



# **Near-Bed Cohesive Sediment Processes**

**Development of a Self-Contained System  
for Long-Term Field Measurements**

**R Atkins  
M C Ockenden**

**Report SR 341  
September 1993**



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## Contract

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## **Summary**

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### **Near-Bed Cohesive Sediment Processes Development of a Self-Contained System for Long-Term Field Measurements**

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This report describes the development of a self-contained system for making long-term field measurements of bed elevation changes and the associated near-bed hydrodynamics and cohesive sedimentary parameters in estuarine environments. These measurements are required to ensure the understanding of these parameters and their interaction with bed elevation changes. In particular, more information is sought on the relative contributions of each tide in a spring-neap cycle and on the effect of waves. This knowledge is necessary to refine and verify the algorithms used in numerical models of the erosion and deposition processes. This should lead to improved confidence in these models, in particular when making long-term predictions of bed elevation changes.

The measurement system will be capable of unattended deployment for a complete spring-neap cycle (15 days) and measures the following:

- (1) Turbulent velocities in 3 orthogonal directions close to the bed.
- (2) Turbidity levels at 3 heights in the bottom 1m of the water column.
- (3) Water depths.
- (4) Wave characteristics.
- (5) Bed elevation changes.

The system has integral signal conditioning, data logging facilities and power supplies. The basic calibrations of all the instruments in the measurement system have been established during laboratory tests.

The instruments included in the measurement system have been selected not only on the grounds of the nature and range of the data required but also to minimise the system's power consumption. The choice of annular electromagnetic current meters ensures the system is suitable for use in wave or current only conditions or combined waves and currents.

All the underwater components of the system have been pressure tested to a depth equivalent to approximately 10m of water column.

A suite of data analysis computer programs has been developed to process the data collected by the measurement system efficiently.

For further information please contact the Marine Sediments Group.



# Contents

Page

Title page  
 Contract  
 Summary  
 Contents

<b>1</b>	<b>Introduction</b> .....	<b>1</b>
1.1	Background .....	1
1.2	Objectives .....	2
<b>2</b>	<b>System design</b> .....	<b>2</b>
2.1	Framework .....	2
2.2	Integral signal conditioning and data logging .....	3
2.3	Power consumption .....	4
2.4	Data processing software modifications .....	4
2.5	Provision of waterproof housings .....	5
<b>3</b>	<b>Instrument specification</b> .....	<b>5</b>
3.1	Turbulent velocities .....	5
3.2	Water depths and wave characteristics .....	6
3.3	Suspended sediment concentrations .....	6
3.4	Bed elevations .....	7
3.5	System control and data logging .....	8
<b>4</b>	<b>Data Analysis</b> .....	<b>9</b>
4.1	Turbidity sensors .....	9
4.2	Electromagnetic Current Meters .....	10
4.3	Pressure transducer .....	12
4.4	Bed elevation monitor .....	13
<b>5</b>	<b>Conclusions</b> .....	<b>14</b>
<b>6</b>	<b>Acknowledgments</b> .....	<b>14</b>
<b>7</b>	<b>References</b> .....	<b>15</b>

## Table

Table 1 Basic instrument calibrations

## Figures

Figure 1 Schematic of long-term field measurement system  
 Figure 2 Data processing flow diagram  
 Figure 3 Calibration of annular electromagnetic current meter: Head A  
 Figure 4 Calibration of annular electromagnetic current meter: Head B  
 Figure 5 Calibration of the pressure transducer  
 Figure 6 Calibration of the turbidity sensors  
 Figure 7 ARX bed elevation monitor calibrations  
 Figure 8 End segment of ARX test

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**Contents** *continued*

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**Plates**

Plate 1	Test assembly of instrument framework
Plate 2	Annular electromagnetic current meters

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# 1 Introduction

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## 1.1 Background

The ability to predict long-term bed level changes is very important to engineers managing coastal areas of mud-flat, saltmarsh or dredged channels, particularly where there has been some man-made change to the estuary. In order to interpret physical model data or apply numerical models to engineering projects with confidence it is important to build on the experience of previous short-term measurements, and to collect field data over longer periods for calibration of models.

This project extends the knowledge and experience gained from an earlier project funded by DoE (PECD 7/6/157) and the Commission of European Communities under MAST-1, G6M, in which a simple bed frame was deployed on inter-tidal mud-flats. The frame was successfully used to measure deposition of cohesive sediment during single tides (spring and neap), (Diserens, Delo and Ockenden, 1991). The data from the deployments was used to test deposition algorithms for short-term predictions (Diserens, Ockenden and Delo, 1991), and to improve the algorithm for a non-uniform cohesive sediment (Ockenden, 1993).

Unattended field measurements have been made by the Cohesive Sediment Dynamics Study Group (COSEDS) in Marsden Bay, off the north-east coast of Britain. Shear stresses were calculated from the velocity energy spectrum, derived from high frequency velocity fluctuations (COSEDS, 1991). Comparisons were made with shear stresses calculated from log-profiles of velocity, and the method of calculating shear stress from the velocity energy spectrum was found to be more applicable for field measurements. However, in contrast to the HR Wallingford deployments on inter-tidal mud-flats, the sediment at the COSEDS study site was predominantly sandy and the deployments were made in quite deep water (approximately 25m).

Measurements of high frequency velocity fluctuations on inter-tidal mud-flats have been made in the Loire Estuary in France by Le Hir, Bassoullet and Jestin (1992). The SAMPLE system (in French: Station Autonome MultiParamétrique pour le Littoral et les Estuaires) was used to measure velocities, suspended sediment concentrations and pressure fluctuations. Some difficulties were encountered during initial deployments with signal interference on one of the velocity components, so shear stresses were calculated from the longitudinal component of kinetic energy. No measurements of bed elevation changes were made, but records of velocity and concentration were made in a fluid mud layer.

These previous studies identified the need to relate the hydrodynamics to the effect on the bed, which may be measured as a change in the local suspended sediment concentration or a change in bed elevation. However, the change in local suspended sediment concentration can be affected by sediment advected from elsewhere. On the other hand, changes in bed elevation may be very small within a tide, so measurements of bed elevation need to be at very high resolution.

## 1.2 Objectives

The objectives of this study are:

- To build a self-contained field measurement system, to deploy the equipment for short and long-term monitoring of hydrodynamics in wave or current only conditions or combined waves and currents and to measure changes in bed elevations.
- To identify the relative contributions from each tide during a spring-neap cycle and to advise on choice of tides (spring, neap or a combination of both) for numerical modelling of cohesive sediment bed changes.

This report describes the development of the self-contained system. The basic idea was similar to the simple bed frame used in the earlier contract, but with a more robust design suitable for unattended deployments of up to several weeks.

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## 2 System design

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The field measurement system designed and used during the previous contract was well suited to the short-term attended deployments described in those contract reports. However, for the long-term unattended deployments on drying mud-flats required in this current contract the earlier system had to be modified to include the following provisions:

- Improve the supporting framework for the instruments and the security of the instruments.
- Provide integral signal conditioning and data logging facilities.
- Optimise the number of instruments deployed to produce sufficient data from which conclusions could be drawn as to the nature of the near-bed hydrodynamic and sedimentation processes.
- Provide enough power for the system to operate for the deployment periods envisaged for the system.
- Modify and/or write data processing software to deal efficiently with the large quantities of raw data expected.
- Provide waterproof housing for instrumentation packages and power supplies.

Figure 1 shows a schematic of the new measurement system.

### 2.1 Framework

For deployments on inter-tidal mud-flats the instruments will be mounted on a 'goalpost' system similar to that used in the fieldwork carried out in the River Taw in August/September 1988 when detailed measurements were made of the hydrodynamic and sedimentary parameters over large sandy bedforms (Atkins, Soulsby, Waters and Oliver, 1988). The 'goalpost' system consists of

a framework constructed from horizontal and vertical elements and results in an extremely rigid base on to which equipment can be mounted. The framework for deploying the new field measurement system on mud-flats is smaller than that used in the Taw and trapezoidal rather than rectangular in plan. It consists of four circular uprights (2m long by 0.045m diameter) driven vertically as deep as possible into the bed. These are connected by horizontal crossbars (also 2m x 0.045m) to form a rigid framework. The use of circular section material minimises the drag forces on the framework and any local bed scour which may be caused in the vicinity of the bed penetrating vertical uprights. The instruments will be mounted on the short side of the trapezoidal frame, which will be aligned parallel with the main flow direction, and the electronics and data logging equipment approximately 5m away beyond the long side of the frame, ie. inshore of the instruments. The framework and instruments are shown in Plate 1.

Initial field deployments of the modified system will be developmental deployments over short periods with personnel in attendance to make adjustments to the measurement system if required. However, with long-term deployments it will be necessary to protect the measurement system as far as possible from (wilful) damage. Measures will be taken to protect any exposed cables, which are arguably the most vulnerable part of the system. This will be achieved by passing the cables through flexible galvanised electrical conduit.

## **2.2 Integral signal conditioning and data logging**

Signal conditioning is the modification of the analogue voltage outputs from the measurement instrumentation included in the system prior to digitisation to ensure that the analogue signals are compatible with the digital data acquisition system. In the modified system all of the instrument outputs are compatible with the selected data logger and signal conditioning is limited to filtering the analogue signals to prevent aliasing. This is achieved using low-pass filters with a 2Hz cut-off frequency. This anti-alias filtering is necessary to prevent high frequency signals, ie signals at frequencies above 2Hz being aliased (folded back) into the signals of interest.

The short-term measurement system had signal output cables running over the beach from the instrumentation to the shored based PC used to collect the field data. This new long-term measurement system has been designed for unattended operation for periods of up to 16 days, ie to include a complete spring-neap cycle. It is anticipated that this new system will evolve such that it can be deployed inter-tidally or wholly submerged, with the instruments mounted on a bed frame for the full period. In an inter-tidal deployment there is a significant risk that if a shore based data logging system were employed output cables, running over a beach, would be damaged either accidentally or wilfully. With a wholly submerged deployment it would be very inadvisable for the data logger to be remote from the instrumentation because of possible damage to cables due to any relative movement between the data logger and the instruments. The data logger would therefore need to be mounted on the bed frame on which the instruments were mounted. For these reasons it was decided that an integral data logger was necessary. The system is then self-contained allowing more flexibility in where it can be positioned. Data logging for this new system has to be capable of performing the analogue to digital conversions (ADC's) on the output signals from the instruments incorporated in the system, preferably at a sampling frequency determined by the user, and storing all the digital data collected internally. The storage of raw data was a



major factor in the choice of data logger. A storage capacity of at least 120Mbytes is required to record integer values (2bytes storage per value) at 5Hz on 8 analogue channels for 16 days.

### **2.3 Power consumption**

As the long-term measurement system has been designed for unattended deployments in excess of two weeks it must have its own underwater power supply and it is important that power requirements are minimised. The system has been designed to be powered from an unregulated 12V DC supply and currently has a total power consumption requirement of approximately 800mA.

### **2.4 Data processing software modifications**

The previous measurement system used a commercial data acquisition and processing software package which required the use of a dedicated computer in both the field and office. The software package was considered too inflexible for processing the data from this new measurement system, mainly due to the large volume of data that is expected. Existing computer programs have therefore been modified and combined to produce a suite of programs for data analysis. Figure 2 shows the flow of data through the analysis procedures.

Data processing consists of a number of stages, each stage being completed with the minimum of intervention (ie. making full use of overnight or weekend computer time). Stage 1 consist of pre-processing operations (programs 'PRETRB' and 'PREARX'). 'PRETRB' reads the raw turbulent data and calculates the time-averaged mean and variance of the uncalibrated data on each data channel. Before proceeding with any analysis, these interim results are examined using the spreadsheet 'MEANS' which automatically plots the uncalibrated time-averaged values. 'PRETRB' also re-writes the raw data into a standard format direct access (DA) file, to minimise the storage needed for the raw data and to speed access time to the data in future applications. A further feature of 'PRETRB' is a searching routine in which possible transients (spikes) in the raw data are identified so that they may be edited from the data if necessary. 'PREARX' is used to append the data retrieved from the ARX bed elevation monitor to the DA file.

Stage 2 (program 'MAINAL') applies the instrument calibrations to the raw data and calculates the time-averaged means of the various measured parameters from the data. A frequency analysis of the velocity records is also carried out. Output from this program includes a file which summarises the calibrated time-averaged results such that they may be examined quickly using the spreadsheet 'MEANS'.

The water depths and wave characteristics are obtained from the pressure transducer data in Stage 3 using the program 'LTWAVE' (a modified version of the standard HR pressure transducer analysis routines developed by HR's Field Studies Section). Prior to running 'LTWAVE' the program 'PTDATA' is used to extract the pressure transducer data from the DA file and apply a calibration.

## 2.5 Provision of waterproof housings

The earlier measurement system used trailing cables up the beach to provide power to the instrumentation and record data at a shore-based logging station. This is not be feasible for long-term unattended deployments. Therefore it is necessary that all power supplies and data logging facilities are provided within a short distance of the measuring instruments. Waterproof 'pods' have been adapted to house all the power supplies and non-waterproof instrument electronics. The pods are cylindrical and cast in glass reinforced plastic, approximately 0.4m diameter and 0.35m high. The top bolts to the main body of the pod with an 'O' ring seal between the two pieces to prevent water entering. The two pods adapted for this measurement system, shown in Plate 1, along with the underwater electronics package for the electromagnetic current meters (see Section 3.1) have been tested to a pressure equivalent to 10m of water column without leaking.

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## 3 Instrument specification

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### 3.1 Turbulent velocities

There is now a large range of current meters available which can be used to make reliable turbulent velocity measurements in water, based on four generic modes of operation. These operating modes are electromagnetic, acoustic, laser and hot film or bead current meters. Of the four systems the electromagnetic and acoustic types are available in a sufficiently robust form for field work, but in view of the type of deployment envisaged with this new measurement system, electromagnetic current meters would be more suitable as they are more rugged in construction. Electromagnetic current meters (ECMs) are available in 3 specific forms: discus, spherical and annular.

The earlier measurement system used discus ECMs which were readily available. Combined wave and current flow fields, in which it is anticipated that this current system will be mainly employed, are three dimensional in nature and discus ECMs are susceptible to flow distortion when the angle of incidence of the flow onto the face of the discus sensor is greater than about 25° (Griffiths, Collar and Braithwaite, 1978). The open construction of the annular ECM head allows uninhibited flow in the vicinity of the sensors on the head and minimises flow distortion around the head. Early discus ECMs were also well known for random changes in zero flow voltage (offsets) caused by electronic drift and the cleanliness of the head. To overcome this problem of drift it was necessary to make a independent measurement of the mean velocity, usually using a propeller current meter in parallel with the ECM, in order that these zero flow voltages could be assessed and reliable results obtained.

To overcome some of these problems a complete Valeport Series 800 model annular ECM system was purchased by HR Wallingford and has been dedicated to this measurement system. This system consists of two 170mm diameter annular heads and an underwater electronics package. The latest electronics are employed in the ECMs making them free from electronic drift, which thus alleviates a main cause of uncertainty in any data collected. However, it has yet to be established what effect head cleanliness has on the offsets. During initial field trials the parallel use of propeller current meters will be continued to assess this problem. The annular ECM heads are shown in Plate 2 in their field configuration for measuring the three orthogonal velocity components.

The system output from each head is nominally  $1\text{V per ms}^{-1}$ , bi-directional on each velocity component. The output voltage range on each component is  $\pm 5\text{V}$ , giving an equivalent velocity range of  $-5\text{ms}^{-1}$  to  $+5\text{ms}^{-1}$ , but this velocity range would need further calibration. The instruments are factory calibrated up to  $\pm 1\text{ms}^{-1}$  and have been rigorously recalibrated in HR's current meter rating tank up to  $\pm 1.5\text{ms}^{-1}$  on the velocity components which will be aligned with the horizontal flow axes (X components); and up to  $\pm 1\text{ms}^{-1}$  on the normal axes (Y or Z components). The HR calibrations are shown in Figures 3 and 4 and are summarised in Table 1. The input power range is 11.5 to 20V DC, with a total current consumption of 590mA. The output from each of the four components is filtered by a factory fitted 9th order equi-ripple low-pass filter which has a -3dB cut-off point at 10Hz. This filter cut-off frequency was specified by HR at the time of purchase and gives a possible range of frequency measurement of up to 10Hz if required. Overall noise levels are equivalent to  $\pm 5\text{mms}^{-1}$ . Factory inter-wiring between the electronics of the two sensors, to synchronise the two clocks, ensures that the sensors can be used in close proximity to each other without electronic or electromagnetic interference.

The electrodes in each ECM head are set at  $90^\circ$  intervals around the inner circumference of the annulus and the tips of the electrodes are on a diameter of 100mm. Voltages are induced between diametrically opposed pairs of electrodes on the annulus due to water flowing through the magnetic field set up by the ECM. The induced voltages are linearly related to the speed of the water. The spherical measuring volume of each ECM head has a diameter in the order of three times the sensor diameter, ie 300mm.

### 3.2 Water depths and wave characteristics

A Druck pressure transducer, model PDCR 930, was used in the previous system and this has been retained. This pressure transducer has an operating range of 0 - 1 bar gauge pressure ( $0 - 10^5\text{Nm}^{-2}$ ) with a corresponding output voltage range of 0 - 1V. The calibration of the pressure transducer is shown in Figure 5 and in Table 1. The actual measurement range of the pressure transducer depends on the density of the water in which it is being used but is approximately 10m water depth. The actual transducer sensor is protected during deployment by a purpose designed solid PVC housing which allows free access to the sensor by the water.

### 3.3 Suspended sediment concentrations

Measurement of turbidity, ie. the opaqueness of water, can be measured using the attenuation of a beam of light. There are several optical turbidity measurement systems available, the main difference between them being the light source used.

The new system includes three Chelsea infra-red turbidity sensors. These were selected because of their low power consumption and the use of infra-red light which means that the instruments are unaffected by ambient light levels. The Chelsea sensor has a single optical path, 1cm wide and across which the light beam is focused. The attenuation of the infra-red beam is measured by comparison with an internal reference beam. The sensors have a turbidity range of 0 - 4000 Formazin turbidity units (FTU). Sensor interfacing electronics are incorporated within the body of the sensor. The power consumption of each sensor and its associated electronics is approximately 30mA. The sensors are constructed from high specification plastic, thus obviating any problems with corrosion, a common cause of problems with

ferrous based metal sensors. Calibration of turbidity sensors in the field uses standard Formazin solutions and recorded output voltages. The basic calibrations of the Chelsea turbidity sensors used in the measurement system are shown in Figure 6 and summarised in Table 1. A relationship between Formazin and locally suspended material is derived either from samples pumped from the measurement point or by recalibrating a sensor in the laboratory in both Formazin and suspensions made from a sample of newly deposited material scraped from the site.

### 3.4 Bed elevations

The ultra-sonic flaw detector, used to make measurements of the changes in bed elevation in the earlier system, was well suited to short term-attended field deployments and was used to obtain very high resolution measurements of bed elevations. However, because of the variations in signal strength due to changing bed densities, the instrument requires a great deal of continuous operator attention to achieve reliable results of bed elevation changes. The size of the flaw detector package would also mitigate against long term underwater use, as would its electrical power requirement. For these reasons an alternative bed elevation monitor was required for the new system.

There are devices available for measuring bed erosion and deposition, but these tend to be very insensitive and are intrusive and can therefore cause localised scour around the instrument. A non-intrusive measurement device, such as the ultra-sonic flaw detector, therefore has obvious advantages over any intrusive measurement device. Ultra-sonic devices are used for measuring water depths (eg the ARX water level measurement system). These systems operate by transmitting a series of sound pulses from a transmitter on a channel bed and measure the time of travel of the pulses echoed back from the water surface. This time of travel can then be converted into a distance.

The manufacturers of the ARX system were approached and they produced a prototype instrument called a sludge blanket detector/bed profiler, in which an ultra-sonic transmitter is positioned above the bed and measures the time of travel of the sonic pulses reflecting off the bed. The prototype system was loaned to HR for evaluation tests and found to be generally satisfactory. The system consisted of an ultra-sonic transmitter and a control/display module and was powered by an unregulated 12V DC supply. Set-up parameters, controlling the operational mode of the bed profiler, are communicated to the instrument via a personal computer. The control/display module has no means by which operating parameters may be altered.

A series of tests was conducted to investigate the response of the prototype instrument in muddy water. Although there were problems with the prototype it was considered that the concept of the instrument was sound. In consultation with the manufacturers a second prototype was produced, incorporating modifications suggested by HR. The second prototype transmitted an acoustic signal at a frequency of 1.1MHz with a beam width of 10°. A beam width of 10° covers a 70mm diameter circle on the bed if the transmitter is at a typical operating height of 400mm above the bed. It was found during preliminary tests that the instrument performed well if it was configured to transmit short duration sound pulses in a burst over a short period of time. The control/display module has an LCD display which was set to display the distance between the transmitter and the bed.

A series of calibration tests was initially conducted to determine the relationship between displayed and actual distances between the transducer and the bed. The tests were carried out in static conditions in a deep bucket. Three different suspensions (fresh water and mud concentrations of approximately 3000 and 4000mg<sup>l</sup><sup>-1</sup>) were used to see if suspended sediment had any effect on the calibration. The calibration tests are shown in Figure 7. A line fitted to this data shows that the measured (actual) distance from the transmitter to the bed was linearly related to the indicated distance with a gradient of 1.0 and an offset of -28mm. No significant difference was observed between clear water and muddy water.

A second, long-term, test was carried out over a period of 8 days in which the transmitter was supported above a mud bed in a deep bucket of water. At intervals during this test a mud slurry was added to the water above the bed and allowed to deposit on to the bed. Records were made of the measured and indicated distances between the transmitter and the bed. The indicated distances were calculated using the calibration relationship. During this test it was considered that a low level of flow past the transmitter might improve the performance of the instruments and a peristaltic pump was used to pump water at low velocity across the face of the transmitter, although there were no obvious benefits in doing this. The results at the end of this test are shown in Figure 8 which shows that the measured and indicated relative distances agree very well. The consistent difference of approximately 5mm between the two measurements is probably due to measurement error but is not important as the instrument will be used for measuring relative changes in bed elevation. The instrument obviously had some difficulty in identifying the bed immediately after addition of slurry, when a very soft mud layer is formed on the bed, ie when there is a small density difference between the 'bed' and overlying water. This problem should only be apparent in the field at times when the bed is fluidised by wave action or when a fluid layer occurs during large amounts of deposition. The bed is identified soon after consolidation begins, and therefore the instrument should still be suitable for the measurement of long term changes in bed elevation.

The ARX instrument is designed as a field instrument and is therefore very robust. No special work is required for the instrument apart from installing its control/display module into the waterproof pod containing all the instrumentation and connection to the integral power supply. The device has a large volume of digital integral storage, in which distances between the transmitter and the bed are stored in engineering units. It has a low power consumption from an unregulated 12V DC supply. An ARX system has been purchased by HR and dedicated to this new measurement system.

### 3.5 System control and data logging

The long-term field measurement system will eventually operate in a number of different modes. At this early stage of development the system will be used in a continuous mode with all instrumentation powered and running. However, in the future it is intended that the system could be operated in the modes summarised below:

- Continuous; in which the system is deployed and data is logged from the instrumentation continuously throughout the deployment.
- Burst; where the system records data for short periods at regular intervals during the deployment.

- Controlled continuous; in which the system will record data continuously during periods of interest, ie periods of significant wave activity.
- Controlled burst; where data is recorded regularly for short periods during interesting periods.

To incorporate a degree of control within the field measurement system, a control/data logging system was purchased. Control decisions, based on the operating modes detailed above, will be made by programmed interrogation of relevant instrumentation and/or by pre-programmed timings.

A 'Tattletale' model 6-1M data logger, a 200Mbyte hard disk drive storage device and associated hard- and software was purchased. The data logger board has 8 channels of 12-bit ADC and 12 channels of serial (digital) input/output capacity which can be used to communicate with external sensors or controls when used in a control mode. The input voltage range of each ADC is -5V to +5V. An onboard computer, with 1Mbyte of RAM, controls the data logging. This is programmable in a subset of the BASIC programming language containing special routines for handling timing control, data sampling and storage routines. A second card contains the hard disk data storage device. The complete system measures 150mm long, 102mm deep and 56mm high and is therefore extremely compact. The 8 channels of ADC are sufficient for the new field measurement system as currently foreseen, but this can be increased if necessary.

The Tattletale's onboard computer is programmed via a standard IBM compatible personal computer (PC) and logging/control programs can either be initiated from the PC or can be 'burnt' into the Tattletale's memory chip, although this technique effectively means the memory chip cannot be re-programmed in the future. Transfer of recorded data from the hard disk storage medium is also carried out using a PC, but special hard- and software were purchased to maximise the speed of data transfer between Tattletale and PC.

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## 4 Data Analysis

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As described in Section 2.4, handling and processing of the data will be conducted by a suite of computer programs developed for this project. All analyses will be carried out over sub-records, typically 5 or 10 minutes in length, and the analysis programs will march through the data sub-record by sub-record. A description of the analysis of the data from each instrument type follows.

### 4.1 Turbidity sensors

The output voltage from the Chelsea turbidity sensor, (a digitally recorded value), is a quadratic function of the concentration of suspended sediment, ie

$$I = A_0 + A_1C_i + A_2C_i^2 \quad (1)$$

where I is the recorded digital value equivalent to concentration  $C_i$  and  $A_0$ ,  $A_1$  and  $A_2$  are calibration constants determined during the calibration procedure.

The suspended concentration corresponding to a particular recorded value is one of the two solutions of the quadratic equation above, and is always the solution given by:

$$C_i = \frac{-A_1 - (A_1^2 - 4A_2(A_0 - I))^{1/2}}{2A_2} \quad (2)$$

After the application of the appropriate calibration to each turbidity sensor the time-averaged mean value ( $\bar{C}$ ) and the root-mean square (rms) ( $\sigma_C$ ) of the concentration fluctuations about the mean value are computed using:

$$\bar{C} = \frac{1}{N} \sum_{i=1}^N C_i \quad (3)$$

$$\sigma_C = \left[ \frac{1}{N} \sum_{i=1}^N (C_i - \bar{C})^2 \right]^{1/2} \quad (4)$$

where  $C_i$  is an individual measured concentration from the time-series and  $N$  is the total number of data points in the sub-record.

## 4.2 Electromagnetic Current Meters

Both components of the ECMs have linear calibrations which relate the recorded digital values to velocity. After application of the correct calibrations to the time-series of digital data corresponding to the two components of each ECM head, the time-averaged velocities in each sub-record are calculated for each component. This information is used to compute the magnitude and direction of the mean streamline during the sub-record. A co-ordinate rotation is then applied to the velocity time-series to align them with this streamline.

$$u = u_i \cos \theta + w_i \sin \theta \quad (5)$$

$$w = u_i \sin \theta - w_i \cos \theta \quad (6)$$

$$\text{Where } \theta = \tan^{-1} (\bar{W}/\bar{U}) \quad (7)$$

$$\bar{W} = \frac{1}{N} \sum_{i=1}^N w_i \quad (8)$$

$$\bar{U} = \frac{1}{N} \sum_{i=1}^N u_i \quad (9)$$

This brings the velocities into a frame of reference in which the transverse time-averaged velocities are zero. Time-averaged mean velocities are then computed from these rotated data. A linear trend, representing changes due to tidal acceleration, is removed from each re-aligned sub-record to leave velocity fluctuations. The rms values of these time-series of fluctuations are then computed using expressions of the form of Equation 4 above.

When both waves and currents are encountered the bed shear stress is a combination of that induced by both the waves and the currents and will depend on their relative directions. In this situation the bed shear stress can be obtained from the Reynolds stresses measured close to the bed or from the total kinetic energy; both of these approaches for estimating the bed shear stress use the measured velocity fluctuations and it is therefore important that the co-ordinate transformation and removal of tidal accelerations described above is applied to the data when obtaining the velocity fluctuations. Soulsby and Humphrey (1990), estimated that non-rotation of velocity data to the mean streamline created Reynolds stress errors of 8% per degree for pure current flow and 156% per degree for the 'waviest' of wave and current flows in their data sets.

The Reynolds stress approach uses the instantaneous turbulent velocity fluctuations  $u$ ,  $v$  and  $w$  from the  $x$ ,  $y$  and  $z$  directions respectively. The sub-record time-averaged Reynolds shear stresses of interest are:

$$\tau_{xz} = -\rho\overline{uw} \quad (10)$$

which is the shear stress in the  $x$  direction acting across the  $x$ - $y$  (horizontal) plane and

$$\tau_{yz} = -\rho\overline{vw} \quad (11)$$

which is the shear stress in the  $y$  direction acting across the same  $x$ - $y$  plane.  $\rho$  is the density of water and the overbar represents a time-average over the record. The choice of averaging time and also the rate at which measurements are taken are discussed in Soulsby (1980). The shear stress at the measurement height is then taken to be the combination of these two orthogonal stress components. The magnitude of the shear stress vector is given by:

$$\tau_{br} = \rho(\overline{uw}^2 + \overline{vw}^2)^{1/2} \quad (12)$$

and its direction is given by:

$$\psi_{br} = \tan^{-1}(\overline{vw}/\overline{uw}) \quad (13)$$

If the measurement height is close to the bed then  $\tau_{br}$  is an estimate of the bed shear stress.

The turbulent kinetic energy density ( $E$ ) is defined as (Soulsby and Humphrey, 1990):

$$E = 0.5(\overline{u_t^2} + \overline{v_t^2} + \overline{w_t^2}) \quad (14)$$

where  $\overline{u_t^2}$  is the variance of the turbulent velocity fluctuations in the longitudinal ( $x$ ) direction due to tidal flow. Similarly  $\overline{v_t^2}$  and  $\overline{w_t^2}$  are the variances in the transverse ( $y$ ) and vertical ( $z$ ) directions. However, the total variance calculated from the measurements of each velocity component contain contributions from not only the tidal velocities but also from the wave action, ie.

$$\overline{u^2} = \overline{u_t^2} + \overline{u_w^2} \quad (15)$$

Similar expressions apply to the transverse and vertical directions. The relative contributions from the tidally induced and wave induced variances can be obtained using the spectrum splitting technique described by Soulsby and Humphrey (1990). Frequency domain analysis of a time-series of velocity fluctuations, for example of the longitudinal velocity component, results in an energy density spectrum,  $S_{uu}(f)$ , where  $f$  is frequency. The area under this spectrum is equal to the total variance  $\overline{u^2}$ . When this spectrum is plotted on log-log axes it can be seen to comprise a conventional turbulence spectrum, having a characteristic  $f^{5/3}$  power law behaviour, onto which is superimposed a wave velocity spectrum, with a peak at a frequency equivalent to the peak wave period, and a characteristic  $f^5$  power law decay towards higher frequencies. Thus the wave and tidally induced contributions to the total variance of each component may be identified and the contributing variances evaluated. The turbulent kinetic energy is then calculated using Equation 14 above. This can be related to the bed shear stress using the empirical relationship (Soulsby and Humphrey, 1990):

$$\tau_{be} = 0.19\rho E \quad (16)$$

where  $\rho$  is the density of the water.

### 4.3 Pressure transducer

The data from the pressure transducer is used to calculate water depths and wave characteristics, (significant wave height and zero crossing period). Digitally recorded values of the output voltage from the transducer are linearly related to actual water pressure. Water depth,  $z$ , is related to pressure,  $P$ , by:

$$z = (P - P_{atmos})/\rho g \quad (17)$$

where  $g$  = acceleration due to gravity.  
 $P_{atmos}$  = atmospheric pressure

The mean depth during a sub-record is calculated as the time-averaged mean of the depths in that sub-record using an expression similar to Equation 3.

Over short periods of time changes in mean water level due to the rise and fall of a tide are assumed to be linear. The time-series of bed pressure head fluctuations during a sub-record is obtained by removing a fitted linear trend to the pressure head time series.

Evaluation of the wave characteristics from each record is achieved using frequency domain (spectral) analysis techniques to obtain the pressure head spectrum at the bed. However, pressure readings at the transducer are subject to attenuation due to vertical accelerations in the water column above the sensor which cause the pressure head variations not to equal the changes in water surface elevation. However, a depth-corrected surface spectrum,  $S_{\eta}(f)$ , can be obtained from the bed pressure spectrum,  $S_b(f)$ , using a standard linear wave theory by the method described by Grace (1978), ie

$$S_{\eta}(f) = \left[ \frac{\cosh(kh)}{\cosh(kd)} \right]^2 S_b(f) \quad (18)$$

where  $h$  is the water depth  
 $d$  is the height of the pressure transducer above the bed  
 $k$  is the wave number which satisfies

$$\omega^2 = gk \tanh(kh) \quad (19)$$

in which  $\omega = 2\pi/T$   
 $g$  is the acceleration due to gravity  
 $T$  is the wave period

The significant wave height ( $H_s$ ) and zero crossing period ( $T_z$ ) are computed from the surface spectrum using the following expressions (IAHR/PIANC, 1986):

$$H_s = 4m_0^{1/2} \quad (20)$$

$$T_z = (m_0/m_2)^{1/2} \quad (21)$$

where  $m_n$  is defined by:

$$m_n = \int_{f^L}^{f^U} S_\eta(f) f^n df \quad (22)$$

$S_\eta(f)$  is the spectral density of the surface elevation spectrum at a frequency  $f$ ;  $f^U$  and  $f^L$  are upper and lower frequency limits. The frequency analysis is carried out at very small frequency increments and smoothed by averaging over a number of discrete frequencies to produce frequency bands. The analysis of field pressure transducer records is fully described in HR Report EX 2701 (1992).

The pressure transducer to be used as part of this field measurement system has been used previously during field work at Portishead in the Severn Estuary (Ockenden and Atkins, 1993). Sensitivity tests have been carried out on data recorded in both storm and calm conditions at the site and this has enabled the presetting of  $f^U$  to 0.45Hz. The lower frequency limit in the integration,  $f^L$ , is set to the frequency band containing the discrete frequency of 0.035Hz as recommended by Tucker (1991).

#### 4.4 Bed elevation monitor

Based on the data obtained during the evaluation tests carried out on the ARX sludge blanket detector/bed profiler, the indicated/stored distances between the transducer and the bed will only require the addition of an offset value to convert them into actual distances (see Figure 7). The ARX instrument can be set up to record distances at various time intervals and it is anticipated that measurements will be made at a time interval comparable with the data analysis sub-record length. The bed elevation results will be combined with the time-averaged results from the other instruments in the system.

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## **5 Conclusions**

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A new field measurement system for making long-term unattended measurements of near-bed hydrodynamics and sediment processes has been designed and assembled. The system consists of the following instrumentation:

- 2 Annular electromagnetic current meters.
  - 3 Chelsea turbidity sensors.
  - 1 Pressure transducer.
  - 1 Bed elevation monitor.
- Underwater integral filtering and data logging.  
Underwater power supply.

The basic calibrations of all the instruments have been established during laboratory tests.

The instruments included in the measurement system have been selected not only on the grounds of the nature and range of the data required but also to minimise the total power consumption to 800mA.

The choice of annular electromagnetic current meters ensures the measurement system is suitable for making measurements in wave or current only conditions or combined waves and currents. All the underwater components have been pressure tested to a depth equivalent to approximately 10m of water column without leaking.

A suite of data analysis computer programs has been developed to process data collected by the measurement system efficiently.

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## **6 Acknowledgments**

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## Table



**Table 1 Basic instrument calibrations**

Instrument		Calibration
ECM Head A:	X component	$V = 1.0040 U_{AX}$
	Y component	$V = 1.0040 U_{AY}$
ECM Head B:	X component	$V = 1.0081 U_{BX}$
	Y component	$V = 1.0204 U_{BY}$
Pressure transducer		$V = 0.9931 P + 0.0027$
Chelsea Sensor No.1		$V = 1.2555 - (0.6391 \times 10^{-3}C) + (72.7 \times 10^{-9}C^2)$
Chelsea Sensor No.2		$V = 1.4727 - (0.6833 \times 10^{-3}C) + (76.0 \times 10^{-9}C^2)$
Chelsea Sensor No.3		$V = 1.4623 - (0.6406 \times 10^{-3}C) + (69.8 \times 10^{-9}C^2)$

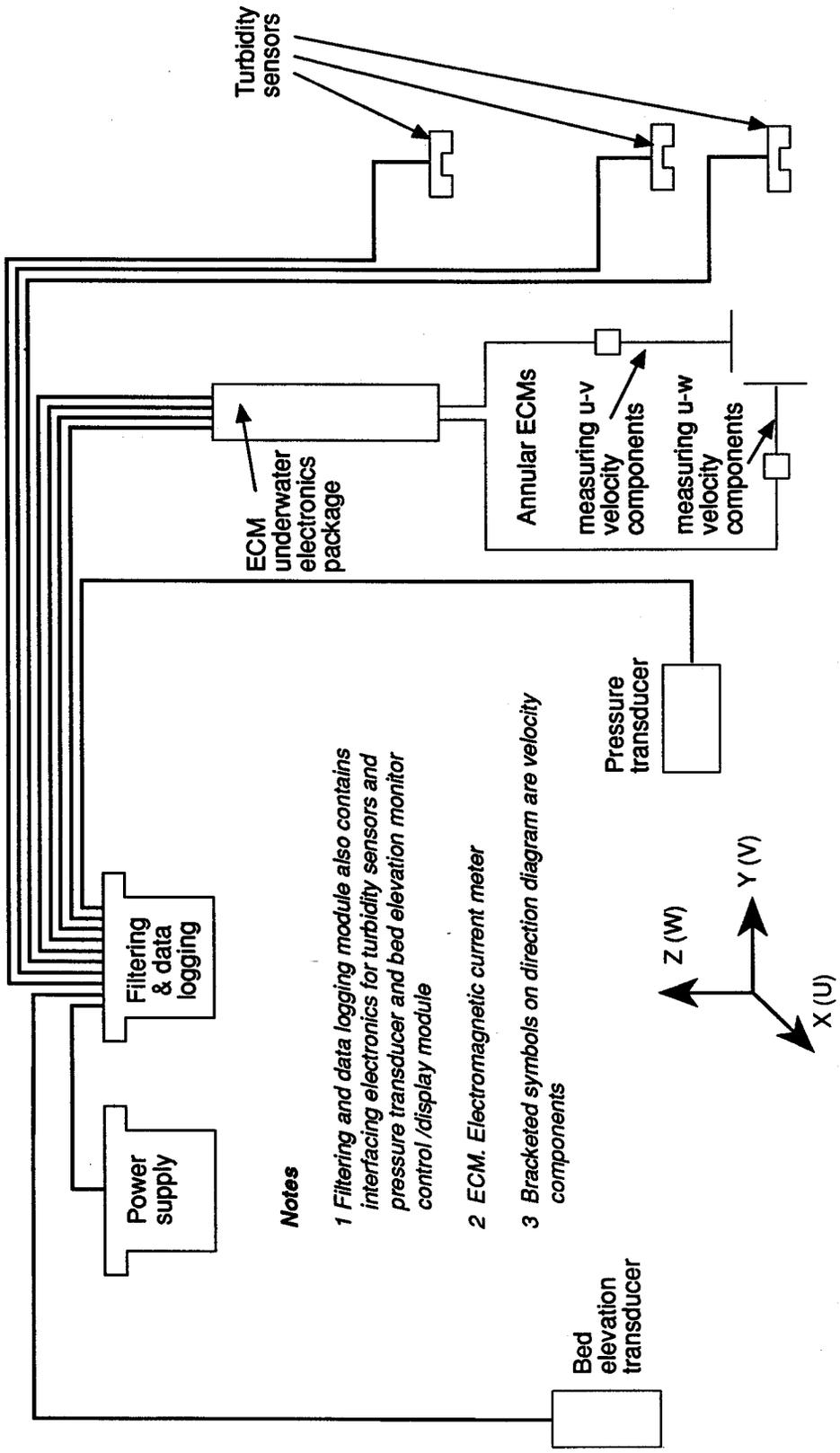
Where

- V = voltage (V)
- U = velocity (ms<sup>-1</sup>)
- P = pressure (bar)
- C = concentration (FTU)



## Figures

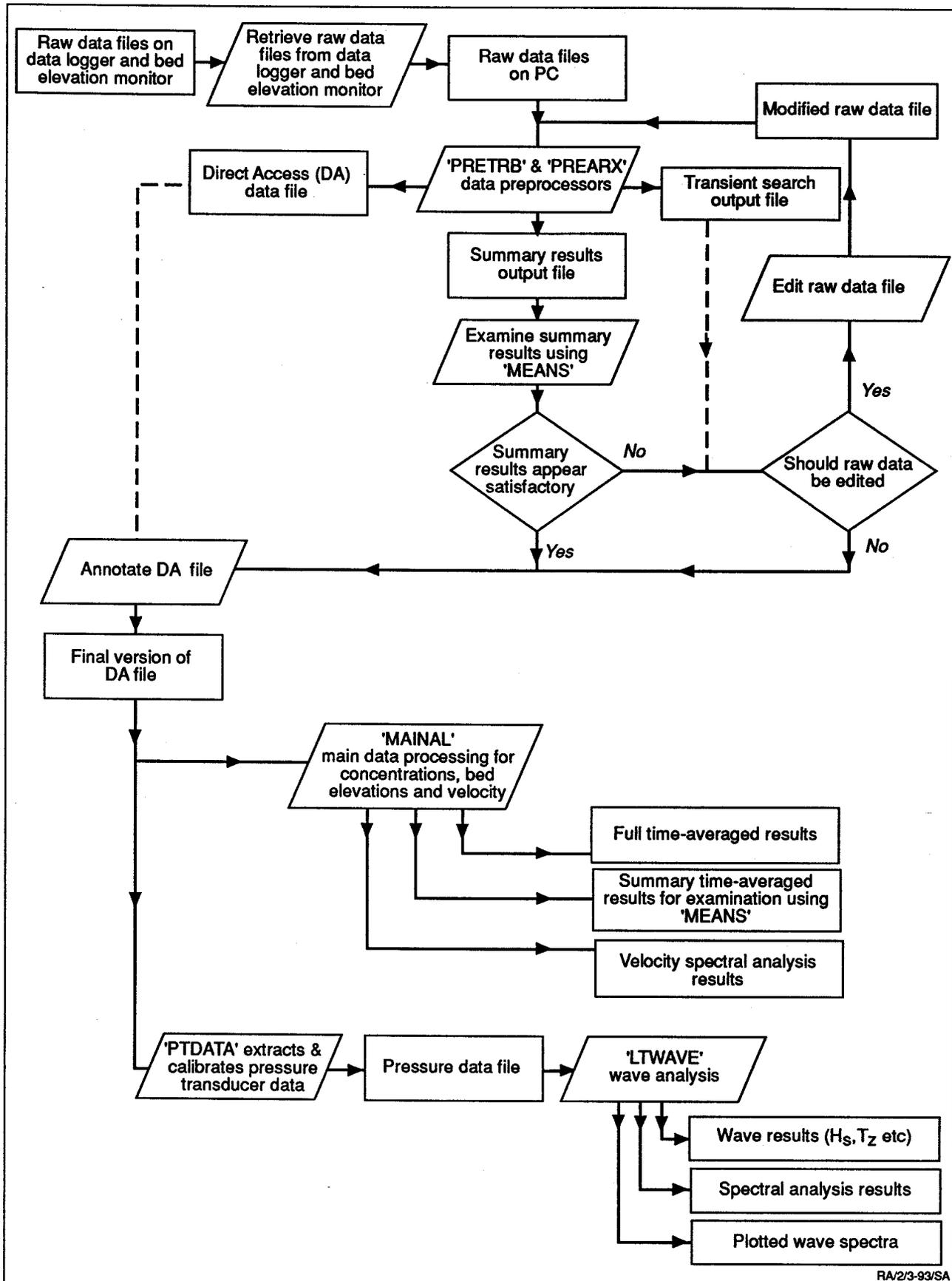




**Notes**

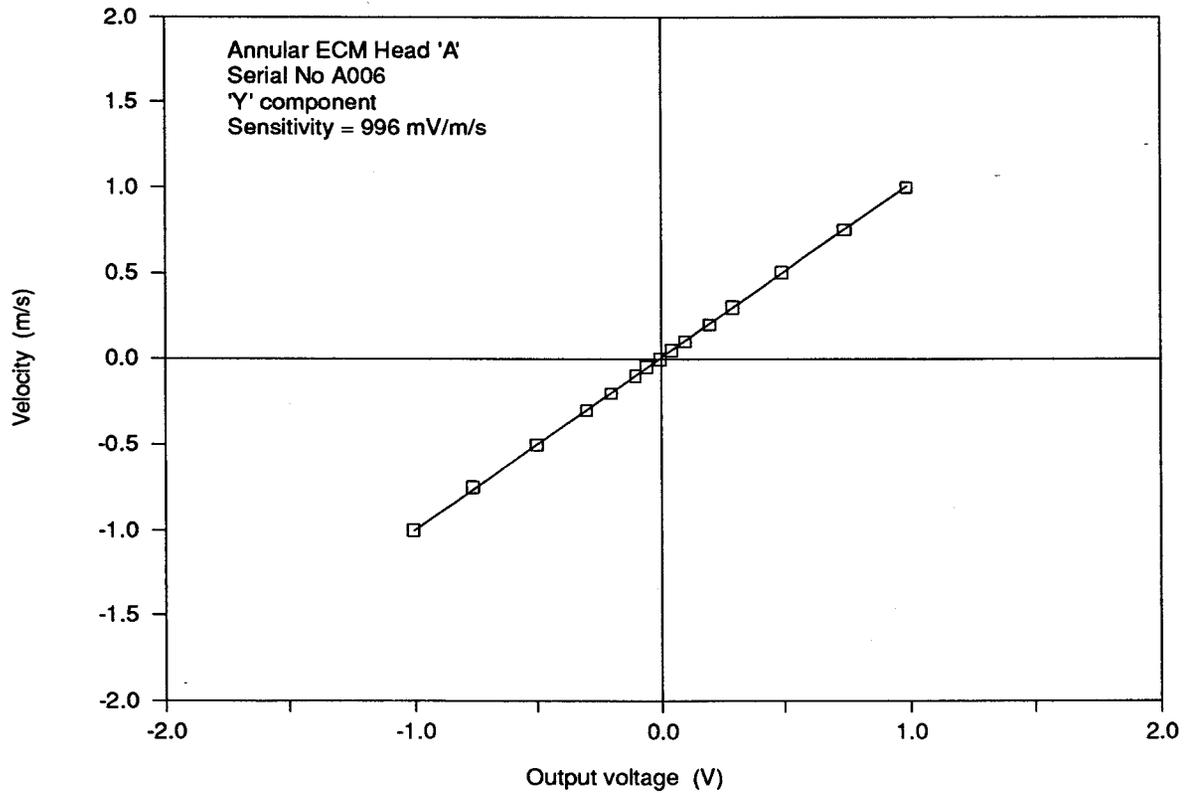
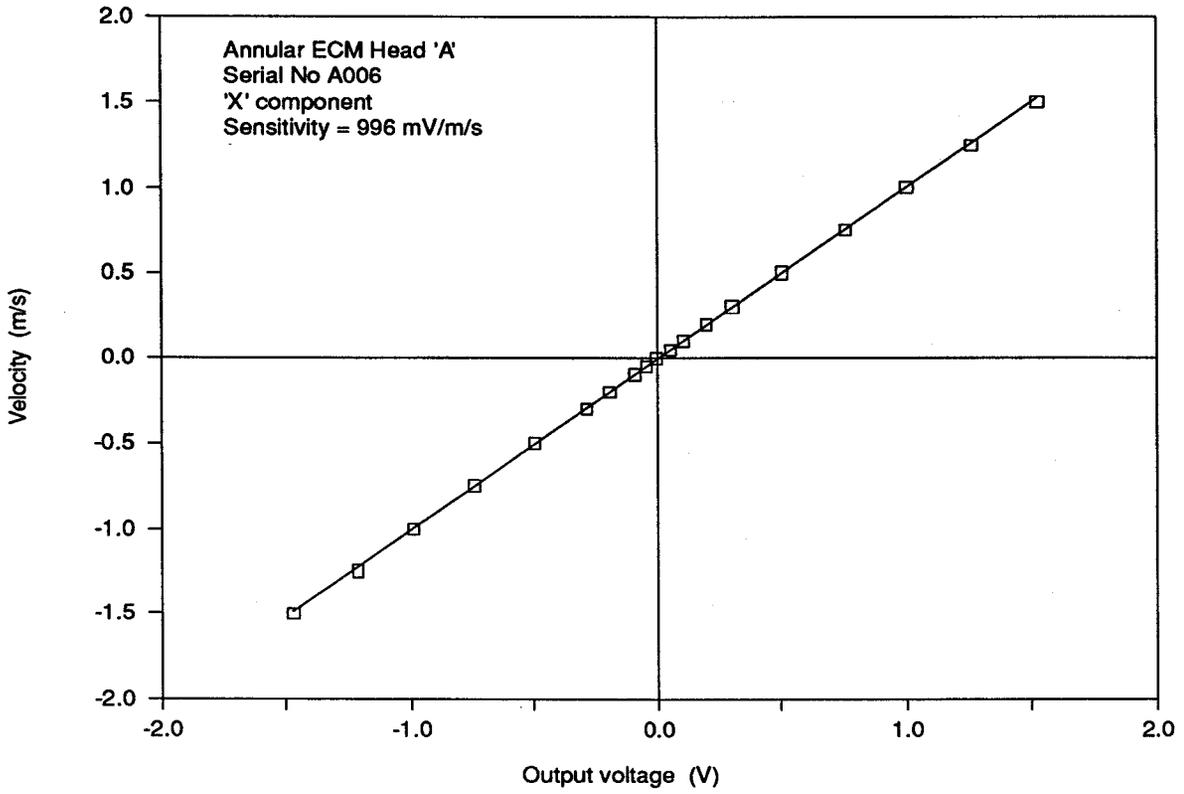
- 1 Filtering and data logging module also contains interfacing electronics for turbidity sensors and pressure transducer and bed elevation monitor control /display module
- 2 ECM. Electromagnetic current meter
- 3 Bracketed symbols on direction diagram are velocity components

**Figure 1 Schematic of measurement system**



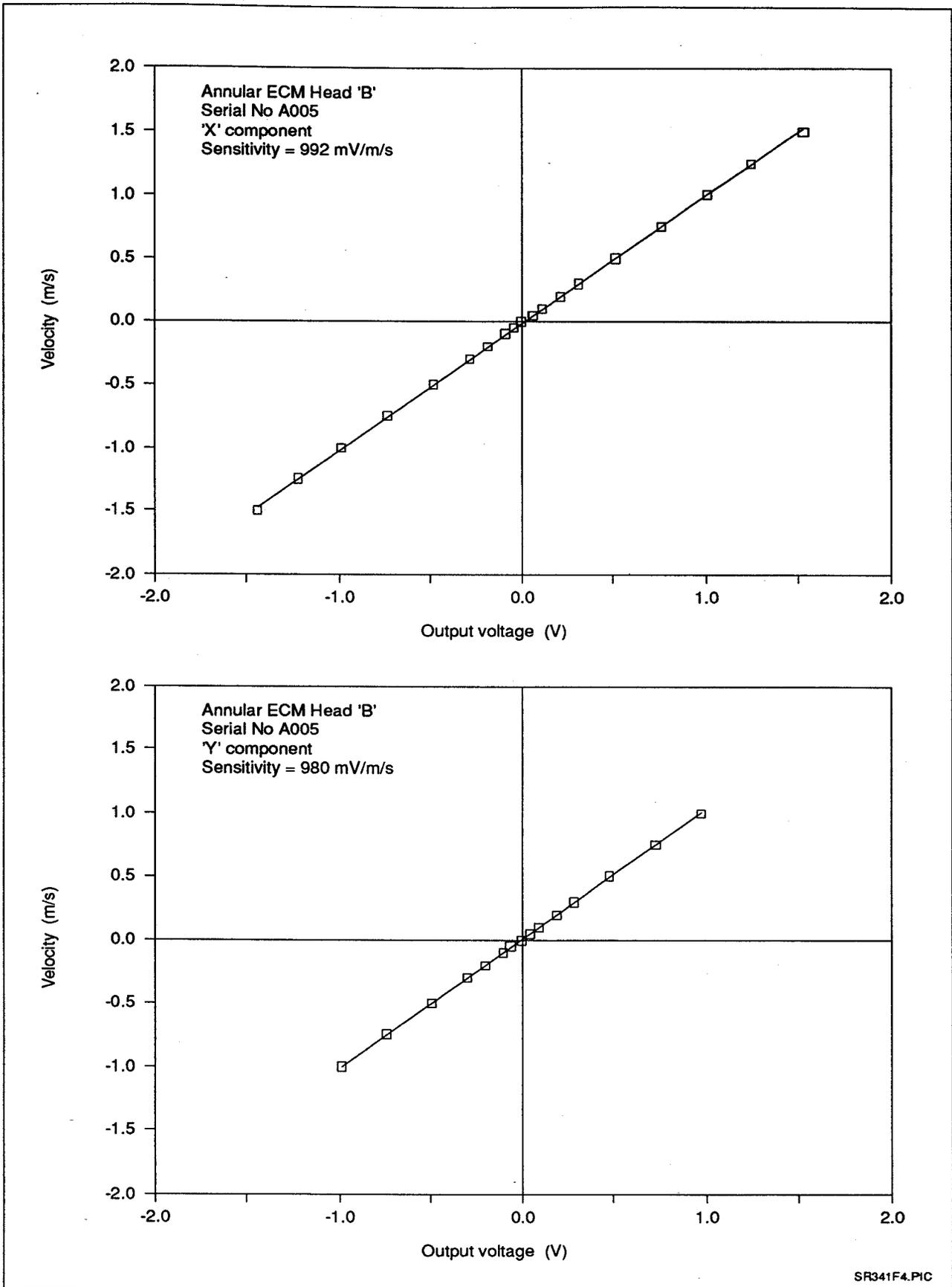
RA/2/3-93/SA

Figure 2 Data processing flow diagram



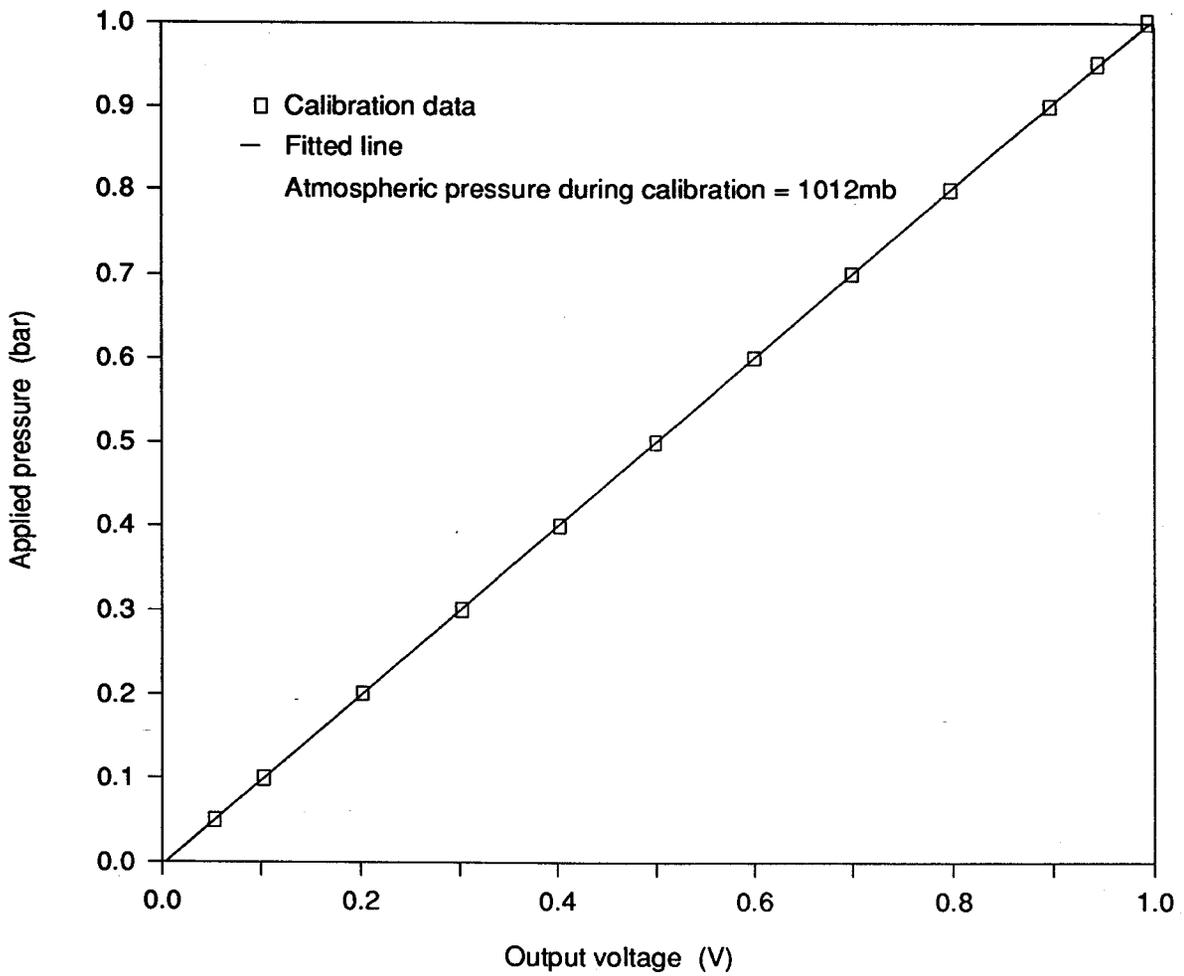
SR341F3.PIC

Figure 3 Calibration of annular electromagnetic current meter: Head A



SR341F4.PIC

Figure 4 Calibration of annular electromagnetic current meter: Head B



SR341F5.PIC

Figure 5 Calibration of the pressure transducer

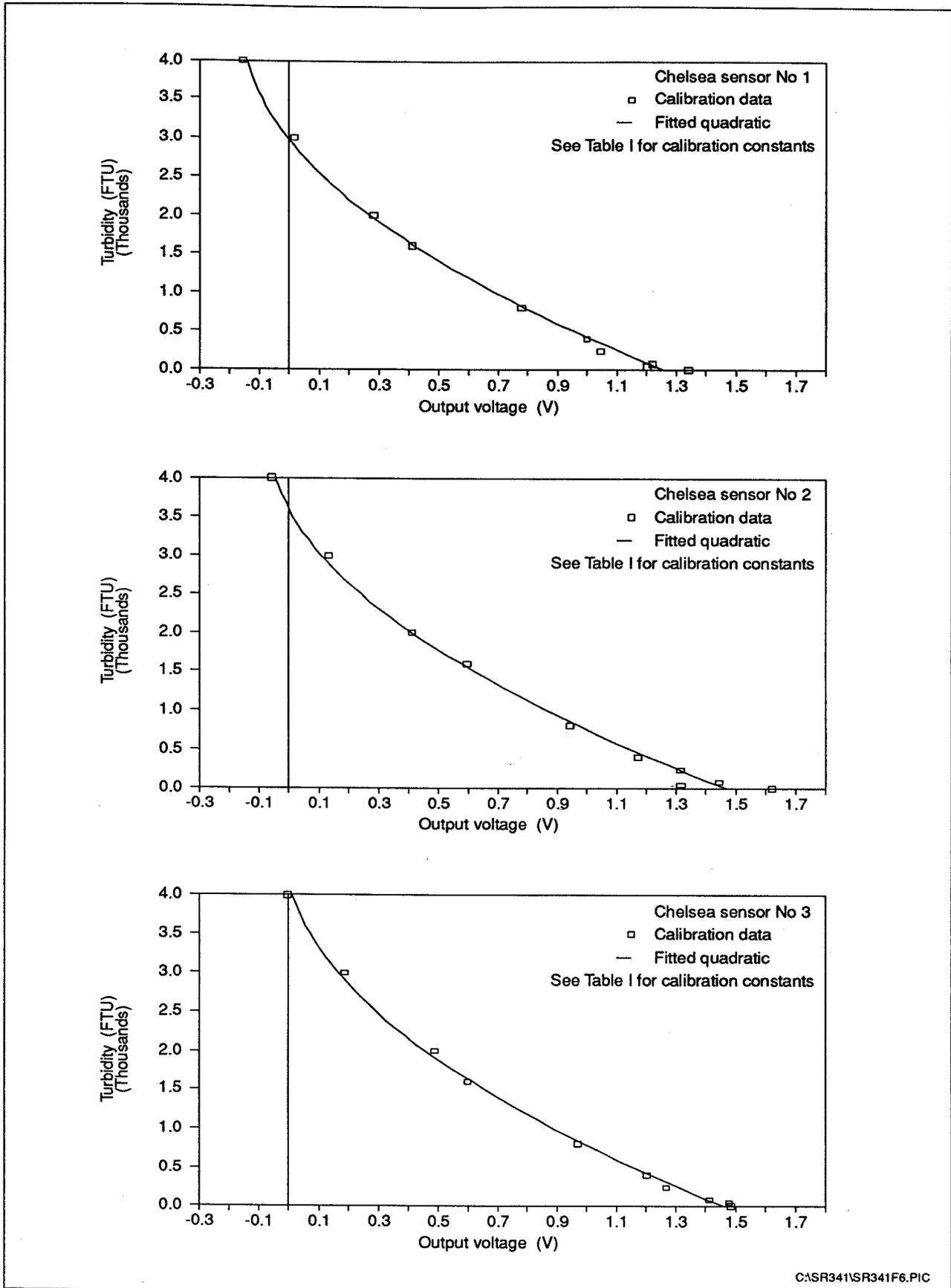
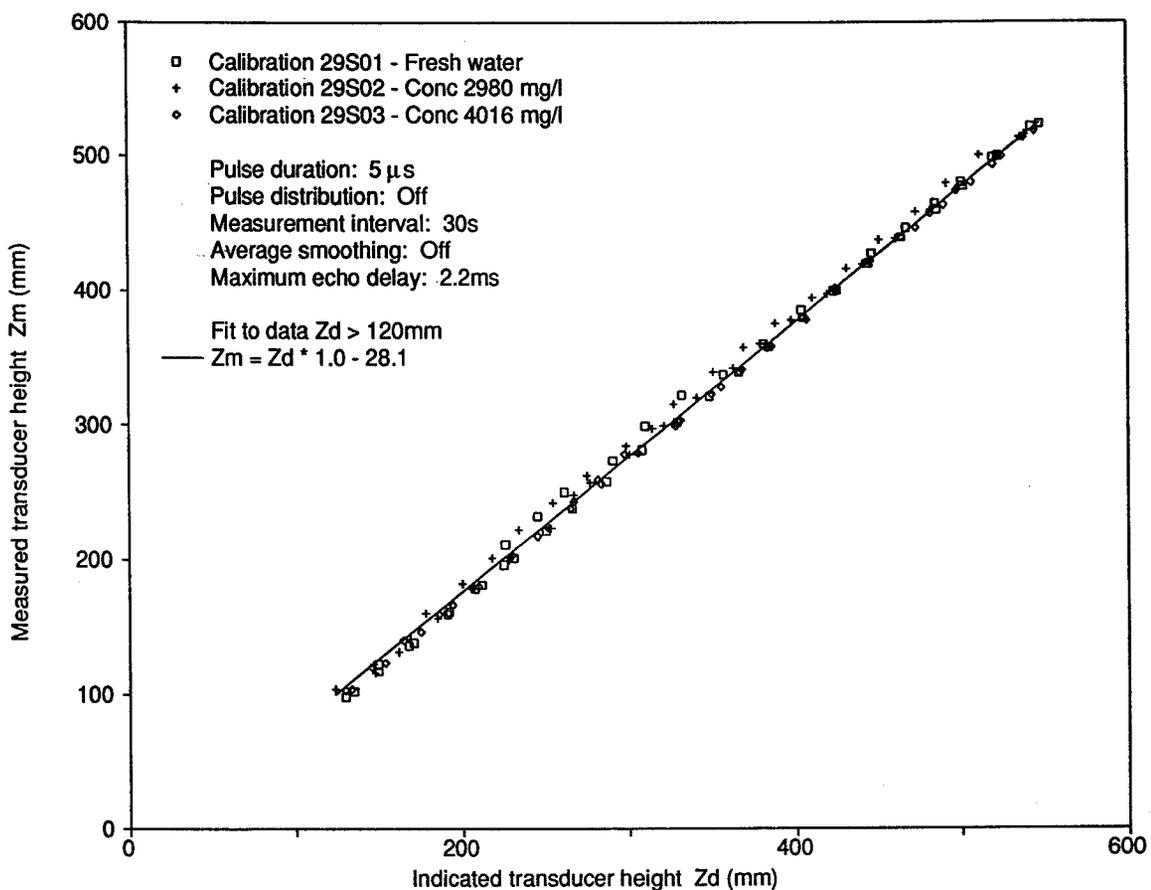
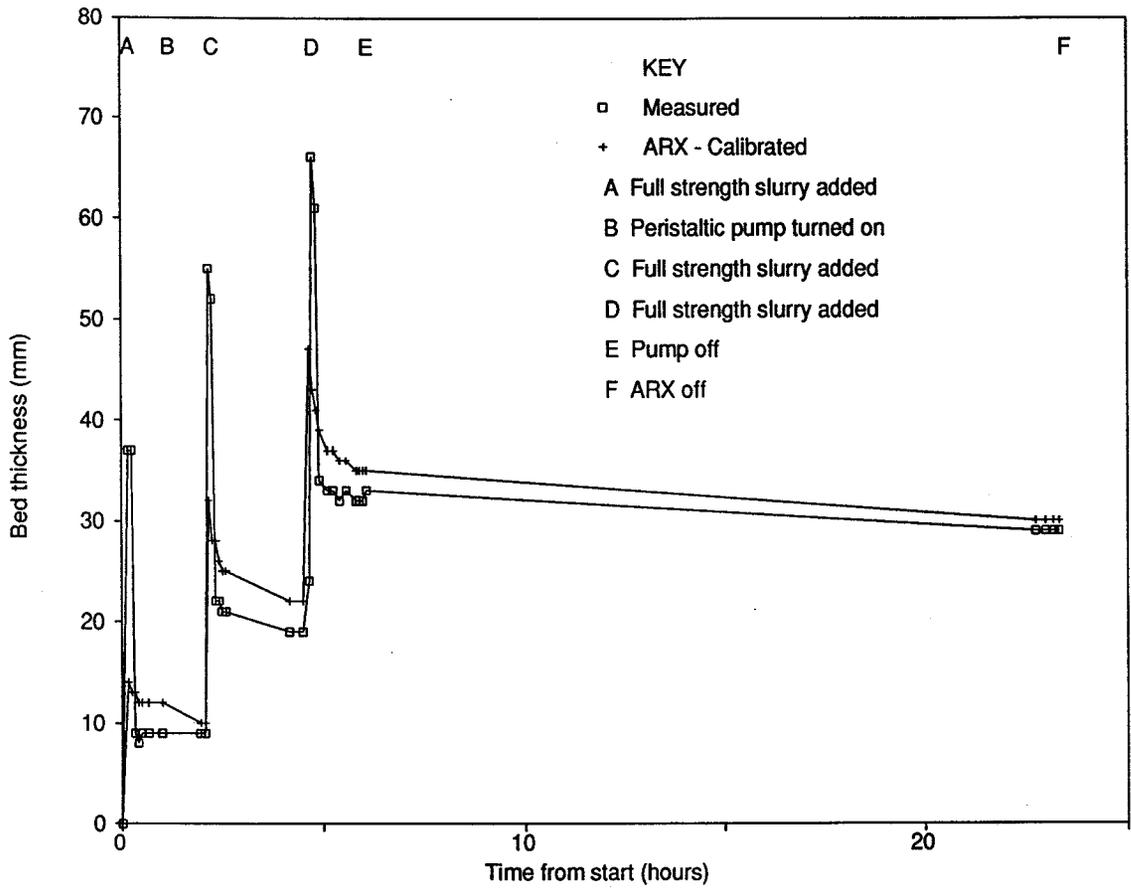


Figure 6 Calibration of turbidity sensors



SR341F7.PIC

Figure 7 ARX bed elevation monitor calibration



SR341F8.PIC

Figure 8 Deposition of mud layers during end segment of ARX test

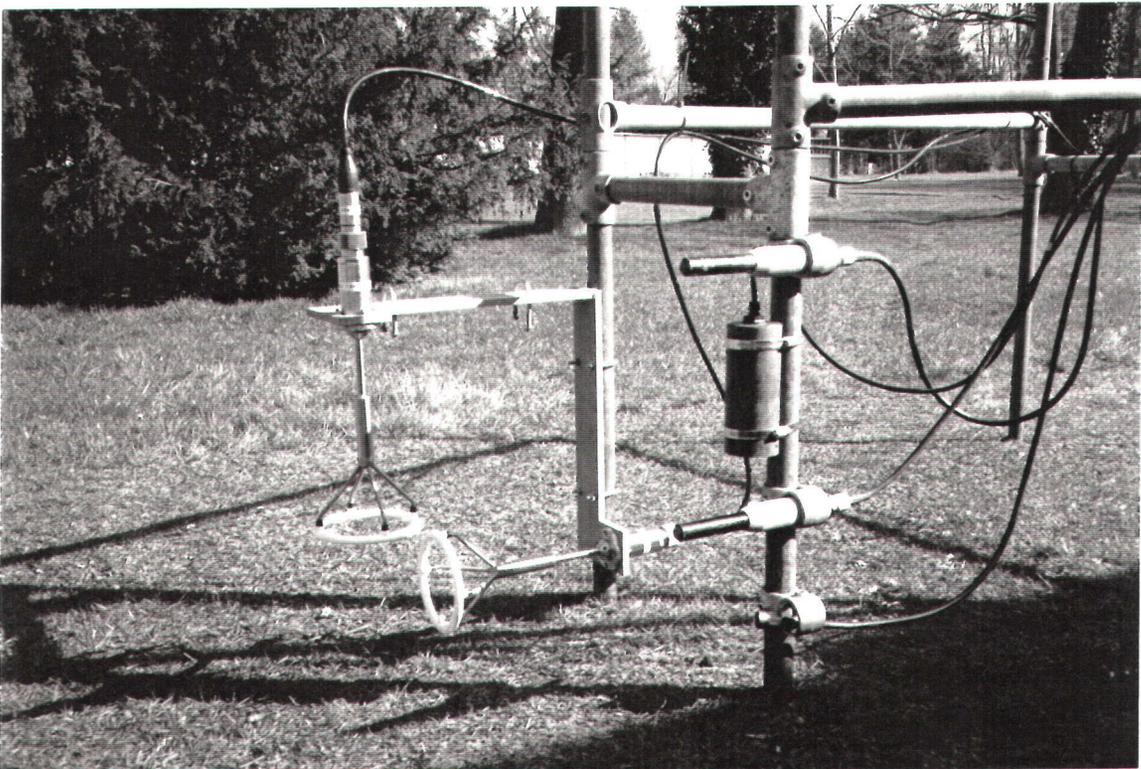


## Plates





**Plate 1** Test assembly of instrument framework



**Plate 2** Annular electromagnetic current meters

