A conceptual study of techniques for measuring global loads on the Terra Nova FPSO

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A CONCEPTUAL STUDY OF TECHNIQUES FOR MEASURING GLOBAL LOADS ON THE TERRA NOVA FPSO

FINAL REPORT

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Submitted to:

National Research Council Canada
Montreal Road, Bldg. M-22, Unit 1
Ottawa, ON
K1A OR6
Attn: Dr. Garry Timco

Submitted by:

Fleet Technology Limited
311 Legget Drive
Kanata, ON
K2K 1Z8

in association with:

Scientific Marine Services
101 State Place, Suite N
Escondidio, CA
92029

FTL Contact: I.F. Glen, President,
Tel.: (613) 592-2830
Fax : (613) 592-4950
Email: iglen@fleetech.com

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REPORT/PROPOSAL: A Concept Study of Techniques for Measuring Global Loads on the TERRA NOVA FPSO

DATE: 23 August, 2000

PREPARED BY: R.B. Paterson, R. Y. Edwards, I.F. Glen

REVIEWED BY: A. Kendrick, Vice President

APPROVED BY: I.F. Glen, President

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AHT	Anchor Handling Tug (AHT)
DGPS	Differential Global Positioning System
DOF	Degree of Freedom
DP System	Dynamic Positioning System
F_g	Total Global Load
FPSO	Floating Production and Storage Offshore (platform)
OPIS	Offshore Production Information System
Q	Thruster torque
ROV	Remotely Operated (Submarine) Vehicle
T	Thruster thrust
TAPMS	Thruster Assisted Position Mooring System
V	Velocity
VISMU	wireless, subsea, inclination and vibration measurement unit
x,y,z,	Vessel translational displacements in surge, sway and heave
α	azimuth angle – thrusters, α_w – wind, α_c current, etc.
ξ,ψ,ζ	Vessel angular displacements pitch, roll and yaw

1. INTRODUCTION

1.1 Background

The TERRA NOVA FPSO is a Turret Moored Floating, Production, and Storage Offshore (FPSO) platform strengthened for ice. The FPSO principal particulars are listed in **Table 1.1**. It will be moored in 95 meters of water using a turret mooring system as shown in **Figure 1.1,** that can be disconnected if the FPSO is threatened by an iceberg incursion or other extreme ice event.

Table 1.1: Principal Particulars – TERRA NOVA FPSO

Length Overall	291m
Length Between Perpendiculars	277m
Beam (moulded)	45.5m
Depth (moulded)	28.2m
Scantling Draft	20.0m
Max. Operating Draft	18.55m
Min. Operating Draft	12.77m
Displacement (Deep)	196,000 tonnes
Displacement (Ballast)	
Cargo Capacity	154.482 m^3
Nominal Ice Class	Baltic 1A; Special strengthening in Bow
Classification	⌘OI 100AT(1) Floating Production and Oil Storage Installation, for TERRA NOVA field offshore Newfoundland, Ice Strengthened

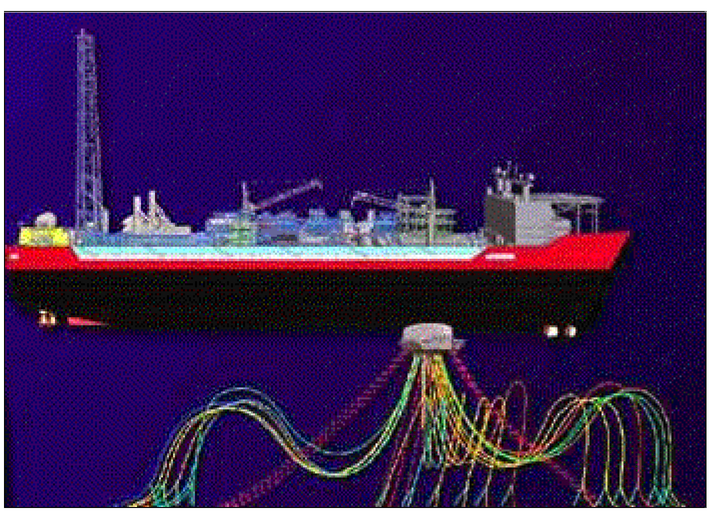

Figure 1.1: TERRA NOVA FPSO

The FPSO is held on station with a fixed mooring system comprising nine chains, grouped in units of three. This arrangement is augmented by a set of azimuthing thrusters, controlled by a dynamic positioning system. The combined system is referred to as the Thruster Assisted Position Mooring System (TAPMS). This system is described in much greater detail in **Section 2.** The mooring system is already installed at the TERRA NOVA site and pretensioned to the Spider buoy. The Spider buoy is presently submerged at a depth of 35 meters.

1.2 Project Objectives

The objective of this project was to explore and evaluate conceptual methods for directly measuring the global loads and mooring line loads on the TERRA NOVA FPSO, with specific emphasis on the loads that result from pack ice intrusions.

The motivation for this latter emphasis is the possibility of relaxing the current disconnect requirement that is based on 5/10 ice cover. The authors were unable to find a sound technical basis for these criteria. A review of model tests of moored structures in ice indicated that loads from pack ice are low until about 8/10 cover, and numerical work also does not support these criteria. However, the current disconnect condition is a critical condition of insurance for the platform. Thus, a feasible load monitoring system could have a role to play in justifying an extended operating window to both the regulators and insurers.

The project team also understands that there is a requirement for monitoring the integrity of the mooring system in real time, for safety and operational reasons, for which a simple DP-based load inference system was deemed unacceptable.

1.3 Report Scope

This report includes a summary of the existing system and documents the review of technologies and new ideas for measuring the global loads on the TERRA NOVA FPSO.

2. CURRENT SYSTEM

2.1 The TERRA NOVA FPSO Thruster Assisted Position Mooring System (TAPMS)

The mooring system consists of nine chains, which are arranged in three clusters of three, at intervals of 120 degrees around the turret. The mooring consists of three components: the top chain, excursion limiter and the ground chain. The excursion limiters are chain mats in the vicinity of the touchdown point, which act like a distributed "clump" weight to provide additional stiffness at larger offsets of the FPSO. The arrangement is shown in **Figure 2.1**. The mooring chains are terminated in a large "Spider Buoy" which is connected to the rotating portion of the turret with a single large "collet" type connector. This facilitates the quick disconnection and reconnection of the mooring and the risers from the FPSO.

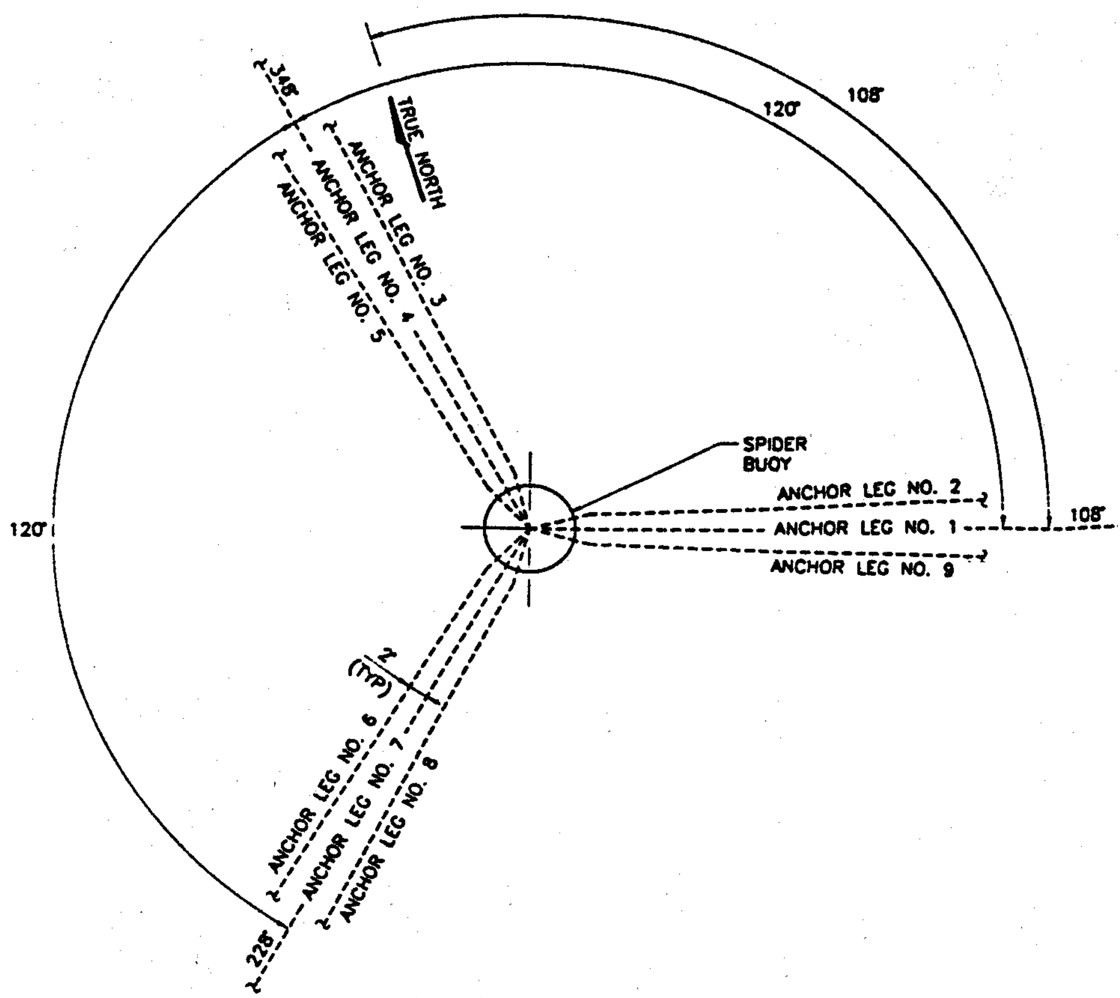

Figure 2.1: TERRA NOVA FPSO Mooring System Arrangement

The mooring system is augmented by a set of five azimuthing thrusters, 5 .0 MW each, two in the bow and three in the stern (see Figure 2.1). These are activated when the FPSO exceeds specific excursion limits set within its watchkeeping circle.

In the currently proposed system, the FPSO position, and thus displacement from a reference position, will be measured with three separate systems as follows:

(a) An Artemis short-wave positioning system that is referenced to the Hibernia platform.
(b) A Differential Global Positioning System (DGPS).
(c) An acoustic system consisting of seabed receivers and a FPSO-mounted pinger.

The principal function of this system is to provide feedback for activating the dynamic positioning system of the FPSO.

2.2 Loads on the Mooring System

The mooring system on the TERRA NOVA FPSO is not currently equipped with any instrumentation to measure either the mooring line tension or the angle of inclination of the chains. The loads exerted by the chain on the FPSO turret in the lateral plane are *estimated* for the purposes of providing modification of the position error signal for the Dynamic Positioning System, which provides thruster assistance to the mooring (see next Section). This function is accomplished using a quasi-static model of the mooring system and the estimate of the offset of the FPSO in the lateral plane from the centre of the “watch circle”, based on the three sensors noted in Section 2.1. The mooring loads on the FPSO are then calculated by the Kongsberg/Simrad system. These loads are subsequently used to estimate the optimum settings for the propulsors to minimize the vessel offset and the load on the mooring system. The accuracy obtained from this system, while adequate for propulsor control, is insufficient for accurate load measurement, and certainly for load component determination.

No instrumentation is currently attached to the mooring lines, nor does SOFEC intend to have any instrumentation attached to the mooring lines while the FPSO is in service. Mooring line inclination angles were measured while the mooring lines and the bundles were installed. However, the low-data rate Sonardyne inclinometers placed on the mooring lines during setup have since been removed.

The relationship between the load on the mooring system, its physical configuration and the vessel location were explored using a mooring system model and reported in [Ref. 1]. This is reproduced in Appendix B where the details of the model input and its limitations may be seen. The results are reproduced graphically in **Figures 2.2 and 2.3.**

Figure 2.2 shows the total restoring force of the mooring system for offset direction aligned with mooring line 1 (+ve offsets) and offset direction bisecting angle between lines 1 and 4 (-ve offsets), for ballast and full load drafts. It can be seen that the Ballast draft configuration exhibits slightly higher forces than the Full Load configuration. In addition, the mooring system is the stiffest for offset directions aligned with mooring lines 1, 4 or 7 (i.e., the slope is steeper).

Figure 2.3 shows the rate of change of total restoring force (Δforce) per metre of offset in the direction aligned with mooring line 1 (+ve offsets) and offset direction bisecting angle between lines 1 and 4 (-ve offsets), for ballast and full load drafts.

Based on this modelling, the sensitivity to an error in position is strongly dependent on the excursion of the vessel from its reference origin, and the direction of that excursion relative to the mooring lines. As can be seen in Figures 2.2 and 2.3, the relative stiffness of the response when the offset of position is along the direction of a mooring line versus midway between the mooring lines is significant.

For example, in the case where the vessel excursion is in a direction between moorings, an error in the measurement of the location of the vessel of about one (1) metre, in the direction of the offset while the vessel is in the vicinity of the equilibrium position, would represent an error of about 50 tonnes force in the estimation of the total restoring force. In contrast, an error of 1 metre in the measurement of the vessel location along the direction of the offset when the offset direction is aligned with a mooring would represent an error of approximately 350 tonnes-force at a vessel offset of 30 meters.

On the basis of these results, there are two critical parameters:

(1) The capability of the thruster systems to intervene and limit the offset displacement of the vessel.
(2) The resolution of the positioning systems;

2.3 Performance of Thruster System

The thruster system is addressed in Section 408 of the Ship Specification [Ref. TN-BR-MR02-V00-002], where reference is made to a PM (T3) notation in LR Rules for Ships, Part 7, Chapter 8, and in some detail in TN-BR-MR16-V91-024, “Basis for Design of FPSO Vessel TAPMS”. However, there is limited performance data in these documents. Additional data extracted by the TERRA NOVA staff from various design documents for the thrusters was reviewed. While the data received was not directly useable in a detailed analysis of the thruster behaviour at this stage, it is clear that the information will be available to model the thruster behavour, including the thrust characteristics at different azimuth angles, and currrents and accounting for the interaction between the thrusters.

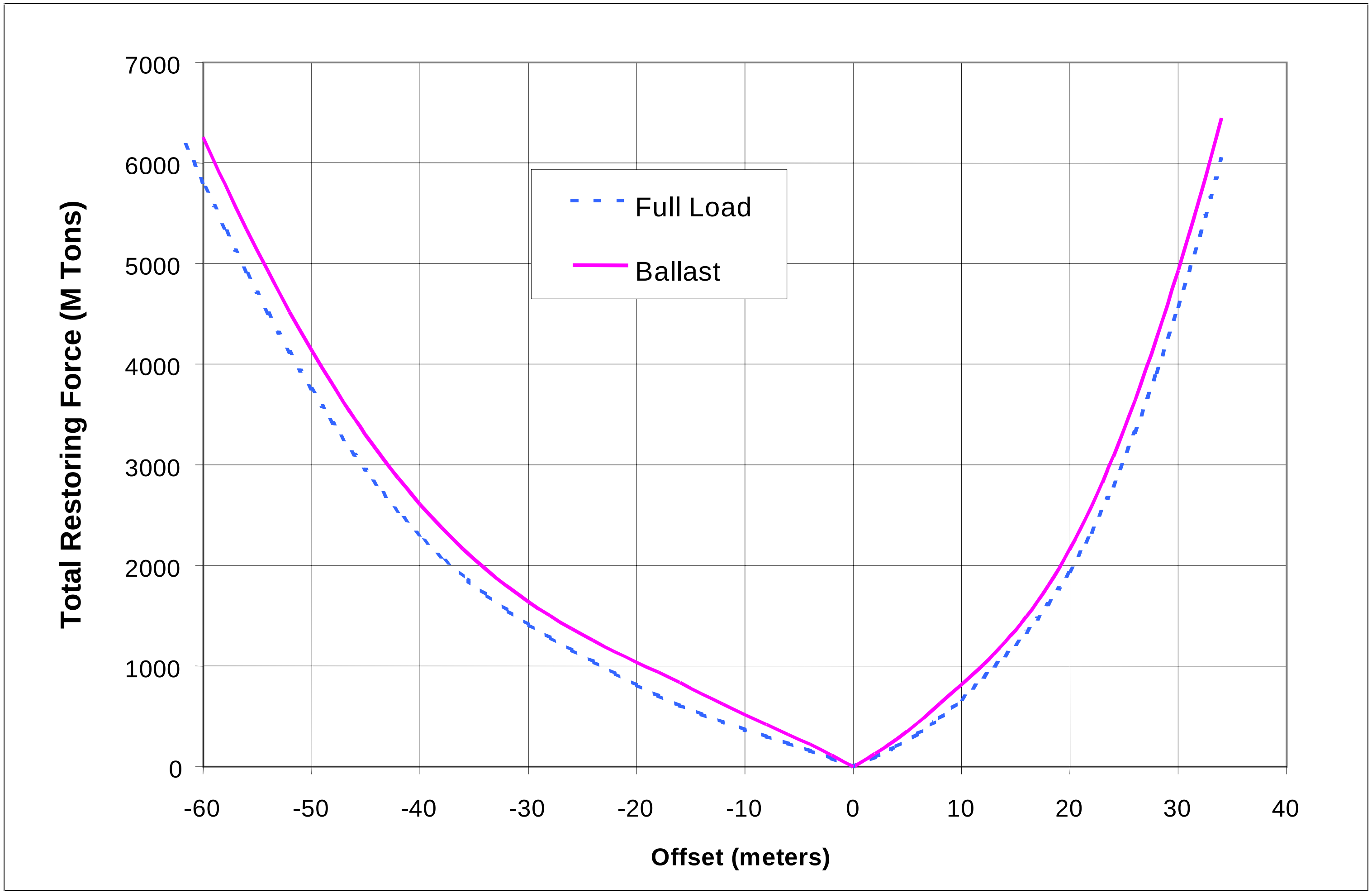

Figure 2.2: Total Restoring Force for Offset Direction Aligned with Mooring Line 1 (+ve Offsets) and Offset Direction Bisecting Angle between Lines 1 and 4 (-ve Offsets), for Ballast and Full Load Drafts

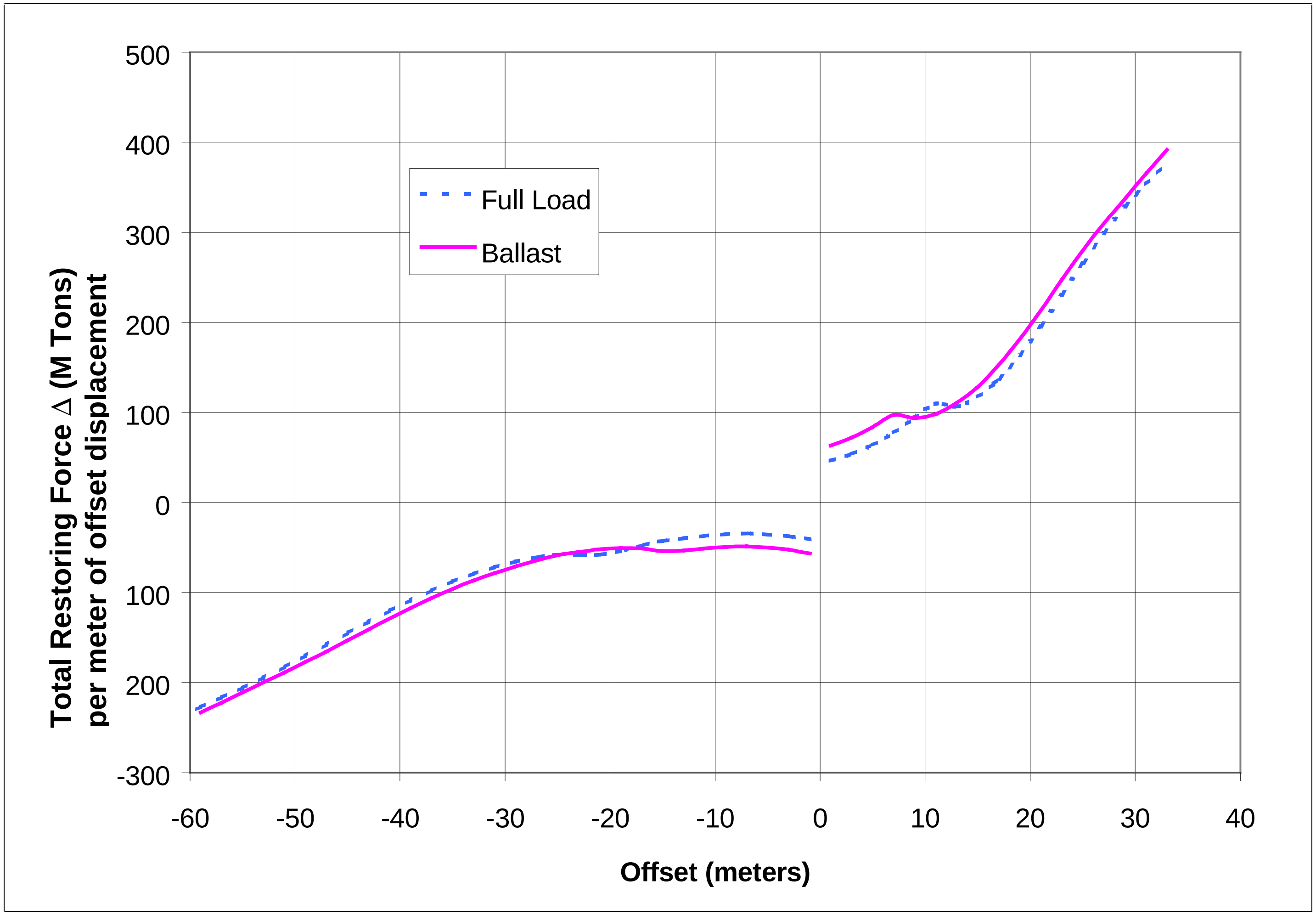

Figure 2.3: Total Rate of Change of Restoring Forces (ΔForce) Per Metre of Offset, in the Direction Aligned with Mooring Line 1 (+ve offsets) and Offset Direction Bisecting Angle Between Lines 1 and 4 (-ve Offsets), for Ballast and Full Load Drafts

In the absence of thrust characteristics, etc., some nominal thruster data was generated in Table 2.1.using standard conversion values for shrouded propellers in an overload condition, and some conservative assumptions concerning loss of thrust when units overlap. This data is sufficient to indicate the magnitude of the restoring force that might be generated from the thruster system.

Table 2.1: Nominal Thruster Data

Installed Power/Unit (MW)	5.00
Conversion Factor - Shaft Power	*0.89*
Shaft Power/Unit (MW)	4.45
Thrust Conversion (t/MW)	*20*
Thrust /unit (tonnes)	89
Nominal Lateral thrust (4 units, tonnes)	356
Nominal Lateral thrust (5 units, tonnes)	400
Nominal Longitudinal Thrust (3 units, tonnes)	267
Nominal Longitudinal Thrust (5 units, tonnes)	356

It is clear when comparing the results from Table 2.1 against the restoring forces shown in Figure 2.2, that the thrust generated is significant compared with mooring extreme loads. For example, from model tests in 100% pack ice, 1m thick, the load estimate is 1500 tonnes. Therefore, the thrusters are supplying 25-30% of the total global load under such an extreme condition.

In order to make an accurate assessment of the net load on the FPSO due to environmental forces, the characteristics of the thrusters in terms of their thrust output as a function of rpm, flow over the propulsor, azimuth angle, the dynamic response of the system and the torque/current characteristics, should be known. The actual thrust being delivered for a particular vessel heading and thruster orientation must be well documented and considered in the load inference system.

During a significant environmental event, both the thrusters and the mooring system will be active. Therefore, any attempt to derive useful global loads will require the monitoring of both the mooring loads and the direction and magnitude of the resultant force exerted on the vessel by the thrusters, for the full range of powers and orientations of the individual thrusters. This might prove to be quite complex, and the dynamic nature of the combined system (vs. the relatively static response of a pure mooring line-based system) may make real time analysis of the global loads problematic. Nevertheless, it is assumed that this can be achieved through shipboard measurements and software.

2.4 Resolution of the Positioning Systems

As discussed in Section 2.1, there are three independent estimates of the FPSO position. One is an “Artemis” microwave positioning system, which, with the Hibernia platform as a reference point, provides the position of the FPSO with a range and bearing to Hibernia.

A differential GPS unit provides a second estimator of location and finally there is an Acoustic Positioning System, which uses the ranges between several subsea beacons on the sea floor and transponders on the FPSO to establish the position of the FPSO.

The result of the mooring system analysis (Appendix B) shows that the resolution of the positioning system is absolutely crucial to the error magnitude associated with inferring the loads from the DP system.

The nominal positional accuracy of each system is typically about 0.5m, and the TN representative has suggested that the GPS system will achieve 1.5m. From Figure 2.3, this would result in large errors in mooring line load estimation at large offsets from the origin position (when knowledge of the loads is most critical). However, the DGPS system offers the potential for much better accuracy (on the order of 10 centimetre) using multiple references and sophisticated post-processing.

A number of GPS- based systems are now offered that would generate accuracies of a few centimetres at least in the horizontal plane. For example, a Real Time Kinematics package from Trimble, based on a 9-channel Trimble 7400rsi base station on Hibernia would deliver accuracies of about 10 cm or better – depending on the update rate among other things. This type of accuracy would reduce the error in a load inference to a few percent.

If real time accuracy is not required – that is, total load can be calculated from archived data - then software is available to post- process the data to achieve an accuracy of 2 parts per million of the base length – in this case the distance from TERRA NOVA to Hibernia. This would result in accuracies of 7cm.

We have been unable to determine from the documents received, the positioning accuracy currently specified for the TERRA NOVA project, and thus the cost increment associated with achieving the required position resolution. It would seem that major improvements in the positioning accuracy from the DGPS, to achieve that which is desired may be achieved with software or equipment ugrades.

2.5 Integrating Environmental Data

The TERRA NOVA Environmental Condition Monitoring Strategy [Ref. TN-PE-X00-009 Rev. M1] indicates regulatory authorities require that environmental monitoring must incorporate four requirements: weather forecasting, oceanographic monitoring, meteorological observation and monitoring, and ice monitoring. Annual reports are required, with frequent weather observations (3-hour intervals in storm conditions). The specific requirements for offshore installations include measurement of:

- Location and movement of any ice floes or icebergs in the vicinity;
- Wind direction and speed;
- Wave direction, height, and period;
- Swell direction, height, and period;
- Current speed and direction;

- Barometric pressure and air temperature;
- Water temperature;
- Visibility;
- Amount of precipitation;
- Forecast of meteorological conditions and ice movement.

It is also indicated that the hull girder stress and motions of the vessel (roll pitch heave) must be monitored, and the tension in the mooring lines [although it is understood this latter requirement has been waived]. *In addition, it understood the Classification society has requested a "real time" integrity monitoring system for the mooring system.*

Table 2.2 provides a summary of the environmental monitoring scheme for the key parameters affecting global loads, as laid out in the TERRA NOVA strategy document. It is noted that there is a separate system for input of wind direction and speed into the TAPMS DP system, independent of the "Metaocean" equipment package listed in Table 2.2. This would appear to indicate that wind direction (and speed) are used as the main environmental indicators in the DP system, presumably to direct the weathervaning of the unit.

Table 2.2: Summary of Environmental Monitoring Scheme – TERRA NOVA Project

Condition	Parameters Monitored	Measurement Technique	Comments
Wind	Speed and Direction	Wind Speed/ Direction Sensor	Note – independent system for TAPMS
Waves – Environment	Wave direction, height, and period Swell direction, height, and period	Wave Radar	Resolution unknown, technique for resolving waves, swell in multi-directional seas?
Waves – Slam Effects	Bow wave pressure impacts, accelerations	Bow Pressure Sensor and Accelerometer	No specific details (yet) Long term data to be stored
Waves – Hull Girder Loads	Deck strain	Strain gauges - fore, aft, amidships	No specific details (yet) Long term data to be stored
Current	Speed and Direction	Undefined	Acoustic Doppler techniques noted as inaccurate near surface
Sea Ice	Coverage, thickness, floe speeds	Ice Radar System (and Overflights)	Resolution unknown
Icebergs	Size, flux, direction, and speed	Ice Radar System (and Overflights)	Resolution unknown

With regard to the resolution of global loads, the resolution of the wave radar and the ice radar are important and this data should be obtained before a detailed system design is carried out.

It is reported that the Metaocean data (including the stress and load readings) are to be stored for long-term analysis, in a database referred to as the Offshore Production Information System (OPIS). This database is to be implemented by the contractor providing the environmental monitoring services.

The importance of the environmental monitoring system is that it must provide crucial information in order to relate the total global load experience by the TAPMS to the causal components. It will be important to understand the uncertainties in defining the environmental loads (due to winds, waves, and currents) which occur at the same time as the ice, and their distributions. This error source is most critical for evaluating ice-induced loads because it is expected that the other environmental loads must be "backed out" before the ice loads can be determined.

2.6 Measuring Total Load using TAPMS

From the information collected on the TAPMS and the results of the numerical modelling of the mooring system, it would appear that determining accurate total mean global loads from the DP system is viable, provided that:

(1) at least one of the positioning systems employed on the FPSO has sufficient resolution to minimize the error in using the load inference model. This resolution should be on the order of centimetres. *If this type of resolution is not available, then upgrading the position system resolution should become one of the primary options for a load monitoring system.*

(2) the interaction between the thruster system and the mooring system loads is comprehensively understood. This may be sufficiently well understood by the supplier; *alternatively, it might be easily investigated during commissioning trials.*

(3) the integrity of the mooring system is known. Clearly if a line fails or a pile anchor fails the result could be a significant anomaly in the predicted global load, and certainly a significant change in the individual line loads. *More importantly, knowledge of this situation is vital to ensure corrective action is taken before it becomes a serious event.*

If these conditions can be complied with, the design problem then becomes a matter of *understanding the relationship between the total global load and the environmental forces driving the loads*. A comprehensive environmental monitoring scheme has been proposed for the FPSO, and thus there should be extensive data available on wind, wave, current, and ice conditions. The structural response of the hull and bow area is also being monitored.

The key component is a model that can integrate this information and provide the transfer function to develop estimates of the mean loads generated by the various environmental components. The model must be capable of providing load estimates on the order of magnitude of the global load estimate, particularly as the pack ice load (the primary load source of interest) is expected to be very small.

The formulation for equations of motion for an FPSO are well established, as a multiple degree of freedom system (6 DOF of the hull, plus the 3 mooring cables, plus the thrusters). The technical challenges are in establishing the influence of cross-coupling between the various responses, and; (most importantly for this proposal) how measured data can be incorporated into the model, and which parameters to measure.

Further, while such a model may be suitable for deducing the mean loads it must be remembered that the loads deduced from the mooring and DP System response include inertial effects, and in this respect differ from the actual direct instantaneous loads applied by the environment. Accounting for these inertial effects is a complex issue.

In order to be able to perform a dynamic analysis of the FPSO, the following parameters are required:

(1) Tensions in the mooring lines, using one of the measurement techniques described in the following section;
(2) Added mass and damping coefficients, which can be deduced from a conventional seakeeping model that has been calibrated with field data taken from the FPSO;
(3) The FPSO response – displacements, velocities, and accelerations. This can be obtained from a motion package (gyro and accelerometers) to augment their position system, or an enhanced positioning system with processing for velocities and accelerations;
(4) Environmental data related to wind, waves, currents, and ice.

The need for real-time measurements or local instrumentation of the hull structure would have to be assessed. Once the model is defined, the calculations can be performed to obtain the transfer functions to relate the response of the FPSO to a “most probable” loading scenario, and provide an estimate of the applied load.

A number of numerical models have been published for turret moored vessels, and some of these are listed in the Bibliography.

2.7 Calibration

In order to validate any proposed load system, a full-scale calibration is highly recommended. Even if no further upgrades to the proposed system are made, such an exercise would be beneficial in validating load estimates, and it would be most beneficial in “fine tuning” any of the systems proposed later in this report.

Such a full-scale calibration must be carefully planned and executed rigorously. A large Anchor Handling Tug (AHT) or iceberg towing vessel would be used to apply known horizontal loads to the FPSO while measuring and recording all of the information available from the DP system and the position monitoring system. Ideally, the numerical model that relates vessel response to mooring loads should be installed on the FPSO to provide estimates of the mooring/DP loads as the experiment progresses.

The horizontal loads are applied by operating the tow vessel at various power levels and in a range of directions relative to the mooring orientation. The measured results will be calibrated against the calculated results from the numerical model.

During the experiment, all the Metaocean environmental data should be recorded in real time. However, during a series of load increments, assuming the environmental conditions remain relatively constant, they are effectively eliminated from the situation.

The experimental set up would involve a load cell in the towing hawser, and the position and heading of the tow (tug), and data from the tug should be sent by telemetry to the rig for integration with all the other input data.

Once the loads in the mooring system are known, these in turn can be used to calibrate the performance of the thrusters in all combinations and in at all angles.

The cost of such a calibration would be in the order of $150K.

3. EVALUATION OF CONCEPTS

3.1 Overview of Requirements

A requirement of this task was to explore various concepts for measuring total load and load components and to assess these in terms of technological, schedule and cost risk.

The requirements for a system comprise two components:

1. Measurement of the total global load acting on the FPSO;

2. Methods for determining the sources of the load (load components).

In addition, it has been determined that there is an additional requirement associated with any system that utilizes the mooring system:

3. Methods to monitor the integrity of the mooring system.

3.2 Concepts Explored

The concepts explored were:

1. Enhanced position monitoring, the total load is inferred from a catenary model, and thruster interaction model.

2. Inclinometer tubes on the mooring lines – the loading can be deduced from the angles of the mooring lines. A system response model is required to determine the global loads from the measured mooring line angles.

3. Tension links in the mooring lines –This is the most direct method. However, it is also the most obtrusive because the tension link will thus become part of the load path. Furthermore, it requires that the existing mooring lines be rolled up, cut, fitted with tension links, and then re-deployed, a situation the TERRA NOVA operator has said is not acceptable. Options for retrofitting must be considered

4. Instrumented turret connector or supporting structure – the degree of success for this approach will be primarily governed by the redundancy and complexity of the structure, and the accessibility of this structure. A global finite element model of the FPSO structure would be developed, as well as local models of the support structure, in order to understand the response of the structure under various loading and to develop a mooring/structure transfer function. A calibration of the system would be required.

Combinations of these are also possible.

These options are assessed qualitatively in **Table 3.1**. The risk is assessed qualitatively on a scale of 1 to 5 where 5 is the highest risk and 1 is the lowest risk.

Table 3.1: Options Assessment

CONCEPT		RISK			
#	Name	Tech	Sched	Cost	Overall
1	Enhanced Position	2	2	2	2
2	Pressure Sensors in Mooring lines	2	3	2	2.3
3	Mooring inclinometer	2	3	3	2.6
4	Tension Links	3	4	4	3.7
5	Instrument Turret	4.5	5	5	4.8

After a brief assessment of the configuration and risk associated with Option 5, it was deemed too high risk and cost and was not considered further. Instrumenting the turret does not lend itself to a retrofit situation.

The option to improve the positioning information is a relatively low-cost and satisfactory option, and will be considered in some depth in the next section.

While Option 3 has been eliminated by the operator as the moorings are already in place, it was decided to leave this option in the discussion until it was clear that it had unacceptable costs and risk, and so it is discussed in the next section.

3.3 Discussion of Options

The options are summarized in **Table 3.2** and discussed below.

3.3.1 Option TN 001: Enhanced Position Monitoring and Thruster Data

In this option, the proposal is to enhance or consolidate the existing systems for position monitoring of the vessel and for monitoring the thruster performance. Combined with an accurate model of the mooring *and the risers*, a load estimate can be made.

The issues in this option are:
- Ensure that all position and thruster parameters are captured on a common well-documented time base.
- (If required) add sensors and data channels to track the torque, RPM, and azimuth angle of each thruster on the above mentioned common database
- Select an independent and widely accepted quasi–static mooring line response program, and ensure that the effect of the risers is modelled as well as the moorings, and

Ensure that the database is supplemented by final surveyed weights, dimensions and anchor positions for use in the mooring model(s).

Table 3.2: Mooring Monitoring Options

Concept Number	Measurement Concept	Concept Description	# of Ch.	Estimated Cost to Retrofit (Subsystem Installed and Commissioned)	Impact on Global Load Precision (0-10)	Comments	Installation Issues
TN001	Enhanced Position Data	Improved Position resolution with full thruster data and valid mooring program	?	<$200,000 CAN	6	Detailed knowledge of existing system and planned thruster measurements is needed before an accurate estimate of $ can be made.	Minimal impact
TN002	Line Pressure Sensor	Pressure sensor in mooring lines and acoustic Tx.	9	<$300,000	3	Monitors integrity only and contributes to load calcs only by virtue of reporting line status. Inaccurate measure of line configuration	Requires diver or ROV
TN003	Line Inclination	Diver Clamp Inclinometer Bottle on Buoy Pendulum Inclinometer Arm-hardwire through moonpool	9	$350,000 CAN	6	Improves estimate of mean static load only-immediate assessment of line integrity-assumes umbilicals can be run through centerwell.	Must run umbilicals through buoy center well-unless extraordinary design effort must replace umbilicals after emergency disconnect.
TN004	Line Inclination	Wireless, ROV/Diver deployable chain inclination system	9	$750,000 to $1,000,000 CAN	5	Improves estimate of mean static load only-immediate assessment of line integrity-eliminates any interface with Spider Buoy and umbilicals but provides periodic data.	Can be done without retrieving chain
TN005	Line Tension and Inclination	Wireless, Diver/ROV Deployable extensometer/inclinometer on 3 lines	6	$750,000 CAN	9	Provides Static Tension and dynamic statistics on tension and line inclination on demand for each line group-good redundancy with chain angle and tension.	Chains must be retrieved to water surface, cut and link inserted.
TN006	Line Tension and Inclination	Wireless, Diver/ROV Deployable extensometer/inclinometer on 9 lines	18	$1,200,000 CAN	9	Provides Static Tension and dynamic statistics on tension and line inclination on demand for each line – good redundancy with chain angle and tension-no umbilicals.	Same X 3
TN007	Line Tension	Strain Gauged Chain Shackle and connecting Link with umbilical	9	$950,000 CAN	8	Realtime-dynamic estimate of line tension-no chain angle.	Chains must be retrieved to water surface, cut and link inserted.
TN008	Line Tension and Chain Inclination	Combination of TN005 and TN001	18	$1,300,000 CAN	10	Realtime Dynamic Line tension and chain inclination-good level of redundancy.	

3.3.2 Concept TN002: Pressure Sensors on Mooring lines

The requirement for mooring line integrity modeling can be addressed by fitting pressure sensors to the mooring lines. This system requires clamping the pressure sensors onto the cable by diver or ROV, and the data is transmitted by an acoustic link. The data from pressure (*depth* of the mooring beneath the wave surface at the point of measurement) is not sufficiently accurate to permit the determination of the mooring configuration for use in the load model. While the basic sensor is relatively inexpensive compared with others mentioned herein, the installation effort is about the same, requiring divers or a ROV and an acoustic link.

3.3.3 Concepts TN003 and TN004: Monitor the Mooring Line Inclination

The accuracy of the total load estimation can be greatly increased if the *inclination* of each mooring line is monitored. A concept based on equipping each mooring line with an ROV or Diver deployable subsea biaxial inclinometer with either a hard wired umbilical or an Acoustic Link (**Figure 3.1**) should be considered. The time history of inclination of the chain provides an estimate of the tension in each line and the direction of the load vector. The sensitivity of this inclination angle to mooring line tension **(Figure 3.2)** indicates between 100 and 200 tonnes per degree of inclination. For an accuracy of 1% on a nominal working load of 1000 tonnes (10 tonnes) and inclination angle accuracy of 0.05 degrees, which is easily achieved with a high quality, quartz flexure, servo accelerometer in conjunction with a 12 bit A to D converter. More information about an existing system of this type system is provided in Appendix C that describes a wireless, subsea, inclination and vibration measurement unit (VISMU). For the TERRA NOVA FPSO, these units would be stripped of the angular rate sensors but in other respects would remain the same. They have been successfully deployed for Petrobras in the Campos Basin and have demonstrated inclination resolution of better than 0.01 degrees.

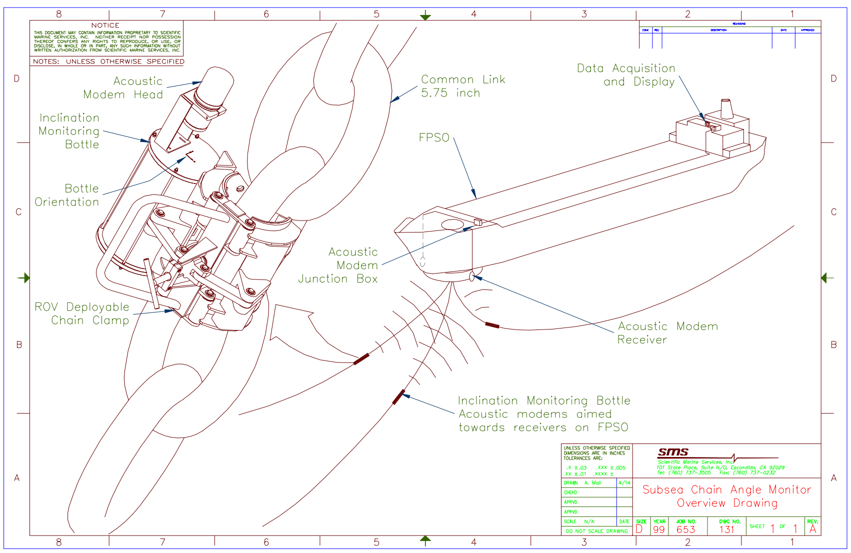

Figure 3.1: Sketch of Wireless ROV Attachable Chain Inclination Monitor

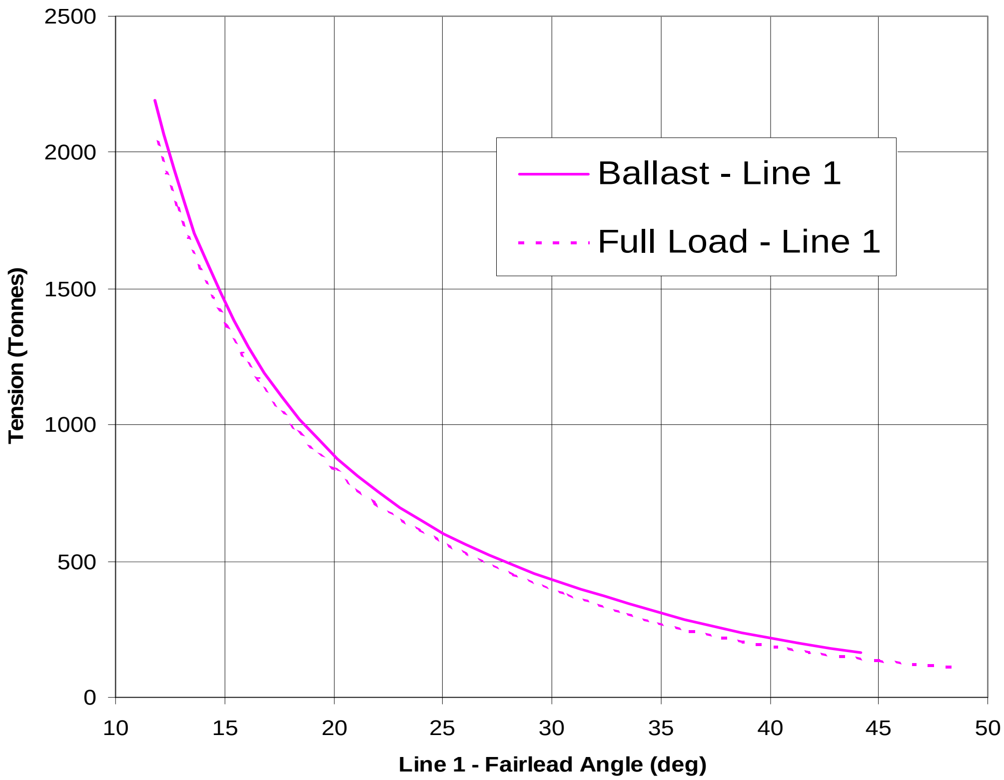

Figure 3.2: Line Tension versus Fairlead Angle

3.3.4 Concepts TN005 and TN006: Monitor Line Strain and Inclination Angle:

Direct measurement of line load can be achieved by partially retrieving each mooring chain and inserting a subsea tension-measuring device. This device can be equipped with either a hardwire umbilical (difficult to retrofit) or an acoustic communication link.

One option could be a link connected by shackles into the mooring chain. The link can be equipped with an extensometer that can be removed by a diver for replacement. The batteries and acoustic link can also be diver serviced. A similar subsea pressure balanced oil filled extensometer presently is installed in the Persian Gulf (see **Figure 3.3**).

3.3.5 Concept TN007: Gauged Shackle

A less expensive option than the subsea extensometer would be the insertion of a submersible-instrumented chain shackle. This approach is shown in **Figure 3.4**. Similar units were recently used to provide an Anchor Leg Load Monitoring System for the Espadarte FPSO in the Campos Basin of Brazil. The instrumented shear pins can be made very resistant to water intrusion during long term immersion to depths in excess of 100 meters.

Figure 3.4 illustrates an option with a diver deployable and retrievable acoustic communication module. The acoustic package data storage unit and battery module can be serviced periodically and replaced without retrieval of the chain, but the instrumented link can only be replaced by retrieving the mooring chain to the deck of an Anchor Handling where the shear pin can be replaced. Both battery-powered acoustic links and a hard wire umbilical would be investigated.

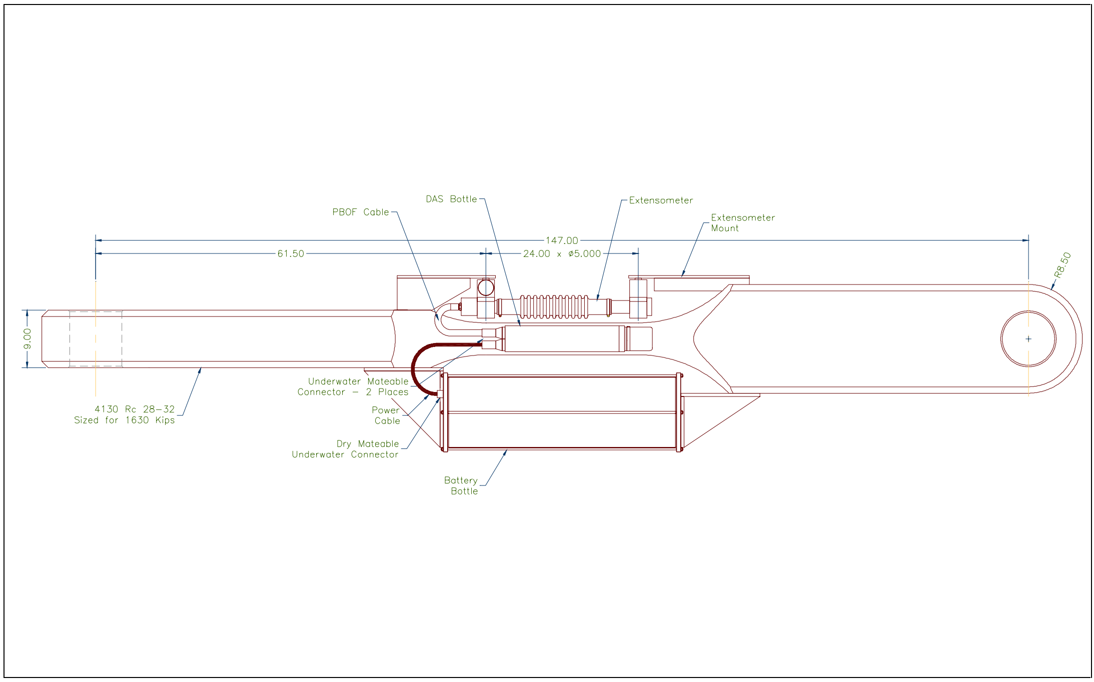

Figure 3.3: Pressure Balanced Oil Filled Subsea Extensometer

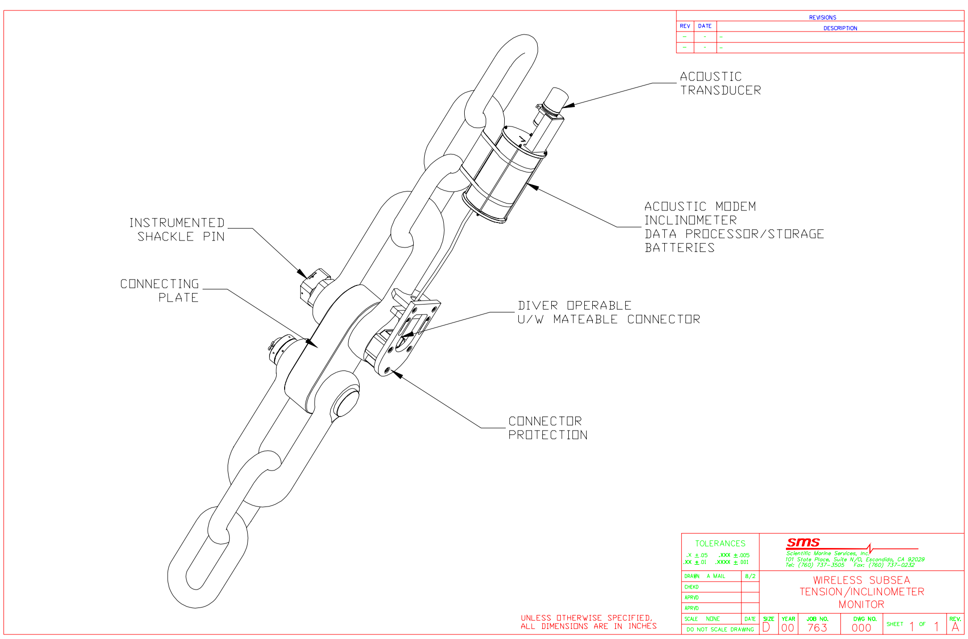

Figure 3.4: Wireless Instrumented Shackle and Inclinometer

3.3.6 Concept TN008 is a combination system of the instrumented shackle and the inclinometer. Since the infrastructure required to process the strain gage signal, store them and send them on demand to the surface will exist for the wireless approach, the addition of the measurement of inclination will result in a nominal cost per mooring line of $79,500 CAN

4. MEASUREMENT OF LOAD COMPONENTS

4.1 Overview

From the foregoing and the results reported in [1], it is concluded that it will be possible to infer the (total) global loads acting on the FPSO using accurate measurements of its displacement, in combination with a numerical model for interpreting the system response of the mooring lines and the thruster units that comprise the TAPMS system.

In addition, the system for measurement of the total global load should be augmented by:

(a) A line integrity monitoring scheme. It is essential that if the loads are to be inferred from the displacement of the unit, that the condition of the mooring system be known. Several candidates have been identified and costed in the previous section.

(b) A method for determining vertical displacements if a high resolution DGPS system is implemented. This could be via a vessel motions package, or using some of the more recent innovations in DGPS Processing (e.g., Ref [2]).

The second requirement for determining the sources or *components* of the total load (e.g., waves, ice, wind), poses a number of significant technical problems, and thus higher risk to the project.

Direct measurement of load components was ruled out early in the project. For example, direct measurement of ice loads on the hull would require a very elaborate sensor system and would provide results of very limited accuracy. While there is a system for measuring strains on the bow and stern of the FPSO, this system provides monitoring of the behaviour of the structure locally to ice or wave loads, and it is not readily used as part of a total ice load monitoring system.

Options for determining the load components are therefore:

(1) *Calculate* those loads for which reliable numerical models are available, based on the real time input of environmental data. In this case, in the absence of a good pack ice model, the loads from the pack ice would be calculated by subtracting the calculated load components from the measured/calculated total load. The presence of pack ice and its velocity could be determined from a video camera and an upward looking sonar. This is the approach set out in overview in **Figure 4.1**, and schematically in **Figure 4.2**.

Assuming that the load components (wind, waves, current, ice) are applied with differing period characteristics frequency), an adaptation of this approach may be to develop a methodology for breaking out the total load component into its frequency components, and deduce the source of the loads in this way.

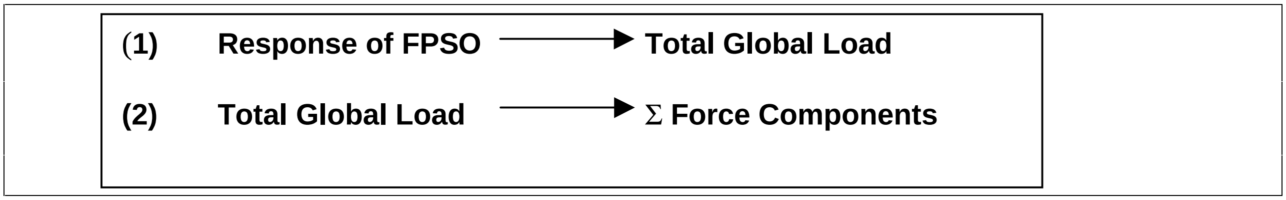

Figure 4.1: Overview of Concept 1 for Load Components

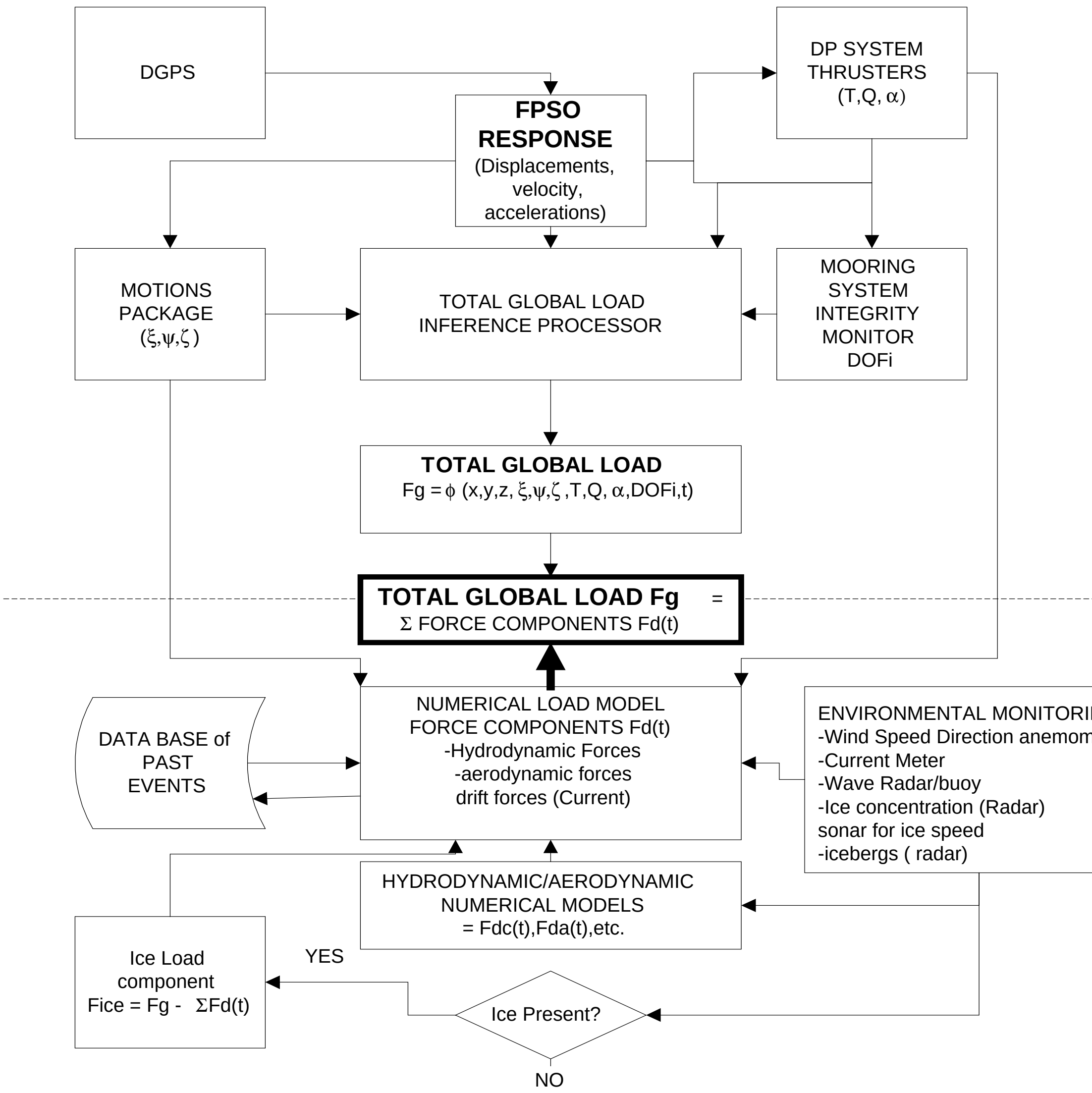

Figure 4.2: Schematic of Concept 1 Approach

(2) *Deduce* or *infer* the load components from the known environmental conditions and the actual response of the vessel using an adaptive database technique in which the experience of the rig is used to deduce the loads that are on it.

This technique does not rely on computations of hydrodynamic and aerodynamic drag forces, but instead depends on the build up of an experience base in an intelligent database that can relate the response of the system to the prevailing environmental conditions. This database is constantly updated and "adapted" to the experience gained from the measured data.

The principal of the load component inference is as follows:

IF $F_{g1} = X_1$ when (Vessel location = x_1, y_1, and Wind = V_{w1}, α_{w1}, and Current = V_{c1}, α_{c1}, Thrusters = T_1, α_1, and "Ice present?" = "NO"….etc
AND
$F_{g2} = X_2$ when (Vessel location = x_1, y_1, and Wind = V_{w1}, α_{w1}, and Current = V_{c1}, α_{c1}, Thrusters = T_1, α_1, and "Ice present?" = "YES"….etc.
THEN
$F_{ice} = F_{g1} - F_{g2}$

With this concept, some initial "priming" of the system would be required before the experience-based database was "populated". In this regard, the concept is similar to the first concept with more emphasis being placed on the use of the database and its update. The concept is shown in **Figure 4.3.**

4.2 Calculation of Load Components

4.2.1 Wind Loads:

The calculation of mean load on the vessel due to wind is relatively straightforward, provided that the mean wind direction and speed are known. A number of models are available. Wind tunnel tests are typically used to determine drag coefficients experimentally. In reality, of course, the wind is varying with time, and some processing of this data to obtain the relevant mean parameters to feed into a model would be necessary. In addition in extreme conditions in particular, the wind vertical profiles become important, and are affected by the wave surface profiles, and are less easily determined from modeling. These factors introduce errors in the processing.

4.2.2 Current Loads

The calculation of current loads using established mathematical models , while appearing to be straightforward, is more problematic given the knowledge of the actual prevailing current and its profile. Depending on the scope and location of current measurement, the data needed to achieve an accurate assessment of current load (drag) may be absent.

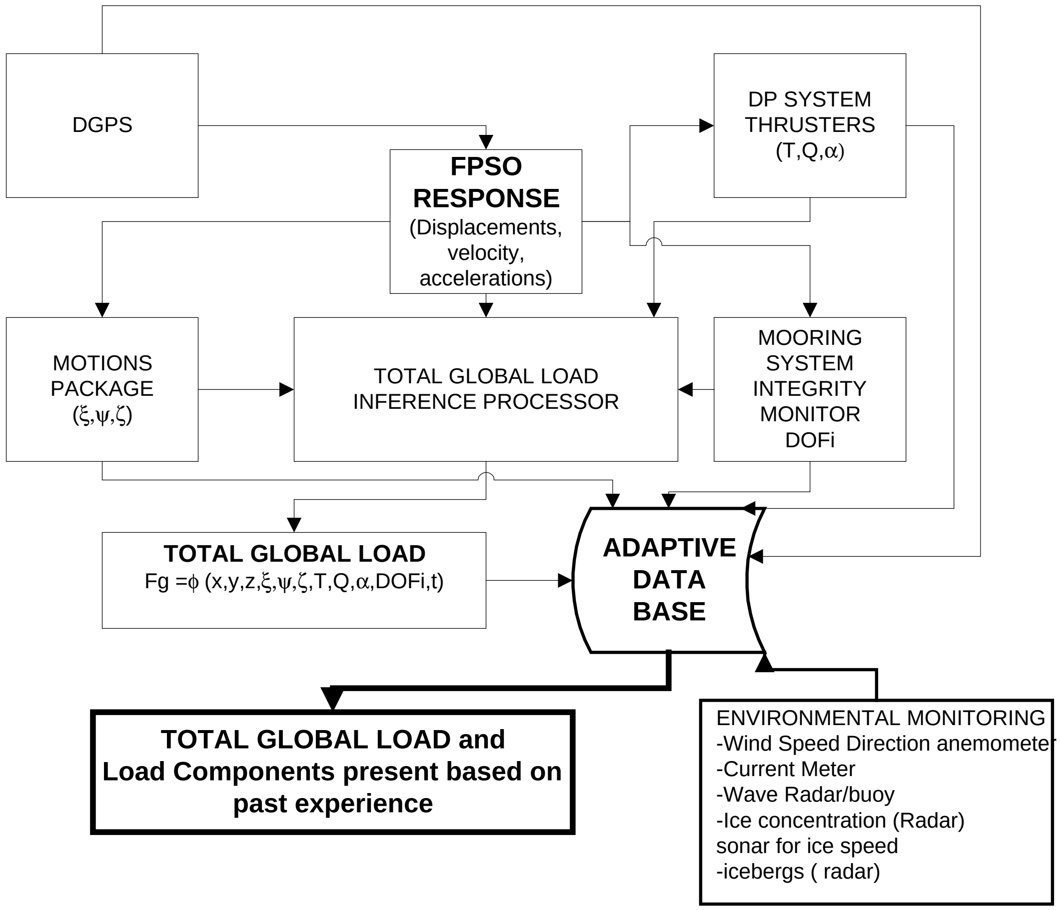

Figure 4.3: Adaptive Database Concept

4.2.3 Wave Loads

Waves have the potential for generating the largest loads by far on the vessel. It is beyond this study to calculate the relative magnitude of the load components but it is known that this data is available from model tests, etc. Wave loads will come in the form of wave drift forces and peak loads from waves. In this configuration, with a stiff mooring and relatively shallow water, the peak loads will be of significance and the performance of the thrusters to respond to the peak wave loads is crucial.

Using radar and/or wave buoys, the waves impinging on the vessel can be measured, a ship motions package could measure the vessel response and software is available to calculate the loads being generated on the system. Time domain and frequency domain models are available. Again there is a range of accuracy in these models as discussed in the following.

In deep water, with no current, relatively small waves and a conventional tanker-type hull, mean wave drift forces can be predicted within 10-15% using conventional second-order equations and first-order 3D wave diffraction theory. However the level of accuracy gets a lot worse (and the numerical models generally seem to underestimate the forces) as the waves become higher and steeper, if there is a strong current, if there are rapid changes in the water plane or the water is shallow.

High waves, and particularly steep waves, invalidate the assumptions of first-order wave theory and second order wave drift force theory. The calculations are likely to be unreliable if the peak period of the wave spectrum lies close to the rapidly-rising part of the drift force transfer curve. Large pitch motions, when the natural period is close to the peak spectral wave period, can substantially increase the wave drift force. A highly flared bow can cause rapid changes in the cut water plane, again invalidating the theory and substantially increasing the forces.

The presence of a strong current can have a major effect on wave drift forces. Empirical procedures exist for correcting forces predicted in the absence of a current, and have been claimed (at least in certain circumstances) to agree well with results obtained from theoretically more complete models.

There are further problems in shallow water:

Linear airy wave theory becomes invalid when the wave height becomes a large part of the water depth. The waves may be breaking or broken, completely invalidating any theoretical model. There are further problems when predicting low-frequency and maximum forces, including:

- Most commercial programs use the Newman approximation (based on mean forces at the mean frequency) to calculate low-frequency forcing. This procedure may not be satisfactory when the wave period is long. Some software offers the full quadratic transfer function method, but numerical accuracy and computational times can become problems.
- Most commercial programs ignore second-order wave hydrodynamics when calculating wave drift forces. This component is also likely to become more important if the wave period is long and the water is shallow.
- Uncertainties in the damping and non-linearities in mooring stiffness have a major influence on the maximum response.

In shallow water there are questions surrounding set-down, edge waves and other non-linearities caused as the waves come from deep water into shallow water.

Therefore the use of theoretical models for estimating wave drift forces and mooring forces in severe wave conditions in shallow water is not recommended. If such a model is used, uncertainties of 100 to 200% (or more) in the predicted loads may be expected. Any such predictions should be carefully validated by model tests or full scale measurements.

4.2.4 Ice Loads

In the absence of an ice loading model, the ice loads will either be calculated by subtracting the total of other calculated loads, based on measured environmental data, from the total load as calculated from the vessel position and mooring system, or will be inferred from the current prevailing conditions and an adaptive database. In the former case, it is required to calculate a relatively small number from the difference between two numbers that could be quite large, and one of which has an error possibly in the order of 5% - leading to an unreliable ice load estimate.

In the latter case, the ice loads are being inferred from all the conditions prevailing, and the accuracy will grow as the experience base grows.

In practice, a combination of these two methods may be desirable.

4.2.5 Inertial Effects

As noted earlier, the difference between the loads assessed from vessel response, and the actual applied loads which would be measured directly, if this was possible, would be accounted for by the dynamic or inertial effects. The calculation of load by the above methods assumes an equilibrium state that may not exist. The response time of the vessel and the mooring is ignored. While the use of accelerometers to determine the transient components is possible, this in turn introduces the inaccuracies associated with the assumed inertia of the vessel and mooring, etc. The solution is to take a medium term approach to the measurements and the load calculations, and to base the analysis on mean loads.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

(1) Total load can be derived from the position of the FPSO and the status of the thrusters, through the use of a mooring model and an algorithm for estimating total thruster forces and moments. However, in view of the sensitivity of the mooring system load/ position relationship, particularly at large offsets, significantly improved accuracy of the positioning monitoring system over that stated as the current target will be required.

(2) Determining the load *components* and their cause is a much greater challenge, particularly in the case of ice loading, for which there is no universally accepted model.

(3) Mooring integrity should also be monitored for safety of operations and in order for any load prediction system to be valid. Non-intrusive mooring monitoring can be achieved with currently available and proven wireless inclinometers that also provide enhanced estimates of mooring forces on the FPSO.

(4) A number of alternatives for achieving the desired goals have been explored, and a number of recommendations have been made with approximate costs and technical risk identified, to meet a range of budgets. The requirements for the required system are:
- Improved positioning measurement
- Direct monitoring of mooring lines
- Development of numerical transfer functions relating TAPMS, DP System, environment and ship position.

5.2 Recommendations

The following actions are recommended:

(1) The GPS positioning system proposed for the TERRA NOVA FPSO should be reviewed for its performance. Using actual data, a study should be performed to determine the degree of accuracy achievable with the proposed system and with the addition of post-processing software.

Est. cost $15K

(2) If necessary and the above does not provide adequate accuracy of position, select equipment upgrades to provide positioning accuracy of 5 –10 cm. It is recommended that a GPS expert be retained to review the current specs and proposed equipment and offer a cost effective solution to ensure that the higher level of accuracy is achieved.

Est. cost: $25K-$80K

(3) Review and select an adequate and available quasi-static mooring model. This should be run with the most accurate information concerning the mooring system, and should include the effect of the risers, to develop the relationship between the mooring response – at all ship orientations – and the applied loads.

Est. Cost $50K

(4) Design and install procedures and possibly equipment to store the propulsor parameters on the Global Load Database

Est Cost $20K-$50K

(5) Review the plan to fit pressure sensors on the chains for integrity and determine if the additional cost of fitting inclinometers warrants this improved system which will provide load information.

Est. Cost. $10K

(6) Wireless inclinometers should be specified for all 9 mooring lines to provide the necessary integrity monitors and to improve the total load computation.

Est. Cost >$750K Can.

(7) A software requirements document should be produced that identifies the functional, data and calculation requirements and algorithms for a software package to determine the total and components of load from the available data. This requirements document will establish the basis for the review and selection of software tools to calculate loads, etc. (see next Recommendation).

Est. Cost $25K-$40K

(8) A detailed review of the software tools available for predicting the mean environmental loads on the FPSO (wave drift, current, wind and- if available – ice) should be made and a selection of those to be used should be made based on the evidence of validity, availability, etc. This will require a detailed review of the real time environmental data that is to be monitored to determine its suitability. These models should be acquired and a software suite developed to integrate these for real time onboard use, along with the load/ mooring model results.

Est. Cost. $150K-$250K

(9) A full-scale calibration of the FPSO System should be planned for execution after installation. Since this will require some significant planning and logistics effort, it should be commenced as soon as practicable.

Est. Cost $150K-$180K

6. REFERENCES AND BIBLIOGRAPHY

6.1 Specific References

[1] FTL 5101 Interim report, dated 31st March 2000

[2] Gale, S.: "*High Accuracy, Real Time Position Monitoring" International Ocean Systems Design*: Vol 3 No 5 Sep/Oct 1999.

6.2 Bibliography for Numerical models for turret-moored and related systems

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APPENDIX A

LIST OF DOCUMENTATION PROVIDED BY THE TERRA NOVA ALLIANCE

List of Information provided for the project: "Techniques for Measuring Global Loads on the TERRA NOVA FPSO" - 21/3/00.

(1) Environmental Conditions

- Predicted ice conditions at the site, including pack coverage, estimates on pack ice speed
- Engineering data for wind, wave, and current conditions

Documentation Received:
Grand Banks Ice Management Plan
Design Environmental Criteria

(2) Environmental Monitoring Plan

- Monitored parameters
- Measuring techniques
  - Details on monitoring instruments, location on FPSO (or from supporting resources)
- Procedures/linkages for distributing the information

Documentation Received:
Environmental Monitoring Plan

(3) FPSO Information

- Particulars of the vessel (dimensions, loading conditions – we have a pre-construction data book only) - X
- FPSO lines plan – X Capacity Plan, GA
- Design ice criteria for the structure - X
- Hydrodynamic data from numerical and/or model tests (and/or RAO data)
- *General Hull structural data (shell expansion, frame expansion or sections) - X*
- Turret and associated support structure – X (not interface)
- Spider buoy and connection details (drawings etc.) - X
- Riser connection details and drawings - X

Documentation Received:
Ship Spec
Ice Strengthening Spec
Drawings – indicated by X
Also: Stability Booklet /Capacities/Load Condition

Requested: IMD Reports (have pack ice report – need iceberg impact study)

(4) Mooring System

- As installed Mooring System Drawings (Chain Weights, Lengths, Common Link Specifications, Chain Shackles,-- all components of the mooring system in sufficient detail to establish the weights, elasticity and lengths of all components) - X
- Details of mooring arrangement including number and orientation of mooring lines. - X
- Type of mooring lines, length, breaking strength - X
- Anchor particulars including type, dimensions, strength etc. -X
- Details of chain connections in the mooring lines, particularly where the three ground chains are connected to the single chain - X
- Details of the mooring system drag chains - X
- Details of chain connection to the turret buoy; Detailed drawings of the chain stoppers on the turret buoy (identify x, y, z location of stoppers) - X
- As installed survey of the anchor points (x, y, z) - X

Documentation Received:
Drawings – indicated by X
Also: Stability Booklet /Capacities/Load Condition

(5) Dynamic Positioning System -

- Thruster information, including: estimated developed thrust, thruster performance plots (Kt-J plots or equal); thruster performance polar plots- including estimates of blockage effects
- List of all DP parameters which are measured and recorded (thruster RPM, Current , voltage and azimuth)
- Details of response time, control limits for activating DP system
- Details of the (three) positioning systems, including location of units on the FPSO.

Documentation Received:
Some unattributed hydrodynamic and power/electrical performance data from various sources.

Other References:

SNAME AGM'97 – General information papers
TERRA NOVA Web site

APPENDIX B

MODELLING OF THE MOORING SYSTEM

A numerical model of the TERRA NOVA FPSO mooring system was developed to analyse the sensitivity of the inferred mooring load to errors in the positioning system. The objective of this study was to determine the discrepancies in the total mooring restoring force between the actual force and that derived from the measured offset of the vessel.

The estimation of the mooring forces from vessel offset depends on several factors. In this study, only those discrepancies produced by an error in the measurement of the offset were analyzed.

The 9 lines spread mooring system was analysed for two vessel conditions:

- Ballast Draft: 12.69 m
- Full Load Draft: 18.56 m

Both cases were analysed in 95.2m depth of water with STATMOOR, a static mooring line model employed by SMS for this type of analysis. This particular model has been extensively validated using model test results.

The number of possible combinations of offsets and directions was very large. It is beyond the scope of this study to fully characterise total restoring force discrepancies due to vessel location errors for every possible location of the vessel. However, a preliminary assessment was performed by examining two limiting conditions:

1. Vessel offset in the direction of one of the central lines in a three-lines cluster (i.e., mooring line 1, 4 or 7);
2. Vessel offset in a direction bisecting the 120 degrees angle between the central lines of any of the three-line clusters (i.e., between 1 and 4, 4 and 7 or 7 and 1).

The stiffest configuration for the mooring system is defined by offset directions corresponding to first condition (item 1) above, whereas second condition is expected to define the softest mooring system response. Total restoring force discrepancies for any other offset-direction combination is bounded by these two conditions.

For each of the limiting conditions, the derivative of the total restoring force of the mooring system with respect to the offset was computed. These derivatives represent the rate of change of force per unit length (metres) of displacement in those directions. These derivatives are then indicative of the order of magnitude of the discrepancies between actual and derived forces due to an error in the measurement of the vessel position relative to the equilibrium position (zero offset).

The mooring system modelled was representative of the "as installed" configuration with the exception of the lines' orientation which corresponded to the design configuration. **Table B.1** shows mooring lines characteristics as modelled. Orientations are relative to True North. Lines lengths and chain diameters were obtained from SOFEC drawing No. 0929-AL-02-01 and No. 0929-AL-02-02. The chains' effective weights (weight in water) were derived according to:

chain effective weight = (D^2*0.0195)*(1-1.026/7.85)

where D = chain diameter in mm. The effective weight per unit length of the excursion limiter chain was determined by computing the total effective weight of the excursion limiter load chain plus the total effective weight of the ten load chains attached to it, divided by the length of the excursion limiter load chain.

The tension-elongation relationship used for each segment was linear and defined by:

elongation = 1/[E][A] * tension

E = Young's Modulus and A = Area, all in metric units

For the Ballast Draft (12.69 m) and Full Load Draft (18.56 m) conditions, the depth of the fairleads relative to the water surface was determined by adding the vessel's draft and the distance between the keel of the vessel and the fairlead. The latter was obtained from SOFEC drawing No. 0929-BS-05-01 (1600 mm = 570 mm + 1030 mm) where elevation 0 coincides with the keel of the vessel.

Table B.1: Mooring Lines Characteristics

LINE	LINE HEADING (DEG)	INDEX	LENGTH (M.)	COMPOSITION	NOMINAL DIAMETER (MM)	EFFECTIVE WEIGHT (KGW/M.)	ELASTIC COEFF. (MTON^-1)
1	108	SUBLN 1	595.8	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
2	106	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
3	350	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
4	348	SUBLN 1	595.8	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
5	346	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
6	230	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
7	228	SUBLN 1	595.8	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
8	226	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06
9	110	SUBLN 1	580.4	ground chain	146.05	374.6	8.03E-06
		SUBLN 2	114.3	exc. limiter	158.75	1294	7.50E-06
		SUBLN 3	100.2	upper chain	146.05	374.6	8.03E-06

Therefore, the fairleads depths were 14.29 m for the Ballast condition and 20.16 m for the Full Load condition. The fairleads are located on a 10 m radius on the buoy and with orientations as shown in **Table B.2**

Table B.2: Fairlead orientations relative to Line 1.

Line	Angle (deg)
1	0
2	15
3	105
4	120
5	135
6	225
7	240
8	255
9	345

Table B.3 summarises the equilibrium parameters for the Ballast and Full Load conditions for all mooring lines.

Table B.3: Summary of Mooring System Equilibrium Parameters.

Parameter	Ballast	Full Load
Anchor to Fairlead Height (m)	80.9	75
Anchor to Fairlead Distance (m)	785.0 (1, 4, and 7) 769.6 (all others)	784.5 (1, 4 and 7) 769.0 (all others)
Unstretched Suspended Length (m)	160.1	135.5
Total Tension (metric tons)	165.03	111.5
Horizontal Tension (metric (tons)	118.34	74.24
Vertical Tension (metric (tons)	115.02	83.19
Declination Angle (deg)	44.2	48.3

A mooring analysis was performed for an offset direction aligned with mooring line 1 and another for an offset direction bisecting the 120 degree angle between lines 1 and 4.

The offset interval was set every 2 meters stepping up from the equilibrium position until the breaking strength of the most exposed mooring line was reached.

The derivative of the total restoring force of the system was computed next. The derivative is the rate of change (Δforce) per unit displacement (metre) and is indicative of the error to be incurred in the estimation of the total restoring force if the location of the vessel, as determined by the positioning system, differs from the actual along the offset direction.

Figure B.2 shows the total restoring force of the mooring system for offset direction aligned with mooring line 1 (+ve offsets) and offset direction bisecting angle between lines 1 and 4 (-ve offsets), for ballast and full load drafts. It can be seen that the Ballast draft configuration exhibits slightly higher forces than the Full Load configuration. In addition, the mooring system is the stiffest for offset directions aligned with mooring lines 1, 4 or 7 (i.e., the slope is steeper).

Figure B.3 shows the rate of change of total restoring force (Δforce) per metre of offset in the direction aligned with mooring line 1 (+ve offsets) and offset direction bisecting angle between lines 1 and 4 (-ve offsets), for ballast and full load drafts.

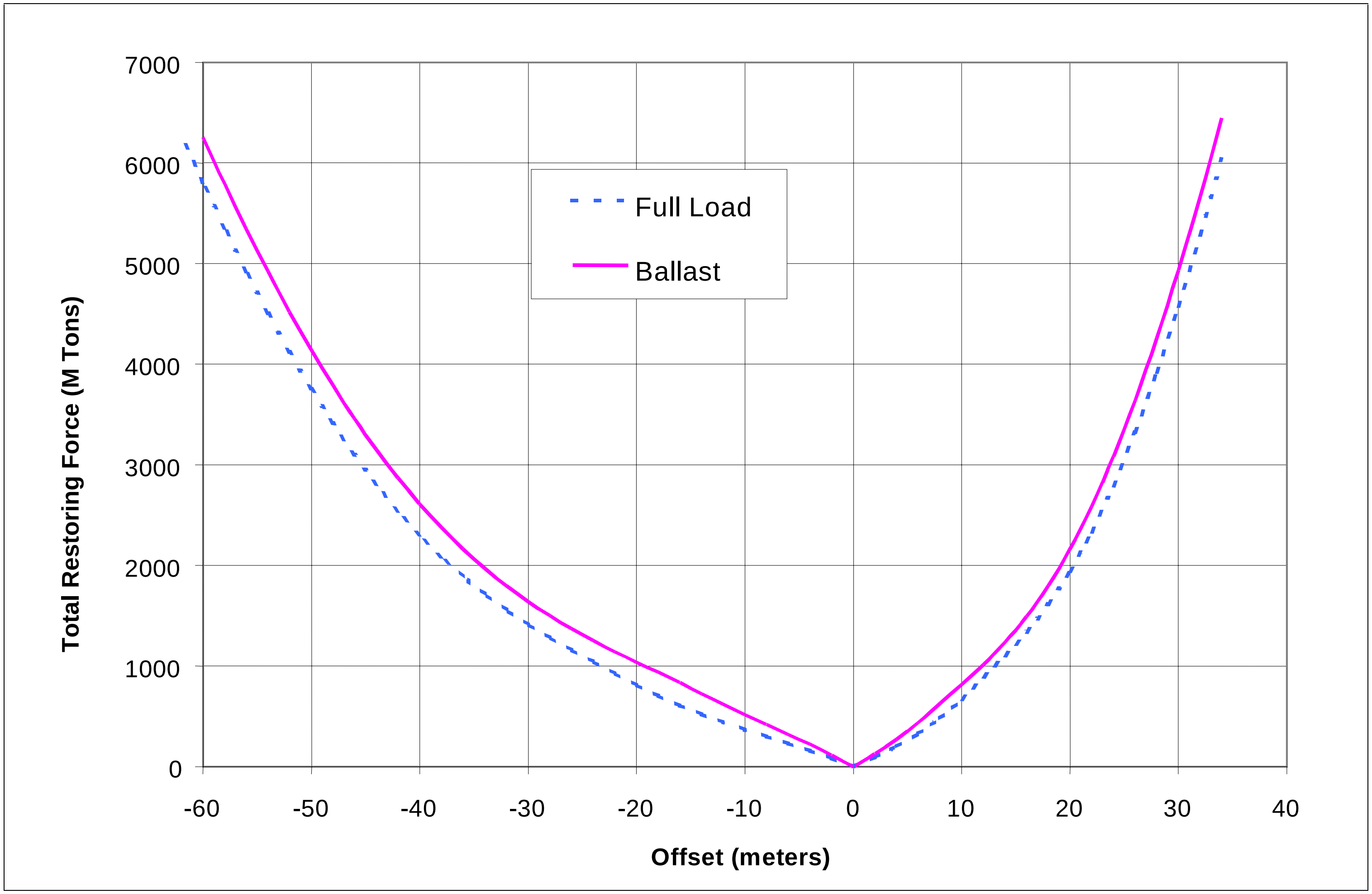


Figure B.2: Total Restoring Force for Offset Direction Aligned with Mooring Line 1 (+ve Offsets) and Offset Direction Bisecting Angle between Lines 1 and 4 (-ve Offsets), for Ballast and Full Load Drafts

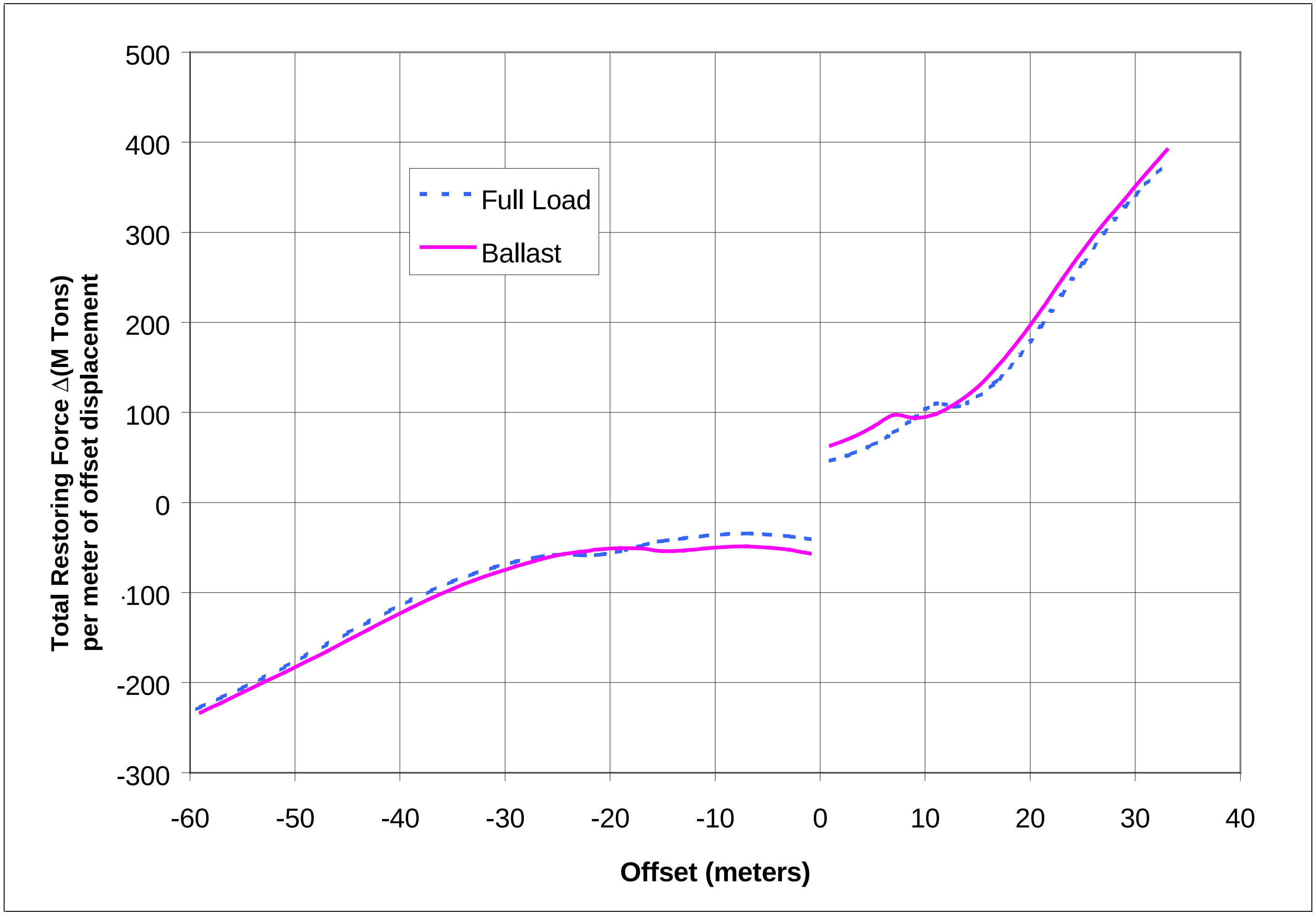


Figure B.3: Total Rate of Change of Restoring Forces (ΔForce) per Metre of Offset, in the Direction Aligned with Mooring Line 1 (+ve Offsets) and Offset Direction Bisecting Angle between Lines 1 and 4 (-ve Offsets), for Ballast and Full Load Drafts

APPENDIX C

SUBSEA WIRELESS INCLINOMETER BASED MOORING LEG TENSION AND HEALTH MONITOR

C.1 BACKGROUND

The Mooring System for the Terra Nova FPSO is installed. It may not practical to retrieve and cut the mooring chains to install a direct tension measuring device. However, it is possible to estimate the tension in each mooring leg by measuring the inclination of the chain and transmitting the inclination measurement to the FPSO. This can be accomplished with either a diver deployable or ROV deployable system. The following sections describe an ROV Deployable, wireless, subsea chain inclination measurement system.

C1.1 Resolution of Tension Derived from Chain Inclination

The program STATMOOR, a static catenary mooring analysis was used to estimate the relation ship between the global load on the FPSO and the chain inclination. The STATMOOR program is configured only to track the angle at the “fairlead”. In practice, an inclinometer installed after the chain installation is complete would be some distance below the fairlead on the disconnectable buoy. However, this should not affect materially, the sensitivity analysis which follows.

Figure C.1 shows the relationship between tension in any of the Terra Nova mooring chains and the angle of inclination. Figure C.2 is a plot of the derivative of the tension with respect to inclination versus tension. It can be seen from these two plots that the sensitivity of line tension to inclination ranges from 100 to 200 tonnes per degree in the normal operating range of the mooring system. For an accuracy of 1% of the normal working load of 1000 tonnes which is 10 tonnes an accuracy of 0.05 degrees is required. This is the equivalent of 0.0008726 g’s. This accuracy can be achieved easily with a quartz flexure, servo accelerometer in conjunction with a 12 bit A to D converter.

With the estimated change in position (accuracy 1.5 meters), the measured inclination and inferred tension, it will be possible to estimate the horizontal components of load exerted by the mooring system on the FPSO with an accuracy of approximately 1-2% of the working capacity of the system.

C.2 SUMMARY OF THE INCLINOMETER BASED LINE TENSION ESTIMATOR

(See Figures C.3 and C.4)

9 sensor "Mooring System Health Monitor". This version of the SMS subsea vibration and inclination subsea measurement units (VISMU) has the angular rate sensors eliminated. Each of the nine units contains the following:

- Bi-Axial Accelerometer
- 12 bit, low power a to d converter with 8 pole butterworth antialiasing filters
- Low power microprocessor linked to a low power, intermediate distance , acoustic modem
- 108 alkaline batteries
- Subsea Pressure Housing

Clamp Components

- ROV Operable Clamp (Attaches the Subsea Pressure Housing to the Parallel portion of the common link)

Topside Components

- We have assumed an industrial installation in a 19 inch full size rack containing a Pentium computer, 10 minute UPS, M/O Drive to store data, 17 inch monitor and three acoustic modems with one modem directed toward each of the three mooring groups.
- There will be a switching circuit to permit connection of the modems to any of the hydrophones (3 are suggested as a minimum to provide redundancy and better "view" of the corresponding subsea transducers associated with each mooring group)
- Graphical user interfaces (see Figures C.5 and C.6).

Noteworthy Capabilities

- Obtains an average bi-axial tilt of the chain using a zero-upcross analysis of a 20 minute record of a tri-axial accelerometer and stores it
- Stores the acceleration time history for future use on solid state storage in bottle
- On demand from topside modem, responds with average angle and time of day, battery level and other diagnostics
- On demand from topside modem responds with a directory of the storage device
- On demand from the topside modem responds with time histories from directory(very power consumptive)
- Inclination Precision 0.005 degrees over range from 0 to 90 degrees
- 50 day life for observations and full time history transmissions every 3 hours-250 day life for 8 measurements daily and one transmission per day. One year life achievable with Lithium Batteries.
- Topside Software proven and operational on Espadarte FPSO (See Figures 5 and 6)

C.3 COST ESTIMATE

The costs to provide the ROV deployable, wireless, subsea inclination measurement system are summarized in Table C.1. That cost estimate does not include the costs of additional infrastructure on the FPSO such as deck cables, junction boxes and cable protection and "sea chests" for the hydrophones. The addition of $100,000 to cover those items is advisable at the budgetary stage.

Table C.1: Cost Estimate for Inclinometer Based System for Estimating Mooring System Loads and Health

Task No.	Task Description	Unit Price	# of units	Total
1.0	System Design & Planning/ Program Management	$15,783	1	$15,783
2.0	Detailed Design	$20,600	1	$20,600
3.0	Software Adaptation	$30,560	1	$30,560
4.0	Subsea Inclinometer Bottles/Acoustic modems	$26,917	9	$242,255
5.0	Fabricate & Test Inclinometer Bottle Clamps	$14,940	9	$134,460
6.0	Fabricate Chain Angle Monitoring Process Console with Three Acoustic Modems	$57,248	1	$57,248
7.0	Procure and Assemble Topside Hydrophones (3) and cables	$15,958	1	$15,958
8.0	Deliver Draft Manuals and Documentation	$12,610	1	$12,610
9.0	Perform Sea Trial & FAT offshore San Diego	$38,070	1	$38,070
10.0	Pack System for shipment to St. Johns	$5,355	1	$5,355
11.0	Deliver Final Manuals and Documentation	$8.723	1	$8,723
	Subtotal F.O.B. Escondido Ca.			**$581,620**
	Time and Materials Tasks			
12.0	Installation Support/Commissioning on FPSO(2 persons-2 weeks)	$45,373	1	$45,373
13.0	Retreival& Redeployment support on FPSO-per retrieval	$14,753	1	$14,753
	Subtotal-Installation			$60,125
	Spare Clamp	$14,940	1	$14,940
	Spare Inclinometer Bottle	$26,917	1	$26,917

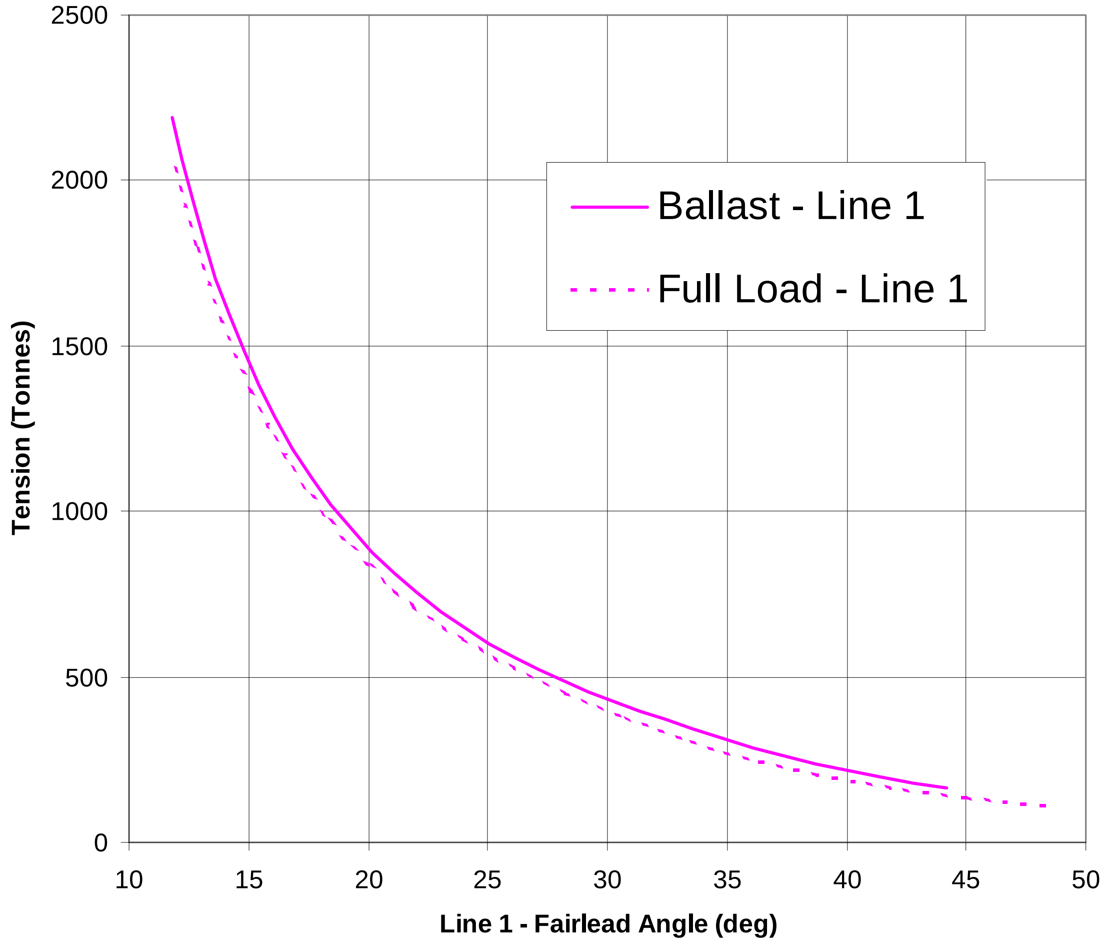


Figure C.1: Line Tension versus Fairlead Angle

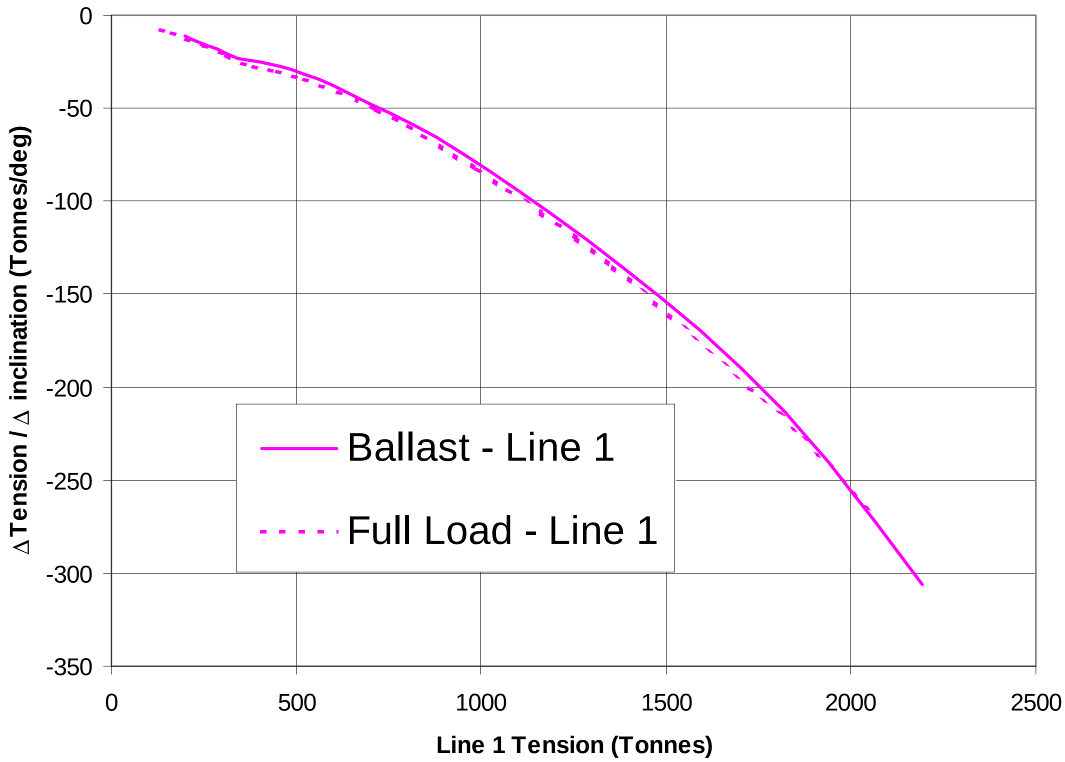


Figure C.2: Derivative of the Tension with respect to Inclination versus Tension

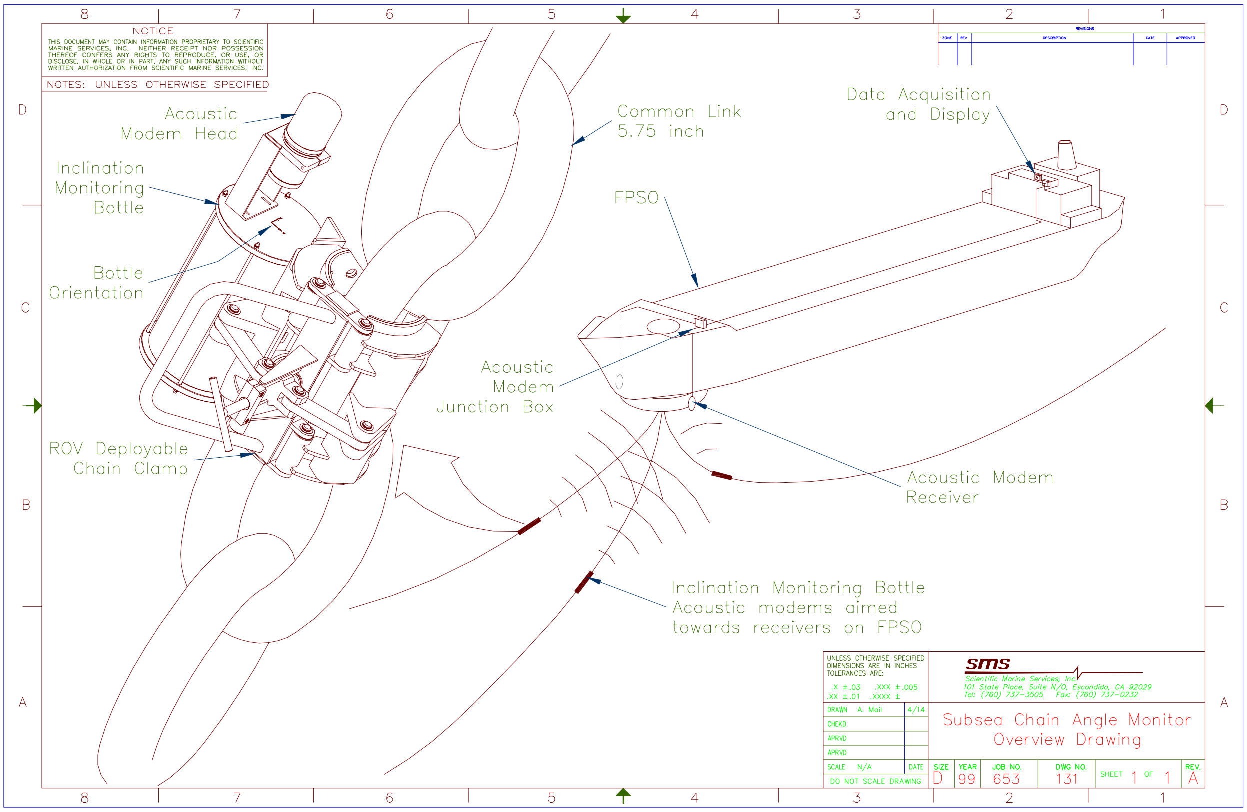
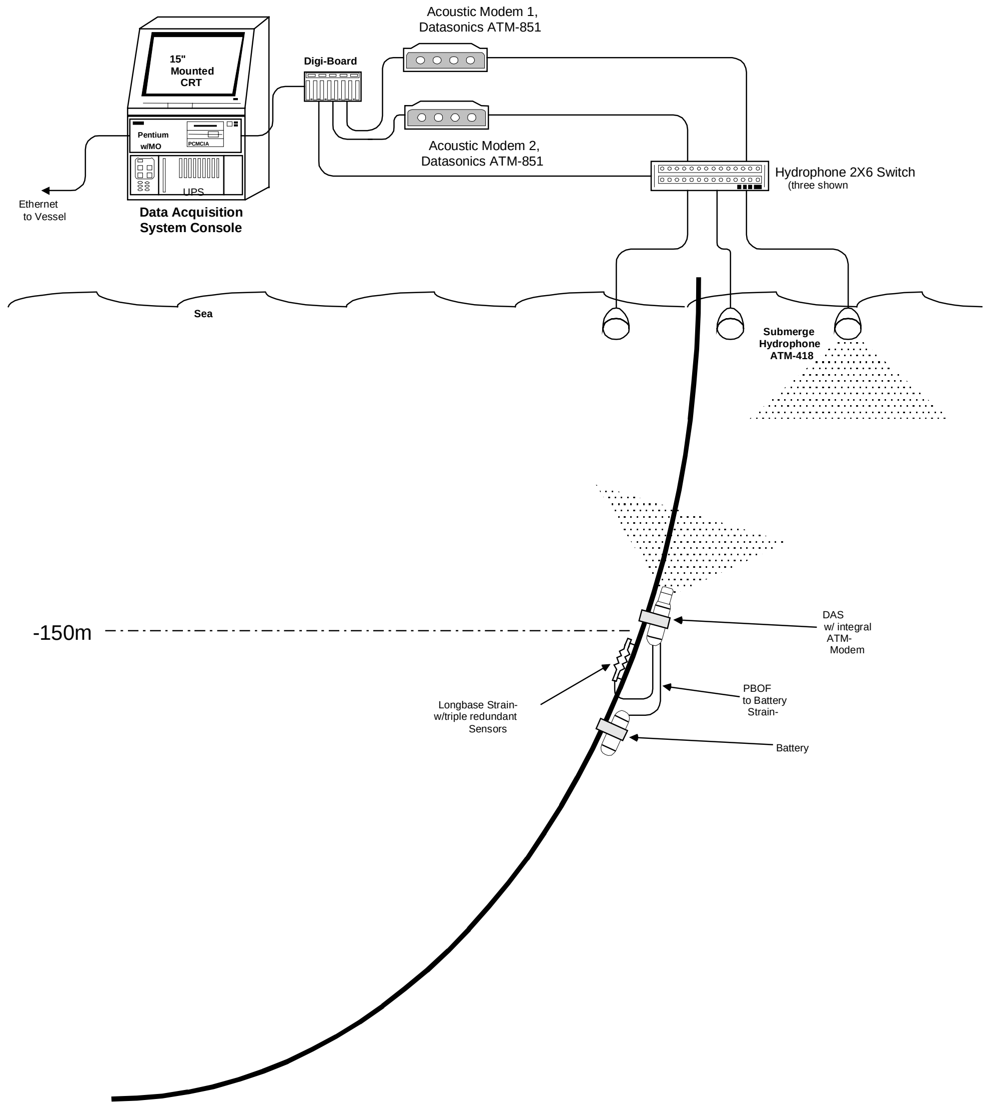


Figure C.3: Overview of Inclinometer Based Line Tension Monitor

SYSTEM OVERVIEW



Prototype Data Acquisition System Block Diagram

Figure C.4: Arrangement for Communications between Surface Vessel and Subsea Inclinometers Clamped to Catenary Mooring

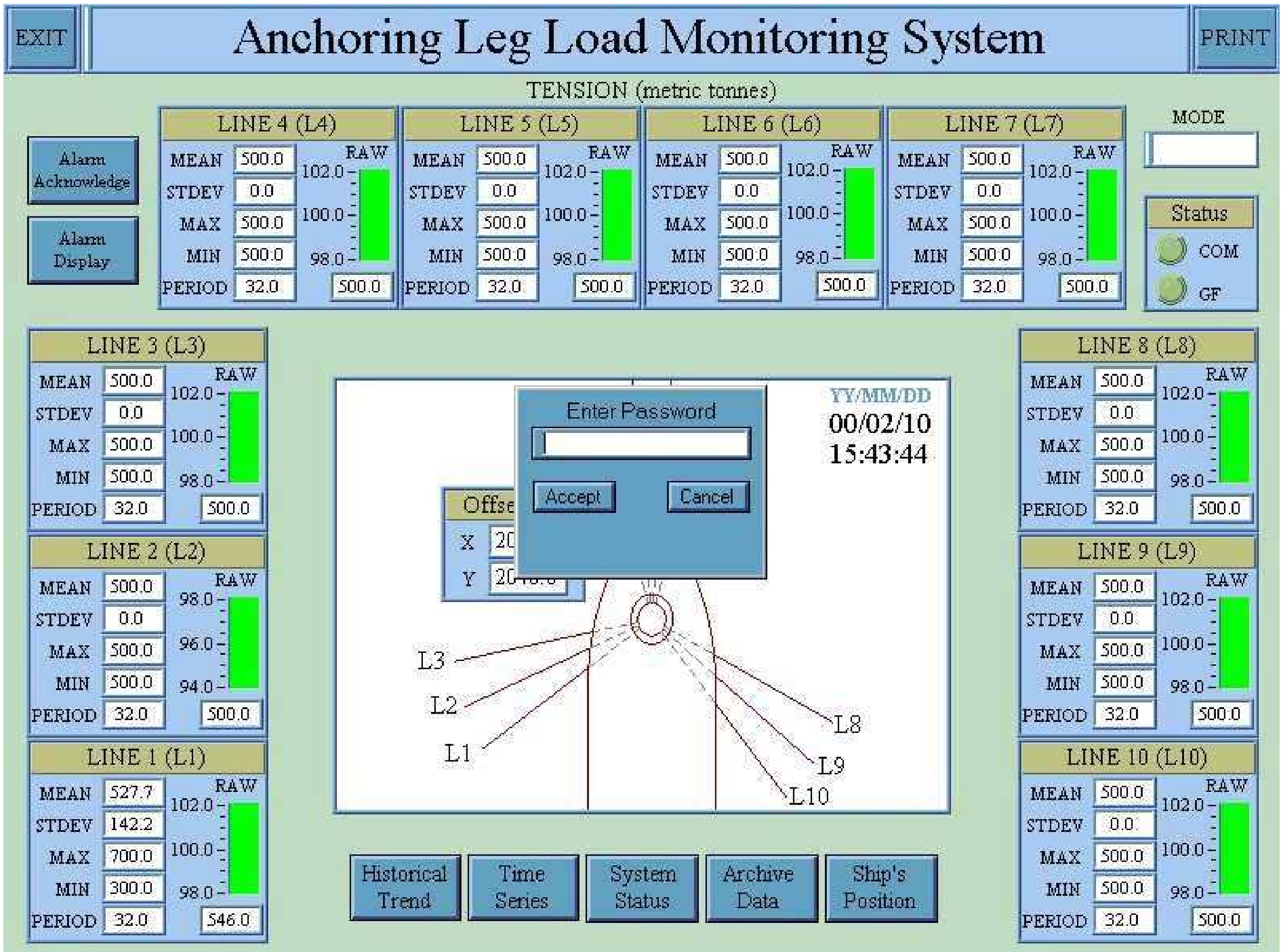


Figure C.5: Main Mooring Screen

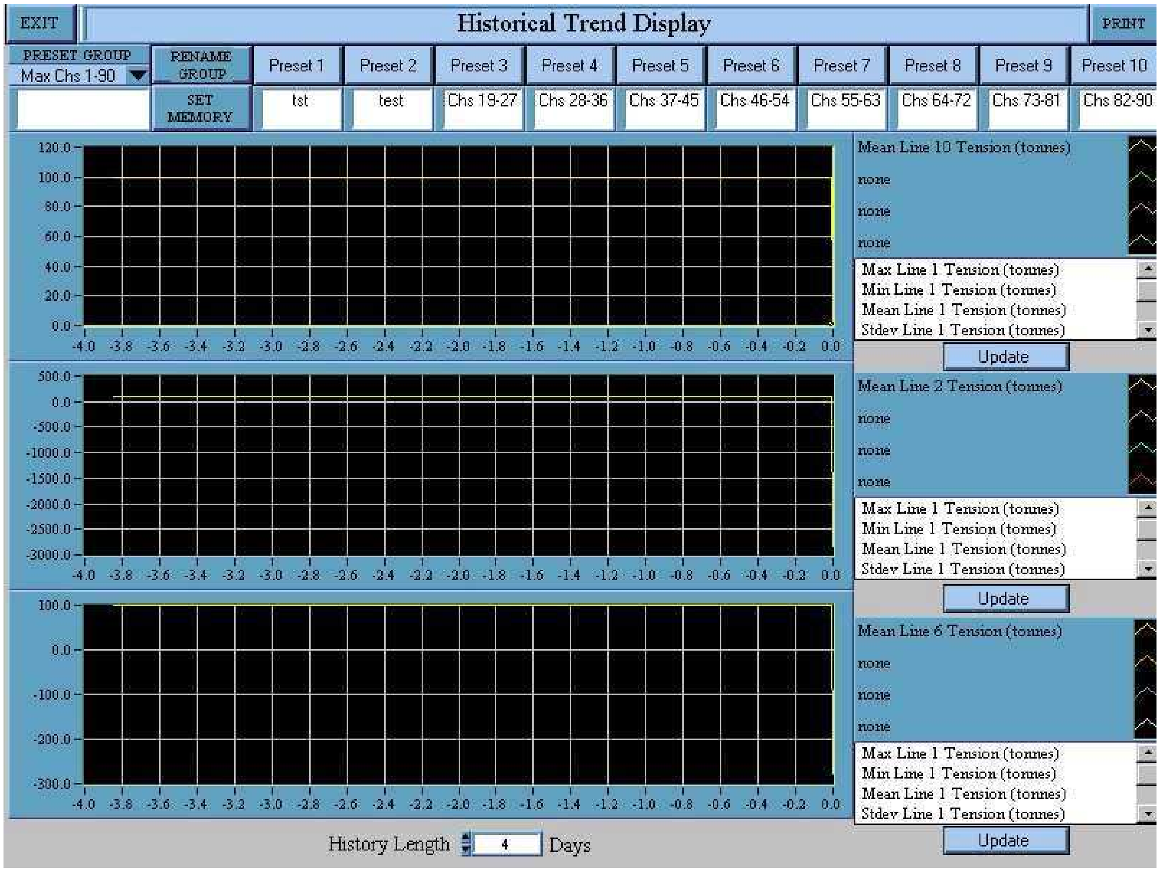


Figure C.6: Historical Trend Plot