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Uncertainty evaluation of *CTD* measurements: a metrological approach to water-column coastal parameters in the Gulf of La Spezia area

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***Abstract* – The ENEA Marine Environment Research Centre S. Teresa has been involved since the '70s in monitoring, analysis and comprehension of physical, chemical and biological processes in marine environment. The purpose of this work is to describe the recently-implemented metrological approach aimed to evaluate the uncertainty associated with measurement results obtained by a *Conductivity-Temperature-Depth* profiler (*CTD*), deployed during routine coastal campaigns in the Eastern Ligurian Sea, close to the Gulf of La Spezia area. Main effort of this work is focused on applying the standard framework necessary to correctly assess the measurement uncertainty for each involved parameter. To this aim, an appropriate uncertainty evaluation is performed by combining type A and B contributions, evaluated from experimental data measured in reproducibility conditions and from calibration certificates periodically supplied by manufacturer, respectively.**

I. INTRODUCTION

The monitoring of chemical-physical parameters in coastal and marine areas is the prerequisite to achieve a Good Environmental Status (GES) [1] and a sustainable and integrated management of environmental resources, in line with both the objectives defined by the Marine Strategy Framework Directive in Europe [2] and the guidelines of IOC (Intergovernmental Oceanographic Commission) in a global perspective [3-4]. Sea monitoring is especially essential in a climate change context: the analysis of long term physical and chemical time series is the first step to support forecast models studying climate changes.

To achieve this goal and study medium and long-term variability of marine ecosystems, it is imperative to evaluate the uncertainty associated with measurements performed in sea context in order to assess their reliability; in this sense, a systematic metrological approach to marine measurements would be advantageous to develop a common database on which the marine observing system can be based. Actually, such approach needs a constant and effective cooperation between all different involved actors, such as oceanographers, metrologists and instrument producers, each of them owning specific expertise to be shared.

Purpose of this work is the description of the metrological approach, recently implemented at the ENEA Marine Environment Research Centre of S. Teresa, aimed to evaluate the uncertainty associated with measurement results obtained by a well-known *Conductivity-Temperature-Depth* profiler [5] (in the following indicated as *CTD*, where the quantity *Depth* is derived from the measured *Pressure*), deployed during routine coastal campaigns in the Eastern Ligurian Sea, close to the Gulf of La Spezia area (Fig. 1).

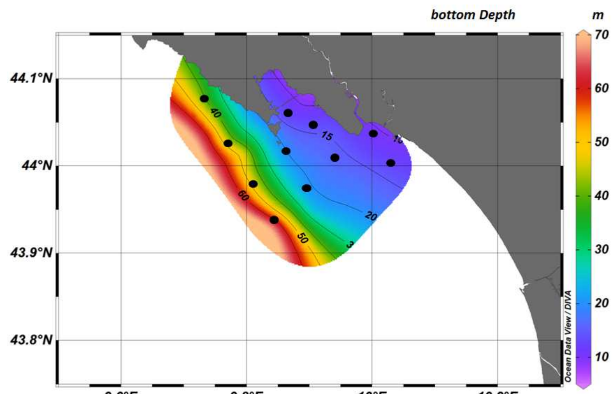

Fig. 1. Region of interest: bathymetry (m) and typical measurement stations where CTD is deployed.

The monitored zone starts at the exit of La Spezia harbour and ranges from coastal areas under the influence of Magra river up to areas more assimilable to open sea, for an overall surface of about 400 km^2. Black dots in Fig. 1 indicate typical measurement stations where *CTD* profiler is deployed in order to perform a rapid, high-resolution vertical sampling on the water column, down to about 65 m water depth. Some views of both the probe and the experimental activity in field are shown in Fig. 2.

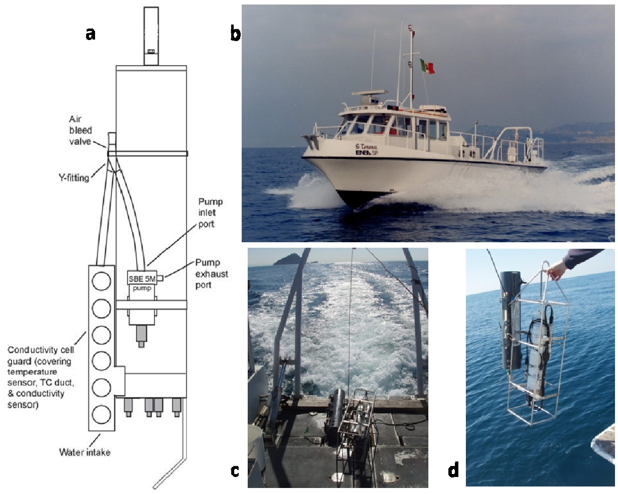

*Fig. 2. **a**) Schematic view of the CTD probe. **b**)ENEA 12-m boat for coastal monitoring campaigns. **c**) CTD probe mounted in parallel with a GoFlo bottle, during the transfer from one measurement station to another. **d**) CTD and GoFlo bottle just before the deployment.*

In this work particular attention is paid to post-processing of acquired data, i.e. the assessment of data reliability by evaluating their combined standard uncertainty. As described in the following, main effort is in fact focused on applying the standard framework necessary to correctly assess the measurement uncertainty for each involved parameter: to this aim, a typical table is compiled as a summary of the standard uncertainy components. Type A and B contributions are evaluated from experimental data measured in reproducibility conditions and from calibration certificates periodically supplied by the manufacturer, respectively. They are listed in the table together with the corresponding sensitivity coefficients. The combined standard uncertainty is then supplied together with the relevant degrees of freedom, so that a corresponding expanded uncertainty can be determined encompassing a large fraction of the distribution of values reasonably attributable to the measurand.

II. *CTD* PROFILER: MAIN FEATURES

A *CTD* probe is a well-known, widespread and reliable multi-parameter instrument used to measure water-column quantities. Starting from the basic measurement of *Conductivity* (*C*), *Temperature* (*T*) and *Pressure* (*p*), to which *Depth* (*d*) is related, it allows the determination of derived quantities like *Salinity*, *Density* and *Sound Velocity*.

All these quantities, usually reported as profiles versus *d*, are of fundamental interest for oceanographers, forming the basis to study, interpret and modelling the interleaving and mixing processes along the water-column [5].

In the following, just a brief overview of the main features of the considered *CTD* is given, referring to proper huge literature [6-10] for a more detailed description of each instrument forming the multi-parameter probe:

- manufacturer: Sea-Bird Electronics (SBE)
- model: SBE *19plus* SeaCAT Profiler
- maximum deployment depth: 350 m
- sampling rate of *p*, *T* and *C* measures: 4 Hz
- lowering speed from the ship: about 0.35 m/s.

The *CTD* uses three independent channels to digitize *p*, *T* and *C* concurrently: each channel converts the corresponding input analog signal into an output digital signal following a proper calibration curve already memorized in the signal-conditioning unit installed on-board. Moreover, *CTD* is equipped with a proper *TC*-duct and pump that provide a constant flow rate through both the sensors (regardless of descent rate) in order to ensure that the measurement of *T* and *C* are made on the same parcel of water (so reducing spikes due to the fact that *T* and *C* sensors are physically separated and characterized by different time responses).

Main metrological features of *p*, *T* and *C* sensors can be summarized as in Table 1 (where f.s. indicates the full range scale of the instrument output).

Table 1. Main metrological features of sensors included in a CTD probe. Abbreviations indicate respectively: M.R. = measurement range, I. A. = initial accuracy, S. M. = stability per month, Res. = resolution.

Features	**Quantities**		
	p	*T*	*C*
Type	Micro-machined semiconductor strain gauge	Ultra-stable aged thermistor	Electrode cell sensor
M.R.	(0 to 350) dbar	(-5 to +35) °C	(0 to 90) mS/cm
I. A.	0.1 % f.s.	0.005 °C	0.005 mS/cm
S. M.	0.004 % f.s.	0.0002 °C	0.003 mS/cm
Res.	0.002 % f.s.	0.0001 °C	0.001 mS/cm

Profiles of *T* and *C* versus *d*, measured at each station while *CTD* is descending, are firstly managed in accordance with the well-consolidated procedures of processing and quality control indicated by specific standards for analysis and validation of oceanographic data [11-13]. Quantities *p*, *T* and *C* here considered vary typically in the following ranges: (0-65) dbar, (12-28) °C and (20-60) mS/cm, respectively. Processed data are then characterized in terms of their uncertainty in accordance with the current international metrological standard for the expression of uncertainty in measurement [14]: analysis is synthesized in the following Section.

III. EVALUATION OF THE UNCERTAINTY ASSOCIATED WITH *CTD* MESUREMENTS

The standard uncertainty for $p(d)$, T and C quantities has been evaluated by compiling a standard table where evidence is given to each uncertainty contribution, as prescribed by [14]. Analysis takes into account in a proper way the uncertainty contributions both declared (and periodically verified) by the manufacturer and those measured on the field in repeatability conditions (with *CTD* profiler maintained at fixed depths for about 25 s for each measurement acquisition).

Compiled tables for each involved quantity are reported in Section V (Tables 2-4).

Symbols used in tables have the following meaning:

- X_i : i-th independent input quantity
- x_i : estimate of the i-th input quantity
- SD: standard deviation
- u_A: type A standard uncertainty, i.e. estimated standard deviation evaluated from the statistical distribution of a series of measurement results
- u_B: type B standard uncertainty, i.e. approximation to the standard deviation of an assumed (a-priori) probability distribution, evaluated from calibration certificate results, experience or other information (in the present analysis, uniform distributions were typically assigned to those input quantities varying within ranges declared by the certificates)
- ν_i: degrees of freedom (DOF) of input quantities (the value of 100 DOF is used when the quality of the information is considered "very funded"). If equal to infinity, the information has been obtained by datasheet or calibration certificate and consequently considered as very reliable
- $u^2(x_i)$: estimated variance associated with input estimate x_i that estimates input quantity X_i
- c_i: sensitivity coefficients obtained from the mathematical model relating the output quantity to the input quantities
- $c^2_i \cdot u^2(x_i)$: contribution to the output variance associated with the i-th input quantity
- $u^4_i(y)/\nu_i$: i-th contribution in the Welch-Satterthwaite formula, used to estimate the actual DOF of the output quantity y
- $u^2_c(y)$: combined variance of the output quantity y
- $u_c(y)$: combined standard uncertainty of the output quantity y
- coverage factor k, calculated by the Student's t-distribution on the basis of both the chosen confidence level and the actual DOF
- expanded uncertainty $U(y)$: calculated as the product between k and $u_c(y)$.

In the following, some specific considerations are developed for each involved quantity.

A. Pressure

With reference to Table 2, the total pressure p_{tot} measured by the *CTD* pressure sensor is by default corrected for the barometric offset p_{atm} of 14.7 psi (corresponding to about 1015 hPa); the correction is performed automatically by the *CTD* signal conditioning unit and should be verified by comparing the default value with the actual barometric value at sea level before deployment. In the evaluation of the uncertainty of p, the correctness of this offset has been verified by comparison with the historical atmospheric pressure mean p_{atm} acquired by the Vaisala-type analog barometer (mod. PTB101B) at ENEA S. Teresa Centre at an altitude of 49.5 m during the last 13 years (and normalized to sea level pressure by well-known formula [15]). The mean value of p_{atm} is (1015 ± 7) hPa, being reasonably comparable with the default value implemented by SBE in the *CTD* unit. Further contributions to uncertainty connected to Vaisala barometer in measuring p_{atm} have been considered in Table 2. The combined standard uncertainty of p (where $p = p_{tot} - p_{atm}$) has been evaluated as equal to 0.24 dbar, the major contribution being the calibration effect.

B. Depth derived from Pressure

The correct expression to calculate d as a function of p include some further terms [4], as follows:

$$d = f(p, Lat, \Psi, \Phi^0) \quad (1)$$

where Lat, Ψ and Φ^0 are respectively the Latitude of the measuring station (deg), the dynamic height anomaly (m^2 s^{-2}) and the geopotential (m^2 s^{-2}) both referred to zero sea pressure. Relationship (1) can be simplified by ignoring the two terms Ψ and Φ^0: this approximation leads to a determination of d values affected by a relative standard uncertainty of about 0.1 %, as declared by [4].

The simplified formula here adopted to calculate d from p is the one reported in [9] and [12], valid for an ocean water column at 0 °C and 35 PSU: ENEA data here reported (typically sampled at about 38 PSU and with higher values of T) have been verified to follow these conditions, belonging to the so-called "oceanographic funnel", as calculated by proper expression in [4]. Therefore, expression (1) can be simplified as follows:

$$d \approx f(p, Lat) = \alpha \cdot p \quad (2)$$

where $\alpha \approx 0.992$ m/dbar is a correction factor determined by EOS-80 expression [12] where the Latitude value has been calculated at the centre of the typical ENEA sampling area (about 44.01°N).

In conclusion, taking into account the uncertainties of both p and α, typical values of relative combined standard uncertainties for p and d are reported in the diagram in Fig. 3. It can be noted that relative standard uncertainty of d is less than 1 % for depth greater than about 30 m.

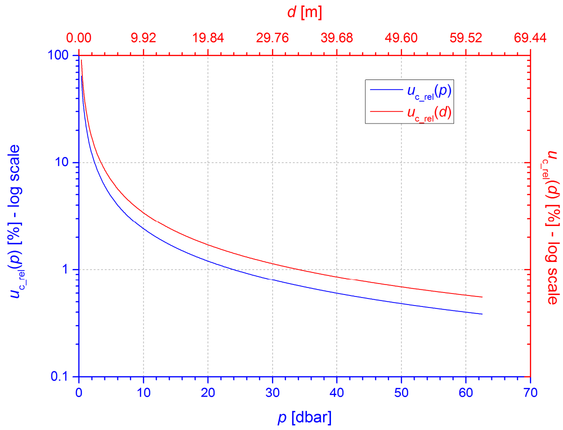

Fig. 3. Values of relative combined standard uncertainty for Pressure and Depth.

C. Temperature and Conductivity

Values of *T* and *C* are direct output of *CTD* probe. Combined standard uncertainty evaluated in Table 3 and 4 in Section V leads, respectively for *T* and *C*, to values equal to 0.023 °C and 0.032 mS/cm. In Figures 4 and 5 typical profiles for *T* and *C* are shown, taking into account uncertainties on both axis.

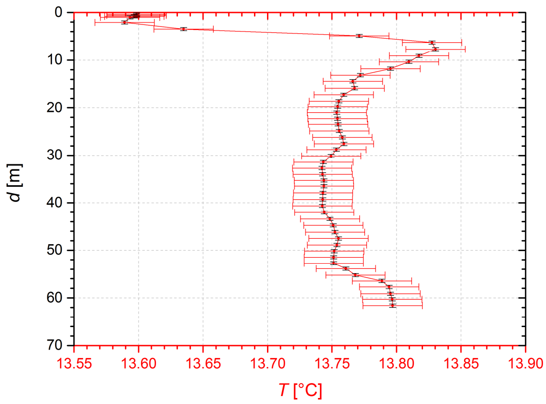

Fig. 4. Values of combined standard uncertainty in a typical Temperature-Depth profile (date of acquisition: 10th of March, 2016. Position: 9.847 °E, 43.935°N).

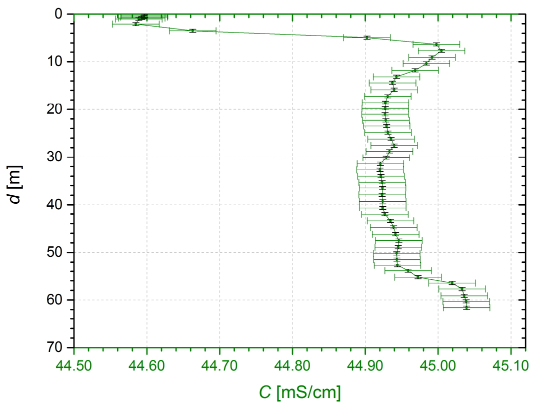

Fig. 5. Values of combined standard uncertainty in a typical Conductivity-Depth profile (date of acquisition: *10th of March, 2016. Position: 9.847 °E, 43.935°N).*

IV. EXAMPLE OF APPLICATION: TEMPERATURE COMPARISON OF MODEL DATA VS EXPERIMENTAL DATA

Uncertainty evaluation described in Section III allows the construction of a reliable experimental database to which model data can be compared in order to validate dedicated forecast systems.

As an example of a possible application, daily mean model data of temperature profiles are compared with ENEA S.Teresa experimental data acquired by *CTD* close to the Gulf of La Spezia, during a monitoring campaign performed on the 10th of March 2016.

Model data have the following features [16]:

- model: Copernicus Mediterranean Forecasting System
- identifier: MEDSEA_ANALYSIS_FORECAST_PHYS 006 001
- horizontal grid resolution: 1/16° (about 5 km and 7 km for Longitude and Latitude, respectively)
- depths: 72 unevenly spaced levels.

Uncertainty assessment allows to compare model data vs experimental data both qualitatively and quantitatively, as shown in Fig. 6.

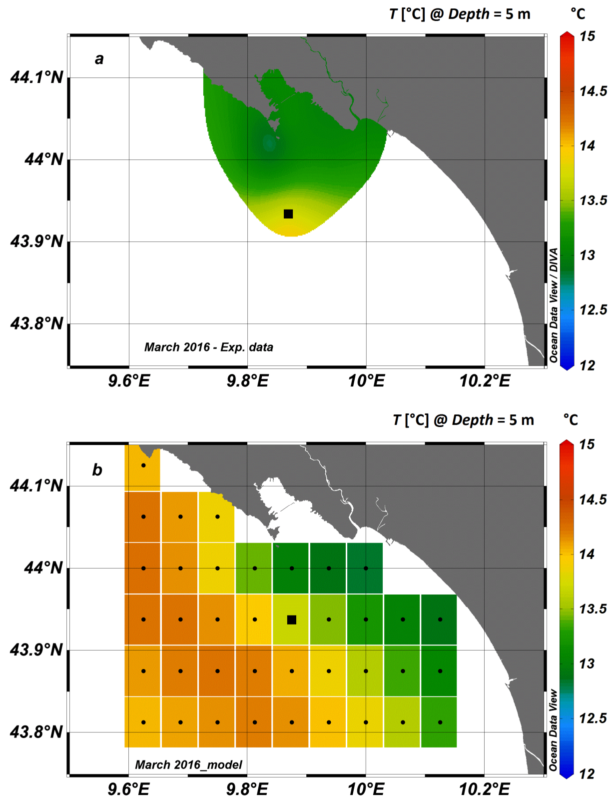

Fig. 6. Temperature data of water column at a depth of 5 m on the 10th of March, 2016. ***a****) Experimental data plotted in a continuous gridded field.* ***b****) Model data discretized at the spatial resolution of 1/16°. The square dot indicates respectively a downcast station where CTD has been deployed and the corresponding, nearest point in the model grid.*

Model data show in fact a trend that is confirmed by experimental data, that is to say a generalized warming ranging from the coast towards opens sea. Moreover, both measures can now be effectively compared in terms of absolute values: at 5 m depth, *CTD* profiler measured a value of *T* equal to (13.786 ± 0.023) °C, while model data provided a measure of (13.68 ± 0.50) °C (temperature accuracy for model data is indicated in [17]). It can be concluded that, in this specific case, model data are reasonably comparable with experimental data. A further validation can be drawn if a larger model database is compared with experimental *CTD* data: as an example, considering again the 5 m depth and experimental measures in the period from March 2015 to March 2016, the mean difference obtained between model data and *CTD* data is equal to (-0.14 ± 0.48) °C, reasonably comparable with the value, reported in literature [17], of (-0.06 ± 0.50) °C in the layer (0-10) m.

V. TABLES FOR UNCERTAINTY ASSESSMENT

Tables for uncertainty assessment associated with the involved quantities are reported in the following.

Blue asterisk indicates the calibration contribution to uncertainty due to calibration curve whose coefficients are directly memorized in the *CTD* unit; these coefficients are properly verified or renewed by means of periodic metrological tests performed at the manufacturer laboratory.

Table 2. Uncertainty evaluation for p measurement.

Underwater pressure p [dbar]	Standard uncertainty components for input quantities X_i				u_A	u_B	ν_i	$u^2(x_i)$	$c_i = \partial f/\partial x_i$	$u^2_i(p)=c^2_i \cdot u^2(x_i)$	$u^4_i(p)/\nu_i$
	X_i	type	source	standard uncertainty estimated by	dbar	dbar		dbar²		dbar²	dbar⁴
$p = f(X_i) = f(p_{tot}, p_{atm})$ $p = p_{tot} - p_{atm}$	p_{tot}	calibration	manufacturer's specifications*	range of variability (0.1 %FSR):		0.202	∞	4.1E-02	1	4.1E-02	1.7E-05
		stability	manufacturer's specifications	range of variability (0.004%FSR per month):		0.097	∞	9.4E-03	1	9.4E-03	8.9E-07
		resolution	manufacturer's specifications	range of variability (0.002%FSR):		0.004	∞	1.6E-05	1	1.6E-05	2.7E-12
		repeatability	repeated observations	SD (CTD fixed at various depth for about 25 s):	0.050		100	2.5E-03	1	2.5E-03	6.3E-08
	*verified by periodical calibration checks at manufacturer's calibration laboratories (once a year)										
	p_{atm}	linearity	manufacturer's specifications	SD, in the range [0 °C,+40 °C]:	0.007		∞	4.6E-05	-1	4.6E-05	2.1E-11
		hysteresis	manufacturer's specifications	SD, in the range [0 °C,+40 °C]:	0.001		∞	5.6E-07	-1	5.6E-07	3.2E-15
		repeatability	manufacturer's specifications	SD, in the range [0 °C,+40 °C]:	0.001		∞	5.6E-07	-1	5.6E-07	3.2E-15
		calibration	manufacturer's specifications	SD, in the range [0 °C,+40 °C]:	0.002		∞	5.1E-06	-1	5.1E-06	2.6E-13
		stability	manufacturer's specifications	range of variability (0.001 dbar per year):		0.007	∞	5.2E-05	-1	5.2E-05	2.7E-11
		resolution	manufacturer's specifications	range of variability (0.001 dbar):		0.001	∞	3.3E-07	-1	3.3E-07	1.1E-15
		reproducibility	repeated observations	SD of very long time series of data:	0.075		657362	5.6E-03	-1	5.6E-03	4.8E-11
									$u^2_c(p)$ [dbar²]	5.8E-02	
									$u_c(p)$ [dbar] and actual DOF	**0.24**	194
									coverage probability *prob*		0.95
									coverage factor $k = t$ (*prob*, DOF)		1.972
									expanded uncertainty $U(p)$ [dbar]		**0.48**

Table 3. Uncertainty evaluation for T measurement.

Water temperature T [°C]	Standard uncertainty components for input quantities X_i				u_A	u_B	ν_i	$u^2(x_i)$	$c_i = \partial f/\partial x_i$	$u^2_i(T)=c^2_i \cdot u^2(x_i)$	$u^4_i(T)/\nu_i$
	X_i	type	source	standard uncertainty estimated by	°C	°C		°C²		°C²	°C⁴
direct measurement T	T	calibration	manufacturer's specifications*	range of variability (0.005 °C):		0.0029	∞	8.3E-06	1	8.3E-06	6.9E-13
		stability	manufacturer's specifications	range of variability (0.0002 °C per month):		0.0014	∞	1.9E-06	1	1.9E-06	3.7E-14
		resolution	manufacturer's specifications	range of variability (0.0001 °C):		0.0001	∞	3.3E-09	1	3.3E-09	1.1E-19
		repeatability	repeated observations	SD (CTD fixed at various depth for about 25 s):	0.023		100	5.3E-04	1	5.3E-04	2.8E-09
	*verified by periodical calibration checks at manufacturer's calibration laboratories (once a year)										
									$u^2_c(T)$ [°C²]	5.4E-04	
									$u_c(T)$ [°C] and actual DOF	**0.023**	104
									coverage probability *prob*		0.95
									coverage factor $k = t$ (*prob*, DOF)		1.983
									expanded uncertainty $U(T)$ [°C]		**0.046**

Table 4. Uncertainty evaluation for C measurement.

Water Conductivity C [mS/cm]	Standard uncertainty components for input quantities X_i				u_A	u_B	ν_i	$u^2(x_i)$	$c_i = \partial f/\partial x_i$	$u^2_i(C)=c^2_i \cdot u^2(x_i)$	$u^4_i(C)/\nu_i$
	X_i	type	source	standard uncertainty estimated by	mS/cm	mS/cm		(mS/cm)²		(mS/cm)²	(mS/cm)⁴
direct measurement C	C	calibration	manufacturer's specifications*	range of variability (0.005 mS/cm):		0.0029	∞	8.3E-06	1	8.3E-06	6.9E-13
		stability	manufacturer's specifications	range of variability (0.003 mS/cm per month):		0.0208	∞	4.3E-04	1	4.3E-04	1.9E-09
		resolution	manufacturer's specifications	range of variability (0.001 mS/cm):		0.0006	∞	3.3E-07	1	3.3E-07	1.1E-15
		repeatability	repeated observations	SD (CTD fixed at various depth for about 25 s):	0.0247		100	6.1E-04	1	6.1E-04	3.7E-09
	*verified by periodical calibration checks at manufacturer's calibration laboratories (once a year)										
									$u^2_c(C)$ [(mS/cm)²]	1.1E-03	
									$u_c(C)$ [mS/cm] and actual DOF	**0.032**	198
									coverage probability *prob*		0.95
									coverage factor $k = t$ (*prob*, DOF)		1.972
									expanded uncertainty U(C) [mS/cm]		**0.064**

VI. CONCLUSIONS

Main results achieved by this work are underlined in the following list:

1. a more detailed knowledge of the nature of both measurand and measurement process for what concerns the direct measurement of *p*, *T* and *C* profiles performed by *CTD* in the specific coastal zone of the Gulf of La Spezia. At the moment, these parameters can be measured with combined standard uncertainties of 0.24 dbar, 0.023 °C and 0.032 mS/cm in typical ranges of 0-65 dbar, 12-28 °C and 20-60 mS/cm, respectively;

2. *CTD* measures acquired and managed at ENEA Centre of S. Teresa, supplied by proper standard uncertainty bars, can now be used to draw metrological-founded conclusions about sea conditions in the coastal zone of interest (i.e. Empirical Orthogonal Functions analysis aimed to optimize the sampling campaigns, or data comparison with forecast algorithms as a support tool to calibrate/validate models);

3. the realization of a well-consolidated framework for uncertainty evaluation, directly extensible to other relevant quantities derived by *CTD* measures (i.e. *Salinity* and *Density*) or measured by dedicated probes mounted together with *CTD* (i.e. *Dissolved Oxygen* concentration, *Turbidity* or *Chlorophyll-a*): uncertainty analysis of these quantities will be the subject of future works, taking into account at the same time the calibration capabilities already available at the ENEA Centre of S. Teresa in terms of internal reference standards (e.g. for *Dissolved Oxygen* concentration).

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