HANDBOOK OF METHOD PROTOCOLS

Procedures on CTD Data Collection, Calibration and Processing

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1. Background

Central to the hydrographic observation and ocean dynamics is the measurement of the physical properties of seawater. Temperature (T) and salinity (S) are the most important parameters since, due to their conservative character, these parameters are used to identify the water masses, their evolution and mixing processes. Furthermore, a precise calculation of the density (ρ) from the Equation of State of Seawater $\rho=\rho(T , S , p)$, where p is the pressure field, is the basis for an accurate determination of the ocean dynamics; thus, under some assumptions, the density-driven ocean currents can be deduced from observations of temperature and salinity.

The most useful instrument for the measurement of the physical variables is the CTD (Conductivity-Temperature-Depth), meaning that the salinity is not directly measured but determined through a conductivity measurement (UNESCO, 1981a) and the CTD does not measure depth (distance from the sea surface) but employs a pressure measurement. Consequently, the depth is deduced by integration of the hydrostatic relation: $\delta z = g \rho \delta p$, where g is gravity and depth z increases downwards. A CTD typically returns temperature to an accuracy of 0.001 °C and salinity to 0.001. The lowest accuracy is actually in the depth since the pressure sensors are usually accurate to 0.01% of full range (e.g. typically sensors in the oceanographic range of 10,000 psia or 6,895 decibars return an accuracy of 0.7 - 1 m). However, since in ocean dynamics the pressure field is calculated from the hydrostatic equation, this reduces the uncertainty in the measurement of depth as a source for inaccuracy. Much care has gone into laboratory determination of density from T, S and pressure; the Equation of State of Seawater now allows to obtain the density to a fractional accuracy of $3\ 10^{-5}$ and an overall standard error of $3.6\ 10^{-3}$ kg m^{-3} (Millero and Poisson, 1981), i.e. comparable to field measurements of T, S and depth.

To obtain highly accurate measurements, several aspects of CTD calibration must be considered, in addition to accurate field procedures and algorithms for data reduction. The electrical sensors employed in CTD do not have a long-term stability, thus the calibration of the temperature, conductivity and pressure must be done at regular intervals to measure and document the drifts correcting data between calibrations. The description of the techniques for laboratory calibration against traceable transfer standards is out of the scope of this manual, since the required instruments are usually detained by the manufactures or national reference institutes, which maintain these instrument calibrated against primary standards. However, in order to combine observations throughout the cruise, the CTD calibration must be done just before and after the cruises. Additional calibration checks achieved at sea by means of independent measurements using digital reversing thermometers and bench salinometers are important to verify that the employed CTD didn't change the sensor's drift during the cruise; this is crucial for the conductivity sensor if, for example, the CTD has been accidentally lowered through oil stains at sea surface.

The focus of this manual is to provide a guidance on procedures and methods to be used for: (i) CTD casts on the basis of the extensive experience of the participants to large monitoring programmes (UNESCO, 1988; WOCE, 1994; Knap et al., 1996) and (ii) post-acquisition data processing (Fofonoff and Millard, 1991; Millard and Yang, 1993). The objective is to provide the cruise participants with some referenced guides in producing comparable CTD data, which, if combined with additional observations from multi-ship experiments and from many other such cruises, will allow a description of the world ocean as a whole.

2. Field sampling strategy and operational protocol

Commercially-available CTDs are usually mounted inside a frame (Rosette sampler) fitted with 12 or more Niskin bottles around it for collecting water samples that will be used for the calibration-checks of the CTD sensors, as well as for other bio-geochemical determinations at predetermined depths. Currently, the majority of the Institutes uses a Sea-Bird SBE 9 plus underwater unit, which, if connected to the SBE 11plus deck unit by a conducting cable, may give real-time, high-resolution profiles of temperature, conductivity and pressure with a sampling rate of 24 samples per second from which salinity and depth are calculated. The system formed by a Sea-Bird SBE 9 plus underwater unit connected to a SBE 11plus deck unit is reported as SBE 911plus.

Advanced CTD system-packages are usually equipped with double sensors of temperature and conductivity to guarantee no loss of data and to serve as calibration-checks. Additional sensors are included to detect dissolved oxygen, phytoplanktonic pigments fluorescence, transmissivity, light scattering, PAR (Photosynthetically Available Radiation), etc. A broad-beamed altimeter or bottom switch is recommended for safety reason in collecting samples near the bottom. The instrument package (CTD and rosette) is deployed by a single conductor armoured wire allowing the real-time data transmission to the deck unit, which decodes the serial data and passes it to a computer for display and archiving. Moreover, the conducting cable allows the CTD power, the data transmission and the telemetry to fire the bottles in areas of interest along the water column signaling also the closure of the Niskin bottles to the deck unit. Since the lowering of the system-package might create a noticeable disturbance on the oceanic temperature/conductivity structure, it strongly recommended to fit the CTD sensors below the Rosette to obtain an undisturbed CTD profile during the down-cast.

The following operational protocol is contingent upon an appropriate use of the sampling equipments (Artegiani, 1996), which must be well maintained during the cruise for CTD measurements and water samples collection.

1. When the CTD is on deck the instrument must be protected from the excessive heating to prevent the formation of salt crystals inside the electrode arrays and Niskin bottles. Pour fresh water over the instrument package after use and flush the T/C ducts with de-ionised water. Similar procedures should be adopted in cleaning the lens of the optical sensors. In the case of long inoperability, wrap a wet towel around the instrument and fill up the T/C ducts and the pumps with distilled water.

2. At the beginning of the cruise an initial CTD-rosette cast is performed firing the complete set of the Niskin bottles to test the CTD, the rosette pylon, the deck unit and the telemetry for data transmission. In addition, water samples are collected for salinity and dissolved oxygen determination. Both procedures are useful to test the correct sequence in closing the bottles as well as to provide a hands-on opportunity for the members of the scientific crew in samples collection. Make sure that the Niskin bottles are not leaking. This is done by open the tap without opening the air flux on the top of the bottle. CTD measurements and sample collections are based upon the concept that sampling techniques from Niskin bottles must be followed in a standardized and coordinated manner (for example, the samples for dissolved gases are drawn prior to the nutrients and salinity samples, etc.) supervised or conducted by experienced personnel.

3. Specific sampling information "metadata" are recorded on log sheet (see Annex 1) at the time of the CTD cast to identify: cruise, station, date and time, cast number, sample number and any other

pertinent metadata. The metadata along with copies of the CTD console illustrating the properties vs. depth are retained in the appropriate cruise notebook. Any problems associated with a particular sample are noted to be evaluated at the time of routinely quality control procedures.

4. At station, when the CTD is on deck, note the CTD pressure and temperature at atmospheric pressure (zero offset) on the log sheet (Annex 1). The CTD sensors must be lowered a few meters below the sea surface for few minutes monitoring the salinity and dissolved oxygen values to insure the thermal equilibration and sensor stabilization. Generally, when power is applied it takes up to three minutes for the sensor equilibration coming to a stable reading. It is recommended to leave the instrument at 10 m below the sea surface for safety reason (i.e. below the keel) facilitating the outflow of bubbles from the tubes connected with the pumped system. It is necessary to verify that the CTD pump starts, checking both the deck unit or software specific signal and the stabilization of temperature and salinity values (to avoid damages, the pump remains off until salty water is detected in the conductivity cell for at least 60 seconds; measured temperature and salinity exhibit large variations while the pump is not working, rapidly reduced as soon as the pump starts to work).

5. At beginning of the cast the instrument package is brought up close to the sea surface as possible (depending from the sea state), preventing that bubbles generated by the breaking wind waves enter T/C duct, and then the measurements start with the down-cast. In case air enters in the T/C duct and pump turns off, switch off power and repeat the previous point (lowering the instrument at 10 m and switching power on).

6. The objective of water column profiling is to obtain data for every dbar. Therefore, to minimize spiking of sensor outputs (i.e. those generated by the difference of time constant between the temperature and conductivity sensor) the CTD descent rate must be slower than 1 m/s. However, too small lowering speed may degrade the data and the reversal of the instrument speed by the ship's movement may introduce noise on the data. It is advisable to keep constant the lowering speed of 0.30 to 1 m/s (UNESCO, 1988). In consideration of the special solutions designed by Sea Bird, in particular the SBE 911plus pumped T/C duct to guarantee constant flushing of the conductivity cell, a lowering speed of 1 m/s should be adopted.

7. Lower the instrument package as close to the bottom as possible to get oxygen concentration in the benthic layer. Enter in the CTD station log (see in the Appendix 1) altimeter distance, CTD depth, sonic depth, and all other information listed on the log-sheet. It is good practice to include on the display the CTD depth to monitor continuously the instrument position while it come near the bottom.

8. CTD data must be recorded at the maximum rate available during both down and up casts as this may give better performance in filtering the data during the post-processing. In order to obtain an undisturbed CTD profile, rosette bottles should be fired during the up cast and only the down-cast is retained in the final CTD data-processing.

9. The first bottle to be fired near the bottom must be equipped with two digital platinum reversing thermometers (or one thermometer and one pressure meter). In this case, waiting for at least 15 seconds before firing the bottle to stabilize the thermometers to surrounding temperature.

10. During the up-cast the CTD/rosette is stopped at sampling depths and one or more bottles are closed at each level to collect water samples for calibration-checks of the conductivity and oxygen sensors. At each level, wait one minute before closing the first bottle for allowing stabilization of water around sensors and in the bottles. When the Niskin bottles are fired, an event mark is generated in the data files to record the time and CTD data. Nevertheless, it is recommended to include on the CTD station log (Appendix 1) the pressure, temperature and salinity values taken

from the display at the moment of firing the bottles. This data may result useful in the case when additional information is needed to ensure the correct bottle firing sequence in the case of failures.

11. When the CTD is back on the deck note on the station log the pressure and temperature. Any discrepancy with the pressure reading at the beginning is due to thermal and mechanical hysteresis of the pressure sensor. Do not use deck pressure readings as offset to correct pressure. The pressure readings should only be used as consistency check of historical drift against laboratory-calibrations.

12. Make a backup of the data immediately at the end of the cast, before carrying out any operation and note the cast file name on the station log.

13. Before samples are drawn from the Niskin bottle make sure that it is not leaking. Leakages should be noted on the station log. When all samples have been taken drain the remaining seawater and flush the CTD/Rosette system with fresh water.

3. CTD sensors calibration-checks

The conductivity, temperature and pressure sensors require accurate calibration in the laboratory, to insure that hydrographic measurements from different cruises and instruments can be combined into a single dataset. The standard practice for data quality is to obtain an overall accuracy and precision for temperature, salinity and depth as published in several documents (Joyce, 1991) and here reproduced :

T: accuracy of 0.002 °C; precision 0.0005°C (ITS90)
S: accuracy of 0.002 PSS-78; precision 0.001 PSS-78
P: accuracy 3 dbar; precision 0.5 dbar

Before proceeding, a verification that the most recent sensor calibration coefficients are in the configuration file of the data-acquisition program should be made at the beginning of the cruise. A CTD calibration data sheet must be prepared at that time with all the information for each sensor (i.e. S/N, date of the calibration, drift encountered, etc.). In addition, calibration checks (i.e. intercomparisons between the primary and secondary sensors as well as the CTD data against independent measurements) are required to map sensor drift that may occur between stations during the cruise.

3.1 Pressure calibration-check

CTD pressure is measured with a 6,000 dbar Paroscientific Digiquartz pressure transducer internally compensated for temperature. Pressure calibration-check for the offset is conducted routinely on deck before the deployment. When the CTD is on deck turn on the deck unit and note the CTD pressure on the log book. The pressure reading in air at sea surface should be a negative value between 0.0 and –0.6 dbar. If not, adjustment should be made once at the beginning of the cruise by running the Sea-Bird SEASOFT software and correcting the calibration parameters to achieve a value in this range. However, if the offset value exceeds ± 1.5, the sensor should be serviced. The pressure output and any changes to the offset value are recorded on the station log (Appendix 1).
The calibration-check of the pressure sensor to full oceanic depth may profitably be conducted by digital reversing pressure meter throughout the water column. The new generation of SIS digital reversing pressure meters could be used for *in situ* calibration-checks since they have now read out to 0.1 dbar and the accuracy specification is 0.1 % of full scale. The measure is corrected from the

air pressure since this latter is set as null reference when the pressure meter is switched to sample mode on deck.
The standard practice is to include at least one electronic pressure meter for checking purposes on the first Niskin bottle that will be usually fired near the bottom. At each pressure the reversing pressure meter is allowed to equilibrate for few minutes before firing the bottles and the pressure delivered by the CTD sensor will be notify on the log sheet.

3.2 Temperature calibration-check

The temperature given by the International Temperature Scale of 1999 (ITS-90) is at present the best approximation to the thermodynamic temperature (T) expressed in Kelvin. The ITS-90 replaced the earlier International Practical Temperature Scale of 1968 (IPTS-68) (Saunders et al., 1991) and it is common practice to define the temperature according to the Celsius scale t (°C) and with t = T-273.15. However, since all the algorithms for calculating physical properties of seawater have been developed using the IPTS-68, the following linear transformation t68 = 1.00024 t90 is used for conversion between IPTS-68 and ITS-90.
A check on the temperature sensors is maintained by intercomparing CTD-recorded temperatures with the readings of at least two digital reversing platinum thermometers.

3.3 Conductivity calibration-check

The conductivity cell is calibrated by comparing CTD-recorded conductivities with conductivities obtained from discrete water samples. Because conductivity is difficult to measure in absolute unit, the standard practice is the measurement of the conductivity ratio by means of bench salinometer standardized against Standard Seawater. The salinity is calculated according to the Practical Salinity Scale of 1978 (UNESCO, 1981a) from the conductivity ratio and salinometer bath temperature. Since the CTD conductivity sensor is to be calibrated, the salinity from sample bottle is inverted to *in situ* conductivity (i.e. using the CTD pressure and temperature from mark file in correspondence of fired bottle)

Salinity samples are collected from the Niskin bottles into a 250 ml polyethylene bottles with plastic insert in the cap to form a better seal, which will be rinsed three times before filling and stored at room temperature near the shipboard salinometer. The time between sample collection and analysis is generally within 1 day or less. If the analyses are performed subsequently at shore-based laboratory, 120 ml Boston Round flint glass bottles with plastic screw caps equipped with Poly-Seal cones must be used to prevent leakage and evaporation (Stalcup, 1991). The integrity of the sample with glass bottles has been tested up to six months.

Prior to analysis, the salinity samples are equilibrated to laboratory temperature and are analysed on a Guidline Portasal Salinometer model 8410A (shipboard salinometer) or Autosal 8400B (shore-laboratory salinometer), standardised against IAPSO standard seawaters of P series (35 PSU) or H series (38 PSU), this latter more suitable for Mediterranean conditions. The shipboard salinometer with a thermostatic bath may reach an accuracy better than 0.003 equivalent PSU. Typically 100 ml (including flushing volume) are required for three replicate analyses from the same water sample; higher accuracy of 0.001 in salinity are possible when special care is taken in water samples collection and the measurements are made in a temperature controlled laboratory.
The remaining sample from the previous use is left in the bottles to prevent the formation of salt crystals due to the evaporation. When tacking a new sample, discard the hold water; the bottle and the cap must be rinsed three times with water from the new sample. If the bottles are inoperative from long time (i.e. 1-6 months) the bottles are rinsed with deionised water and then rinsed five times with copious amounts of samples before filling (Knap et al., 1996).

Given the framework of the CTD measurements in the Mediterranean Sea, at least three samples must be collected per cast taking into account the presence of three main water masses: i.e. the AW, the LIW and the MDW both in the west and in the east. Thus to describe any non-linearity of the sensors, the water samples for conductivity check must be chosen one in correspondence of salinity minimum (in the mixed layer), one for the salinity maximum (LIW layer) and in the deep layers to get the best possible salinity profile. Deep water samples (> 3000 m) are duplicated.

4. CTD Post-processing

The post-acquisition CTD data processing requires the data to be submitted to quality control through the following stages (Millar and Yang, 1993):

- convert raw CTD scans into scaled physical units by applying pre-cruise CTD sensor calibration coefficients against traceable transfer standards;
- filter various channels according to specific criteria;
- apply sensor or specific response correction models;
- final CTD data editing and processing to an uniform pressure intervals.

Once the CTD data are corrected by deck determined pressure offset, temperature and conductivity calibration coefficients are applied, they are subject to screening and quality control.
First check is for spikes and missing values generated by electrical interference on the conducting cable. Spikes are automatically checked with a 9-point median filter and wrong data are interpolated. A second step is to eliminate manually failures (obviously erroneous data) by visual inspection. The third step is to check density inversions that can be induced in high-gradient ship-generated vertical motion of the rosette. After this initial screening, the data are averaged over ½ second intervals (i.e. 12 bin average). This processing in the time-domain is required to minimize the effect of the existing lag between the C and T sensor responses.
The corrections derived from calibration checks as above described are applied to the temperature, conductivity and dissolved oxygen. The data are pressure-sorted to remove the effects of ship-roll (i.e. keeping only data when the CTD is moving downwards) and finally averaged over 1 dbar interval.

Considering the SBE 911 plus system, the following specific procedure can be applied using the Sea Bird SEASOFT:

- the eventual corrections are applied to the calibration file and the raw data are converted into scaled physical units (DATCNV program); converted data include pressure, temperature, conductivity, dissolved oxygen (SBE 43 sensor recommended), fluorescence, turbidity, light transmission, pH, PAR, SPAR, CPAR, etc.
- low-pass filter pressure to increase pressure resolution for loop editing (due to wave motion) if needed, and low-pass filter temperature and conductivity to smooth high frequency data (FILTER program)
- advance conductivity, temperature, and oxygen relative to pressure, to align parameters in time (ALIGN CTD program); normally, primary conductivity and temperature should not need time shifting if the deck unit is specifically programmed (with SBE 11 V2 deck unit, also secondary temperature and salinity should not need advance), and dissolved oxygen advance varies from 2 seconds at 25 ºC to approximately 5 seconds at 0 ºC
- mark a data value with badflag to eliminate eventual wild points (WILDEDIT program)
- perform conductivity cell thermal mass correction (CELL THERMAL MASS program)

- if needed, mark scans where CTD is moving less than minimum velocity or traveling backwards due to ship roll (LOOP EDIT program)
- compute salinity, density, oxygen from oxygen signal (SBE 43) and other parameters (DERIVE program)
- average data into 1 dbar bin, corresponding to about 1 m (BIN AVERAGE program)
- plot the data and verify presence of spikes, density inversions and other anomalies, in particular check the difference between primary and secondary temperature and conductivity; in case, adopt specific actions

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ANNEX 1

CTD STATION LOG

Ship____________________ Station Name____________ Date____________________ Operator________________
Cruise____________________ Station N.______________ File Name_______________

POSITION	Latitude	Longitude	Time (GMT)	Sonic Depth
Start				
Bottom				
End				

Secchi Disk______________
S.S.T.__________________

CTD OFFSET CONTROL	On Deck Press.	On Deck Temp.
Before Lower		
After Lower		

BOTTOM

Altimeter	
CTD Depth	
Sonic Depth	

WATER SAMPLES		CTD RAW DATA (Deck Unit)			Salinity Samples	Therm. N.	Temp.	Comments
Btl. N.	Btl. Depth	Press.	Temp.	Salinity				