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The Validation and Practical Applications of a Sub-Surface Mooring Model

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Canadian Technical Report of Hydrography and Ocean Sciences

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ABSTRACT

Hamilton, James M. 1989. The validation and practical applications of a sub-surface mooring model. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 119: iv + 45 pp.

The validation of a computer model which predicts the equilibrium shape of sub-surface moorings is presented. Using current meter data as input, model predictions are compared to time series of measured excursions for several different instrumented moorings. To obtain a model which accurately predicts shape for a variety of mooring designs and conditions, an upward adjustment of the normal drag coefficient of the mooring line to a value of 2.6 is required. This value is consistent with measurements made by other investigators, where drag is shown to be enhanced by strumming of the mooring line.

The utility of the validated model as an engineering tool for mooring development work is demonstrated. Other applications, where this accurate model may be used to enhance the scientific data set, are also discussed.

RÉSUMÉ

Hamilton, James M. 1989. La validation et quelques applications d'un model numérique pour mouillage sous-marine. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 119: iv + 45 pp.

La validation d'un model numérique qui prédit la forme d'un mouillage sous-marine est presentée. Utilisant les données des courantomètres comme entrées, les prédictions du model sont comparées avec les déplacements mesurés sous plusieurs conditions pour différents mouillages instrumentés.

Pour obtenir un bon accord, il a fallu augmenter le coefficient de trainée du cable à 2,6. Ce résultat est en accord avec des mesures faites pars d'autres chercheurs qui ont montré que la trainée est augmentée par la vibration du cable de mouillage.

L'utilité du model validé comme outil pour déveloper des mouillages est démontrée. D'autres applications sont aussi discutées òu ce model précis peut être utilisé pour améliorer les données scientifiques.

187,680

TABLE OF CONTENTS

1.0 INTRODUCTION

Many of the scientific programs at the Bedford Institute of Oceanography rely on quality measurements from instrumented, sub-surface, oceanographic moorings. These moorings, deployed for periods of up to 18 months, must not only be reliable, but must also be designed to ensure that instrument excursions and inclinations are kept within acceptable limits.

A computer model can be used to predict the equilibrium configuration of a mooring under the influence of a user-defined current profile. The designer can then determine the expected excursions and inclinations of the in-line mooring components for any particular design, given a reasonable estimate of the currents in the area where the mooring is to be deployed. The model can also provide information on other critical parameters, such as the line tension and reserve buoyancy at any point along the line. The performance and reliability of the mooring design depends on accurate estimates of these model predicted quantities.

The three dimensional mooring model used routinely in the design of sub-surface moorings at the Bedford Institute of Oceanography (BIO), has undergone extensive testing and modification in the last few years. A rigorous analysis of the formulations used has led to significant changes to the program. The result is an improved solution method which provides verified 3-d results, and faster convergence.

Validation of the model has been accomplished through the development of a batch version of the static mooring model. Here, actual current meter data sets are used as input to generate a time series of model predictions. These predictions are compared to measurements of mooring orientation collected from specially instrumented moorings, and from operational current meter moorings equipped with pressure sensors. The results of a sensitivity analysis have subsequently been used to provide direction for the fine-tuning of the model.

The updated computer model provides accurate estimates of mooring orientation, making it a valuable tool for ensuring that established design criteria are met for any operational mooring. It is also extremely useful in evaluating new mooring designs as attempts are made to improve operational current meter mooring performance. This is demonstrated in the recent redesign of BIO deep-ocean, high-current regime moorings, where the model has been used to establish a mooring design with much improved performance characteristics.

An accurate model may even be used to supplement the scientific data acquired by the instruments in a mooring. Predictions can be used to reconstruct the depth record of any mooring component, be it to improve the depth resolution of thermistor chain records, or to provide a depth record for a current meter whose pressure sensor has failed.

2.0 MOORING DESIGN AND THE COMPUTER MODEL

Sub-surface oceanographic moorings are routinely used to provide long time-series information about currents, temperature and salinity at levels determined by the location of current meters along the line. These moorings are typically deployed for periods from 6 to 18 months. Recovery is made possible through the use of an acoustic release mounted near the bottom of the mooring. A large main float as well as back-up buoyancy along the line act to maintain the line tensions required to limit instrument excursions. Common mooring line types are 1/4 in. jacketed kevlar, and 3/16 in. plastic-jacketed galvanized steel wire. Frequently both of these materials are used in a single design since the use of kevlar is restricted to depths greater than 2000 meters to avoid fish-bite problems. Kevlar is the preferred material since its reuse makes it more economical, and its light weight reduces the amount of back-up buoyancy required. A typical sub-surface deep ocean mooring is shown in Figure 1.

The design of a sub-surface current meter mooring must meet a set of established criteria to ensure that reliability and data quality standards are met. These criteria are:

1) Vertical excursions of instruments under expected current conditions must be within acceptable limits. Maximum excursions greater than 10% of the mooring length are considered excessive.

2) Current meter inclinations must not exceed operational limits under expected current conditions. For Aanderaa current meters, inclinations should not be greater than 27 degrees, the limit of the gimbal mount.

3) Line tensions must not exceed prescribed limits. For kevlar, tensions should not exceed 33% of the rated breaking strength, while for wire rope the criterion is 50% of the rated breaking strength.

4) A net positive buoyancy must be maintained through-out the line. This ensures that regardless of where a failure may occur, there is sufficient buoyancy to bring the remainder of the mooring to the surface upon the triggering of the acoustic release.

5) The use of kevlar is restricted to depths greater than 2000 meter due to concerns about fish-bite.

An accurate computer model is essential to determine whether these specifications are met, and is therefore an integral part of the design process.

The model used at BIO is a three-dimensional model which computes the equilibrium configuration of a mooring under the influence of a user-defined current profile. (Dynamical effects due to waves are neglected as it is assumed that sub-surface moorings are below the depth where this effect is a factor). A

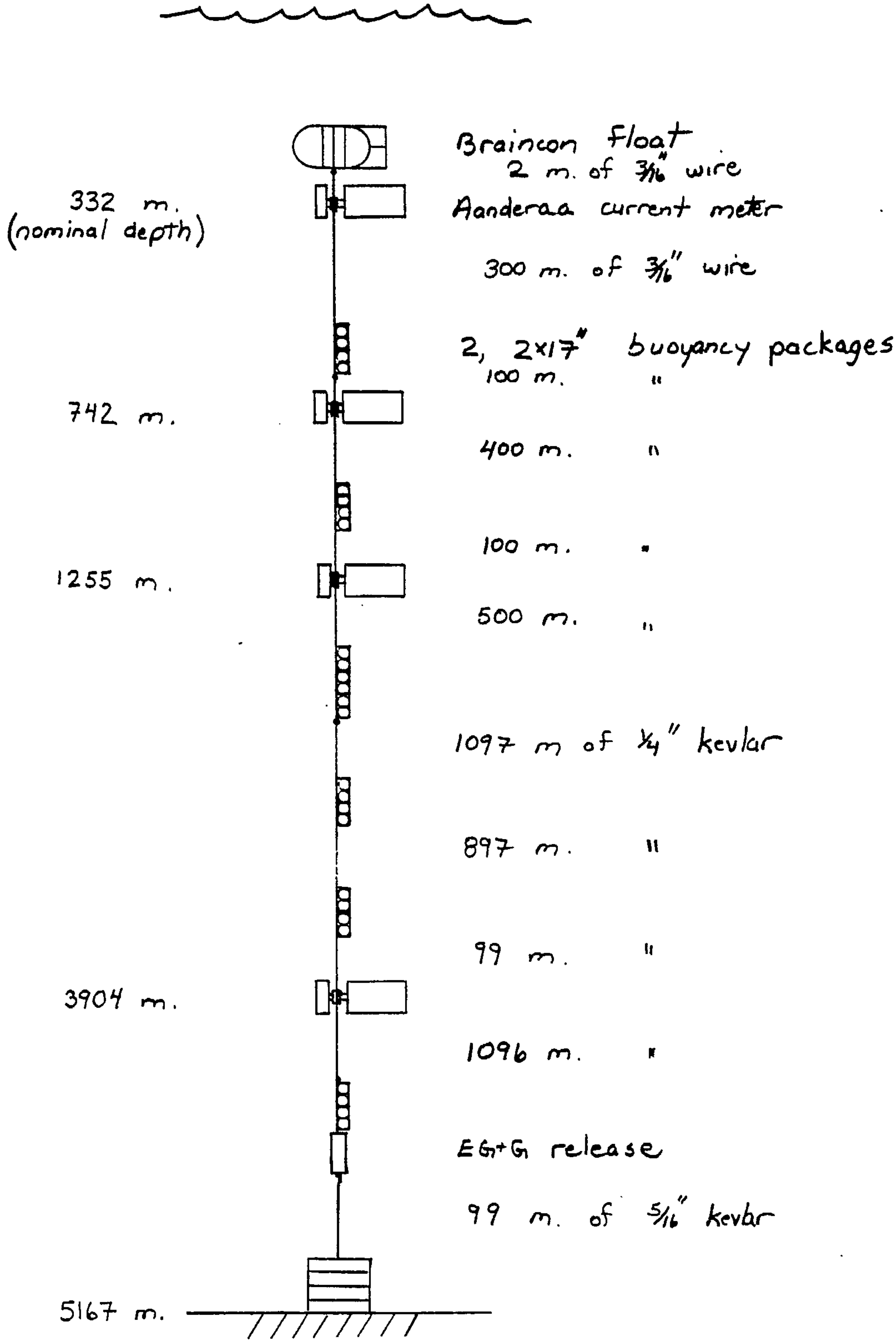


Figure 1 - Gulf Stream mooring, #557.

flow chart of how the model is used in the design process is shown in Figure 2. An initial design based upon information provided by the scientist on desired instrument levels is used as input to the model, along with an estimate of the maximum expected current profile. Adjustments to the design are then made until model predictions demonstrate that all of the design criteria are met.

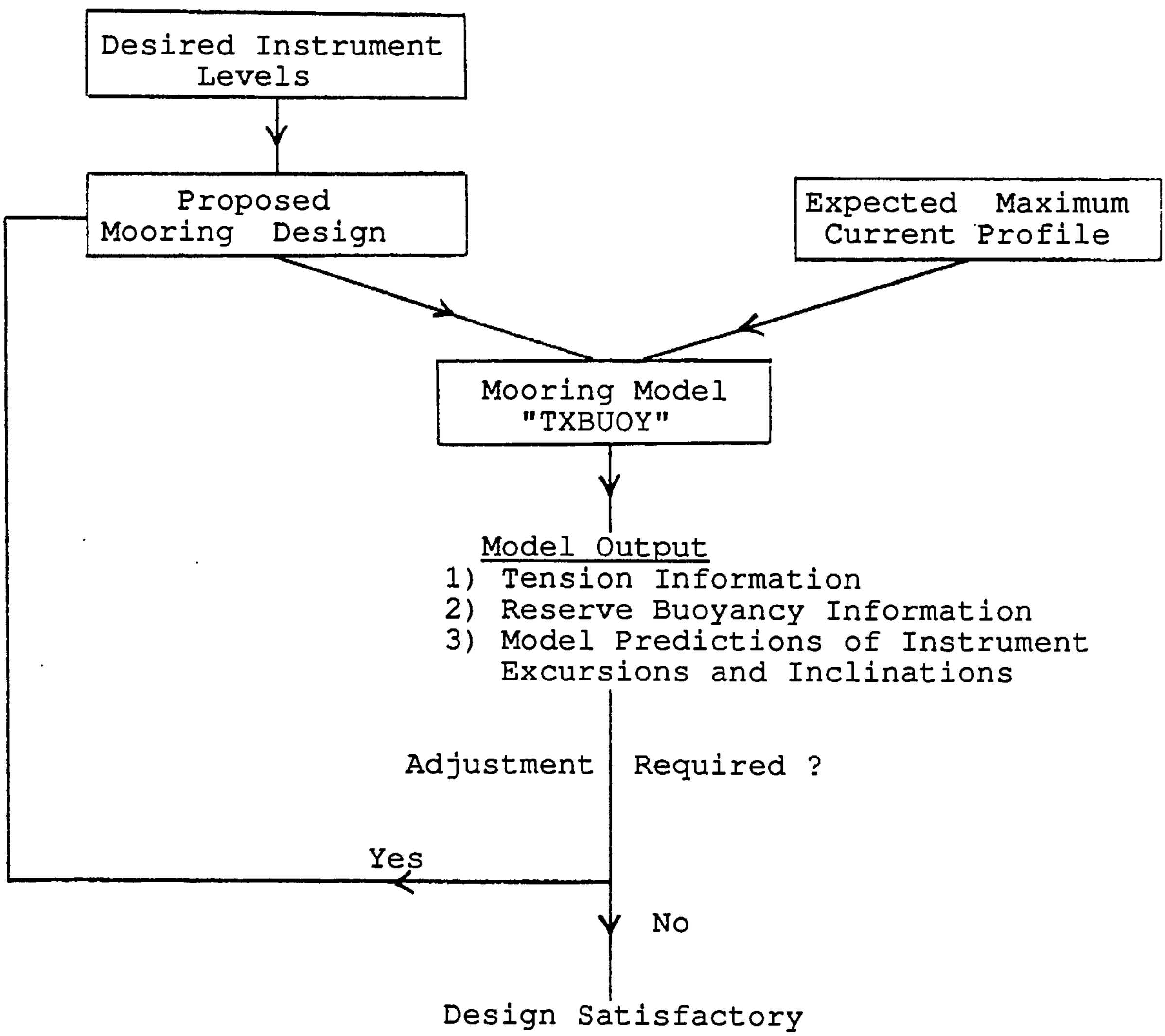


Figure 2 - An illustration of the use of the mooring model as a tool for operational mooring design.

3.0 HISTORICAL DEVELOPMENT OF THE MOORING MODEL

The original working mooring model at the Bedford Institute of Oceanography was adapted from a program developed by W. A. Moller (Moller,1976), for use on the HP1000 computers here at the Institute. Used as a guideline for the design of current meter moorings, the model developed to become an important part of the mooring program. In 1982 the program was transferred to the Cyber (the main-frame computer at BIO), and was largely recoded in the translation to obtain more manageable modules and to generally clean up the code. In the process numerous coding errors were detected and corrected.

As a next step in the development of the model, MacLaren Plansearch Ltd. was contracted to evaluate the mooring model by comparing model predictions to pressure and tilt data from current meter moorings previously deployed. However, where real current meter data was used, serious convergence problems were encountered. Since the practice was to use unidirectional current profiles for the design of moorings, this problem had not previously been recognized. In order to validate the model by comparison with current meter data this problem was addressed, since profiles derived from real data will demonstrate directional variability with depth.

The thrust of MacLaren Plansearch's work then shifted as it became obvious that verification of the code and model formulations was essential. Several major modifications to the code were recommended by the contractor. The force vector resolution scheme which caused the problems in the three-dimensional case was analysed, and a correct formulation proposed. An improved solution scheme which is technically more correct and computationally efficient was also suggested. Correction of the drag formulations, the alteration of certain arrays, standardization of units, and the inclusion of a U,V-components type of current profile interpolation were also recommended.

These changes were subsequently implemented in a later contract with ASA Consulting Ltd. and Wycove Systems Ltd., resulting in an extensively rewritten program which is very different than Moller's original mooring model. A complete description and justification of these changes is presented in the report, "An Evaluation of the Atlantic Oceanographic Laboratory Mooring Model" (MacLaren Plansearch, 1983).

Further work by MacLaren Plansearch included a theoretical analysis of the time response of moorings to determine the feasibility of using the model to predict changes in mooring shape as currents changed with time. Results indicated that mooring response is sufficiently quick that this approach is reasonable so long as the user does not attempt to model response to current fluctuations of periods shorter than several minutes (MacLaren Plansearch, 1983). Based on the conclusions of this analysis, a time series version of the mooring model was developed by Wycove Systems Ltd. under contract to the Atlantic Oceanographic Laboratory. This recently developed time-series version of the mooring model has proven to be an excellent tool with which to validate the model. A rigorous evaluation has been undertaken and the results are presented in this report. Data from moorings specifically instrumented for this purpose, as well as data from selected operational current meter moorings have provided data sets from which a validation of the model has been accomplished. Fine-tuning of the model, directed by the results of a sensitivity analysis, has been undertaken so that model predictions reasonably match measured data for a variety of moorings.

4.0 MODEL EVALUATION

4.1 The Time Series Version

The same solution scheme used in "TXBUOY" (described in Section 2.0) is used in the time series mooring model, "BCBUOY". This procedure is set up to accept a series of current profiles so that a time series of model predicted mooring orientations is produced in a single batch job (see Figure 3).

To generate the input file from actual current meter data, the procedure "CPSEL" has been developed. With this procedure,the user can specify a time series of current profiles based on the data records collected by instruments on the mooring being analyzed. Normally, the currents at a specific level in a profile are defined by the depth, rate and direction records from the corresponding current meter. Additional levels can also be specified as user-defined weighted combinations of the records from any of the instruments, or as constant values. This provides the user with the flexibility of incorporating other information about the oceanography of the area in the current profile generation process. Currents between the defined levels are calculated by the program through linear interpolation.

Time series of predicted mooring orientations can be plotted by a third procedure, "TSPLOT". This program can plot up to four predicted values as a function of time, but can also plot the original current meter data used as input to the model. The user can then compare actual measured values of instrument depth and inclination with model predicted values, a valuable feature in the model validation process.

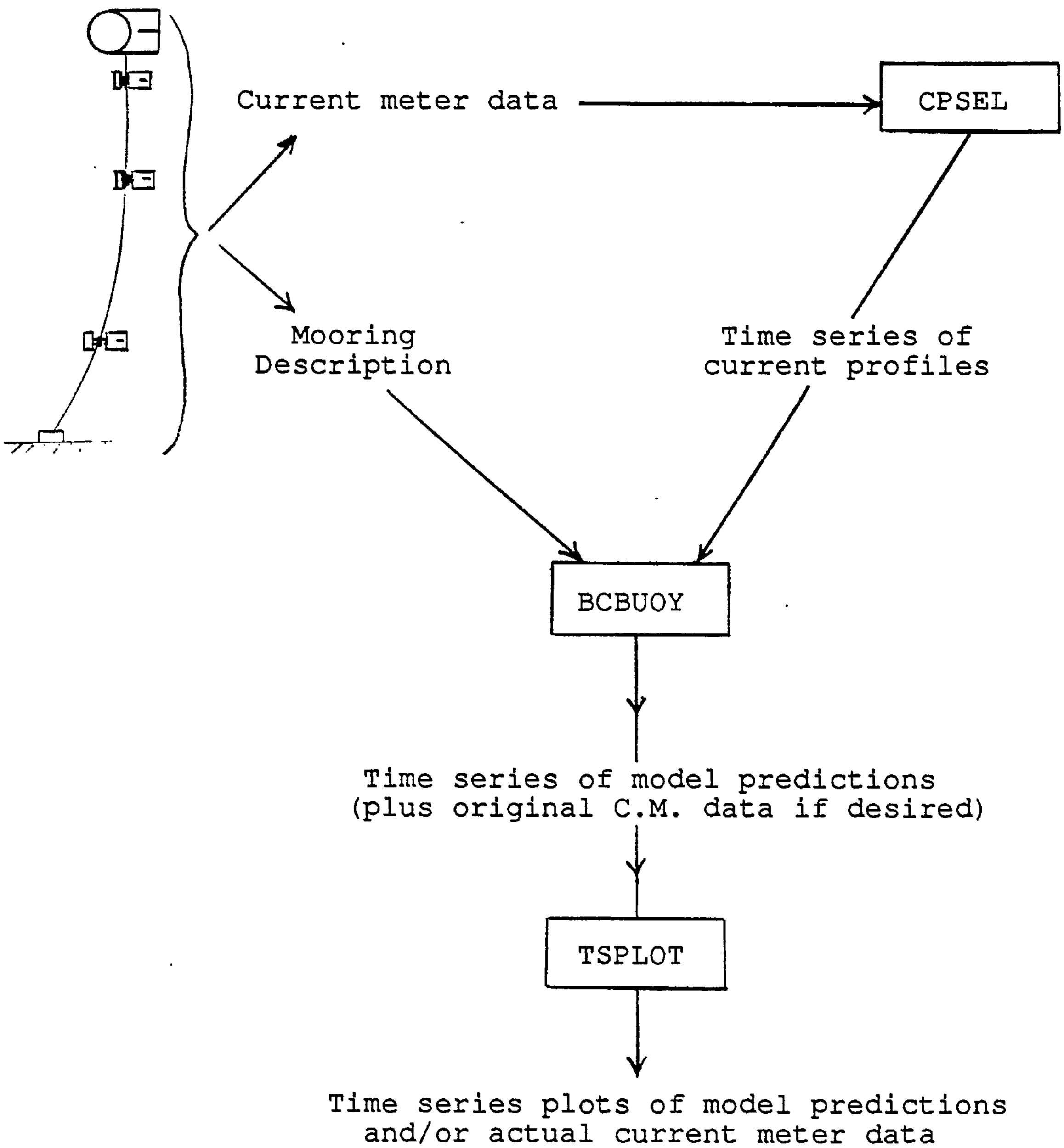


Figure 3 - Using the time series mooring model, "BCBUOY". A file produced by "CPSEL" with actual current meter data provides the required profiles for input into the model. The program "TSPLOT" is used to display model results.

4.2 Model Sensitivity Analysis

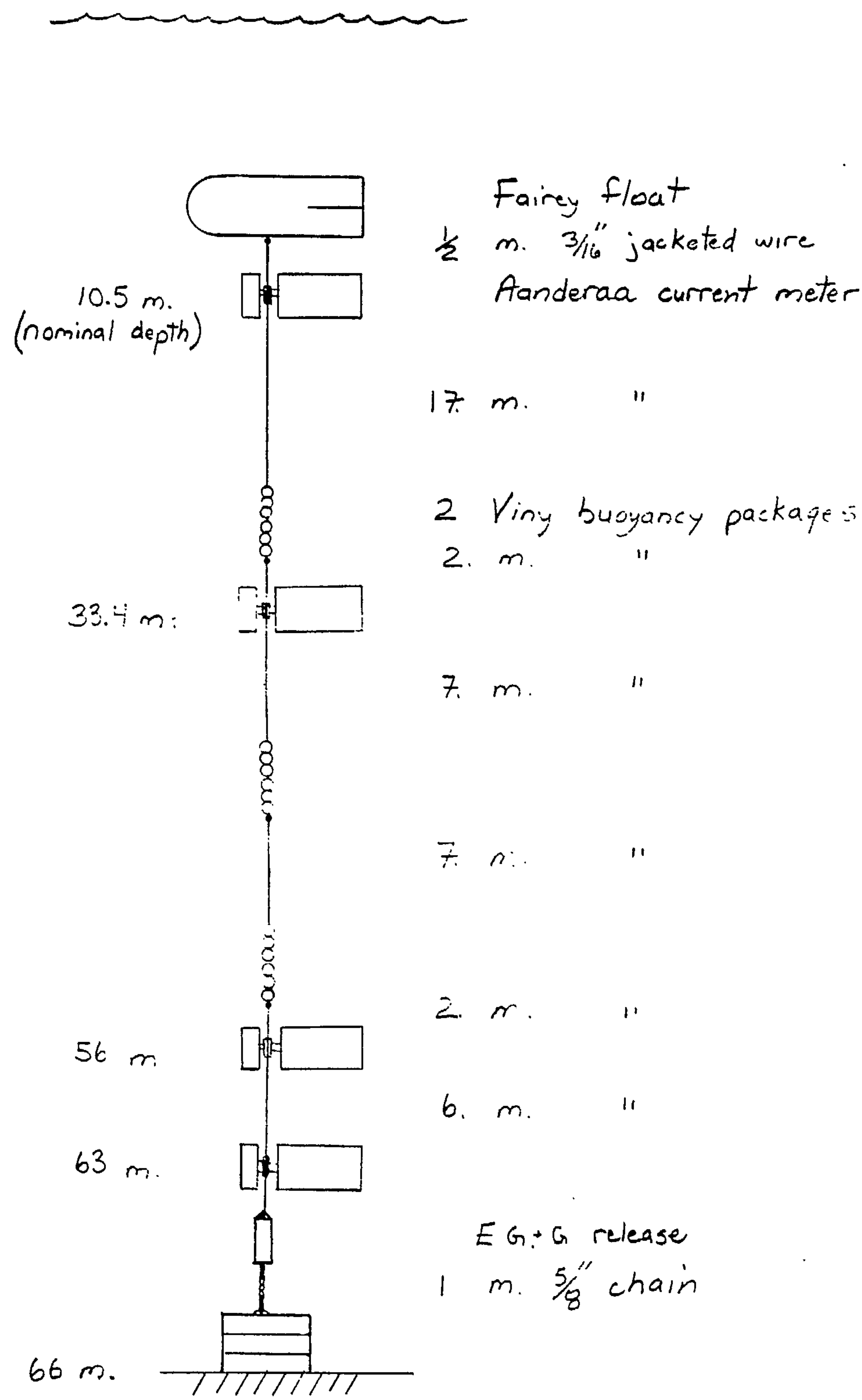
Another important tool in the validation and fine-tuning process is the sensitivity analysis, which reveals how variation in the different model parameters affects model output. Such an analysis is invaluable because it focuses attention on those parameters which are most critical for accurate model predictions. It can also be very useful as a development tool. Given that the model provides a reasonable simulation to the actual system being modeled, this analysis provides insight into where engineering efforts would be most effective towards improvement of mooring design.

A sensitivity analysis of TXBUOY was performed by MacLaren Plansearch Ltd. as part of their model evaluation work. As there were extensive changes to the computer model since the MacLaren Plansearch report, this analysis has been repeated. Results from the sensitivity analyses of mooring #557, a deep ocean, Gulf Stream mooring (Figure 1), and mooring #893, a shallow water design deployed on George's Bank (Figure 4), are described here.

In the sensitivity analysis, each of the variable parameters of the model were adjusted from baseline values, one at a time, and the effect on model output was observed. Baseline values used were those specified as the default values of the mooring model. Parameters varied were component buoyancy, line normal drag, instrument normal drag (all mooring components except lines), tangential drag, line elasticity, and current magnitude.

Results from the analysis of the long mooring (#557) are shown in Figures 5,6 and 7, displaying the effect of varying the different parameters on vertical excursion, horizontal excursion, and inclination of the bottom current meter respectively. Clearly, for this long mooring, model output is most affected by variation in current magnitude, and buoyancy of the mooring components. Variation in line normal drag has the third largest effect on model output, followed by instrument normal drag which plays a significantly smaller role. The effect of varying the line elasticity and tangential drag is pretty well negligible, over the +30% to -30% range studied here.

The results of the sensitivity analysis of the short mooring (#893) are displayed in Figures 8,9 and 10. Results are similar to the long mooring case with one notable exception. For short moorings the model is more sensitive to variation in instrument normal drag than line normal drag. The opposite was true for the long mooring, and is a consequence of the fact that the line makes a much smaller contribution to the total frontal area of the mooring in the short mooring case.



<u>Figure 4</u> - Georges Bank mooring, #893.

Moor #557 - Vertical Excursion Sensitivity

\+ buoyancy
✲ current
△ line normal drag
× instrument normal drag
○ line elasticity
□ tangential drag

z = predicted depth of top of mooring
z_B = predicted depth of top of mooring under "baseline" conditions
ML = Mooring Length = 4838 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	.6
900	.6
1300	.38
1850	.39
2000	.31
5167	.31

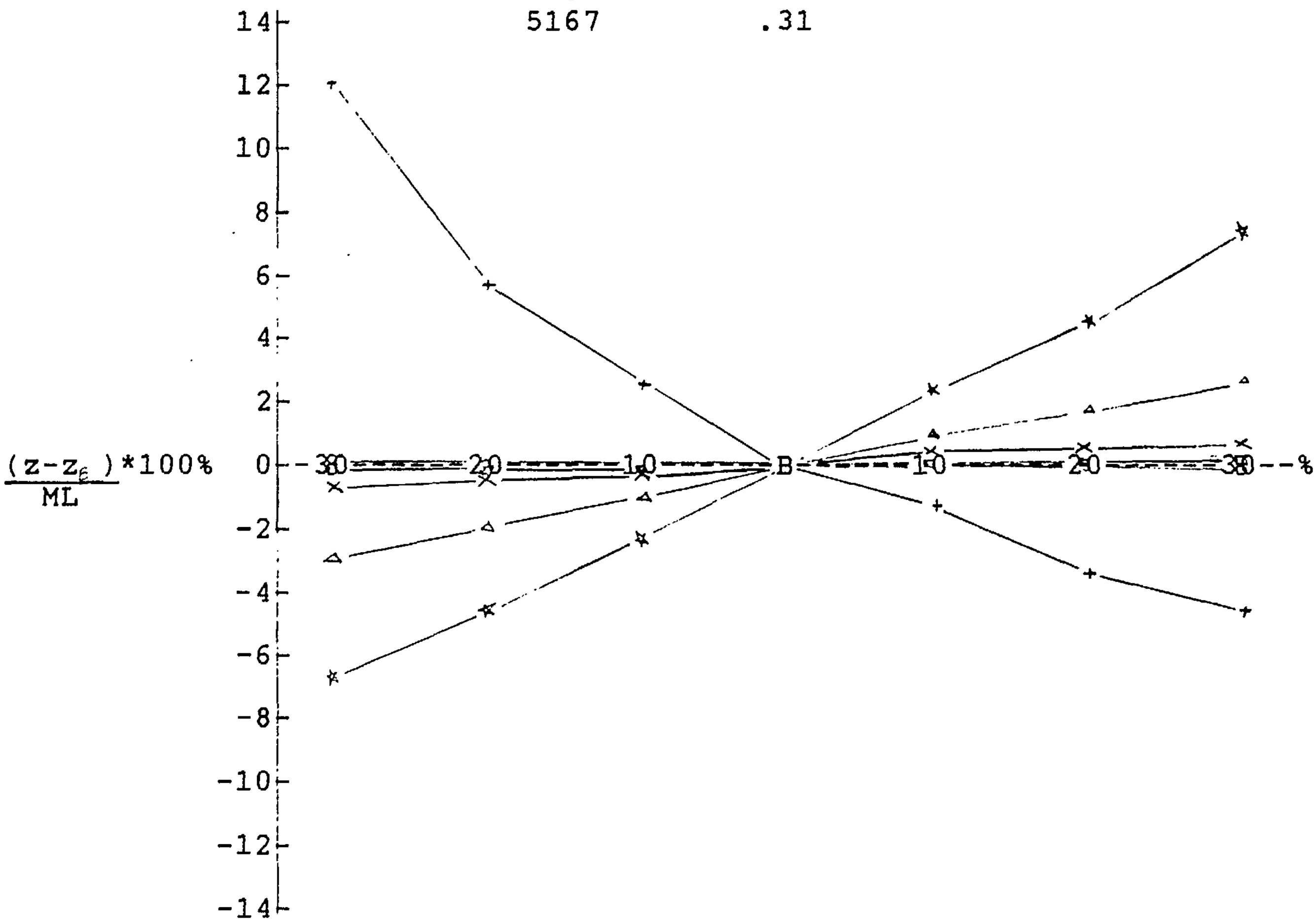


FIGURE 5 - The sensitivity of model predicted depth to variations in the values of different model parameters.

Moor #557 - Horizontal Excursion Sensitivity

+ buoyancy
* current
△ line normal drag
× instrument normal drag
○ line elasticity
□ tangential drag

x = predicted downstream excursion of top of mooring
x_B = predicted downstream excursion of top of mooring under "baseline" conditions
ML = Mooring Length = 4838 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	.6
900	.6
1300	.38
1850	.39
2000	.31
5167	.31

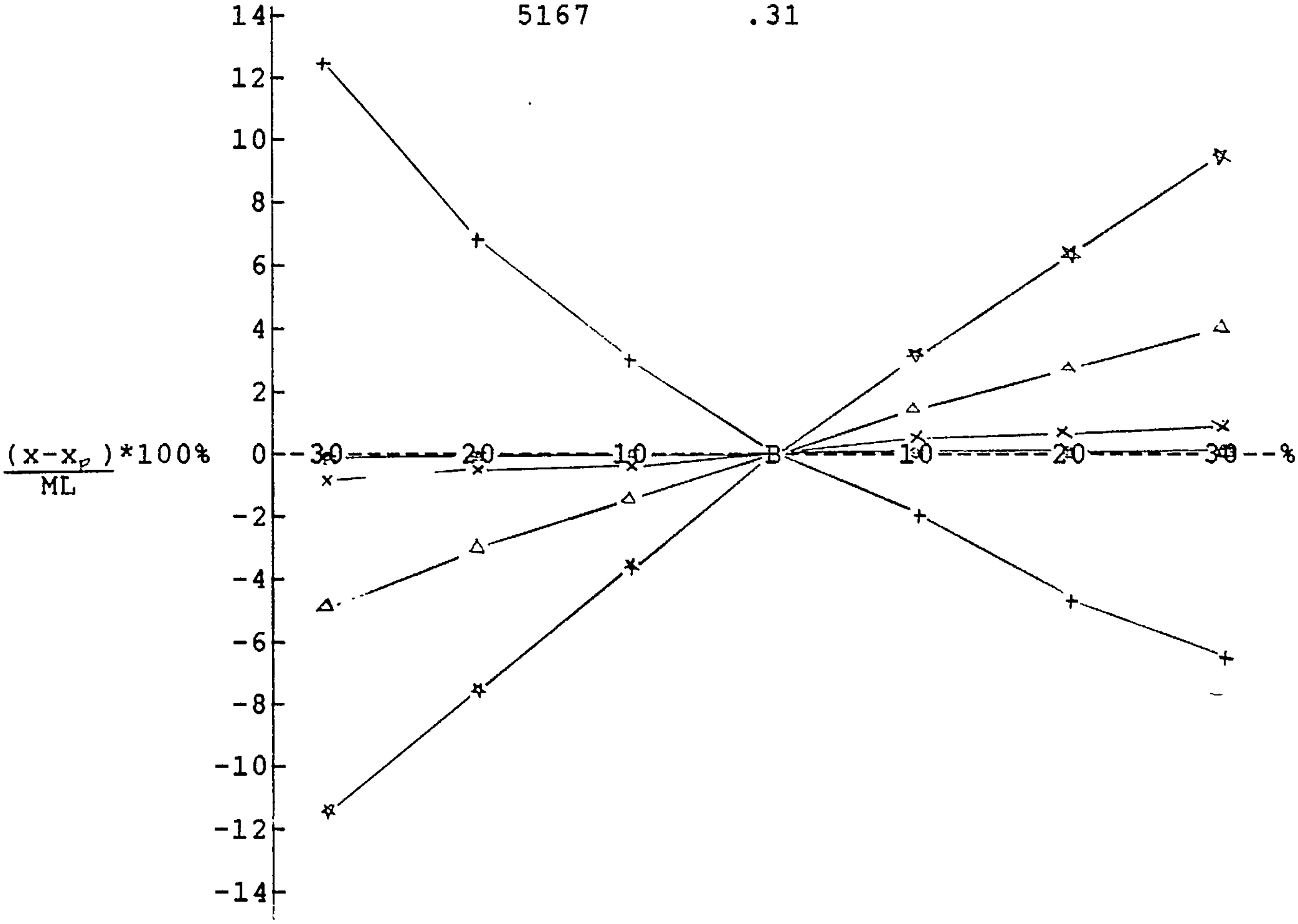


FIGURE 6 - The sensitivity of predicted downstream excursion to variations in the values of different model parameters.

Moor #557 - Inclination Sensitivity

+ buoyancy
✱ current
△ line normal drag
× instrument normal drag
o line elasticity
□ tangential drag

θ = predicted angle of bottom current meter
θ_B = predicted angle of bottom current meter under "baseline" conditions
ML = Mooring Length = 4838 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	.6
900	.6
1300	.38
1850	.39
2000	.31
5167	.31

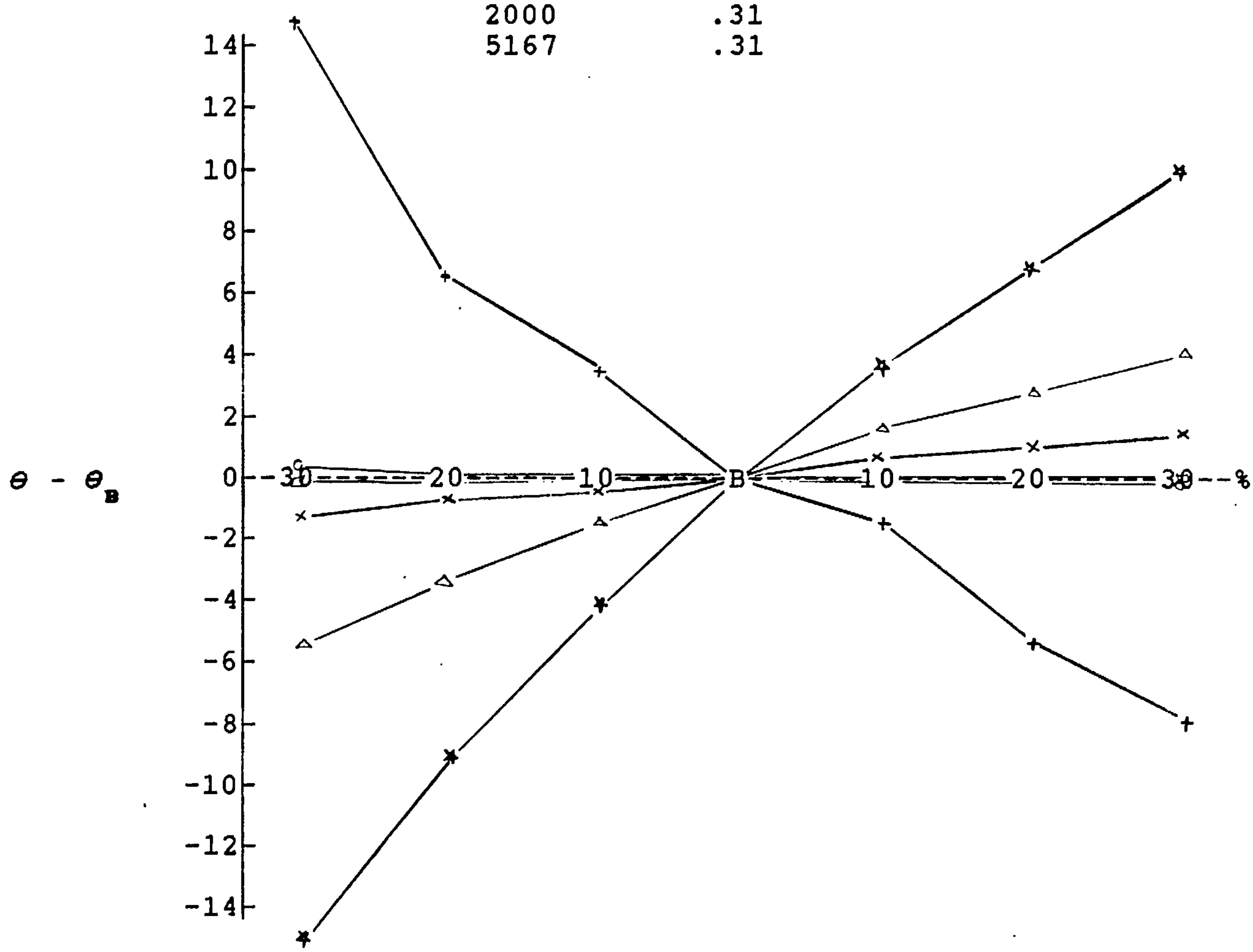


FIGURE 7 - The sensitivity of predicted instrument inclination to variations in the values of different model parameters.

Moor #893 - Vertical Excursion Sensitivity

+ buoyancy
☆ current
△ line normal drag
× instrument normal drag
○ line elasticity
□ tangential drag

z = predicted depth of top of mooring
z_B = predicted depth of top of mooring under "baseline" conditions
ML = Mooring Length = 57 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	1.5
66	1.5

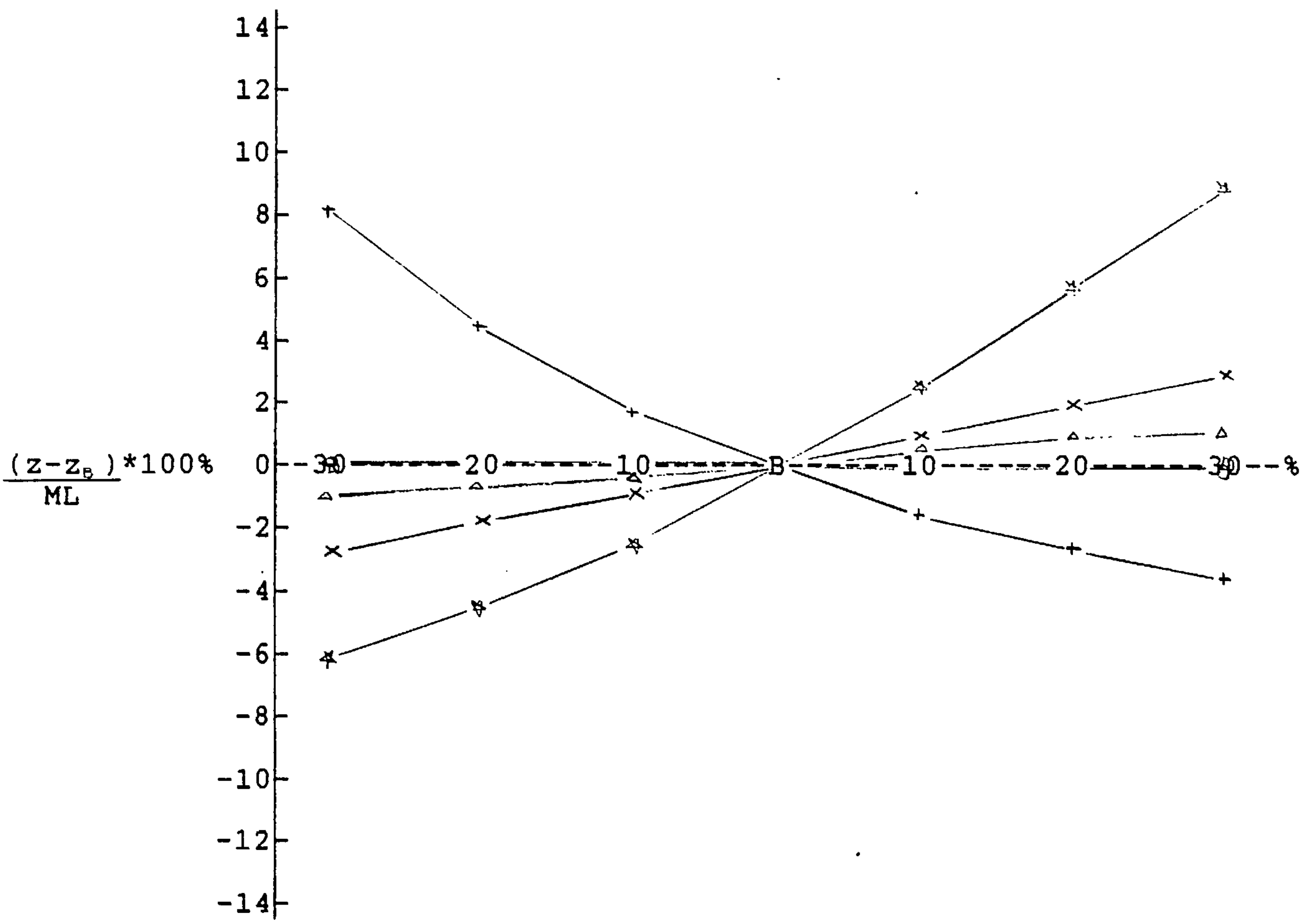


FIGURE 8 - The sensitivity of model predicted depth to variations in the values of different model parameters.

Moor #893 - Horizontal Excursion Sensitivity

- \+ buoyancy
- ✱ current
- △ line normal drag
- × instrument normal drag
- ○ line elasticity
- □ tangential drag

x = predicted downstream excursion of top of mooring
x_B = predicted downstream excursion of top of mooring under "baseline" conditions
ML = Mooring Length = 57 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	1.5
66	1.5

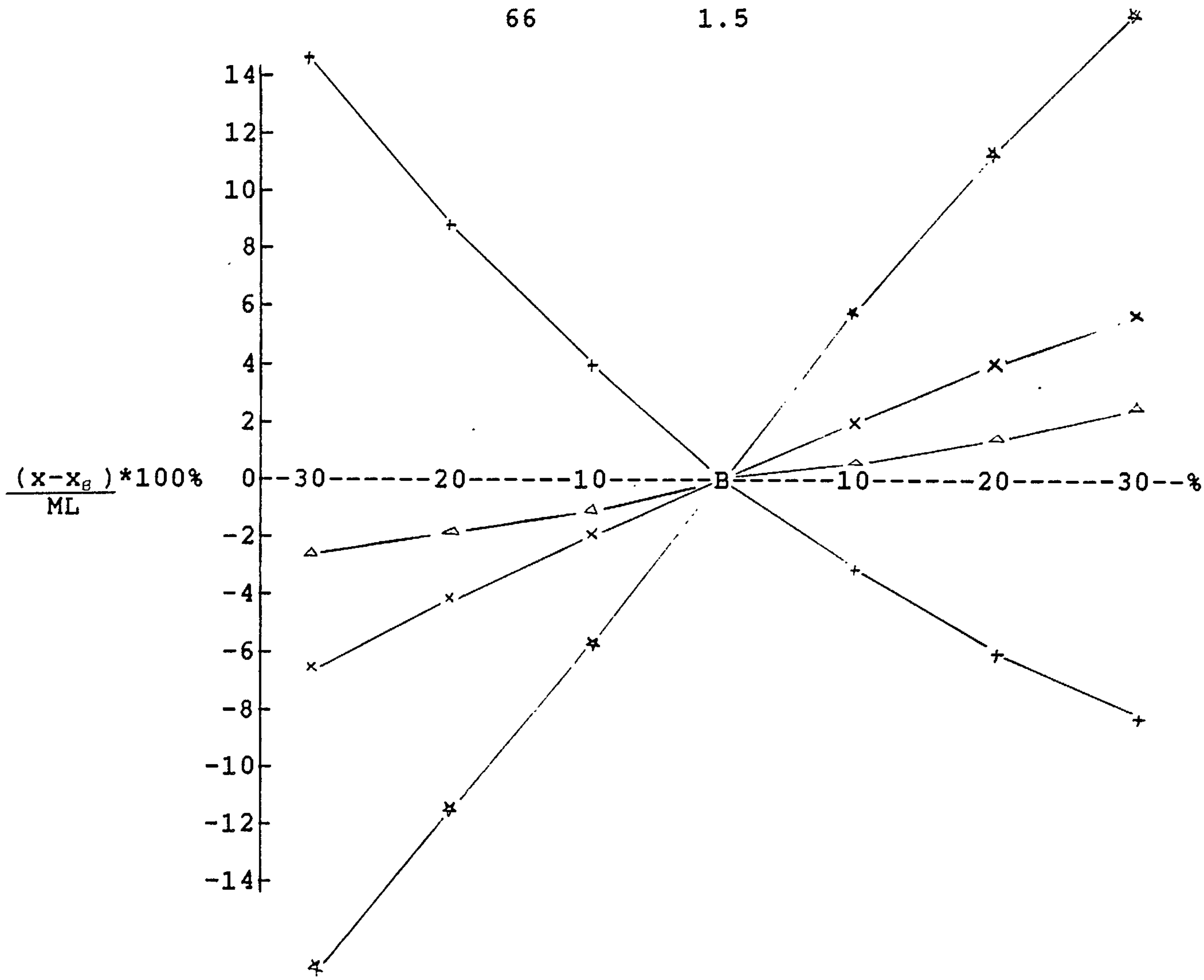


FIGURE 9 - The sensitivity of predicted downstream excursion to variations in the values of different model parameters.

Moor #893 - Inclination Sensitivity

+ buoyancy
✻ current
△ line normal drag
× instrument normal drag
○ line elasticity
□ tangential drag

θ = predicted angle of bottom current meter
θ_B = predicted angle of bottom current meter under "baseline" conditions
ML = Mooring Length = 57 m.

Baseline Current Profile

Depth(m)	Rate(m/s)
0	1.5
66	1.5

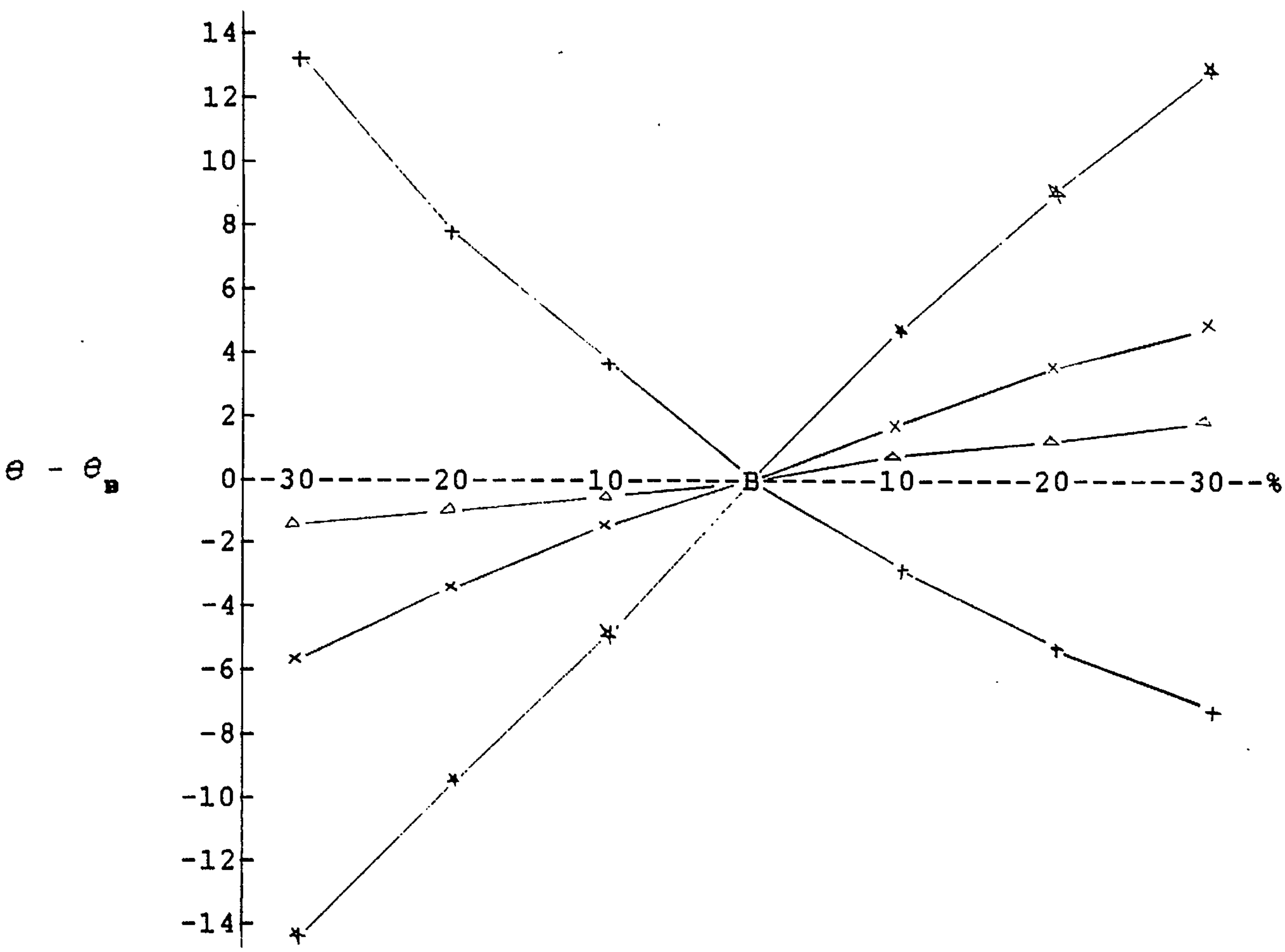


FIGURE 10 - The sensitivity of predicted instrument inclination to variations in the values of different model parameters.

4.3 Model Validation and Fine-Tuning

The time series version of the model and the results of the sensitivity analysis were an effective combination of tools in the validation and fine-tuning of the model. However, before conducting a comparison of model predictions with position data for specific moorings, several areas of concern were identified. The high sensitivity of model output to variations in buoyancy prompted a check on the buoyancy of all of the standard BIO mooring components. Many buoyancies as listed in the model were found to be inaccurate and were subsequently corrected in the computer code.

The importance of accurate current profiles for good model predictions was also recognized. Since the current meter data collected by instruments on the tested mooring are used as input to the model, accuracy of the predictions depends not only on the model computations, but also on the accuracy of the current profiles used as input. The user must interpolate between current meters to obtain the required input profiles. Depending on the current structure and what is known about it, this may be a source of significant uncertainty. Since the goal is to determine the accuracy of the model itself, the data sets most suitable for the validation work are cases where current structure is well resolved.

One other important consideration in any precision checks on the model, is the accuracy with which mooring line lengths are measured. Presently the accuracy of our line measurement is about 0.5%. This can result in a serious uncertainty when model predictions, which rely on accurate input of line lengths, are compared to measured depths. The problem can however be circumvented by examining the depth records provided by instruments in the test mooring. The minimum depth measured during the entire deployment can be assumed to represent the "no current" orientation of the mooring, so long as currents at this point in the record are in fact small. Line lengths in the model mooring can then be adjusted to match this "no current" condition.

The first mooring considered for the comparison of model predictions of excursions with actual mooring position data was the long mooring #557 (Figure 1). This mooring is ideal for this type of analysis because of the unidirectional nature of the observed currents (see Figure 11), which makes interpolation between instruments less uncertain.

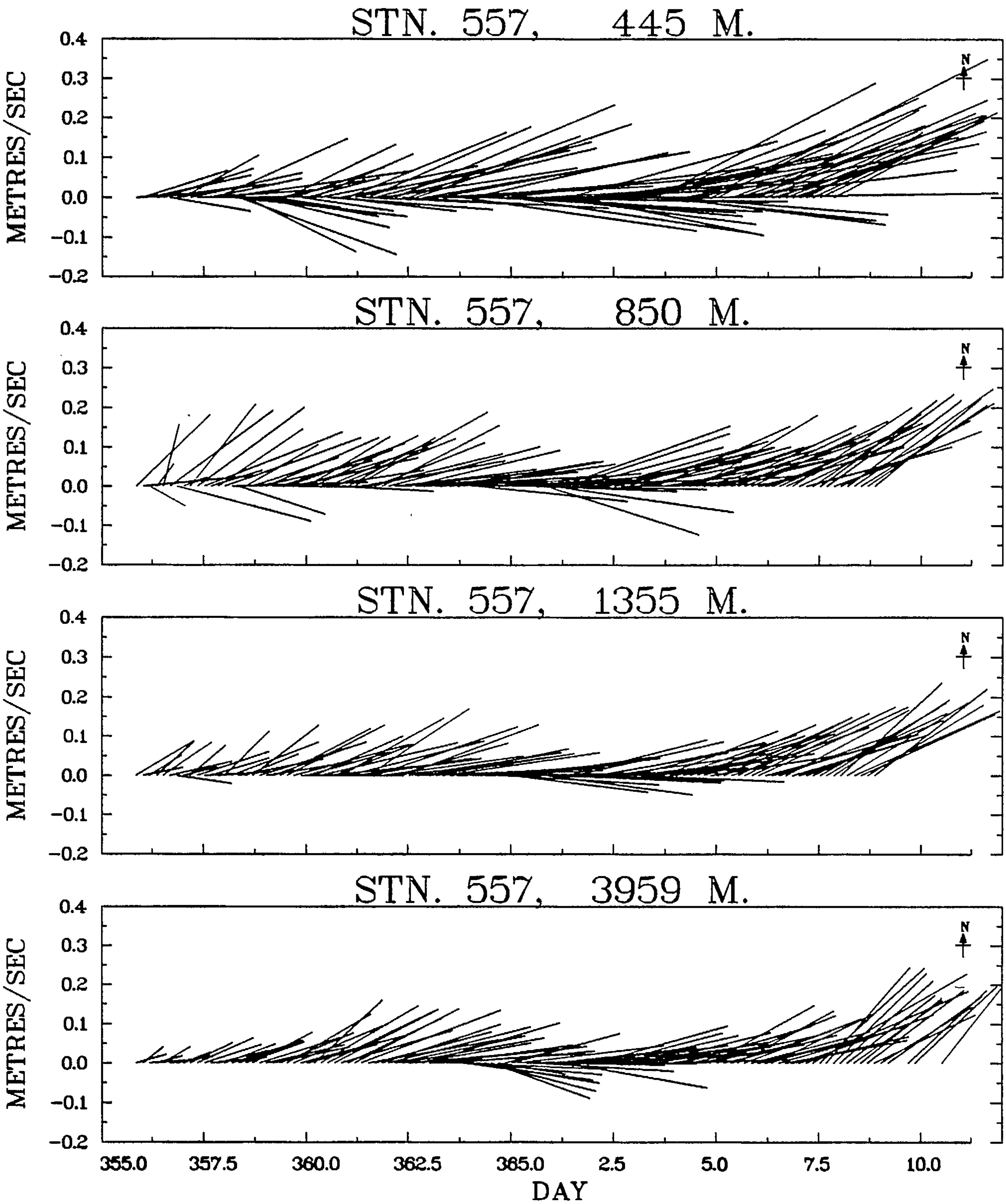


Figure 11 - Currents as measured by the 4 Aanderaa instruments on mooring #557.

A series of 500 profiles was generated from hourly data collected by each of the four current meters in the mooring. Input from an oceanographer knowledgeable of the current structure in the area (R. Hendry, BIO, pers. comm.), provided realistic interpolation of currents between the instruments. Model results using this time series of current profiles as input, are shown in Figure 12. Predicted depth of the top current meter, computed for each profile, is shown as the solid line. The broken line is the instantaneous depth as measured once an hour by the pressure sensor in that same instrument. Clearly the model is seriously underestimating vertical excursions. The extent of this disagreement would be unacceptable in any practical design work.

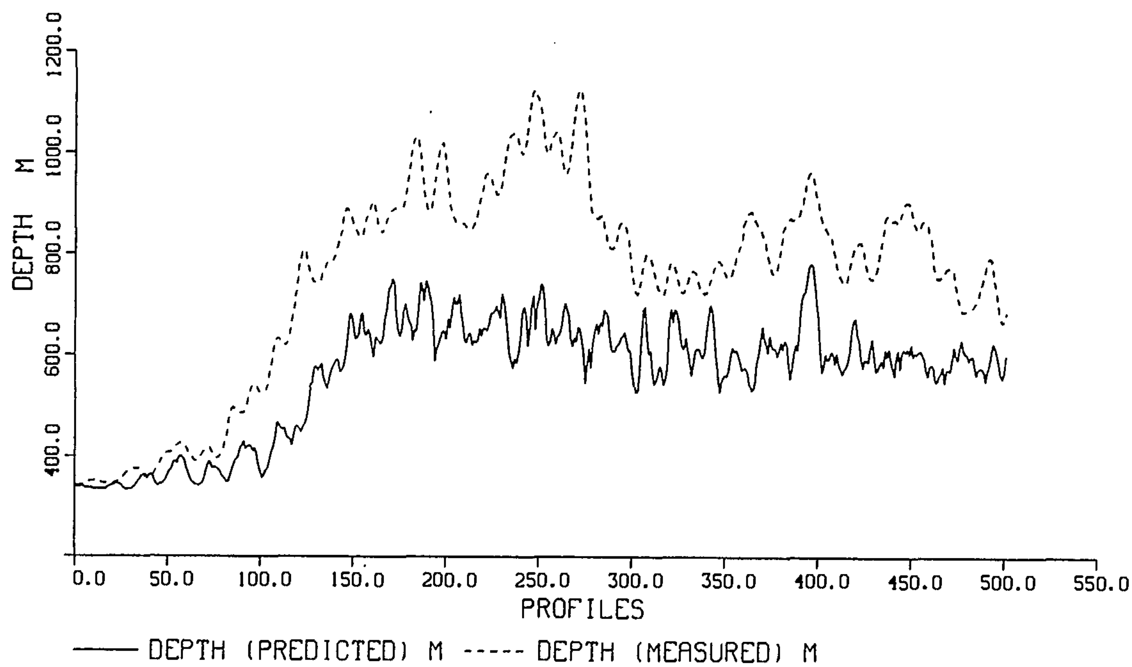


Figure 12 - Measured vs. Predicted depth of the top current meter of mooring #557 over a 500 hour period. The value used for the normal drag coefficient of the mooring line was 1.4.

The poor agreement of model predictions with actual position data prompted an attempt to tune the model output by adjustment of specific model variables. Since component buoyancies and current magnitudes are fixed measured values, normal drag coefficients become the obvious choice as "tuning parameters". For a long mooring, results of the sensitivity analysis indicate that the line drag coefficient is the best choice. Many of the drag coefficients used in the model are based on approximations to shapes with known drag characteristics, although some values are the result of actual flow studies. For the mooring line, the baseline value used was Cd_n=1.4, a value which is in line with published data from laboratory experiments on long cylinders. On the other hand, the wide and generally higher range of values determined in the field by different investigators, means that the appropriateness of this value is uncertain. Many investigators have observed strumming of mooring lines which results in increased drag. Subsequently the use of an effective drag coefficient much larger than the "textbook" value of 1.4 is frequently used in the analysis of moored and towed cables.

For the long deep-ocean mooring #557, the normal drag coefficient for both the kevlar and steel mooring lines was adjusted upward from a value of 1.4, to see if agreement between model predictions and measured depths could be improved. When a value of 2.6 was used, agreement was excellent as shown in Figure 13 except for an inability for the model to mimic measured high

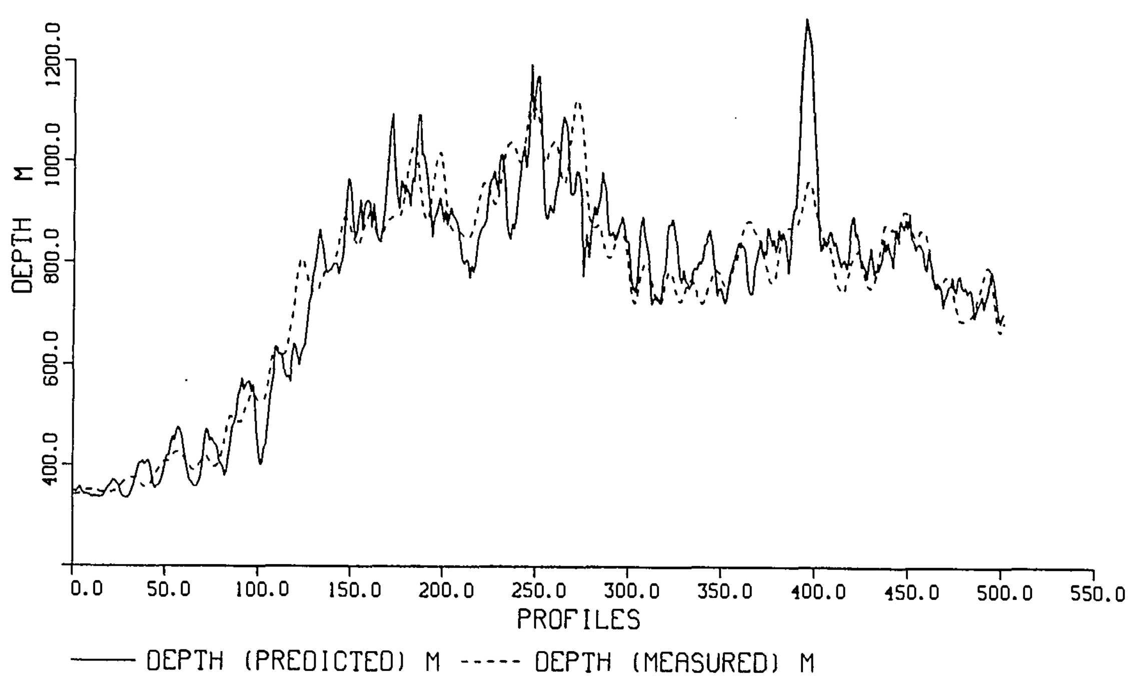


Figure 13 - Measured vs. Predicted depth of the top current meter of mooring #557 over the 500 hour period. Here a value of 2.6 is used for the mooring line drag coefficient.

frequency variations in depth. There are several possible reasons for this discrepancy. Because of the design of the Aanderaa current meter, the current profiles used to drive the model are based on hourly averages of rate while the measured depth (as well as direction) is an instantaneous reading taken at the end of the hourly cycle. Agreement on this time scale can therefore not be expected. The fact that the actual mooring system has a finite response time while the model response is instantaneous is an additional complication. Furthermore, a linear interpolation based on 4 discrete measurements to obtain profiles over 5000 m. is a significant simplification of the actual current structure. Better resolution of currents both in space and time would likely be required to mimic this higher frequency variability. As an operational tool for mooring design, the resolution of these smaller, higher-frequency depth fluctuations is not necessary since the primary objective is to predict the mooring configuration well enough to ensure that the design criteria are met.

Only on one occasion is there significant disagreement between the model prediction and the actual measured depth. Around profile 390 of Figure 13 the model greatly over-predicts the depth excursion. A closer look at the current records at this time reveal a distinct pulse in the velocity record of the top current meter (see Figure 11). The passage of this odd feature which was only 2-3 hours in duration may have been too quick to allow for full response of the mooring, although calculations in the MacLaren Plansearch report indicate that this would not be the case. A more likely explanation is that there was a complicated current structure associated with this strong current pulse seen by the top current meter which was not resolved properly in the generation of input profiles. Only extra current meters would have helped if this were true.

A second data set used in the assessment of the model was provided by mooring #619 which is shown in Figure 14. Deployed on the Scotian Shelf slope in 2005 m. of water, the mooring and its environment were different from #557 in several major ways. This mooring was less than half the length of #557, and was of a much slacker design with a typical line tension of 1200 N. (less than 1/3 that of #557). Currents were measured by four Aanderaa current meters at a frequency of one sample per minute. Rates were low and a large degree of directional variability with depth was observed (see Figure 15). In addition to a pressure sensor in the top current meter, positioning information was provided by two acoustic transponders. By deploying an array of three acoustic transponder buoys around the instrumented current meter mooring, the three-dimensional position of two in-line transponders was obtained (See McKeown (1974) for a description of this positioning technique).

Mooring #619

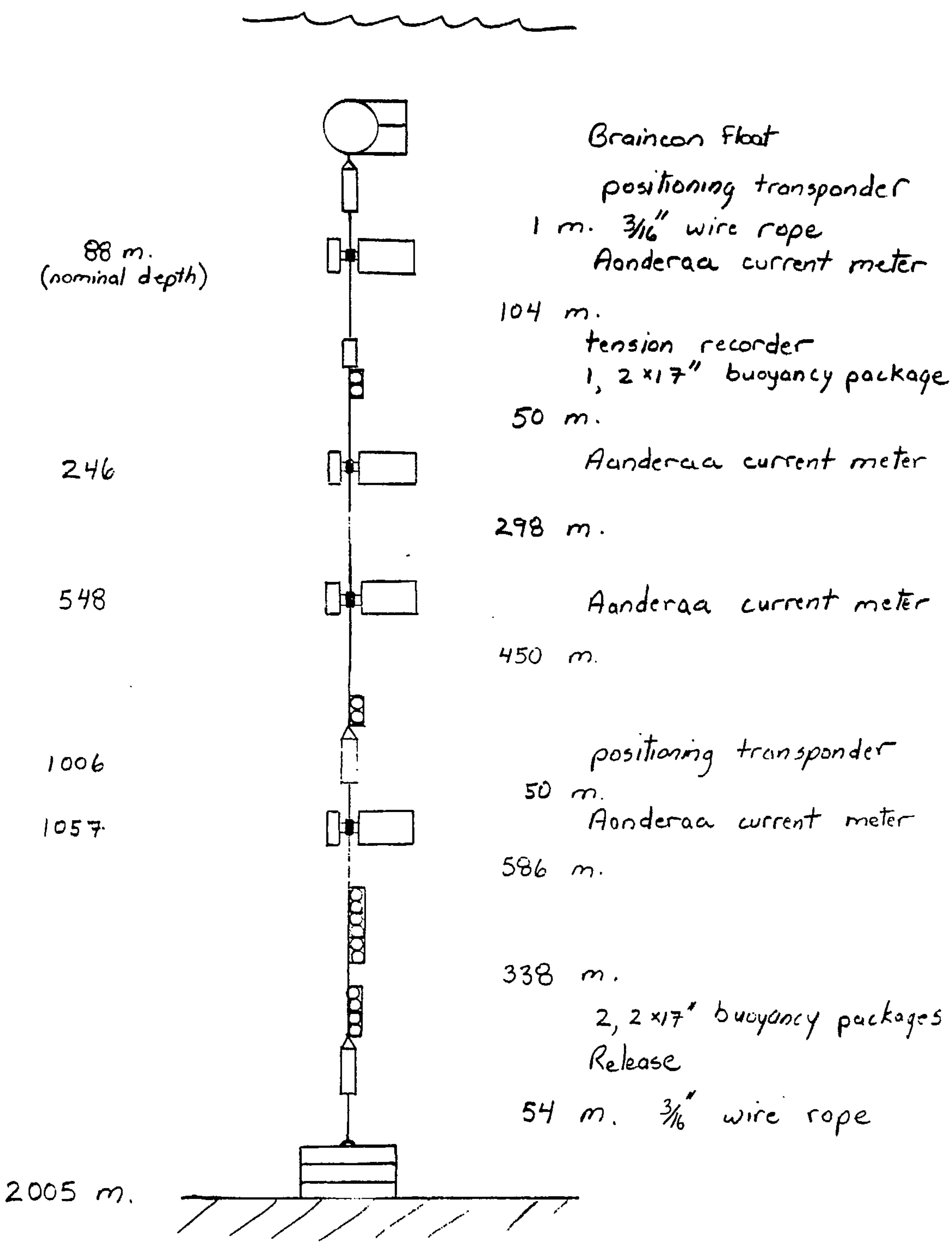


Figure 14 - An illustration of the specially instrumented mooring #619, deployed on the Scotian Slope for the acquisition of mooring excursion data.

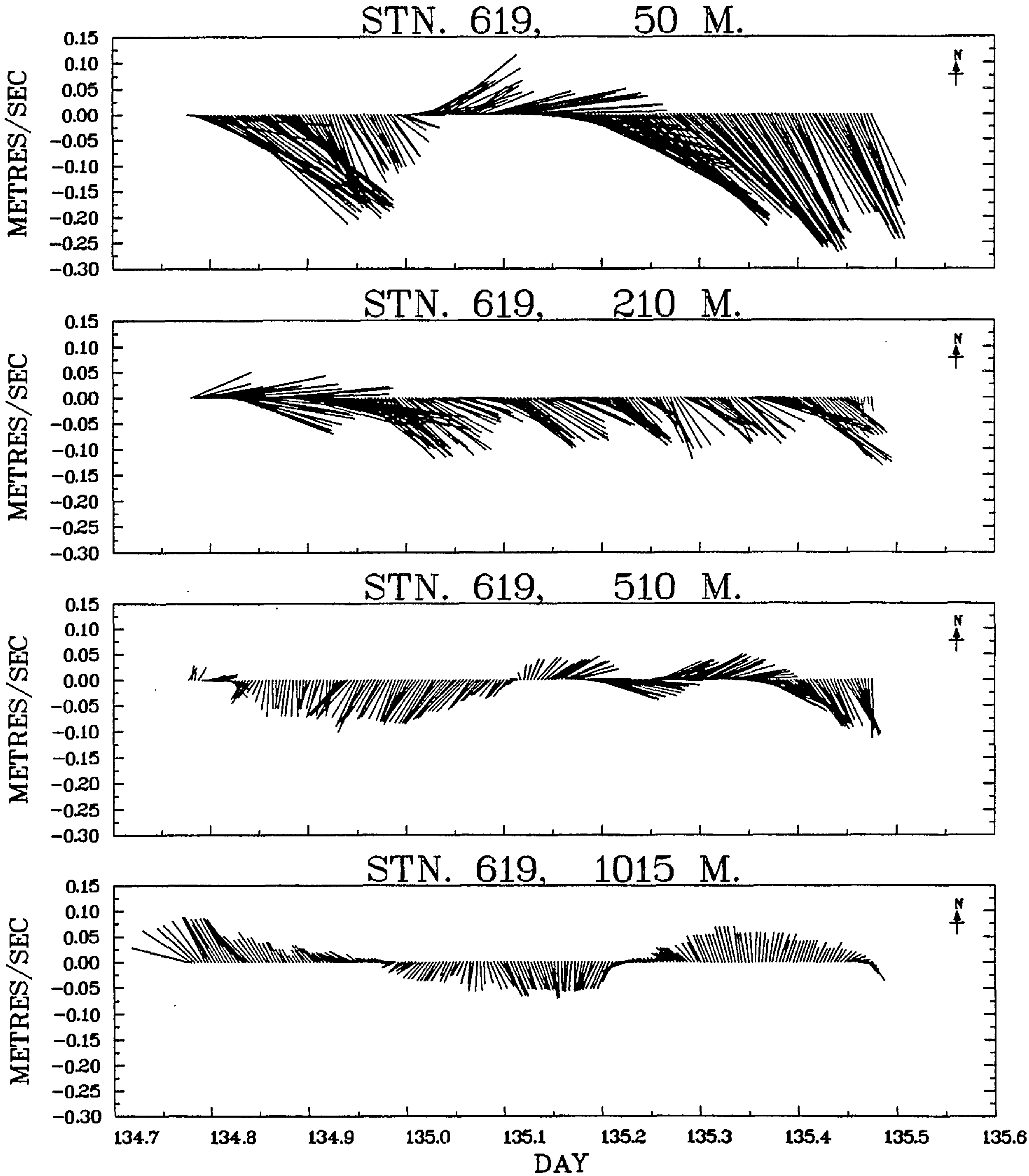


Figure 15 - 1000 minutes of current data as measured by the 4 Aanderaa instruments of mooring 619.

Model predictions of the depth of the top current meter are compared with the positioning data over a 1000 minute period in Figure 16. Two sets of predictions are shown, one using a drag coefficient of 1.4 for the mooring wire (the dotted line), and the second run with $Cd_{n(wire)}=2.6$ (the solid line). For comparison, the depth of the top current meter as measured by its pressure sensor is shown as the broken line. The depth of the top positioning transponder (located 2 m. above the current meter in the mooring line) is also displayed and is seen to correspond quite well with the pressure sensor. Only small pieces of data are available from this source because of the logistics of switching between transponders, and the rejection of poorer quality data.

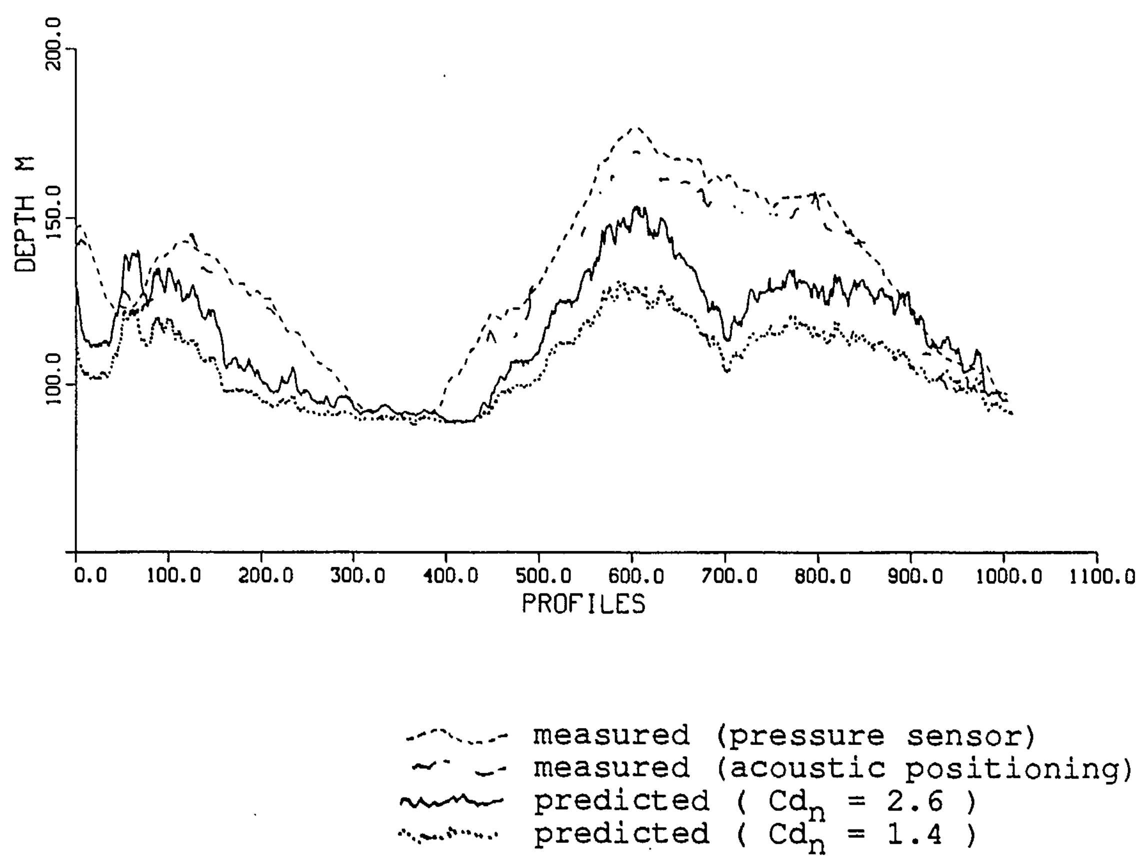


Figure 16 - Measured and predicted depths of the top current meter of mooring #619 over a 1000 minute period.

Although model agreement with the measured depth is significantly improved by increasing the line drag coefficient from 1.4 to 2.6, there are still large discrepancies between measured and predicted values. Over much of the record, the model is underpredicting the depth excursion by 20 to 30%. Around profile 700, agreement is particularly poor, with the model catching only about 1/3 of the observed excursion. The fit could be improved by further increasing the line drag. However, a comparison of the measured and predicted horizontal excursions at the top of the mooring suggests that the inaccuracy is due to insufficient resolution of the current profile. The two components of the horizontal excursion of the top of the mooring are shown in Figure 17. Over most of the period of comparison, there is fairly good agreement between the predicted and measured Y-excursion. The X-excursion however, is consistently underestimated. Since there are no computational differences in the way that these two components of down-stream excursion are treated by the model, it is likely that the discrepancies are a result of the fact that the X-component of the current forcing has been under-estimated. On two occasions, the Y-excursion too, is poorly predicted (profiles 0-50 and 650-850). Considering the good agreement otherwise, the argument that certain current events have not been resolved here as well is plausible.

Position information at a point half way down the mooring was also acquired with a second acoustic transponder. Depth, X, and Y-excursions for this instrument over the same period are shown in Figure 18. The model predictions, shown as the solid lines, show a similar kind of fit to the positioning data as the instrument at the top of the mooring. It is interesting to note that excursions at a point halfway down the mooring are about 70% those at the top, indicating that the bulk of the catenary is in the lower section of the mooring for this relatively slack, low-current case. The model is successful in mimicking this behavior, demonstrating that the "shape" of the mooring is resolved. Two of the current meters were also fitted with tilt sensors, but unfortunately the data obtained were unreliable.

Without having acquired 3-dimensional positioning data it would have been very difficult to determine the origin of the discrepancy between predicted and measured vertical excursions for this mooring. Even with the data, the interpretation above might be considered somewhat conjectural. However, the large directional variations in currents with depth (see Figure 15) are indicative of a complicated current structure. In such an environment, four instruments were insufficient in providing enough data from which to extrapolate reliable current profiles. Since model output is highly sensitive to the current profiles provided as input, accurate predictions can not be expected in this case. This is an important point to consider if the model is to be used to supplement scientific data sets by reconstructing records where sensors have failed. Such an application will be discussed later.

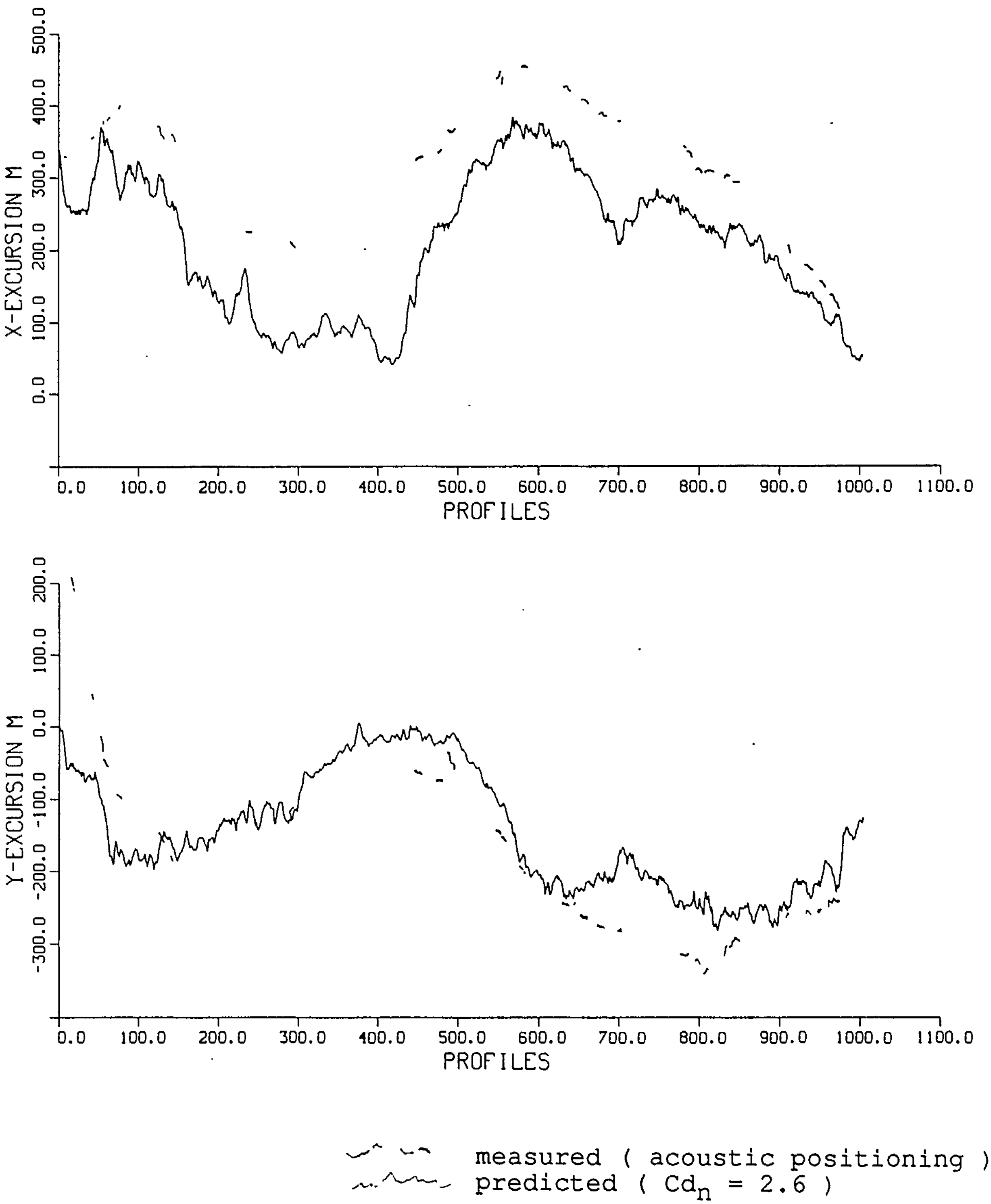


Figure 17 - Measured and predicted X and Y positions of the top of mooring #619, over a 1000 minute period.

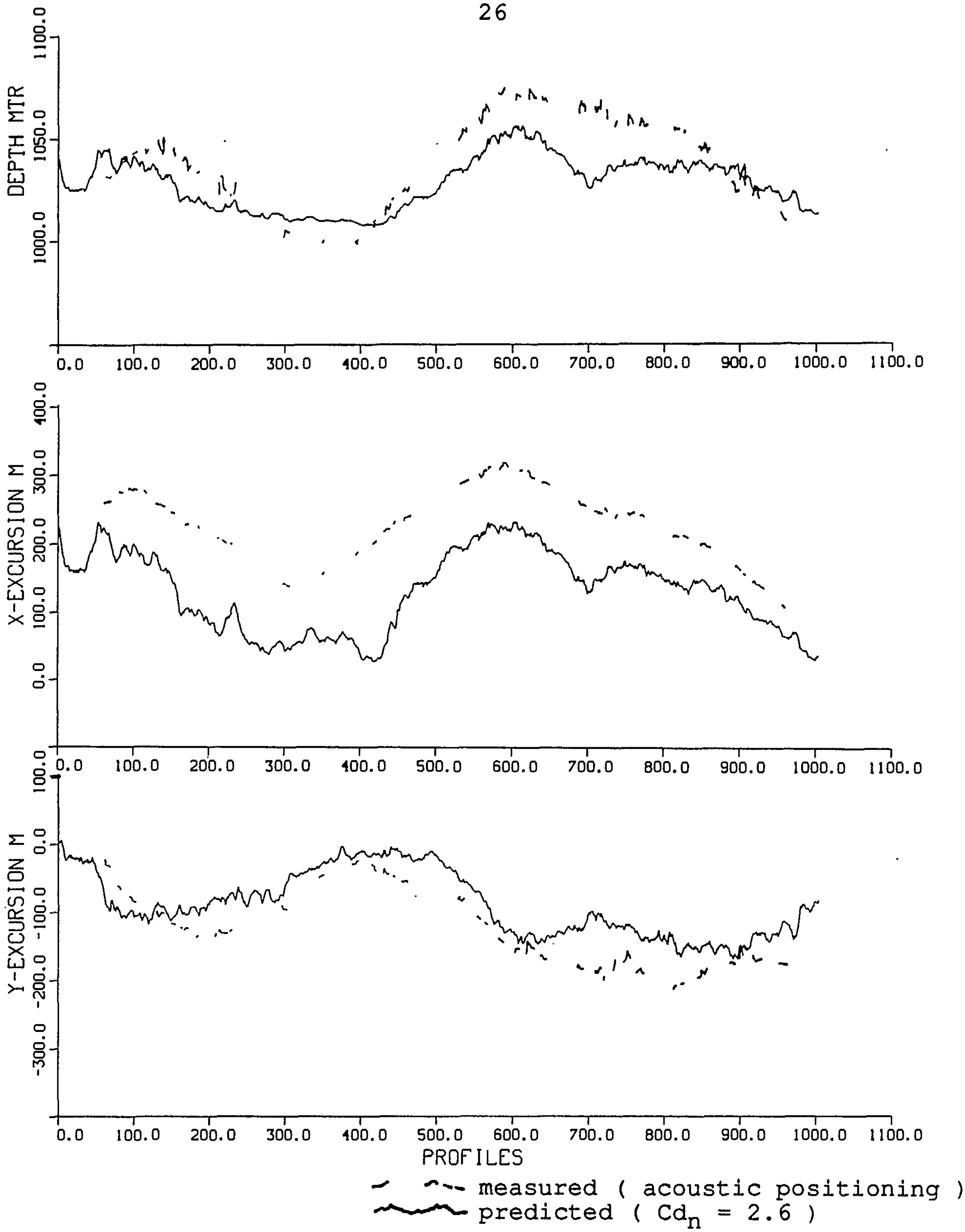


Figure 18 - Predicted and measured position of an acoustic transponder located halfway down the line on mooring #619.

Another mooring considered here for validation purposes is the short mooring, #893, shown in Figure 4. This mooring, deployed in 67 m. of water on Georges Bank, was subjected to high tidal currents with peak rates exceeding 1.4 m/s. Vertical excursions were minimized by designing the mooring to be relatively taut (3500 N typical line tension). Time series of 30 minute averaged rates as recorded by the 4 current meters are shown in Figure 19. Current direction varied through 360 degrees over the tidal cycle, but exhibited little variation with depth, and is not shown here.

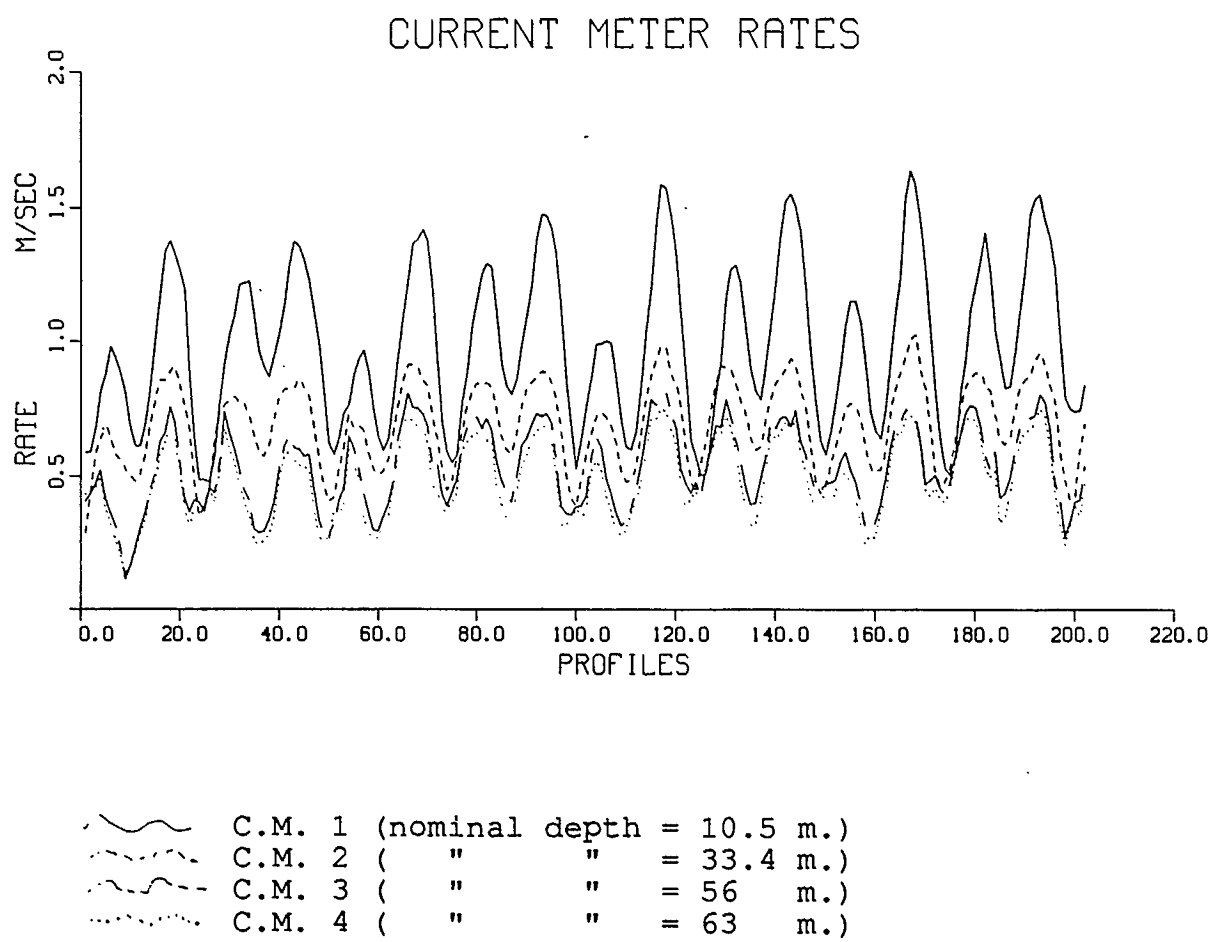


Figure 19 - 100 hours of 30 minute averaged rate data as measured by the 4 Aanderaa current meters of mooring #893.

Rates measured simultaneously by an RDI acoustic doppler profiler moored within a kilometer of the current meter mooring are shown in Figure 20. The levels shown correspond to the 4 current meter levels. There is some disagreement between the two measuring systems. The top current meter typically reads 10% higher than the corresponding RDI bin. This discrepancy is likely due to an underestimate of the near-surface currents by the RDI profiler, due to mispositioning of the doppler trackers (D. Belliveau, BIO, pers. comm.). At the 34 and 56 m. levels, the current meters typically read 10-15% lower than the RDI profiler. The RDI measurements at these levels are consistent with measurements obtained from a ship-mounted Ametek Doppler Profiler and the results of a tidal current prediction model run for this area, while those from the two current meters are not. This discrepancy is discussed in detail by Loder et. al. (1989), where it is hypothesized that the underestimation of currents by the two current meters is due to a shielding of the paddle-wheel rotors when mooring strumming prevents the instruments from staying aligned directly into the flow.

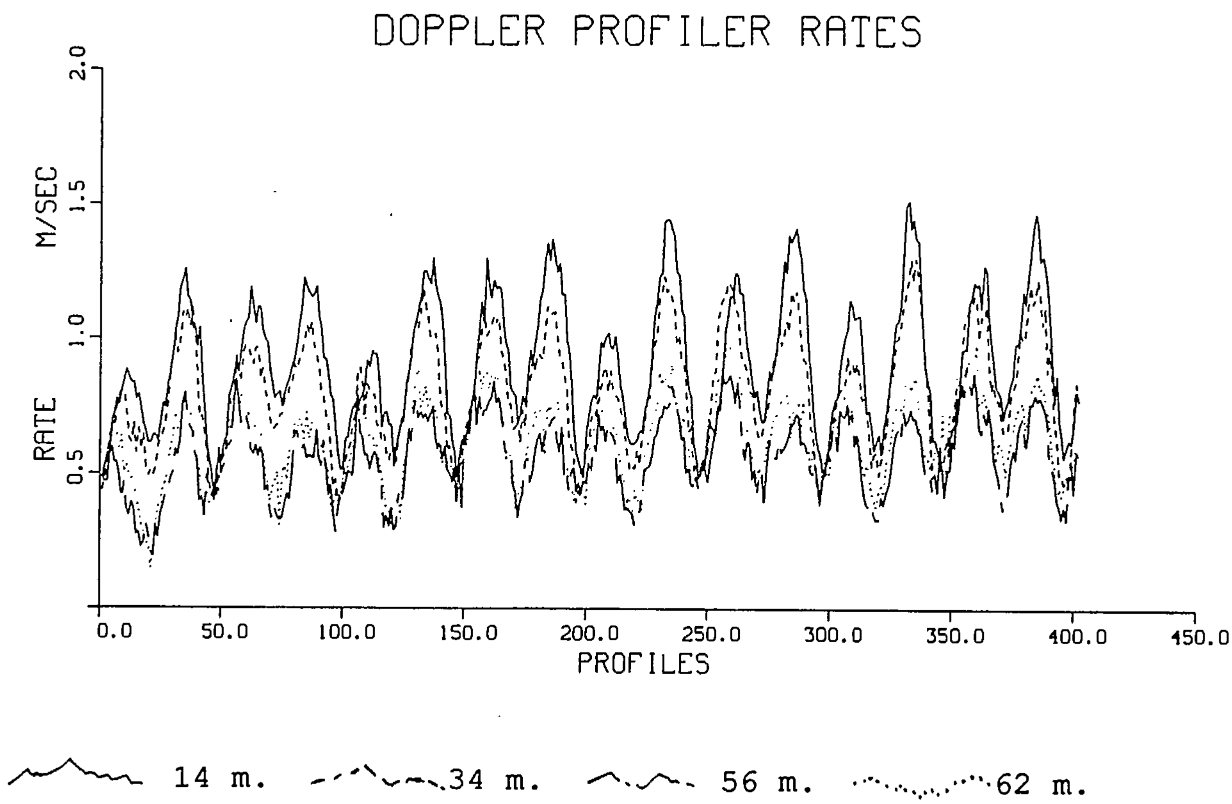


Figure 20 - 100 hours of 15 minute averaged RDI Doppler Profiler rate data. The displayed levels correspond to the approximate depths of the Aanderaa instruments of mooring #893, moored nearby.

The sensitivity analysis demonstrated that of the adjustable parameters, model output was most sensitive to instrument normal drag. For mooring #893, the Viny floats used for in-line buoyancy comprise 70% of the total frontal area presented by the mooring. The normal drag coefficient of this mooring component is therefore the obvious choice for a "tuning parameter" when model predictions are matched to measured depths. The baseline value of 1.1 is based on empirical evidence for similar packages.

Shown in Figure 21 is a comparison of the model predicted depth of the top two current meters with depths as measured by pressure sensors mounted on the current meters. Profiles for input to the model were generated from the rate and direction data provided by the 4 current meters on the mooring. A correction for the change in water depth due to the M_2 tide whose amplitude was approximately 0.6 m, has been made to the pressure record. Corrections for the other tidal components which are of smaller amplitude, have not been made. The drag coefficient for the Viny float package has been adjusted upwards to 1.5 for this best fit.

A similar comparison using RDI data as input to the model instead of the current meter data is shown in Figure 22. A much more detailed profile has been produced by using currents measured at 9 different levels. The resulting predictions using a value of 1.1 for the normal drag coefficient of the Viny package provide an excellent match to the measured depth. As well as allowing for the reduction of the drag coefficient for the Viny float from 1.5 to 1.1 (our baseline value), the RDI data provided better resolution of certain features, particularly at the 11^{th} and 15^{th} peaks (Figure 22 vs. Figure 21). The maximum error in the predicted excursion over the 100 hour period is only 1/2 m. Depth variations due to the effects of other tidal components may in combination, be of this magnitude.

The final mooring considered in this evaluation is very similar to mooring #893, and was also deployed on Georges Bank. This mooring however, which is shown in Figure 23, was equipped with Interocean S4 current meters which record instrument tilt. Using the current data collected by the three Aanderaa instruments as input to the model, the measured depth and inclination of the lower S4 instrument was compared to model predictions, and is shown in Figure 24. A drag coefficient of 1.1 for the Viny buoyancy packages has been, used and a correction for the M_2 tidal amplitude has been made. Over the 150 hour period considered, the maximum discrepancy between the measured and predicted inclinations is only 3 degrees. It is interesting to note that although the model tends to under-predict vertical excursions during one phase of the tide (every second peak), predicted inclinations are still in excellent agreement with the measurements. Since mooring catenary is concentrated near the bottom, predictions of inclination further up the line are less sensitive to inaccuracies in the current profiles used for input than are the predictions of depth.

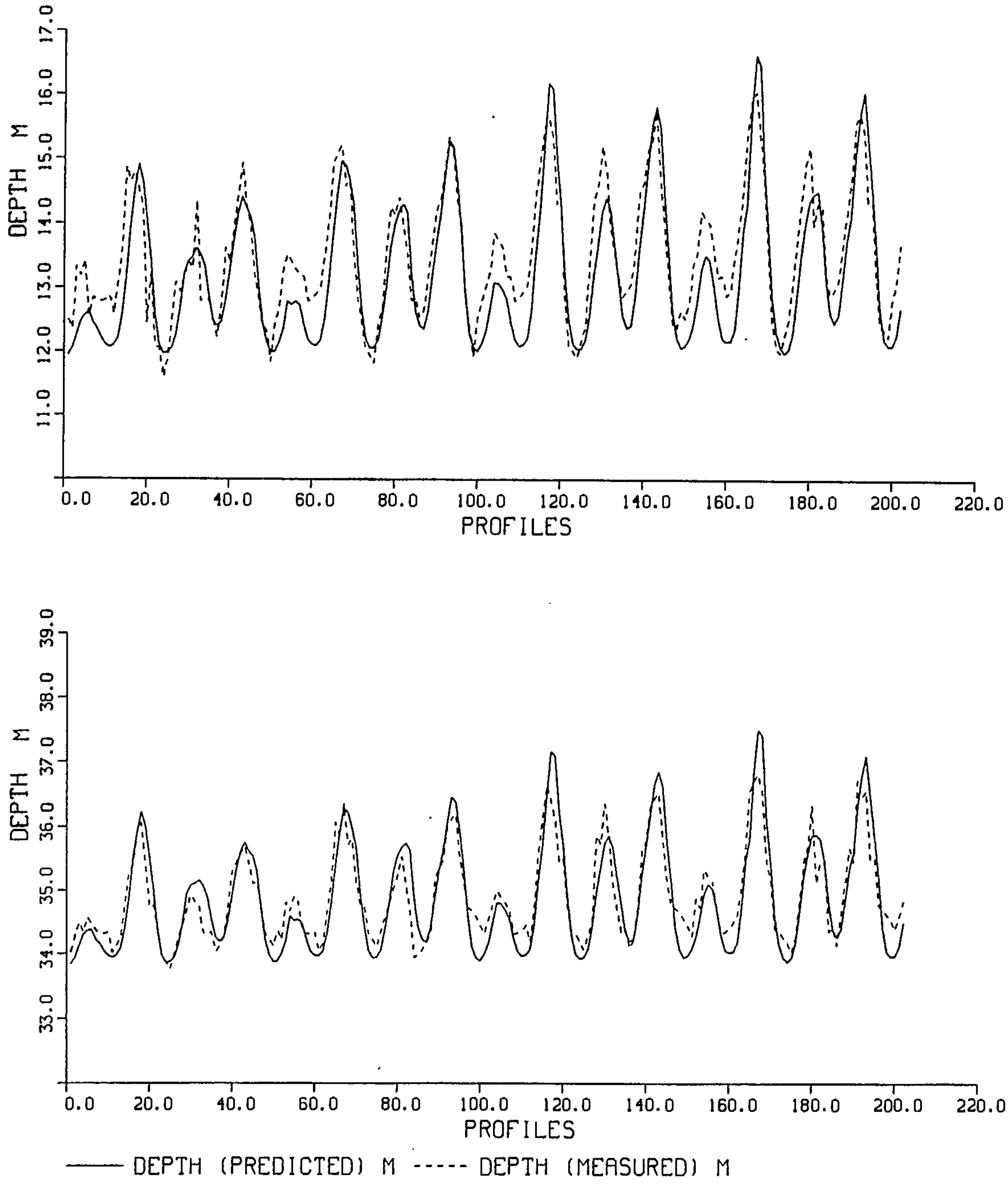


Figure 21 - Measured and predicted depths of the top two current meters of mooring #893 over a 100 hour period. Predictions are based on model output where current meter data was used as input and the drag coefficient for the Viny reserve buoyancy packages was set at 1.5.

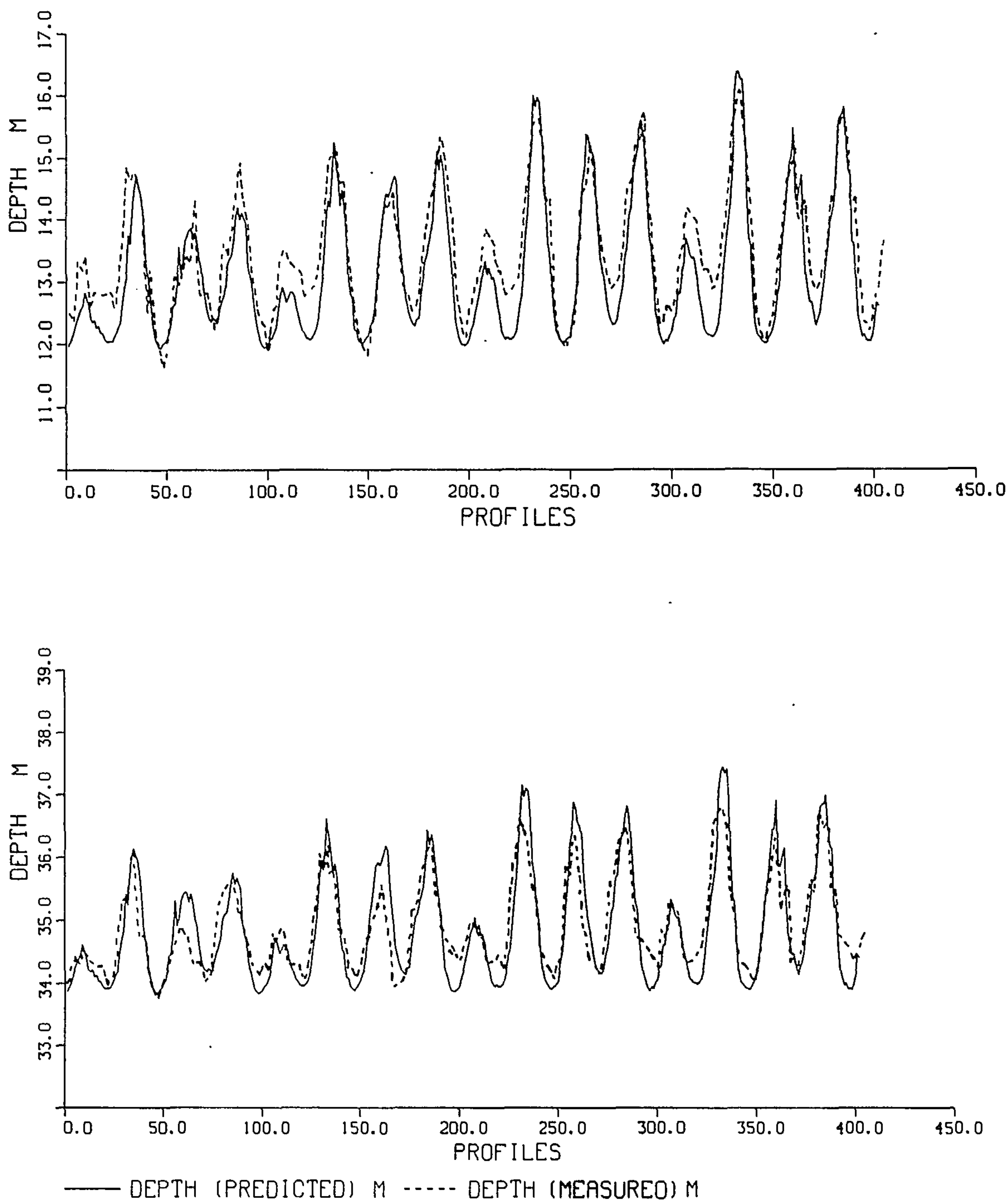


Figure 22 - Measured and predicted depths of the top two current meters of mooring #893 over a 100 hour period. RDI data has been used as input to the model, and the drag coefficient for the Viny packages was set at 1.1.

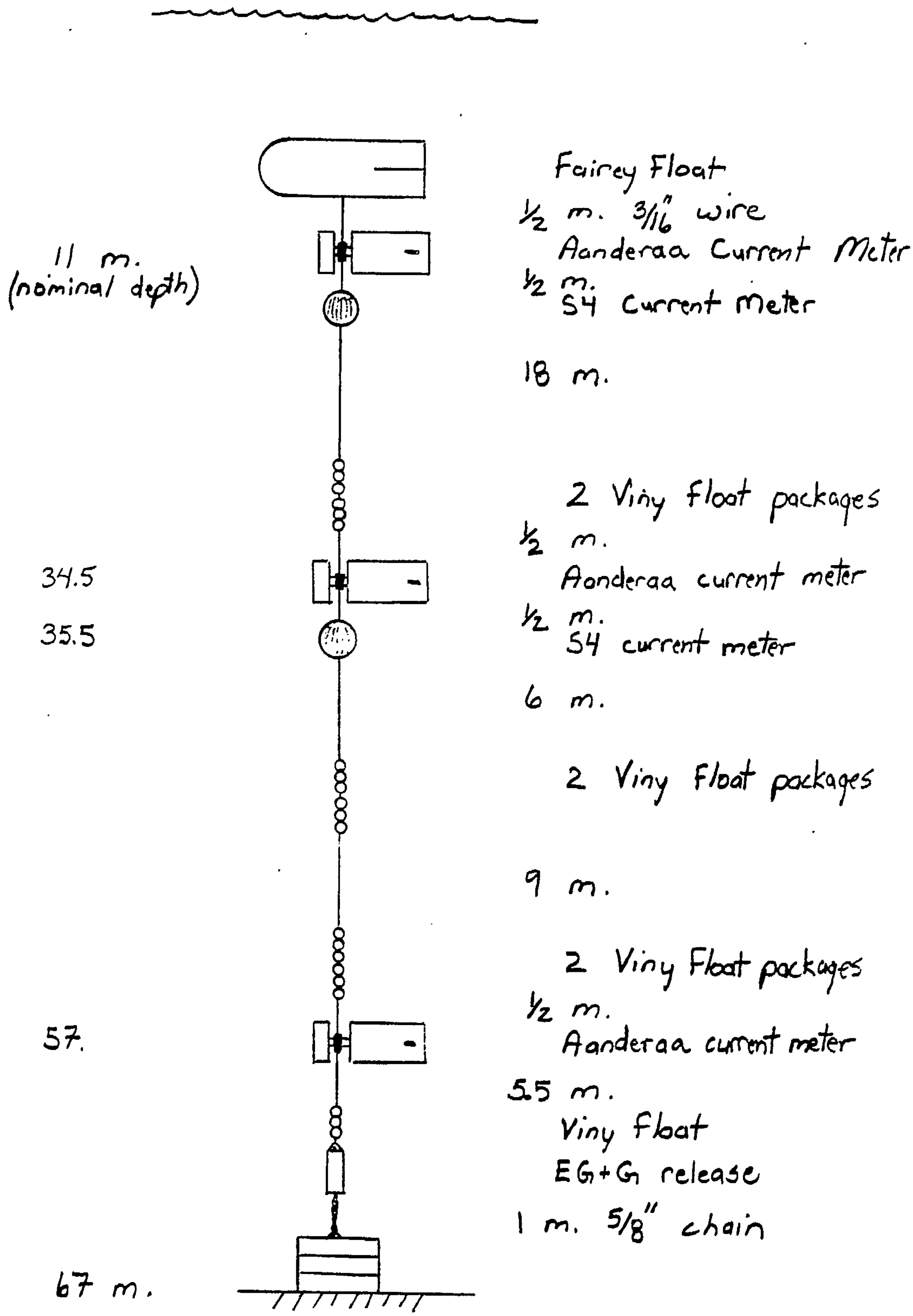
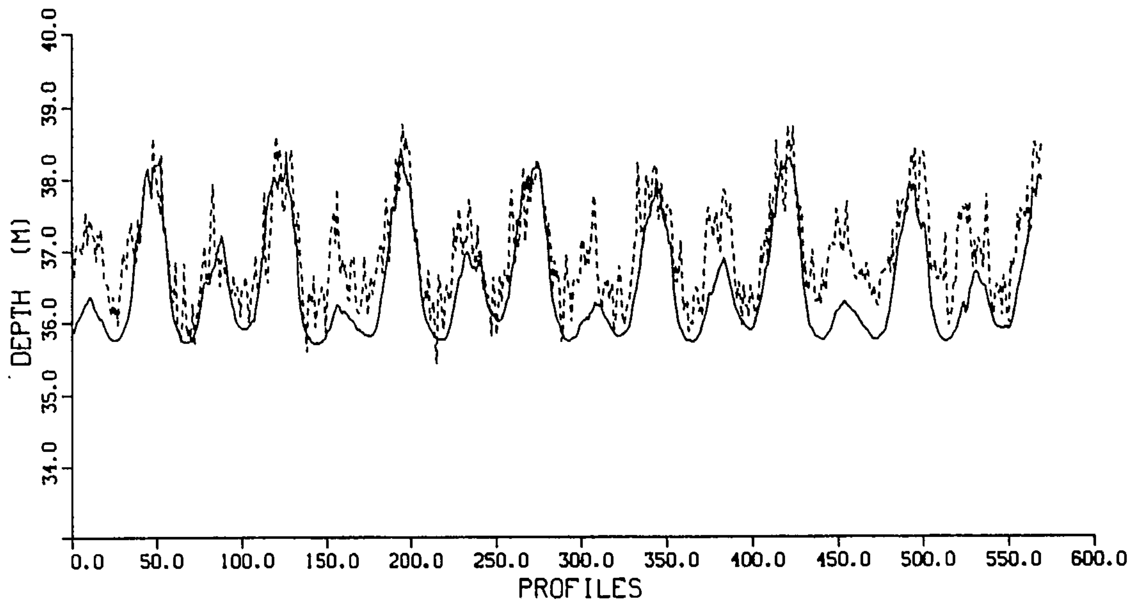


Figure 23 - Georges Bank mooring, #955.



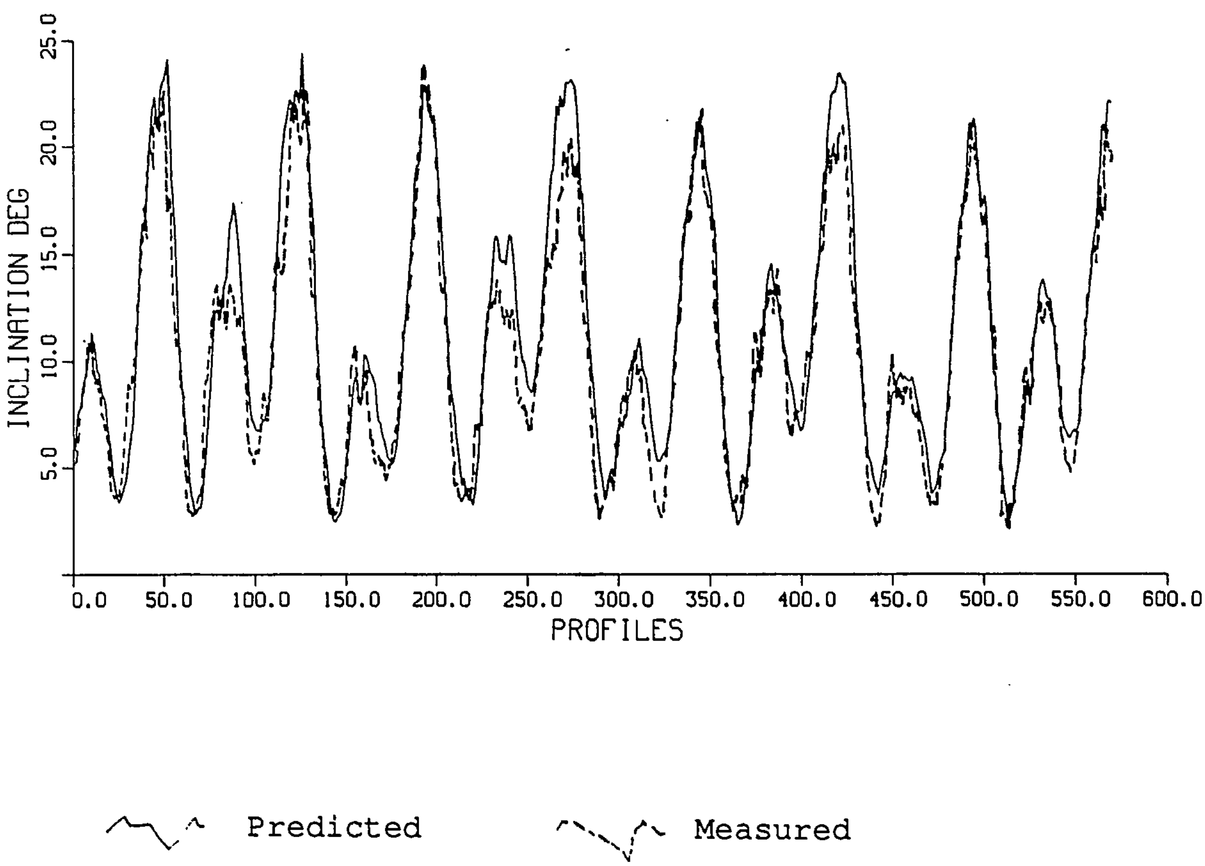


Figure 24 - Measured and predicted depths and inclinations of the lower InterOcean S4 current meter from mooring #955. Four days of 10 minute averaged data is shown. A drag coefficient of 1.1 has been used for the Viny buoyancy package.

4.4 Justification of Drag Constants Resulting from Model Tuning

The good agreement between model predictions and mooring excursion data for the four different cases studied, demonstrates that the model can accurately predict mooring excursion given that currents are sufficiently resolved. Only a minimal amount of "parameter tuning" was required to obtain a model which is accurate for the wide range of mooring types and conditions shown here. The only change was to adjust the normal drag coefficient for mooring lines upward to a value of 2.6.

Measured drag coefficients for non-vibrating cables are typically lower than 2.6. Experimental data from many investigators has been compiled by Dalton (1977), and reveals a wide range of normal drag coefficients. Numbers for both jacketed and non-jacketed stranded steel cables fall anywhere between 0.8 and 2.5. Some dependence on line type is apparent in this collection of data, but correlation with Reynolds number is low or non-existent. Coupled with the fact that the Reynolds number varies by no more than a factor of 10 or so for the range of currents expected, a dependence of model drag coefficients on Reynolds number is not justified for non-vibrating cables.

In the case of a mooring system, higher drag coefficients can be expected due to cable strumming. Meggitt et al (1981) have measured drag coefficients of 2.2 to 2.5 for various vibrating cables in the laboratory, but suggest that since it is unlikely that strumming would be occurring simultaneously over the full mooring length, these numbers represent the maximum values when applied in the field. Griffin and Vandiver (1984) have also conducted experiments to determine drag coefficients for strumming cables. They measured drag coefficients that varied with time over a range of 2.4 to 3.2 for both bare cables and for cables with attached masses. The consistency of their results over many trials using several different cable/attached-mass configurations indicate that the effect of strumming is not highly intermittent, but results in a fairly steady and repeatable enhancement of the normal drag of the system. The value of 2.6 required to obtain the best model fit to data is well in line with these observations and has proven to be suitable with a range of mooring designs and environmental regimes.

Vandiver's data presented by Griffin (1982) demonstrates that although the drag coefficient for a vibrating cable varies substantially (from 2 to 3) at a frequency on the order of 0.05 hz., variation at lower frequencies is very much smaller. Since mooring response is on the order of minutes, most of the dynamical effect of fluctuating drag due to strumming will not affect mooring orientation, if Vandiver's results are representative. The use of a constant effective drag coefficient which includes the mean effect due to strumming is therefore reasonable for predicting mooring orientation. A comparison of model predictions and measured depths for mooring #557 (figure 13) supports this notion. There is generally good agreement over the entire 500 hour period indicating that the use of a constant drag coefficient is adequate.

It must be pointed out that where fatigue due to tension cycling of cables and in-line mooring components is the primary concern, it is important to model fluctuating tensions and therefore changes in effective drag coefficients, at all frequencies. Where predictions of mooring orientation are the objective, these dynamical effects are far less of a concern.

An overview of the cable strumming problem by Griffin (1982) discusses several different mooring models, both static and dynamic, all of which take strumming affects into account. Some of these models include numerical techniques to predict strumming, while others simply rely on a strumming amplification factor to apply to the line normal drag coefficient.

The BIO mooring model does not at present include code to predict strumming. The results presented here indicate that a constant value of 2.6 for the line drag coefficient is suitable for making predictions of mooring orientation. The user can however alter drag coefficients easily. As more data sets become available, it will be possible to determine whether some adjustment of drag coefficients for different "classes" of moorings is appropriate so that model predictions match measurements for all cases. If necessary, a set of "strumming amplification factors" can be generated where each factor would be appropriate for a certain type of design and current regime.

Since the contribution of the mooring line to the total frontal area of a short mooring is small, uncertainty in an appropriate line drag coefficient is of little consequence. For mooring #893, the in-line buoyancy was the main drag element. The normal drag coefficient for this mooring component was increased to 1.5 to get the best fit when current meter data was used as input, but when RDI data was used, the base-line value of 1.1 was appropriate. Even though the RDI profiler underestimated near-surface currents, the effect was limited to the top few levels of a detailed profile that was generated from estimates at 18 levels. The impact of this instrument problem on the model estimates is therefore quite small. Considering the better fit provided by the RDI profiler driven model predictions, and indications that the 34 and 56 m. level current meters were reading low, the value of 1.1 for the Viny buoyancy package drag coefficient is clearly the better choice.

It is not entirely clear, however, that variation in the drag of in-line mooring components such as the Viny buoyancy package, may not be a factor. Cable strumming has already been discussed, and has been shown to significantly degrade mooring performance. It is likely that the in-line packages also oscillate over a certain Reynolds number range. Submerged spheres and cylinders in steady flow generate a wake as Karman vortices are shed in a regular fashion, over a Reynolds number range of 10^4 to 10^5 (Albertson et. al., 1960, Hoerner, 1965). This phenomenon will tend to cause the object to oscillate at the Strouhal frequency (= 0.2 * Velocity / Diameter), thereby increasing its drag. As currents vary, and mooring components pass into and out of this regime, their effective drags may change. There is no indication of this effect from the model work on mooring #893. Although current speed and therefore the Reynolds number, vary by more than a factor of three, the match between predictions and measurements remains excellent using constant drag coefficients.

Listings of all of the relevant coefficients and characteristics of the various mooring components is provided in the Appendix of this report. Besides replacing component weights with more accurate values, the only other change made to achieve good agreement between predictions and measured excursions for the four different moorings considered here, was to increase line normal drag coefficients to 2.6. These lists then, reflect the results of the model validation work, and provide a description of the various mooring components appropriate for moorings of very different designs and environments. With these parameters the model accurately predicts mooring orientation over a wide spectrum of mooring designs.

Further improvements to model accuracy may be possible as more data sets like the four considered here become available. Of primary concern is to establish if differences in design and environment significantly affect the strumming properties of a mooring, and therefore the choice of a line drag coefficient. However, the high level of accuracy achieved at this point, easily meets that required for mooring design, and engineering studies. In fact in its present state, the model can be used to enhance the scientific data set as well. Applications of the model are discussed in the next section.

5.0 Practical Applications of the Validated Model

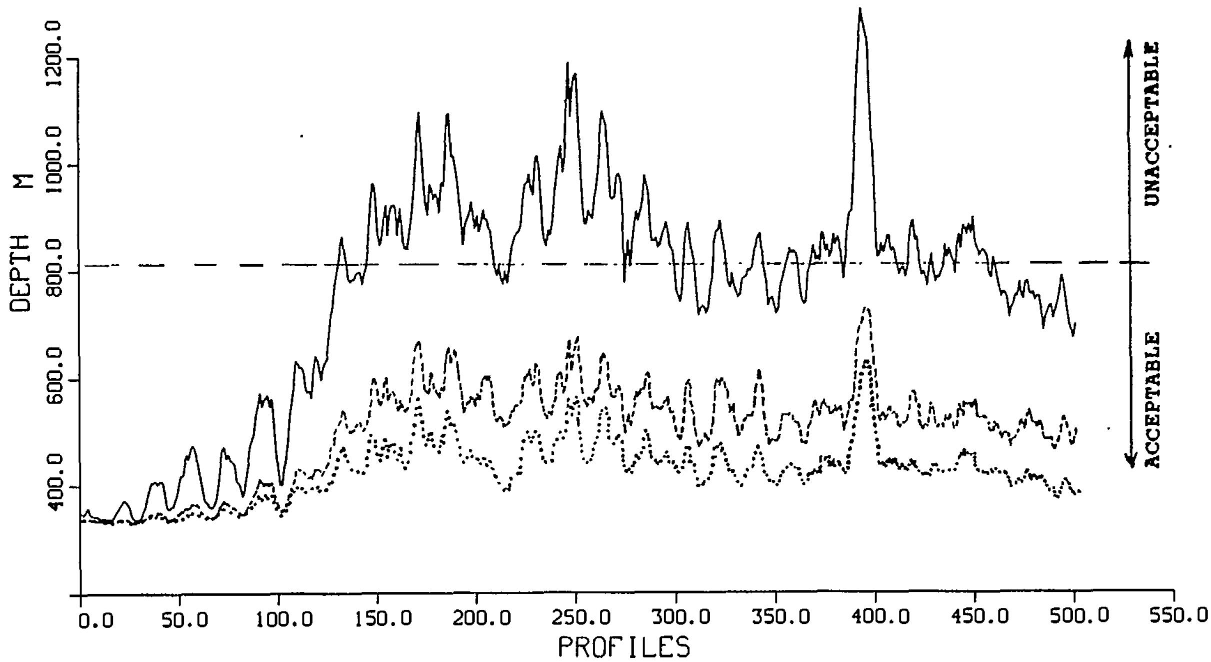
The validated computer model is a valuable tool for ensuring that all established design criteria are met. By determining that the model accurately predicts mooring orientation for a variety of designs and conditions, this routine operational procedure can be done with confidence. For the scientist, accurate predictions of instrument excursions can be important in the experimental design. Knowing the extent to which instruments will be displaced before-hand may affect the sampling strategy.

The mooring model also plays a critical role in engineering efforts towards improving mooring design. In conjunction with results of the model sensitivity analyses, the model can be used to indicate what changes to the mooring design are most effective in improving performance. Engineering and monetary efforts can therefore be applied in the most efficient manner. Recently, the model has been used to redesign BIO's high-current, deep water moorings. Instrument excursions and inclinations observed by mooring #557 during the year long deployment in the Gulf Stream were excessive on many occasions. Predictions over a 500 hour period using actual current meter data as input are shown as the solid line in Figure 25. (Predicted and measured depths were shown to agree well when a normal drag coefficient of 2.6 was used for the mooring line; see Figure 13). Shown in the lower graph is the predicted inclination of the bottom current meter over the same interval. The predicted vertical excursions as great as 900 m. and instrument inclinations in excess of 40 degrees, clearly exceed established design criteria.

By studying the results of the sensitivity analysis for long moorings (Figures 5 - 7), it is clear that the only two viable ways of significantly improving performance are by increasing the amount of buoyancy in the mooring, or by reducing the normal drag of the mooring line. The broken lines in Figure 25 represent the predicted performance of a redesign of mooring #557 which operates at higher tension. The buoyancy of the main float has been increased to 8900 N. (50 % of the rated breaking strength of 3/16" wire rope), 1/4" kevlar has been replaced with 5/16" kevlar, and in-line buoyancy is distributed to keep tensions as close to the prescribed tension limits as possible while still maintaining sufficient reserve buoyancy. With these changes vertical excursions have been reduced by a factor of 3 or 4, and instrument inclinations have been brought to within acceptable bounds. Operational tensions could be increased even further by going to heavier mooring cables but the required changes to rigging, and the scaling up of other mooring components make this option undesirable.

Further improvement to the mooring design can be made by reducing the drag of the mooring line. Clay and Berteaux (1987) faired the top 500 m. of line in their "High Performance Oceanographic Mooring" (HIPOM) design to reduce excursions. The effect of a similar change on the mooring evaluated here is also shown in Figure 25. The dotted lines represent predictions for the high tension case where all of the 3/16" wire rope (that is, the top 1400m. of the mooring cable), is faired. A drag coefficient of 0.4 has been chosen based on the results of other investigators who have used strut fairings to reduce mooring line drag (Milburn (1977), Schott et. al. (1985), Clay and Berteaux (1987)). This improvement is partially offset by the increased line diameter due to the fairing, but there is still a factor of 4 reduction in the normal line drag over the faired section of the mooring and consequently, a further reduction in mooring excursion and instrument inclination.

The results of this analysis have led to a redesign of BIO's deep-ocean, high-current moorings. The replacement of the main buoyancy package with a more efficient float, and the use of 5/16" kevlar to allow for operation at higher tension, have been incorporated into the design. Although fairing the upper portion of the mooring would further improve performance, this option has been rejected since it was felt that the limited improvement provided could not at present be justified when costs and operational concerns were considered.



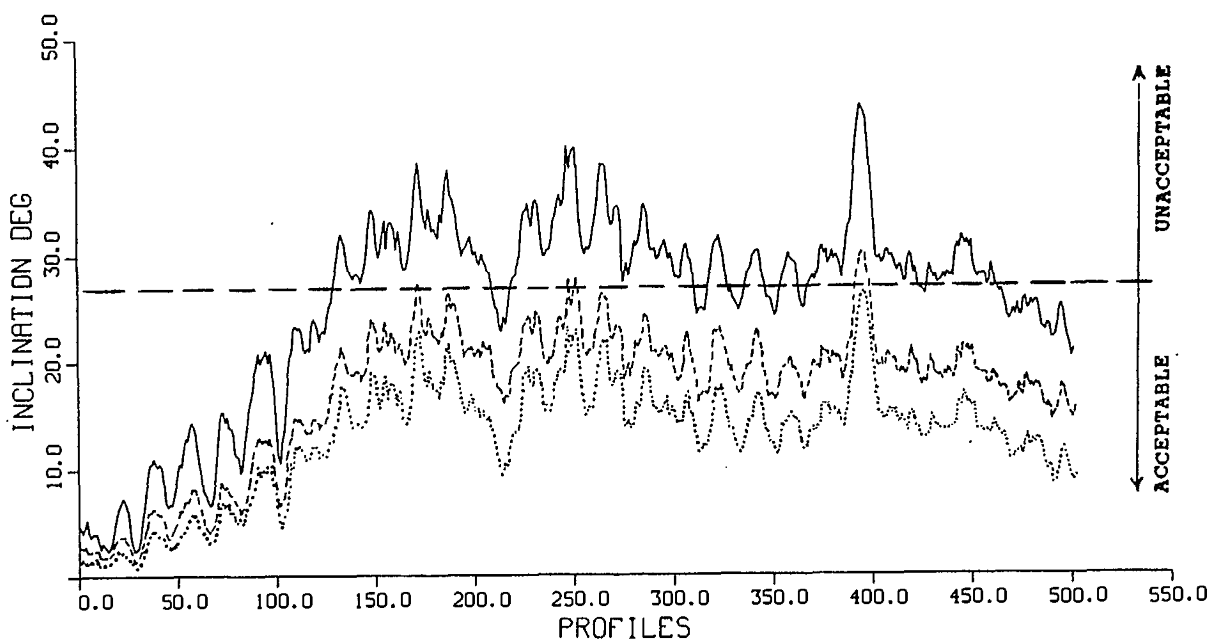


Figure 25 - Predictions of the depth of the top current meter, and the inclination of the bottom current meter for mooring #557. The solid lines are for the mooring as shown in Figure 2. The dashed line is for a modified design where the buoyancy of the main float has been increased to 8900 N., and the 1/4" kevlar has been replaced with 5/16" kevlar to handle the greater tension. The dotted line is the predicted performance of the high tension design with the top 1400 m. of mooring line faired.

The high degree of accuracy exhibited by the model in the analysis of mooring #893 suggests other promising applications for the model. Often additional depth information could enhance the scientific data set collected by an instrumented mooring. As an example, some moored thermistor chains which measure temperature at many levels along the mooring only provide a depth record at the top of the chain. If current information is available from measurements made nearby, the model can be used to derive depth records for any number of points along the chain. This was the case in a study of frontal processes on Georges Bank. Besides an extensive current measuring array of which mooring #893 and the doppler profiler records discussed earlier were a part, moored thermistor chain measurements were also made. One of the objectives of this study was to look at lateral temperature fluxes. In the presence of strong vertical temperature gradients as occur in the seasonal thermocline, vertical excursions of the thermistors can result in temperature variations that contribute to artificial temperature fluxes. When accurate current information is available, the computer model can be used to construct depth records which coincide with each of the thermistors in the chain so that these extraneous temperature variations can be eliminated. Using a similar approach, the model could also be used to reconstruct depth records where current meter pressure sensors have malfunctioned, or were not available for all instruments in a mooring.

Another application for the scientist is to use the model as a check on the validity of the user-defined interpolation of currents between instrument levels. The number of instruments in a mooring is often limited by financial constraints. Although one would hope that the experimental design will be such that the depth resolution of the data collected will be sufficient to meet the scientific objectives of the experiment, it is possible that a more complicated current structure than anticipated might be encountered. In this situation, the scientist may want to make inferences about currents at unsampled levels based on other sources of data or theoretical arguments. By comparing model predictions with the measured instrument depths, the scientist can determine whether these inferences are reasonable. Clearly, there are applications for an accurate computer model beyond those of design engineering.

6.0 Summary

The development and enhancement of the BIO mooring model has resulted in the evolution of a reliable and accurate tool for the design of operational current meter moorings. A comparison of model predictions with actual mooring position data has been completed using moorings with very different characteristics. Tuning of critical model variables has provided a model which accurately predicts an equilibrium mooring orientation for a full range of sub-surface designs.

Adjustment of model variables was minimal with the exception of the alteration of the normal drag coefficient of the mooring lines. To obtain a good fit to measurements for a long mooring, this value was increased from 1.4 to 2.6, a value consistent with drag coefficients quoted in the literature for strumming cables. Other investigators have also accounted for this effect in similar models, and in dynamic mooring models as well, where predictions of high frequency tension fluctuations are required. The model does not provide a way of predicting the extent to which a specific design will strum but relies on the user providing appropriate drag coefficients. Further work is therefore required to determine whether different "strumming amplification factors" are appropriate for the different mooring designs and conditions possible. This can be accomplished by comparing depth information with model predictions for moorings representative of different types, as the data becomes available. For short moorings, this is not a critical factor.

An accurate mooring model is a valuable tool considering the critical role moored instrumentation plays in many oceanographic programs. Its use in the design process not only ensures that established criteria are met, but that mooring motion is minimized so that the best possible platform for instrumentation is provided. As a development tool it can be used to ensure that engineering and monetary efforts directed towards improving operational designs are applied in the most effective manner. This was the case for the redesign of BIO's deep-ocean high-current moorings. Model runs, and the results of the sensitivity analysis, demonstrated that the largest gains in mooring performance could be made by increasing mooring tension. Subsequently, the choice to go to a larger sub-surface buoyancy package was made.

Considering the high degree of accuracy attainable, as demonstrated in the analysis of the short mooring #893, other applications are possible. Several techniques have been suggested here which will allow the scientist to enhance a data set after mooring recovery. As familiarity with the model increases and the limitations associated with these types of applications are kept in perspective, it is hoped that the model will prove useful not only at the design stage, but also in the processing and interpretation of the scientific data collected by moored instruments.

Acknowledgements: The author wishes to thank Dave McKeown for making the acquisition of the acoustic positioning data presented in this report possible. I also would like to thank George Fowler and John Loder for their helpful suggestions during the preparation of this manuscript.

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APPENDIX - Mooring Component Description

B.I.O. STANDARD COMPONENTS

1	3/16 IN GALVANIZED STEEL WIRE (3X19)	
2	UNSPEC GALVANIZED STEEL WIRE	
3	JACKETED 3/16 IN STEEL WIRE	(OD 1/4)
4	UNSPEC STEEL WIRE	
5	UNSPEC STEEL WIRE	
6	3/16 IN STAINLESS STEEL WIRE (3X19)	
7	UNSPEC STAINLESS STEEL WIRE	
8	UNSPEC STAINLESS STEEL WIRE	
9	UNSPEC STAINLESS STEEL WIRE	
10	UNSPEC STAINLESS STEEL WIRE	
11	3/16 IN KEVLAR 29 (JACKETED)	
12	1/4 IN KEVLAR 29 (JACKETED)	
13	5/16 IN KEVLAR 29 (JACKETED)	
14	UNSPEC KEVLAR	
15	UNSPEC KEVLAR	
16	UNSPEC SYNTHETIC LINE	
17	UNSPEC SYNTHETIC LINE	
18	UNSPEC SYNTHETIC LINE	
19	UNSPEC SYNTHETIC LINE	
20	UNSPEC SYNTHETIC LINE	
21	3/8 IN CHAIN	
22	1/2 IN CHAIN	
23	5/8 IN CHAIN	
24	3/4 IN CHAIN	
25	UNSPEC CHAIN	

CYLINDRICAL INSTRUMENTS

26	AANDERAA C.M.	(0.8M)
27	VACM	(2.0M)
28	BRAINCON C.M. #381	(0.8M)
29	UNSPEC	
30	UNSPEC	
31	UNSPEC	
32	UNSPEC	
33	DAC RELEASE #723A, NO TENS BAR	(1.1M)
34	AMF RELEASE #322	(1.6M)
35	DAC RELEASE #723A, TENSION BAR	(1.1M)

SPHERICAL INSTRUMENTS

36	S4 CURRENT METER	(0.5M)
37	UNSPEC	
38	UNSPEC	

BUOYANCY PACKAGES

39	PKG OF 3 VIMY FLOATS	(1.2M)
40	PKG OF 2 17IN GLASS BALLS	(1.0M)
41	UNSPEC	
42	UNSPEC	
43	FAIREY FLOAT, LARGE	(0.5M)
44	DEEP SUBSUR. BUOY, BENTHOS BALLS	(1.3M)
45	DEEP SUBSUR. BUOY, CORNING BALLS	(1.3M)

COMPONENT CHARACTERISTICS

	A M**2/M	W NEWTON/M	AW M**2	RBS NEWTON
1	.4762500E-02	-.7673184E+00	.1781393E-04	.1808202E+05
3	.6350000E-02	-.6289973E+00	.3166922E-04	.1808202E+05
6	.4762500E-02	-.7673184E+00	.1781393E-04	.1494603E+05
11	.4762500E-02	-.4554980E-01	.1781393E-04	.1556800E+05
12	.6350000E-02	-.7966766E-01	.3166922E-04	.2668900E+05
13	.7937500E-02	-.1252175E+00	.4948315E-04	.3736500E+05
21	.3492500E-01	-.2145304E+02	.9579938E-03	.4715116E+05
22	.4445000E-01	-.3677664E+02	.1551792E-02	.8006801E+05
23	.5715000E-01	-.5925126E+02	.2565207E-02	.1227709E+06
24	.6850000E-01	-.8464465E+02	.3685285E-02	.1734807E+06
26	.8150000E-01	-.2377019E+03	.5216811E-02	
27	.1500000E+00	-.1712566E+03	.1767146E-01	
28	.1210000E+00	-.8618431E+02	.1149901E-01	
33	.1400000E+00	-.7683293E+02	.1539380E-01	
34	.1375000E+00	-.1946097E+03	.1484893E-01	
35	.1400000E+00	-.1577097E+03	.1539380E-01	
36	.1131748E+00	-.2940000E+02	.4908739E-01	
39	.3000000E+00	.4250000E+03	.7068583E-01	
40	.4660000E+00	.4403740E+03	.1705539E+00	
43	.4400000E+00	.4448223E+04	.1160000E+01	
44	.9000000E+00	.2634716E+04	.2920000E+01	NDISK = 2
45	.9000000E+00	.1881940E+04	.2240000E+01	NDISK = 0

STRETCH COEFFICIENTS

		STRUCT STR	YOUNGS MOD (NEWTON/(M**2)
1	3/16 IN GALVANIZED STEEL WIRE (3X19)	.1370000E-02	.2068300E+12
2	UNSPEC GALVANIZED STEEL WIRE	.1370000E-02	.2068300E+12
3	JACKETED 3/16 IN STEEL WIRE (OD 1/4)	.1370000E-02	.2068300E+12
4	UNSPEC STEEL WIRE	.1370000E-02	.2068300E+12
5	UNSPEC STEEL WIRE	.1370000E-02	.2068300E+12
6	3/16 IN STAINLESS STEEL WIRE (3X19)	.3030000E-02	.1999400E+12
7	UNSPEC STAINLESS STEEL WIRE	.3030000E-02	.1999400E+12
8	UNSPEC STAINLESS STEEL WIRE	.3030000E-02	.1999400E+12
9	UNSPEC STAINLESS STEEL WIRE	.3030000E-02	.1999400E+12
10	UNSPEC STAINLESS STEEL WIRE	.3030000E-02	.1999400E+12
11	3/16 IN KEVLAR 29 (JACKETED)	.1270000E-01	.1500000E+11
12	1/4 IN KEVLAR 29 (JACKETED)	.1270000E-01	.1500000E+11
13	5/16 IN KEVLAR 29 (JACKETED)	.1270000E-01	.1500000E+11
14	UNSPEC KEVLAR	.1270000E-01	.1500000E+11
15	UNSPEC KEVLAR	.1270000E-01	.1500000E+11

DRAG COEFFICIENTS

			NORMAL	TANGENTIAL
1	3/16 IN GALVANIZED STEEL WIRE (3X19)		.2600000E+01	.1000000E-01
2	UNSPEC GALVANIZED STEEL WIRE		.2600000E+01	.1000000E-01
3	JACKETED 3/16 IN STEEL WIRE	(OD 1/4)	.2600000E+01	.1000000E-01
4	UNSPEC STEEL WIRE		.2600000E+01	.1000000E-01
5	UNSPEC STEEL WIRE		.2600000E+01	.1000000E-01
6	3/16 IN STAINLESS STEEL WIRE (3X19)		.2600000E+01	.1000000E-01
7	UNSPEC STAINLESS STEEL WIRE		.2600000E+01	.1000000E-01
8	UNSPEC STAINLESS STEEL WIRE		.2600000E+01	.1000000E-01
9	UNSPEC STAINLESS STEEL WIRE		.2600000E+01	.1000000E-01
10	UNSPEC STAINLESS STEEL WIRE		.2600000E+01	.1000000E-01
11	3/16 IN KEVLAR 29 (JACKETED)		.2600000E+01	.1000000E-01
12	1/4 IN KEVLAR 29 (JACKETED)		.2600000E+01	.1000000E-01
13	5/16 IN KEVLAR 29 (JACKETED)		.2600000E+01	.1000000E-01
14	UNSPEC KEVLAR		.2600000E+01	.1000000E-01
15	UNSPEC KEVLAR		.2600000E+01	.1000000E-01
16	UNSPEC SYNTHETIC LINE		.2600000E+01	.1000000E-01
17	UNSPEC SYNTHETIC LINE		.2600000E+01	.1000000E-01
18	UNSPEC SYNTHETIC LINE		.2600000E+01	.1000000E-01
19	UNSPEC SYNTHETIC LINE		.2600000E+01	.1000000E-01
20	UNSPEC SYNTHETIC LINE		.2600000E+01	.1000000E-01
21	3/8 IN CHAIN		.1400000E+01	.1000000E-01
22	1/2 IN CHAIN		.1400000E+01	.1000000E-01
23	5/8 IN CHAIN		.1400000E+01	.1000000E-01
24	3/4 IN CHAIN		.1400000E+01	.1000000E-01
25	UNSPEC CHAIN		.1400000E+01	.1000000E-01
26	AANDERAA C.M.	(0.8M)	.1400000E+01	.1050000E+01
27	VACM	(2.0M)	.1400000E+01	.1050000E+01
28	BRAINCON C.M. #381	(0.8M)	.1400000E+01	.1050000E+01
29	UNSPEC		.1400000E+01	.1050000E+01
30	UNSPEC		.1400000E+01	.1050000E+01
31	UNSPEC		.1400000E+01	.1050000E+01
32	UNSPEC		.1400000E+01	.1050000E+01
33	DAC RELEASE #723A, NO TENS BAR	(1.1M)	.1400000E+01	.1050000E+01
34	AMF RELEASE #322	(1.6M)	.1400000E+01	.1050000E+01
35	DAC RELEASE #723A, TENSION BAR	(1.1M)	.1400000E+01	.1050000E+01
36	S4 CURRENT METER	(0.5M)	.6000000E+00	.6000000E+00
37	UNSPEC		.6000000E+00	.6000000E+00
38	UNSPEC		.6000000E+00	.6000000E+00
39	PKG OF 3 VIMY FLOATS	(1.2M)	.1100000E+01	.6000000E+00
40	PKG OF 2 17IN GLASS BALLS	(1.0M)	.1100000E+01	.6000000E+00
41	UNSPEC		.6000000E+00	.6000000E+00
42	UNSPEC		.6000000E+00	.6000000E+00
43	FAIREY FLOAT, LARGE	(0.5M)	.6000000E+00	.1400000E+01
44	DEEP SUBSUR. BUOY, BENTHOS BALLS	(1.3M)	.6000000E+00	.1400000E+01
45	DEEP SUBSUR. BUOY, CORNING BALLS	(1.3M)	.6000000E+00	.1400000E+01