

# Electronic Digitization and Sensor Response Effects on Salinity Computation from CTD Field Measurements<sup>1</sup>

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## ABSTRACT

Spikes are often observed in salinity profiles computed from measurements of conductivity, temperature and pressure. Many of these spikes are not real and are the result of a mismatch in the response functions of the sensors. Some of the spikes are also due to the sequential sampling technique used by most digitizers whereby the sensors are not sampled at the same time or position. We derive expressions to linearly correct for these two causes of spikes. When the corrections are applied to measurements in the North Pacific, a significant reduction in the number and size of the spikes is observed in high gradient regions such as the thermocline.

## 1. Introduction

Electronic conductivity-temperature-depth sensors (CTD), are extensively used to determine the thermo-

haline structure of the ocean. The *in-situ* measurements of these three variables are digitized by a data acquisition system onboard ship. The digitized output is used to compute salinity and density by means of suitable equations and tables (Cox *et al.*, 1967; Rohde, 1972; Knowles, 1974). This seemingly straightforward con-

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TABLE 1. Comparison of time offset corrections(s) of two data acquisition systems and of the Plessey 9040 CTD to interpolate the pressure and temperature to the time of conductivity.

	Data logger correction†	Sensor response correction	Data acquisition system	Order of sampling
Pressure	0.612	-0.03	H-P 2010B	1. pressure
Temperature	0.314	0.93		2. temperature
Pressure	0.085	-0.03	Plessey 8114	3. conductivity
Temperature	-0.057*	0.93		1. pressure
				2. conductivity
				3. temperature

† Assuming a depth = 360 m, temperature = 10°C, conductivity = 3.5 siemens m<sup>-1</sup>.

\* The negative correction is due to the fact that temperature is scanned after conductivity.

version cannot be done properly unless the digitizing characteristics of the data acquisition system and the response function of the CTD are known and corrections applied.

Although the influence of the sensor response upon the determination of the salinity has been recognized earlier (Gaul, 1968; Goulet and Culverhouse, 1972; Pingree, 1971), little, if any, attention has been paid to the influence of the electronic digitization process on data gathering. The main influence arises from the fact that (with most presently available systems) conductivity, temperature and pressure are measured sequentially and not simultaneously, which means that the variables are not measured at the same time. It is necessary to estimate the values of the three variables at the same time or position before calculating salinity. This estimation must include both correction due to sequential sampling and the correction due to the response time of the sensors. These corrections vary with the particular data acquisition system and sensor, and are important parameters in computing salinities from CTD field measurements. Failure to consider these effects will yield salinity profiles which are

excessively noisy and have unrealistic spikes in regions of high gradients, such as the thermocline.

## 2. Instrumental sampling and time constant corrections

We consider two data acquisition systems, the H-P 2010B used by the University of Washington on the R/V *Thomas G. Thompson* and the more often used Plessey 8114 digital data logger. These both sample four quantities sequentially. In the case of the H-P 2010B system, the order was pressure, temperature, conductivity, and a reference signal. For the Plessey system it is pressure, conductivity, temperature, and sound velocity. For discussion below, call the channels *A*, *B*, *C* and *D*.

The time the data acquisition system takes to scan its channels and return to the initial state is a function of the commutator switching time  $t_s$  (if the commutator is a stepping relay, the latch time  $t_l$  for the contact bounce to disappear must be added), the reset time  $t_r$ , the period count time  $t_p$  (time for sampling all the data channels), and the return time  $t_{ret}$  (time for the

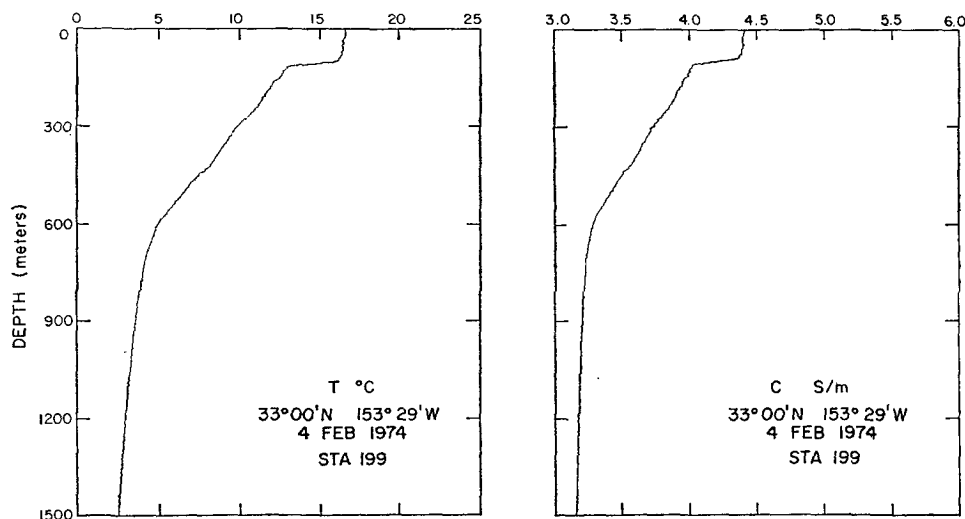


FIG. 1. Vertical profiles of temperature (left) and conductivity (right) obtained by a 9040 CTD and digitized by a H-P 2010B shipboard data acquisition system.

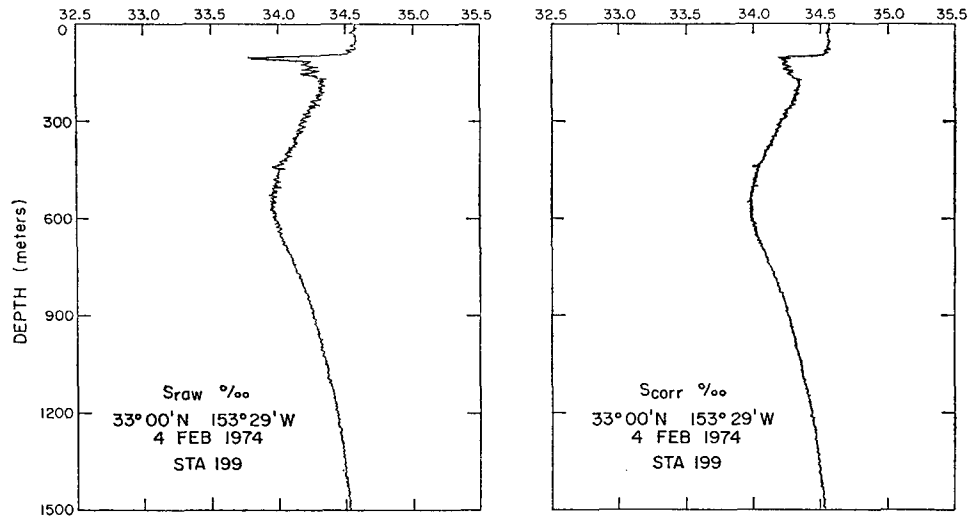


FIG. 2. Vertical profiles of salinity obtained by using the uncorrected pressure, temperature and conductivity profiles (left) and by applying linearized corrections for digitizing offset and CTD time constants (right).

commutator to go from the last required channel back to the first). The sample time  $t_p = N/f$ , where  $N$  is the frequency divider and  $f$  is the sensor frequency for the corresponding channel. The total scan time is then

$$\Delta s = \sum_j (t_{s,j} + t_{t,j} + t_{r,j}) + \sum_j \frac{N_j}{f_j} + t_{ret}, \quad (1)$$

where the summation index  $j$  is over each of the four variables  $A$ ,  $B$ ,  $C$  and  $D$ . With typical values for the CTD frequencies, the total scan time is about 1.5 s for the H-P 2010B system and 0.2 s for the Plessey system.

It is to be noted that the sampling interval  $\Delta t$ , which is the time between successive recorded scans, is equal to or greater than the total scan time  $\Delta s$ . For the

H-P 2010B system  $\Delta t = \Delta s$ , but for the Plessey system  $\Delta t$  is selected by a front panel switch. The data logger samples with the scan time  $\Delta s$ , but only records on tape the scans which occur at  $\Delta t$  intervals, not averaging but ignoring the intermediate scans.

To estimate the value of a measured variable between any two recorded values, we use a linear interpolation in time. To correct for the response time of the sensors, we apply a constant  $\tau_j$  (the time for the sensor output to come to  $1/e$  of the equilibrium state when a step function is applied). In a dynamic environment this approach is not entirely satisfactory. To calculate the response function of the sensor to an arbitrary excitation is difficult, however, and will not be attempted here.

If one interpolates the readings of channels  $A$  and  $B$  to the time of  $C$ , taking into account the sensor time

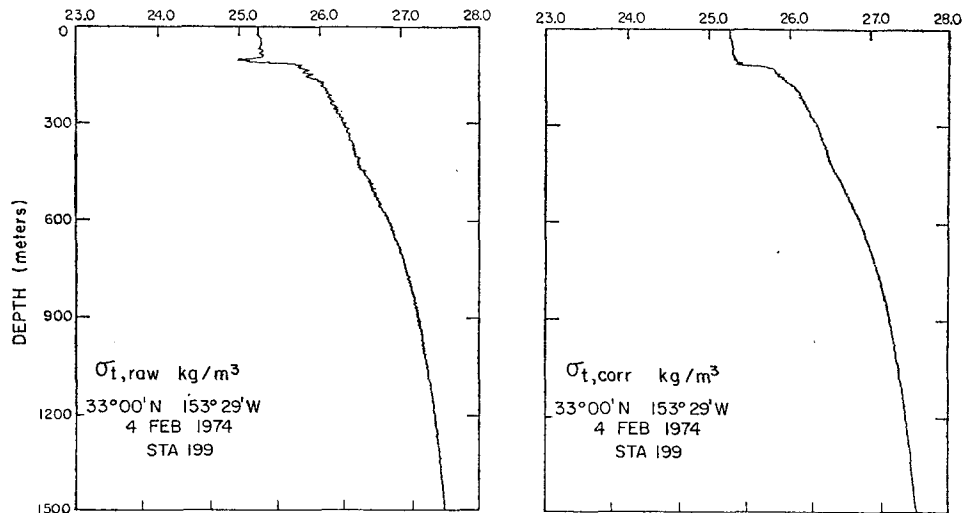


FIG. 3. Vertical profiles of sigma- $t$  corresponding to the salinity profiles in Fig. 2.

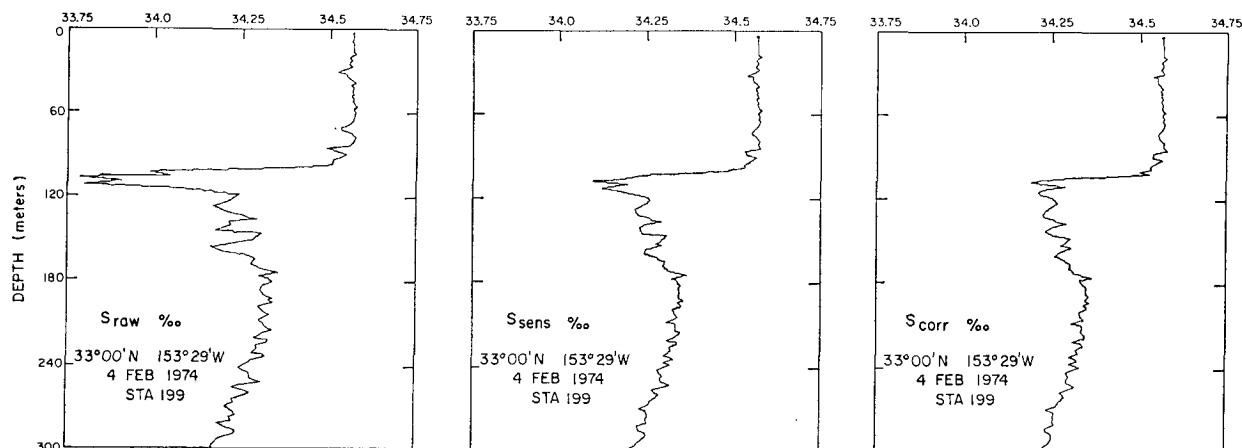


FIG. 4. Expanded profiles of salinity as shown in Fig. 2 (left and right). The center profile was obtained by applying only the CTD time constants and no digitizing offset corrections.

constants, one finds the value of the variable  $A$  at the time of  $C$  to be

$$A_c = A_i + \frac{A_{(i+1)} - A_i}{\Delta t} \times \left[ 2\alpha + \frac{N_A}{2f_A} + \frac{N_B}{f_B} + \frac{N_c}{2f_c} + \tau_A - \tau_C \right], \quad (2)$$

and the value of the variable  $B$  at the time of  $C$  to be

$$B_c = B_i + \frac{B_{(i+1)} - B_i}{\Delta t} \left[ \alpha + \frac{N_B}{2f_B} + \frac{N_c}{2f_c} + \tau_B - \tau_C \right], \quad (3)$$

where  $a = t_s + t_i + t_r$ .

It is seen that the corrections to the recorded values of  $A$  and  $B$  are proportional to the time gradients of these quantities. These values will be largest in the regions of the thermocline and when the CTD is being lowered rapidly. The terms in the brackets are the time-offset corrections due to the digitizer and the time constant mismatch of the sensors.

### 3. Determination of the salinity from digitized values of pressure, temperature and conductivity

We apply the above considerations to field measurements made aboard the R/V *Thomas G. Thompson* in the central North Pacific in January 1974. The shipboard H-P 2010B digitizing system has the measured time constants  $\alpha = 0.0697$  s,  $t_{rel} = 0.588$  s, and  $t_p$  (for reference signal) = 0.010 s. Assuming a flow rate of  $2 \text{ m s}^{-1}$  past the instrument in a vertical direction, the Plessey 9040 CTD has sensor time constants  $\tau_p = 0.040$  s,  $\tau_c = 0.038$  s, and  $\tau_t = 0.540$  s (National Oceanographic Instrumentation Center, 1973). Since our measurements were made at slower lowering rates ( $1\text{--}1.5 \text{ m s}^{-1}$ ),

we used larger time constants ( $\tau_p = 0.04$  s,  $\tau_c = 0.07$  s,  $\tau_t = 1.00$  s). Table 1 lists the time-offset correction factors for the digitizer and sensor response times for the interpolation of pressure and temperature to the time of conductivity. It should be noted that the temperature sensor time constant is much greater than either conductivity or pressure. Also note that the time constants are a function of the flow past the sensors, and at slower lowering rates the time constants become larger.

The measured profiles of temperature and conductivity are shown in Fig. 1. The profiles are smooth and show three layers: an upper mixed layer about 100 m thick, a region of sharp temperature and conductivity decrease around 100, and a deep layer, where these variables decrease more gradually with depth. The strong similarity between temperature and conductivity profiles is due to the strong temperature dependence of the conductivity.

The conversion of conductivity to salinity, using the CTD values, was based on the equations of Bradshaw and Schleicher (1965) and Cox *et al.* (1967), taking  $C(35,15,0)$  as  $4.2896 \text{ siemens m}^{-1}$ .

Two salinity-depth profiles for the central North Pacific are shown in Fig. 2, with the corresponding sigma- $t$  profiles shown in Fig. 3. The profile on the left is based on the uncorrected raw record and that on the right is based on the corrected values of temperature and pressure to the time of conductivity measurement and takes into account both the digitizing and sensor time constant corrections. The difference in the two profiles is quite apparent. In the left profile there is a large spike in the region of the thermocline and a considerable number of smaller spikes in the region below. In the right profile, the large spike is absent and the smaller spikes have been reduced considerably. Fig. 4 shows the two salinity profiles on an expanded scale. The center plot shows the salinity profile when only

the sensor time constant is considered. It is apparent that there is still about one-quarter of the peak remaining which is due to digitizer sampling. Thus it appears important to correct the raw data for the digitization and sensor time constants before computing salinity from conductivity, temperature and pressure.

A comparison of the H-P 2010B and the Plessey 8114 data acquisition systems is given in Table 1. In the Plessey system, the digitizing corrections are an order of magnitude smaller, but still important in the thermocline region. The Plessey system scans temperature after conductivity (the reverse of the H-P system), which tends to reduce the overall digitizing correction. In general, it is preferable to scan the sensors in an order which minimizes the corrections in Eqs. (2) and (3).

#### 4. Conclusions

It has been shown that to calculate the salinity from measurements of conductivity, temperature and pressure is not trivial and that one must consider the digitizing error of the data acquisition system and the response time of the sensors. When these are considered, even by the simple scheme outlined above, one obtains a substantial improvement in the profiles of salinity vs depth by the elimination of artificial spikes in the region of the thermocline. This becomes particularly important when calculating certain derived thermodynamic coefficients, such as stability, from CTD field measurements.

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