Bermuda Biological Station For Research, Inc.
Bermuda Atlantic Time-series Study

Chapter 3. CTD and Related Measurements

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1.0 Scope and field of application

This chapter describes an appropriate method for a Sea-Bird CTD. The CTD with additional sensors is used to measure continuous profiles of temperature, salinity, dissolved oxygen, beam attenuation and *in vivo* fluorescence.

2.0 Apparatus

The Sea-Bird CTD instrument package is mounted with either a 24 position General Oceanics Model 1016-24 smart rosette or a 24 position Sea-Bird Electronics model 32 rosette, either of which is equipped with 12 l Ocean Test Equipment bottles (O.T.E. bottles).

The basic system used to acquire CTD data is a Sea-Bird SBE-09 *plus* CTD, with an internal Digiquartz pressure sensor, a Sea-Bird SBE-03f temperature sensor, a Sea-Bird SBE-04 conductivity cell and a Sea-Bird SBE-05 pump. Additional sensors include the Sea-Bird SBE-13 dissolved oxygen sensor, the Sea-Tech transmissometer and the Chelsea fluorometer. Present configuration also includes a secondary temperature sensor, conductivity sensor and pump, which are connected independently from the primary units. The temperature and conductivity sensors are connected by a standard Sea-Bird "TC-duct" (clear, low viscous type) which ensures that the same parcel of water is sampled by both sensors, improving the accuracy of the computed salinity. The dissolved oxygen sensor is connected downstream from the conductivity cell and the flow rate through this sensor configuration is maintained at a steady rate by the inertia balanced SBE-05 pump. This pumped flow-through system introduces a slight warming of the water parcel as it passes trough the "TC-duct" due to viscous effects (Nordeen Larson, Sea-Bird Electronics, personal communication). The error in measured temperature is greatest in the deep water and is typically less than 0.003°C. A correction for this heating effect will be made available in the near future. The pressure sensor is insulated by standard Sea-Bird methods and consequently has minimal thermal errors in its signal.

2.1 *Pressure:* Sea-Bird model 410K-023 digiquartz pressure sensor with 12-bit A/D temperature compensation. Range: 0–7000 dbar. Depth resolution: 0.004% full scale. Response time: 0.001 s.

2.2 *Temperature:* SBE 3–02/F. Range: -5 to 35°C. Accuracy: ±0.003°C over a 6 month period. Resolution: 0.0003°C. Response time: 0.082 s at a drop rate of 0.5 m sec^{-1}.

2.3 *Conductivity:* (flow-through cell): SBE 4-02/0. Range: 0-7 Siemens m^{-1}. Accuracy ±0.003 S m^{-1} $year^{-1}$. Resolution: 5×10^{-5} S m^{-1}. Response time: 0.084 s at a 0.5 m s^{-1} drop rate with the pump.

2.4 *Pump:* SBE 5-02. Typical flow rate for the BBSR system is approximately 15 ml s^{-1}. (The pump is used to control the flow through the conductivity cell to match the response time to the temperature sensor. It is also used to pull water through the dissolved oxygen sensor.)

2.5 *Dissolved Oxygen:* (Flow-through cell): SBE 13-02 (Beckman polargraphic type) Range: 0-15 ml l^{-1}. Resolution: 0.01 ml l^{-1}. Response time: 2 seconds.

2.6 *Beam Transmission:* Sea Tech, 25 cm path-length. Light source wavelength = 670 nm. Depth range: 0–5000 m. eighth

2.7 *Fluorescence:* Chelsea-MkIII Aquatracka (Chlorophyll *a*) SN 88/2615/132. Sensitivity: 0.01 µg l^{-1} to 100 µg l^{-1} with an accuracy of +/- 0.01 µg l^{-1}. Excitation: 430 nm peak, 105 nm FWHM. Emission: 685 nm peak, 30 nm FWHM. Depth range: 0-6000 m.

The temperature sensor, conductivity cell and dissolved oxygen sensor are returned to Sea-Bird approximately twice a year for routine calibration. Pumps are returned to Sea-Bird once a year for routine diagnostic checks for RPM accuracy and pump head integrity. The pressure transducer is calibrated every 3 years and it is usual that this calibration is performed during complete CTD maintenance checks or upgrades at Sea-Bird.

3.0 Data Collection

The CTD is operated as per Sea-Bird's suggested methods. The CTD is powered up and allowed to stabilize at a depth of approximately 5 meters prior to profiling. This stabilization period is important for both the conductivity and dissolved oxygen sensors which have typical warm up times of one and five minutes respectively. Once stable the CTD is brought back to surface from which point the profile begins. The package is dropped at 30-60 m per minute for the first 200 m and then 45-60 m per minute from 200 meters down. The larger 24 position rosettes are found to give significant eddy wake problems which are most obvious in stratified regions. During high sea states these wakes can result in sections of the water column, as large as 4 m, being contaminated with entrained water. To help alleviate this mechanical problem, the CTD is always dropped at the maximum permitted speed. At present, BBSR is experimenting with mounting the secondary temperature and conductivity sensors away from the rosette package on the exoskeleton type frame. On discussion with Sea-Bird, some data processing steps were suggested to help reduce these bad data. However, at this stage no suitable algorithms other than the accepted velocity and acceleration filters have been developed. Ultimately, we believe this problem needs to be addressed as a package dynamics problem as opposed to a software filter routine. A offset exists between the down- and upcast profiles which is most likely an additional artifact of the package wake. The offset is greatest in the seasonal and permanent thermoclines where differences between the down- and upcast temperatures can be as large as 0.4°C. Since the sensors are mounted below the OTE bottles, we believe the error to be biased in the upcast data (Nordeen Larson, personal communication).

Water samples are collected on the upcast. Prior to closing each OTE bottle, the CTD is kept at the desired depth for a minimum of 90 seconds which ensures that the entrainment from the following wake has been removed. Analysis of the temperature and conductivity data at the time of the OTE bottle closure (following the wait period) shows good agreement with the downcast data. Once the water sample is taken the CTD immediately continues with the upcast at an ascent rate of 60 m per minute.

Except as noted, data are acquired using the Sea-Bird software "Seasoft" at the full scan rate of 24Hz. The data are stored directly on a PC-486. Immediately following the completion of the cast the data are backed up to a Pinnacle Micro PMO-650 magneto optical drive. During each cast a CTD log sheet is filled out (Figure 1). The ship's position is recorded directly from the DGPS. Relevant information such as weather conditions are added in the notes section.

The file naming convention used for BATS CTD data is as follows:

GF###C@@

Where:

is the cruise number (e.g. 108 for the one hundred and eighth BATS cruise)

@@ is the cast number on that cruise (e.g. 04 for the fourth cast)

The Sea-Bird software produces four files for each cast using the above BATS prefix convention. The four files are:

GF###C@@.DAT	Raw 24Hz data file, binary

GF###C@@.HDR	Header file, lat, long, time, etc.
GF###C@@.CON	Configuration file, containing instrument configuration and calibrations used by the software
GF###C@@.BL	Bottle file, a record of time and scan number range (1.5 seconds) when bottle is fired

Sea-Bird data acquisition and processing software are used during the cruise for preliminary observations of raw data. The programs are:

SEASAVE:	Display, recording and playback of data.
SEACON:	Entry of calibration coefficients and recording of the configuration.

4.0 Data Processing

Data processing is completed at BBSR and can be divided into two major stages: 1) CTD signal conversion and dynamic sensor correction; 2) static drift corrections and empirical field calibrations.

4.1 *Stage 1: CTD Signal Conversion and Dynamic Sensor Correction.* This stage is performed on an IBM PC using Sea-Bird "Seasoft" software and on a UNIX Sparc station using the Matlab (The Math Works, Inc., 21 Elliot Street South, Natick, MA 01760 USA) environment (see Figure 2 for programs and sequence of operations).

4.1.1 *Preliminary CTD Sensor Quality Check*: First, all CTD cast *.CON files are checked for correct sensor calibration coefficients using Seacon. The raw 24 Hz data are converted to engineering units using the most recent calibrations; it is then averaged to 2 Hz. Using Matlab the difference between primary and secondary temperature and conductivity sensors and computed salinity are computed for both the upcast and downcast. These differences are plotted and used to check individual sensors for drift, response and other obvious signs of sensor malfunction.

4.1.2 *Determination of Dynamic Coefficients*: The next step in CTD processing is the determination of the coefficients used in the Alignctd and Celltm Seasoft programs. The Alignctd program corrects for the different response times and physical alignment of the CTD sensors so that all sensors are measuring the same parcel of water. Pressure, temperature, conductivity, oxygen current and oxygen temperature data are converted to engineering units for the calibration cast (a single 400m profile without bottle fires) only. For the Alignctd coefficient determination, a series of files are created using Alignctd by varying the ratio of oxygen signal advancement from 2.0 to 8.0 seconds in 0.5 second increments. Next the parameters potential temperature and oxygen are computed using the Seasoft program Derive. A velocity filter (Loopedit) removes all scans when the CTD is moving less than 0.3 m s^{-1}. Finally, using Matlab, the sum, mean and the standard deviation of the difference between the downcast and the upcast oxygen profiles are computed for each file. The time advancement for the oxygen cast with the lowest sum and mean is then applied to all casts.

A similar procedure is used to calculate the coefficients used in Celltm, a program which corrects for thermal mass problems associated with the conductivity cell. Using the calibration cast, a series of files are created by varying alpha, the thermal anomaly amplitude from 0.02 to 0.06 and tau (1/ß), the thermal anomaly time constant, from 6.0 to 9.0. Next, using Derive, salinity is calculated for each file and the velocity filter (Loopedit) removes all scans when the CTD is moving less than 0.3 m s^{-1}. In Matlab the sum, mean and standard deviation of the difference between the downcast and the upcast salinity are computed for each file. The alpha and tau for the file with the lowest sum and mean difference are later applied to all casts.

4.1.3 *Stage 1 Final Processing*: Next the raw data are again converted to engineering units and the values of salinity and oxygen are computed. A 1.5 second average of the data is computed for each bottle fire. All CTD channels and voltage frequencies are converted to engineering units. All primary and secondary channels, plus the oxygen current and oxygen temperature, are run through a 21 point median filter. If a standard resolution pressure sensor is used then it is necessary to smooth the digitized pressure signal by application of a suitable filter. The oxygen channels have a large variance in their signals which is effectively reduced by applying a 21 point Gaussian filter. Additional channels used to measure beam attenuation and in vivo fluorescence are not passed through any filters. The dissolved oxygen is then aligned in time relative to pressure according to the advance in oxygen which best minimized the difference between down- and upcast oxygen in the coefficient determination step described previously. It should be noted that the SBE-11 *plus* deck unit is set to automatically advance primary conductivity 1.75 scans, but secondary conductivity must be advanced using the Alignctd program. The next step is to correct the conductivity cell for its thermal mass using the coefficient which best minimized the difference between down- and upcast salinity in the coefficient determination step described above. Once the dynamic corrections have been applied the salinity and the dissolved oxygen are computed. The data are then passed through a velocity filter. This filter excludes all scans for which either the pressure is not increasing or the descent rate is less than 0.3 m s^{-1}. Finally the data are averaged in 2Hz bins.

4.2 *Stage 2: Static Drift Corrections and Empirical Field Calibrations.* This stage of processing is done on a Sun Sparc station using the Matlab programming environment. It involves applying the static drift corrections and any empirical field calibrations to the dynamically corrected 2 Hz data ultimately yielding a final 2 dbar data stream (see Figure 3 for programs and sequence of operations).

4.2.1 *Temperature Corrections*: The Sea-Bird temperature sensors are found to have characteristic drift rates which are linear in time with a small or zero dependency on the temperature (for $2°C < T < 30°C$). For each cruise the calibration history is used to determine monthly drift rates which are applied to the most recent calibrations. The corrected temperature measurement T, is given by:

$$T = T_u + t(T_s T_u + T_o)$$

Where:

T_u = uncorrected *in situ* temperature (°C)

t = time from most recent calibration (months)

T_s = slope correction (month^{-1})

T_0 = offset correction (°C month^{-1})

4.2.2 *Pressure Corrections*: The Sea-Bird Digiquartz pressure sensor is found to have a characteristic linear drift with time which is typically less than 0.5 dbar per year. The drift is monitored on a 6 monthly basis under stable conditions at the dock. To determine the drift the CTD is allowed to stabilize for a about 3 hours. The drift, P_d (in dbar), from Seabird calibrations is determined by:

$$P_d = P_s - \frac{(P_a - P_{astd})}{10}$$

Where:

P_s = stable CTD pressure reading (dbar)

P_a = atmospheric air pressure (mbar)

P_{astd} = one standard atmosphere (1013.25 mbar)

4.2.3 *Conductivity Corrections*: The Sea-Bird conductivity sensors are found to have a drift rate which is a linear function of time and conductivity. For each cruise the calibration history is used to determine monthly drift rates which are applied to the most recent calibrations. The corrected conductivity measurement C_c, is given by:

$$C_c = C_u + t(C_s C_u + C_o)$$

Where:

C_u = uncorrected *in situ* conductivity(S m^{-1})

t = time from most recent calibration (months)

C_s = slope correction (/ month)

C_o = offset correction (S m^{-1} $month^{-1}$)

The conductivity cell is calibrated against samples taken from the OTE bottles during the upcast. Typically we have 36 samples ranging from 0-4200m. The discrete samples are measured for salinity on a Guildline 8400A autosal. The conductivity is back calculated from the salinity value and then matched to the corresponding in-situ conductivity reading. A 3s average prior to the OTE bottle closure is used for the in-situ value. These matched pairs from all casts for each particular cruise are grouped together to produce a single equation for the field correction. The deviation between the CTD and bottle value is modelled as a polynomial expression given by:

$$\Delta C = \sum_{i=0}^{n} a_i C_c^i$$

Where:

ΔC = Discrete conductivity - CTD

C_c = *in situ* conductivity (S m^{-1})

a_i = regression coefficients

The corrected continuous CTD conductivity (C) is then given by:

$$C = C_c + \Delta C$$

The order of the polynomial is modified to provide the best fit for the lowest order polynomial. The best fit is determined from the RMS value and a graphical examination of the residuals. The polynomial is usually linear or quadratic. The corrected conductivity and temperature are then used to calculate a calibrated salinity (PSS - 78). The residuals between CTD calculated salinity and bottle salinities are typically less than 0.0015.

4.2.4 *Oxygen Corrections*: There are 36 replicate discrete oxygen samples from 0-4200 m. These oxygen samples from the upcast are mapped to the downcast profile at the temperature of the OTE bottle closure. These matched pairs from all associated casts are grouped together to determine a single equation for the complete depth range. The measured bottle oxygen values are regressed against temperature, pressure, oxygen current, oxygen temperature and oxygen saturation such that the CTD oxygen is directly predicted by the following equation:

$$MO = 300\left(R_0 + \sum_{i=1}^{l} A_i\left(\frac{P}{4300}\right)^i + \sum_{i=1}^{m} B_i\left(\frac{OT}{30}\right)^i + \sum_{i=1}^{n} C_i\,(\mathrm{OC})^i + \sum_{i=1}^{o} D_i\left(\frac{OS}{300}\right)^i \right)$$

Where:

MO = model CTD oxygen

R_0 = linear offset

P = pressure (dbar)

OT = oxygen temperature (°C)

OC = oxygen sensor current (μA)

$OS\,(T,p,S)$ = oxygen saturation value at measured temperature, salinity and pressure (μmol kg^{-1})

A_i, B_i, C_i, D_i = regression coefficients

l, m, n, o = order of the polynomial functions ($l, m, n = 2$, $0 = 1$ or 2, depending on structure in upper ocean.

The order of each polynomial is determined by comparing successive fits until the correlation coefficients stabilize, and the residuals seem randomly distributed. The standard deviation of the residuals is typically less than 1.5 μmol kg^{-1}.

4.2.5 *Transmissometer Calibration*. The transmissometer shows frequent offsets in deep water which indicate variations in its performance. The theoretical clear water minimum beam attenuation coefficient is 0.364 (Bishop, 1986). We assume that the minimum beam 'C' value observed at the BATS site in the depth range 3000-4000 m is representative of a clear water minimum. We equate this minimum value with the theoretical minimum to determine an offset correction. The correction is given by:

$$\text{offset} = 0.364 - \text{BAC}_{\text{min}}$$

where BAC_{min}=minimum beam 'C' for 3000 m<depth<4000 m. This offset is applied to the entire profile.

The Sea Tech transmissometers used on these cruises have had a series of problems, some of them associated with component failures on the deeper casts. Other problems are associated with the temperature compensation unit in the transmissometer. These temperature related problems give rise to a variety of suspect behaviors: 1) high surface values (well beyond normal) that correlate with the time of day (highest at noon); 2) exponential decay within and below the mixed layer; 3) linear or exponential decays in the permanent thermocline; and 4) high cast to cast variability, even in deep water. As a result of these problems, some beam attenuation profiles are only good to certain depths. This depth is usually in the upper thermocline which does not allow us to compare the minimum in the profile with the theoretical clear water minimum. For these cases we choose a depth to which we believe the profile to be good and then compare this with the historical mean profile. The offset is then calculated at this depth and applied to that portion consider to be acceptable. The rest of the profile is designated as bad and set to -9.990. The ability to distinguish between genuine patterns and instrument problems can be difficult. The beam attenuation data should be considered qualitative and no attempt should be made to compare absolute numbers from one cruise to another.

4.2.6 *Fluorometer Calibration*: The fluorometer returns a voltage signal that is processed by the Seasoft software to a chlorophyll concentration. There is a standard instrument offset which is determined from the voltage reading on deck with the light sensor blocked off. Previous data reports have documented a field offset which is applied to the fluorometry data. We now believe this offset to be inappropriate and do not perform such a correction.

4.2.7 *Final Data Format*: Once all corrections have been applied the data are compared graphically against historical data envelopes. In particular, the modelled salinity and dissolved oxygen are plotted against potential temperature to ensure that no distortions to the profiles have been introduced as a result of the regression type modelling. The downcast data are then averaged in 2 dbar bins, ready for dissemination. A descriptive header containing relevant cast information is appended to the top of the 2dbar data.

5.0 References

Bishop, J. (1986). The correction and suspended particulate matter calibration of Sea Tech transmissometer. *Deep-Sea Research* **33**, 121-134.

Sea-Bird Electronics, Inc. CTD Data Acquisition Software manual.

Figure 1.1 CTD Log sheet 1

CTD LOG SHEET		
Cruise:	Leg:	Station:
Cast#:	Type:	Date:

CTD Status	Time (lt)	Lat (1)	Long (1)	System(1)	Lat (2)	Long (2)	System (2)
In water							
On deck							

Niskin #	Niskin Serial #	Unique bottle ID	Desired depth (m)	Actual Depth (m or mb)	Time tripped	Temp at bottle fire	Comments
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							

Figure 1.2 CTD Logsheet 2

CTD Model:

Operator:

SENSORS (tick)	SERIAL NUMBER	COMMENTS (offsets,performance,MLD,max,min...)
PRESSURE		
TEMPERATURE		
CONDUCTIVITY		
DISS. OXYGEN		
TRANSMISSOMETER		
FLUOROMETER		
ALTIMETER		
BOTTLES (type)		
OTHER		

Raw data filename:
Config. file:

Software version:
Averaging:

Computer(Zeos, Compaq):
Plots:

Backup name and medium:

Additional comments:

WEATHER AND SEA CONDITIONS

Wind spd:
Wind dir:
Gusts:

Seastate:
Swell:
Local wind waves:

Sun intensity:
Cloud cover:

AIR Temp:
Rainfall:

Met. & Sea Synopsis(fronts,HP,LP,storms...):

Figure 2. CTD Processing Stage 1

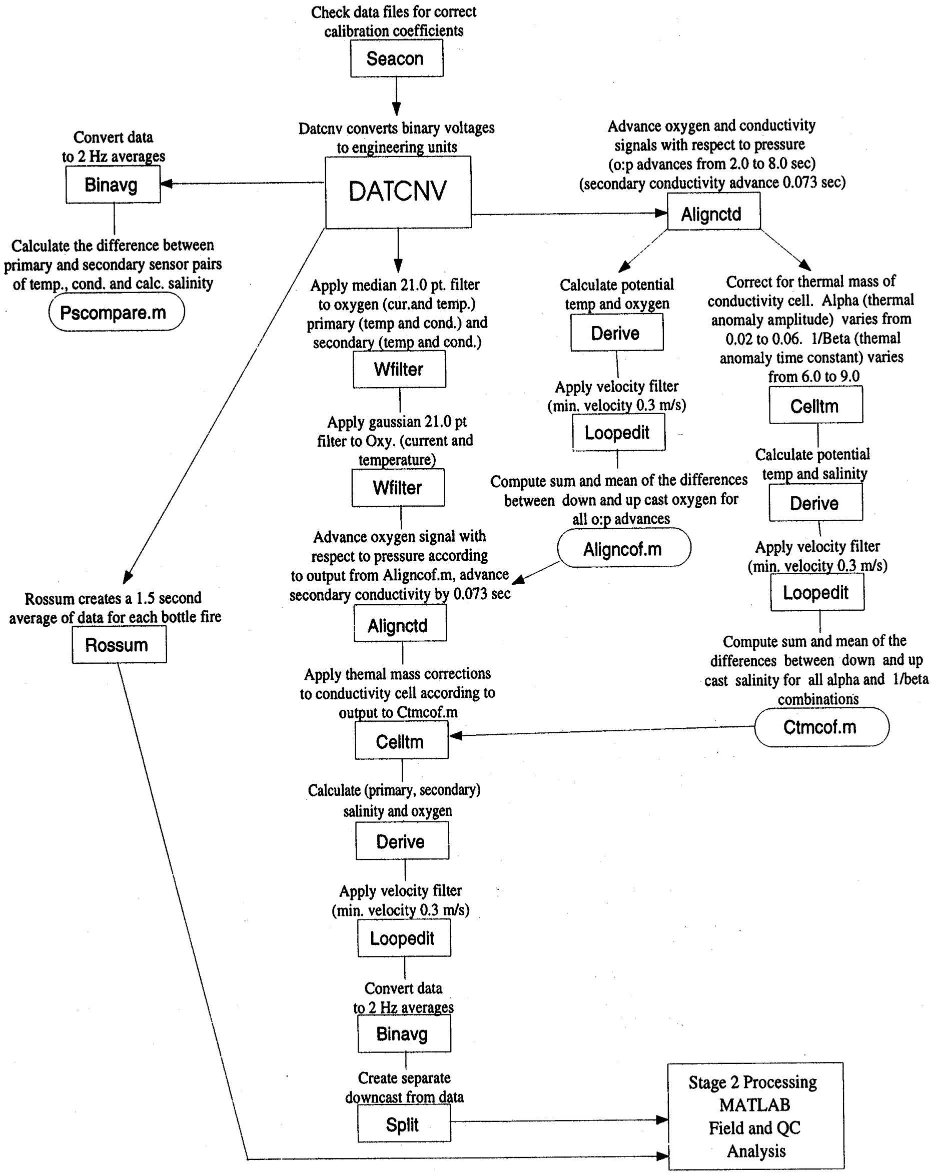

Figure 3.1 CTD Processing Stage 2

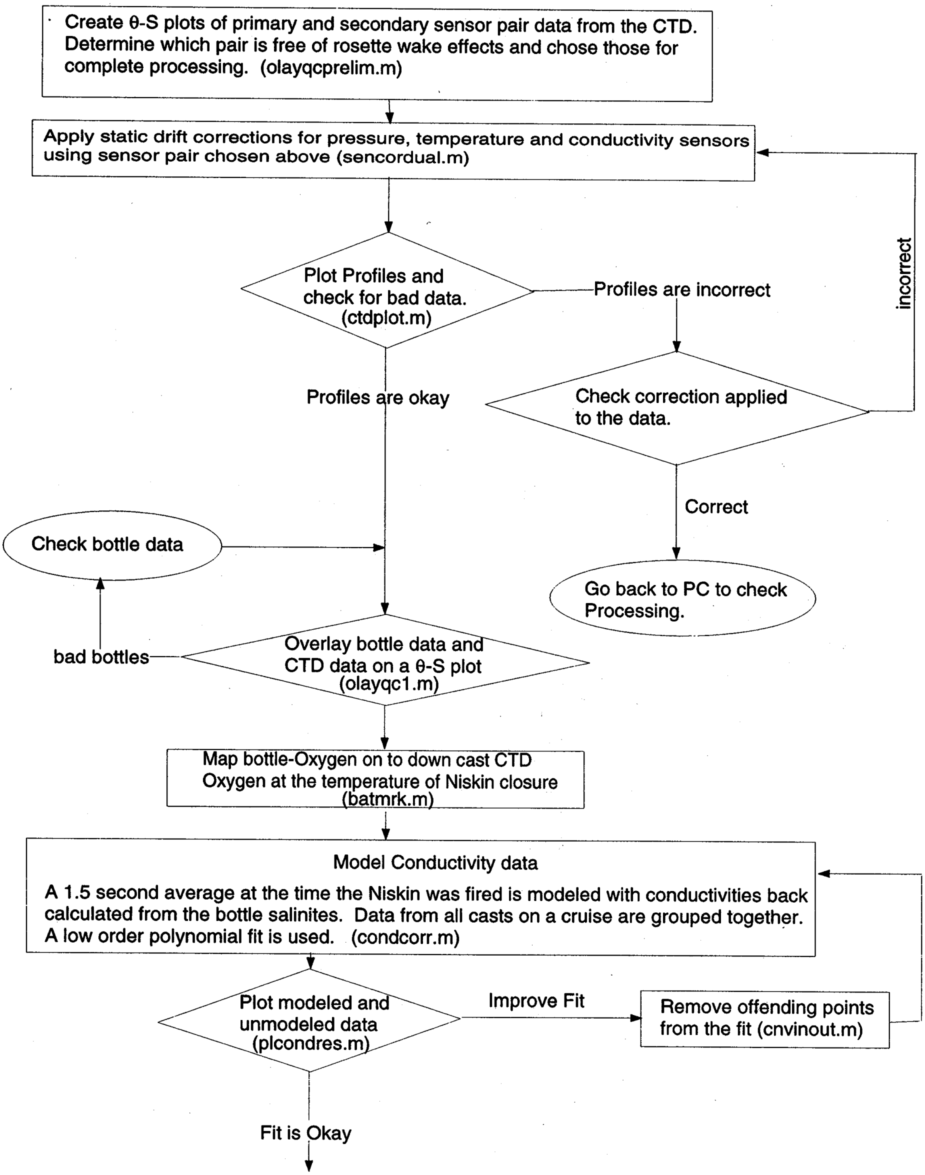

Figure 3.2 Continuation of Stage 2 Processing