Pergamon

Deep-Sea Research 1, Vol. 44, No. 1, pp. 147—165, 1997
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Printed in Great Britain
0967-0637/97 $17.00+0.00

PII: S0967–0637(96)00087–8

INSTRUMENTS AND METHODS

A towed **CTD chain for two-dimensional high resolution hydrography**

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(*Received* 23 *February* 1995; *in revised form* 1 *April* 1996; *accepted* 26 *July* 1996)

Abstract—The need for accurate two-dimensional datasets of temperature and salinity in the upper ocean led to the development of a new type of towed chain. Low-cost sensors are moulded in fins and may be randomly placed on the tow cable, to which they are inductively coupled for power supply and communication with a deck unit. Construction and operation of the chain are described, and examples of measurements in the Norwegian and Greenland Seas are given. © 1997 SACLANTCEN. Published by Elsevier Science Ltd

1. INTRODUCTION

No type of instrument is able to measure comprehensively the three-dimensional, time varying fields of temperature and salinity at sea, or the related parameters of conductivity, density and sound velocity. A single probe fixed in one location does yield a Eulerian time series, or the Lagrangian rate of change if drifting. Every sensor movement through the field that differs from these two cases results in a measurement containing a mixture of temporal and spatial changes. *A priori* knowledge about the physical processes is then needed for the interpretation of the results. Often velocity of the sensor movement allows the measured field to be considered as frozen, a hypothesis which usually is valid for vertical profiles of conductivity and temperature versus depth (CTD) measured from a slip on station.

There are two common approaches for the measurement of physical parameters in a vertical section through the ocean, namely towed undulating fishes and towed multi-sensor chains. The vertical dimension of internal structures in the ocean is two orders of magnitude smaller than the horizontal dimension. When a sensor package oscillates through the water column, the response of the sensors must be fast enough to resolve the smallest structures of interest. On the other hand, horizontal resolution is limited by the wavelength of the towed body oscillation. In a highly variable field, undersampling will occur. To keep this to a minimum the towing speed may be low and the sensor package guided by an almost vertical cable pulled down by a heavy mass (Cairns, 1980; De Strobel and Gualdesi, 1994). Cairns identifies internal waves as the major source of variability. Internal waves are eliminated from towed fish measurements in the analysis of mesoscale processes by taking isopycnal surfaces as reference coordinates (Minnett, 1978). In all cases of towed fish measurements upward and downward profiles could not be combined for a consistent image, because the response of the sensors to various environmental conditions is not known in sufficient detail.

Undulating sensor packages have certain advantages over towed chains, apart from size and

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simplicity in handling. Vertical gradients are readily available, and limitations in their accuracy are almost exclusively due to sensor noise. In towed chain measurements, vertical gradients are calculated as differences between values of adjacent sensors. Offset errors divided by sensor distance add up to gradient errors that increase if the spacing is reduced. The shape of vertical profiles in chain measurements is usually created by direct connection of data points. Sensor spacing has to be close enough to make linear interpolation a good approximation. Step-like structures therefore can be resolved only by ascending and descending devices. In chain measurements they are sometimes identified from their appearance as a staircase when a sensor path crosses the layer boundary (see Fig. 8 in Marmorino *et al.,* 1985). In contrast to undulating devices the response time of chain sensors may be long and staircases invisible.

Towed chains and vertically profiling sensor packages are complementary instruments. With horizontal tows the sensor tracks are essentially parallel to layer boundaries instead of crossing them at high angles. In this instance, the time constant of the measuring device can be adjusted to the horizontal length-scale of interest. The sensor averages over microscale fluctuations, but no undersampling occurs for the horizontal coordinate. Numerous sensors are needed for the coverage of a vertical plane. The number and spacing of sensors determine the vertical resolution and aperture of the system. Sensor spacing on the chain should be adjusted to the vertical scale of those phenomena that can be resolved in a horizontal direction. Note that horizontal smoothing caused by the time constants of the chain sensors also softens the steps and spikes that appear in vertical CTD profiles.

Investigation of fine-scale variability requires horizontal high frequency sampling. One particularly important application of towed chains is ocean acoustics. The modification of the sound velocity profile with horizontal distance obviously has more impact on a horizontally spreading sound field than high resolution details of the vertical profile (Sellschopp, 1991).

Towed thermistor chains have been used for many years by various researchers. Richardson and Hubbard (1960) were the first to report a chain with 23 thermistors 25 ft apart. With the 600 ft chain they reached a depth of 450 ft at 11 kn. Isotherms were automatically calculated and plotted. A similar system was used by Lafond (1963). Hudimac *et al.* (1963) mounted a vertical strut on the bow of a submarine with 26 thermistors spaced at 1 ft intervals. Lyamin *et al.* (1965) used a chain with four thermistors in the Baltic Sea. With the exception of the main thermocline, they calculated the standard deviation of filtered signals and compared temperature variations at the different levels. Miropol‘skiy and Filyushkin (1971) calculated wave-number spectra of internal waves measured with the towed thermistor chain. They corrected for the Doppler shift in the spectrum, but doubted whether most of the variability in the temperature structure was due to internal waves. Keunecke and Magaard (1975) found a drifting mesoscale eddy in the Baltic Sea. They interpreted the wave-number spectrum at that location as that of geostrophic turbulence. In the records of an experiment near the Azores, internal tides of 15 km wavelength are dominant. Only the fluctuations observed in the North Sea are more likely to be due to internal waves.

The thermistor cable developed by Keunecke (1972) differs from previous and subsequent constructions in its mechanical arrangement. Keunecke’s design consisted of a single cable with a strong core surrounded by 120 conductors in two layers. Sixty openings in the outer cover with 1 or 3 m spacing for the shallow or deep water versions are provided for the thermistor connection. Moulded in blocks, they have a time constant of about 40 s to allow for data acquisition on punched paper tape, while also smoothing the effects of motion due to the sea state. With only minor modifications the cable was used in the sometimes hostile North and Baltic Seas for many years. Examples of chain measurements for different hydrographic situations in shallow water have been compiled by Wille (1986).

The thermistor chain designs introduced by Mobly *et al.* (1976) and Morris *et al.* (1983) still follow the principle of no wetside electronics. Mesecar *et al.* (1983), however, used underwater modules cast in resin and fitted into the fairings for signal preconditioning. They intended to overcome the constraints of the limited number of twisted signal wire pairs by multiplexing up to 16 digital signals to one wire pair. It was planned to use slotted ferrite cores to couple power and addressing information to, and data information from, the *in situ* module. The Lane and Scott (1986) thermistor chain carried all digitising sensor electronics in pods distributed along a tow cable. Serial data were multiplexed into two pairs of signal wires. Another pair was used for power supply. The chain was deployed and recovered in sections of 8 m in length, connected with shackles and watertight couplers. Morris *et al.* (1987) attached a 20 m thermistor chain to a depth controlled tow body, which contained the electronics for digitisation and serial transmission to a deck unit.

A single cable of 10 mm diameter, equipped with fairings and freely rotating sensor fins, was reported by Sellschopp (1988) to function in water up to 600 m deep. An inductive link was used for power supply and communications. Sea water was used for signal return. The system was developed into a reliable, highly accurate two-dimensional profiling system, with full CTD capability (Sellschopp, 1992). The system was used in the Norwegian and Greenland Seas in the period 1992—1994, and in the Mediterranean and Black Seas in 1995.

2. SYSTEM OVERVIEW

A completely new approach was chosen in order to eliminate many of the technical problems affecting towed thermistor chains, such as the large cross-section of chains, mechanical vulnerability of cable bunches, sensitivity of high impedance sensor circuits to connector resistance, leakage and imprinted noise, lack of sensor stability and unavailability of two-dimensional fields other than temperature. The basic idea for a new chain design was to use a simple tow cable with a single conductor and serial digital data transmission multiplexed in time. Most of the following design criteria are consequences of that concept.

Analog to digital conversion at sensor location

As the lines of the analog circuits are kept short, noise from ambient sources does not affect the measurement. The analog-to-digital (A/D) converters need not be faster than the scan rate of the chain. Cheap and accurate integrating converters can be used. The conversion time using a quad-slope 16-bit device is approximately 15 ms.

Data transmission to a deck unit

Assessment of the oceanographic situation in real time on board the towing ship is essential. The dataset of every sensor is transmitted within a data cycle initiated by a deck unit. It takes some time to serially transmit frequency shift keyed digital data, so that the minimum cycle time is of the order of a second. The constant transmission of data obviates the need for data storage inside the sensors.

Sensors called by address

The command to start a measurement cycle and the requests for data are sent as 1 byte by the deck unit. Cycle start is common to all sensors, while calling addresses are individual for each sensor in a chain. As soon as a sensor receives its address, it sends a message containing the momentary dataset.

Sensor intelligence by microcontrollers

Microcontrollers in the sensors allow for special operation modes to be selected by commands from the deck unit. Conductivity and pressure, the response time of which is much shorter than the cycle time, are sampled at 50 ms intervals by the microcontroller and averaged in accordance with the time constant of the temperature sensor.

Inductive coupling to the tow cable

The tow cable is a simple insulated steel wire. It is connected to the deck unit at the upper end and to an electrode at the lower end. The current loop from the electrode to the deck unit is closed by the sea water. The tow cable runs through ring cores, which are part of the sensor electronics. It acts as the primary coil of inductive couplers. The other side of each coupler is connected to send and receive circuitry of the sensor.

Power supply from deck unit

No battery is needed in any underwater unit. Energy to drive the sensor electronics is supplied by the deck unit, which periodically switches between send and receive. The 1-byte transmission time, which would be sufficient to control the chain, is prolonged in order to power the sensors. The few milliseconds of interruption, when the deck unit interrupts its transmission, are easily bridged by the capacitor in the power supply circuit of the sensor.

Moulded sensor fins

Watertight housings for sensors and electronics are expensive and usually large and heavy. The CTD chain uses moulded sensor fins, which withstand not only water pressure at up to 1000 m depth, but also the necessarily rough handling on board a ship in heavy weather conditions.

The operational use of the system is described below in more detail, and examples of measurements in the Norwegian and Greenland Seas are given.

3. SENSOR OPERATIONS

The electronics boards in all sensor fins are equipped with bridge circuits for all three parameters: temperature, conductivity and pressure. Only two of them are used in each fin. It is not necessary for a pressure measurement to be made at every sensor location. Since the sensor distances are known, the curvature of a towed chain will be apparent, if only some pressure sensors are spread along the chain. The depths of all other sensors are calculated by interpolation. In order to obtain sensor messages of equal length, conductivity cells were included only in those sensor fins that do not contain pressure sensors. Every sensor fin contains two probes: a platinum resistance thermometer (PT 100) and either a piezoresistive pressure transducer (Keller PA-10) or a four-electrode conductivity cell.

Provision had to be made for the different response times of temperature and conductivity, because computed salinity and density react sensitively to a mismatch, with false spikes at temperature gradients. In contrast to single CTD probes, where sampling intervals may be shorter than sensor response times and filters may be utilized during the subsequent data reduction phase, a CTD chain with, say, 50 sensors needs a cycle time of about 1 s for serial transmission of all the data. The application of filters on slowly sampled chain data to smooth salinity spikes would waste much of the high spatial resolution of the data.

The microcontroller in a sensor fin can be switched to a special mode, which is used only for laboratory calibration. In this mode, temperature is measured and displayed every 50 ms. Thus, the response of the platinum thermometer to changes of the ambient temperature field can be measured with high temporal resolution. The simplest theoretical model of a temperature sensor considers the heat storage of the sensor volume, but ignores delays due to heat conduction to the inner zone of the volume. With such a model, the rate of change of the sensor temperature θ is proportional to the difference between the temperature of the surrounding water Θ and the sensor temperature:

$$\frac{d\theta}{dt} = \frac{\Theta - \theta}{\tau}, \tag{1}$$

where τ is the sensor response time. The solution of this first order differential equation is the average of the past temperature weighted by an exponential of the elapsed time. After an ambient temperature jump from $\Theta_1$to Θ_2 at $t = 0$, the measured sensor temperature for $t > 0$ will be

$$\theta_j = \Theta_2 + (\Theta_1 - \Theta_2) e^{-\frac{t}{\tau}}. \tag{2}$$

The graph of the function

$$f_j(t) = \ln \frac{\theta_j(t) - \Theta_2}{\Theta_1 - \Theta_2} \tag{3}$$

constructed with measured data should be a straight line that starts at 0 for $t = 0$ and falls with the inclination $-1/\tau$. Any deviation indicates that the model assumptions are not applicable. One possible reason for deviation from a line is insufficient thermal insulation of the sensor from adjacent parts that do not follow the ambient temperature as fast. Figure 1(a) shows the curves for a chain sensor and Fig. 1(b) shows those of a design that was rejected because the sensing element was not sufficiently far from the anchoring point of the temperature sensor.

The response time of the thermometers located in the closed tip of bronze tubes is *ca* 0.6 s and varies somewhat with the towing speed. The conductivity cell is much faster. To prevent salinity spiking, conductivity is smoothed by a filter that puts the same time behavior on conductivity data as the thermometer does on temperature. The filter used for a numerical scheme is taken from equation (1).

$$x_{n+1} = x_n + \alpha(X - x_n). \tag{4}$$

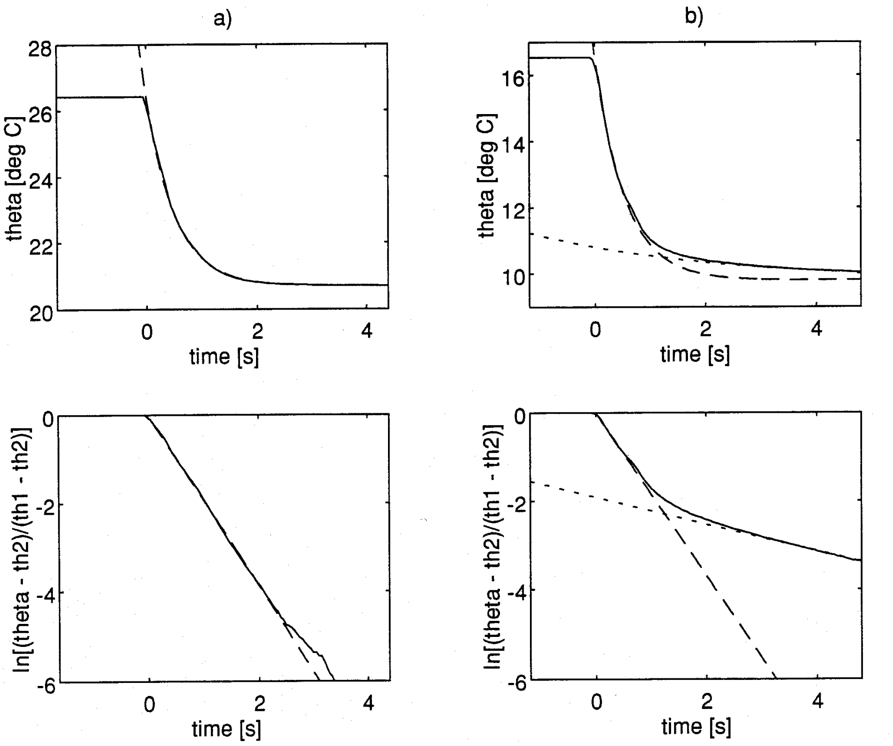

Fig. 1. Response of temperature sensors to a thermal jump. The time constant is approximately 0.5 s in both cases. Dashed curves are theoretical responses of an ideal temperature sensor. (a) Response of a CTD chain sensor. (b) Thermal coupling between sensing element and carrier inhibits fast transition to end temperature. The time constant of the carrier is 3.3 s in this case (dotted curves). This sensor design was rejected.

where x_n is the filtered value and X is the actual measurement; α is the quotient of the scanning interval Δt divided by the response time τ of the temperature sensor. For stability, α is restricted to numbers between 0 and 1, which means that the scanning interval for conductivity must be smaller than the thermometer response time. The internal scanning interval of the microcontroller program is set to 50 ms.

The same algorithm (4) is applied to pressure data in order to adjust the pressure response time to the chain cycle time and suppress random depth deviations due to the pressure effect of short surface waves.

As soon as the sensor fin is powered up, periodic interruptions are generated by the timer in the microcontroller every 50 ms. This starts the A/D conversion of conductivity (or pressure). Triggered by the conversion complete signal, the microcontroller fetches the 16 bit binary result. Only the very first value is stored to memory as it is and serves as the initial value x_0. After that, only the weighed increments are added to the former result, according to equation (4).

A chain data cycle is initiated by a 1-byte message from the deck unit. The start byte, consisting of 8 zero bits, is common for every sensor in the chain. When it arrives at the communications port of the microcontroller, the next filtered data value x_{n+1} will be copied to an output buffer, and a temperature measurement will be initiated, which, after completion, is also saved for output. Every sensor is ready to send a fresh dataset from its output buffer 50—100 ms after the cycle start.

Up to 255 sensors may be aligned in a CTD chain. The upper limit is due to the fact that every sensor owns a unique 8-bit address. When a sensor receives its address as 1 single byte from the deck unit, it immediately sends the 4 byte contents of the output buffer followed by a checksum byte. The deck unit and the connected computer start a measurement cycle and, after a 100 ms lag, interrogate all sensors in the chain in a predetermined sequence (see the section below on chain control and data collection).

4. SENSOR COUPLING

Transmission of data

The deck unit sends to, and receives from the towing cable, a single conductor cable without shield, i.e. a steel wire of 8 mm diameter with 1 mm insulation. Jnstead of a shield, sea water is used for signal return. The tow cable runs through one edge of each sensor fin (see Fig. 2), where it passes a ring core to form an inductive coupler. The other side of the coupler is connected to the sensor power supply and send and receive circuits. All data bytes from the deck unit to the sensors and back are sent at 9600 baud in asynchronous mode with 8 data bits plus parity, frequency coded. The deck unit sends at 41.0 and 51.2 kHz and receives at 68.3 and 76.8 kHz.

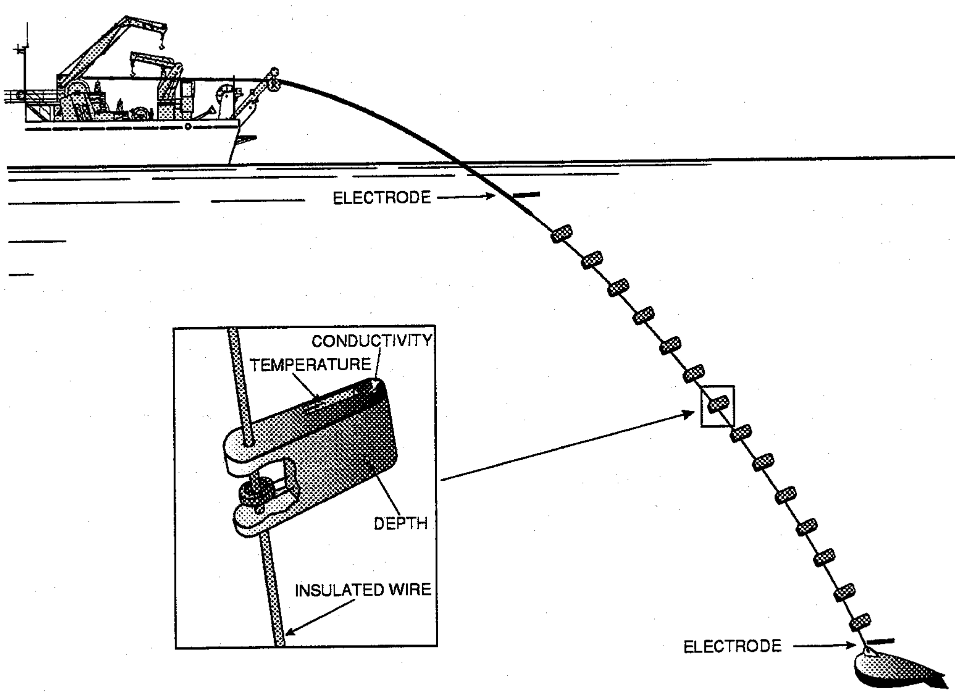

Fig. 2. Diagram of the CTD chain. The sensors are inductively coupled to the towing cable. The current loop is closed by sea water.

The signals sent by the deck unit are at high amplitude and superimposed noise is negligible. The frequency detector in the sensor uses a counter with a 1.23 MHz clock to measure the duration of each period of the received a.c. signal; 17—22 μs are accepted as representative for 51.2 kHz. Periods of this length produce a low level at the communications input pin of the microcontroller; otherwise the level is high. The sequence of signals results in high and low level segments of about 104 μs duration, which is the bit length at 9600 baud. The communications port tolerates deviations from the exact bit length and ignores single short peaks of inverted polarity.

The messages sent by the sensors and received by the deck unit are more critical. A narrow filter may be used in the receiver, because the ratio of the frequencies representing 0 and 1 bits is 8/9. The filtered input signals are formed into a rectangular shape and led to a programmable logic device (PLD), where frequency is sensed by an autocorrelation method, which is more sophisticated than the stopwatch used in the sensor. The output signal of the PLD consists of high or low level periods of exactly 104 μs duration. The bit stream is thus appropriate for any normal 9600 baud data communications port.

To increase data reliability, a parity bit is added to every transmitted byte and a checksum byte added to sensor messages. A sensor will not react on a received byte, even its own address, if the parity check fails. When a sensor message contains an error the program that runs in the background of the deck unit will decide what to do. The most appropriate procedure is to start a new data request on the same sensor.

Transmission of energy

Deck unit data transmission time constitutes only 15% of the data traffic, because only 1-byte calls are required from the deck unit to the sensors, whereas the sensor messages are 5 bytes long (two 16-bit data words and a checksum). However, the sensor fins take the energy to power the electronic circuits from the signals they receive from the deck unit. In order to increase the sending time, transmission of the deck unit is switched on and the data line left idle for some milliseconds before the transmission of the byte starts. Usually, sending and listening times of the deck unit will be made approximately equal (Fig. 3). In order to establish constant conditions for sensors and deck unit, the periodic send and receive intervals are maintained all over the chain data cycle, even when no commands have to be sent and no data are expected. The request-to-send line (RTS) of a communications port, which connects the deck unit to a computer, defines whether the deck unit transmits or listens.

Less than 20 mA at 5 V are required by the sensor electronics. This is provided by a voltage regulator in the power supply circuit of the sensor. A mean alternating current of 0.5—1 A in the tow cable is sufficient to fill the capacitor of the power supply in the sensor fin. A higher current raises the voltage in the capacitor. In a laboratory configuration and also in a short (50 m) CTD chain at sea, all sensors are supplied at the same rate, because the current is constant along the wire that leads through all ring cores. The current, which is provided by the deck unit, may be adjusted so that all sensors are operative and no power supply capacitor exhibits excessive voltage.

On a long cable, however, the current through the sensor couplers at different positions differs for two reasons. First, if the length of the chain has the same order of magnitude as the wavelength of a 50 kHz electromagnetic wave, a standing wave is generated by reflection at the end of the tow cable, which leads to current maxima and minima at quarter wavelength intervals along the cable. This effect can be avoided by an appropriate resistance at the cable

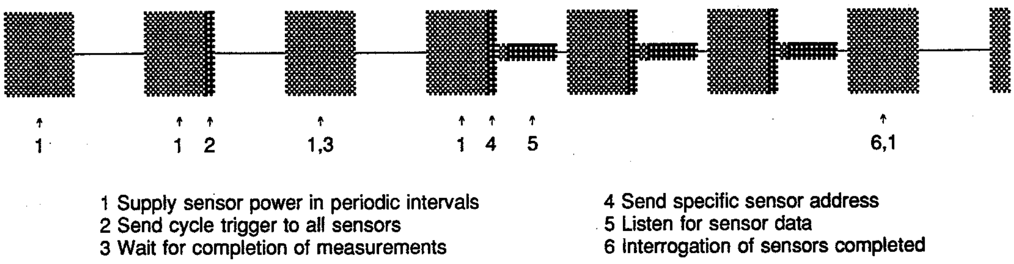

Fig. 3. Communication between deck unit and sensors. Periodic send and receive intervals are maintained during a data cycle.

end if necessary. The other reason for different sensor supply is the continuous leakage caused by the capacitance of the cable. A deck unit has to provide sufficient current to supply even the last sensor in a chain, leading to excessive current through the first sensor.

An excess sensor supply is doubly undesirable. Provision had to be taken to ensure that electrical energy was not wasted and converted to heat and that the voltage in the buffer capacitor did not rise to such a high level that the voltage regulator or even the capacitor itself was destroyed. The feeding of the capacitor in the power supply is interrupted by a shortcut over the sensor input as soon as the voltage increases to an upper limit. The shortcut is removed when the buffer voltage sinks to the minimum value. By this procedure the input impedance of sensors, which is also felt by the deck unit, is changed between low and very low values. This means that in a short chain, where cable losses can be neglected and all sensors switch independently, the total chain impedance decreases when the chain current increases.

The microcontroller of each sensor captures the switching moments and calculates the proportion of time, T_S when the shortcut is active. A supply rate S may be defined as

$$S = \frac{1}{1 - T_S}. \tag{5}$$

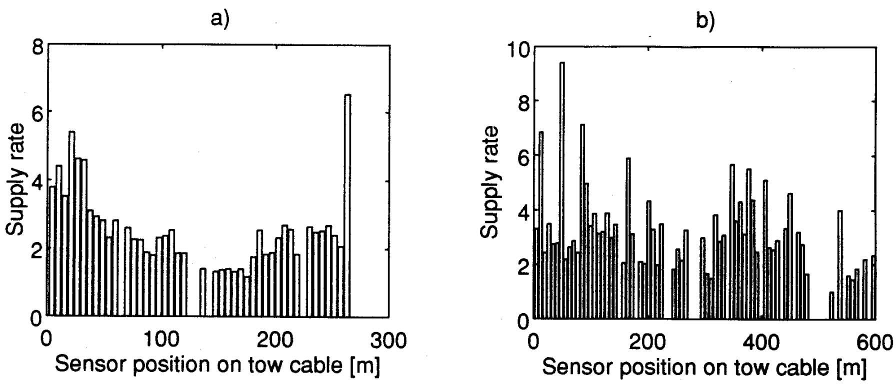

Fig. 4. Supply rates of sensors aligned on a CTD chain. A supply rate of n indicates that the sensor power supply needs only $1/n$ of supply time to fill the storage capacitor. A missing bar means that the sensor did not respond. (a) The 270 m chain was directly coupled to the sea water at its lower end. (b) The 600 m chain was coupled to the sea water via a 30 Ω resistor.

A special command can be sent to all sensors to switch them into a mode in which they transmit buffer voltage and switch off time instead of temperature and conductivity or pressure. The supply rates on a 600 m chain displayed in Fig. 4 were measured in this mode.

5. CHAIN CONTROL AND DATA COLLECTION

The deck unit of the CTD chain system also could be called a modem, because it only converts the serial bit stream (TxD) to a pair of frequencies, which are sent to the tow cable, or it receives another pair of frequencies from the tow cable, which are converted to a bit stream (RxD). Send only or receive only is selected by the status of the request-to-send line (RTS) of the same communications port, which contains the data lines TxD and RxD. The communications port of the deck unit connects to a port of a computer, which has to control the chain, observe all timing aspects, and display and store the data, which are received in response to sensor interrogation.

A standard personal computer (PC) using DOS is host for the CTD chain. The program for the chain accesses hardware components of the PC directly, namely the CMOS real time clock, the timer and a communications port. Interrupt processing is enabled for the timer and communications port hardware, and interrupt service routines are incorporated in the chain program. Timing and control of the CTD chain and data reception are interrupt driven and take only a small portion of the available computer time. For the rest of the time the main program is free to display data on the screen and process operator commands.

In standby mode before a data cycle starts, the RTS line is toggled on and off with the same duration of send and listen phases as will be used later in the data transfer mode. The timer of the PC, which in normal DOS operation produces time ticks five to six times a second in continuous mode, is used in single shot mode to provide interruptions at RTS switch times. With the change of the second, which is read from the CMOS real time clock, a measurement cycle is initiated and a start byte (all bits zero) sent at the end of the next transmission (RTS on) phase. The start byte may be followed immediately by one of the special commands mentioned earlier. For another 100 ms, the standby mode is resumed. The sensors complete their measurement and prepare data for output. During data transfer mode one sensor address is sent at the end of every transmission phase. After the RTS line is switched to listen the addressed sensor waits for 0.5 ms and then sends its 5-byte message. The computer is interrupted for every received byte. Even if the deck unit did not receive a complete sensor message, the listening phase is finished by the timer interrupt after 7 ms (see Fig. 3). When all sensors have delivered their data, standby mode is resumed. Data are saved to disk in the 100 ms gap after the start of the next cycle.

6. CHAIN APERTURE

The thickness of the surface layer that can be covered by the sensors of the CTD chain depends on the cable length and the effectiveness of the depressor at the selected tow speed. There are certain limitations on the operational parameters.

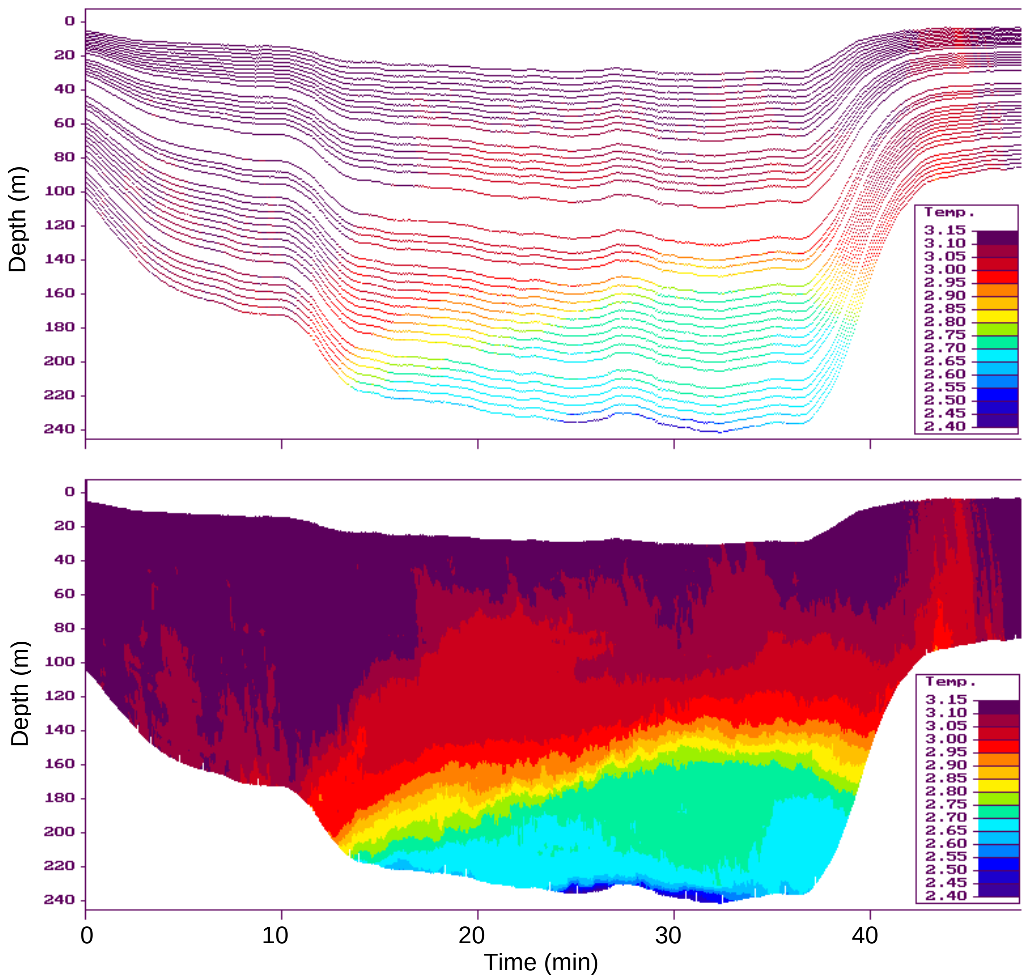

Fig. 5. Temperature section in the Norwegian Sea at 73°30'N 6°50'E in February 1993. The towing ship slows down and is almost stationary for 12 min when the downmost sensors reach 245 m; it then speeds up to 8 kn again. (a) Every coloured pixel represents the average of two consecutive temperature measurements. The pixels are colour-coded according to the temperature scale on the right. Missing sensors were destroyed in an emergency manoeuvre. (b) Data are linearly interpolated in the vertical direction.

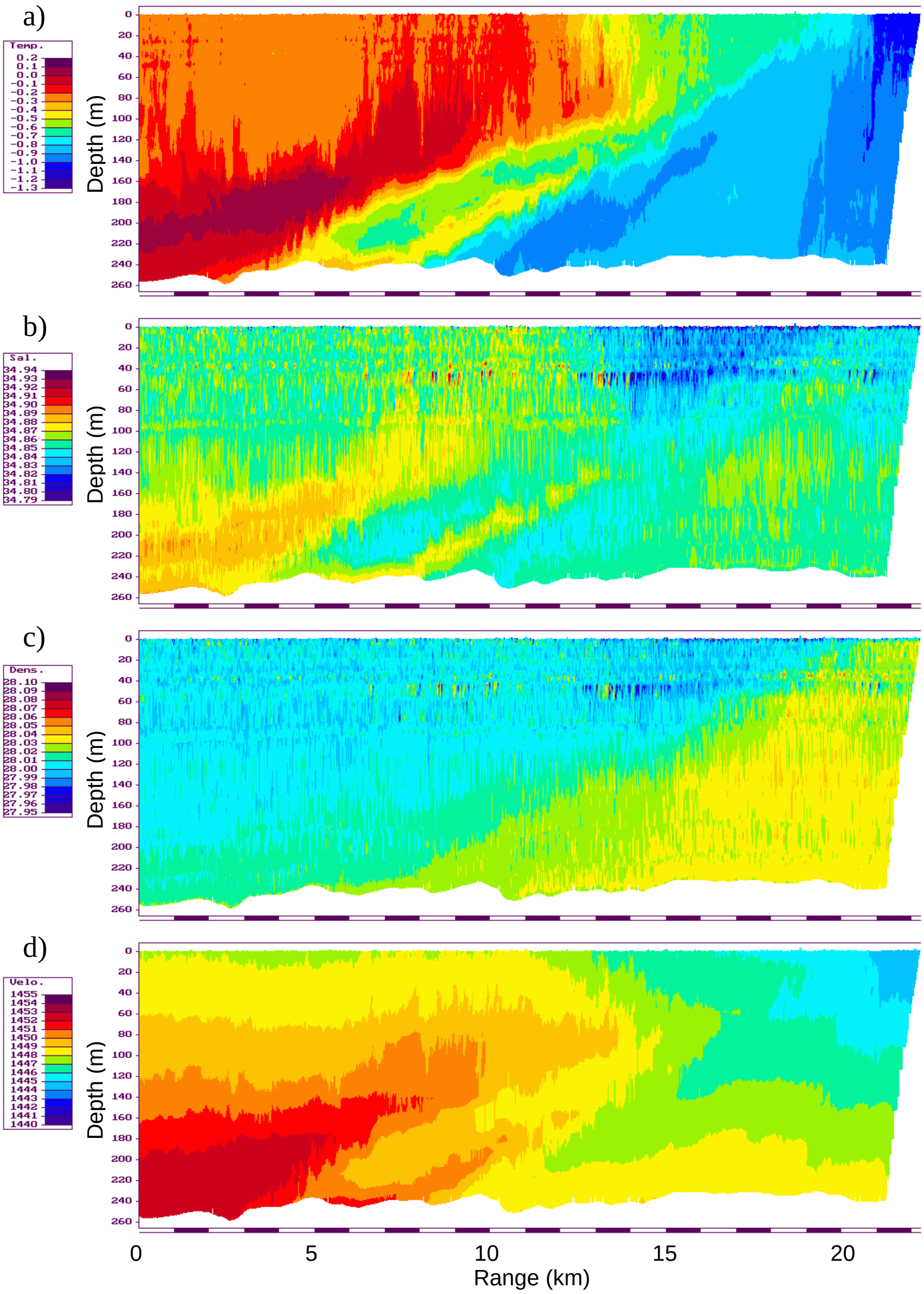

Fig. 6. Boundary of a patch or tongue of advected water in the Greenland Sea. (a) Temperature, (b) salinity, (c) density, (d) sound velocity. The intermediate temperature maximum at the cold water interface is balanced by salinity and has no corresponding density.

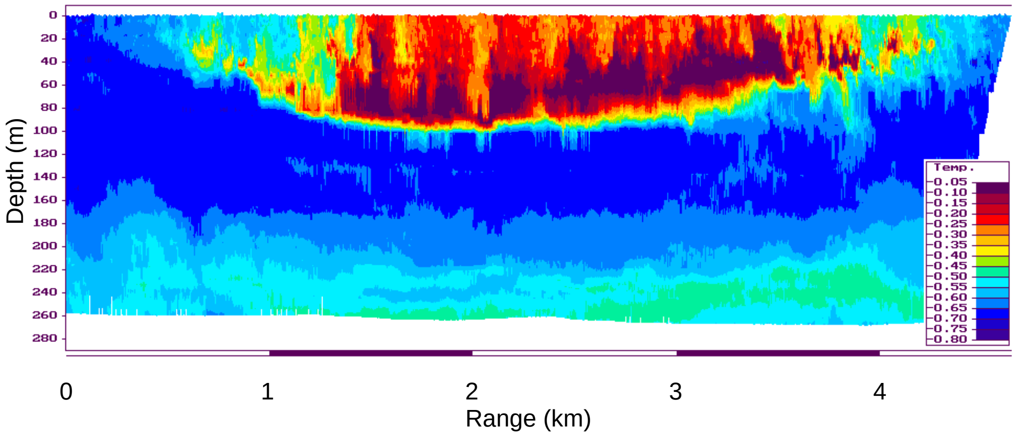

Fig. 7. Lens of warmer (by 0.5°C) and more saline (by 0.04 units) water in the surface layer of the Greenland Sea in March 1994, which is eroded by mixing and heat flux to the air. Wind speed is about 8 m s^{-1}, air temperature –9°C.

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Cable length

On long cables in particular, the space between sensor fins should be filled with fairings in order to avoid vibration and reduce drag. Turns on the winch drum should be parallel in one layer, a requirement that limits cable length, given that nearly 2 m^2 of drum surface are required per 100 m chain length.

Figure 4 shows that the chain length is also confined by the maximum electric power that the deck unit can provide. If every sensor receives the minimum of energy, indicated by a supply rate 1, the supply current at the upper part of the chain is many times higher than necessary. For a 600 m chain the transmitted power had to be 1 kW, most of which is dissipated by cable loss. If the chain is very long the reception of sensor messages may be hampered, because the signal amplitude becomes low and the duration of distinct frequencies uncertain. Tests at sea showed that a 600 m chain is not affected in this respect.

Tow speed

A CTD chain of 270 m length was towed at 8 kn in 1993. There was no evidence of damage to the tow cable, sensor fins, or fairings after a period of several days. The electrodes in the conductivity cells proved too vulnerable and were bent by the high speed flow through the cells. For a chain with improved conductivity cells the upper tow speed limit is above 8 kn.

Depressor characteristics

The resistance of the towed cable against the flow of the water tends to lift the lower chain end. The downward force of an ideal depressor increases with tow speed and balances the lifting force in a wide speed range. For a long chain and in bad weather conditions it is more convenient to use a smaller or weaker depressor, which puts less tension on the cable and also reduces the aperture. Figure 5 is an example of a measurement with a 270 m chain at different speeds and greatly changing aperture—in this case, a roof type depressor was used. In 1995 a depressor shaped like a venetian blind proved to be much more efficient.

Cable strength

For a desired aperture greater than 100 m the parameters tow speed, cable length and depressor size cannot be selected independently, because the limiting factor is the strength of the cable. An 8 mm wire coated with 1 mm insulation was selected as a compromise between the demands for highest potential durability and smallest possible system size. Its specified breaking strain is 38 kN.

Wave motion

Cyclic peaks of cable tension in bad weather are primarily due to heaving at the stern of the towing ship. A cable tensioner similar to that presented by Kidera (1983) and used by Morris *et al.* (1983) could be a solution for maintaining a more constant tension. In our 1995 cruises the chain was decoupled from the heave by towing a surface float 30 m behind the stern and attaching the chain below the float. For safety, a weak link was incorporated in the towing cable between ship and float. With these precautions it was possible to use a very efficient depressor, which pulled the 240 m chain down to 200 m at 5 kn. The tension on the tow cable was then 10 kN or less.

7. ACCURACY

The data are sampled with a 16 bit analog-to-digital converter. Since a 16 bit data word covers the temperature range from -2 to 30°C, conductivity from 0 to 60 mS cm^{-1} or pressure from 0 to 600 dbar, the resolution is approximately 0.0005°C, 0.001 mS cm^{-1} or 0.01 dbar.

Thermistors as sensing elements were rejected because of their limited stability. Even after careful calibration, thermistor chain data need minor adjustments in the sensor-to-sensor means, so that the horizontally averaged profiles are smooth (Dugan *et al.*, 1992). It is often observed that isotherms tend to follow, to a degree, the vertical excursions of the chain (Marmorino *et al.*, 1987). The only reliable method for intercalibration of thermistors was applied by Stalcup and Dugan (1990). They moved the chain up and down on an 11 km track in the thermocline and stated that the most probable temperature at the depth of a certain sensor is the temperature of the neighbouring sensor at the time when it was at the same depth shortly before. By the so-called towyowing method they achieved a gradient estimation of better than 0.05°C m^{-1}. Measurement errors turned out to be of the order of several tenths of degrees.

Unlike thermistors, the accuracy and stability of platinum thermometers are presumed to be no worse than the resolution of the A/D converter. The error from the noise of the sensor electronics is less than 0.003°C. The precision of the laboratory calibration is better than 0.01°C. Subsequent calibrations after 6 months differed by even less.

Piezoresistive pressure transducers were selected for the CTD chain sensors because of their small size and low power consumption. The transducers are almost linear in respect to pressure and are temperature-compensated by the manufacturer. The affirmed accuracy of 0.1% full scale, that is 50 cm for a 50 bar sensor can be enhanced by the application of a correction term for the residual temperature coefficient, which is of the order of 0.1 dbar $°C^{-1}$.

The most difficult measurement on a chain is that of conductivity. Both widely used approaches, electrode cells (e.g. Ginzkey, 1977) and inductive sensors (e.g. Striggow and Dankert, 1985) are possible candidates. Several attempts were made to develop an appropriate conductivity sensor for towed chains (Meagher *et al.*, 1982; Farruggia and Fraser, 1984) or to test an existing sensor for this purpose (Gregg *et al.*, 1982; Okawa and Dugan, 1984). Accuracy was always found to exist only in a relative sense (Marmorino *et al.*, 1986). Mack (1989) stated that there are no conductivity sensors available with the longer term stability necessary for meaningful vertical gradients.

Conductivity sensors were used in towed chains because their response time is shorter than that of thermistors and therefore extends the range of wave-numbers under investigation (Washburn and Gibson, 1982; Dugan *et al.*, 1986; Marmorino *et al.*, 1986). Salinity differences were small and conductivity used as an equivalent to temperature. On the contrary, the inclusion of conductivity in the present chain at almost every sensor position was determined by the large salinity contrasts in the ocean areas under investigation. Salinity and density were to be measured as accurately as possible.

According to availability and price, the decision was taken for a four electrode cell that had behaved well in a standard CTD package. When they are moulded together with the sensor electronics, the usual problem of a watertight cable connection does not exist. The laboratory calibration of these cells did not reach the appropriate quality, probably because of microscopic bubbles that could not be removed. Using the precalibration results the measured conductivities deviated by several tenths of a mS cm^{-1} from the true value. In order to produce the salinity and density fields of Fig. 6 it was necessary to adjust the calibration factors. During that cruise, the calibration error was not constant because the electrode material was too weak. A version with stainless steel electrodes used in the Mediterranean Sea in 1995 was stable over many hours.

8. SUMMARY AND CONCLUSION

Inductive coupling of sensor fins to a simple coated steel wire is the basic concept for a mechanically simple chain of CTD sensors. Because they are without tethers, the sensors may be shifted to any desired position on the cable. There are no problems if the towing ship is stationary. The accuracy of every sensor on the chain is comparable to standard CTD probes in temperature and pressure. In respect to conductivity, accuracy is obtained by *in situ* cross-calibration.

The development of the CTD chain was directed by the need for a manageable instrument that measures the ocean structure in much more detail than distributed vertical profiles can. Towed thermistor chains have been successful tools for the investigation of internal waves and ocean fine-structure in the thermocline. They are also suitable instruments for the localisation and description of fronts (Scott and McDowall, 1990). Calculation of ocean dynamics from measured temperature fields alone requires *a priori* knowledge of temperature–salinity relations, which is not available for plumes, intrusions, convective overturning, and other structures of size between mesoscale motion and turbulence, except internal waves.

Sellschopp (1995) analyzed towed chain data in the surface mixed layer that for every single sensor gave the appearance of waves, but were instead the manifestation of convective circulation. Warmer water with higher salinity moved to the surface and was cooled by heat flux to the atmosphere. The correlation coefficient between temperature and salinity decreased from 0.75 at 80 m to nearly 0 at the surface; that of temperature and density decreased from +0.35 to -0.35 over the same range. Mean vertical gradients were so small that the three variables did not correlate with pressure, which fluctuated due to surface waves and towing speed variations. The same situation is present in Fig. 7 in the middle of the warmer lens at the surface. At the edges the layer is destroyed by vertical circulation. The figure combines domains of possible double diffusion, salt fingering and Langmuir circulation.

Ocean modelling deals with progressively smaller grid size and depends on *in situ* measurements of similar scale for initialization and validation of computational results. Similarly ocean acoustics depends on detailed and realistic sections of the ocean environment as an input to more and more refined sound propagation models.

Acknowledgements—The CTD chain was developed at the Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik, Kiel. I thank all my colleagues, primarily D. Beling, who contributed to the progress of the system by qualified suggestions and active work.

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