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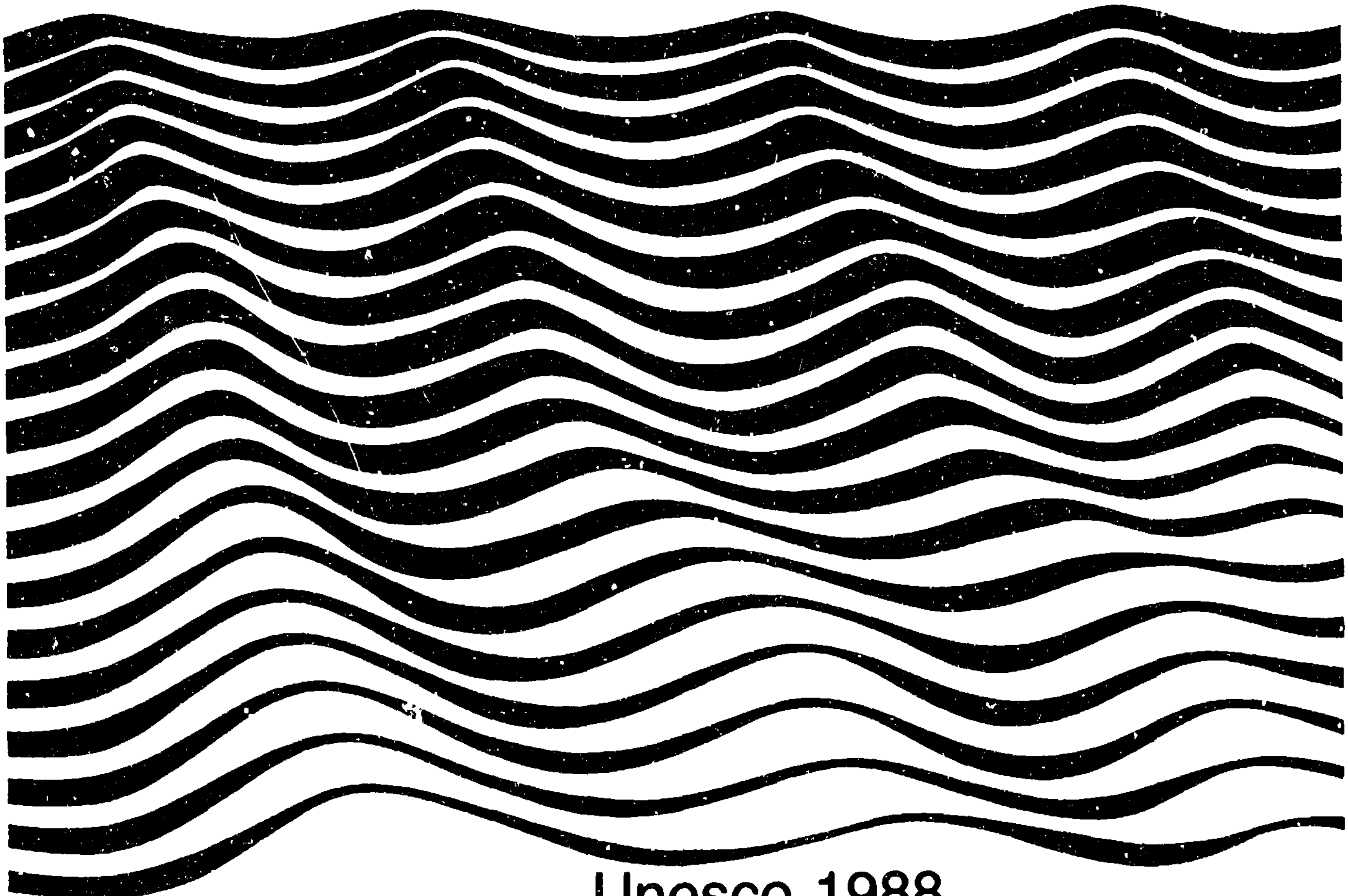
The acquisition, calibration, and analysis of CTD data

A Report of SCOR Working Group 51



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PREFACE

This series, the Unesco Technical Papers in Marine Science, is produced by the Unesco Division of Marine Sciences as a means of informing the scientific community of recent advances in oceanographic research and on recommended research programmes and methods.

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ABSTRACT

In this report the members of SCOR Working Group 51 have attempted to describe the total process involved in obtaining salinity and temperature profiles with modern CTD instruments. Their objective has been to provide a guide to procedures which will, if followed, lead to the acquisition of good and consistent data sets.

Successive chapters proceed from a discussion of the sensors, through their calibration and operation, to a detailed discussion of data processing options. The final chapter gives guidelines, adopted by ICES, for data exchange.

Five appendices go into more detail on topics which include, the design of an observational program, efficient low-pass filters, data exchange formats, the algorithm for Practical Salinity as a function of conductivity ratio, and lastly, the determination of the ice-point correction of thermometers.

RESUME

Dans le présent rapport les membres du Groupe de travail 51 du SCOR ont tenté de décrire dans son ensemble le processus permettant d'obtenir des profils de salinité et de température au moyen d'instruments CTP modernes. Leur objectif était d'établir un guide des procédures à suivre pour acquérir des séries de données valables et cohérentes.

Les différents chapitres sont consacrés à l'étude des capteurs, de leur étalonnage et de leur fonctionnement, et à un examen détaillé des options qui s'offrent en matière de traitement des données. Le dernier chapitre indique les directives adoptées par le CIEM pour l'échange des données.

Cinq appendices traitent de façon relativement détaillée des sujets suivants : la conception d'un programme d'observation, les filtres passe-bas efficaces, les formats d'échange des données, l'algorithme de la salinité pratique en fonction du rapport de conductivité et, enfin, la détermination de la correction à apporter à l'indication du point de congélation sur les thermomètres.

RESUMEN

En el presente informe los miembros del Grupo de Trabajo 51 del SCOR se proponen describir el proceso integral utilizado para obtener los perfiles de salinidad y temperatura con los modernos instrumentos CTD. Se trata de facilitar una guía de los procedimientos que debidamente aplicados permiten obtener conjuntos de datos precisos y fiables.

En los diferentes capítulos se analizan los sensores, su calibración y su funcionamiento, para pasar luego a un debate detallado de las distintas opciones del procesamiento de datos. En el último capítulo figuran las directrices adoptadas por el ICES para el intercambio de datos.

En los cinco apéndices se analizan pormenorizadamente los siguientes temas: diseño de un programa de observación, filtros de paso bajo de buen rendimiento, formatos de intercambio de datos, el algoritmo de salinidad práctica como función del promedio de conductividad y, por último, la determinación de la corrección del punto de congelación de los termómetros.

РЕЗЮМЕ

В этом докладе члены Рабочей группы СКОР 51 попытались описать весь процесс, связанный с получением профилей температуры и солености при помощи современных инструментов для измерения электропроводимости, температуры, глубины. Их цель заключалась в том, чтобы обеспечить руководство для процедур, которые, если их придерживаться, способствуют получению полных и совместимых серий данных.

В последующих главах рассматривается вопрос о калибровке и работе датчиков, подробно излагаются альтернативные возможности обработки данных. В заключительной главе содержатся руководящие принципы, принятые МСИМ в отношении обмена данными.

В пяти дополнениях более подробно излагаются темы, включающие структуру программ наблюдения, эффективные фильтры с низкой пропускной способностью, форматы обмена данных, алгоритмы для практической солености в качестве функции коэффициента проводимости и, наконец, определение поправок термометров на точке замерзания воды.

ملخص

حاول أعضاء فريق عمل سكور ٥١ في هذا التقرير أن يصفوا جميع العمليات اللازمة للحصول على جداول لبيان درجات الملوحة والحرارة بواسطة أجهزة م.ح.ع. (الموصلية ، درجة الحرارة ، العمق) الحديثة . وهم يستهدفون تقديم دليل لاجراءات من شأنها أن تؤدي ، اذا ما اتبعت ، الى الحصول على مجموعات من البيانات الجيدة والثابتة .

وتتناول الفصول المتتالية موضوعات مختلفة بدءا باجهزة الاحساس ومعايرتها وطريقة تشغيلها ، الى مناقشة مفصلة لخيارات معالجة المعلومات . وترد في الفصل الأخير مبادىء توجيهية اعتمدها المجلس الدولي لاستكشاف البحار (ايكس) ، لتبادل المعلومات .

وثمة خمسة ذيول تتناول بمزيد من التفصيل موضوعات مثل تصميم برنامج للمراقبة ، والمرشحات عالية الكفاءة لتمرير الترددات المنخفضة فقط ، والأشكال البيانية لتبادل البيانات ، والخوارزمية المتعلقة بقياس الملوحة العملية كدالة لنسبة الموصلية ، وأخيرا ، تحديد عملية تصحيح الترمومترات عند نقطة الثلج .

摘 要

本文是海洋研究科学委员会第5 1工作组的组员对运用现代电导率—温度—深度仪器获取盐度及温度剖面图的描述。他们的目的是提供一部操作准则，遵循准则即可获得一套可靠一致的数据。

本文各章内容依次为：传感器，传感器的校准与运转，以及对数据处理备选方法的详细讨论。最后一章提供了国际海洋考察理事会通过的供数据交换使用的准则。

五篇附录就许多专题做了深入探讨，其中包括观察计划的设计，高效低通滤波器，数据交换编排，实际含盐量作为传导率的一个函数的算法，最后探讨了如何确定温度计冰点的校正。

Foreword and Acknowledgements

SCOR Working Group 51 was formed with Terms of Reference :

- To identify problems in correcting temperature, conductivity and pressure measurements made with profiling instruments and in calculating salinity and density;
- To consider instrumental tests, calibrations and intercalibrations required before the above problems can be resolved;
- To review correction and conversion methods presently used by the major laboratories;
- To advise on procedures for obtaining CTD data sets

SCOR Working Group 77 on Laboratory Tests Related to Basic Physical Measurements at Sea has since been established and has taken up the second term of reference. This report therefore mainly addresses the other terms of reference.

An additional source of information on the subject is the excellent series of papers presented at a symposium of the ICES Hydrography Committee in London in 1985.

The report consists mainly of edited versions of substantial written contributions made by several members of the group. Some of these are available in extended form in Unpublished Reports of their Institutes and are listed with the references. As chairman I am most grateful to them and to all members of the group for their hard work. Any errors in fact or interpretation which have arisen as a result of this editing process are to be attributed to me. I also thank Dr. Ferris Webster and the College of Marine Studies, University of Delaware for their hospitality in this last year.

The membership was J.Crease (Chairman)(IOS/UK), T.M.Dauphinee (NRC/Canada), P.L.Grose (NOAA/USA), E.L.Lewis (IOS/Canada), N.P.Fofonoff (WHOI/USA), E.A.Plakhin (Institute of Oceanology/USSR), K.Striggow (IfM Warnemünde/DDR) and W.Zenk (IfM Kiel/FRG). I am also grateful to the rapporteurs of the Group: to Paul Tchernia (France) and, more lately, to Henry Charnock (U. of Southampton/UK) who assisted greatly in the final editing of the report.

James Crease

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Chapter 1

Introduction

For many years measurements of salinity were made by the Knudsen titration method on samples obtained by using water bottles, such as Nansen bottles, to trap the water from a particular depth at a chosen station location. At the same time as the samples were obtained, protected and unprotected reversing mercury thermometers were operated to obtain simultaneous observations of the in situ temperature and of the depth (pressure) from which the sample was obtained.

During the 1950's the titration method for salinity was gradually replaced by a method involving the estimation of salinity from the electrical conductivity of seawater at a known temperature and pressure. Ship-borne salinometers were used to compare the electrical conductivity of a sample, directly or indirectly, with that of standard seawater. The methods used to obtain the samples, and to measure the temperature and depth, were unchanged.

From about 1970 the traditional 'water-catching' method of obtaining samples from discrete depths for analysis in a laboratory, at sea or ashore, was gradually replaced by the use of profiling instruments which could be lowered into and recovered from the ocean and which produced a continuous record of salinity and temperature and depth. The salinity was calculated from determination of the electrical conductivity, temperature and pressure.

Such profiling instruments are inevitably much more complicated than the sampling bottles and mercury thermometers they have largely replaced; they are lowered on electrical conductor cables instead of the simple hydrographic wire and the winches involved are bigger and more complex; the sensors are delicate and need careful calibration; advanced electronic circuitry is involved; neither operating procedures nor methods of data analysis is yet standardized.

Nevertheless such profiling instruments, CTDs, have changed our perception of the vertical structure of the ocean: temperature and salinity are now accepted to vary markedly in the vertical, leading to better understanding of horizontal stratification and interleaving of water masses, to clearer delineation of frontal structures and to an opening up of a whole new field of research into microstructure. The newly attained vertical resolution is improving our knowledge of heat and salt transfer in the ocean and has stimulated research into the physico-chemical properties of seawater as well as into the problems of instrument design and operation and into the processing, archiving and exchange of the much larger quantities of data obtained.

		Range	Accu'cy	Resolution	Stability /month
Conductivity	$mS.cm^{-1}$	1-65	.005	.001	.003
Temperature	°C	-2 to 32	0.003	0.0005	0.001
Pressure	dbar	0-300	0.5	0.005	0.3
	$=10^4$Pa	0-650	1.0	0.01	0.7
		0-6500	6.5	0.1	6.5

Table 1.1: Specifications

This report seeks to assess present methods of using instruments of the CTD type and to identify good practice in the hope that methods used by the wide variety of observers will converge towards the production of data of uniformly high standard that can be conveniently and confidently archived and exchanged.

No particular instrument is singled out for discussion; a variety exists, with a range of sensor types and specifications and, others are being developed: the discussion is limited to instruments lowered on a single-core conductor wire from a nearly stationary vessel to obtain temperature and salinity measurements on a vertical scale of 1m or larger i.e. for fine-structure rather than microstructure. A typical instrument specification is shown in table 1.1.

Chapter 2 deals with the sensors used in CTD instruments and Chapter 3 with calibration. Chapter 4, which deals with the CTD operations assumes little or no previous experience so will be of particular interest to newcomers to the field. Chapter 5 is devoted to data processing and chapter 6 to guidelines for data exchange. Appendix A is an extended treatment of one group's use of the techniques described in the earlier chapters. Appendix B gives the characteristics of some of the low pass filters discussed in Chapter 5. Two further appendices give the exchange formats and algorithms endorsed by the international community. Finally Appendix E describes how to check the ice-point of thermometers.

Chapter 2

The Sensors

2.1 Conductivity

The ability of seawater to conduct electrical current is caused by the mobility of its dissociated ions. The specific electrical conductivity C can be expressed as

$$C = N.n.e.(u_+ + u_-)$$

with N the number of ions, n valence, e elementary charge, u_+ an d u_- the mobility of positive and negative ions. From this we see that the conductivity of sea water C depends on its salinity expressed through the number of dissociated ions. Pressure and temperature change the conductivity by their influence on the mobility of ions. In oceanography the conductivity unit $mS.cm^{-1}$ equivalent to $mmho.cm^{-1}$ is generally used. The conductivity of sea water under natural conditions ranges between 20 and 55 $mS.cm^{-1}$ although at certain extreme locations such as estuaries isolated from the open ocean (Eastern Baltic) or near hot brines, this range must be extended to between 1 and 60 $mS.cm^{-1}$. Conductivity changes of 0.01 $mS.cm^{-1}$ can be caused by either temperature changes of 10 mK or salinity variations of 0.01 on the practical salinity scale or by pressure variations of about 20 $dbar$. These numbers demonstrate the physical constraints within which conductivity observations have to be made to be an adequate substitute for direct salinity measurements by titration.

2.1.1 Measuring Technique

In all cases the measurement of electrical conductivity is performed by the determination of the resistance of a test water column. The relationship between conductivity C and resistance Rc, (or conductance G), is given by the "cell constant" k of the measuring device as $Rc = 1/G = k/C$ with $k = l/q$, where l is the length of the water column, q its cross section.

Cells to measure the electrical conductivity of sea water use two basic sensing methods: inductive and conductive.

- In the inductive sensor, the sea water is the medium linking two coils in a transformer and the losses associated with this linkage are measured to give a conductivity value.

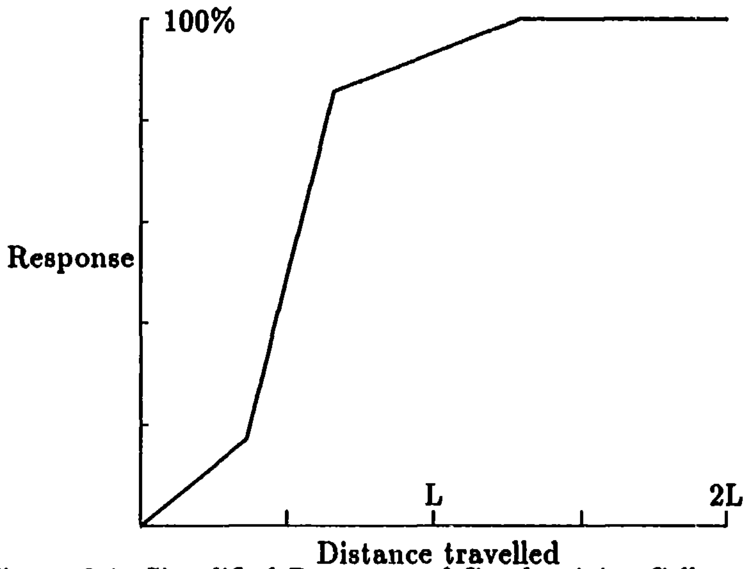


Figure 2.1: Simplified Response of Conductivity Cell to a step change

A typical configuration is a short cylinder containing coils pierced by an axial hole of diameter 1 or 2 cm; there is no direct electrical contact between the circuit and the sea water. A crucial problem in developing an appropriate circuit is to prevent the inevitable non-linear shift of the permeability of the cores of the coils, due to pressure and temperature changes, affecting the instrument's output (Striggow and Dankert,1985). In theory, the magnetic and electric field patterns of this sensor extend out to infinity, but in practice the conductivity measured is predominantly that of the water within the central hole. Nevertheless external bodies such as pressure cases, walls of laboratory tanks, etc. within tens of centimetres of the cell may affect its reading. This "proximity" effect makes them difficult to calibrate.

- In a conductive sensor at least two, and usually four, electrodes are in direct contact with the sea water and these are typically contained within a glass or ceramic tube having a length of order centimetres to tens of centimetres and 0.5 to 1 cm diameter so as to provide a suitably high electrical impedance (100 ohm) to the circuit. For example, the Guildline Mk IV CTD conductivity cell consists of a pyrex glass tube of internal diameter about 6 mm and length 14 cm, having four side arms containing the electrodes. The proximity effect is far less marked than for inductive sensors.

The time constants of these cells are primarily affected by the time taken for water to be exchanged, that is, they are "flushing" time constants, any delays due to the electrical circuitry usually being insignificant in comparison. The typical shape of a conductivity versus time curve for either of these conductivity cells responding to a sudden change in water properties is shown in Figure 2.1. The response reaches 63% when 0.55 of the cell is immersed in the new water. The initial slow rise corresponds to the change approaching the cell, the steep slope to a change of water mass within the cell or between the electrodes, and the reduction to lower slope as the change moves away. In both cases there is a long

	$\alpha/°C$	$\beta/dbar$
Quartz	5.1×10^{-7}	9.0×10^{-8}
Pyrex	3.2×10^{-6}	1.0×10^{-7}
Alumina	6.5×10^{-6}	1.5×10^{-8}

Table 2.1:

tail as it approaches the final value due to the boundary layer of "old" water remaining near the wall until flushing is complete. The proximity effect causes inductive sensors to have an effective length considerably greater than the physical length, more than is the case for conductive sensors.

2.1.2 Pressure and temperature dependence

In all cases conductivity cells separate a certain test volume electrically from their environment. In general the test volume is measured within a tube whose cell constant k varies under hydrostatic pressure and with thermal expansion. The relative change of k can be expressed as

$$\Delta k/k = -\alpha.(T - T_0) + \beta.(P - P_0)$$

with T_0, P_0 the temperature and pressure at a reference level, α the coefficient of linear expansion and β the coefficient of linear compressibility (1/3 of the volume compressibility).

Table 2.1 gives α and β for some commonly used materials in conductivity cells. The equation to correct the conductivity is

$$C = (k/Rc).(1 - \alpha.(T - T_0) + \beta.(P - P_0))$$

The reference temperature T_0 and pressure P_0 will be given by the calibration conditions. Often they will coincide with the laboratory room temperature and atmospheric pressure. In special cases it is convenient to use T_0 and P_0 for deep ocean conditions as Fofonoff et al (1974) did for the Mid Ocean Dynamics Experiment ($T_0 = 2.8°C$ and $P_0 = 3000\,dbar$). Fofonoff et al (1974) and Ginzkey (1977) have shown that cell deformations under high pressures (5000 $dbar$) and large temperature changes (20$°C$) cause the conductivity to be underestimated by as much as 0.012 $mS.cm^{-1}$, yielding a salinity error of 0.015 if not corrected for by the above procedure.

2.1.3 Practical use and maintenance of conductivity cells

As described above all conductivity cells are sensitive to variation in cross section during profiling. Such obstructions can be caused by drifting objects, salt crystals or biological fouling. In addition electrode cells have to be protected against hydrocarbon contamination and calcium carbonate covering. In general, contaminations will cause lower conductivity indications. Cleaning procedures with non-ionic detergents and micro-organism growth presenting solution have been described in the literature (Pederson and Gregg, 1979). Occasional ultrasonic bath cleaning followed by flushing seems to be a useful method for conductivity cells. However, in many cases a baby-bottle brush will be sufficient as a standard cleaning tool. Fouling with salt crystals may be prevented by filling the cell with distilled water between operations.

2.2 Temperature

2.2.1 Measuring techniques

Practically all temperature sensors used in CTD instruments use the variation with temperature of the resistance of a length of platinum, or occasionally copper, wire. They have proved to be very stable and so superior to semiconductors such as thermistors. They are more accurate than mercury-in-glass thermometers so comparisons between them are only useful as an indication of gross malfunction, The pressure sensitivity of a typical resistance thermometer is only about $0.04°C/km$ but compensation may be unreliable due to hysteresis so the elements are normally enveloped in a pressure resistant casing so that corrections are not required. This necessarily involves an increased thermal lag so exposed elements are sometimes used if rapid (millisecond) response is needed. These can be resistance thermometers, thermocouples or thermistors for which, as they do not require high absolute accuracy, adequate corrections can be made from the pressure measurements; they are of more interest for microstructure than fine structure, so peripheral to the main subject of this report. Some commercial CTD instruments, however, use a combination of a relatively slow but accurate resistance thermometer with a fast response thermistor to record rapid fluctuations only.

Several different types of electronic circuits are used in conjunction with the resistance elements the four most common ones being:

- Frequency modulation of an oscillator having the thermometer as an element of its frequency control circuit (Brown,1968). This type of circuit is widely used for thermistors and lower accuracy systems and has the advantage that the readout is a simple count of the oscillations over a fixed time period, or of a carrier frequency over a fixed number of cycles of the basic frequency.

- A two-phase circuit(Kroebel,1980) with 90° phase angle between a bridge arm made up of the thermometer and reference resistor in series and a ratio arm with + and − reference taps, so that the phase shift of the reference voltages (vs. the common point of the bridge arm) due to temperature changes are in opposite directions. The total phase shift is measured by counting a high multiple of the excitation frequency between zero crossings.

- Subtraction of the voltages across a thermometer and a series reference resistor by capacitative transfer to give a square wave difference voltage which is amplified with precise gain and demodulated to give an output proportional to temperature (Dauphinee,1972)

- A transformer coupled AC thermometer bridge with inductive ratio arms and negative feedback with a linearising network to give an output voltage proportional to the deviation from the balance temperature(Brown,1974). The deviation is read with a 16 bit inductive-ratio AC A/D converter.

2.2.2 Sensor performance at sea

All these circuits are capable of impressively high accuracy under laboratory conditions—the errors result from the great difference between laboratory and field conditions rather than the primary calibration. These include:

Electrical leakage Control of leakage is largely a matter of attention to detail in ensuring a permanent effective conduction barrier across every potential leakage path. In a really dry environment a few tenths of a millimeter of clean insulating surface is sufficient to ensure electrical isolation at the voltage levels found in most CTD probe circuits. Even a small amount of salt contamination can be tolerated, since dry salts are insulators as well. Unfortunately a truly dry environment is almost impossible to maintain if the probe has to be opened at sea and the least amount of moisture will tend to make conductive any salt film left by the fingers in handling or by settling of airborne droplets. Even oil films or solvent residues can be slightly conductive at high humidities. So rigid attention to cleanliness and moisture control in the probe is essential. The interior of the probe must be kept free of salt water and at low humidity, with packs of drying agent wherever appropriate. The probe should preferably not be opened at sea or, if necessary for maintenance, opened under dry conditions if possible. The points of maximum risk are of course the sensor leads and low-level sections of the circuit, particularly where they lie close to power and output lines, for instance at the IC pins. Electrical leakage in external plug connections and connecting cables can be controlled by careful attention to drying before assembly, by filling all voids into which water might be forced under pressure with an incompressible insulator such as oil or grease, and by arranging for pressure equalization, or better still, some positive internal pressure at the mating surfaces in contact with seawater. It is very important to remove all traces of salt and moisture from the plug connections, in particular from the blind holes in the female receptacles, and to apply enough grease to fill all voids and prevent leakage across the mating surfaces before joining the plug. Otherwise leakage across the surfaces between pins will cause trouble. The open-hole design of some plugs gives good leakage protection, but the forces involved in separating these plugs have in our experience led to many plug failures through breakage of conductors.

Temperature variations Probe temperature can affect the resistances of leads and circuit components, including gain control resistors and trimming potentiometers, and particularly solid state components. It can also affect thermal emfs and zero offset in dc parts of the circuit. Aside from the sensor leads, the resistors of the basic measuring bridge are likely to be most critical. Power and space requirements usually prevent thermostatting but low-temperature-coefficient, stable resistors are now available which with selection allow stable balances to 1 mK if all resistors are at the same temperature. Potentiometric circuits allow use of relatively simple temperature compensation networks.

Lead lengths and positioning of sensors AC circuits, particularly those operating at high frequency, usually require some form of phase balancing which, if accurately done, eliminates the frequency error. However, serious errors can occur when the sensor is moved with respect to the probe body or extension leads are used if the original phase balance no longer applies or the automatic phase balance has exceeded its range. Any circuit that doesn't give a true potentiometric balance is likely to be susceptible to changes in lead resistance , with significant changes to the mK level being milli-ohms or less. Consequently, major changes from the manufacturer's configuration are likely to require complete recalibration or careful adjustment of the lead resistances. Any added resistances in the leads must be small enough that variations in them due to temperature or mechanical stress do not result in significant errors.

Mechanical effects Certain types of mechanical stress can have a major and serious effect on the temperature sensor and the precision resistors in particular. Stability depends on the resistive elements being maintained in the same shape and state of anneal, at least between calibrations. In general any deformation that exceeds the elastic limit at any point will result in a permanent change of calibration, including the deformations that go with vibration or with exposure to extremes of temperature or major shock. Strong variation is particularly dangerous because of the long periods over which it is likely to occur. In addition to a progressive change of calibration of the sensor there is a possibility of fatigue cracking or weld separation at joints or bend points with subsequent flooding when exposed to high pressures. The following general rules should be followed at all times if a stable calibration is to be maintained

- Protect the probe against extremes of temperature, and allow only slow changes beyond the normal range. Only specially adapted probes should be exposed to winter arctic temperatures or to high-altitude air travel in an unheated cargo bay.
- Make sure that the thermometer is mounted so as to avoid striking any solid object, or ensure sufficient care that it doesn't do so. A bent thermometer will probably still work but its calibration may be changed by many millidegrees. The stainless steel helix types can take much more distortion than most others.
- Isolate the probe from ships vibration when on deck or in storage.
- Protect the probe from violent shocks such as striking the side of the ship, and from rough handling in shipment. A damped-spring type mechanism is preferable for shipping and on-board storage. The protective cage should give a little if it strikes the ship to reduce the probe accelerations.
- Avoid icing of the sensors to avoid stress induced calibration changes or damage. The results will be useless anyway until the ice is completely melted.
- Flush the thermometer with fresh water after the cast and whenever it has been splashed with seawater. In particular, dont allow it to dry with seawater on it

or stand partially immersed in unstirred salt water. Electrolytic action at the air-water interfaces causes pit corrosion which, given time, can penetrate right through the sheath.

Heat dissipation Many circuits dissipate enough power to heat the water near the probe surface significantly at low flow rates. It is important that this heated water does not heat the sensors. The temperature and conductivity sensors themselves are capable of changing the temperature of the small volume of water immediately around them by a few millidegrees when there is low flow in the field or laboratory calibration.

Chapter 3

Calibration of CTD systems

3.1

The laboratory calibration of a CTD system presents a number of special problems. This is because one needs to simulate the combination of a set of conditions not actually realizable in the laboratory. the calibration must be done in such a way that the effects of the combined errors for any particular combination of pre-history of T, C,and P that may occur in the real ocean will lead to an acceptably small error in the determination of these parameters as well as in S. Consequently the thermometer should not be treated as a completely independent sensor; in many cases a small error in T can be tolerated as long as the T and C readings can be correlated to give an accurate value for S.

Equally one cannot treat the T, C,and P calibrations independently since the easiest way to determine the conductivity ratio

$$C_{s,t,0}/C_{35,15,0} = R_t.r_t$$

of the water in the test tank is by calculation, using a standard thermometer for temperature and a laboratory salinometer for salinity, along with the Practical Salinity Scale 1978 algorithm (UNESCO,1981 and Appendix 4) There is no point in carrying out calibrations outside the combination of T, S,and P found in the real ocean or to an accuracy greater than the combination justifies. For instance only a narrow range of S and T around S=35 and $T = 0°C$ is significant at very high pressures, except in enclosed seas, while the normal variation of estuarine salt makes real precision unnecessary.

An additional complication is that the sensors are attached to a probe of frequently inconvenient shape that in many cases cannot be separated from it without serious uncertainties in the calibrations. The result has been that nearly all CTD casts have given results that are far less accurate than the theoretical potential of the system over at least part of the range, and almost always through the thermocline. Recovering even part of the lost accuracy by allowances for previous observations, time constants, etc., often involves computer programming and calibration time out of all proportion to the benefits achieved. But there can be few systems whose accuracy cannot be improved by calibration, and certainly none so reliable that routine checks against gross calibration changes can be safely eliminated.

The crucial objective of a CTD calibration is to establish a relationship between the readings of the various sensors and the water parameters they purport to measure, as they exist *in-situ*. Calibrations usually give numbers corresponding to static conditions when all the relevant parameters are held constant and can be measured most accurately. The heat capacity and bulk of the probe make it very difficult to determine the deviations from static behaviour that occur in periods of rapid change. Unfortunately those deviations are very important since one must be able to correct for rate-dependent errors, either by matching time constants so that simultaneously determined readings correspond to the same point in ocean space, or by choosing reading times for the different sensors on the basis of known time constants, accomplish the same purpose. At the same time we must account to the required accuracy for any long term, history dependant changes.

The most obvious effect will normally be on the lags of the various sensors, causing them to read a time-weighted average of the true value, which smears out the shape of the variations. The thermometer usually has the longest time constant while the conductivity cell is limited only by the rate at which the old water can be replaced by new water in it, the cell itself having no significant intrinsic time constant. The pressure transducer usually gives a nearly instantaneous response but is the most likely sensor to give trouble with sensitivity or zero shifts and hysteresis. Some matching of sensor responses can be done either electronically or by computation, but precise matching by this means is time consuming and usually dependent on drop rate through the water.

The length of time between switching on the power in a uniform environment and final settling to the true value is easier to determine. It can take a considerable time, even minutes, as the various components self-heat to operating temperatures and the conductivity electrodes stabilise. The effect of thermal shock on the system can also be determined fairly easily if the T and S sensors can be separated from the probe or substituted with appropriate resistances while the probe is transferred from room temperature to an ice-bath or vice-versa. An approximate correction for the transients caused by the thermocline and first insertion into the water can then be made on the basis of the rise and decay time constants of the transients.

Calibration under static conditions is usually carried out in a temperature controlled, stirred bath at a number of salinities and and normal surface pressures. A description of the methods adopted by one major user is given later in this chapter.

Calibration under pressure is much more difficult, particularly the conductivity measurement, because of problems with water circulation and thermal contact inside the pressure housing and inability to assure that there are no bubbles in the cell. Fortunately, most thermometers have a pressure isolation jacket to protect the element and should give the same calibration whether under pressure or not. An exposed thermometer that is truly strain-free will change reversibly by about $0.04°C/km$ depth (Bridgeman,1916) with possibly a small hysteresis to the recovery after pressure (Kroebel,1980). A conductivity cell is normally in hydrostatic equilibrium with its surroundings and will change reading according to the pressure coefficient of conductivity of seawater (see PSS 1978 equations) and slightly because the compression of the cell changes its cell constant by 1/3 of the bulk compressibility, a number easily found for most cell materials in the published literature.

Because of the problems of performing pressure calibrations in all but a fully equipped standards laboratory the usual practice has been to carry out routine T, S calibrations to establish performance of the equipment at surface pressure and then assume that the sensors are behaving according to plan under pressure. Any slight deviation from theoretical is then corrected for in the adjustment for pressure sensor error that is normally made on the basis of bottle samples taken at the same time as the *in-situ* profiles are taken.

Even if there is insufficient time, or if the necessary equipment for a full calibration isn't available, there are still a few checks that can be made to verify that a CTD is giving reasonable answers. Temperature is one of the easiest of these, because the most likely error to occur is a shift of the whole scale as a result of damage to the thermometer or a change of a resistor in the measuring circuit. The easiest way to detect such an error is to take an ice point on the thermometer. Appendix E gives a description of how to prepare a reproducible ice bath using the simplest of equipment. Once the bath is prepared, the thermometer and any other part of the probe that will go into the ice should be washed carefully and rinsed with clear water (distilled or de-ionized) to prevent contamination. The thermometer is inserted in the icewater slush, and the reading taken as soon as equilibrium is reached, then moved in the ice and read again. Once the ice point has been checked the sensitivity can be checked quite accurately by placing the thermometer, and probe if necessary, in a stirred, insulated tank at a temperature near the top of the range of a good reversing thermometer, which has also had its ice point checked, and which is used to measure the temperature of the bath. The two point calibration gives a highly accurate location of the zero, and about a 1 in a 1000 check of the slope, sufficient for a few millidegrees accuracy over the most crucial lower end of the scale.

For the greatest precision the triple points of a number of substances can be used to calibrate a temperature transfer standard to millidegree accuracy at points over the entire oceanographic range. Examples of these substances and their triple points are water at 0.0100°C, Phenoxybenzene at 28.8686°C and Ethylene Carbonate at 36.3226°C A second useful check that should be carried out before every cruise, and occasionally during the cruise if possible, is a comparison of the salinities calculated from the CTD readings when in the stirred bath with salinometer samples taken from the bath. If the bath can be maintained near the ice point (or other triple point), so much the better since the thermometer will be more accurate there and any error can be attributed to the conductivity measurement. Measurement at two salinities near the ice point can check the salinity circuit which can then be used with the salinometer at higher temperatures to check the thermometer more accurately.

3.2 An Institute's calibration system

In this section we bring together the calibration techniques for each of the CTD sensors as described by one major user (WHOI). In other chapters reference will be found to variants on the methods adopted here . These reflect the effect of availability of different instruments and resources.

The discussion refers to three NBIS CTD systems in which the fast response thermistor input to the platinum thermometer interface, incorporated to provide high frequency response, has either been dispensed with or is digitized as a separate data channel on one CTD (Millard, Toole and Swartz, 1980). The three CTDs have a temperature compensation collar on the pressure transducer and measure conductivity with the 3 centimeter general purpose cell. The larger cell and the use of the platinum thermometer without thermistors reflects the present feeling that high resolution microstructure work demands specialised instrumentation.

3.2.1 Laboratory Calibration

The CTD temperature, conductivity, and pressure sensors are calibrated against transfer standards prior to and after each cruise. Calibration adjustments are not made to the CTD electronics except when sensors are replaced. It is easier to monitor the performance of the instrument if such adjustments are made only rarely: only the laboratory calibrations are relied on to adjust the calibration coefficients of temperature and pressure. However the main use of the laboratory calibration of conductivity is to check the linearity of the sensor: the conductivity cell drifts sufficiently to require field calibration to obtain salinities to better than .01.

CTD temperature and conductivity laboratory calibrations are made against an NBIS calibration unit transfer standard with the CTD system fully immersed in a temperature regulated bath at salinity approximately 35. Figure 3.1 shows CTD temperature correction curves (calibration unit minus uncorrected CTD temperature) for two of the CTDs versus temperature over an 18 month period for two CTDs. One drifted 6 millidegrees colder while the other drifted 8 millidegrees warmer in 14 months. These are unacceptable errors in deep water if left uncorrected. The parabolic curvature of the calibration curves is removed by fitting the temperature to a second order polynomial. The accuracy of the laboratory temperature calibration is better than $.003°C$ over the range 0 to $30°C$ with a greater uncertainty away from $0°C$ if only the triple point of water is used as a reference. The uncertainty in the CTD temperature accuracy in the field must include the sensor drift with time of about $.0005°C$ per month. The reversing thermometers used to check the CTD temperature are usually not accurate enough to recalibrate the CTD in the field although small range (-2 to $2°C$) thermometers can with care be calibrated to $.003°C$ so as to provide a useful field check on the CTDs whose temperature sensor is suspected of temperature jumps in the field of this order, especially when transfer standards described above are not available. Replacement of reversing thermometer checks by redundant electrical thermometers is increasingly preferred. This practice saves all the time lost on station waiting for the reversing thermometers to equilibrate.

The calibration unit conductivity residuals from a linear fit with CTD conductivity are plotted in Figure 3.2 for the two CTDs over the same time period as the temperature calibration in Figure 3.1. The calibration unit conductivity sensor can only be immersed 6 inches while the CTD conductivity sensor is normally 30 inches below the surface. Vertical conductivity gradient corrections as large as $.003\,mS.cm^{-1}$ are applied to the calibration unit conductivity. Figure 3.2 shows that the conductivity of both CTD 8 and 9 are linear to within $.0015$ $mS.cm^{-1}$ over the range 29 to 59 $mS.cm^{-1}$.

The CTD pressure calibration is made against a deadweight tester with corrections described in Fofonoff et al (1974). Figure 3.3 shows a plot of the residuals of a least squares linear fit between CTD and dead weight pressures over increasing and decreasing

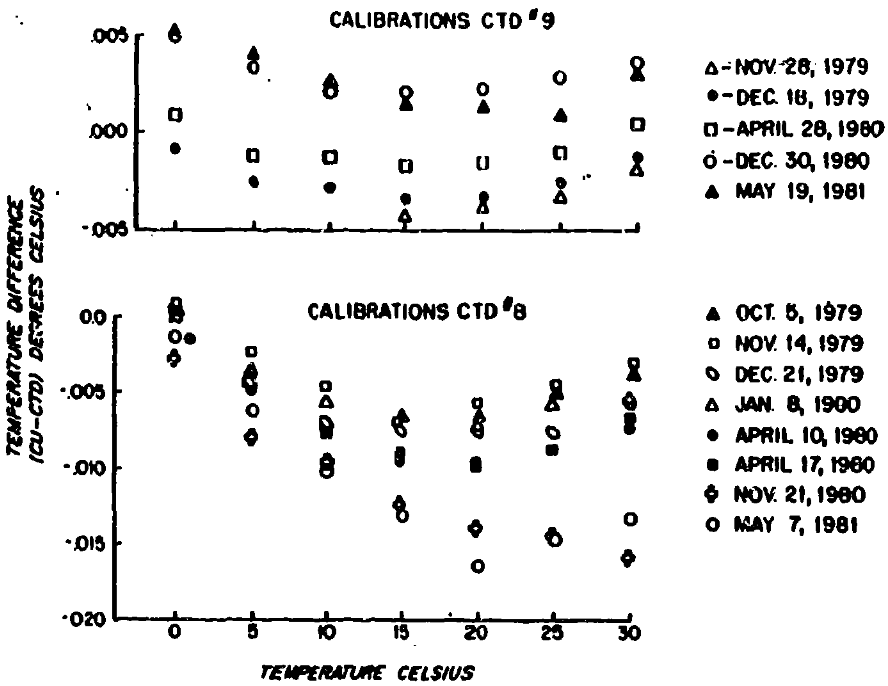


Figure 3.1: Temperature calibration curves (calibration unit - uncorrected CTD) over a period of a year for CTD 9 and CTD 8

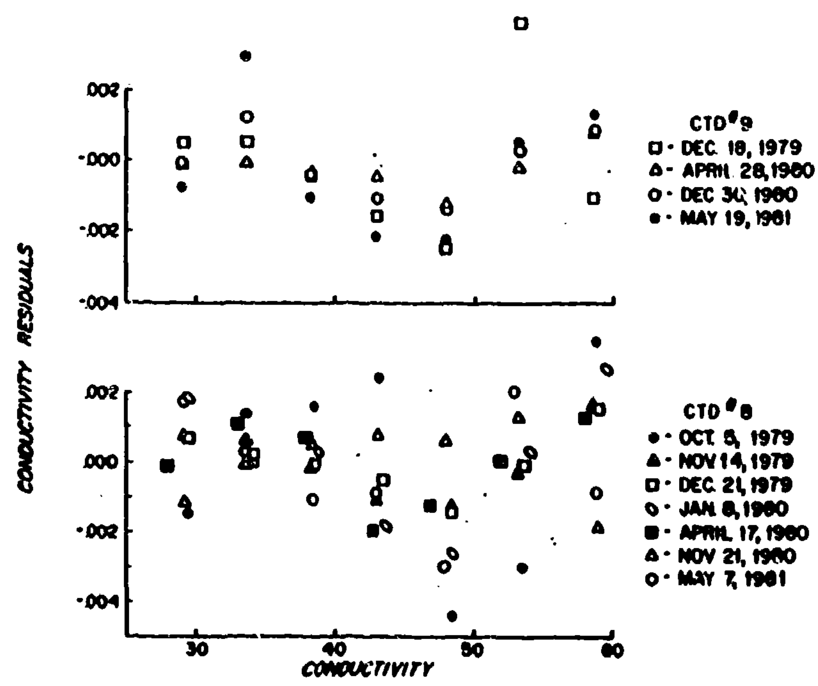


Figure 3.2: The residuals from a linear fit of the NBIS calibration unit conductivity to CTD conductivities.

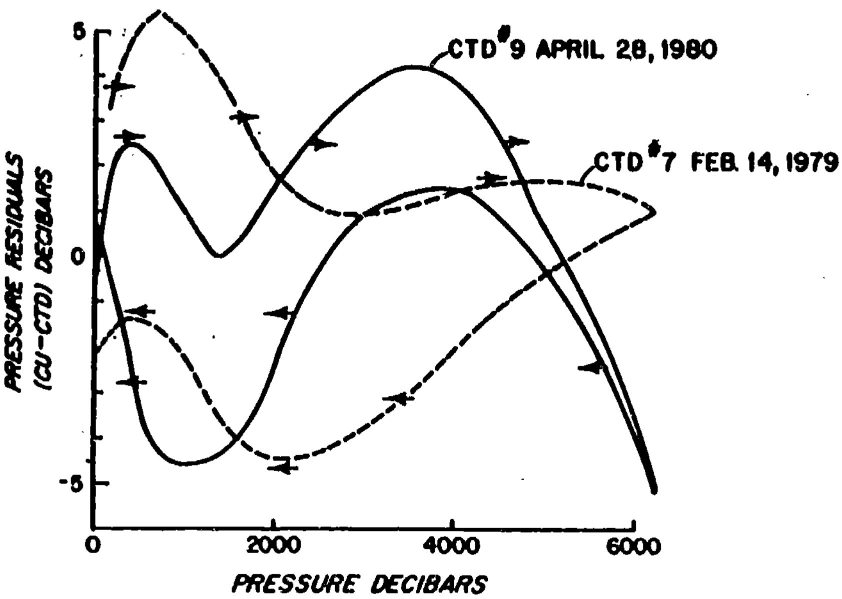


Figure 3.3: The residual pressures between the corrected deadweight tester and a linear fit to the increasing → and decreasing ← CTD pressure values.

values. CTD 9 shows the largest deviations from linearity while CTD 7 shows the largest hysteresis between increasing and decreasing pressure. The CTD pressure transducer is calibrated with a third order polynomial fitted separately to the increasing and decreasing pressure values.

3.2.2 Field comparisons with sample bottles

Water samples are normally collected on each CTD station using a 12 or 24 bottle rosette sampler mounted 1 meter above the CTD sensors. The Niskin bottles are closed during the up cast of the station while the CTD is stopped. The salinity samples are analyzed on a salinometer in which a precision of .001 is achievable under careful laboratory conditions (Mantyla, 1980). The poor temperature stability of the ship's laboratory at sea usually degrades this precision. To evaluate the CTD systems' salinity precision, Rosette salinity observations have been compared with simultaneous CTD observations from 3 NBIS CTDs. The water samples were collected over a temperature range of 0 to 28°C and a pressure range of up to 5600 decibars.

3.2.3 Conductivity calibration

To compare conductivity and salinity an algorithm to convert one to the other is required along with a decision about which variable should be compared. Since the CTD conductivity sensor is to be calibrated, Rosette salinity is inverted to an *in-situ* conductivity using the CTD temperature and pressure. The 1978 Practical Salinity Scale algorithm was used for conversion between salinity and conductivity (see Appendix 4). An error of $.001\,mS.cm^{-1}$ *in-situ* Rosette conductivity results from the following individual errors.

- Salinometer salinity error =.001
- CTD pressure error= 2.5 *dbar*.
- CTD temperature error= $.001^{\circ}C$

The CTD conductivity is corrected for the sensor deformation with temperature and pressure as described in Chapter 2.

$$C(CTD) = Ck(1 - \alpha T + \beta P)$$

The conductivity cell factor k is chosen to minimize the least square differences between CTD and Rosette conductivities over a group of stations (see Appendix of Fofonoff and Bryden 1975 for discussion). Conductivity differences are defined as

$$\delta c = C(Ros) - C(CTD)$$

$$\text{and}\, C(Ros) = SAL78(S(Ros), T, P, 1),$$

and $C(Ros)$ is the Rosette conductivity , $S(ROS)$ is Rosette salinity. $SAL78$ is the 1978 Practical Salinity scale algorithm (appendix 4). P and T are CTD pressure and temperature. The conductivity differences shown in Figures 3.4 through 3.8 have been edited to remove spurious observations with differences exceeding $.013\,mS.cm^{-1}$, unless otherwise indicated. This editing criterion typically removes between 2 and 4 percent of the comparisons of a cruise.

3.2.4 Field conductivity comparisons

Atlantis II cruise 107 from May to October 1980 provided 3600 water sample/CTD comparisons with CTDs collected over a 5 month interval using a 24 bottle Rosette sampler. These conductivity comparisons are summarized by station in Figure 3.4 a-c, corresponding to cruise legs 8, 10 and 11 respectively. The CTD conductivity of each leg has been adjusted by a single cell factor annotated on the figures. Notice the value of cell factor shifts between leg 8 and 10 by an amount equivalent to .01 (Figure 3.4) in the expected sense for gradual coating of the cell. The station averaged conductivity difference is plotted as an indication of when further refinements of the conductivity calibration might be necessary. Average conductivity differences of $.005\,mS.cm^{-1}$ are apparent within each leg and are usually associated with the CTD hitting bottom (indicated with an arrow on the figure).

A useful guide as to when the average conductivity difference of any individual station is sufficiently different from the average of the station group is the student-t test. Each leg has a mean conductivity difference of zero. The 95% confidence limit for a typical group of 1000 observations with a standard deviation of $.003\,mS.cm^{-1}$ is $.0013\,mS.cm^{-1}$ when each station has 24 observations. The limits are shown in Figure 3.4a and stations 112

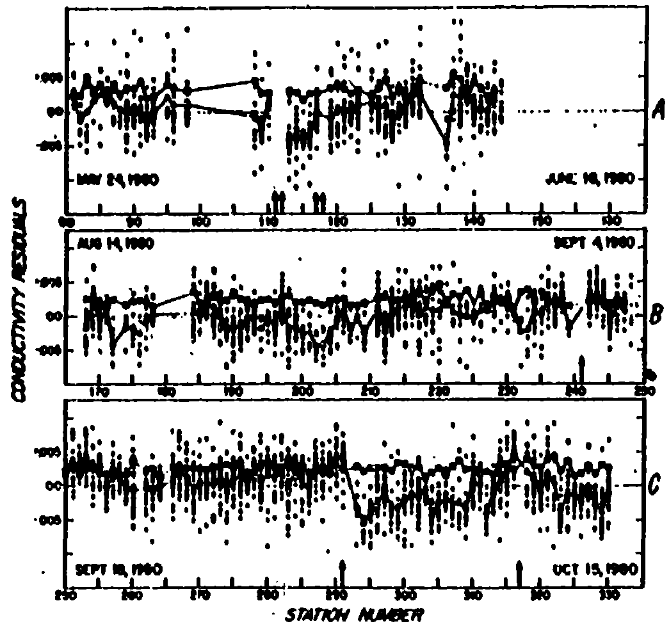


Figure 3.4: 3500 conductivity differences (*in-situ* Rosette - CTD) versus station on Atlantis II Cruise 107. Figures a, b, and c are three separate legs, the conductivity slope of each leg is fitted separately. The symbols for each station are: • - individual differences △ -average difference of station □ - standard deviation of differences within a station.

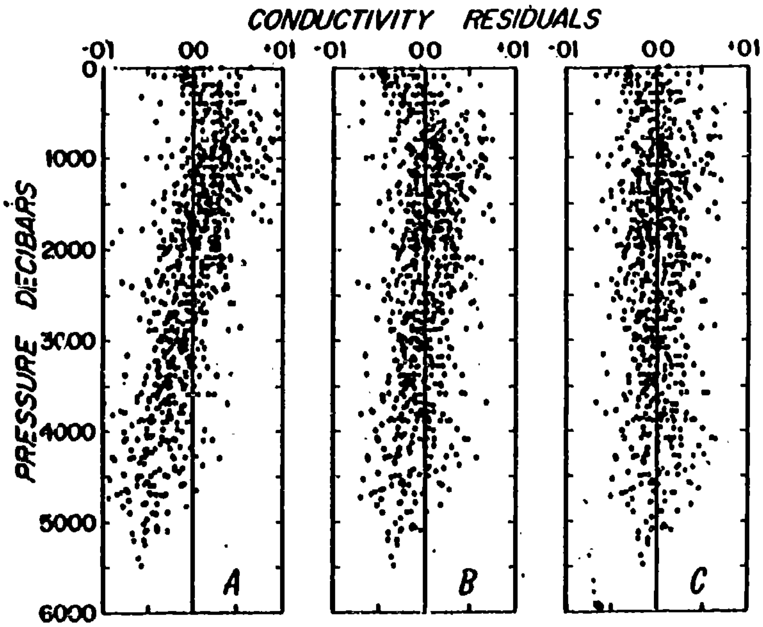


Figure 3.5: Conductivity differences versus pressure for stations 250 through 290 in Fig. 3.4c. In *a*) SAL69 is used with the increasing linear pressure calibration for CTD 8. *b*) uses SAL78 and linear increasing pressure calibration. In *c*) SAL78 is used together with the proper decreasing pressure calibration.

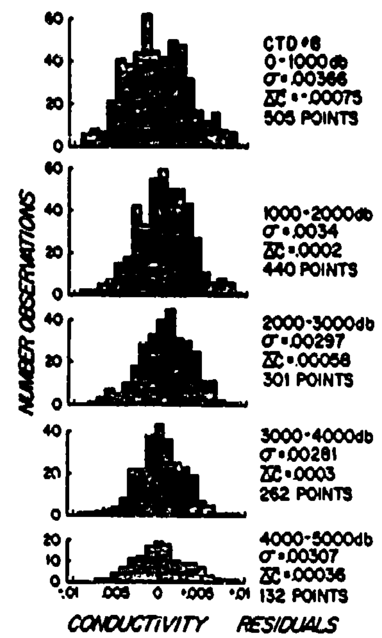


Figure 3.6: Histograms of conductivity differences in 1000 decibar intervals for stations 250 through 331 in Figure 3.4c. Note the decrease in the standard deviation of the differences at depth where vertical gradients are weaker

CTD conductivity calibration shifted is made more likely by the fact the CTD hit bottom on stations 111 and 112. One should be careful not automatically to interpret a station averaged conductivity difference outside the 95 percent limits as a CTD sensor shift since the Autosal salinometer measurement uncertainty is also reflected in the difference. Sometimes it is helpful to check the internal consistency of the Rosette and CTD salinity separately across questionable station groups using temperature-salinity diagrams to resolve shifts.

The old WHOI conductivity to salinity algorithm (Fofonoff et al, 1974) has been found to leave conductivity errors in the vertical as shown in Figure 3.5. Part of this error was the result of CTD pressure hysteresis between down and up casts, as comparing Figure 3.5b and c show. Figure 3.5b shows the effect of applying the 1978 salinity scale (SAL78) but vertical conductivity errors are still apparent and are associated with using the down pressure calibration. Figure 3.5c clearly demonstrates this with the up pressure calibration. The conductivity differences shown in Figure 3.5a-c are from stations 250 through 290 in Figure 3.4c. These stations have a vertical temperature range of 11 to $0.3^{o}C$. The scatter of the conductivity differences are found to decrease with increasing pressure as can be seen in the histograms in Figure 3.6. The histograms of conductivity differences are grouped in 1000 decibar intervals in the vertical between the surface and 5000 decibars. The fine structure in the higher vertical gradient upper 1000 decibars contributes to the larger standard deviation.

The conductivity difference variation with station has been examined for CTD 7 on a three week cruise in the tropical Indian Ocean. Figure 3.7a-c shows a linear drift of the conductivity sensor between stations 3 and 25. The sense of the drift is again

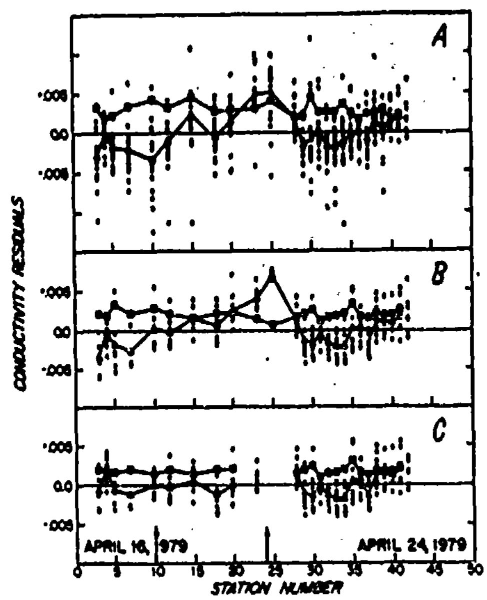


Figure 3.7: Conductivity differences versus station for CTD 7; *a*) all pressure levels, *b*) for 0 to 2000 decibars and *c*) for 2000 to 6000 decibars

of the conductivity sensor between stations 3 and 25. The sense of the drift is again consistent with something coating the interior of the sensor. The CTD hit the bottom on stations 10 and 24 as noted on the plot. The conductivity sensor behaved erratically on station 25 and was cleaned in 0.1 Normal HCl prior to station 28. The conductivity cell appears to continue to clean itself until station 30. Figure 3.7b-c show the conductivity differences broken up into 0 to 2000 decibars (Figure 3.7b) and 2000 to bottom intervals (Figure 3.7c). The standard deviation of the conductivity differences (+) is smaller at depth as the histograms in Figure 3.6 suggest. Also the station to station variation of the mean conductivity difference is also better behaved. Typically the conductivity slope is determined from the deeper observations as shown in Figure 3.7c, not only because the conductivity differences variance is smaller but also to minimize any systematic errors in salinity in the part of water column where the salinity signal between stations is usually smallest.

The range of the conductivity variations for CTD 7 between stations seen in Figure 3.7 is the same $0.005\,mS.cm^{-1}$ as found for CTD 8 in Figure 3.4. Finally the precision of the vertical calibration of the CTD system is checked across CTDs 8, 7 and 9 in Figure 3.8a-c respectively. Figure 3.8a shows a systematic error between top and bottom of $.002\,mS.cm^{-1}$ part of which is consistent with the upper 700 decibar salinity gradient of .0025/decibar and the 1 meter Rosette—CTD separation. Note that the 1978 Practical Salinity Scale algorithm is only accurate to .0015 across the oceanographic range. The systematic variations show no pattern across the 3 CTDs. The vertical temperature range over which the 3 comparisons were made are approximately 25 to $0.5°C$. The vertical conductivity variations are slightly greater than expected from the SAL78 algorithm.

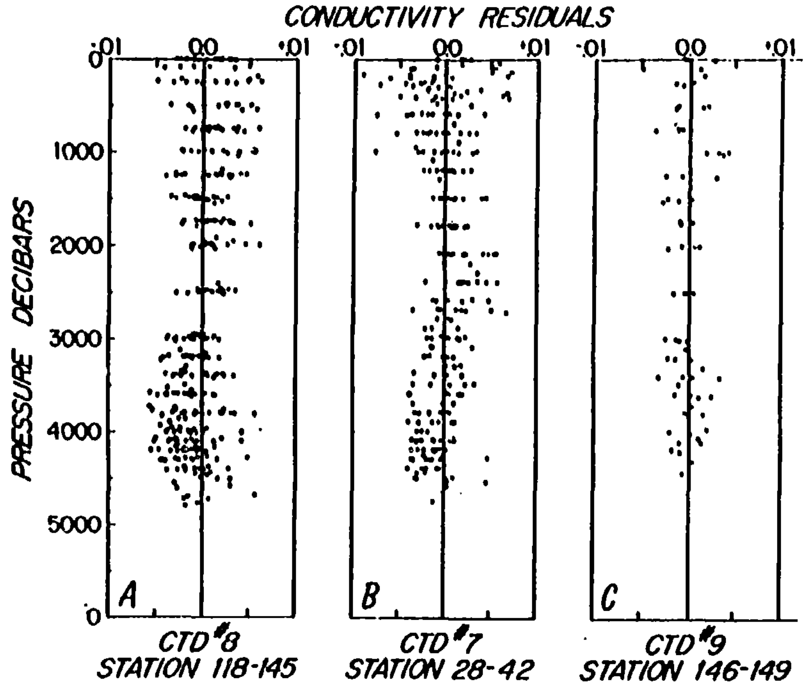


Figure 3.8: Conductivity differences plotted versus pressure for three CTD systems. (a) is for CTD 8 stations 118-145 of Figure 3.4a. (b) is for CTD 7 stations 28-42 shown in Figure e 3.7a. (c) shows four stations using CTD 9.

3.3 Summary

The 1978 Practical Salinity Scale gives a significant improvement in the vertical precision of salinity obtained with the WHOI/Brown CTD System compared with the previous WHOI Salinity algorithm described by Fofonoff, et al (1974). The conductivity sensor must be continually checked at sea in order to obtain salinities more accurate than .012. Also efforts to transfer a conductivity and temperature substandard to the CTD sensors in the field should be explored. The conductivity cell expansion coefficients (α and β) published in Fofonoff, et al (1974) seem to produce well calibrated data in the vertical. The correction of the CTD pressure for down/up hysteresis is important, particularly for the calculation of salinity from the CTD.

3.4 Conclusions

In ocean zones where conditions are relatively uniform and changing slowly with depth, and with appropriate corrections, water temperatures can be determined probably to a few millidegrees and salinities to the corresponding few parts per million of salt, with resolution over short distances to possibly a millidegree and .001.

Chapter 4

CTD Operations

Different groups evolve their own standards of good operating practice, some of which will be particular to the type of instrument used. In this section we cover some basic points which may seem trivial but will assist inexperienced users; several aspects will be taken up in more detail.

4.1 Pre-cruise preparations

A thorough test of the complete equipment (including recording facilities) should be made prior to the cruise; it is best done before casting off! Take great care in transporting the unit from laboratory to ship. Good shock resistant transport cases are desirable. Remember the disks, tapes, sample bottles, rosette, Niskin bottles, thermometers and their calibrations, manuals and all the other items of equipment needed to deal with system operations and possible system failure in adverse as well as perfect conditions.

4.2 Log books

A typical CTD log is shown in Figure 4.1 but the specific data required in the log is often the bare minimum. These notes can contain a lot of errors after a hard nights work. At the beginning of the cruise a precise procedure for carrying out a CTD station should be developed, discussed, put down in writing and strictly kept to by the team. It is preferable to augment it by text notes. Therefore, enthusiastic use of a "special events" section is recommended, especially including for example such items as ship manoeuvres on station, error conditions in the system, heavy rain etc. It is especially important to note when there is a change in CTD sensors in the equipment in use.

4.3 Maintenance on board

The CTD should be protected against strong heating due to exposure due to the sun or other causes. Pour fresh water over the instrument after use. Keep a sound velocity sensor in a bucket of fresh water or at least put a plastic bag around it. If an oxygen sensor is

CTD CRUISE LOG

Ship/Cruise ______ Chief Scientist __________ Start Date _____ End Date ______

Observer __________ Port ______ Port ______

STA	CAST/ INST	Y-M-D	START LAT (N S)	LON (E/W)	END LAT (N/S)	LON (E W)	END GMT	POS METH	WIND M P S	CORR DEP(M)	DATA QUAL	PRES LIMITS	START GMT	PRES BIAS	SV MVAL	RMIN	RMAX				

CTD STATION LOG

Ship & Cruise
Sta No
Date (Y-M-D)
Nominal Posn

Instr No
Mag Tape Label
File No

	GMT	DECK UNIT PRES	Confirmed Positions Latitude	Longitude	Mthd
On Deck (Start)					
Deepest					
On Deck (Stop)					
			N S	E W	

Sonic Depth M/F
Corr Depth M F
Carter's Area

Observer
Wind Speed
Wind Direc

Raw CTD Data (Deck Unit):									Computed CTD Data (Aqui List):											Sample #'s			W.S. Data:			W.S. Data—Comp. CTD Data:	
REC TAG	NOM PRESS	PRESS	TEMP	COND	O_2 CURR	O_2 TEMP		BOTT CONF	PRES	TEMP	COND	SALT	O_2	POT TEMP						NISK BOTT #	SAL / O_2		SAL	O_2		ws-ctd SAL	ws-ctd O_2

COMMENTS:

Figure 4.1: Sample CTD Logbook

fitted it should not be allowed to dry out between casts. Proceed similarly with optical sensors and protect them against dirt (special care is needed in port). After a long period of use or after a period when the instrument has not been operated the electrode arrays of conductivity sensors should be cleared using a suitable brush and a lot of water.

4.4 Special problems in measuring pressure

Pressure measurement are affected by a drift of the zero and by hysteresis and by temperature changes. These properties are worst with wide range sensors (6000 dbar).

1. Zero offset

   Each profile should be corrected individually. Therefore the reading at atmospheric pressure should be noted in the log book. As the sensor is sometimes temperature sensitive temperature should also be recorded at this time. A record of sufficient length (allowing for some averaging) while the CTD is still on deck will help later with corrections. If the record in air is not routinely available, this will lead to difficulty in processing data.

2. Hysteresis

   The actual reading with the instrument at constant true pressure depends on the prior history of the sensor. Lowering and hoisting do not yield comparable profiles. One deep station within a series of shallow casts, may lead to an offset of the pressure reading.

3. Temperature

   The pressure sensors are often temperature sensitive. In strong near surface thermoclines this can lead to different pressure readings on lowering and hoisting.

4.5 Starting a CTD cast

- Leave the CTD in the sea for a couple of minutes prior to starting the measurements if it has been heated up or if the sea- air temperature difference is large. If necessary, hoist the CTD briefly above the surface to read the pressure offset.

- If the near-surface zone is of interest, it is best to start recording while the CTD is still situated above the sea surface. However, this is recommended only for calm conditions. In rough sea states bubbles due to breaking waves may lead to problems of conductivity measurement. As the ocean is rather well-mixed under such conditions, it is often sufficient to start the profile at the safer depth of a few metres. Alternatively, stabilise the instrument a few metres down, bring it up to the surface briefly and then continue with the down cast. Avoid any plume of sewage or engine-room discharge! .

4.6 Lowering speed

In general there is a mismatch of the time constants of the different sensors of a CTD. This can be more easily corrected if the CTD is not lowered too quickly, so as to ensure a sufficiently high data recording rate (see Chapter 5 and Appendix A). However, too small lowering speeds may degrade the data: the flushing rate of the conductivity sensor may become rather small. In addition the ship's movement is felt strongly if the CTD is lowered slowly. Reversal of the instrument velocity (leading to loopings in the analogue trace) should be avoided under all circumstances . Some CTDs can, through their configuration, yield rather low quality up profiles. Note too that the time constants of the sensors possibly depend on the lowering speed and direction. Therefore it is advisable:

- to choose a constant lowering speed for a series of casts;
- to select lowering speeds of 30 to 100 cm/s. Choose the higher values at higher sea states, bearing in mind that the freefall velocity of the instrument package yields an upper limit to the range of possible lowering speeds and that greater speeds can lead to disaster with the wire over-running the CTD. Further discussion of these aspects occurs in other sections

4.7 Recording rate

It is advisable to record data at the maximum rate available as this will give some increased scope for filtering of the data later.

4.8 Calibration and comparison

It is clear that a poor calibration can be seriously misleading. Experience has shown that it is unwise to assume that laboratory calibration of the conductivity sensor will remain stable over a cruise: further checks by means of Nansen cast or analogous means of sample collection are essential.

We emphasise that, if the CTD cast and corresponding Nansen measurements are not taken with great care, accurate calibration is impossible. The Nansen cast data should ideally cover the range of temperature, salinity and pressure encountered. If no rosette sampler is available a Nansen bottle can be fixed to the cable some 2m above the CTD. (Note the risk that the messenger, which usually travels at 2-3 m/sec, may get stuck on the cable; while hoisting at high speed this can cause the cable to break as the messenger will not run through the winch block!) For comparison with Nansen samples the CTD is preferably positioned within a zone of small, preferably vanishing, vertical gradient. While one waits, typically for 5 minutes, for the deep-sea thermometers to adapt (if in use) to the surrounding temperature, the CTD data display is sampled and the values are entered into the CTD log. There may be problems in very calm conditions or on a fixed platform with flow blocking or self- heating if the CTD is held fixed. In this case having located a well mixed layer one can use a rosette or other electrically triggered bottle to take a sample on a second run through the layer.

At least two water samples are usually taken from each Nansen bottle. Sample bottles should be left with the residual sea- water sample in them and at the end of the cruise rinsed with fresh water and afterwards dried. They are stored with closed cap which must have an efficient plastic or rubber seal. Do not touch the upper edge of the bottle or the inside of the cap else salt from ones fingers will contaminate the sample. Both cap and bottle are rinsed several times with the sample water. It is more effective to rinse often with a little water at a time than seldom with a lot of water. The sample bottles are filled only up to 0.5 to 1 cm below the cap. Be sure that no water from the outside of the Nansen bottle drops into the sample and that the bottle is not leaking.

Pressure sensors can be statically calibrated precisely and reliably in the laboratory. It is also possible to test the static temperature dependence of the pressure reading but difficult to measure either the dynamic response or hysteresis. Useful static and dynamic calibration of the pressure sensor can often be done when the sea-floor is flat by comparing the pressure measurement with the difference between the depth of the instrument determined from the difference between precision echo- sounder observations on the ship and bottom pinger measurements from the CTD. If there is no alternative but to use reversing thermometers as a check on the temperature then those having a smooth correction curve are preferred.They should be calibrated every year particularly at the ice-point. Temperatures should be read carefully, by more than one person, using a magnifying lens, waiting at least 5 minutes for temperature equilibration.

Chapter 5

Data Processing

5.1 Introduction

This chapter describes the problems, considerations, and possible approaches for processing CTD profile data. There are many different CTD instruments in use and the hardware design and method of operation will dictate the optimum processing scheme. This chapter is divided into 4 parts: Introduction, Definition of Terms, Data Processing, and Recommended practices. Appendix B contains additional information on Digital filters. There are two stages in CTD data processing; converting the data into physical units and correcting the data for instrumental and sampling aliases or biases.

5.1.1 Conversion to Physical Units

As recorded at sea, CTD data consist of digitized voltages or frequencies acquired from *in-situ* sensors at predetermined intervals of time. Typically these intervals are generally equally spaced at 1 second or less, although some systems record at predetermined pressure intervals. The pressure interval technique is not recommended if time lag corrections are required. Raw data values must be converted to physical units of conductivity, temperature, and pressure. They also must be edited to remove clearly erroneous values. After this first stage of processing, the dataset should have the uniform characteristics of being equally spaced in time and being in a readable form on a convenient storage medium.

5.1.2 Adjustments to the Data

The second stage is to correct the data using calibrations and known sources of errors . It is desirable to minimize the amount of processing required bearing in mind the potential accuracy of the acquisition system as well as the desired accuracy for the intended use of the data.

5.2 Definition of Terms

Accuracy The root-mean-square deviation will be used as the measure of accuracy.

Compaction Compaction of data is the process of reducing the number of data values used to describe the measured environment. Common techniques of compaction would include: decimation, subsampling, interval averages, or flexure points.

Dataset The collection of data values collected during a single CTD cast.

Editing Editing is the removal of individual data values thought to be erroneous from the data set. New values or default "missing" values may be inserted to preserve the time sequence.

Errors

Random Errors Random errors develop from the electronics and coupling devices within the CTD system and are distributed uniformly in the frequency domain.

Biases These are shifts in calibration which are generally constant during a cast but may change from cast to cast.

Trends or Drift These errors are introduced by steady long term drifts in calibration of sensors over periods of days and are characterized by predictable values.

Scaling By scaling is meant the conversion of raw values into physical units of temperature, pressure and conductivity.

Time Lag A delayed response of one sensor relative to the output of other sensor.

5.3 Data processing

5.3.1 General View of Processing

Scale to physical units

The raw data are generally digitized voltages, frequencies, or periods. These raw digital values must be scaled to appropriate physical units such as decibars for pressure, °C for temperature, ratio for conductivity, and Practical Salinity for salinity.

Edit and filter

In this stage, data values which are not physically realizable are eliminated by using maximum and minimum bounds derived from instrument range and/or typical climatological data.

Another process in this stage is ensuring that no unrealistic discontinuities exist within the data. Typically this editing is based on maximum allowable gradients or deviations between adjacent values. Statistical schemes can be used to identify values which deviate by more than a given number of standard deviations from a general curve fitted through a small section of the dataset.

Smoothing of the data (low-pass filtering) may be performed to reduce the random noise in the data.

Finally, data values are substituted for time intervals where no data is available. This allows subsequent processing to be performed on an equally spaced series.

Time lag correction

The data are corrected to account for the different lag responses of the various sensors. Usually the temperature sensor has a significantly longer time constant than either the conductivity or pressure sensors.

Miscellaneous Adjustments

Adjustments may be required to temperature, pressure, or conductivity because of variations in calibration during the cast or because of sensor design or arrangement. These adjustments are completed after the time lag corrections but before salinity is computed.

Computation of Salinity

Salinity is computed as a function of temperature, pressure, and conductivity values. The 1978 definition of salinity (UNESCO,1981) should be used for all computations. Values of salinity acquired during periods of poor flushing of the conductivity cell should be discarded.

Compaction

The dataset is compacted to bring it to a usable resolution in time and space. The sequence of editing, smoothing, and substituting into the series prior to time lag corrections or salinity computation is necessary since time derivatives are used in the correction and the algorithm for salinity is highly non-linear.

5.3.2 Details of Processing

Scaling

Scaling is a process with very little option available to the investigator. The instruments produce signals which must be scaled according to the appropriate calibration for each individual sensor.

Editing and Filtering

There is no procedure for editing data which will apply to all cases. Each investigator must design his scheme to the characteristics of his raw data.

- Extreme Data Values

  An initial improvement in the data is the removal of values which are instrumentally impossible or climatologically unreasonable. The detection of erroneous data values is accomplished by comparison with maximum and minimum bounds of acceptable values.

A more sophisticated (and expensive) data dependent editing scheme is based on statistical properties of the data. An analytical curve is fitted to a subset of the data using least squares techniques, and all values in the subset which deviate more than a given number of standard deviations are deleted. The investigator must take care that such a curve fit is reasonable for the particular environment in which he is gathering data and that the window and length of fit are well matched.

- Replacement of Edited Values

  In order to maintain an equally spaced dataset, edited or missing data values should be replaced with expected values. Expected values should be derived by either linear or second order interpolation, depending on the observed trend in the dataset for the affected part of the water column.

- Filtering and Smoothing (filter design)

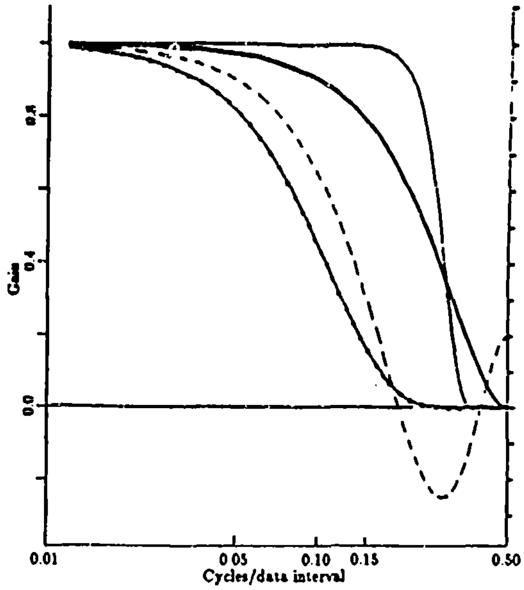
  Certain correcting algorithms (e.g. time lag and fall velocity) require derivatives of the data series for computations. Random errors within the dataset can cause large errors in these estimates, especially when the signal to noise ratio is small. Digital low-pass filters are used to reduce random errors in the dataset. The goal is to attenuate the noise in the data without affecting the signal content. Any filter used will attenuate both the signal and noise, however, so that at frequencies where the signal to noise ratio approaches or is less than unity, the signal will be lost. The minimum possible noise content, E, in the recorded data is that generated by quantisation. This level can be estimated as:

$$E = \Delta^2/12\,\text{(analogue)} \tag{5.1}$$

$$E = \Delta/6\,\text{(period or frequency digitising)}$$

  where Δt is the least count value of the digitizing (Irish and Levine, 1978). The variance of this noise is distributed as white noise in the frequency domain. To this noise must be added noise introduced from other sources in the acquisition hardware. Two cautions must be made in performing filtering. First, the filtering should not introduce phase shifts in the signal. This requires that a symmetrical digital filter must be used. Second, it should be remembered that the sharper the cutoff in the frequency response of the filter, the more will be the oscillations (Gibbs phenomena) in the output of the filtered data. Figure 5.1 shows the frequency responses for some commonly used filters. Specifications and weights of some of these digital filters are contained in Appendix B Table B.1. These symmetrical digital filters are applied with the following algorithm:

$$X'(n) = W(0)X(n) + \sum_{k=1}^{k=K} W(k)[X(n-k) + X(n+k)] \tag{5.2}$$



Running Mean 5 points	— — — —
Stop band starts (1% gain)	0.195
Max overshoot	-25.0% at 0.289
Elementary Binomial	▬▬▬▬
Stop band starts (1% gain)	0.465
Max overshoot	0.0% at 0.289
Normal Curve $\sigma = 2$	•—•—•—•
Stop band starts (1% gain)	0.238
Max overshoot	0.0% at 0.500
Filter #4 App. B.4 10 weights	———
Stop band starts (1% gain)	0.355
Max overshoot	0.4% at 0.406

Figure 5.1: Frequency responses of selected filters

where the filter $W(k)$ of K weights is applied to 2K+1 data points in series $X(n)$ yielding the filtered data series $X'(n)$. the frequency response, $R(f)$, of these symmetric filters was computed using the relationship:

$$R(f) = W(0) + 2\sum_{k=1}^{k=K} W(k)\cos(2\pi f k) \tag{5.3}$$

Additional information on digital filtering can be found in Gold and Rader (1969) and Holloway (1958).

Time Lag correction

The purpose of time lag correction is to remove the effect of the mismatch in time constants between the temperature sensor and the depth and conductivity sensors. The response of

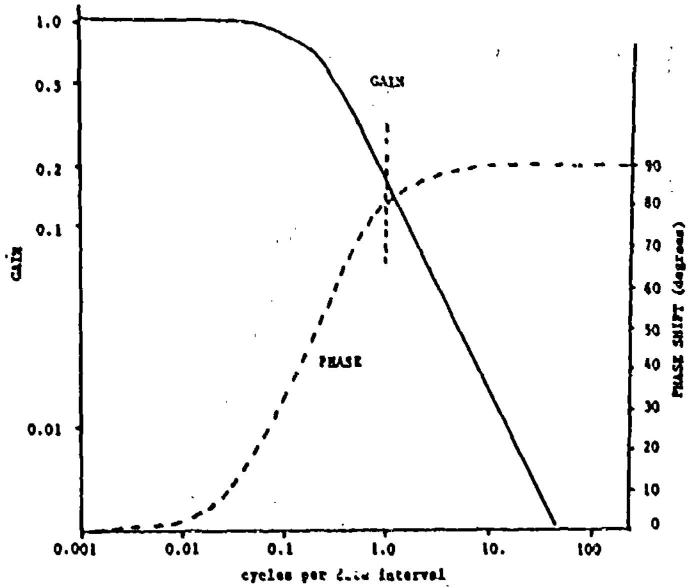


Figure 5.2: Complex frequency response of analogue time lag operation

simple thermometers is modelled by an exponential decay such that the rate of change of the sensor output T_0 is proportional to the instantaneous error in measurement $(T_i - T_0)$:

$$\frac{dT_0}{dt} = \frac{T_i - T_0}{\tau_1} \tag{5.4}$$

Where τ_1 is the time constant of the sensor. As seen in figure 5.2, the frequency response function of this analogue transfer function attenuates and introduces a phase shift into the high frequency part of the signal. By itself, the attenuation is not of real concern since typically the measurements contain higher frequency content then are required. However, the phase shift introduces a delay into the signal which causes the temperature data to be non simultaneous with the conductivity data; this generates salinity biases. This distortion is evident at frequencies greater than $1/(20\tau_1)$. Two basic approaches can be used for time lag correction:

1. removal of the shift from the measured temperature values or

2. adding a shift to the conductivity and pressure values so the time lags of all the sensors are equal.

Historically, the approach has been to attempt removal of the shift in the temperature data (Scarlet, 1975; Fofonoff et al. 1974; and Millard et al. 1980). However, in recent years more emphasis has been put on adding time shift to the other sensor series since computationally it is simpler and noise amplification is eliminated (Walker, 1978). Moreover, it has been recognized that the responses of conductivity cells are not instantaneous but depend on the CTD lowering rate as discussed in appendix A. Thus a complete treatment of lag correction should include these velocity effects.

Six cases will be presented describing the various methods which can be used for performing lag corrections on CTD data. The first 3 cases deal with methods for removing

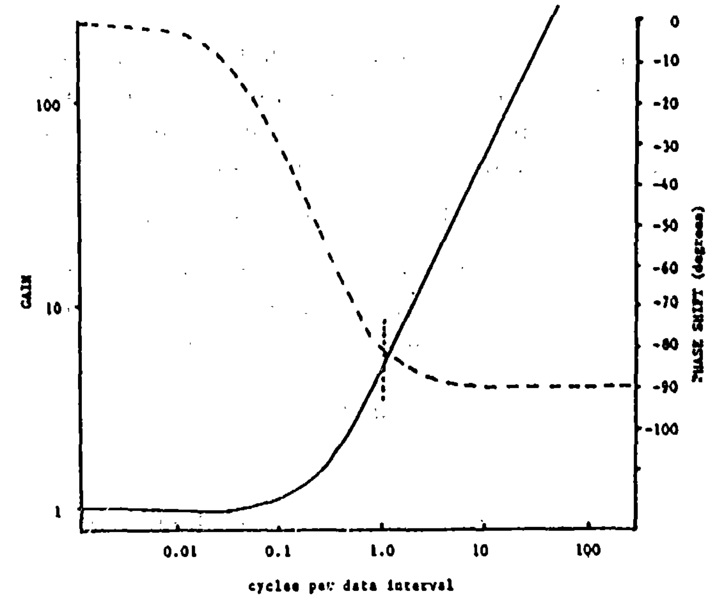


Figure 5.3: Complex frequency response of analogue lag correction scheme

the lag effects from the data (temperature) in an attempt to match the sensor responses at the time constant of the faster sensor (conductivity). None of these three methods are recommended but are included for historical purposes and for completeness. The last three cases describe methods for adding lag effects so that the data all contain the same effective lag responses. In general, these techniques are preferred over the lag removal techniques described in cases 1, 2, and 3. Case 6, adding lag responses which include the velocity dependent nature of the conductivity response is the preferred method for lag correction because of its completeness. As an alternative; case 5, adding lag response containing only simple exponential time effects, is highly recommended.

It should be noted that none of the 6 methods described utilize our full understanding of the response behaviour of the CTD sensors and all use simplifying assumptions. In particular, the most common assumption is that simple exponential decay, or at most dual exponential decay, properly describes the responses of the sensors.

1. Lag correction applied to the temperature series.

   Based on the assumed exponential decay model, recovery of the signal is accomplished by adding a correction derived from the instantaneous time derivative of the output signal:

$$T_c = T_0 + \tau_1 \frac{dT_0}{dt} \tag{5.5}$$

   where T_c is the corrected temperature. The frequency response function of this correction scheme is shown in figure 5.3. This correction scheme amplifies and phase shifts the measured values to restore the true values.

   If the data acquisition system were strictly passive and added nothing except the exponential lag response, the above scheme would fully correct the data and the corrected output T_c would be equal to the input signal T_i. Acquisition systems, however, introduce noise into the recorded data. This noise is not attenuated by the lag response but will be amplified by the correction scheme. Through the correction process, this noise can become larger than the signal. Thus it is usually necessary to reduce the noise content by low-pass filtering.

CASE 1: Sampling interval greater than time constant

The simplest time lag correction scheme is a direct implementation of equation 5.5 using the two adjacent temperature values to estimate the derivative as described by Scarlet (1975). For the jth temperature value:

$$T_c(j) = T_0(j) + N_1[T_0(j+1) - T_0(j-1)] \tag{5.6}$$

where N_1 is the time lag expressed in terms of sampling intervals $N_1 = \tau_1/\Delta t$. This algorithm is only appropriate when the sampling interval, Δt, is larger than the time constant (Scarlet, 1975).

CASE 2: Sample interval less than time constant

For the situation where the sampling interval is shorter than the time constant and the noise content of the data is not negligible, the time derivative should be approximated by a Least Squares slope as detailed in Fofonoff et al. (1974, p18 eq.14,15):

$$T_c(j) = \sum_{k=1}^{k=N} A_k T_0(j - N/2 + k) \tag{5.7}$$

where the filter weights, A_k, for Least Squares smoothing are:

$$A_k = \frac{1}{N} + N_1 \left| \frac{(12k - 6(N+1))}{(N(N^2-1))} \right| \tag{5.8}$$

and the sum of the weights is unity. Details of the choice of N and its effect on noise level can be found in Fofonoff et al.

Two value estimation ($N = 2$) degenerates to using first differences and effectively follows the exact transfer of the analogue correction. Three value least square regression attenuates at higher frequencies in a simple manner, while higher order smoothing creates multiple lobes in the response. Three value Least Squares estimation of the gradient is recommended for removal of simple exponential lag response.

CASE 3: Higher order response models.

The exponential decay model is not exact for simple thermometers (Hurst, 1975) and can lead to serious errors when used to model compound thermometers (Millard et al, 1980). For compound thermometers, the decay model can be generated empirically from the observed or derived response function of the sensor. As outlined by Millard et al. (1980), these response functions can be estimated from the phase and coherence between conductivity and temperature data collected in a region with a well defined temperature-salinity relationship. A digital filter, $W(k)$, can then be designed using

Least Square techniques to approximate the inverse of this response function (Horne and Toole, 1980) which can be used to correct the measured temperature:

$$T_c(n) = \sum_{k=M_1}^{k=M_2} T_0(n+k).W(k) \tag{5.9}$$

where $W(k)$ are the weights of the non-symmetric filter approximating the inverse response of the sensor. If further smoothing of high frequency noise is required after time lag corrections using any of the above techniques, the corrected data can be filtered again. For this situation the final transfer function will be the product of the response of the time lag correction, $R_1(f)$, and the final filter, R_f.

$$R'(f) = R_1(f)R_f(f) \tag{5.10}$$

The total noise increase can be determined by integrating the final transfer function (equation 5.10) from 0 to the Nyquist frequency. The minimum accuracy of the corrected data can then be estimated by multiplication of this increase by the digitizing noise estimated from equation 5.1.

2. Lag correction applied to associated variables.

   Rather than attempting to correct the sampled data to true values, it is possible to adjust the faster responding parameters so that the responses of the temperature, conductivity, and pressure data are all equal and equal to that of the slowest sensor (temperature). The effect of applying a time lag to the faster sensors during processing has two advantages:

   - It is computationally simple and easy to implement and
   - Noise amplification at high frequencies is avoided.

   An additional benefit from this method is the effective low pass filter gained by application of the lag correction. Separate filtering for noise removal thus may not be necessary. The disadvantage in this procedure is the suppression of fine structure content of the series. For most applications this is not critical since data at 1 or 2 decibar intervals will not contain fine-structure and most sensor systems are not designed for such high resolution measurements. Another slight drawback is the loss of the first part of the data series, $3\tau_1/\Delta t$, because of poor correction at the start.

   CASE 4: Recursive digital filtering

   The most general implementation to add time lag response to data is by using a recursive digital filter:

$$X'(n) = W(0).X(n) + \sum_{k=1}^{k=K} W(k)X'(n-k) \tag{5.11}$$

   where the sum of the filter weights, $W(k)$ is equal to unity.

The response function of equation 5.11 is given by:

$$R_1(f) = \frac{W(0)}{1 - \sum_{k=1}^{k=K} W(k)\exp(-\imath^2\pi f k\Delta t)} \tag{5.12}$$

where f is in units of cycles per sampling interval.

CASE 5: Exponential lag response

Simple exponential lag response for a time constant of τ_1 seconds and a sampling interval of Δt seconds can be achieved from equation 5.12 by letting $K = 1, W(0) = 1 - \exp(-\Delta t/\tau_1)$, and $W(l) = exp(-\Delta t/\tau_1$

$$X'(n) = [1 - \exp(-\frac{\Delta t}{\tau_1})].X(n) + \exp(-\frac{\Delta t}{\tau_1}).X'(n-1) \tag{5.13}$$

Millard has evaluated this technique (equation 5.13) in comparison to a transverse filter designed to correct for higher order lag response (equation 5.10) as derived by Horne and Toole (1980) and found no apparent differences in salinity to 0.002.

CASE 6: Velocity dependent exponential lag response

As discussed in appendix A, the response of conductivity cells can be described by a distance, related to cell geometry, at which 63% of a step change is recorded. As a first approximation for conductance cells this "distance constant" (D) is about 55% of the cell length (for inductive cells it is probably equal to or greater than the cell length because of far field effects). Through the lowering rate of the CTD, $V(t)$, this distance constant can be transformed into an effective time constant, T_c, for the cell by:

$$T_c = \frac{D}{V(t)} \tag{5.14}$$

Because of noise, the pressure data should be severely filtered to eliminate high frequency content before being differentiated to estimate the lowering rate.

Using equation 5.14 , we can match the responses of the conductivity sensor to that of the thermometer by adding a lag related to their time constant differences:

$$\tau = \tau_1 - \tau_2 \tag{5.15}$$

The recursive correcting algorithm (equation 5.13) then becomes:

$$C'(n) = [1 - W(1)].C(n) + W(1).C'(n-1) \tag{5.16}$$

where:

$$W(1) = \exp[-\frac{\Delta t}{T_c - D/V(n)}] \tag{5.17}$$

It should be noted that at slow lowering rates, the effective cell time constant becomes large and, at a critical velocity V_c, it will be equal to that of the temperature sensor time constant τ_1:

$$V_c = \frac{D}{\tau_1} \tag{5.18}$$

Assuming the shape of the response functions are similar, then no further lag corrections would be required. At speeds much below this critical velocity (and upcast speeds where the data are distorted by the turbulent wake of the CTD) the conductivity data are probably unreliable because of self-heating. Salinities derived during these slow lowering speeds should be disregarded. Operationally, this method can be implemented by shifting the parameter to be corrected from conductivity to temperature when the lowering speed is below the critical velocity.

For V(t) greater than V_c:

$$C'(n) = (1 - W(1)).C(n) + W(1).C'(n-1) \tag{5.19}$$

$$T'(n) = T(n)$$

$$W(1) = \exp[-\frac{\Delta t}{T_c - D/V(n)}]$$

For V(t) equal to V_c:

$$C'(n) = C(n) \tag{5.20}$$

$$T'(n) = T(n)$$

And, for V(t) less than V_c:

$$C'(n) = C(n) \tag{5.21}$$

$$T'(n) = (1 - W(1)).T(n) + W(1).T'(n-1)$$

$$W(1) = \exp[-\frac{\Delta t}{(D/V(n) - T_c)}]$$

For this comprehensive approach (equations 5.19 to 5.21), salinity values computed at lowering speeds less than 1/4 of the critical velocity should be discarded during compaction. However during the correction, these very low or negative speeds should be replaced by $0.25V_c$ to avoid numerical difficulties and to maintain the recursive algorithms. Where the lag response to be added is more complex than that approximated by the simple exponential decay model, a recursive filter of a few weights can be derived using Least Square techniques to match equation 5.13 to the desired response function.

Since adding lag distortion only requires past historic information in the data series, this approach for time lag correction is very simple to implement and very efficient. The first few seconds of filtered output will not be fully corrected (approximately $3\tau_1/\Delta t$ data values) and should be discarded.

3. Frequency Domain Approaches

There are two possible implementation techniques for applying lag corrections to discretely sampled data, either in the frequency domain or in the time domain discussed above. Physically they are equivalent. The frequency domain approach entails computing the Discrete Fourier Transform (DFT) of the recorded data, applying a complex correction (multiplication by $[1+2\imath\pi\tau_1]$ for simple exponential decay model) and then performing an inverse DFT to regenerate the corrected data. This approach has not been used in the past. In its simplest form, the processing would be as follows for lag correction:

(a) Perform an aperiodic Discrete Fourier Transform (DFT) on the temperature time series using any of the Fourier or Fast Fourier Transform techniques (such as Gold and Rader, 1969):

$$F_0(f) = DFT[T_0(t)] \tag{5.22}$$

(b) Multiply each of the frequency estimates by the inverse of the lag response to determine the corrected Fourier transform:

$$F_c(f) = F_0(f).R_1(f) \tag{5.23}$$

Where $R_1(f)$ is the inverse of the lag response (for the simple exponential decay model $R_1(f)$ is equal to $(1+2\imath\pi f\tau_1)$.

(c) Resynthesize the corrected time series by performing an Inverse aperiodic Discrete Fourier Transform:

$$Tc(t) = DFT^{-1}[F_c(f)] \tag{5.24}$$

Smoothing can be easily added to the processing by multiplication of the corrected Fourier Transform by the response function of the desired filter, $R_f(f)$, before resynthesis:

$$F_c'(f) = F_c(f).R_f(f) \tag{5.25}$$

The great advantage of this approach is the simplicity of changing the filter characteristics in the software. The filter is easily specified and can be tailored directly to the desired response. The disadvantage is that it can cause severe oscillations in the resynthesized time series which then propagate from the ends towards the middle. This phenomena is compounded by the input time series having a trend (temperature decreasing with depth) which requires Fourier components similar to that of a saw tooth wave to reconstruct it. Many of these components have substantial amplitudes at high frequencies which the time lag correction may amplify. To reduce these oscillations caused by the periodic nature of the DFT, it is possible to divide the original time series into short sections overlapping by 1/4 or 1/3 sections and using only the non- overlapping portion to reconstruct the corrected data. In addition it may be useful to remove any linear trend before the DFT is computed and restore the trend after resynthesis, along with a constant lag correction to account for the trend ($\tau*$ slope of trend).

Frequency domain techniques can also be used to add lag effects to the conductivity and pressure data. For this use, the response function, $R_1(f)$ in equation 5.25, would be the actual lag response of the temperature sensor rather than its inverse. For those instruments where the lag responses of the conductivity and pressure sensors are not near unity (time constants not equal to 0) this response function, $R_1(f)$, would be the ratio of the temperature response divided by the conductivity or pressure response as appropriate.

In general, for either of the approaches to time lag correction discussed above, special operations must be included to prevent the undesired amplification of the noise into the corrected data. For the time domain approach this is accomplished by low pass filtering. For the frequency domain approach, this is accomplished by filtering and overlapping of the data sections during processing.

Miscellaneous Adjustments

Adjustments may be necessary in order to make the conductivity and temperature values correspond to the same horizontal pressure level and to account for *in-situ* calibrations.

- Adjustments for Pressure Level

  Depending on the mechanical configuration of the sensors on the instrument, the sensor sampling sequence, and any delays introduced by time lags, it may be necessary to adjust the dataset so that the values of temperature and conductivity correspond to the same pressures. Linear interpolation between data values should be used to make this adjustment.

- Corrections for *in-situ* Calibrations

  Any precision sensor may shift its calibration as a function of time and CTD sensors are no exception. Since the relationship between temperature, conductivity, pressure and salinity is non- linear, any calibration shifts must be applied before the computation of salinity. These corrections are determined using independent measurements of these values *in-situ*.

- Zero pressure correction is determined by wire angle and length for a shallow depth of about 1% of full scale pressure. This zero pressure should be used to correct the pressure data for each lowering to account for the small random bias in depth caused by the initial non-linearity of sensor output as it departs from its rest value at zero pressure.

- For conductivity, a modified cell constant can be computed by measuring the salinity of a water sample acquired *in- situ* and deriving the "true" conductivity using corrected pressure, temperature from the CTD, and this salinity value. Data from several casts should be used to determine this modified cell constant. A more complete description of how to determine these corrections can be found in chapter 3

Computation of Salinity

Salinity is computed from corrected, *in-situ* values of temperature, conductivity, and pressure using the salinity definition of 1978 (Appendix D). To maintain comparability between different data sets, no other algorithms should be used.

Removal of Erroneous Salinity Values

We now have a complete time series of corrected temperatures, corrected pressures and computed salinities at the original sampling interval. Scarlet (1974), Walker (1978), Gregg et al. (1981), and Topham (1981) describe the responses of some conductivity sensors. These responses are not instantaneous and require flow through their bore to maintain calibration. Under low flow conditions, water is trapped inside the cell, usually at the sides, and thus the mean conductivity of the water within the cell is not the same as that outside in the water column. This is particularly true when large gradients are present.

Because these errors are difficult to determine or model analytically, the investigator should discard all salinity values corresponding to times when the flow through the conductivity sensor is less than that required for proper flow or when the lowering speed is so slow that the effective time constant of the conductivity cell is much larger than that of the temperature sensor. In addition, downcast data acquired while the CTD is moving upwards during wave motion should also be discarded because water entrained by the shape of the CTD will alter the water column being measured. For this same reason, upcast data should not be reported. Flow conditions through the conductivity sensor may also be low when the downwards velocity approaches or is equal to the terminal velocity of the CTD. At these speeds the instrument may be tumbling or moving sideways because of the weight of the cable.

To make these deletions for low flow conditions, the velocity of the CTD is calculated from the pressure data. Since the resolution of the pressure sensor is relatively coarse and has a high noise content, filtering is necessary. Either low-pass filtering (equation 5.2) followed by differencing:

$$\frac{dP'}{dt} = \frac{P'(n+1) - P'(n-1)}{2\Delta t} \tag{5.26}$$

or gradient estimation by linear Least Squares can be used to determine the velocity of the CTD. Linear least squares estimation using 2K+1 data values is done according to:

$$\frac{dP'}{dt} = \frac{\sum_{k=1}^{k=K} k.P(n-k)}{2\sum_{k=1}^{k=K} k^2} \tag{5.27}$$

The larger the number of data values used in equation 5.7, the smoother will be the estimate of the gradient. If the variation of pressure with time is not linear over these $2K + 1$ data intervals then the estimate will deteriorate and low-pass filtering would be a better approach. The number of data intervals, $2K + 1$, included in the least squares estimation should not greatly exceed the reciprocal of the sampling interval in seconds. This preserves the ship roll signal in the series ($\approx$ 4 sec period). The mass of the CTD and constant winch speeds allow severe smoothing on the depth data. Cutoff frequencies of from 1 to 2 hertz are not unreasonable unless ship roll motions are quite irregular or markedly non-sinusoidal.

Compaction

The purpose of compaction of the dataset is to reduce the dataset to a manageable size and to make the dataset monatonic in pressure. Two techniques are routinely used: averaging within pressure (depth) intervals (basketing) and representation by flexure values. For most applications the data stored by either technique are equivalent. However, the spectrum of the reconstituted data and the extreme values may be different between the two methods.

- Pressure Interval Averaging (Basketing)

  The most common form of compaction is forming arithmetic averages of temperature and salinity for a set of desired pressure intervals (δp). Except for micro- or fine-structure instruments, the pressure interval should not be smaller than 1 decibar. The reported pressure of each interval should be the center of the interval (i.e. 50 decibars would represent the interval from $50 - \delta p/2$ to $50 + \delta p/2$). Only valid, corrected data are used to compute the average within each averaging interval.

- Flexure Value Compaction

  Another method for compacting data is by derivation of flexure points. This method is predominantly used by archive centers because of the significant reduction in volume of data. The complete valid dataset is stored by saving the ends of straight line segments which when joined end for end, will duplicate the high resolution set with no deviations between the straight line segments and the original dataset greater than a predetermined error (flexure criteria). Fig 5.4 shows an example of high resolution data and flexure points which reproduce these data to a known uncertainty.

5.4 Recommended Practices

5.4.1 Time Lag Corrections

For the processing of non fine structure temperature and salinity profile data (output data intervals of 1 or 2 decibars) the recursive filtering technique (equation 5.13) to generate uniform lagged responses for temperature, conductivity, and pressure is highly recommended. For more comprehensive correction, the recursive technique is still recommended, but the filter should be designed to match the differences in actual lag responses of the sensor pairs

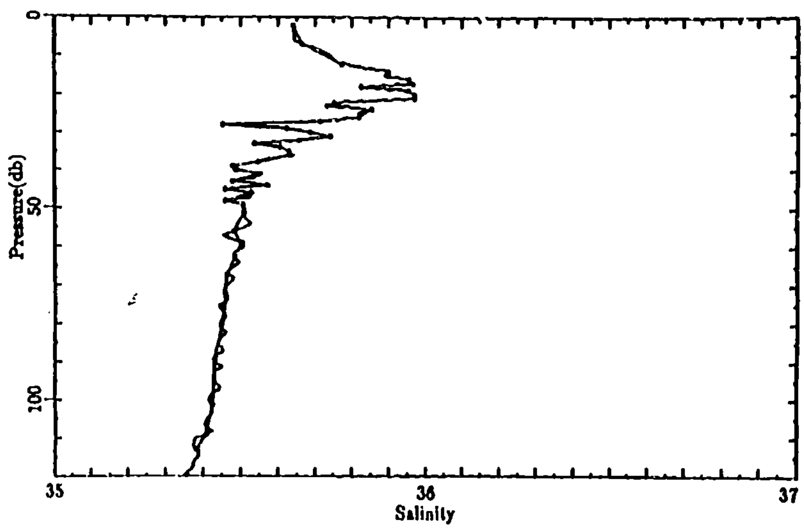


Figure 5.4: Compaction of data by flexure points. Error in $S < .04$ and in $T < .03$

(equations 5.13 and 5.14) (CASE 4) and account for the velocity dependence of the cell response (equations 5.18 and 5.19) (CASE 6).

5.4.2 Units

The recommended units are degrees Celsius (^{o}C) for temperature data, milli-Siemens (mS) for conductivity and decibars (dbar or 10^4 Pascals) for pressure. Practical Salinity is dimensionless. If the pressure data are converted to depth (not recommended) using the hydrostatic relationship, the units should be reported in meters (m).

5.4.3 Precision

Data values should be reported with sufficient precision to insure that meaningful truncation does not occur. This precision should have the least significant digit one order of magnitude better than the accuracy of the value (a value with an accuracy of 0.02 should be reported to a precision of 0.001 units). Recommended minimum precisions for reporting data are: 0.001deg C for temperature, 0.001 mS for conductivity, 0.001 for salinity, and 0.1 dbars for pressure.

Chapter 6

Guidelines for Exchange[1]

6.1 Introduction

It is recognised that, with modern CTD systems and careful *in-situ* calibration, it is now possible to obtain good quality, high resolution vertical profiles of temperature and salinity (or conductivity). It is also recognised from past experience that the majority of secondary users are likely to prefer compressed versions of these data, at intervals more compatible with classical water bottle data or the ICES STD Standard Criteria of 1969. However, in satisfying this majority user need, it is important to ensure that good quality, high resolution data are not lost to those scientists that require them. Laboratories should endeavour to maintain versions of these data with minimal loss of information, in addition to any compressed versions that might be prepared for more general use.

These guidelines relate specifically to data maintained to minimise information loss, rather than to versions compressed to satisfy particular user needs. It is, however, recognised that on occasions these two versions may sometimes be one and the same, and that on occasions data compression techniques may be applied without significant loss of real information.

6.2 Data Standards

1. As a matter of routine, data should not be exchanged at a finer resolution than 2 decibars in oceanic depths, and 1 decibar in continental shelf depths. Only if the data have been collected for some specialist study, e.g. micro- or fine-structure measurements, should finer depth resolutions be considered.

   It is recognised also that in many cases calibrated data sets may only have been produced to coarser resolutions arising either, for example, from the circumstances of the instrument performance, or from the nature of the data originator's investigations.

   The recording of data at flexure points may be seen as a means of achieving economy of storage relative to recording at fixed pressure intervals. If this technique is used,

[1]These were initially developed by the ICES Working Group on Marine Data Management

there should not be significant loss of information about the profile in comparison with fixed pressure interval data prepared according to the above.

2. All relevant corrections should be applied to the data including instrumental calibrations, and field corrections. The data should be fully checked for quality and pre-edited or flagged for erroneous values such as spikes, gaps etc. An explicit statement should be made of the correction, checks and editing applied to the data.

3. If available, the reference values used for *in-situ* calibration/comparison (for example reversing thermometer measurements, bottle salinities), should accompany the data.

4. Sufficient self-explanatory series header information and documentation should accompany the data so that they are adequately qualified and can be used with confidence by scientists and engineers other than those responsible for their original collection, processing and quality control

5. All data values should be expressed in oceanographic terms, in SI units, (although decibars are permitted alternative) which should be clearly stated. Salinity values will be expressed in Practical Salinity Units and should be clearly distinguished from the earlier pre-1978 definition of salinity.

6. Other parameters measured as part of the series e.g. sound velocity, oxygen, should be included with the data.

7. Unless calibrated against depth measurements, the data cycles should include pressure and not depth. If conductivity is included instead of salinity, then pressure should always be included.

6.3 Format Standards

1. Data should be exchanged in GF-3 format. An example is given in Appendix C

2. Guidelines for the formatting of CTD data in GF-3 may be obtained from: RNODC (Formats), ICES Service Hydrographique, Palaegade 2–4, DK-1261 Copenhagen K, Denmark or from Marine Information and Advisory Service, Proudman Oceanographic Laboratory, Bidston Observatory, Birkenhead, Merseyside L43 7RA.

6.4 Series Header Information

Each CTD series should include entries in the appropriate GF-3 fields for the following:

1. Name of the country and organisation responsible for collection and processing of the data.

2. Project, platform (e.g. ship) and cruise identifiers.

3. Dates and times of start and end of CTD cast.

4. Originator's reference number/identifier for the series.

5. Latitude, longitude, (start and end positions if known) and sea floor depth.

6. Reference values collected for *in-situ* calibration/comparison e.g. reversing thermometer measurements, bottle salinities.

6.5 Data Documentation

Sufficient plain language documentation should accompany the data so as to ensure that they are adequately qualified and may therefore be used with confidence by a secondary user. Such documentation should be included within the plain language part of the GF-3 format and, where applicable, should cover all items listed below. (Note that a worked up example of a fully documented CTD series may be found in the GF-3 guidelines referenced in 6.3.2.).

1. Instrumentation:

   (a) Description of each instrument used—manufacturer and model number. Refer to publication or briefly describe.

   (b) Instrument modifications and their effect on the data.

2. Data Collection:

   (a) Description of operational procedures for collecting CTD data and *in-situ* calibration data—indicate whether data are from down cast or some combination of down and up casts.

   (b) Sampling rate, sensor resolutions, and lowering rate—indicate any changes during the cast.

   (c) Method to monitor CTD depth or CTD height above sea floor.

   (d) Methods of position fixing and sea floor depth determination.

3. Data Calibration/Quality: for each parameter or sensor

   (a) Type or principle of sensor (e.g. platinum resistance, thermistor).

   (b) Method, quality (including response range) and dates of sensor calibration.

   (c) Method and quality of *in-situ* comparisons.

   (d) Report on corrections applied to data including corrections for bias, drift, calibration and system malfunctions, and

   (e) Estimate of final uncertainty in the data as evidenced by the calibrations and comparisons, and by sensor performance.

4. Data Processing: brief description of processing procedures (and their sequence) used to obtain final data values starting from original samples including

(a) filtering/de-spiking/smoothing methods.

(b) editing/quality control procedures—indicate how missing or erroneous data were identified and treated.

(c) time lag correction scheme (for each sensor in question) and values used.

(d) adjustments made because of variations in calibration during cast or because of sensor design and arrangement.

(e) computation of salinity.

(f) pre-sorting of data by pressure.

(g) data compression method e.g. pressure interval averaging—state the interval, flexure point compression—state the criteria averaging over n original data cycles edited version of original data set.

5. Report any additional item or event that may have affected the data, or have a bearing on the subsequent use of the data.

Appendix A

The Design of Observational Programmes

A.1

Several decisions must be made.

1. Decide the depth intervals d for which representative salinity and temperature values are required. This means that the smallest feature required to be observed in the ocean should exceed 2d.

2. Determine

   (a) The time constant of the temperature sensor, τ_1 and of conductivity sensor,τ_2 (they may not be as quoted by the supplier)

   If τ_2 is not available use $0.55L/V$ where L is the length of the cell ,and V the probe descent velocity. If possible choose V so that $\tau_1 \sim \tau_2$.

   (b) Time lag δt between the measurement of conductivity and temperature values in a single cycle.

   (c) Time interval, Δt, between successive samplings of C, T and pressure.

   (d) Does the instrument record every sample (at intervals Δt) or does it record a block average of N samples (at intervals Δt)?

   (e) Determine the sensor separation, h .

3. If Δt is equal to or greater than τ_i, construct $\tau_i^* = \tau_i/\Delta t$ and $f^* = \Delta t V/d$ Use figure A.1 to estimate the extent of aliasing of higher frequencies.

4. Determine the attenuation at the frequency of interest, V/2d, from the abscissa of Figure A.1a and decide if it is acceptable.

5. If not, then alter d or the instrumer ; time constants to suit, possibly by altering V to change τ_2.

6. Proceed to make measurements and calculate salinities as discussed in the chapter on data analysis.

7. Example Suppose it is required to resolve 0.5 m "slices" of an oceanographic profile (d = 0.5 m). τ_1 is given as 0.1s and L as 18 cm so that $\tau_2 = 0.55 \times 0.18/V$. If the sample interval Δt is 0.15s then $\tau^* = 2/3$ and from figures A.1a and b aliassing will be about 10%. If 20% attenuation is acceptable at 1m wavelength then the figures show that $f^* < 0.36$. Thus $V < 1.2$ m/s. To match time constants $\tau_1 = \tau_2$, we need $(0.55 \times 0.18)/V = 0.1$ giving $V = 1$ m/s. The physical separation between the sensors could now be adjusted to compensate for the time interval δt, between their sampling in a single record. If $\delta t = 0.05$s then $h = V\delta t = 1 \times 0.05m = 5$cms. Alternatively and more practically, to cope with varying velocities of descent, (V variable) the time series for conductivity and temperature may be "slipped" i.e. interpolated by an interval $(h/V - \delta t)$ so that salinity calculation are carried out on values measured at the same location. Note that 7 measurements per meter are necessary to resolve the desired half meter slice thickness adequately at the selected 1 m/s lowering speed. $f^* = 0.3$ and Figure A.1 shows that the half meter signal is attenuated by only 15% by the sensor time constants, and that only 7% (Figure A.1a) and 3% (Figure A.1b) of any energy available at wavelengths of 18 cm and 13 cm respectively will appear aliased onto the 1 m wavelength record (d = 0.5 m).

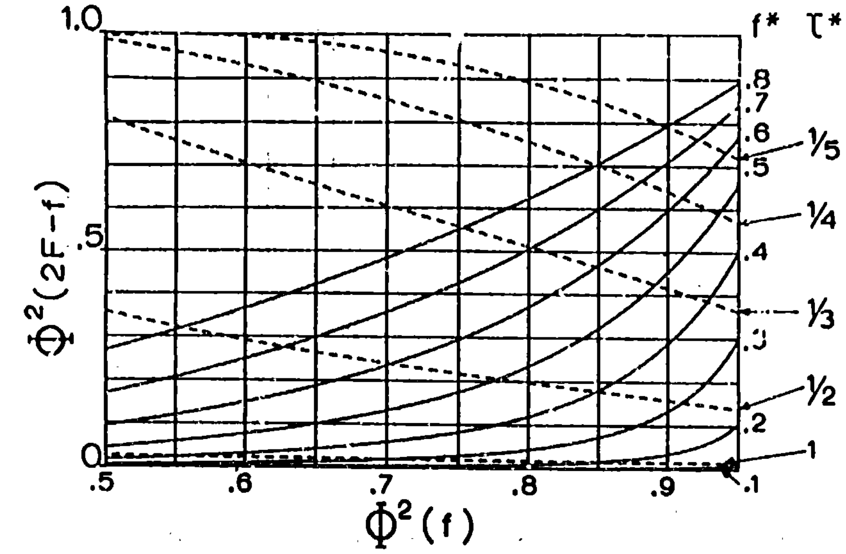
A.2 Sensor Response

To deal with the sometimes non-exponential response of the temperature system we shall generalize the concept of time constant (which strictly speaking applies only to the simple exponential rise) and define it as that time taken for the response to reach 63% of the amplitude of the temperature step.

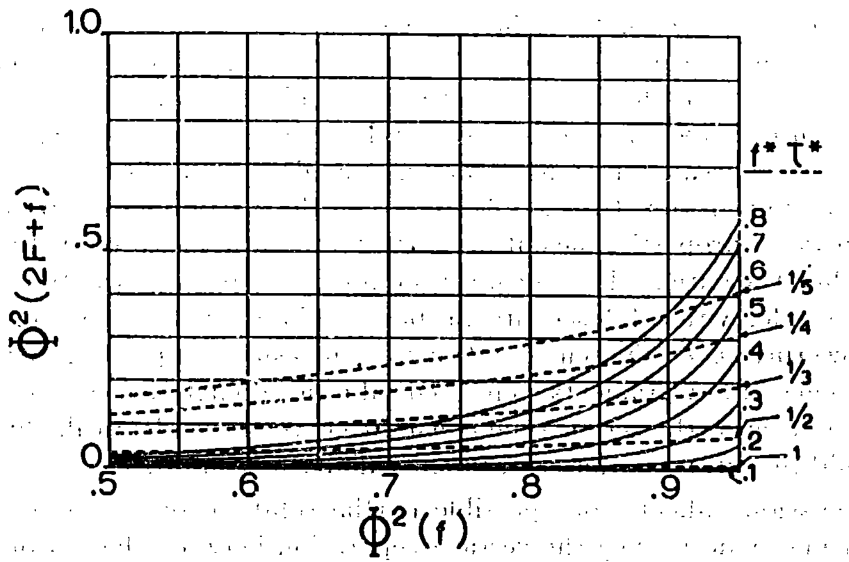
Although the salinity calculation is not very sensitive to time constant effects in the pressure sensor, hysteresis problems can be important when the CTD is being lowered from a vessel subjected to major pitching and rolling which periodically alters the rate of descent. Under these conditions, the computation of the lowering rate from small pressure differences is usually made unstable by noise and resolution problems so that only greatly smoothed estimates of lowering rate can be obtained from the pressure record. These estimates are generally not good enough to aid in the reconstruction of small scale features through knowledge of the sensor response characteristics.

A.3 Sensor time constants and sampling considerations

In the usual CTD lowering, temperature, conductivity and pressure are sampled and recorded sequentially. Depending on the electronics available, a set of values may be available up to 25 times per second; in other systems one complete scan of all three sensors takes more than a second. The factors of time constant, lowering rate and sampling speed



A.



B.

Figure A.1: *a)* Nomogram relating frequency of interest, f, sampling interval Δt, time constant τ with signal attenuation $A(f)$ and aliasing. F is the Nyquist frequency, equal to $0.5\Delta t$ and $\tau^* = \tau/\Delta t, f^* = f/F$. Entering with given values of the last two parameters gives signal attenuation at the frequency of interest (abscissa) and the proportion of any power existing at frequency $(2F - f)$ that will be aliased onto the frequency of interest (ordinate). *b)* Same, but for frequency $(2F + f)$.

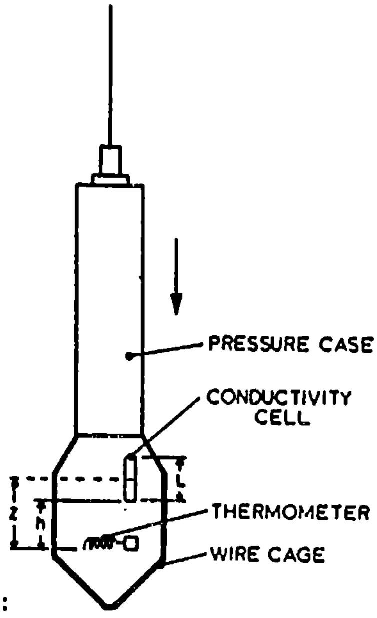


Figure A.2:

are all interrelated in planning to obtain optimum salinity information and the discussion of these inter-relationships is the main subject of this section.

To illustrate the problem involved take the case of slow sequential sensor sampling at a lowering rate of 1m/s so that the instrument moves a significant distance during one complete scan of the sensors. Figure A.2 shows a sketch of the sensor positions on their protective cage beneath the CTD pressure case and defines appropriate geometric parameters. It is assumed that the sensors are sampled in the order pressure, temperature and conductivity. Very frequently sensors are mounted so that they are at the same horizontal level at any given time (i.e. $z = 0$) so that as the instrument is lowered through a sudden change in water properties the output of the temperature and conductivity sensors are not sampled when they are at the same position in relation to the discontinuity in water properties. For example, with a 1/3 sec interval between individual sensor sampling and a 1 metre/second lowering speed the sensor outputs are measured at positions 33 cm apart, so that in the presence of any gradients computed salinities do not give the value at either position. Therefore, even if the sensor time constant curves were identical, this sampling position offset could produce a major error in the salinity so computed.

The above discussion indicates one possible partial solution for sensor time constant differences; increasing or decreasing the vertical separation between the sensors around a central value dictated by the sampling interval. However, it must be noted that this is only good for one lowering rate; at 1 m/s, the 1/3 of a second interval was equivalent to a 33 cm sensor separation — at 2 m/s it corresponds to 66 cm. Most oceanographers work from ships where, if the winch pays out cable at 1.5 m/s, the actual velocity of movement of the CTD fish may vary from 0.5 to 2.5 m/s according to the pitching and rolling of the vessel. Thus the appropriate separation for the sensors on the cage becomes problematical. Again, a "first-go" solution would be to determine the rate of pressure change with time from the data so collected, and to eliminate that data where the velocity of descent varied widely from 1.5 m/s, the undisturbed value.

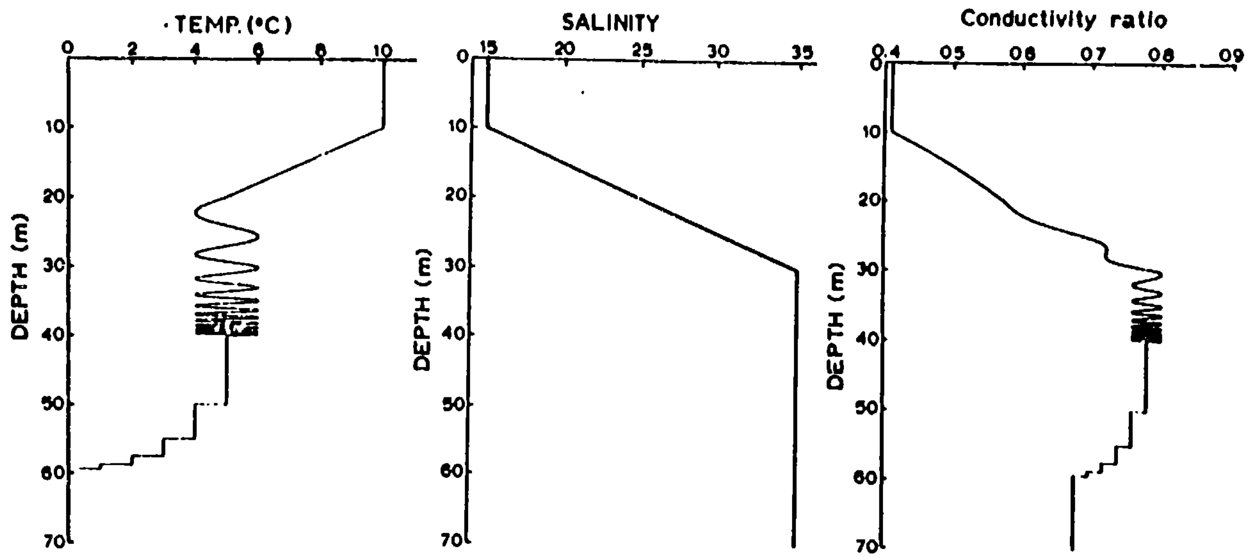


Figure A.3: Artificial sea designed to demonstrate CTD response

A.4 Computer simulations of CTD observations

To appreciate the complex interrelationships between sensor time constants and sampling rate, we consider the response to synthetic temperature and salinity profiles containing features designed to illustrate their effects.(Figure A.3). They do not of course represent the real ocean.

For example, take values typical of one of the older CTD designs, in which a cell of length 20 cm is paired with a temperature sensor with time constant 200ms. These two sensors are at the same level (z=0 in Figure A.2), are being lowered at 1 m/s and scanned once per second with 1/3 second between the measurement of temperature and conductivity values. The standard ocean of figure A.3 is recorded as in figure A.4 by this instrument. At the given lowering speed temperature and conductivity sensors are approximately 33 cm apart at the time their outputs are being sampled, and when there is a change of salinity with depth, between 10 and 20 m for example, a salinity offset results due to the combination of temperature and conductivity readings from the two different levels. The level ascribed to the salinity so calculated is that of the depth of the centre of the conductivity cell. As the depth increases from 20 to 40m the temperature sensor can no longer follow the sine wave so that as the frequency increases, an increasingly attenuated temperature signal results. In the end aliasing occurs, the high frequency is not resolved and a spurious slow change in temperature appears. In the same interval the salinity has errors up to nearly 2 units. Large errors also occur where step changes in temperature have been imposed, for example at 50m.

A first attempt to correct this state of affairs is to optimize the sensor positions in terms of their time constants, the lowering rate and the sampling frequency. It would be desirable that both sensors, when sampled, should have reached the same level of response to changing values in the ocean. As the two response curves are differently shaped, this can only be made to be true exactly at one point. Rather arbitrarily we will select the

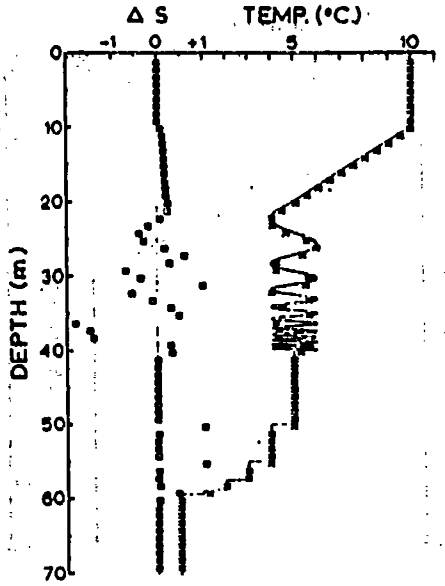


Figure A.4: CTD Response—example 1. ΔS is "(observed -true") salinity

instant at which they have reached 63% of their final value, that is one time constant after the start of a step change. Suppose the sensors were sampled simultaneously. The distance moved by the probe during the time for the temperature sensor to reach 63% of its final value is $t.V$, where V is the lowering speed of the instrument. If, at this time, the conductivity sensor has reached the same percentage response approximately .55 of its length will be immersed in the new field so that we may write the equation (Figure A.3 defines h and L).

$$h = V\tau_1 - 0.55L$$

However, sampling is not usually simultaneous but separated by a time interval δt and we will assume that this quantity is positive if the temperature sensor is sampled before conductivity. A further distance $V\delta t$ between the sensors must be introduced to compensate for this interval so that the total distance h from the bottom of the conductivity cell to the temperature sensor can be expressed as

$$h = V(\tau_1 + \delta t) - 0.55L \tag{A.1}$$

This arrangement should match the response of the sensors at one point, the 63% value, but if it is possible to control V, the lowering speed, a match at a second point is possible. With the temperature sensor a distance h in front of the conductivity sensor there is a distance $h - V\delta t$ when only one sensor will have responded to the step change. Should sampling occur in this interval, major errors will result. Ideally it should be set to 0 which is equivalent to making both sensors match at the start of their response as well as at the 63% level. In this case, $h = V\delta t$ and V is defined by

$$V = 0.55L/\tau_1 \tag{A.2}$$

Using the dimensions as for Figure A.4 as an example, this would give a lowering rate of about 55 cm/s.

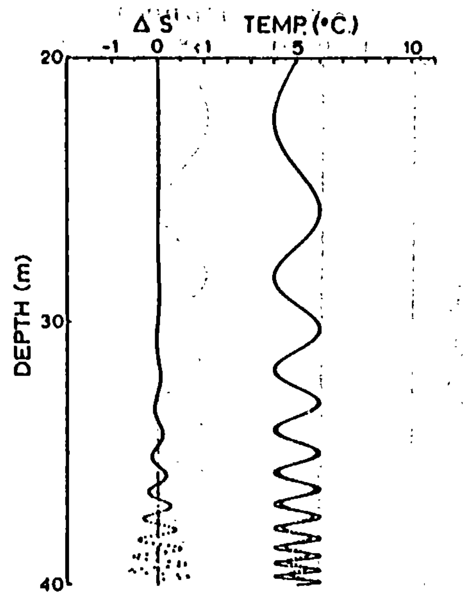


Figure A.5: CTD Response—Example 2. "Fast" sampling system

Full details of the effect of these two corrections on the series are to be found in Perkin and Lewis 1982.

Consider now as an example of a fast sampling system a CTD instrument using the same sensors. In producing Figure A.5 we have taken 25 scans per second and applied equation A.1 to illustrate the performance of such a CTD in the depth interval 20-40 m in our standard ocean. Aliasing is no longer present, though the higher frequency portion of the sine wave becomes severely attenuated by the slow response of the temperature sensor. A considerable degree of salinity noise is present at these higher frequencies which, as mentioned above, is due to there being an interval $(h - V\delta t)$ where the temperature sensor will have started to respond to the change without the conductivity sensor having yet "felt" it. Figure A.6 shows the reduction in salinity noise brought about by applying both equations A.1 and A.2 to the same sensors (optimising both the drop rate and the separation of the sensors). As the lowering speed has dropped from 1 m/s to 55 cm/s the attenuation of the sine wave had been materially reduced due to the temperature changes being sensed at a lower frequency and the remaining salinity noise is now primarily due to the difference in shape between the temperature and the conductivity sensor response curves; we have forced them to agree at the 0 and 63% values. This represents just about the best it is possible to do with the instrument. If one wishes to resolve these high frequencies a faster time constant is required.

Another illustration of the difference in salinity readings obtained by varying the descent velocity is given in Figure A.7 which illustrates the response to the temperature discontinuity at 50 m in our standard ocean at various lowering rates. In going from the fastest to the slowest lowering rates $(h - V\delta t)$ goes from being positive to negative through zero at the optimum lowering rate of 55 cm/s fixed by equation A.2 and by the sensor separation. Thus at the fastest rates the temperature sensor starts its response before the conductivity sensor. At the lowest rates the opposite is true. The optimum constitutes a balance between the two effects minimizing the salinity swing on either side of its correct

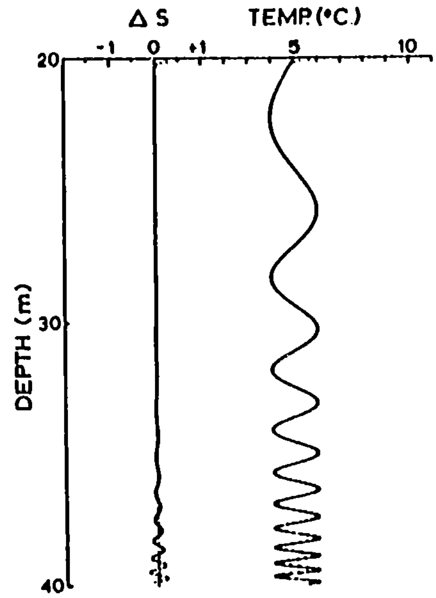


Figure A.6: CTD Response—Example 3. Same as Ex. 2 but optimized both for drop rate and sensor separation

constant value.

A.5 Examples using observational data

A.5.1 calm conditions

The ideas developed in the preceding sections will now be applied to field data. Data acquired from ships frequently shows large fluctuations in the velocity of descent of the CTD but that acquired from the sea ice surface has usually been obtained at a constant velocity. The latter data is considered first as a simple case. Figure A.8 shows sections from two CTD profiles from the Canadian Beaufort Sea taken in November/December 1979. Both sets of curves show the temperature profile and the salinity as calculated for various values of τ_1 as defined for use in equation A.1. The instrument was a Guildline Mk IV CTD with a thermometer time constant of 50 ms as given by the manufacturer ($\tau_1 \sim 25$ ms) and a conductivity cell length of 14 cm. From the pressure sensor readings it was determined that the instrument was lowered at a speed of 1.5m/sec $\pm$ 10%. The sensors are mounted on the instrument so that z=0, i.e. 7 cm of the vertically mounted conductivity cell are on each side of the axis of the thermometer, a helical coil, which is horizontal during a vertical descent. The sensor outputs were sampled 25 times per second, and there was a delay of 5 ms between the sampling of the temperature and conductivity sensors (δt = 5ms).

At this fast sampling rate it is not necessary to move the sensors with respect to each other as illustrated in figure A.2. The water mass properties have been taken every 6 cm during the descent and as neither sensor will respond significantly to fluctuating water properties at a smaller length scale, the time series of temperature and conductivity values

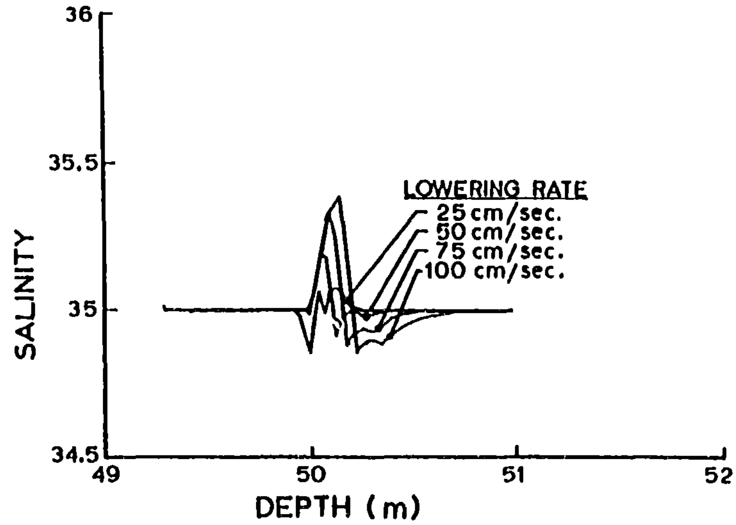


Figure A.7: CTD Response—Example 4. Effect of velocity variations

may be considered smooth for interpolation purposes. The temperature and conductivity values to be combined to calculate a salinity are then selected from their time series so as to be separated by a time interval h/V, which is equivalent in this case to an actual physical separation of h. This procedure of "slipping" the time series is far more convenient as for a given δt one would have to alter the value of h for each new value of V, were it necessary to achieve the desired effect by actual sensor separation. For slowly sampled instruments, for example those having a second between samples as used to produce Figure A.5, an actual physical separation is necessary as the sensors could respond significantly to unresolved fluctuations in the water mass properties during that interval.

Figure A.8a shows the remarkable improvement obtained by applying equation A.1 each profile being characterized by a particular value of τ_1. It is seen that τ_1 = 50ms produces by far the smoothest result and that quite a number of "significant features" in the salinity profile have been eliminated by this processing technique. In an environment with a smoothly changing salinity/depth profile, major temperature fluctuations, combined with conductivities taken at the "wrong time" have produced artificial salinity changes. It is important to realize that these spurious features have been generated solely by allowing a variation of τ_1 from 0 to 100 ms. Figure A.8b illustrates the well-known phenomenon of "spiking" at sudden changes in the slope of a temperature or conductivity curve, and its elimination by proper processing.

The question does arise of how the curve for τ_1 = 50ms is selected as being "best". It is noted for example that the feature at the 65 db pressure level on Figure A.8 has very noticeably reversed its direction to turn from a salinity reduction to a salinity increase as the value of τ_1 is increased, and is flattened out at τ_1=50 ms. On figure A.8b the spikes of temperature and salinity at about 38 db are certainly associated with each other and the use of τ_1=50 ms has resulted in the elimination of the salinity spike. Nevertheless, some subjectivity still exists in the argument, which is one of the reasons why the criteria were applied to a known computer- generated ocean in earlier sections.The next logical step

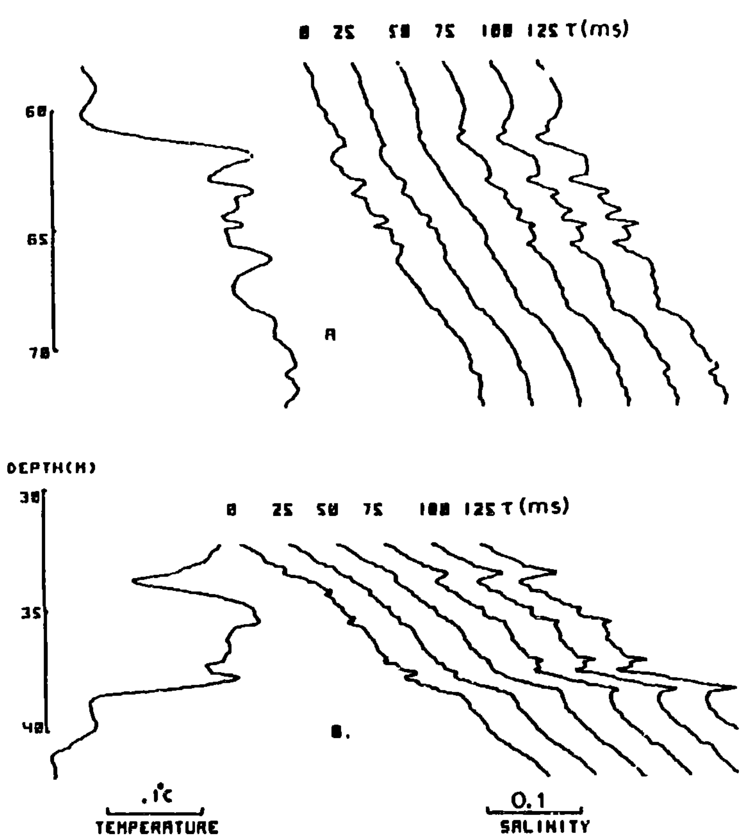


Figure A.8: The processing of two sections of data from the Beaufort Sea. In both cases the salinity is increasing steadily with depth but temperature, the left hand curve in both cases, has considerable structure. The set of six curves on the right are labelled with the values of τ_1 taken for the computation of salinity using equation A.1 to move the temperature and conductivity ratio time series in relation to each other. It is seen that most of the salinity structure is removed by taking $\tau_1 = 50$ ms, which is the manufacturer's given value. It is interesting to note the spurious "intrusive layers" created by taking other values.

would be to apply equation A.2 to the τ_1=50 ms curves of Figure A.8 to see if a further improvement to this data would result. On putting appropriate values into equation A.2 it is found that an optimum value for the descent velocity would be 1.54 m/s so that the difference between this ideal rate and that actually used in practice is too small to make any significant difference in the result.

In shipborne use, where the velocity of descent of the probe may go through large and sometimes violent fluctuation, including reversal, this simple approach cannot be expected to compensate for the complicated fluid dynamical processes which result. It is best to specify a range of lowering rates and data taken outside these limits can be excluded from processing or flagged to indicate their lower expected accuracy. The remaining data can be processed as described above.

A.5.2 Moderate and rough conditions

This was done for two stations taken during Discovery Cruise 81 by the Institute of Oceanographic Sciences, Wormley, U.K. in January 1980. The instrument used was a Neil Brown CTD equipped with a 200 to 250 ms time constant temperature sensor. The conductivity sensor, whose effective length is about 3 cm, responds much more rapidly than the temperature sensor and this difference must be reconciled in data processing. The velocity of descent of the probe varied between 12 cm/s and 175 m/s as the data shown in figure A.9 was collected. Figure A.9 a shows the results obtained by application of equation A.1. The features at 665 and 690 db pressure are responding to the changes in τ_1 and appear to reach a minimum at between 250 to 300 ms. Figure A.9 b shows the result of filtering the conductivity so as to artificially increase time constant to match that given by equation A.2 (see also chapter 5 case 6). As is seen from the equation the filtering required is a function of velocity of descent so that the filter is continuously varying. Note the general loss of detail and the smoothing of sharp features such as the step at 660 db pressure as this artificial time constant is increased. For this reason, it is difficult to make an objective assessment of the quality of the profiles but τ_1=275 ms appears to be close to the optimum.

Figures A.10 a and b show the same procedure applied to a profile with a more violently changing lowering rate (2.5 m/s to -0.4 m/s in 4 m) in a section of water with greater temperature gradients. In A.10 a, many of the high frequency salinity features seem to arise in the presence of high temperature gradients independent of lowering rate variations. These are mainly due to the time constant mismatch and are largely damped out in the second stage of processing, Figure A.10 b. Some features such as the spike just about 670 db arise from negative lowering rates (in the presence of a temperature gradient) and are deleted by ignoring all data taken below a 0.50 m/s lowering rate which has been done in Figure A.10b, where the varying filter of equation A.2 is used.

Features of questionable validity such as at 645 db still survive. Nevertheless, the τ_1=275 ms curve still seems to produce the best result. This serves to demonstrate the limitations of this kind of processing which produces an optimum profile to be viewed critically before being accepted. In practice it is generally agreed that all CTD data taken with negative portion to the probe velocity cycle is of little use. Water is dragged along by the probe which is engulfed by this wake as it rises and in these circumstances it appears

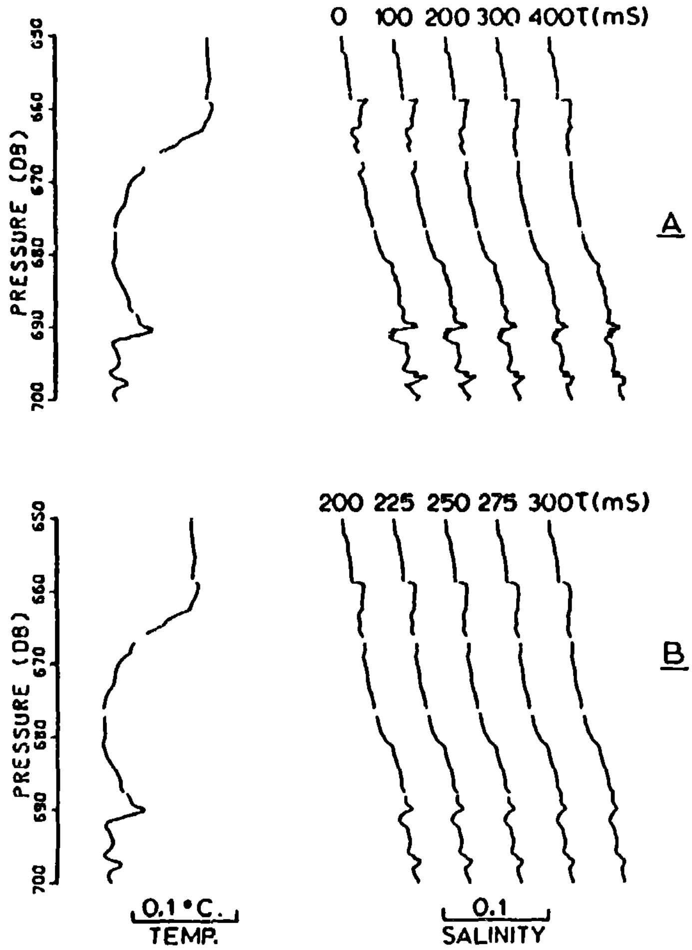


Figure A.9: Processing of section of data collected by I.O.S., Wormley, U.K. The velocity of descent varied from 12 cm/sec to 175 cm/sec during this record. The range 200ms < τ_1 < 300ms is selected from A as optimum for adjustments based on equation A.1 of text, and then applied to produce a filter for the conductivity sensor data with the result shown in B. Temperature profiles are given on the left. All values taken when the probe was moving at less than 50 cm/sec have been eliminated from the record.

impossible to place bounds on the precision or accuracy of the data. In this case, the effect of the processing scheme on the salinity profile of Figure A.10 has been to change the computed salinity (10 m. average) by up to .006 depending on the temperature gradient. Effects of this size can have a large effect on stability calculations.

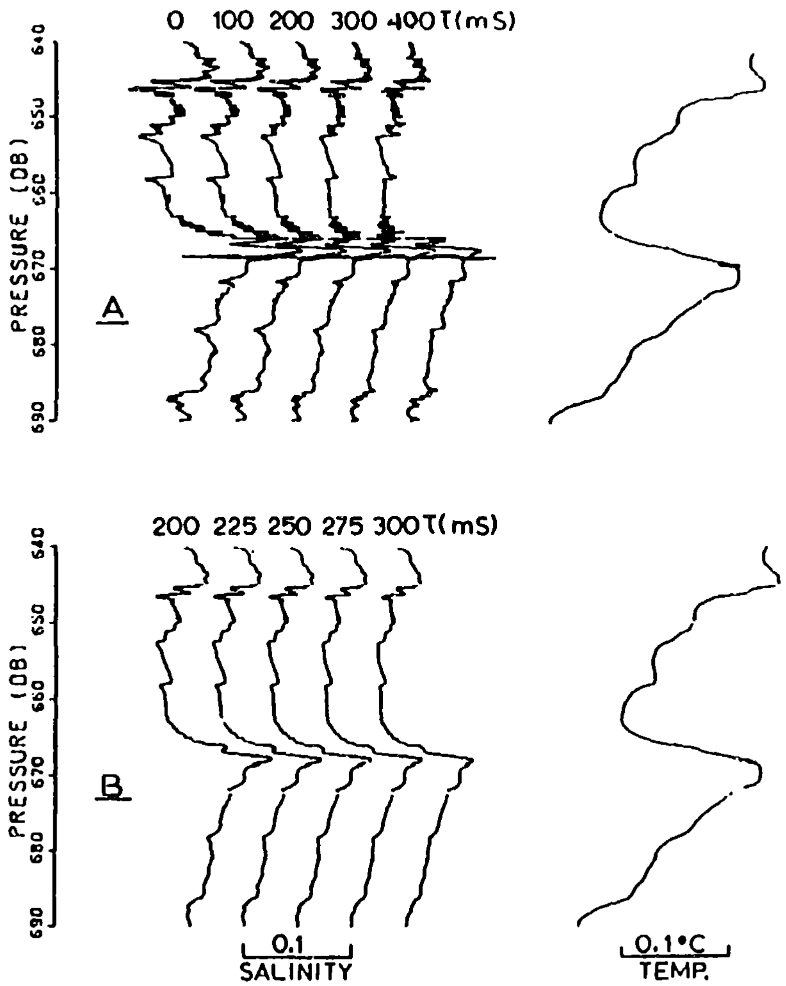


Figure A.10: *a* and *b* Processing of I.O.S., Wormley data having negative probe lowering rates due to violent ship movement. *a)* shows all the data and the application of Equation A.1 allowing selection of τ_1 within range 200 to 300 ms. Feature at 669 db caused by velocity reversal. *b)* shows application of Equation A.2 and elimination of all values taken when probe was moving at less than 50 cm/sec. Temperature profiles are given on the right.

Appendix B

Digital Low-pass Filters

B.1

This Appendix contains selected digital low pass filters and their characteristics which may be useful for smoothing CTD data series. Characteristics of each filter are given to aid the user in choosing a particular filter for his data.

Filters are applied using the following equation:

$$X'(n) = W(0)X(n) + \sum_{k=1}^{k=K} W(k)[X(n-k) + x(n+k)] \quad \text{(B.1)}$$

Where $X(n)$ is the original, equally spaced data series, $W(k)$ are the K weights of the filter, and $X'(n)$ is the new data series. Note that $2k+1$ input data values are combined to make each filtered data value. These filters are symmetric to prevent phase shifts and K data values will be lost at the beginning and at the end of the filtered data series.

Two aspects need to be considered when choosing a digital filter: the frequency response and the convenience of application of the filter.

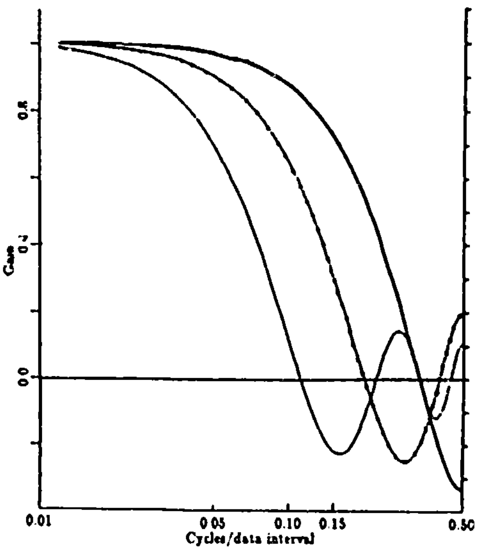
The frequency response of symmetric filters is computed as:

$$\text{Gain}(f) = W(0) + 2\sum_{k=1}^{k=K} W(k)\cos(2\pi fk)$$

with f being in units of cycles per data interval. The response curves for the attached figures were computed at 128 equally spaced frequencies from 0 to 0.5 cycles per data interval.

B.2 Running Mean filters

Running mean filters are filters whose weights are all equal. The responses of 2-, 3-, and 5-weight (3, 5, and 9 data points used respectively) running mean filters are shown in figure B.1. In this figure it can be noted that all input frequencies are attenuated and that large negative response ripples occur in the stop band. These negative ripples are undesirable. They indicate a phase shift of 180° (maxima become minima and vice-versa).



Running Mean 3 points	
Stop band starts (1% gain)	0.328
Max overshoot	-33.3% at 0.500
Running Mean 5 points	
Stop band starts (1% gain)	0.195
Max overshoot	-25.0% at 0.289
Running Mean 9 points	
Stop band starts (1% gain)	0.109
Max overshoot	-22.7% at 0.160

Figure B.1: Cosine response for several running mean filters

As a general rule, running mean filters are not useful even though easy to apply because of the poorly behaved response functions.

B.3 Normal and Binomial Filters

Normal filters are those whose weights are proportional to a Gaussian or normal distribution as indicated in table B.1. The start of the stop band (0.01 gain) is determined by σ. The larger the value of σ, the lower the frequency of the stop band. Binomial filters are those whose weights are proportional to the coefficients of a binomial expansion. The simplest binomial filter, $K = 2$, has weights of $W(0) = 0.5$ and $W(1) = 0.25$ and is called the elementary binomial filter (Hanning). Both the normal and binomial filters are well behaved in their response functions (figure B.2) as they have no negative gains. However, all low frequencies are attenuated and the cutoff frequency band is very broad. With the exception of the elementary binomial filter (Hanning) which is well behaved and easy to apply, better response functions (sharper cutoffs) can be achieved with designed digital filters.

Filter	Weights	Response
M Point Equally Weighted Running Mean	$w(k) = \begin{cases} 1/M & k = 0, K \\ 0 & k > K \end{cases}$	$\frac{\sin(\pi fm)}{\pi fm}$
M Point Equally Weighted Running Mean Applied twice		$[\frac{\sin\ (\pi fm)}{(\pi fm)}]$
Normal Curve Smoothing	$w(k) = \frac{\exp(-k\ \sigma\ /2)}{\sqrt{2\pi\sigma}}$	$\exp(-2\pi^2\sigma^2 f^2)$
Elementary Binomial Smoothing	$w(0) = 0.5$ $w(1) = 0.25$	$\cos^2(\pi f)$
Designed Filters Filter #4	see Figures B.2 to B.9	(not analytical)

Table B.1: Weights and responses of some filters

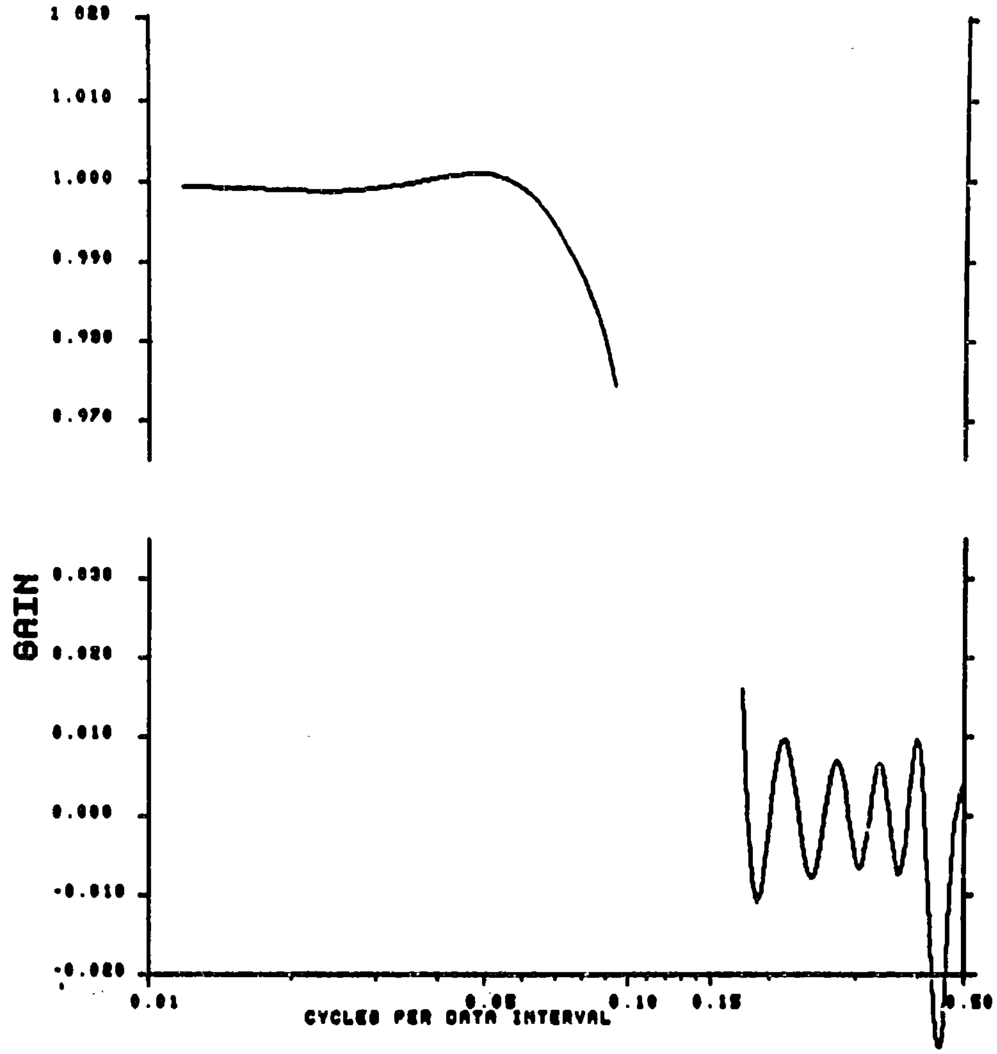
B.4 Designed Filters

Digital filters with specified response functions can be designed using Least Squares techniques (Millard et al. 1980). The number of degrees of freedom (number of weights) must be greater than the number of constraints imposed upon the shape of the response function. The values of the individual weights are computed such that the undesirable overshoots or ripples (Gibbs phenomena) in the pass and stop bands of the response are minimised. Figure B.2 through B.9 contain 8 such designed filters which have a variety of response functions. This selection of response functions is probably adequate for normal processing of CTD data. Some of these filters are designed to lower the frequency cutoff (frequency of 0.99 gain). Others are designed for less overshoot. As the number of weights increases, it is possible to have both a low frequency cutoff and minimum overshoot (figure B.7). The cost of this response is an increased loss of data at the beginning and end of the series and longer computation times. The response function of the filters can be shifted to lower frequencies by applying the weights to every other or every third input data value. The frequency response is then shifted by a factor of 1/2 or 1/3 respectively:

$$X'(n) = W(0)X(n) + \sum_{k=1}^{k=K} W(k)[X(n-jk) + X(n+jk)]$$

$$Gain(f) = W(0) + 2\sum_{k=1}^{k=K} W(k)\cos(2\pi.fk/j)$$

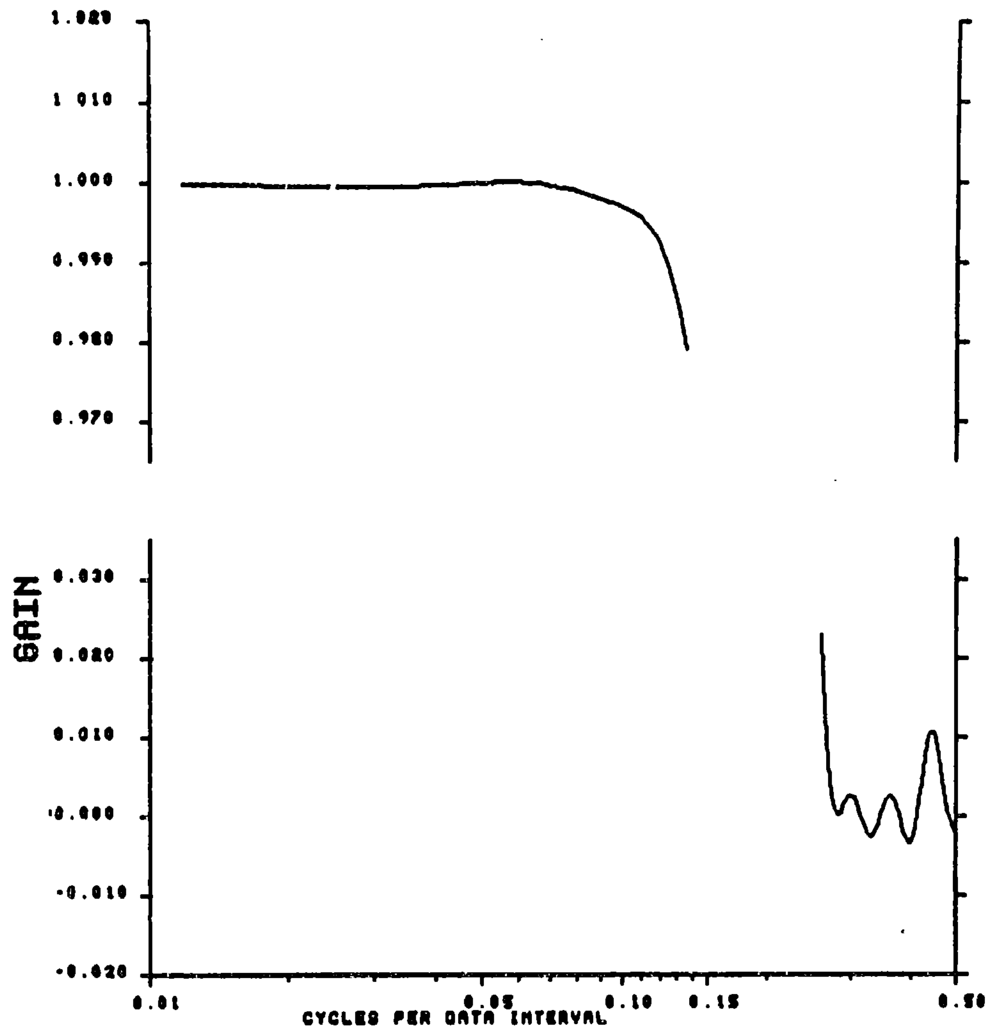
where j=2 or 3 respectively depending on the shift desired. However, the highest frequencies will not be attenuated unless filtered separately. For more detailed discussion on filter design and usage the reader is referred to Gold and Rader (1969) and Holloway (1958).



Pass band ends	(99% gain) 0.074	Stop band starts	(1% gain) 0.176
Max overshoot	0.11% at 0.047	Max overshoot	-2.9% at 0.445

W_0	0.2768802	W_1	0.2442462	W_2	0.1496963	W_3	0.0488144
W_4	-0.0260295	W_5	-0.0493596	W_6	-0.0319492	W_7	-0.0036896
W_8	0.0190385	W_9	0.0162940	W_{10}	0.0082729	W_{11}	-0.0066539
W_{12}	-0.0074337	W_{13}	-0.0052996	W_{14}	0.0009787	W_{15}	0.0046339

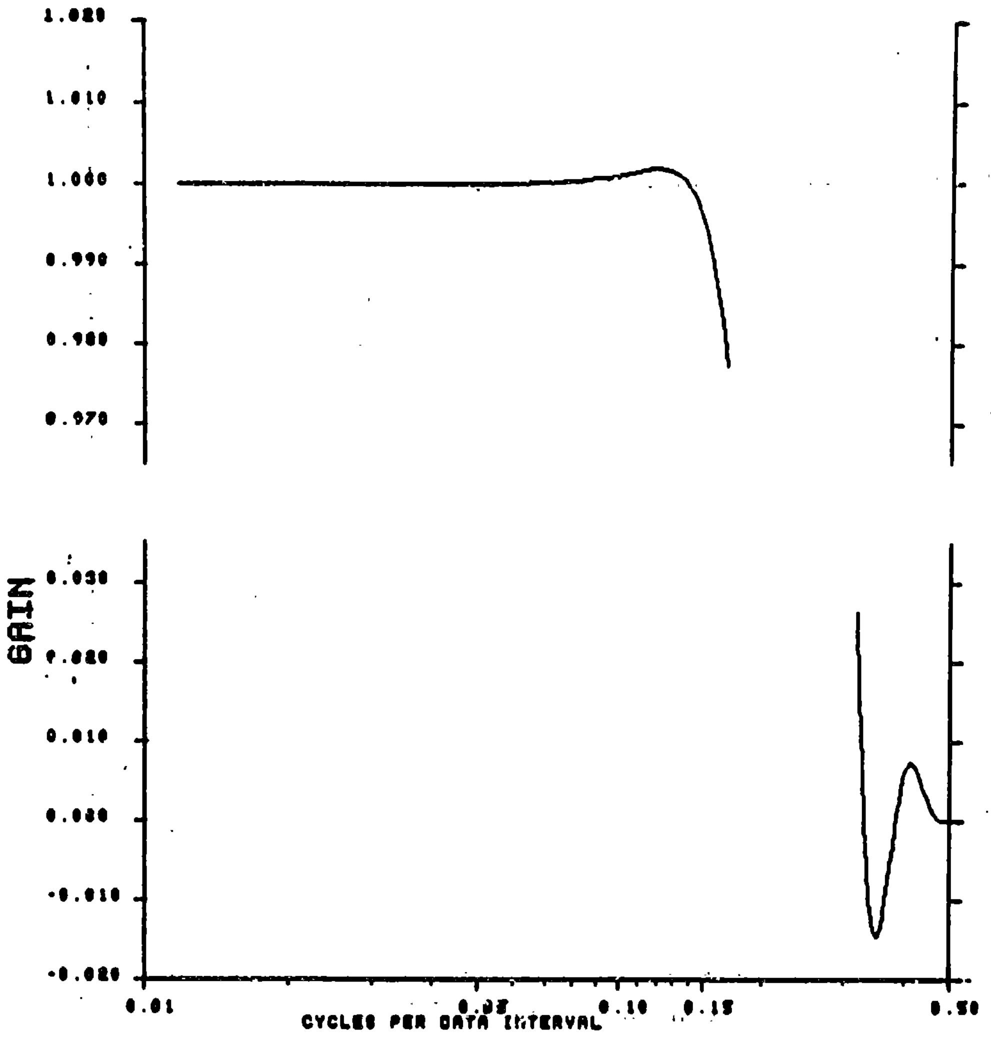
Figure B.2: Cosine Response for filter #1 of 16 weights



Pass band ends	(99% gain) 0.121	Stop band starts	(1% gain) 0.266
Max overshoot	0.01% at 0.059	Max overshoot	1.06% at 0.445

W_0	0.4190081	W_1	0.3013399	W_2	0.0722501	W_3	-0.0658397
W_4	-0.0488515	W_5	0.0146972	W_6	0.0268943	W_7	0.0004853
W_8	-0.0135485	W_9	-0.0017893	W_{10}	0.0049278	W_{11}	0.0024629
W_{12}	-0.0029224	W_{13}	-0.0008220	W_{14}	0.0012218		

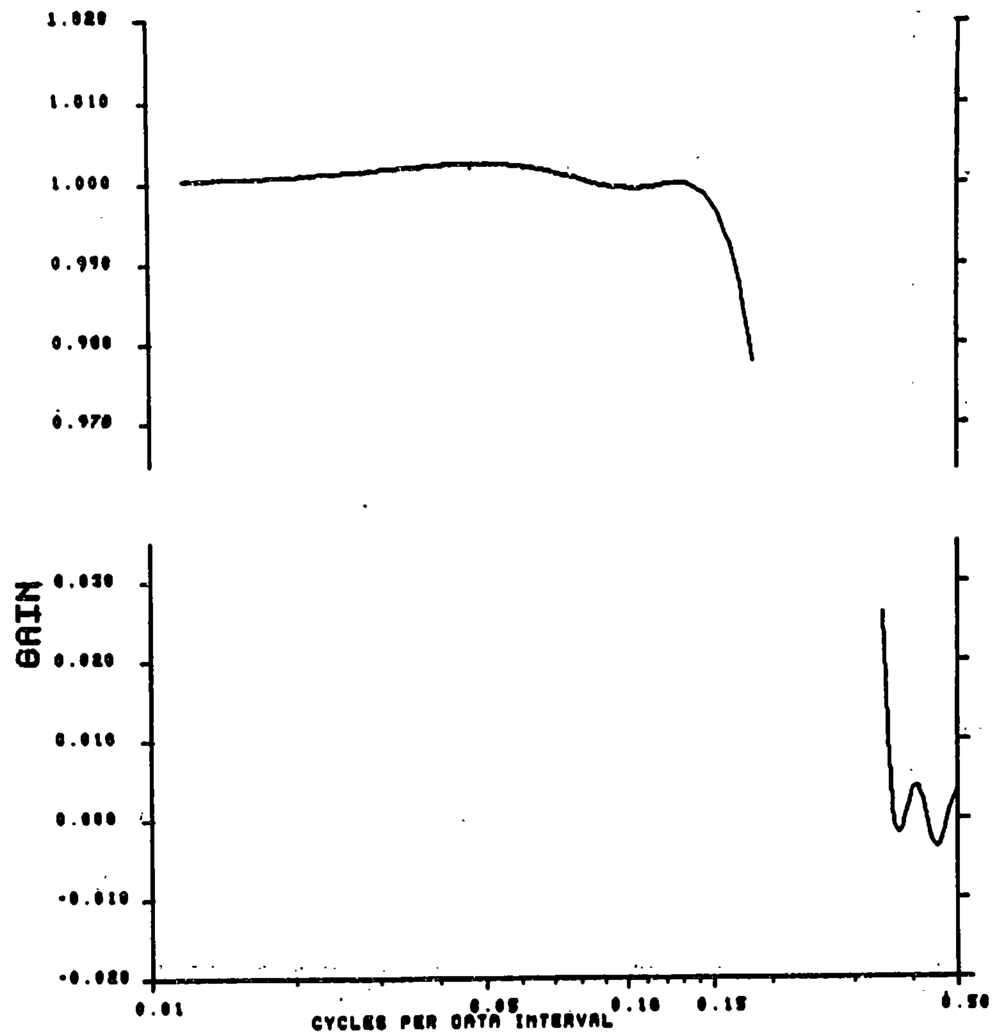
Figure B.3: Cosine response for filter #2 of 15 weights



Pass band ends (99% gain) 0.156	Stop band starts (1% gain) 0.324
Max overshoot 0.20% at 0.121	Max overshoot -1.46% at 0.352

W_0	0.5010932	W_1	0.3085158	W_2	-0.0010790	W_3	-0.0803063
W_4	0.0031749	W_5	0.0272290	W_6	-0.0043802	W_7	-0.0054385
W_8	0.0017376						

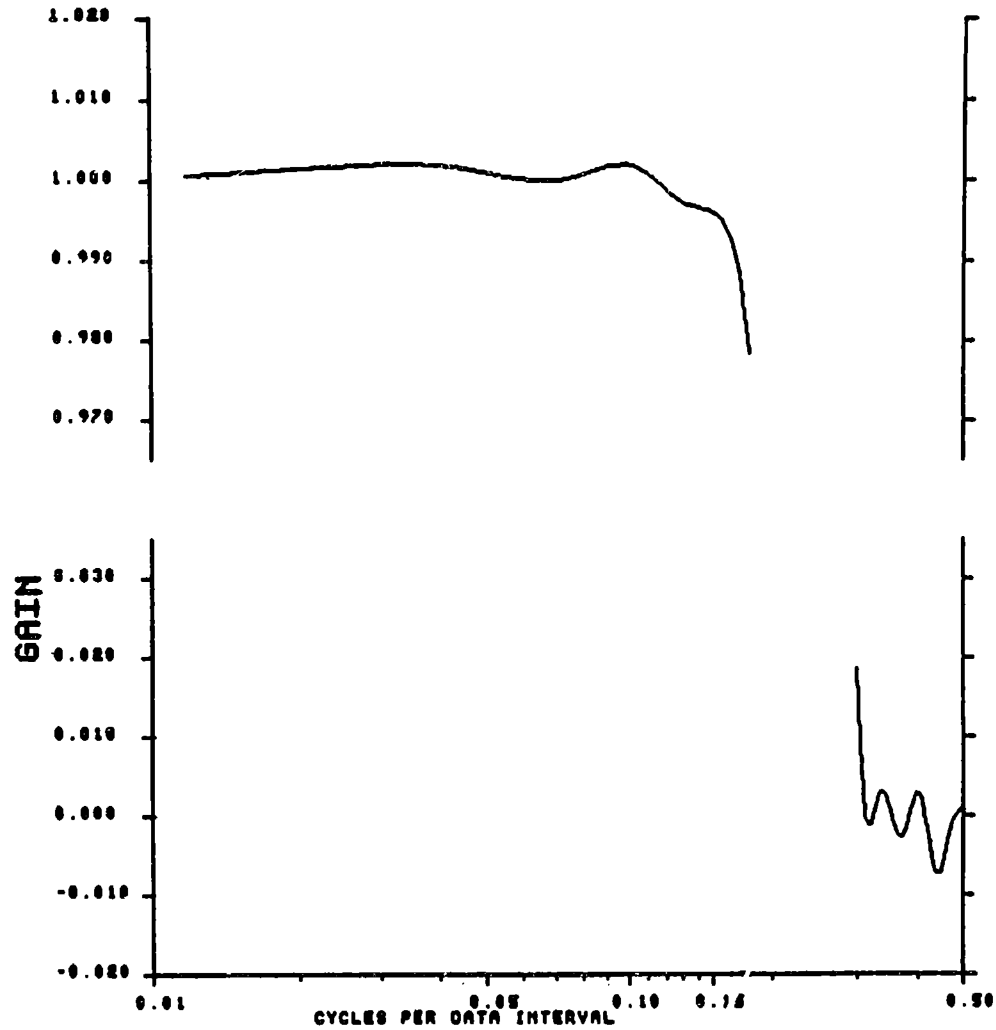
Figure B.4: Cosine response for filter #3 of 9 weights



Pass band ends	(99% gain) 0.164	Stop band starts	(1% gain) 0.355
Max overshoot	0.25% at 0.047	Max overshoot	0.40% at 0.406

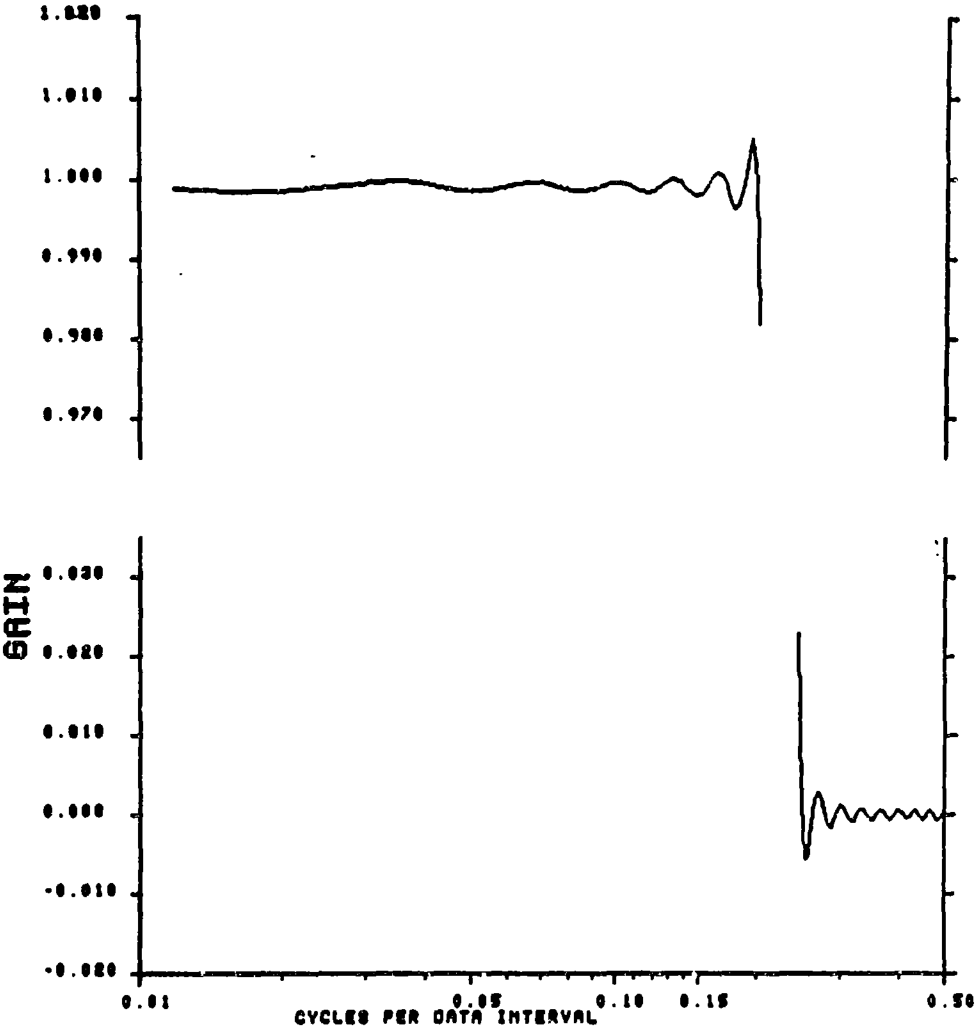
W_0	0.5584561	W_1	0.3029849	W_2	-0.0511726	W_3	-0.0654825
W_4	0.0348655	W_5	0.0129523	W_6	-0.0172377	W_7	0.0021056
W_8	0.0051739	-0.0033275					

Figure B.5: Cosine response for filter #4 of 10 weights



Pass band ends		(99% gain) 0.168		Stop band starts		(1% gain) 0.301	
Max overshoot		0.20% at 0.031		Max overshoot		-0.73% at 0.441	
W_0	0.4991365	W_1	0.3133391	W_2	-0.0005088	W_3	-0.0903099
W_4	0.0021894	W_5	0.0415346	W_6	-0.0037534	W_7	-0.0204751
W_8	0.0047479	W_9	0.0088399	W_{10}	-0.0034032	W_{11}	-0.0041089
W_{12}	0.0031772	W_{13}	0.0009740	W_{14}	-0.0018111		

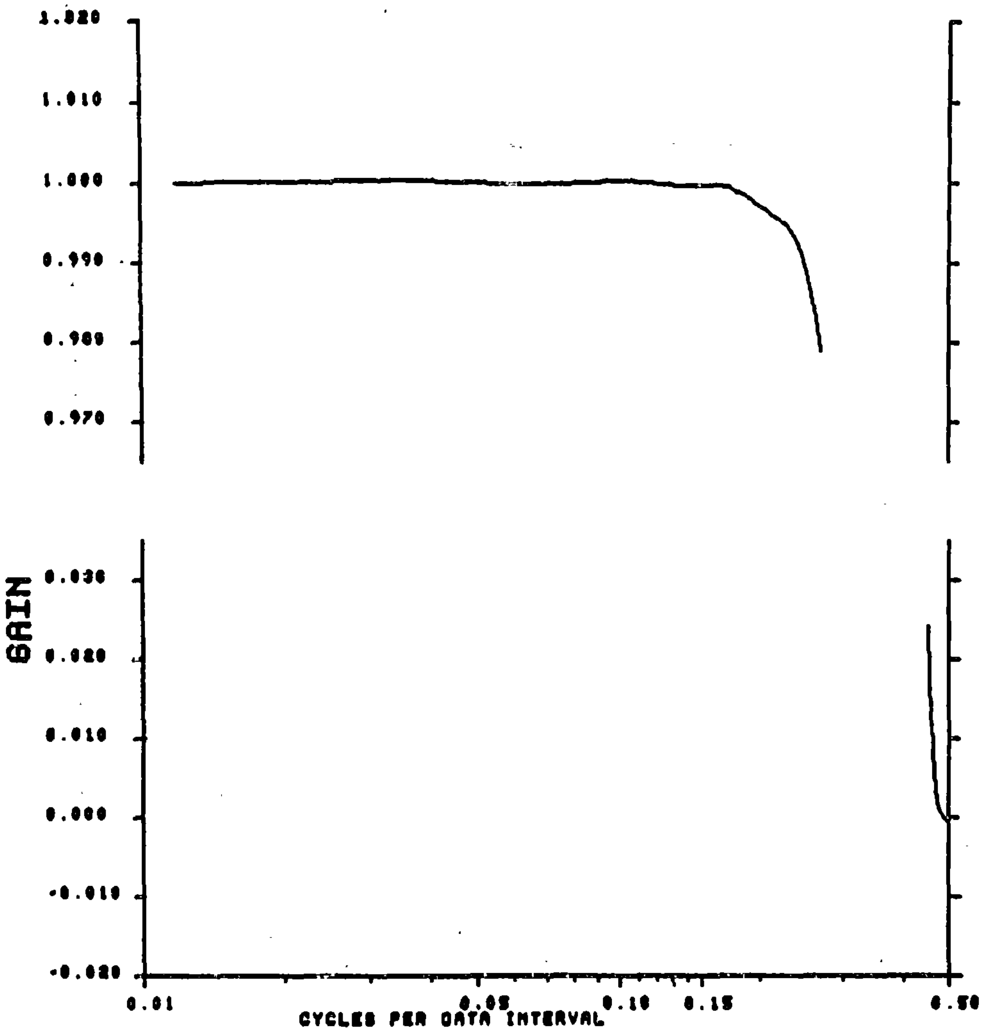
Figure B.6: Cosine response for filter #5 of 15 weights



Pass band ends	(99% gain) 0.199	Stop band starts	(1% gain) 0.246
Max overshoot	0.50% at 0.195	Max overshoot	-0.56% at 0.254

W_0	0.4495917	W_1	0.3133727	W_2	0.0486798	W_3	-0.0924791
W_4	-0.0450054	W_5	0.0424056	W_6	0.0393836	W_7	-0.0183585
W_8	-0.0324500	W_9	0.0045547	W_{10}	0.0249799	W_{11}	0.0033714
W_{12}	-0.0176984	W_{13}	-0.0073033	W_{14}	0.0112562	W_{15}	0.0084840
W_{16}	-0.0060543	W_{17}	-0.0078532	W_{18}	0.0023246	W_{19}	0.0062613
W_{20}	0.0000078	W_{21}	-0.0043260	W_{22}	-0.0010949	W_{23}	0.0025664
W_{24}	0.0013402	W_{25}	-0.0012029	W_{26}	-0.0009825	W_{27}	0.0003937
W_{28}	0.0005411	W_{29}	-0.0000384	W_{30}	0.0001281		

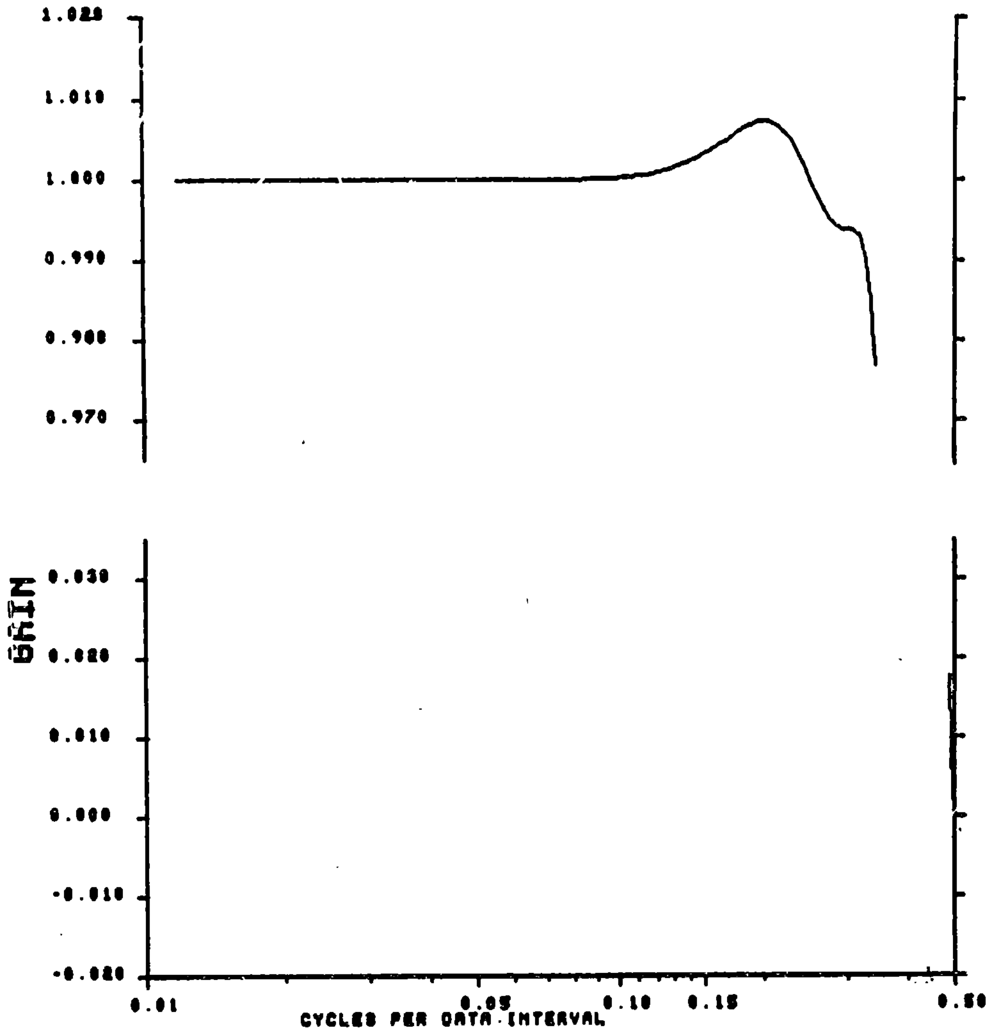
Figure B.7: Cosine function for filter #6 of 31 weights



Pass band ends	(99% gain) 0.246	Stop band starts	(1% gain) 0.461
Max overshoot	0.04% at 0.102	Max overshoot	-0.04% at 0.500

W_0	0.7535998	W_1	0.2130059	W_2	-0.1352064	W_3	0.0577258
W_4	-0.0084005	W_5	-0.0112546	W_6	0.0130043	W_7	-0.0086977
W_8	0.0044511	W_9	-0.0015815	W_{10}	-0.0000139	W_{11}	0.0005426
W_{12}	-0.0004948	W_{13}	0.0003637	W_{14}	-0.0002439		

Figure B.8: Cosine function for filter #7 of 15 weights



Pass band ends (99% gain) 0.324				Stop band starts (1% gain) 0.488			
Max overshoot 0.72% at 0.199				Max overshoot 0.10% at 0.500			
W_0	0.8483344	W_1	0.1428571	W_2	-0.1161113	W_3	0.0802535
W_4	-0.0490476	W_5	0.0252545	W_6	-0.0087691	W_7	0.0013958

Figure B.9: cosine response for filter #8 of 8 weights

Appendix C

GF3 Standard Subset for CTDs

The GF3 Format has been adopted by the International Committee for Oceanographic Data Exchange and is now in regular use by data centres and some institutions for exchange and in several cases, for archival of a wide variety of data types.

Though originally designed for sequential use on tape, it is now finding wider application. Its most important qualities lie in its definition records, which allow for the description of the format and of the variables present in the header and data records. The possibility of placing data in headers allows one to place calibration data sets or other data relevant to entire series there. Plain language records give unlimited scope for a description of the series. The records are all 1920 bytes long. By the use of scaling factors defined for each variable in the definition record it is easy, within the confines of an ASCII format, to closely pack the records. The header and definition records have mostly fixed format fields.

For commonly used data sets such as those from CTDs, standard subsets of GF3 have been adopted. Legibility with simple dump programs rather than close packing is the criterion used but if this is not acceptable then all that need to be changed are the scaling factors and format description in the definition record.

The following pages show such a dump for a CTD data set together with an annotation of the definition records. A full description of the fields in the header records that are not immediately apparent can be found in Manuals and Guides No. 17, vol. 2,Technical Description of the GF3 Format (UNESCO, 1987).

```
TEST FILE
*********

     FILE CONTAINS  44 RECORDS.

     ALL RECORDS CORRECTLY FORMATTED.

     END OF FILE.


TAPE HEADER FILE
****************

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     TRANSLATION TABLE CHECKED, ALL CHARACTERS VERIFIED.

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185110782050699999999999HONEYWELL66 GF3.2                                     002
11234567890=;> /STUVWXYZ,(-JKLMNOPQR*]$+ABCDEFGHI.)[<                    1920003
1                                                                             004
1 ***** GF-3 DEMONSTRATION TAPE FOR CTD DATA ****************************     005
1                                                                             006
1                                                                             007
1                                                                             008
1                                                                             009
1                                                                             010
1                                                                             011
1                                                                             012
1                                                                             013
1                                                                             014
1                                                                             015
1                                                                             016
1                                                                             017
1                                                                             018
1                                                                             019
1                                                                             020
1                                                                             021
1                                                                             022
1                                                                             023
1                                                                             024


     RECORD      2      PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

03 EXPLANATORY NOTES ***                                                      001
0                                                                             002
0  THIS TAPE IS FORMATTED TO CONTAIN A SERIES OF MULTISERIES DATA FILES       003
0  - EACH DATA FILE COMPRISING A CONSISTENT SET OF CTD SERIES E.G. FROM       004
0  A SPECIFIC CRUISE (FOR THIS DEMONSTRATION THE TAPE CONTAINS A SINGLE       005
0  DATA FILE WITH A SINGLE DATA SERIES).                                      006
0                                                                             007
0  DOCUMENTATION APPLICABLE TO A DATA FILE AS A WHOLE IS FOUND IN PLAIN       008
0  LANGUAGE RECORDS FOLLOWING THE FILE HEADER RECORD WHILE DOCUMENTATION      009
0  SPECIFIC TO AN INDIVIDUAL SERIES IS FOUND FOLLOWING THE APPROPRIATE        010
0  SERIES HEADER RECORD.                                                      011
0                                                                             012
0  THE USER FORMATTED AREA OF THE SERIES HEADER CONTAINS HANSEN CAST          013
0  /MULTISAMPLER DATA USED FOR CALIBRATION. CORRESPONDING VALUES FROM THE     014
0  CTD CAST ARE ALSO INCLUDED FOR COMPARISON.  THE METHOD FIELD IN THE       015
0  PARAMETER CODE DISTINGUISHES BETWEEN DATA COLLECTED BY THE CTD SENSORS     016
0  AND THAT MEASURED BY REVERSING THERMOMETER OR BENCH SALINOMETER.           017
0                                                                             018
0  IN THE DATA CYCLE RECORDS EACH DATA CYCLE HAS SEA PRESSURE,TEMPERATURE     019
0  AND PRACTICAL SALINITY WITH QUALITY CONTROL FLAGS (LEFT UNSPECIFIED IE     020
0  BLANK IN THIS DEMONSTRATION). BLANK FIELDS IN THE FORMAT SPECIFICATION     021
0  PERMIT A NEAT 80 COLUMN LAYOUT.                                            022
0  FURTHER PARAMETERS CAN OF COURSE BE DEFINED AND ADDED WITHIN THE GF-3      023
0  FORMAT. INFORMATION ON PARAMETER CODES IS IN PART 2 OF THE GF-3 MANUAL.    024
```

RECORD 3 SERIES HEADER DEFINITION RECORD.

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3                                                                            002
3                                                                            003
3 PRES7PRD   SEA PRESSURE(CTD)     DBAR.I   5-94   0.1         0             004
3 TEMP7STD   SEA TEMPERATURE(CTD)  DEG.CI   5-94   0.001       0             005
3 PSAL7PRD   PRAC.SALINITY(CTD)         I   5-94   0.001       0             006
3 PRES7RTD   SEA PRESSURE(THERM)   DBAR.I   5-94   0.1         0             007
3 TEMP7RTD   SEA TEMPERATURE(THERM)DEG.CI   5-94   0.001       0             008
3 PSAL7BSD   PRAC.SALINITY(BOTTLE)      I   5-94   0.001       0             009
3                                                                            010
3                                                                            011
3                                                                            012
3                                                                            013
3                                                                            014
3                                                                            015
3                                                                            016
3                                                                            017
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3                                                                            021
3                                                                            022
3                                                                            023
3                                                                            024
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RECORD 4 DATA CYCLE DEFINITION RECORD.

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4                                                                            003
4 PRES7PRD   SEA PRESSURE  DB=10KPASCAL I   5-94   0.1         0             004
4 FFFF7AAN   QUAL.FLAG PRESSURE         A   1                                005
4 TEMP7STD   SEA TEMPERATURE      DEG.C I   5-94   0.001       0             006
4 FFFF7AAN   QUAL.FLAG TEMPERATURE      A   1                                007
4 PSAL7PRD   PRACTICAL SALINITY         I   5-94   0.001       0             008
4 FFFF7AAN   QUAL.FLAG SALINITY         A   1                                009
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4                                                                            011
4                                                                            012
4                                                                            013
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4                                                                            015
4                                                                            016
4                                                                            017
4                                                                            018
4                                                                            019
4                                                                            020
4                                                                            021
4                                                                            022
4                                                                            023
4                                                                            024
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END OF FILE.

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CONTENTS OF DATA FILES
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5                                                                             003
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523700  N 2100  W4400  N 1300  W23A  A CR117-CTD       1          0          0005
5                                                                             006
5                                                                             007
5                                                                             008
5                                                                             009
5                                                                             010
5                                                                             011
5                                                                             012
5                                                                             013
5                                                                             014
5                                                                             015
5                                                                             016
5                                                                             017
5                                                                             018
5                                                                             019
5                                                                             020
5                                                                             021
5                                                                             022
5                                                                             023
5                                                                             024


      RECORD      2      PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

00   ****DOCUMENTATION FOR CTD DATA FROM DISCOVERY CRUISE 117****             001
0                                                                             002
0    *FULL DOCUMENTATION AVAILABLE IN SAUNDERS P.M. (1981), CTD DATA          003
0     OBTAINED DURING DISCOVERY CRUISE 117, IOS DATA REPORT NO 26 - SUMMARY   004
0     GIVEN BELOW                                                             005
0                                                                             006
0    **INSTRUMENTATION/DATA COLLECTION**                                      007
0     NEIL BROWN CTD PROFILER (SEE BROWN, N AND G. MORRISON (1978), WHOI/     008
0     BROWN CTD MICROPROFILER, WHOI-78-23) HELD IN FRAME WITH GENERAL         009
0     OCEANICS MULTISAMPLER WITH 12 NISKIN BOTTLES.  DATA COMPUTER LOGGED ON  010
0     BOARD AT NEAR 30 SAMPLES/SECOND WITH RESOLUTIONS OF 0.5 MILLIDEGREES    011
0     C., 0.1 DECIBARS AND 0.001 MILLIMHOS/CM.  CTD PROFILE OBTAINED ON       012
0     UNINTERRUPTED DOWN LOWERING AT SPEEDS BETWEEN 0.5 AND 1.0 M/SEC.        013
0     BOTTLE SAMPLES AND REVERSING THERMOMETER MEASUREMENTS (PROTECTED AND    014
0     UNPROTECTED) COLLECTED ON ASCENT AT SELECTED LEVELS WITH INSTRUMENT     015
0     HELD FOR 5 MINUTES TO ALLOW THERMOMETERS TO COME TO EQUILIBRIUM.        016
0     SIMULTANEOUS CTD PRESSURE AND TEMPERATURE WERE ALSO RECORDED AT EACH    017
0     BOTTLE SAMPLE LEVEL ON ASCENT.  SEAWATER SAMPLES ANALYSED ON BOARD      018
0     WITH GUILDLINE AUTOLAB SALINOMETER - THREE SAMPLES BEING DRAWN OFF      019
0     EACH BOTTLE.  REVERSING THERMOMETERS CALIBRATED BEFORE AND AFTER        020
0     CRUISE - NO SIGNIFICANT CHANGE DETECTED.  CLOSE TO SEA FLOOR THE        021
0     HEIGHT ABOVE FLOOR WAS MONITORED USING A FREE RUNNING 10KHZ PINGER      022
0     ATTACHED ALONGSIDE THE CTD AND MULTISAMPLER.                            023
0                                                                             024
```

```
RECORD      3      PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

00   TWO CTD UNITS WERE EMPLOYED - THE FIRST FOR ONLY STATIONS 10261 AND
0    10263 AND THE SECOND FOR THE REMAINDER.  AFTER 11 STATIONS WITH THE
0    SECOND UNIT THE CONDUCTIVITY CELL WAS REPLACED IN THE HOPE OF REDUCING
0    THE CALIBRATION DRIFT.  FOLLOWING DOCUMENTATION APPLIES ONLY TO THE
0    SECOND CTD UNIT AND NOT TO STATIONS 10261 AND 10263.
0
0    **DATA CALIBRATION/QUALITY**
0
0    *PRESSURE SENSOR CALIBRATED IN LABORATORY SEPTEMBER 1980 USING DEAD
0     WEIGHT TESTER - DECK OFFSET WAS STABLE AT 8 DBAR.  DIFFERENCE DURING
0     CRUISE BETWEEN PRESSURES FROM PAIRS OF REVERSING THERMOMETERS
0     (PROTECTED AND UNPROTECTED) AND SIMULTANEOUS CTD PRESSURE MEASURES,
0     EACH MADE AFTER 5 MINUTE STOP ON RAISING OF INSTRUMENT, WERE VERY
0     SMALL.  30 SUCH COMPARISONS IN RANGE 0-2000 DBAR GAVE MEAN DIFFERENCE
0     OF 0.5 DBAR (CTD HIGHER) WITH STANDARD DEVIATION OF 2 DBAR.  52 IN
0     RANGE 2000-5600 DBAR GAVE MEAN DIFFERENCE OF 2 DBAR (CTD HIGHER)
0     WITH STANDARD DEVIATION OF 4 DBAR.  A FURTHER CHECK WAS OBTAINED BY
0     CONVERTING PRESSURES AT THE BOTTOM OF THE CAST TO DEPTH, ADDING THE
0     PINGER HEIGHT ABOVE BOTTOM TO GIVE WATER DEPTH, AND COMPARING WITH THE
0     ECHO-SOUNDER DEPTH CORRECTED USING CARTER'S TABLES.  FOR 25 SUCH
0     OBSERVATIONS IN THE DEPTH RANGE 5200-5500M, THE ECHO-SOUNDER DEPTH
0     EXCEEDED THE CTD CALCULATED DEPTH BY A MEAN OF 6M WITH A STANDARD
0     DEVIATION OF 5M.
0


RECORD      4      PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

00   *TEMPERATURE SENSOR (PLATINUM RESISTANCE) CALIBRATED IN LABORATORY
0     SEPTEMBER 1980 BUT, IN COMPARISON WITH 90 REVERSING THERMOMETER
0     MEASUREMENTS TAKEN SIMULTANEOUSLY WITH CTD SENSOR MEASUREMENTS DURING
0     CRUISE, A CALIBRATION SHIFT WAS NOTED REQUIRING THE ADDITION OF AN
0     AMOUNT 0.044 + 0.00050042*RAWTEMP. DEG.C. - ORIGIN OF THIS ERROR, OF A
0     MAGNITUDE COMMONLY FOUND, REMAINS UNKNOWN.  CORRECTED CTD TEMPERATURE
0     MINUS REVERSING THERMOMETER TEMPERATURE FROM 31 COMPARISONS DURING THE
0     CRUISE FOR TEMPERATURES GREATER THAN 5 DEG.C. GAVE A MEAN OF 0 DEG.C.
0     WITH A STANDARD DEVIATION OF 0.006 DEG.C.  59 COMPARISONS FOR
0     TEMPERATURES LESS THAN 5 DEG.C. GAVE A MEAN OF -0.001 DEG.C. WITH A
0     STANDARD DEVIATION OF 0.004 DEG.C.
0
0    *DURING THE CRUISE BOTTLE SALINITIES AND REVERSING THERMOMETER MEASURE-
0     MENTS REVEALED A LINEAR POTENTIAL TEMPERATURE (POTT) - PRACTICAL
0     SALINITY (S) RELATIONSHIP FOR POTT LESS THAN 2.6 DEG.C. OF S = 34.698
0     + 0.098*POTT WITH A DATA SCATTER ABOUT THE LINE OF +/- 0.002 IN
0     PRACTICAL SALINITY, APPROX SAME AS RMS ERROR OF SALINITY MEASUREMENTS.
0     FOR EACH STATION THE MEAN OF 20 CTD SALINITY ESTIMATES (2.1 < POTT <
0     2.2) WAS DETERMINED AND ADJUSTED TO FIT THE ABOVE RELATIONSHIP THUS
0     PRODUCING A MULTIPLICATIVE FACTOR FOR CORRECTING THE CTD SALINITIES.
0     FOR THE CELL USED ON STATIONS 10264-74 THE FACTOR VARIED BETWEEN
0     STATIONS (NOT SMOOTHLY) CORRESPONDING TO A PRACTICAL SALINITY CHANGE
0     OF 0.008.  FOR THE CELL ON STATIONS 10275-94 THE CORRESPONDING
0     VARIATION WAS 0.004.  IN THE 0-2000 DBAR RANGE 58 COMPARISONS DURING
```

```
RECORD     5     PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

U0    THE CRUISE OF BOTTLE SALINITY WITH CORRECTED CTD SALINITY AT THE SAME    073
0     TEMPERATURE GAVE A PRACTICAL SALINITY MEAN OF 0.002 (CTD HIGHER) WITH    074
0     A STANDARD DEVIATION OF 0.008.  IN THE 2000-5600 DBAR RANGE 70           075
0     COMPARISONS AT THE SAME PRESSURE GAVE A MEAN OF 0.001 (CTD LOWER) WITH   076
0     A STANDARD DEVIATION OF 0.0025.                                          077
0                                                                              078
0     **DATA PROCESSING**                                                      079
0     *ORIGINAL VALUES WERE AVERAGED OVER AN INTERVAL OF ONE SECOND AND        080
0     CALIBRATION COEFFICIENTS AND CORRECTION FACTORS APPLIED.  TO MATCH THE   081
0     SLOWER RESPONSE OF THE PLATINUM RESISTANCE THERMOMETER IN RELATION TO    082
0     THE OTHER SENSORS, THE TEMPERATURE WAS CORRECTED AS FOLLOWS - TEMPC =    083
0     TEMP + TOR*DELTAT WHERE TOR IS THE TEMPERATURE TIME CONSTANT (TAKEN AS   084
0     0.22 SEC), AND DELTAT IS THE DIFFERENCE BETWEEN THE INSTANTANEOUS        085
0     TEMPERATURE AT THE BEGINNING AND END OF THE AVERAGING INTERVAL.          086
0     *DATA EDITING - DIFFERENCES BETWEEN SUCCESSIVE VALUES OF EACH PARAMETER  087
0     WERE EXAMINED - FIRST BY DETERMINING THE MEAN DIFFERENCE AND ITS         088
0     STANDARD DEVIATION AND THEN BY LISTING OUT ALL VALUES WHERE THE          089
0     DIFFERENCE WAS GREATER THAN SEVERAL STANDARD DEVIATIONS FROM THE MEAN    090
0     DIFERENCE.  THESE LISTS WERE THEN INSPECTED FOR GENUINELY SUSPECT        091
0     DATA WHICH WERE REPLACED BY LINEARLY INTERPOLATED VALUES.                092
0     *TO REMOVE THE EFFECT OF SHIPS HEAVE THE DATA CYCLES WERE SORTED BY      093
0     PRESSURE BEFORE ALL VALUES WERE FINALLY AVERAGED AT 5 DBAR INTERVALS,    094
0     CENTRED AT 2.5 DBAR, 7.5 DBAR ---                                        095
0                                                                              096
```

```
RECORD     6     PLAIN LANGUAGE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

06    **NOTE ON CALIBRATION DATA**                                             097
0                                                                              098
0     THE UP CAST BOTTLE AND REVERSING THERMOMETER DATA FOR EACH STATION ARE   099
0     ENTERED IN THE SERIES HEADER RECORD TOGETHER WITH THE CORRECTED UPCAST   100
0     VALUES OF CTD PRESSURE AND TEMPERATURE.  NOTE THAT THE CTD SALINITIES    101
0     IN THIS RECORD WERE TAKEN FROM THE DOWN CAST - FOR COMPARISON WITH THE   102
0     BOTTLE SALINITIES THE CTD SALINITY VALUES WERE EXTRACTED AT THE SAME     103
0     TEMPERATURE FOR OBSERVATIONS MADE SHALLOWER THAN 2000 DBAR AND AT THE    104
0     SAME PRESSURE FOR OBSERVATIONS MADE DEEPER THAN 2000 DBAR.  THIS         105
0     COMPENSATES FOR TEMPORAL VARIATIONS WITHIN THE THERMOCLINE BETWEEN THE   106
0     DOWN AND UP CASTS.                                                       107
0                                                                              108
0                                                                              109
0                                                                              110
0                                                                              111
0                                                                              112
0                                                                              113
0                                                                              114
0                                                                              115
0                                                                              116
0                                                                              117
0                                                                              118
0                                                                              119
0                                                                              120
```

RECORD 7 SERIES HEADER RECORD.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

67             749010 UNITED KINGDOM   INST.OCEANOG.SCI. 851107122625CTD DEMO 2  C01
631 SHIP   474-74DISC R.R.S. DISCOVERY      CRUISE117 19810119      19810212    C02
6                                                                                C03
6198102082336  198102090332  375350N 170380W 20 5518 999999999999    0  5487 C04
69999999 9999999 999999 9999999 23A  A   STN.10294999999         10          0CC5
   90 15230 36062    100 15226 36060       4960 11230 35548 -9999 -9999 35549
 9900 10787 36005   9880 10786 36000      14890  6877 35472 -9999 -9999 35469
19930  4568 35137 19930  4567 35140       26920  3110 34970 -9999 -9999 34967
32540  2740 34939 -9999 -9999 34934       39820  2574 34916 39800  2580 34913
44940  2505 34903 -9999 -9999 34902       55700  2598 34898 55360  2607 34898
```

RECORD 8 DATA CYCLE RECORD.

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

77  92         0     1
   25 15260 36068      75 15262 36069      125 15262 36068      175 15264 36069
  225 15265 36068     275 15264 36069      325 15265 36069      375 15267 36068
  425 15265 36068     475 15266 36069      525 15267 36068      575 15270 36069
  625 15268 36068     675 15269 36067      725 15271 36068      775 15271 36068
  825 15264 36066     875 15260 36066      925 15256 36065      975 15256 36065
 1025 15203 36060    1075 15076 36041     1125 14808 35998     1175 14326 35936
 1225 14164 35900    1275 14115 35906     1325 14060 35900     1375 13984 35892
 1425 13861 35876    1475 13782 35868     1525 13682 35851     1575 13571 35841
 1625 13496 35824    1675 13431 35814     1725 13366 35806     1775 13279 35794
 1825 13182 35781    1875 13032 35756     1925 12980 35751     1975 12905 35738
 2025 12841 35734    2075 12757 35719     2125 12722 35713     2175 12693 35711
 2225 12644 35705    2275 12603 35699     2325 12576 35700     2375 12547 35696
 2425 12496 35692    2475 12450 35685     2525 12405 35682     2575 12349 35674
 2625 12313 35672    2675 12254 35664     2725 12216 35656     2775 12167 35650
 2825 12142 35646    2875 12121 35643     2925 12099 35641     2975 12059 35638
 3025 12043 35634    3075 12020 35635     3125 11964 35627     3175 11946 35626
 3225 11864 35618    3275 11831 35612     3325 11818 35610     3375 11808 35609
 3425 11787 35607    3475 11766 35605     3525 11744 35602     3575 11727 35600
 3625 11704 35598    3675 11691 35597     3725 11669 35595     3775 11640 35591
 3825 11622 35589    3875 11609 35587     3925 11592 35585     3975 11571 35584
 4025 11558 35582    4075 11547 35580     4125 11537 35578     4175 11519 35576
 4225 11497 35573    4275 11483 35572     4325 11448 35569     4375 11404 35563
 4425 11372 35562    4475 11336 35557     4525 11307 35553     4575 11286 35551
```

```
       RECORD      9     DATA CYCLE RECORD.

          1         2         3         4         5         6         7         8
 12345678901234567890123456789012345678901234567890123456789012345678901234567890

|77  92         92     2
|  4625 11266 35550     4675 11239 35546     4725 11224 35549     4775 11198 35549
|  4825 11176 35544     4875 11159 35541     4925 11153 35544     4975 11148 35549
|  5025 11142 35549     5075 11120 35549     5125 11112 35549     5175 11081 35550
|  5225 11062 35548     5275 11059 35549     5325 11051 35543     5375 11037 35553
|  5425 11021 35552     5475 11031 35557     5525 11031 35562     5575 11025 35562
|  5625 11037 35570     5675 11045 35575     5725 11039 35575     5775 11033 35579
|  5825 11026 35581     5875 11013 35583     5925 10998 35584     5975 10985 35588
|  6025 10972 35591     6075 10977 35599     6125 10979 35607     6175 10974 35613
|  6225 10972 35617     6275 10968 35623     6325 10966 35629     6375 10966 35649
|  6425 10966 35644     6475 10972 35651     6525 10972 35653     6575 10977 35664
|  6625 10982 35674     6675 11011 35684     6725 11023 35693     6775 11030 35697
|  6825 11008 35700     6875 10991 35704     6925 11011 35715     6975 11025 35722
|  7025 11018 35722     7075 11020 35724     7125 11058 35740     7175 11108 35762
|  7225 11140 35775     7275 11184 35791     7325 11247 35815     7375 11269 35835
|  7425 11210 35834     7475 11136 35823     7525 11101 35811     7575 11141 35827
|  7625 11098 35831     7675 11063 35823     7725 11067 35828     7775 11159 35861
|  7825 11183 35850     7875 11140 35873     7925 11189 35889     7975 11256 35909
|  8025 11332 35941     8075 11373 35961     8125 11419 35978     8175 11382 35988
|  8225 11247 35954     8275 11226 35946     8325 11329 35978     8375 11268 35977
|  8425 11139 35946     8475 11035 35925     8525 11071 35935     8575 11054 35934
|  8625 11116 35953     8675 11134 35968     8725 11078 35959     8775 10950 35936
|  8825 10903 35925     8875 10862 35918     8925 10972 35923     8975 10853 35934
|  9025 10888 35937     9075 10897 35941     9125 10934 35958     9175 10877 35953


       RECORD     10     DATA CYCLE RECORD.

          1         2         3         4         5         6         7         8
 12345678901234567890123456789012345678901234567890123456789012345678901234567890

|77  92        184     3
|  9225 10903 35959     9275 10904 35968     9325 10876 35962     9375 10872 35961
|  9425 10864 35965     9475 10843 35969     9525 10847 35975     9575 10821 35975
|  9625 10765 35964     9675 10742 35958     9725 10761 35964     9775 10745 35966
|  9825 10709 35964     9875 10650 35951     9925 10680 35963     9975 10692 35972
| 10025 10689 35976    10075 10766 35998    10125 10849 36031    10175 10820 36027
| 10225 10693 36007    10275 10706 36008    10325 10643 35998    10375 10586 35987
| 10425 10558 35983    10475 10575 35989    10525 10575 35994    10575 10537 35991
| 10625 10493 35985    10675 10488 35984    10725 10478 35998    10775 10453 35984
| 10825 10420 35982    10875 10386 35976    10925 10372 35976    10975 10383 35989
| 11025 10385 35994    11075 10374 35997    11125 10355 35998    11175 10335 35998
| 11225 10303 35999    11275 10260 35997    11325 10228 35994    11375 10236 35998
| 11425 10149 35988    11475 10091 35975    11525 10032 35968    11575 10010 35964
| 11625 10007 35963    11675  9994 35967    11725  9976 35968    11775  9939 35963
| 11825  9860 35955    11875  9777 35941    11925  9729 35933    11975  9699 35929
| 12025  9658 35923    12075  9644 35921    12125  9615 35918    12175  9586 35913
| 12225  9575 35911    12275  9555 35910    12325  9542 35908    12375  9562 35918
| 12425  9521 35913    12475  9433 35897    12525  9404 35892    12575  9400 35896
| 12625  9354 35893    12675  9267 35873    12725  9193 35863    12775  9105 35845
| 12825  9026 35831    12875  8965 35820    12925  8874 35804    12975  8814 35793
| 13025  8746 35780    13075  8694 35770    13125  8706 35774    13175  8659 35775
| 13225  8633 35770    13275  8580 35764    13325  8544 35757    13375  8474 35747
| 13425  8393 35732    13475  8286 35715    13525  8224 35702    13575  8195 35695
| 13625  8160 35689    13675  8127 35683    13725  8062 35674    13775  8046 35669
```

ETC. ETC.

END OF FILE.

TAPE TERMINATOR FILE
****

```
     RECORD      1      FILE HEADER RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

58         99    UNSPECIFIED       UNSPECIFIED       999999                  001
5  UNSPEC.           UNSPECIFIED                                             C02
5                                                                            C03
59999999999999999999999999999999999999999999999999999999999999999999999999999C04
59999999999999999999999999999999                  999999         0          UC05
5                                                                            C06
5                                                                            C07
5                ********************************************                008
5                *                                          *                C09
5                *                THIS IS A                 *                C10
5                *                                          *                C11
5                *         DUMMY FILE HEADER RECORD         *                C12
5                *                                          *                C13
5                *   WHICH IS INSERTED SOLELY TO INDICATE   *                C14
5                *                                          *                C15
5                *             THE BEGINNING OF             *                C16
5                *                                          *                C17
5                *         THE TAPE TERMINATOR FILE         *                C18
5                *                                          *                C19
5                ********************************************                C20
5                                                                            C21
5                                                                            C22
5                                                                            C23
5                                                                            C24

     RECORD      2      END OF TAPE RECORD.

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

89999999999999999999999999999999999999999999999999999999999999999999999999999001
8                                                                            002
8                                                                            C03
8                                                                            C04
8                                                                            C05
8                                                                            C06
8                                                                            007
8                                                                            C08
8                                                                            C09
8                                                                            C10
8                                                                            C11
8                                                                            C12
8                                                                            C13
8                                                                            014
8                                                                            C15
8                                                                            C16
8                                                                            C17
8                                                                            C18
8                                                                            019
8                                                                            C20
8                                                                            C21
8                                                                            C22
8                                                                            C23
8                                                                            C24

     END OF FILE.

     END OF FILE.

     *** END OF PROGRAM GFLIST ***
```

ANNOTATED LISTING OF SAMPLE SERIES HEADER RECORD

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

67          749010 UNITED KINGDOM     INST.OCEANOG.SCI.  8205061030  CTD DEMO 2  001
631 SHIP    474-74DISC R.R.S. DISCOVERY    CRUISE117 19810119     19810212     002
6                                                                              003
6198102082356  198102090332  375350N 170380W 20 5518 999999999999    0  5487 004
69999999 9999999 999999 9999999 23A  A    STN.10294             10            005
   90 15230 36062   100 15226 36060      4960 11230 35548 -9999 -9999 35549
 9900 10787 36005  9880 10786 36000     14890  6877 35472 -9999 -9999 35469
19930  4568 35137 19930  4567 35140     26920  3110 34970 -9999 -9999 34967
32540  2740 34939 -9999 -9999 34934     39834  2574 34916 39800  2580 34913
44940  2505 34903 -9999 -9999 34902     55700  2598 34898 55560  2607 34898
```

No. of data cycles in record

Fixed format part of record

Ninth data cycle in record

Practical salinity (bench salinometer) = 34.902

Sea temperature (reversing thermometer) = no measurement

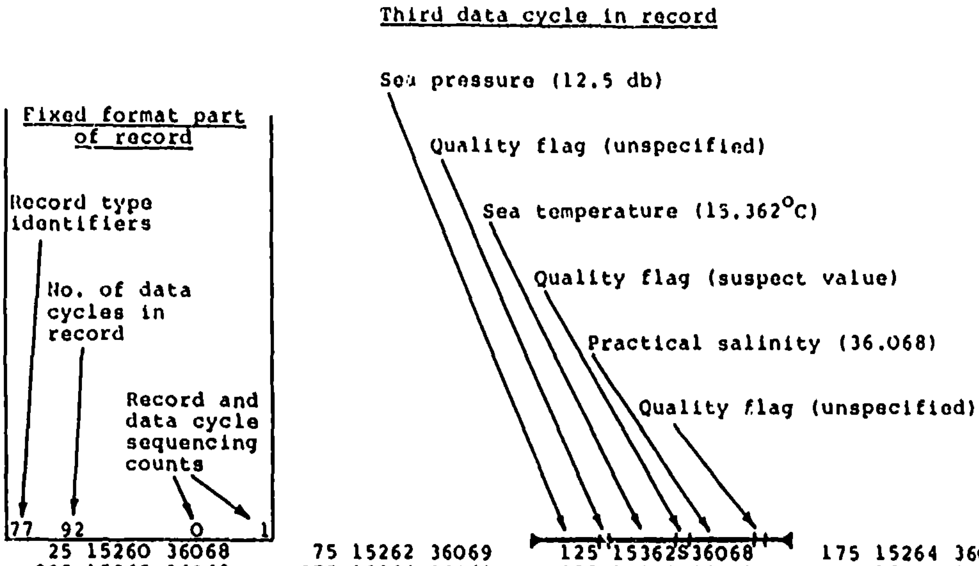
Sea Pressure (reversing thermometers) = no measurement

Practical salinity (CTD probe) = 34.903

Sea temperature (CTD probe) = 2.505°C

Sea pressure (CTD probe) = 4494.0 dbars

ANNOTATED LISTING OF SAMPLE DATA CYCLE RECORD



25	15260	36068	75	15262	36069	125	15362S	36068	175	15264	36069
225	15265	36068	275	15264	36069	325	15265	36069	375	15267	36068
425	15265	36068	475	15266	36069	525	15267	36068	575	15270	36069
625	15268	36068	675	15269	36067	725	15271	36068	775	15271	36068
825	15264	36066	875	15260	36066	925	15256	36065	975	15256	36065
1025	15203	36060	1075	15076	36041	1125	14808	35998	1175	14326	35936
1225	14164	35900	1275	14115	35906	1325	14060	35900	1375	13984	35892
1425	13861	35876	1475	13782	35868	1525	13682	35851	1575	13571	35841
1625	13496	35824	1675	13431	35814	1725	13364	35806	1775	13279	35794
1825	13182	35781	1875	13032	35756	1925	12980	35751	1975	12905	35738
2025	12841	35734	2075	12757	35719	2125	12722	35713	2175	12693	35711
2225	12644	35705	2275	12603	35699	2325	12576	35700	2375	12547	35696
2425	12496	35692	2475	12450	35685	2525	12405	35682	2575	12349	35674
2625	12313	35672	2675	12254	35664	2725	12216	35656	2775	12167	35650
2825	12142	35646	2875	12121	35643	2925	12099	35641	2975	12059	35638
3025	12043	35634	3075	12020	35635	3125	11964	35627	3175	11946	35626
3225	11864	35618	3275	11831	35612	3325	11818	35610	3375	11808	35609
3425	11787	35607	3475	11766	35605	3525	11744	35602	3575	11727	35600
3625	11704	35598	3675	11691	35597	3725	11669	35595	3775	11640	35591
3825	11622	35589	3875	11609	35587	3925	11592	35585	3975	11571	35584
4025	11558	35582	4075	11547	35580	4125	11537	35578	4175	11519	35576
4225	11497	35573	4275	11483	35572	4325	11448	35569	4375	11404	35563
4425	11372	35562	4475	11336	35557	4525	11307	35553	4575	11286	35551

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

Appendix D

Algorithms for Practical Salinity Computation

The following FORTRAN Function designed by Fofonoff and Millard(UNESCO, 1983) implements the 1978 definition of Practical Salinity as a function of conductivity ratio and also the inverse calculation.

```
C***********************************************************************
C
      REAL FUNCTION SAL78(CND,T,P,M)
C
C ***********************************************************************
C     THE CONDUCTIVITY RATIO (CND) = 1.0000000 FOR SALINITY = 35 PSS-78
C     TEMPERATURE = 15.0 DEG. CELSIUS , AND ATMOSPHERIC PRESSURE.
C
C  FUNCTION TO CONVERT CONDUCTIVITY RATIO TO SALINITY (M = 0)
C  SALINITY TO CONDUCTIVITY RATIO (M = 1,CND BECOMES INPUT SALINITY)
C
C   REFERENCES:   ALSO LOCATED IN UNESCO REPORT # 37 1981
C  PRACTICAL SALINITY SCALE 1978: E.L. LEWIS IEEE OCEAN ENG. JAN. 1980
C ***
C UNITS:
C       PRESSURE        P        DECIBARS
C       TEMPERATURE     T        DEG CELSIUS (IPTS-68)
C       CONDUCTIVITY    CND      RATIO     (M=0)
C       SALINITY        SAL78    (PSS-78)  (M=0)
C ***
C  CHECKVALUES:
C      SAL78=1.888091 :CND= 40.0000,T=40 DEG C,P= 10000 DECIBARS:    M= 1
C      SAL78=40.00000 :CND=1.888091,T=40 DEG C,P=10000 DECIBARS:    M=0
C***
C SAL78 RATIO: RETURNS ZERO FOR CONDUCTIVITY RATIO:  < 0.0005
C SAL78: RETURNS ZERO FOR SALINITY:  < 0.02
```

```
C ***
C INTERNAL FUNCTIONS
C ***
C  PRACTICAL SALINITY SCALE 1978 DEFINITION WITH TEMPERATURE CORRECTION
C  XT=T-15.0 : XR=SQRT(RT)
      SAL(XR,XT) =((((2.7081*XR-7.0261)*XR+14.0941)*XR+25.3851)*XR
     X-0.1692)*  XR+0.0080
     X  +(XT/(1.0+0.0162*XT))*(((((-0.0144*XR+
     X    0.0636)*XR-0.0375)*XR-0.0066)*XR-0.0056)*XR+0.0005)
C  DSAL(XR,XT)  FUNCTION FOR DERIVATIVE OF SAL(XR,XT) WITH XR.
      DSAL(XR,XT) =((((13.5405*XR-28.1044)*XR+42.2823)*XR+50.7702)*XR
     X    -0.1692)+(XT/(1.0+0.0162*XT))*((((-0.0720*XR+0.2544)*XR
     X    -0.1125)*XR-0.0132)*XR-0.0056)
C  FUNCTION RT35 :  C(35,T,0)/C(35,15,0) VARIATION WITH TEMPERATURE
C  WITH TEMPERATURE.
      RT35(XT) =  (((1.0031E-9*XT-6.9698E-7)*XT+1.104259E-4)*XT
     X    + 2.00564E-2)*XT + 0.6766097
C POLYNOMIALS OF RP: C(S,T,P)/C(S,T,0) VARIATION WITH PRESSURE
C  C(XP) POLYNOMIAL CORRESPONDS TO A1-A3 CONSTANTS: LEWIS 1980
      C(XP) =  ((3.989E-15*XP-6.370E-10)*XP+2.070E-5)*XP
      B(XT) =  (4.464E-4*XT+3.426E-2)*XT + 1.0
C  A(XT) POLYNOMIAL CORRESPONDS TO B3 AND B4 CONSTANTS: LEWIS 1980
      A(XT) =  -3.107E-3*XT + 0.4215
C***
C ZERO SALINITY/CONDUCTIVITY TRAP
      SAL78=0.0
      IF((M.EQ.0).AND.(CND.LE.5E-4)) RETURN
      IF((M.EQ.1).AND.(CND.LE.0.02)) RETURN
C ***
      DT = T - 15.0
C SELECT BRANCH FOR SALINITY (M=0) OR CONDUCTIVITY (M=1)
      IF(M.EQ.1)  GO TO 10
C ***
C CONVERT CONDUCTIVITY TO SALINITY
      R = CND
      RT = R/(RT35(T)*(1.0 + C(P)/(B(T) + A(T)*R)))
      RT = SQRT(ABS(RT))
      SAL78 = SAL(RT,DT)
      RETURN
C *** END OF CONDUCTIVITY TO SALINITY SECTION
C ***
C INVERT SALINITY TO CONDUCTIVITY BY THE
C  NEWTON-RAPHSON ITERATIVE METHOD.
C ***
C FIRST APPROXIMATION
```

```
   10 RT = SQRT(CND/35.0)
      SI = SAL(RT,DT)
      N = 0
C
C  ITERATION LOOP BEGINS HERE WITH A MAXIMUM OF 10 CYCLES
C
   15 RT = RT + (CND - SI)/DSAL(RT,DT)
      SI = SAL(RT,DT)
      N = N + 1
      DELS = ABS(SI - CND)
      IF((DELS.GT.1.0E-4).AND.(N.LT.10))GO TO 15
C
C  END OF ITERATION LOOP
C
C COMPUTE CONDUCTIVITY RATIO
      RTT = RT35(T)*RT*RT
      AT = A(T)
      BT = B(T)
      CP = C(P)
      CP = RTT*(CP + BT)
      BT = BT - RTT*AT
C
C SOLVE QUADRATIC EQUATION FOR R: R=RT35*RT*(1+C/AR+B)
C
      R = SQRT(ABS(BT*BT + 4.0*AT*CP)) - BT
C CONDUCTIVITY RETURN
      SAL78 = 0.5*R/AT
      RETURN
      END
```

Appendix E

Ice-point Checks of Thermometers

The equipment needed for checking ice-points consists only of the normal thermometer reading equipment plus a wide mouth Dewar flask about 8cm internal diameter and long enough to hold the thermometer, a large Dewar of 15 cm internal diameter, a source of clean and pure shaved ic, a pail to hold it, which is used for nothing else, some pure water either distilled or, at least, de-ionised, an aluminium or stainless steel stirrer. A pair of light rubber gloves would be helpful.
The procedure is as follows:

All of the utensils, the stirrer, and the thermometer are carefully cleaned with mild detergent solution then rinsed two or three times with ordinary water, at room temperature. The larger Dewar is 2/3 filled with distilled water, and shaved ice is added (avoiding contamination by hands) with strong stirring until it can be made into a water-ice slush mixture thin enough that the stirrer will pass through it easily but thick enough that some ice can be picked up on the stirrer if it is lifted out slowly. The slush-ice is then transferred with the stirrer to fill the smaller Dewar. Aerated distilled water water, precooled by ice, is added to fill it almost to the top, but preferably not enough to float the ice. The pre-cooled thermometer is then thrust as far as possible into the centre of the ice mixture, i.e. with liquid-in-glass thermometers until the ice-point marking is just above the lip of the Dewar. With thermocouples and resistance thermometers it is preferable to have at least 30cm of immersion. If there is any doubt as to the efficiency of immersion the thermometer should be read a second time with 5cm less immersion to confirm that the reading is independent of immersion depth. It is *absolutely* essential that the sensing element does not go beyond the bottom of the ice since very pronounced temperature layering can exist in the water below ice level.

Final readings should not be taken until temperature equilibrium has ben achieved as indicated by a constant reading over several minutes. A useful check against contamination is to quickly withdraw the thermometer and re-insert it in a different location and repeat the measurement procedure.

With liquid-in-glass thermometers an infrared filter is used on the illuminator to prevent heating of the bulbs by radiation. In very precise work or when immersion ids limited a clean aluminium foil over the top of the ice should be used to prevent transmitted radiation from affecting the temperature of the sensing element. For very best accuracy resistance thermometer readings should be taken at two currents, and extrapolated to zero input power, but this is not usually necessary when checking ice-points if identical conditions are maintained.

It is extremely important that all equipment be clean and rinsed. The ice should not be touched by the hands at any time, but washed rubber gloves can be used provided they do not touch the *outside* of any containers. The ice is best made in an ice machine that does not freeze *all* of the water since the freezing process helps in the purification and concentrates the impurities in the unfrozen part. With commercial ice that is frozen in large blocks the centre of the block, which freezes last, should not be used, just the clear outer layers with the surface washed to avoid contamination.

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