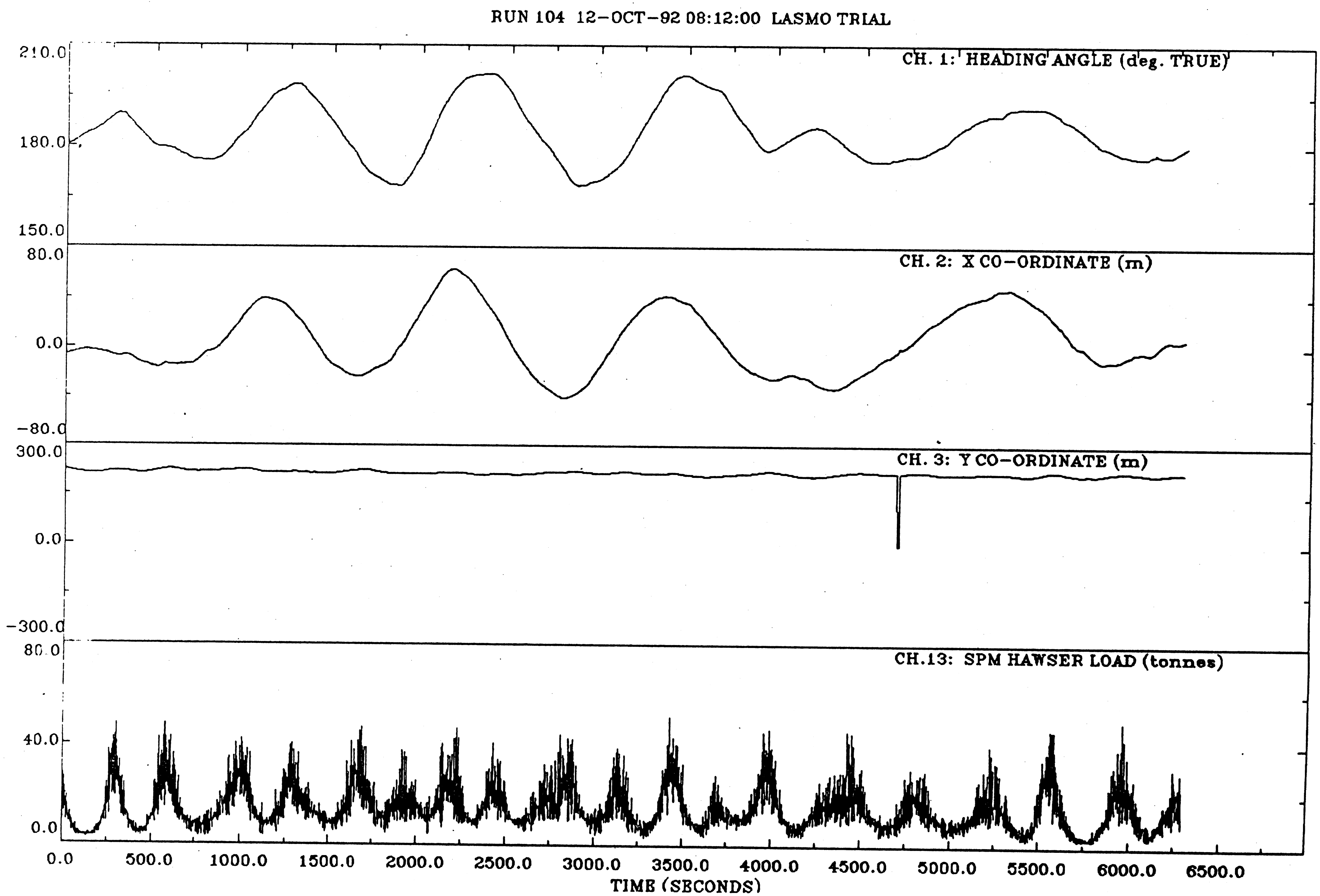
TYPICAL MOORED CONDITION

Fig. 3



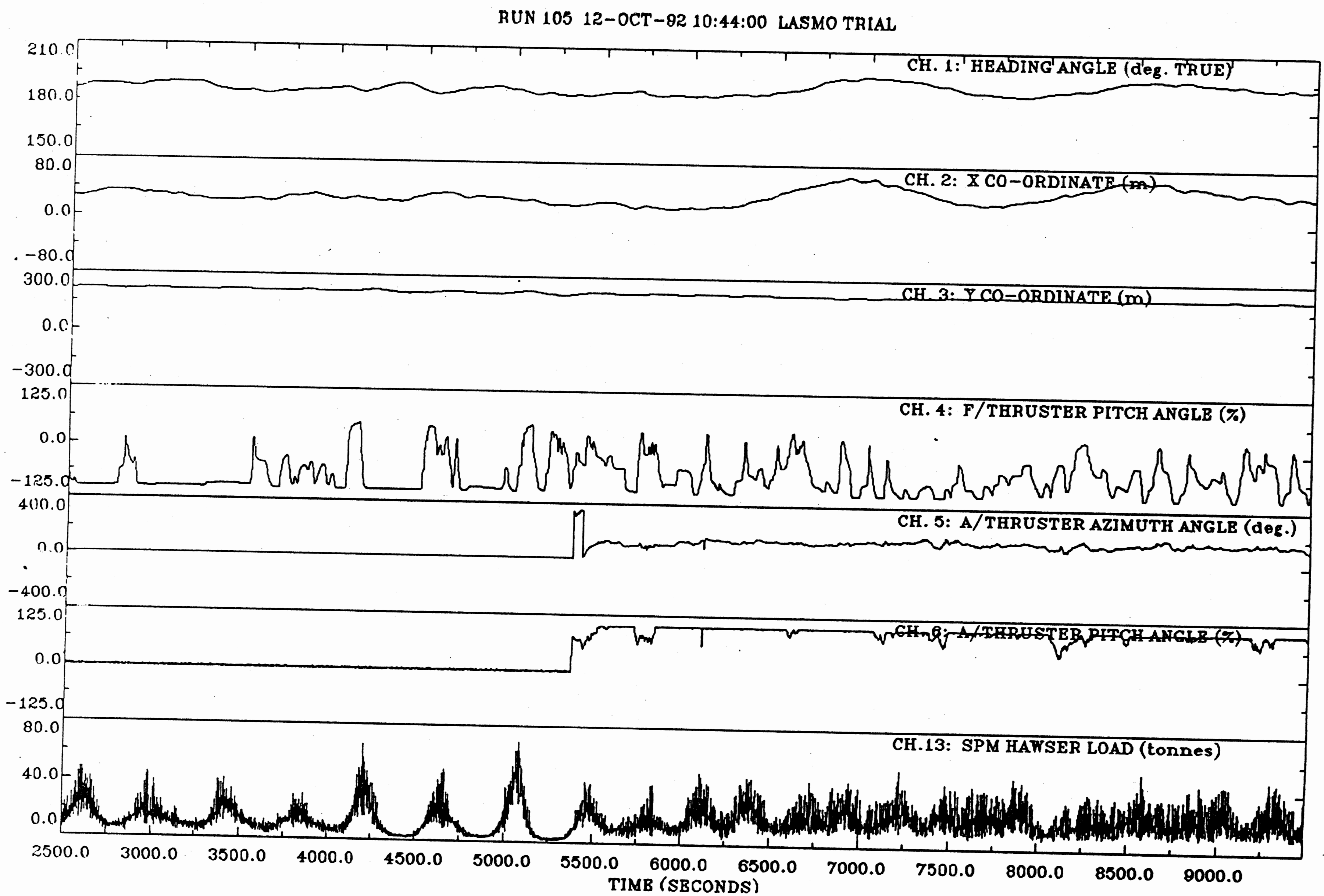
EFFECT OF BOW THRUSTER TURNED ON

Fig. 4



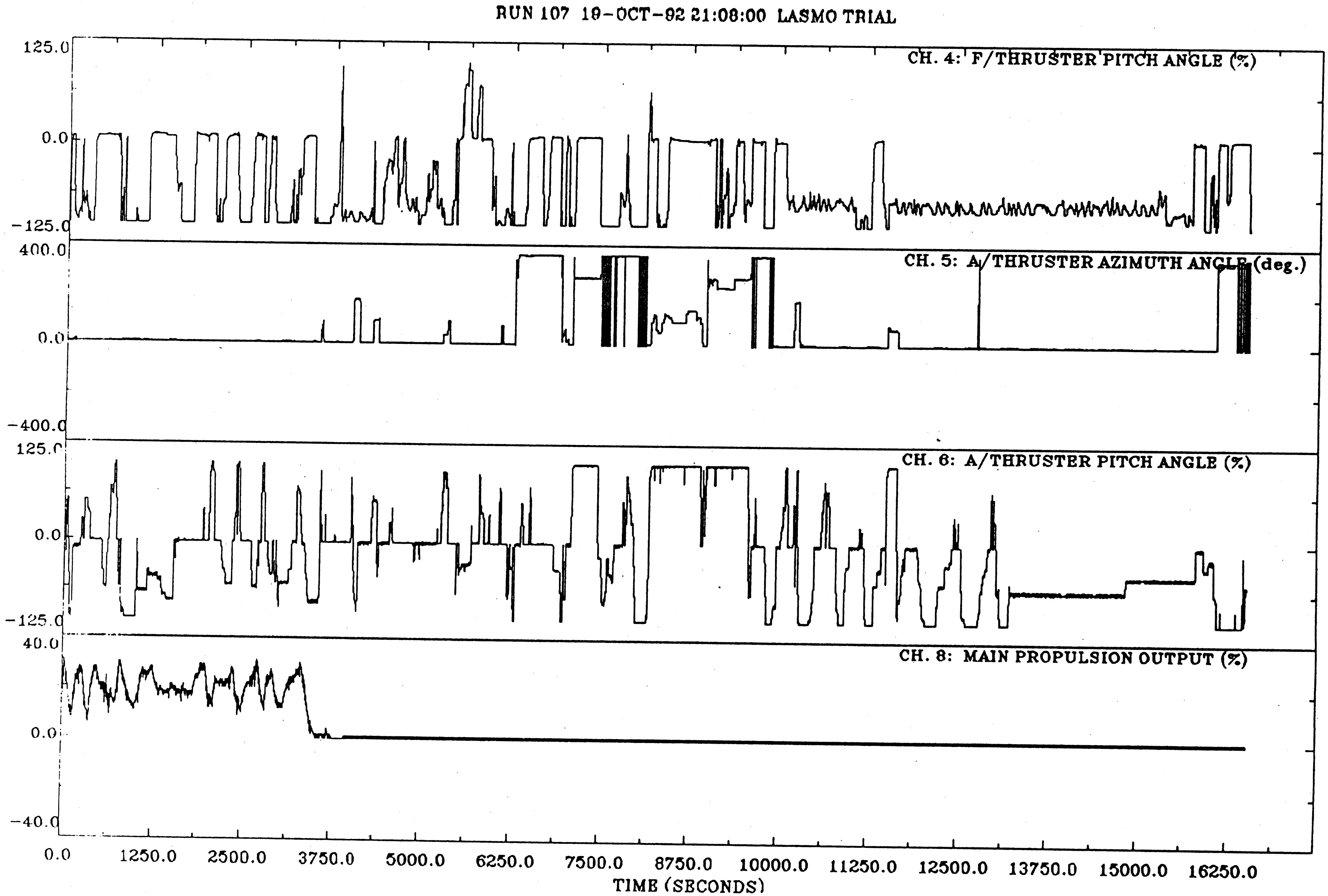
NO THRUSTERS ON

Fig. 5



STERN THRUSTER TURNED ON

Fig. 6



THRUSTER AND MAIN PROPULSION SYSTEM ON MANUAL CONTROL

Fig. 7

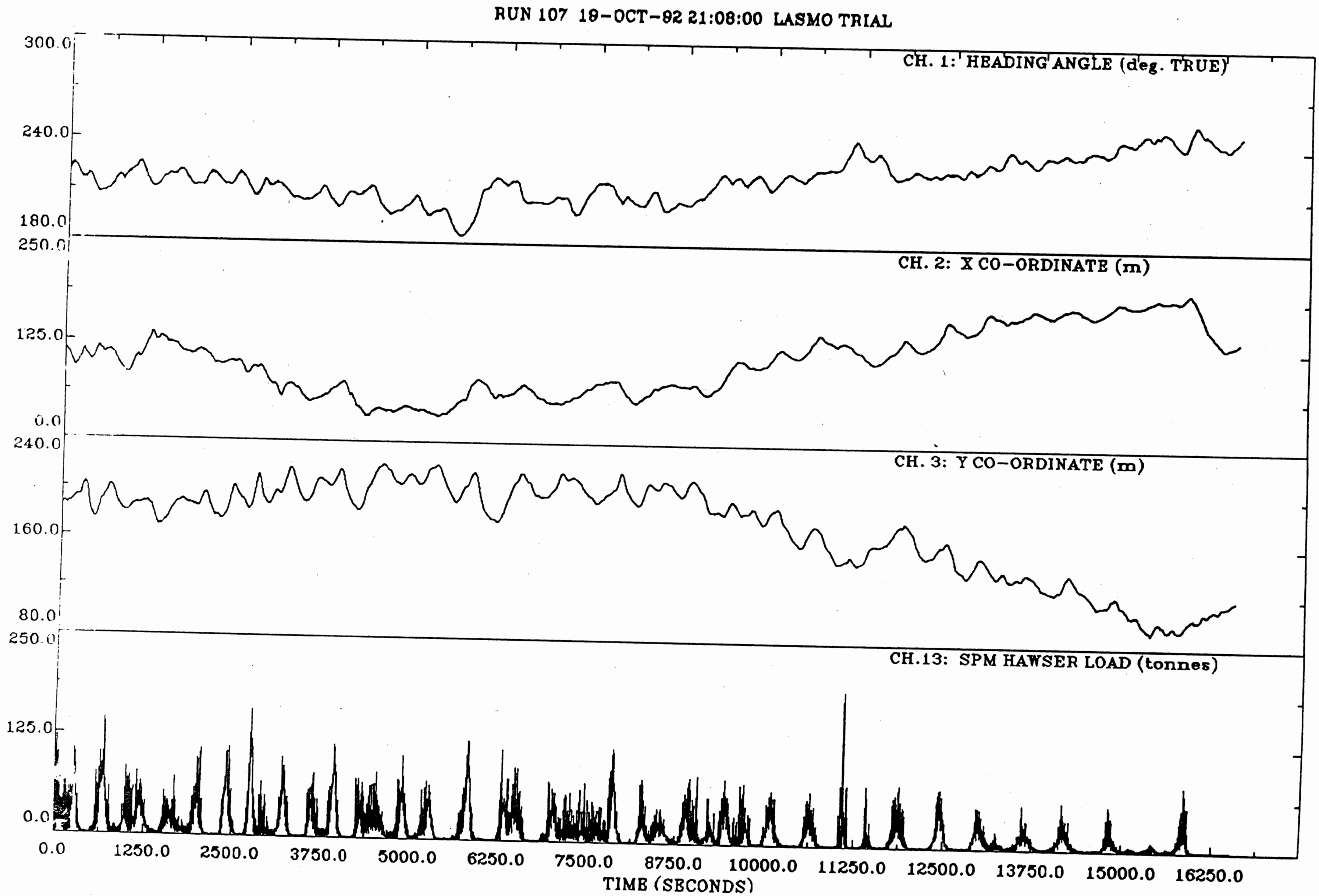
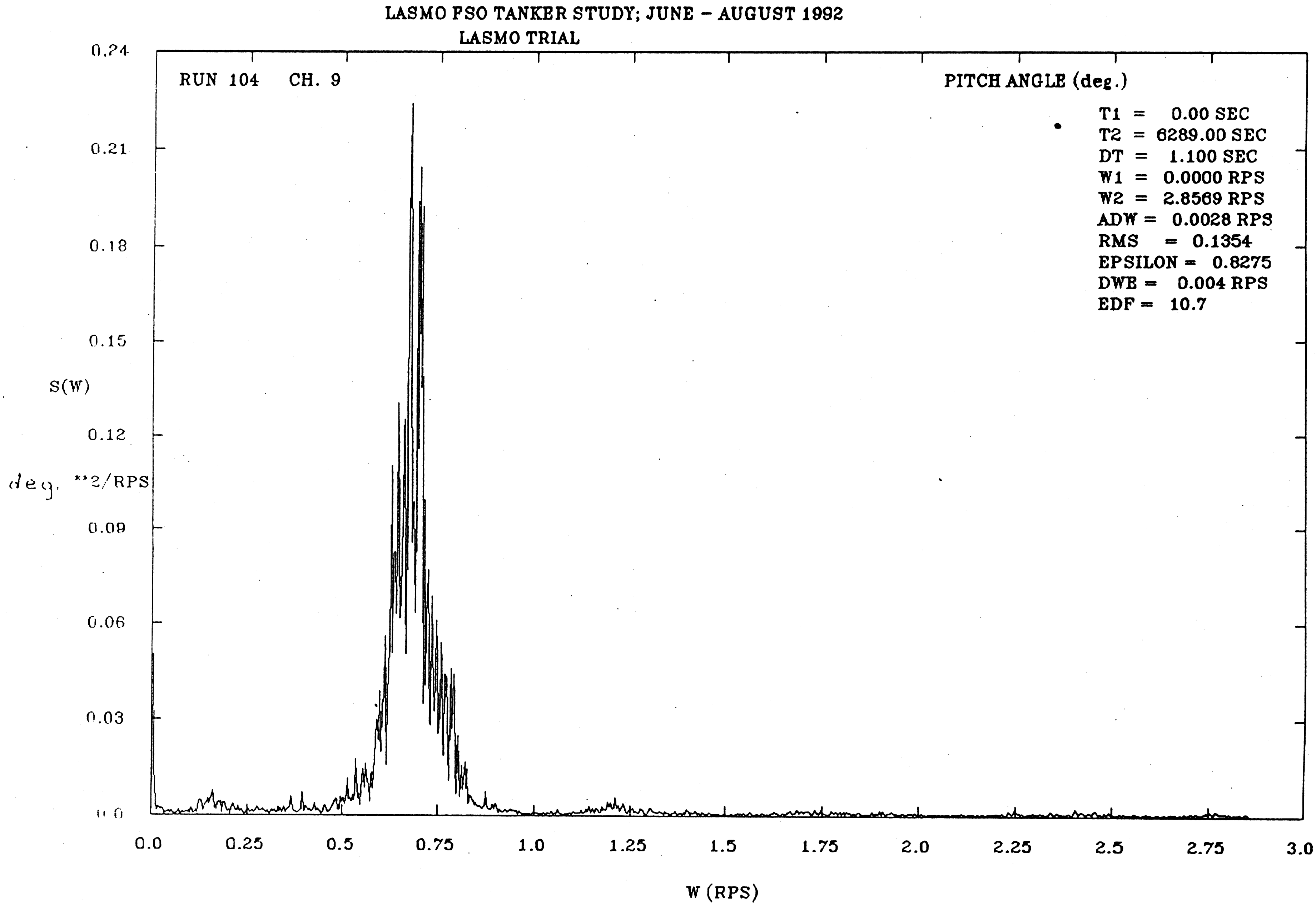


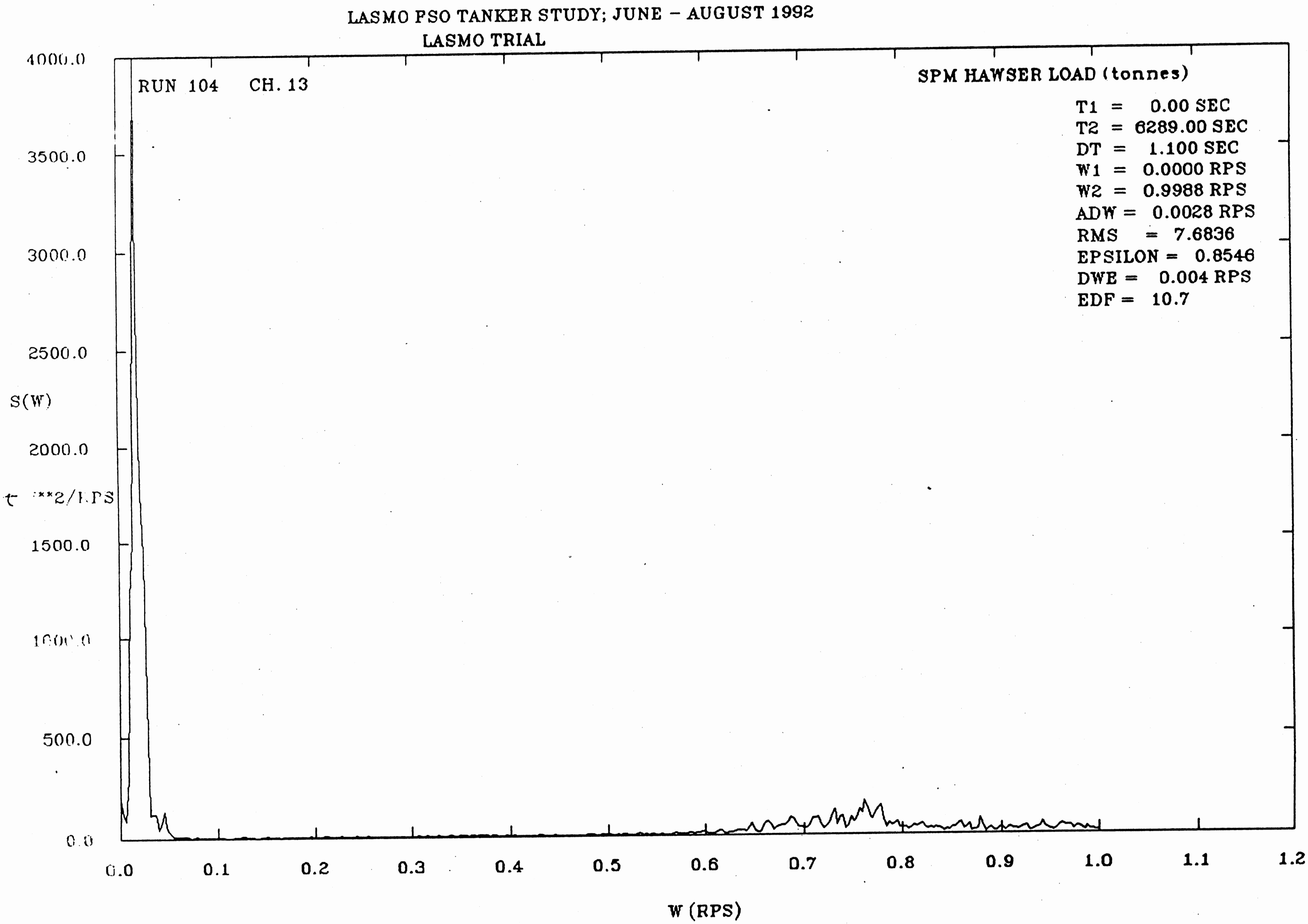
Fig. 8

FSO BEHAVIOR ON MANUAL CONTROL



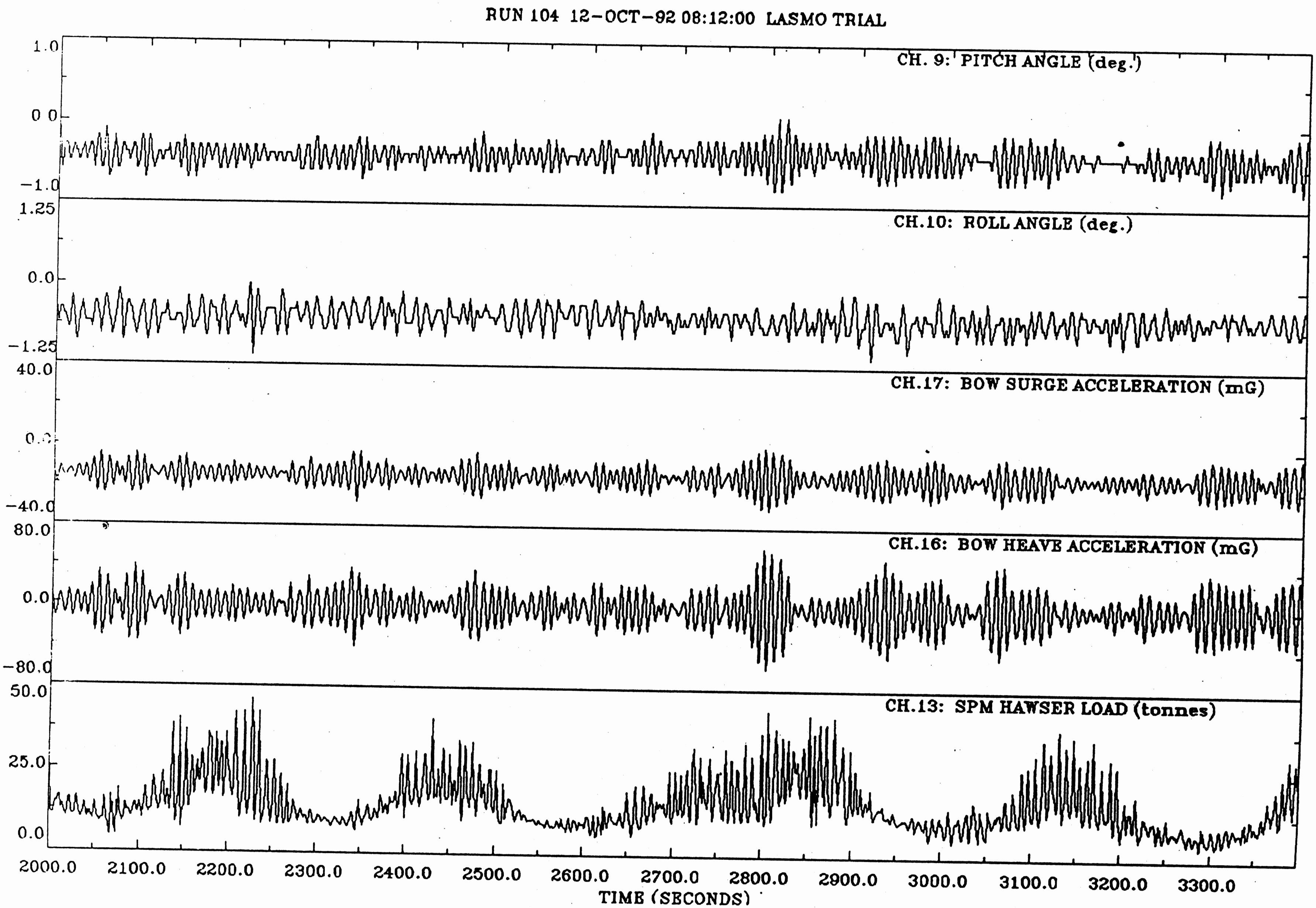
TYPICAL PITCH ANGLE SPECTRUM

Fig. 9



TYPICAL HAWSER LOAD SPECTRUM

Fig. 10



RUN 104 12-OCT-92 08:12:00 LASMO TRIAL
CH. 9: PITCH ANGLE (deg.)
CH.10: ROLL ANGLE (deg.)
CH.17: BOW SURGE ACCELERATION (mG)
CH.16: BOW HEAVE ACCELERATION (mG)
CH.13: SPM HAWSER LOAD (tonnes)
1.0
0.0
-1.0
1.25
0.0
-1.25
40.0
0.0
-40.0
80.0
0.0
-80.0
50.0
25.0
0.0
2000.0 2100.0 2200.0 2300.0 2400.0 2500.0 2600.0 2700.0 2800.0 2900.0 3000.0 3100.0 3200.0 3300.0
TIME (SECONDS)

Fig. 11

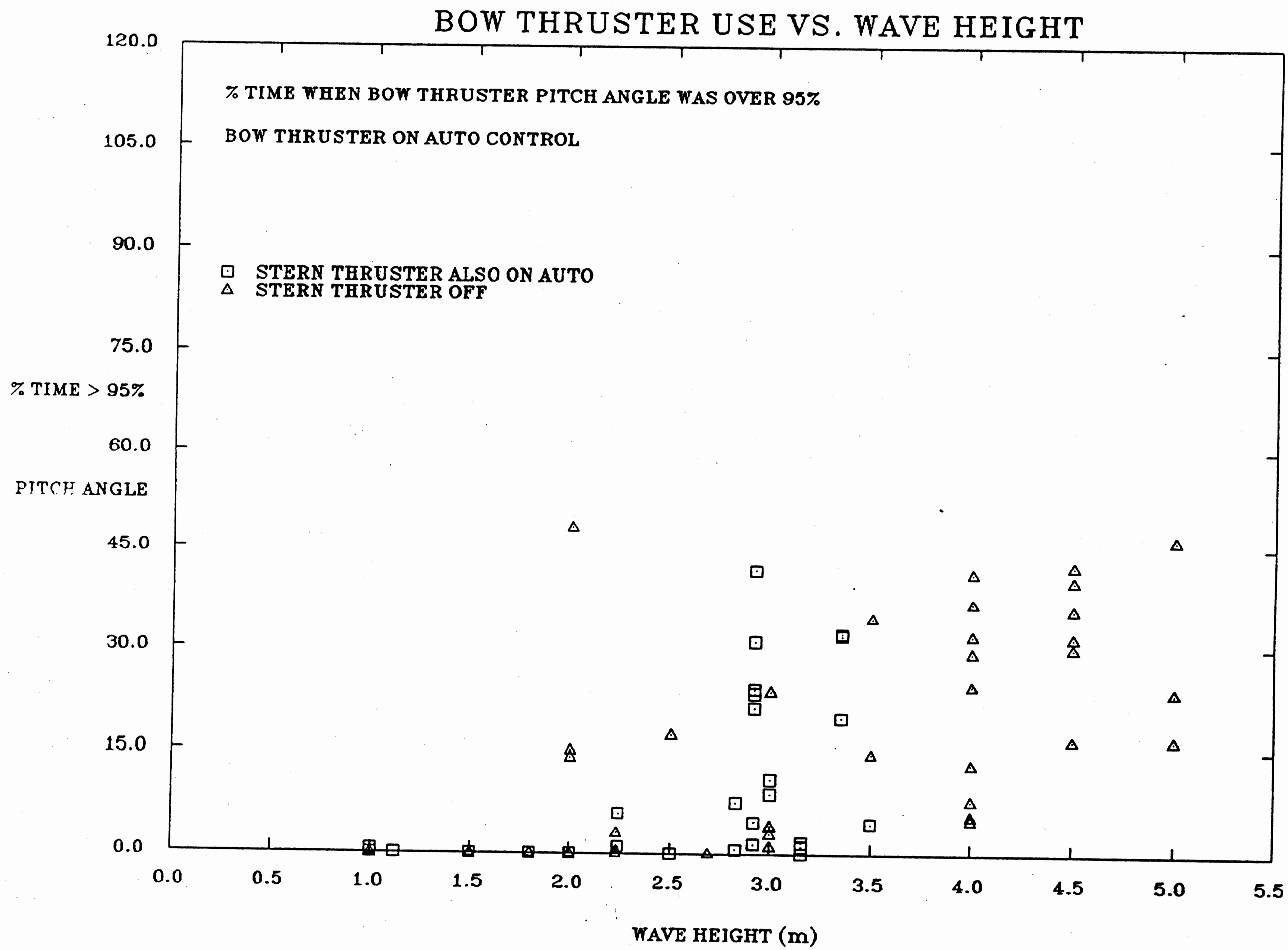

BOW THRUSTER USE VS. WAVE HEIGHT
% TIME WHEN BOW THRUSTER PITCH ANGLE WAS OVER 95%
BOW THRUSTER ON AUTO CONTROL
STERN THRUSTER ALSO ON AUTO
STERN THRUSTER OFF
% TIME > 95%
PITCH ANGLE
WAVE HEIGHT (m)
120.0
105.0
90.0
75.0
60.0
45.0
30.0
15.0
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5

Fig. 12

STERN THRUSTER USE VS. WAVE HEIGHT

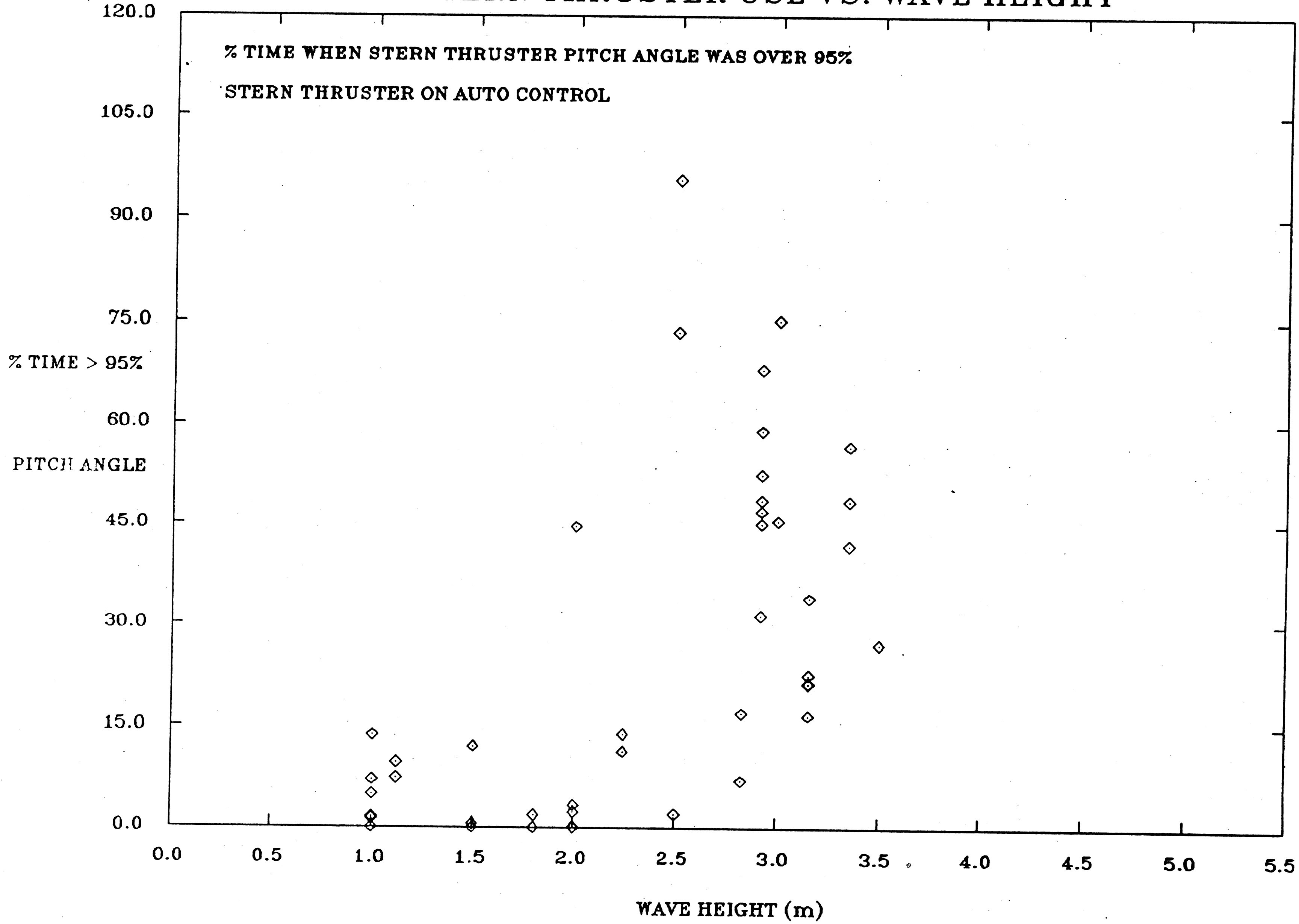


Fig. 13

Fig. 14 Histogram of Relative Wind Direction, Symmetric Distribution

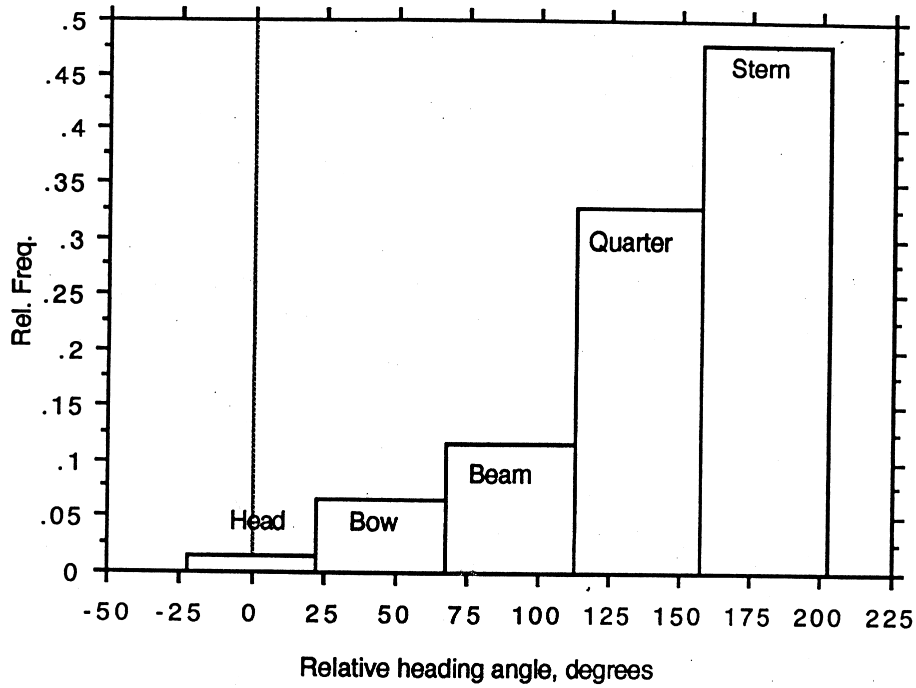


Fig. 15 Histogram of Relative Current Direction, Symmetric Distribution

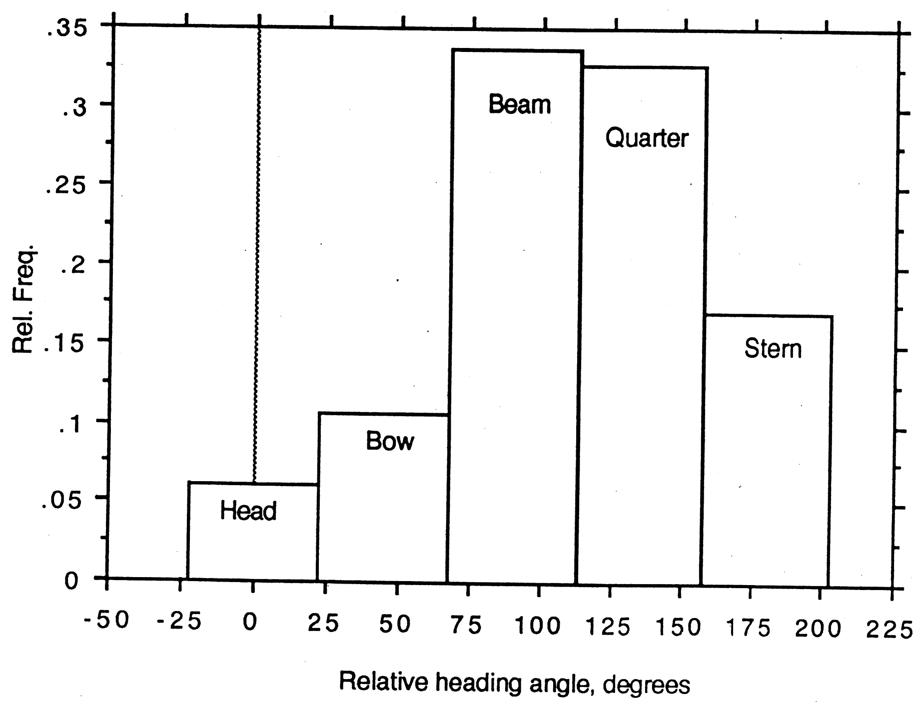


Fig. 16 Peak Hawser Load against Significant Waveheight,

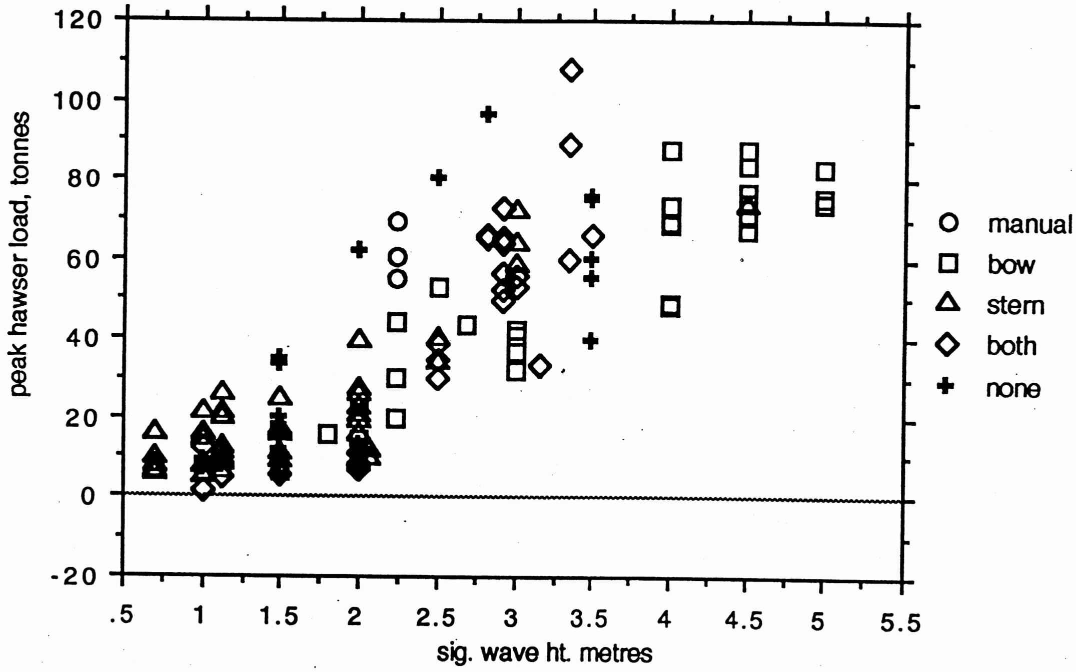


Fig. 17 Peak Hawser Load against Wind Speed,

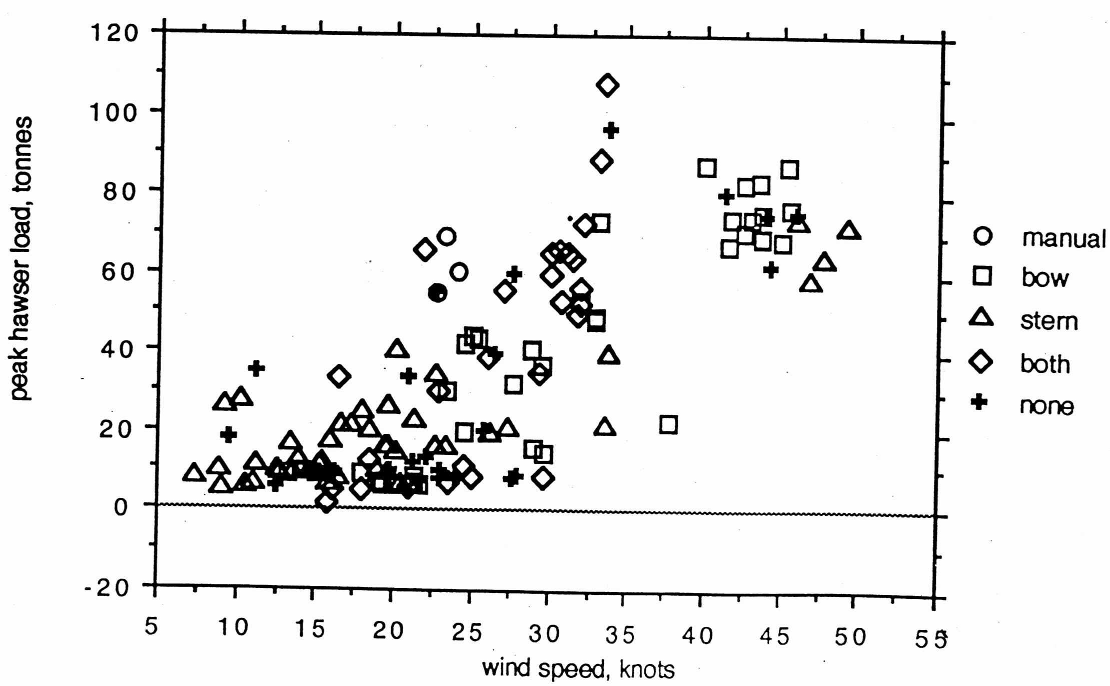


Fig. 18 Peak Hawser Load against Current Speed, Stern Wind

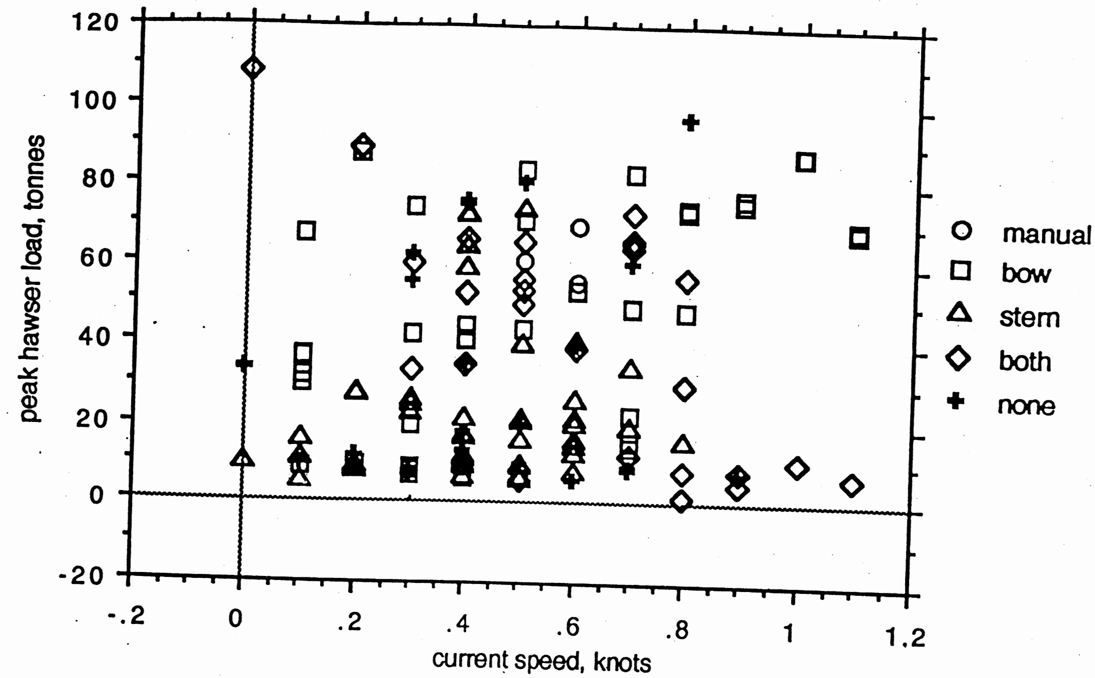


Fig. 19 , Peak Hawser Load against Significant Waveheight, All Data

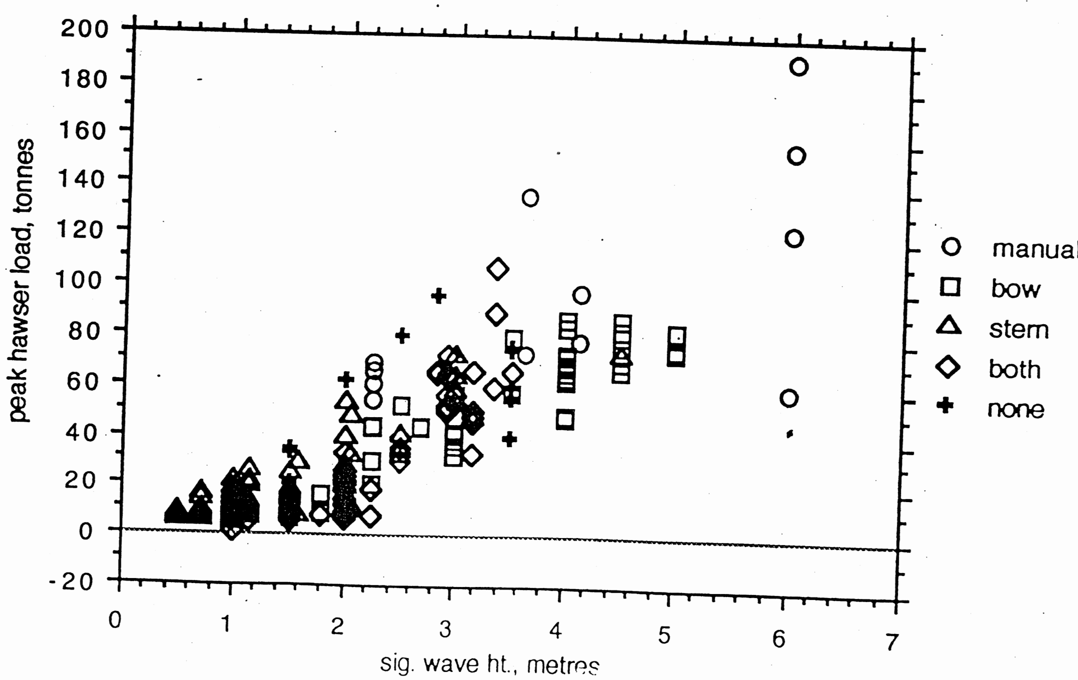


Fig. 20 Effect of TAP Operation on Average Peak Hawser Load

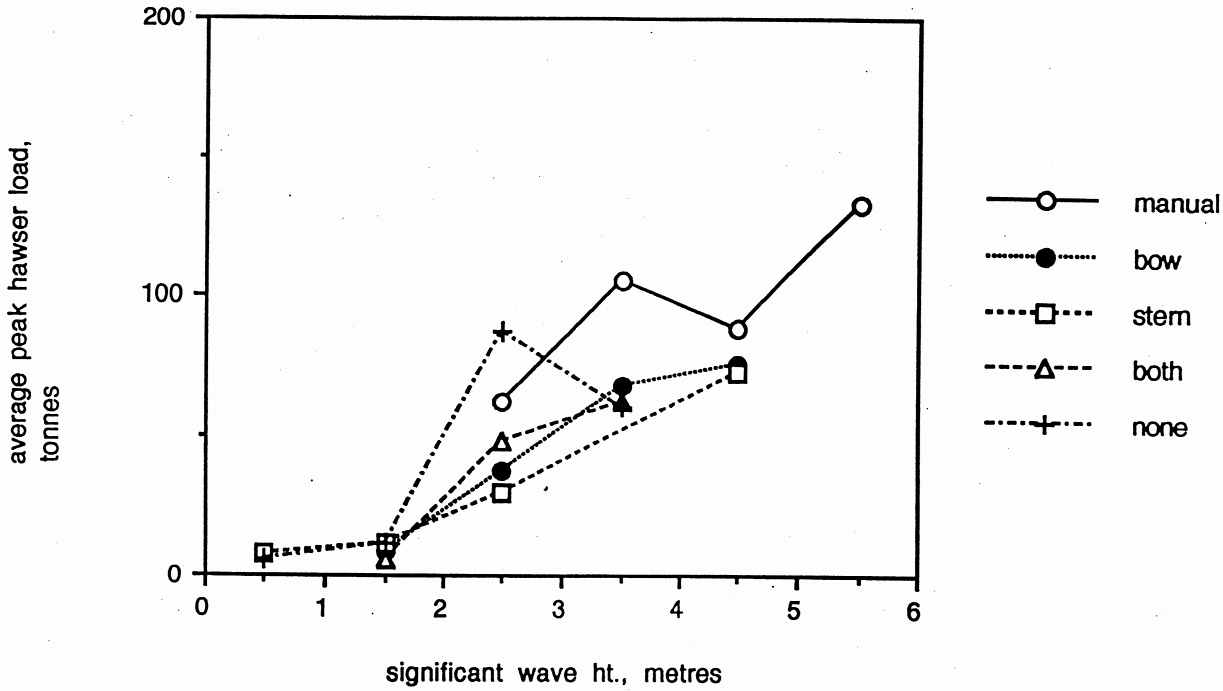


Fig. 21 Peak Hawser Load against Significant Waveheight, All Data