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The absolute salinity of seawater and its measurands

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12 Abstract:

13 Salinity is an essential quantity to calculate many of physical properties of oceans, but it is
14 also a quantity hardly definable considering the complexity of this material in its bio-geo-
15 chemical composition and the imperfections of the existing measurement techniques. The
16 TEOS-10 gives several definitions to the notion of absolute salinity, usable in function of the
17 properties to study, but they are based on the concept of a constant elemental composition of
18 seawater, so that, if its major inorganic components are well known, its real composition
19 varies in time and space and its determination is still a challenge.

20 Most of salinity calculations are based on conductivity measurements. This publication
21 reviews other techniques which are used or could be used to assess the absolute salinity of
22 seawater, and question about the measurand of these techniques and the possibility to redefine
23 the concept of salinity from physical properties.

25 **Keywords:** Seawater, Salinity, Conductivity, Density, Refractive index, Speed of sound

27 Introduction

28 In June 2009, the 25th Assembly of the International Oceanographic Commission adopted the
29 description of the thermodynamic properties of seawater and of ice I_h , to replace the document
30 EOS-80 (Equation of State of Seawater of 1980) [1] as the official description of seawater and
31 ice properties in marine science. These properties are described in the document entitled the
32 Thermodynamic Equation Of SeaWater – 2010, or TEOS-10 [2].

33 So that the EOS-80 was based on the concept of practical salinity S_p , the TEOS-10 is based on
34 the concept of Absolute salinity S_A . The practical salinity rests on the measurement of
35 conductivity ratio, temperature and pressure of seawater samples, and also, on the using of
36 empirical equations [1]. All the salinities stored in oceanographic databases are practical
37 salinities, and to keep the compatibility between the requirements of the TEOS-10 and the
38 databases contains, a concept of Reference salinity S_R has been defined. This Reference
39 salinity allows also the correction of bias between the definition of the practical salinity at 35
40 and a Reference-Composition Salinity (RCS) defined by Millero in 2008 [3], and the amount
41 of this correction is not negligible: $0.165\ 04\ \text{g kg}^{-1}$.

42 In order to approach the concept of Absolute salinity defined as the mass fraction of dissolved
43 material in seawater, a salinity anomaly δS_A is added to the calculated S_R . δS_A can be
44 determined by vibrating tube densimeter measurements and the inversion of the TEOS-10
45 equation for density to determine S_A . Before using the densimeter, seawater samples are
46 filtrated with a $0.2\ \mu\text{m}$ filter to eliminate suspended particles and, according to Millero and
47 Pierrot [4], a material is defined as dissolved if it passes through a $0.2\ \mu\text{m}$ filter. The practical

48 salinity of the sample being known, δS_A can be deducted. This method has been used in 2012
49 by McDougall *et al.* [5] to establish an algorithm based on the observed correlation between
50 $S_A - S_R$, and the silicate concentration of seawater samples, the silicate concentration being
51 estimated by interpolation of a global atlas.

52 Nowadays, the determination of S_A is therefore dependent on the RCS which can evolve in
53 time according to the variations of the atmospheric CO_2 and its absorption by the oceans, and
54 of two different measurement techniques: the conductivity cells associated with the Practical
55 Salinity Scale of 1978 (PSS-78) formulation and the vibrating tube densimeter. That shows
56 that it is not so easy to define the measurand when defining the salinity. That's as much true
57 that the oceanic medium is chemically very complex as it will be shown below.

58 In the last years, advances have been realized in the adjustment of refractive index techniques
59 [6], [7], [8], [9], [10] or speed of sound measurements [11] to assess *in situ* salinity. These
60 developments press on to question again about the definition of the absolute salinity
61 measurand in the meaning developed in the International Vocabulary of Metrology (VIM) 2nd
62 edition: 'particular quantity subject to measurement'. The goal of this paper is to lead the way
63 to a new definition of the concept of absolute salinity, in accordance to the VIM 3rd edition
64 (JCGM 200:2012), where it is written: 'the specification of a measurand requires knowledge
65 of the kind of quantity, ..., body or substance carrying the quantity, including any relevant
66 component, and the chemical entities involved'.

68 **1 – The actual definitions of the absolute salinity and the real composition of seawater**

69 **1.1 – The actual definition of the absolute salinity**

70 Natural seawater is a complex material because oceans are sources of life and they are in
71 chemical and physical interaction between the seabed and the atmosphere. Their salinity is a
72 quantity recognized as a key climatological observable, object of a metrological challenge for
73 measurements [12]. Until the approval of the TEOS-10 by the oceanographic community, it
74 was largely admitted that the salinity of seawater can be defined by the mass fraction of its
75 principal ionic constituents.

76 This ionic mass fraction has been assessed during several years by the notion of chlorinity.
77 The chlorinity Cl was defined as the mass (in g) of halogens contained in a kilogram of
78 seawater, the bromide and iodide ions being replaced by their equivalents in chloride. Its
79 measure was made in laboratories on discrete samples of seawater. Actually it is defined as
80 0.3285234 times the ratio of the mass of pure silver required to precipitate all dissolved
81 chloride, bromide and iodide in a sample of seawater to the mass of this sample [3].

82 With the perfecting of conductivity sensors in the '70s, it was possible to measure, *in situ*, a
83 quantity which variations are proportional to chlorinity at constant temperature and pressure,
84 and to obtain continue salinity profiles thanks to the calculation of a conductivity ratio and to
85 the formulas of the PSS-78. But, seawater conductivity is strongly dependent on temperature

86 and pressure. An increase of temperature leads a decrease of the density of seawater and then
87 a decrease in the number of ions per unit volumes and a decrease of the viscosity. Ions have
88 then a higher mobility and the measured conductivity increases. At constant temperature, a
89 pressure increase leads an increase of the volumetric concentration of ions. It improves also
90 the dissociation of solutes and the conductivity increases in measurable proportions.
91 Temperature and pressure change the stoichiometric composition of seawater but not its
92 elemental composition.

93 As conductivity is strongly dependent on the effects of temperature and pressure on the ions
94 concentrations, it is a good proxy of the entropy, the free energy and the enthalpy of the
95 seawater. For example, a supply of solute modifies the free energy of the water according to
96 the temperature of the middle. It increases also the entropy of the system.

97 But, according to Woosley *et al.* [13], trace and minor components of seawater such as
98 nutrients or inorganic carbon affect the evaluation of these properties. Conductivity
99 measurements don't take into account the effects of the non-ionic components, and the non-
100 ionic components have an effect on the density. Density variations are to the origin of the
101 thermohaline circulation and they are of a great importance in oceans numerical models. It is
102 why, the TEOS-10 manual defines (page 11) the notion of 'Density-salinity' or S_A^{dens} which is
103 the best estimate of S_A because it is measurable and traceable to the SI [14], and the notion of
104 salinity anomaly δS_A .

105 This manual tries also to define the notion of 'dissolved material' which is in the definition of
106 S_A , and it takes the example of the CO_2 dissolution. This dissolution in water produces
107 amounts of CO_2 , H_2CO_3 , HCO_3^- , CO_3^{2-} , H^+ , OH^- and H_2O according to the sensitivity of
108 dissociation constants to temperature, pressure and pH. That leads to define a 'Solution
109 Absolute Salinity' or S_A^{soln} as 'the mass fraction of dissolved non- H_2O material after a
110 seawater sample is brought to a constant temperature of 25 °C and a pressure of 101 325 Pa'.
111 This non- H_2O material includes non-ionic components. If their concentrations can be assessed
112 by laboratory measurements on discrete samples, no method exist to measure them *in situ*.

113 Other cases can be met where the composition of the seawater differs of the Reference-
114 Composition defined by Millero [3]. For example, discharges of rivers or hydrothermal vents
115 into the ocean lead to define an 'Added-Mass Salinity' or S_A^{add} at a temperature of 25 °C and a
116 normal pressure.

117 Salinity is used also to trace seawater masses and to model ocean dynamics. This traceability
118 can be obtained by excluding the effects of the biogeochemical processes on S_A^{dens} , S_A^{soln} or
119 S_A^{add} to calculate a 'Preformed Absolute Salinity' called S^* . These four definitions and
120 approach of the salinity are equivalent to S_R , only for samples of standard seawater. When the
121 composition differs, a salinity anomaly δS_A must be calculated with the McDougall *et al.*
122 algorithm [5]. In order to form this algorithm, measurements of the density of 811 seawater
123 samples from most of the major basins of the world ocean, so that measurements of their
124 practical salinity, were made. Thereafter, using the samples reference salinities, reference
125 densities from the TEOS-10 equations were calculated and compared to the measured

10

126 densities. The difference $\delta\rho = \rho_{mes} - \rho(S_R, 25\text{ }^\circ\text{C}, 0\text{ dbar})$ was used to estimate $\delta S_A = S_A^{dens} - S_R$
 127 [3] knowing the empirical value of the partial derivative of density with respect to S_A :

$$128 \quad \left. \frac{\partial \rho}{\partial S_A} \right|_{t=25^\circ\text{C}, p=0\text{dbar}} \approx 0.7519 \quad \text{kg m}^{-3}/\text{g kg}^{-1} \quad (1)$$

129 Among various components of seawater (total alkalinity, total carbon dioxide or nitrates),
 130 silicate concentrations are best correlated with δS_A . According to McDougall *et al.* [5], that
 131 can be explained because it is correlated with the other variables responsible for errors in
 132 using S_p to determine S_A . It accounts for about 60 % of the variations of the above species and
 133 it has no significant effect on conductivity while it has a direct effect on density.

134 Since the density of seawater is rarely measured, a fit was then realized between $\text{Si}(\text{OH})_4$
 135 concentrations and δS_A for the world oceans (with a standard error of 0.0054 g kg^{-1}) and for
 136 the different basins to estimate δS_A from measurements of $\text{Si}(\text{OH})_4$ concentrations and to
 137 obtain values of $S_A(S_p, \phi, \lambda, p)$ where ϕ is the latitude, λ the longitude and p the sea pressure.
 138 But, this assessment method rests on a simple correlation, and a relatively small number of
 139 samples compared to the ocean's volume. Formulas to calculate δS_A are independent of
 140 spatial-temporal evolutions, so that silicates were used during a long time as tracers of water
 141 masses, and they are not appropriate to coastal areas, to the proximity of hydrothermal vent or
 142 to polar countries.

143 δS_A can be estimated also from measurements of nitrate and silicate concentrations, and the
 144 differences between the Total Alkalinity (*TA*) and Dissolved Inorganic Carbon (*DIC*) of the
 145 sample, and the best estimate of *TA* and *DIC* in standard seawater (expressed in mol kg^{-1}). To
 146 retrieve S_A^{dens} that gives:

$$147 \quad \delta S_A = (50.7 \times \Delta[\text{Si}(\text{OH})_4] + 38.9 \times \Delta[\text{NO}_3^-] + 4.7 \times (\text{DIC} - 2.080 \times S_p/35) + 55.6 \times (\text{TA} - \\ 148 \quad 2.300 \times S_p/35)) / \text{mmol kg}^{-1} \quad (2)$$

149 According to Wright *et al.* [15], the standard uncertainty of the model fit is 0.08 mg kg^{-1} over
 150 the oceanic range, if all quantities are known precisely, and according to McDougall *et al.* [5],
 151 the difference between the two methods is less than 0.005 g kg^{-1} .

152 These methods using S_p are based on conductance measurements. Conductance depends on
 153 the seawater conductivity, but also on the geometry of the measurement cell, on the frequency
 154 of the applied signal and on the polarization effects at the electrode-solution interface,
 155 according to Pawlowics *et al.* [16]. Polarization effects arise as ions accumulate near the
 156 electrodes, inducing an extra capacitance and this phenomenon can't be neglected at the
 157 uncertainty level required in S_p calculations. S_p calculation is based on conductivity ratio, but,
 158 because of polarization effects, Pawlowics *et al.* [16] underline that the ratio of two measured
 159 conductances of two solutions differing in conductivity or composition is not necessarily
 160 equivalent to the ratio of their conductivities. As much to say, for seawater conductance
 161 measurements, the measurand is not only the seawater conductivity but it should include
 162 polarization effects also.

163 The TEOS-10 definitions of S_A rest on the concept of a Reference-Composition Salinity
164 (RCS). This RCS is based on the concept of constant mass ratio of the major inorganic
165 components of seawater, but the exact composition is not known in detail [3]. If changes in
166 the carbonate system or in the concentration of silicates, CaCO_3 , CO_2 or nutrients occur, they
167 must be taken into account in δS_A , but it is not always possible to assess their values
168 completely. Furthermore, in polar countries, the sea ice cover contains concentrated brines
169 which are the site of *in situ* chemical and biological reactions [17]. Measurements made by
170 Butler *et al.* [17] have shown substantial divergence of S_P from S_A at very low temperatures,
171 creating inaccuracies and errors in the calculation of physical sea ice parameters, when S_P is
172 assumed to be equivalent to S_A . To model their observations they refined an S_P - T relationship
173 for sea ice brine to -22.8 °C.

174 **1.2 – Some other components of the complete composition**

175 Considering difficulties in conductivity measurements, the concept of RCS excludes a given
176 number of components which concentrations are highly variable according to ocean places
177 and depths. Among these components there are the dissolved organic materials, which
178 concentration is assessed by CDOM (Colored Dissolved Organic Matter) measurements. The
179 CDOM is defined as one part of the organic matters which absorbs the light in the ultra-violet
180 and the blue parts of the spectrum and passes through a $0.2 \mu\text{m}$ filter according to Bricaud *et al.*
181 [18] and Kirk [19]. Therefore, according to Millero and Pierrot [4] it can be considered as
182 dissolved material. It comes from the degradation of the organic matter in coastal waters and
183 from the photosynthetic activity of macro-alga according to Carder *et al.* [20] or Hulatt *et al.*
184 [21]. It comes also from interactions between microbes, bacteria and phytoplankton [22], [23],
185 present in seawater. It is composed essentially of humic and fulvic acids, but its composition
186 is variable and stays relatively unknown. At the surface, the sun light breaks the big molecules
187 and the smaller are suppressed by microbes according to Miller and Moran [24]. The CDOM
188 can be found in all the oceans but with different concentrations. Organelli *et al.* [25] have
189 shown recently that, for example, the Black Sea was characterized by very high CDOM
190 contents, that the subtropical gyres (Atlantic and Pacific Oceans) have optical properties
191 consistent with previous bio-optical models and that high latitude (North Atlantic and
192 Southern oceans) and temperate (Mediterranean Sea) seas have optical properties which
193 depart from existing bio-optical models. The North Atlantic subpolar gyre, observed in
194 wintertime, shows also high CDOM concentrations according to them.

195 CDOM plays an important role in the carbon cycle according to Blough and Del Vecchio
196 [26]. Consequently, it modifies the stoichiometric and elemental composition of the seawater
197 and its salinity. In 2011, Pawlowicz, Wright and Millero [27] have tried to assess the effect of
198 these biogeochemical processes on oceanic salinity or density relations by mathematical
199 analysis, the use of different salinity variables and haline contraction coefficients. This work
200 has led the definition of S_* which represents, according to them, ‘the Standard Seawater
201 component of a real seawater to which biogeochemical processes add material’. But, in 2016
202 Pawlowicz *et al.* [16] recognized that ‘the practical importance of the remaining organic
203 material is poorly understood’. To illustrate this sentence, Jessika Füssel *et al.* [27] have

204 shown that the poorly studied *Nitrococcus* bacterium is found in oceans worldwide.
205 *Nitrococcus*, and other similar bacteria, replenish nitrate (NO_3^-) in the ocean through the
206 oxidation of nitrite (NO_2^-), and convert carbon dioxide (CO_2) at the same time. Nitrogen is
207 needed for the making of proteins and nucleic acids, and its most abundant and stable form is
208 nitrate.

209 More of these biogeochemical processes, a big number of molecules like Chlorofluorocarbons
210 (CFCs) or polycyclic aromatic hydrocarbons (PAHs), resulting of the anthropic activities can
211 be found in seawater to the state of traces. PAHs absorb also the light in the ultra-violet part
212 of the spectrum. They come from petrol combustion, mineral oils or fuels and are composed
213 of naphthalene, acenaphtene, phenanthrene, chrysene, pyrene or anthracene molecules.
214 According to the proximity of fooling sources, PAHs concentrations can vary from 0 to a few
215 $\mu\text{g l}^{-1}$ or mg l^{-1} . CFCs were used in refrigerants and aerosols. They cannot be broken down by
216 seawaters, and they travel deeper over time, so that they can be used to date water masses in
217 the deep ocean. In the deep ocean and to the vicinity of natural hydro-thermal springs,
218 hydrogen sulfide distributions can be found in the same way.

219 Seawater contains also Suspended Particles Matter (SPM) measured by filtering a given
220 quantity of seawater and weighting the dried filter used. Measuring SPM indicates the
221 complete particles load of a sample. It is generally admitted that SPM concentrations can be
222 between 0.5 mg l^{-1} and 4 mg l^{-1} in the oceans fields, 4 mg l^{-1} to 100 mg l^{-1} in some coastal
223 waters and 100 mg l^{-1} to several g l^{-1} in estuaries. SPM contains organic (plankton and other
224 micro-organisms) and mineral particles placed in suspension by waves, storm [28] and carried
225 by the currents: alluvium, clay, inorganic matter, or aerosol particles, some of them passing
226 through a $0.2 \mu\text{m}$ filter. Bourin *et al.* [29] have shown, with measurements made in the Gulf
227 of Lion, that during storms all the water column can be impacted, with maximal
228 concentrations of 40 mg l^{-1} in this area.

229 The effect of low concentrations of suspended particulate matter on these measurements is
230 badly documented, but the theories developed to explain and predict the conductivity of
231 sediments show clearly that, under an electrical field, they interact with the ionic composition
232 of seawater [30]. Le Menn and Pacaud [31] have shown experimentally with sand, that for
233 low concentrations the effects on conductivity measurements are negligible, but they cannot
234 be neglected near some seabed or coastal areas. They have shown also that density
235 measurements are more sensible to SPM and the threshold to keep the uncertainty under 4 g
236 m^{-3} is close to the concentrations met in the open oceans.

237 SPM can also take the form of microplastics. By studying 17 salt brands originating from 8
238 different countries, Ali Karami *et al.* [32] have found recently that they contained
239 microplastics-like particles larger than $149 \mu\text{m}$. According to them, 'out of the 72 extracted
240 particles, 41.6% were plastic polymers, 23.6% were pigments, 5.50% were amorphous
241 carbon, and 29.1% remained unidentified'. As a conclusion of this first part, the complexity of
242 the seawater composition shows the difficulty in defining the measurand of the salinity,
243 intended as quantity, and also the better way to assess it.

245 2 – Problems in measuring the density of natural seawaters

246 2.1 – Measurements with Vibrating Tube Densimeters

247 At this time, no instrument allows a direct measurement of density *in situ* and only a discrete
 248 sampling can be made thanks to laboratory Vibrating Tube Densimeters (VTD). According to
 249 Seitz *et al.* [33], the density measurements seem to be the best way to trace Standard Seawater
 250 (SSW) bottles to the SI. SSW is recognized by the International Association for the Physical
 251 Sciences of the Ocean (IAPSO). These bottles are used to calibrate with the PSS-78 formulas,
 252 reference laboratory salinometers like Autosal or Portasal from the Guildline company. They
 253 contain seawater taken in the North Atlantic Ocean, filtrated and adjusted to obtain a salinity
 254 close to 35. As SSW has a natural origin, the stability of its chemical composition cannot be
 255 guaranteed, so that its traceability on a long-term to a stable and ubiquitous reference like the
 256 SI.

257 In 2017, Schmidt *et al.* have therefore made measurements with VTD's on SSW at the
 258 atmospheric pressure and under pressure, and they have determined relations linking the
 259 density to the salinity, the temperature and the pressure for standard seawater [34]. When
 260 salinity increases from 0 to 35 g kg⁻¹, density shows a small increase of only 3 %. Therefore,
 261 density has to be measured with a relative uncertainty of 10⁻⁶ to follow salinity variations to
 262 the level of 10⁻³ g kg⁻¹. That can be obtained with VTD only under hard experimental
 263 conditions described by Schmidt *et al.* [35]. The substitution method they use needs 20 h per
 264 sample on condition that the correction be unaffected by scattering. Consequently that
 265 protocol cannot be applied for routine samples measurements, but in the case of SSW, on
 266 absolute seawater densities they claim combined standard uncertainties of 2 g m⁻³ at
 267 atmospheric pressure to 34 g m⁻³ up to 65 MPa. For relative densities, the uncertainty is
 268 limited to 6 g m⁻³ up to 65 MPa [34]

269 VTD consists in measuring the oscillation period τ of a glass tube filled with the seawater. At
 270 atmospheric pressure, density ρ is obtained with an empirical relation:

$$271 \quad \rho = A Q^2 - B \quad (3)$$

272 where Q is the quotient of τ by the oscillation period of a reference oscillator, A and B
 273 constants depending on the characteristics of the cell, the temperature and the viscosity of the
 274 fluid under test [36]. Therefore, they make relative density measurements thanks to a
 275 calibration made with air and distilled water. In the range of seawater density variations, there
 276 is no other pure substance which relation density – temperature is known with a sufficiently
 277 low uncertainty. Schmidt *et al.* [33] used volatile substances, *n*-nonane and
 278 tetrachloroethylene, with a standard uncertainty of respectively 2.5 g m⁻³ (determined from
 279 hydrostatic weighing) and 25 g m⁻³ (determined from measurements with a VTD DMA
 280 5000M), to adjust their VTD used under high pressure.

281 In this instrument the measurand is the oscillation period from which the seawater density is
 282 deducted by a relation of calibration. But, since the fluid is vibrating, its viscosity, leading
 283 energy loss by rotational movement of the fluid called damping, introduces measurement
 284 errors [37]. A third term can be added to the relation (3) to correct the damping. Densities not
 285 corrected for this effect can be overestimated systematically. For seawater with $S_p = 35$, the
 286 correction can be close to 2 g m^{-3} .

287 The damping effect leads to question about the effect of suspended particles on this correction
 288 and also on the homogeneity of the small quantity of seawater ($\approx 1 \text{ ml}$ for the DMA 5000M)
 289 introduced in the low diameter (2 mm) U-tube of the VTD when the sample is charged with
 290 particles of different sizes. The small diameter of the U-tube makes necessary the filtration of
 291 the seawater. As natural seawater must be filtrated before measurements it is difficult to
 292 determine its real density.

293 2.2 – Measurements by pycnometry

294 VTD are not the only laboratory instruments to measure density. Pycnometry can be an
 295 alternative method for density measurements, being usually less affected than VTD by the
 296 physical properties of the examined fluid, i.e. viscosity and surface tension.

297 Pycnometers are generally flasks of different shapes and materials (usually glass or metal for
 298 higher pressures), which volumes are known, filled with the liquid to be measured [38]. The
 299 measurement principle is based on the density definition, namely mass per unit volume of the
 300 substance. The measurement procedure consists of two steps: the determination of the
 301 pycnometer volume and the determination of the mass of the fluid contained in the
 302 pycnometer.

303 Commonly, because most of the pycnometers have irregular shape, the volume is obtained
 304 gravimetrically, at a reference pressure, p_0 , and temperature, T_0 , by weighting (for comparison
 305 with standards weights) the mass of the empty pycnometer, M_0 , and the mass of the
 306 pycnometer, M_{ref} , filled with a reference liquid of known density, ρ_{ref} :

$$307 \quad V_0(T_0, p_0) = \frac{M_{\text{ref}} - M_0}{\rho_{\text{ref}}} \quad (4)$$

308 Every mass value measured with an analytical balance is intended corrected for the buoyancy
 309 by the air density measured during the weighing process. Usually as reference fluid, pure
 310 water is used, having density known with an uncertainty of 0.0001% at ambient pressure and
 311 less than 0.003% for pressure up to 100 MPa [39].

312 To measure density over a wide (T, p) range, the reference volume of the pycnometer has to
 313 be corrected taking into account the deformation due to the effects of temperature and
 314 pressure. So the volume should be expressed as:

$$315 \quad V(T, p) = V_0 [1 + \alpha(T - T_0) + \beta(p - p_0)] \quad (5)$$

316 where α and β are the thermal expansion and the isothermal compressibility of the pycnometer
317 respectively.

318 The pycnometer is filled with the fluid sample at a nominal temperature and compressed. The
319 pressure is adjusted to the nominal value while the temperature is controlled. After reaching
320 the thermodynamic equilibrium pressure and temperature are recorded. By the difference
321 between the weight of the empty pycnometer, M_0 , and the pycnometer filled with the fluid, M ,
322 measured through an analytical balance, the mass of the sample, m , is determined. The density
323 is calculated by

$$324 \quad \rho(T, p) = \frac{(M - M_0) \rho_{\text{ref}}}{(M \zeta_{\text{ref}} - M_0) [1 + \alpha(T - T_0) + \beta(p - p_0)]} = \frac{m}{V} \zeta \quad (6)$$

325 Contrary to hydrostatic weighing, the use of pycnometers has the advantage that, since the
326 fluid sample is held in the cell, it is shielded during the entire measurement procedure from
327 the ambient or phenomena which may affect its composition, e.g. evaporation or
328 sedimentation. For these reasons, pycnometry would seem to be a suitable technique to
329 measure seawater density. However, the drawback in using a pycnometer to determine
330 seawater density is its associated relative uncertainty higher than 10^{-6} that is necessary for
331 salinity determination. In fact, nowadays the density uncertainty with the pycnometer is
332 usually in the order of 10^{-4} both at ambient pressure and high pressure. However, for
333 pycnometry, the estimation of the uncertainty is rather difficult and variable based on the
334 experimental apparatus and strongly dependent on the available instruments and the pressure
335 range of measurement. The main source of uncertainty is due to the volume determination,
336 which involves the uncertainty of reference water density and weighing procedure.
337 Considering only the water density as source of uncertainty, the IAPWS-95 formulation stated
338 an uncertainty of 0.0001 % at ambient pressure, while at higher pressure the uncertainty
339 increases from 0.001% to higher values (0.05%) [39]. Definitely at pressure higher than
340 atmospheric pressure, density uncertainty cannot be lower than present stated density
341 uncertainty of water. Considering measurements at ambient pressure the accuracy cannot be
342 better than 10^{-6} even if the overall uncertainty is strictly dependent on the balance resolution
343 and the ratio between the masses of the pycnometer and the sample inside it (the actual
344 measurand).

345 Nevertheless, an evaluation of the best possible accuracy that can be obtained with a
346 pycnometer is demanding. First of all it is necessary to have an analytical balance with a full-
347 scale and a resolution such that their ratio is lower than 10^{-6} in order to measure a volume and
348 a mass with an uncertainty of the order of 10^{-6} . Consequently, the ratio between the balance
349 resolution and the difference between the pycnometer and the amount of fluid inside, must be
350 lower than 10^{-6} ; thus, the pycnometer must be designed according to this requirement.

351 However, up to now and to the best of authors' knowledge, only the hydrostatic weighing can
352 achieve a density measurement resolution of 10^{-6} .

353 **2.3 - Hydrostatic weighing**

354 As said before, for many fluids, and in particular for liquids, the most accurate density
 355 measurements are obtained using the method of the hydrostatic weighing. The measurement
 356 principle is based on the possibility to weight a sinker, usually made of a chemically inactive
 357 solid material with long term stability, both in air and when immersed in the testing fluid. In
 358 these configurations, an analytical balance measures the sinker apparent-mass
 359 $m_{\text{air}}^i = m - \rho V$, where m and V are the sinker mass and the sinker volume respectively while
 360 ρ is the density of the fluid surrounding the sinker (air or testing fluid). Considering both
 361 the weighing, the following system of equations can be obtained:

$$362 \quad \begin{cases} m_{\text{air}}^i = m - \rho_{\text{air}} V \\ m^i = m - \rho V. \end{cases} \quad (7)$$

363 From which it is possible to eliminate m and calculate the density of the liquid ρ according
 364 to:

$$365 \quad \rho(T, p) = m_{\text{air}}^i - \frac{m^i}{V(T, p)} + \rho_{\text{air}}(T, p, x) \quad (8)$$

366 where x expresses the composition of the air accounting for molar fraction of carbon-dioxide
 367 and argon. Using this approach, the measurand is the apparent mass of the sinker.

368 It is quite common to have a certificate of the sinker mass and volume, measured at specified
 369 temperature and pressure, in this way m is known, and its uncertainty includes the uncertainty
 370 on air density determination. In this way, the first equation of (7) can be eliminated. For
 371 density measurements, obtained in conditions different from those of the sinker certificate,
 372 volume corrections are needed. This condition sets limits to the sinker materials since, when
 373 requested uncertainty is in the order of few part per million, the isothermal compressibility
 374 and the thermal expansion coefficients have to be known with the necessary level of
 375 uncertainty.

376 When density measurements are requested as a function of pressure, hydrostatic weighing
 377 have to be significantly modified to weight the sinker when set into a pressure vessel. The
 378 widely used solution to this problem is to adopt a magnetic suspension capable to transmit the
 379 weight force through the top of the pressure vessel. However the magnetic suspension
 380 introduces new sources of uncertainty, for example the repeatability of the floating position
 381 and the force transmission error, so that these types of densimeters are affected by
 382 uncertainties that are sensibly higher than those obtained without a magnetic suspension.

383 Performances of hydrostatic weighing, used by national metrological institutes, are checked
 384 by sophisticated procedures of comparison named "key comparisons" regulated by the Bureau
 385 International des Poids et Mesures (BIPM). This approach is necessary since, despite a
 386 rigorous uncertainty analysis, it is possible that systematic errors may be hidden. According to
 387 the updated Calibration and Measurements Capabilities (CMC) [40], the best hydrostatic
 388 weighing, working at ambient pressure, are characterized by expanded uncertainties ($k=2$)

24

389 around 0.004 kg/m³ (~4 parts per million, ppm) for density values of approximately
 390 1000 kg/m³. However these instruments are not equipped with magnetic suspensions and
 391 cannot operate at pressure different from ambient. When instruments are equipped with
 392 magnetic suspensions, uncertainty is around (15 or 20) ppm even when operating at ambient
 393 pressure. If measurements are carried out at higher pressure, uncertainty can only grow.
 394 Furthermore it has to be considered that, for obtaining results with such accuracy, only
 395 chemically stable fluids are adopted, usually *n*-nonane and water.

396 Hydrostatic weighing can of course be used to measure the density of seawater samples both
 397 at ambient and higher pressure, but it has to expect that measurements will be affected by a
 398 higher uncertainty since seawater is chemically active and not as stable as other reference
 399 fluids.

400

401 3 – Problems encountered with the refractive index measurements

402 Another way to assess the seawater absolute salinity and density is to measure its refractive
 403 index *n*. The Lorentz – Lorenz formula gives a direct relation between *n* and ρ :

$$404 \quad \frac{(n^2 - 1)}{(n^2 + 2)} = \frac{m_r \rho}{W} \quad (9)$$

405 *m_r* being the molar refractivity and *W* the molecular weight of the species constituting the
 406 fluid. For pure water, *m_r* depends strongly of the wavelength λ , and it varies slowly with
 407 temperature *t* (no more than 1 % between ambient temperature and boiling point) and molar
 408 density ρ [41]. Hence the molar refractivity of pure water behaves in the same way that other
 409 elementary fluid, for a given wavelength. This can be explained theoretically and modelled by
 410 an empirical relation function of ρ , *t* and λ [42]. Several authors attempted to establish
 411 empirical relations between the seawater refractive index and its variations in wavelength,
 412 temperature, salinity and pressure. In 1990, Millard and Seaver proposed a 27-terms algorithm
 413 covering the range 500 - 700 nm in wavelength, 0 - 30 °C in temperature, 0 - 40 in practical
 414 salinity and 0 - 11000 dbar in pressure, to compute the seawater refractive index [43]. By
 415 measuring the refractive index and inverting this algorithm, salinity can be extracted with
 416 accuracies close to oceanographic purposes at low pressure, but not at high pressure.

417 With techniques giving access to the phase of light waves, with several wavelengths it is
 418 theoretically possible to measure absolute refractive index values and then to retrieve the
 419 value of seawater salinity knowing the exact values of the wavelengths and by measuring the
 420 temperature and the pressure of the middle. In this case, the measurand is an optical property
 421 of the middle, its refractive index.

422 *n* is sensible to all the constituents of the fluid and is therefore a good proxy of the concept of
 423 salinity and techniques based on the measurement of *n* shows generally a good linearity
 424 versus the salinity. It can give access to an *S_A* or to a true δS_A by comparison to CTD values,

425 but Laser Gaussian beams are also sensible to turbidity. According to the wavelength and the
 426 size of particles it leads diffraction phenomenon and that can be an obstacle to the using of
 427 interferometric techniques *in situ*, so that they allow the achievement of the best resolutions.
 428 But, as shown by Hou *et al.* [10], turbidity can also contribute to a light beam deviation more
 429 than refractive index. This deviation is therefore a good proxy of the real density of the
 430 middle but it leads errors in the measure of n and subsequently in the calculation of the
 431 salinity with the Millard and Seaver algorithm for example. In the case of a refractometer,
 432 Hou *et al.* have shown that theoretically the same beam can be used to measure the turbidity
 433 and the refractive index, and n can be corrected.

434 Demonstrations have been made of the using of refractometers *in situ* [6], [9] but several
 435 obstacles stay to make of them, instruments able to challenge conductivity cells in resolution
 436 and precision. Like conductivity cells, they need a calibration with reference formulas linking
 437 the measurand to salinity, temperature and pressure, the wavelength being a supplementary
 438 quantity to determine. Another obstacle is the inaccuracy of Millard and Seaver relations with
 439 pressure because of the low number of reference data used to fit the relations, or because of
 440 the using of S_p instead of S_r or S_A in these relations, and the questionable real uncertainties of
 441 all the reference data used to build the algorithm.

443 **4 – Problems encountered with the speed of sound measurements**

444 Speed of sound w is a thermodynamic quantity directly linked to the adiabatic compressibility
 445 of the sample, namely $w^{-2} = (\partial \rho / \partial p)_s$ [44]. There are, mainly, two methods for measuring
 446 speed of sound and they can be distinguished by the use of steady state waves or transient
 447 waves. Steady states approach is very favorable when speed of sound is measured in gases,
 448 but the method needs to use ultrasonic sources with almost flat frequency dependence. Such
 449 transducers are usually not suitable to be used at high pressure, furthermore, the high acoustic
 450 impedance of seawater makes this measurement method unsuitable, since the frequency
 451 response of the resonant cavity does not show an evident frequency peak. On the contrary,
 452 many of the oceanographic speed of sound sensors are based on a transient method, named
 453 single path pulse-echo. This acoustic scheme uses an ultrasonic source to generate a wave-
 454 packet that spreads into the seawater and then it is reflected back to the source by a reflector.
 455 The sensor measures the time t that signal needs to get back and, knowing the travelled
 456 distance $2L$, it is possible to determine the speed of sound $w = 2L/t$. These kind of
 457 oceanographic sensors are mechanically robust and can operate at pressure up to 90 MPa
 458 (~ 9000 dbar) [45]. Since variations of temperature and pressure change the distance at which
 459 the reflector has been set, speed of sound sensors have to be calibrated with a reference fluid
 460 in suitable temperature and pressure ranges. The most used calibration fluid is pure water that
 461 is one of the most studied. The equation of state for pure water [39] was realized considering
 462 several sets of speed of sound measurements and recently Trusler [46] suggested to reduce the
 463 estimated uncertainty of the equation of state to 0.03 % (now 0.1 %) for high pressure ranges.

464 For TEOS-10 [47], the equation of state of seawater, the uncertainty estimation is still debated
465 [48], however it cannot be better than that one of pure water, reasonably. Equations of states,
466 both for pure and seawater, are very important since their predictions are often used to
467 calibrate oceanographic sensors. In this case, *in situ* speed of sound measurements are
468 affected by an uncertainty that is, at least, that one of the equation but, typically it is even
469 larger.

470 For speed of sound, the measurand is a time-of-flight that can usually be determined with a
471 resolution in the order of 10 ppm and a repeatability of 20 ppm, in laboratory conditions.
472 However, the main sources of uncertainty for speed of sound measurements are due to the
473 determination of the acoustic path-length, as a function of the temperature and pressure, and
474 the measurement of the absolute pressure. Once the speed of sound is measured, the salinity
475 can be estimated using empirical relations obtained in controlled laboratory conditions. As an
476 example, Allen *et al.* [49] state that the use of speed of sound for calculating the salinity is
477 limited by the accuracy of the equations they found since they have uncertainty of 0.05 m/s.
478 Declared uncertainty corresponds to a relative uncertainty of 33 part per million when it is
479 calculated for pure water at ambient temperature and pressure. The same paper reports also
480 that there are commercial sensors able to reach the uncertainty of 0.02 m/s, or 13 part per
481 million in pure water, but it sounds strange since the best water speed of sound measurements,
482 obtained in controlled laboratory conditions, are affected by a relative uncertainty of 10 part
483 per million and the agreement with independent measurements is 30 part per million [50]. It is
484 possible that the authors fell in the common misunderstanding to use the *repeatability* of a
485 measurement to declare instrument *uncertainty*. To confirm this hypothesis, Von Rohden *et*
486 *al.* [45] calibrated a set of state-of-the-art commercial sensors using pure water for measuring
487 the speed of sound in North Atlantic seawater. They found a repeatability in the order of 20
488 ppm, but an agreement between different sensors is approximately 200 ppm that sounds more
489 realistic and representative of the typical measurement uncertainty, considering that all
490 measurements were obtained at ambient pressure.

491 For speed of sound sensors, based on transient method, the uncertainty budget is usually
492 dominated by the uncertainty associated to the determination of the travelled distance and the
493 pressure measurement. This means that for *in situ* measurements, the uncertainty can only
494 increase with respect to that one estimated in [45]. The calibration procedure is mainly
495 dedicated to the determination of the acoustic-path length at different temperatures and,
496 hopefully, pressure. Furthermore, in many cases, time-of flight measurements are not
497 corrected by diffraction effects since the necessary technical specifications (like source
498 diameter and source resonant frequency) are not declared and cannot be easily determined
499 during calibration. Diffraction corrections are in the order of 100 ppm and they strongly
500 depend on the measured speed of sound. For this reason, it is not rigorous to calibrate a sensor
501 in pure water and then measure seawater speed of sound, without correcting both the
502 calibration and the *in situ* measurement by diffraction effects.

503 Effects of pressure on the speed of sound uncertainty evaluation is twofold. Firstly, pressure
504 changes the distance between the source and the reflector and, secondly, the uncertainty on

30

505 pressure measurement leads to a wrong association between the speed of sound measurement
506 and the correspondent thermodynamics state. Usually, temperature acts on the same way of
507 the pressure.

508 In an optimistic view, if the laboratory and *in situ* uncertainty was the same, speed of sound
509 could be measured with a relative uncertainty of about 300 ppm up to high pressure.
510 Considering the sensitivity coefficient that links salinity to speed of sound, the uncertainty
511 associated to the salinity determination, starting from speed of sound, temperature and
512 pressure measurement, should be in the order of 1 %.

513

514 **5 – Conclusion**

515 Salinity is an essential quantity to calculate many of physical properties of oceans, but it is
516 also a quantity hardly definable considering the complexity of the material in its bio-geo-
517 chemical composition and the imperfections of the existing measurement techniques.

518 The TEOS-10 gives several definitions to the notion of absolute salinity, usable in function of
519 the properties to study. They are all based on conductivity or density measurements.
520 Conductivity measurements offer a precision suitable with the oceanographic requirements,
521 but they suffer of inaccuracies in relation with the amounts of non-ionic components present
522 in seawater. The inaccuracies are also in relation with the defaults of the salinity scale
523 originally based on the Marcet principle of a constant elemental composition of seawater. To
524 complement the practical salinity measurements, the using of vibrating tube densimeters
525 developed in the last years. They allow the determination of salinity anomalies and the
526 approach of an absolute salinity, so that a better traceability of the standard seawater to the SI.
527 But they make relative density measurements with a calibration resting essentially on the air
528 and the pure water density relations.

529 Taking into account the volume and the dynamic variations of oceans, oceanographers need *in*
530 *situ* salinity or density profiles. Vibrating tube densimeters, pycnometric or hydrostatic
531 weighing methods are not usable *in situ*. For this reason two other techniques are under
532 development. The first one is based on refractive index measurements and the second one on
533 the speed of sound. The refractive index and the measurement techniques of Laser beam
534 deviations present the advantage to be sensible to all the components of the medium and they
535 could allow a new definition of the salinity based on a physical property of the seawater and
536 not on a chemical composition exhaustively unknown at this time and variable in time and
537 space. But, the perfecting of refractometers or interferometers insensible to the temperature
538 and pressure constraints of the medium is not easy and the oceanographic uncertainty
539 requirements on salinity are difficult to keep with this quantity, taking into account its
540 variation range and the necessary resolution.

541 The speed of sound measurements are challenging the refractometers because speed of sound
542 profilers are still used in hydrography for several years to correct hydrographic multi or

543 mono-beam echo sounders. The more recent ones allow resolutions inferior to one centimeter
544 per second, but the uncertainty of their measurements is more close to 200 ppm at ambient
545 pressure and could be 300 ppm at high pressure. That corresponds to 0.35 for a salinity of 35
546 g/kg, which is not sufficient to reply to oceanographer's requirements described in references
547 [51] and [52].

548 In the seventieth, the perfecting of conductivity cells leded to the abandon of chlorinity
549 measurements and to the definition of the PSS-78. That definition with its imperfections, and
550 the definitions of S_A described in the TEOS-10 manual, will stay probably as long as no other
551 technology will have perfectly demonstrated its ability to retrieve in situ density or salinity
552 profiles with a precision close to the precision of conductivity cells.

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