

can damp the oscillation. The predictability of El Niño is therefore limited, because the westerly wind bursts cannot be anticipated far in advance. (Several models predicted that El Niño would occur in 1997, but none anticipated its large amplitude.)

These results concerning the stability properties of ocean–atmosphere modes come from analyses of relatively simple coupled models: the ocean is a shallow-water model with a mixed, surface layer in which sea surface temperatures have horizontal variations; the atmosphere is also a single layer of fluid driven by heat sources proportional to sea surface temperature variations. These models deal only with modest departures from a specified background state that can be altered to explore various possible worlds. The results are very helpful in the development of more sophisticated coupled general circulation models of the ocean and atmosphere which have to simulate, not only the interannual Southern Oscillation, but also the background state. At this time the models are capable of simulating with encouraging realism various aspects of the Earth's climate, and of the Southern Oscillation. As yet, the properties of the simulated oscillations do not coincide with those of the Southern Oscillation as observed during the 1980s and 1990s, presumably because the background state has inaccuracies. The models are improving rapidly.

## Conclusions

The Southern Oscillation, between complementary El Niño and La Niña states, results from interactions between the tropical oceans and atmosphere.

The detailed properties of the oscillation (e.g. its period and spatial structure) depend on long-term averaged background conditions and hence change gradually with time as those conditions change. The ocean, because its inertia exceeds that of the atmosphere by a large factor (oceanic adjustment to a change in forcing is far more gradual than atmospheric adjustment), needs to be monitored in order to anticipate future developments. The development of computer models capable of predicting El Niño is advancing rapidly.

## See also

**Elemental Distribution: Overview. El Niño Southern Oscillation (ENSO). Rossby Waves. Satellite Remote Sensing of Sea Surface Temperatures. Wave Generation by Wind.**

## Further Reading

- The *Journal of Geophysical Research* Volume 103 (1998) is devoted to a series of excellent and detailed reviews of various aspects of El Niño and La Niña.
- Neelin JD, Latif M and Jin F-F (1994) Dynamics of coupled ocean–atmosphere models: the tropical problem. *Annual Review of Fluid Mechanics* 26: 617–659.
- Philander SGH (1990) *El Niño, La Niña and the Southern Oscillation*. New York: Academic Press.
- Zebiak S and Cane M (1987) A model El Niño Southern Oscillation. *Monthly Weather Review* 115: 2262–2278.
- Schopf PS and Suarez MJ (1988) Vacillations in a coupled ocean–atmosphere model. *Journal of Atmospheric Science* 45: 549–566.

# ELECTRICAL PROPERTIES OF SEA WATER

**R. D. Prien**, Southampton Oceanography Centre, Southampton, UK

Copyright © 2001 Academic Press

doi:10.1006/rwos.2001.0328

## Introduction

The oceans are the biggest reservoir of electrolyte solution on Earth. The electrical properties of the sea water are mainly determined by the ions dissolved in it when DC or low-frequency AC electric fields are involved. It should be noted, however, that the water plays an important role in producing the ions from the electrically inert salt crystals. For

high-frequency electric fields and electromagnetic wave propagation, the properties of the water itself become more important, since the mechanism of conduction changes.

The electrical conductivity has become the most important electrical property of sea water because the definition of salinity is based on conductivity ratios. Thus, salinity in its current definition is an electrical property.

Other consequences of the sea water being an electrolyte might not be as obviously relevant to the marine scientist as is the conductivity. Whenever instruments that consist of metal parts are lowered into the sea, the galvanic potential has to be considered, either because it might influence electric

measurements carried out by the instrument or because of the accelerated corrosion it causes. The fact that the ions in the water are moved with it in the Earth's magnetic field by the ocean currents can be used to determine water velocities. Finally, the optical properties of the sea water are by their nature electromagnetic properties.

## Electrical Conductivity

Electrical conductance is the property of a body quantifying the ability to conduct an electric current. The electrical conductance  $G$  is given as the ratio of electric current  $I$  and voltage  $V$  and therefore equals the reciprocal of electrical resistance  $R$ :

$$G = \frac{I}{V} = \frac{1}{R} \quad [1]$$

The electrical conductance of a body is dependent not only on its material but also on the geometric properties of the body. A thin, long cylinder, for example, has a lower conductance than a thick, short cylinder of the same volume. To get a measure independent of the shape and size of the body of a material, the conductivity of media is given in terms of the specific conductivity  $\sigma$ . For a cylindrical volume of material with length  $l$ , cross-sectional area  $A$ , and resistance  $R$  between its plane, parallel faces, the specific conductivity is given by

$$\sigma = \frac{l}{AR} \quad [\Omega^{-1} \text{m}^{-1} = \text{S m}^{-1}] \quad [2]$$

Thus, the specific conductivity is normalized by the geometry and is a property of the material only.

When considering the electrical conductivity of a material one must differentiate between direct-current and low-frequency conductivity on the one hand and high-frequency conductivity on the other. The latter will be discussed in a separate section below.

Whereas in metals the electric conductivity is based on electron conductance only, in electrolytic fluids – and therefore in sea water – the conductivity is based on ion conductance only, as far as direct-current and low-frequency conductivity is concerned. Both types of ions, positively and negatively charged, contribute to the electrical conductivity.

### Source of Ions

While pure fresh water conducts electric current only very weakly (owing to a slight dissociation of the water molecules), the addition of salt (e.g.,

NaCl) to the water results in a significant rise in conductivity, although the compound NaCl is electrically neutral. It is known, however, that salt crystals consist of positive and negative charged ions that are attracted together by the Coulomb force given by

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 \epsilon r^2} \quad [3]$$

where  $Q_1$  and  $Q_2$  are the charges of the ions,  $\epsilon_0$  is the permittivity of vacuum,  $\epsilon$  is the permittivity of the medium, and  $r$  is the distance between the ions. To separate the ions, an amount of work

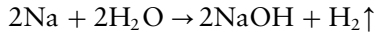
$$W = \int_b^\infty F dr \quad [4]$$

has to be carried out, where  $b$  is the distance between the  $\text{Na}^+$  and the  $\text{Cl}^-$  ions in the salt crystal (for NaCl,  $b \simeq 0.2 \text{ nm}$ ). In air ( $\epsilon \simeq 1$ ) the work to dissociate a NaCl molecule is  $1.15 \times 10^{-18} \text{ J}$ , but in water ( $\epsilon \simeq 81$ ) only  $1.42 \times 10^{-20} \text{ J}$  is needed. Owing to their polar nature, the water molecules in the vicinity of the ions are orientated according to the charge of the ions and form a layer around the ions. This process is called hydration and it sets energy free that then is used to separate the ions of the NaCl molecules. Thus, after salt is added to the pure water the dissolved salt molecules are dissociated into ions. The process of separation of the ions of the dissolved molecules is called electrolytic dissociation.

The fact that the salt molecules are dissociated can be seen not only by carrying out a conductivity measurement (which implies the application of an electric field between the measuring electrodes) but also from the properties of the electrolyte. It is known that in solutions an osmotic pressure is present that leads to a decrease of vapor pressure and ice point as well as an increase of the boiling point. These effects are proportional to the concentration of the solution, as is shown by the Raoult laws. The solutions of water, however, show deviations of these properties from the values predicted by the Raoult laws. This can be explained only by the dissociation of the solute, because its effective concentration is higher. The effective concentration can be obtained by combining the concentrations of the dissociated components. Therefore, the effects mentioned above are more pronounced for electrolytic solutions.

It seems surprising at first that, for example, the sodium ions can exist in the water without the

well-known reaction



taking place but it has to be borne in mind that the chemical properties of atoms and molecules are determined almost exclusively by the electron configuration of the outer electron shell, which in the case of the  $\text{Na}^+$  ion is a noble gas configuration and therefore quite different from the configuration of a sodium atom.

### Mechanism of Conductivity in Electrolytes

A potential difference between two electrodes that are lowered into an electrolyte creates an electric field in the electrolyte, by which positively charged ions (anions) are forced towards the cathode and negatively charged ions (cations) towards the anode. At the electrodes the anions receive electrons from the cathode while the cations donate electrons to the anode. The movement of ions in the water therefore results in a flow of electrons between the electrodes and thus a current in the external circuit. It should be noted that current flow in electrolytic fluids (in contrast to current flow in metals) is connected to a mass flow (Figure 1).

The electric field created by the voltage applied to the electrodes results in a force on the ions, which are accelerated towards the electrodes. Since the ions are moving in the fluid, friction opposes the electric force and after a short period of acceleration the frictional force balances the electric force and the ions move with constant velocity. According to Stokes' law, the frictional force and therefore the resulting velocity is a function of the size of the ions. It should be mentioned that the friction of the

ions in the fluid results in an increase of temperature of the fluid.

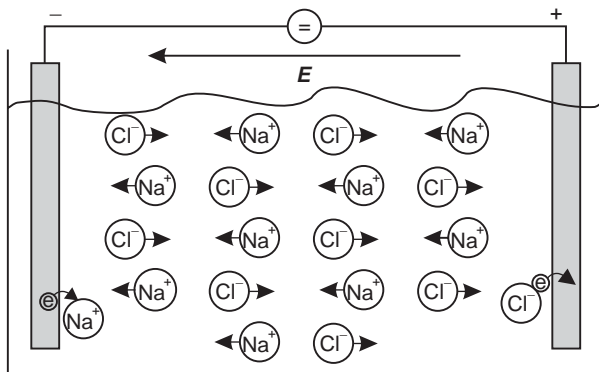
The water molecules do not play an important role in the low-frequency or DC conductivity of the electrolyte. However, the water molecules have a dipole moment because of their polar nature. Each hydrogen–oxygen bond is polar covalent, with the hydrogen end positive with respect to the oxygen end. When no external electric field is applied, thermal agitation keeps the molecular dipoles randomly oriented; when a field is applied, the dipoles align themselves and the fluid takes on an electric polarization.

### Factors Determining Conductivity

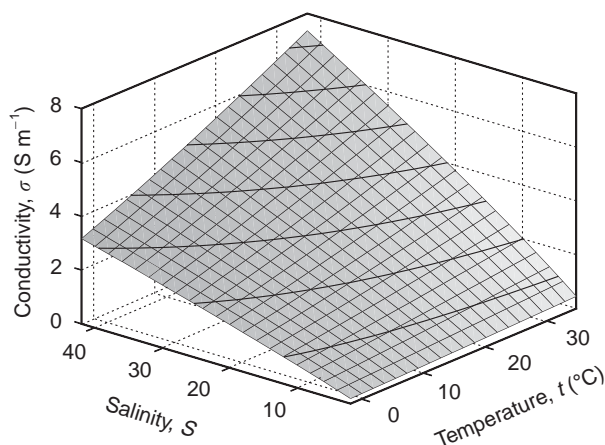
The conductivity of an electrolyte is a function of the concentration of ions. The greater the number of ions that are moving towards the electrodes, the greater is the number of electrons that can be interchanged at the electrodes and the higher is the resulting current. If all molecules of the solute are dissociated, the conductivity is a linear function of the concentration of the solute. This linear relation between concentration of the solute and conductivity of the electrolyte holds true only for low concentrations. It was shown above that the dissociation of the salt molecules depends on the permittivity of the water. The permittivity is a macroscopic property and if a salt molecule is surrounded not only by water molecules but also by other salt molecules, the permittivity in the vicinity of the salt molecule is altered. At higher concentrations not all of the salt molecules are dissociated and therefore the increase of conductivity of the electrolyte as a function of concentration is weakened. This effect can be seen in Figure 2, which shows the conductivity as a function of salinity and temperature. The conductivity is not linearly increasing with increasing salinity; the slope is decreasing for higher salinities. For high-precision determination of salinity this effect has to be taken into account, although the salt concentration in sea water is not very high.

Another factor determining the conductivity of an electrolyte is the mobility of the ions. As was mentioned above, the size of the ions determines their velocity in the electrolyte when under the influence of an electric field. The higher this velocity, the more ions reach the electrode in a given time interval and thus the higher is the current.

The conductivity of an electrolyte is also a function of temperature. The viscosity of the solvent (here, water) decreases with temperature and the ion mobility is increased. The degree of dissociation



**Figure 1** Schematic of ionic conductivity mechanism in sea water. The ions are moving towards the electrodes under the influence of the electric field created by the voltage applied between the electrodes. When the ions reach the electrodes, cations donate electrons while anions receive electrons. Thus, an electric current between the electrodes results.



**Figure 2** Conductivity of sea water as a function of temperature and salinity. The conductivity was calculated assuming an absolute value of conductivity  $\sigma(S = 35, t = 15^\circ\text{C}, p = 0 \text{ dbar}) = 4.2194 \text{ S m}^{-1}$ . The bold lines denote constant conductivities from  $1 \text{ S m}^{-1}$  to  $7 \text{ S m}^{-1}$ .

of the electrolyte also changes with temperature. Some electrolytes show an increase of the degree of dissociation with higher temperatures; most of them, however, show a decrease of the degree of dissociation with an increase of temperature. This explains why for some solutions the conductivity first increases with temperature and then decreases, after passing a maximum of conductivity, for further temperature increase.

### Definition of Salinity of Sea Water

Since the end of the nineteenth century it has been known that the composition of sea water is almost constant in space and time. It is therefore justified, to a good first-order approximation, to assume that sea water consists of just two components, the first being pure water and the second representing all dissolved ions that contribute to the mass of sea water. The concept of constant composition allows the choice of one type of ions to represent all other types. In the early 1900s, the salinity  $S$  of sea water was defined in terms of chlorinity  $Cl$ , defined as the chloride-equivalent mass ratio of halides to the mass of sea water, by a linear least-squares regression formula fitted to mass ratios of salt residues of nine sea water samples evaporated to dryness. The regression formula, known as the Knudsen formula, is

$$S = 0.030 + 1.8050 Cl \quad [5]$$

In the mid to late 1950s, the use of conductivity bridges for salinity determination was increasing

and led to a concern about using a chlorinity standard to serve as a conductivity standard. In 1960, a study of the relationships between chlorinity, conductivity, and density on several hundred samples of sea water from widely distributed locations was undertaken at the British National Institute of Oceanography. A markedly higher correlation was found between density and conductivity than between density and chlorinity, and subsequently a Joint Panel on the Equation of State of Seawater was formed to review the relationship of the equation of state to chlorinity, salinity, electrical conductivity, and refractive index. The findings of the panel led to the definition of salinity in terms of the electrical conductivity ratio  $R_{15}$  at  $15^\circ\text{C}$  to that of sea water having a salinity of 35.

The initial recommendation was to define salinity in terms of density, which would have allowed construction of formulas relating density to a measured variable such as electrical conductivity, refractive index, or density itself. It turned out, however, that the necessary precision for the determination of absolute density and conductivity of standard sea water was not achievable at the time.

Owing to problems arising from using standard sea water as a reference, it was agreed to use a potassium chloride solution as a standard to determine the salinity of the standard sea water. This definition was published as the Practical Salinity Scale 1978 (PSS78). Therefore, the salinity of sea water in its current definition is an electrical property.

In the following the nomenclature of the Unesco technical papers in marine science will be used, where  $C$  denotes the conductivity and  $R$  the conductivity ratio. If  $C(S, t, p)$  is the electrical conductivity of sea water at practical salinity  $S$  (PSS78), temperature  $t$  (International Practical Temperature Scale 1968 (IPTS68)) and pressure  $p$  in decibars, the conductivity ratio is defined to be

$$R = \frac{C(S, t, p)}{C(35, 15, 0)} \quad [6]$$

where  $C(35, 15, 0)$  is the conductivity of standard sea water of practical salinity 35, and  $15^\circ\text{C}$  and atmospheric pressure, defined to be equal to the conductivity of a reference solution of potassium chloride (KCl) at the same temperature and pressure. This KCl reference contains 32.4356 g of KCl in a mass of one kilogram of solution.

The conductivity ratio can be factored into three parts:

$$R = R_p \cdot R_t \cdot r_t \quad [7]$$

where

$$R_p(S, t, p) = \frac{C(S, t, p)}{C(S, t, 0)}$$

$$R_t(S, t) = \frac{C(S, t, 0)}{C(35, t, 0)}$$

$$r_t(t) = \frac{C(35, t, 0)}{C(35, 15, 0)}$$

Since the ratios  $R_t$  or  $R$  are the properties measured with conductivity bridges together with temperature and pressure, formulas have been developed for the ratios in these variables rather than in salinity  $S$ .

When measuring the conductivity ratio  $R$  together with temperature  $t$  and pressure  $p$ , the ratio  $R_p$  can be obtained as

$$R_p = 1 + \frac{p(e_1 + e_2p + e_3p^2)}{1 + d_1t + d_2t^2 + (d_3 + d_4t)R} \quad [8]$$

with the coefficients

$$\begin{aligned} e_1 &= +2.070 \times 10^{-5} \\ e_2 &= -6.370 \times 10^{-10} \\ e_3 &= +3.989 \times 10^{-15} \\ d_1 &= +3.426 \times 10^{-2} \\ d_2 &= +4.464 \times 10^{-4} \\ d_3 &= +4.215 \times 10^{-1} \\ d_4 &= -3.107 \times 10^{-3}. \end{aligned}$$

The ratios  $r_t$  can be calculated from the temperature as

$$r_t = c_0 + c_1t + c_2t^2 + c_3t^3 + c_4t^4 \quad [9]$$

where

$$\begin{aligned} c_0 &= +6.766097 \times 10^{-1} \\ c_1 &= +2.00564 \times 10^{-2} \\ c_2 &= +1.104259 \times 10^{-4} \\ c_3 &= -6.9698 \times 10^{-7} \\ c_4 &= +1.0031 \times 10^{-9} \end{aligned}$$

The ratio  $R_t$  then can be obtained from

$$R_t = \frac{R}{R_p \cdot r_t}$$

With the ratio  $R_t$  and the temperature  $t$ , the practical salinity  $S$  then can be computed using the equation

$$S = a_0 + a_1R_t^{1/2} + a_2R_t + a_3R_t^{3/2} + a_4R_t^2 + a_5R_t^{5/2} + \Delta S \quad [10]$$

with the coefficients

$$\begin{aligned} a_0 &= +0.0080 \\ a_1 &= -0.1692 \\ a_2 &= +25.3851 \\ a_3 &= +14.0941 \\ a_4 &= -7.0261 \\ a_5 &= +2.7081 \end{aligned}$$

where

$$\sum_i a_i = 35.0000$$

The term  $\Delta S$  in equation [10] is given by

$$\Delta S = \frac{t - 15}{1 + k(t - 15)} (b_0 + b_1R_t^{1/2} + b_2R_t + b_3R_t^{3/2} + b_4R_t^2 + b_5R_t^{5/2}) \quad [11]$$

where

$$\begin{aligned} b_0 &= +0.0005 \\ b_1 &= -0.0056 \\ b_2 &= -0.0066 \\ b_3 &= -0.0375 \\ b_4 &= +0.0636 \\ b_5 &= -0.0144 \\ \sum_i b_i &= 0.0000 \end{aligned}$$

and

$$k = +0.0162$$

The given equations are valid over a temperature range from  $-2^\circ\text{C}$  to  $35^\circ\text{C}$  and practical salinity from 2 to 42. The pressure range is not explicitly stated but a table of maxima of the range of pressures over which the pressure correction to conductivity ratio was computed is given in the original publication. It should be noted that no absolute

conductivity value is given in the PSS78 since it is not required. A reference value given in literature is  $C(35, 15, 0) = 4.2194 \text{ S m}^{-1}$ .

## Electromagnetic Wave Propagation

The mechanisms of conductivity change dramatically when the voltage applied to two electrodes in sea water changes from DC or low frequency to high frequency. At low frequencies there is not much change in the mechanism of conductivity as the ions are accelerated up to their constant velocity and slow down again when the sign of the electric field changes. The conductivity is slightly decreased compared to the DC values because of repetitive acceleration of the ions. When the frequency is further increased, the ions are no longer accelerated to the point of constant velocity in the fluid, but are only slightly shifted from their position before the sign of the electric field changes and the ions are forced back. At even higher frequencies, the ions are not accelerated any more and the ion and its associated water molecules only change orientation according to the electric field and their electric dipole moment. The water molecules are also polarized according to their dipole moment, which means that the molecules undergo rapid rotations, aligning themselves with the electric field. The sea water therefore takes on an orientational polarization. The conductivity and the permittivity become functions of the frequency of the electromagnetic field.

When the frequency is too high for the molecules to be able to follow the field changes, because of their inertia, their contribution to the polarization decreases and the permittivity drops markedly. For water, the permittivity is fairly constant ( $\sim 81$ ) for frequencies up to about 10 GHz, after which it falls off quite rapidly. At higher frequency, the electronic polarization becomes the main factor determining the permittivity. Electronic polarization arises when the electron clouds are shifted relative to the nuclei and generate a dipole moment.

This means that for high-frequency electric fields the mechanism of conductivity changes and is no longer connected to a mass transport. While ion mobility is a main factor for low-frequency and DC conductivity, the dipole moment of the sea water and its frequency dependence play the major role in high-frequency conductivity.

The change in mechanism also needs another formulation and the theory of electromagnetic wave propagation in matter must be applied. For isotropic homogeneous media and in the case of pure periodic functions of time of the form  $\exp\{i\omega t\}$ , where  $\omega$  is the frequency of the field, the Maxwell equations

for the components of the magnetic field  $\mathbf{B}$  and electric field  $\mathbf{E}$  are reduced to the wave equations:

$$\Delta \mathbf{B} + q^2 \mathbf{B} = 0 \quad [12]$$

$$\Delta \mathbf{E} + q^2 \mathbf{E} = 0 \quad [13]$$

Here  $\Delta$  is the Laplace operator and the complex wavenumber  $q$  is related to the wavenumber *in vacuo*,  $q_0$ , and the complex refractive index,  $m$ , by

$$q = mq_0 \quad [14]$$

with

$$q_0 = \frac{2\pi}{\lambda_0} = \frac{\omega}{c} \quad [15]$$

and

$$m = \sqrt{\varepsilon\mu - i\frac{4\pi\sigma}{\omega}} \quad [16]$$

Here  $\lambda_0$  is the wavelength in vacuum,  $c$  is the velocity of light in vacuum,  $\varepsilon$  is the permittivity,  $\mu$  is the magnetic permeability, and  $\sigma$  is the conductivity of the medium. The complex refractive index  $m$  can be separated into the real and imaginary part:

$$m = n - ik \quad [17]$$

where  $n$  is the ordinary refractive index and  $k$  is the electrodynamic absorption coefficient. The permittivity  $\varepsilon$  also is a complex quantity and can be written as

$$\varepsilon = \varepsilon' - i\varepsilon'' \quad [18]$$

With  $\mu \approx 1$ , an approximation valid for most materials, the two equations [16] and [17] for the refractive index  $m$  show the relation  $n$  and  $k$  to the permittivity and the conductivity:

$$\varepsilon' = n^2 - k^2 \quad [19]$$

and

$$\varepsilon'' + \frac{4\pi\sigma}{\omega} = 2nk \quad [20]$$

The solutions of the wave equations are of the form

$$\exp[i(\omega t - qz)] = \exp[-kq_0z] \exp[i(\omega t - nq_0z)] \quad [21]$$

This is a damped plane wave propagating in the  $z$ -direction with a damping factor of  $kq_0$ . The real

and imaginary parts of the refractive index therefore represent two different properties, the ordinary refractive index  $n$  gives the phase advance of the wave, while the electrodynamic absorption coefficient  $k$  determines the reduction in amplitude of the wave. The dependence of  $n$  and  $k$  on the frequency of the field is governed by the various polarization mechanisms contributing to the dipole moment at the particular frequency.

## Galvanic Couples

When a metal body is lowered into water, ions of the metal will be dissolved in the water. An equilibrium is reached when the osmotic pressure of the metal ions dissolved in the liquid balances the metal's solution tension. Since the metal electrode loses positively charged ions, it becomes negatively charged while the liquid becomes positively charged. Therefore, an electric field is created between the liquid and the electrode. The resulting electric force opposes the further solution of metal ions in the liquid and the system is in equilibrium. The potential difference between the metal and the water is called the galvanic potential. It should be mentioned that the galvanic potential cannot be measured directly, since this would always involve a second electrode being lowered into the solution; therefore only the potential difference between two electrodes can be measured.

It is this potential difference between two electrodes in the electrolyte that can lead to oxidation of one of the electrodes. If the electrodes are of different metals, they are called a galvanic couple. It should be noted that not only different metals form galvanic couples; other materials (e.g., carbon) can also be part of a galvanic couple. The galvanic potential between the electrolyte and the electrode is built up at both electrodes. Since the electrodes consist of different metals, their respective galvanic potentials are different and a voltage is built up between the electrodes. This voltage results in a current through the electrolyte and therefore in reduction of one electrode and oxidation of the other.

The potential difference between two materials can be obtained from the electrochemical series, in which the potential differences of different materials in respect to a common reference electrode (e.g., the standard hydrogen electrode) are listed. The voltage between two electrodes of different materials is the difference of the listed values of the potential series.

The electrochemical reduction and oxidation effects have to be considered when designing instruments for the marine environment. The housings of instruments have to be designed to exhibit as little

oxidation in the sea water as possible. When different metals are used in the vicinity of each other (e.g., an instrument and a sensor housing), one of the metals is reduced. To avoid this process, electrodes are sometimes added to the instrument housing, either made of a suitable metal or connected to a voltage, so that all other metals of the instrument are at a negative potential to the electrolyte. The additional electrodes are dissolved slowly in the sea water and therefore have to be replaced from time to time. They are accordingly called sacrificial electrodes.

Another method for avoiding corrosion by electrochemical processes is the surface coating of housings by adding an electrical isolation layer to the metal. A common treatment for aluminum, for example, is anodizing. The material to be treated is used as the anode for the electrolysis of a suitable electrolyte (e.g., sulfuric acid). An oxide layer is formed on the anode surface that is electrically isolating and can be hardened by further treatment to increase scratch resistance of the material.

## Velocity Measurement

The conductivity of the sea water is not the only electric property used for making measurements of the state of sea water. The fact that sea water is an electrolytic solution and contains free charges (the ions) is also used to determine current velocities on various scales.

If a conductor is moved in a magnetic field, a current is induced in the conductor according to Faraday's law. Since sea water is a conductor, a flow of sea water can be seen as the movement of a conductor and therefore Faraday induction can be used to measure the water velocity. If displacement currents in the water can be neglected, the electric potential distribution is given by the equation

$$\nabla^2\Phi = \nabla \cdot (\mathbf{v} \times \mathbf{B}) \quad [22]$$

where  $\Phi$  is the electric potential,  $\mathbf{v}$  is the velocity of the water and  $\mathbf{B}$  is the magnetic field. In an ideal case, where the flow is laminar and uniform, the voltage  $V$  between two electrodes in contact with the sea water is

$$V = rBv_n$$

where  $r$  is the distance between the electrodes,  $B$  is the magnitude of the magnetic field, and  $v_n$  is the velocity component normal to  $\mathbf{B}$  and  $\mathbf{v}$ .

These velocity measurements can be carried out in the earth's magnetic field or by generating a local magnetic field.

### Measurements in the Earth's Magnetic Field

The geomagnetic electrokinetograph (GEK) consists of two electrodes that are towed through the water, behind a ship. The resulting voltage between the electrodes gives a measure of the vertical integrated flow perpendicular to the ship's path.

The expendable current profiler (XCP) is a sensor with two pairs of electrodes attached to the surface of the sensor, which sinks in the earth's magnetic field. The resulting voltage between the electrodes measures the current velocity perpendicular to the sensor's movement; it therefore measures the horizontal components of the water velocity. On descent, the probe is rotated around the vertical axis (the axis of descent) to determine any constant-voltage offsets induced by galvanic potentials.

Another method for estimating large-scale, slowly varying currents is the use of seafloor cables. A cross-basin cable is used to sense the potential difference between the two sides of the basin, which is proportional to the water flow perpendicular to the cable and the earth's magnetic field.

### Measurements with Artificial Magnetic Fields

Another kind of electromagnetic velocity sensors uses the creation of magnetic fields by the use of coils. An alternating current in the coil induces an oscillating magnetic field. Two sensing electrodes are used to define the length of the conductor and the amplitude of the oscillating voltage between the electrodes is proportional to the velocity of the water. A constant-voltage signal can arise from galvanic potentials and therefore is subtracted. Thus, the water velocity can be determined from the oscillating voltage.

### Symbols used

#### Electrical conductivity

$G$	Conductance ( $S = \Omega^{-1}$ )
$V$	Voltage (V)
$I$	Current (A)
$R$	Resistance ( $\Omega$ )
$\sigma$	Conductivity ( $S m^{-1}$ )
$F$	Force (N)
$Q$	Charge (C)
$\epsilon_0$	Permittivity of vacuum ( $A s V^{-1} m^{-1}$ )
$\epsilon$	Relative permittivity
$W$	Work (Nm)

#### Definition of salinity of seawater

$S$	Salinity
$R$	Conductivity ratio
$C$	Conductivity ( $S m^{-1}$ )

$t$	Temperature ( $^{\circ}C$ )
$p$	Pressure (dbar)

#### Electromagnetic wave propagation

$B$	Magnetic field ( $V s m^{-1}$ )
$E$	Electric field ( $V m^{-1}$ )
$q$	Wavenumber ( $m^{-1}$ )
$\lambda_0$	Wavelength (m)
$\omega$	Frequency ( $s^{-1}$ )
$c$	Speed of light ( $m s^{-1}$ )
$\sigma$	Conductivity ( $s m^{-1}$ )
$\epsilon$	Relative permittivity
$\mu$	Relative magnetic permeability
$n$	Refractive index
$k$	Electrodynamic absorption coefficient
$t$	Time (s)

#### Velocity measurement

$\Phi$	Electric potential (V)
$v$	Water velocity ( $m s^{-1}$ )
$B$	Magnetic field ( $V s m^{-1}$ )
$V$	Voltage (V)
$r$	Distance (m)

### See also

**CTD. Expendable Sensors. Inherent Optical Properties and Irradiance. Profiling Current Meters. Single Point Current Meters.**

### Further Reading

- Dexter SC (1979) *Handbook of Oceanographic Engineering Materials*, Ocean Engineering Series. New York: Wiley-Interscience.
- Fofonoff NP (1985) Physical properties of seawater: a new salinity scale and equation of state for seawater. *Journal of Geophysical Research* 90(C2): 3332–3342.
- Krause G (1986) In-situ instruments and measuring techniques. In: Sündermann J (ed.) *Landolt-Börnstein, New Series, Group V, Geophysics*, vol. 3, *Oceanography*, Subvolume a, pp. 134–232. Berlin: Springer.
- Robinson RA and Stokes RH (1959) *Electrolyte Solutions*. London: Butterworth.
- Sanford TB (1971) Motionally induced electric and magnetic fields in the sea. *Journal of Geophysical Research* 76: 3476–3492.
- Shifrin KS (1988) *Physical Optics of Ocean Water*, AIP Translation Series. New York: American Institute of Physics.
- Unesco (1983) Algorithms for computation of fundamental properties of seawater. *Unesco technical papers in marine science* 44, 53pp. Paris: Unesco.
- von Arx WS (1950) An electromagnetic method for measuring the velocities of ocean currents from a ship under way. *Papers in Physical Oceanography and Meteorology* 11(3): 1–62.