OCEANOGRAPHIC EQUIPMENT

The oceans consist of nearly 1.4 billion km^3 of salt water that accounts for nearly 97% of the free water on earth (1). The great volumes of water in the oceans influence the earth's climate by storing, absorbing, transporting, and releasing water, heat, and trace gases. Predictions of future climate conditions depend on understanding the processes that control ocean circulation and water mass formation. The goal of oceanography in general, and physical oceanography in particular, is to develop a quantitative understanding of the physical processes of the ocean. Some important processes include circulation, mixing, waves, energy flux transfer, momentum, as well as the production and distribution of chemical and biological substances within the ocean and across its boundaries. Addressing these problems requires sustained large-scale observations of the world oceans. A successful observation can only be achieved by employing and advancing measurement and computation technology. The design and deployment of a global observation system is an important but difficult task, as such a system would require existing measurement parameters as well as observations that may be different from the routine. In order to achieve these scientific objectives, and to make more comprehensive observations, oceanographers must use both proven methods and new technologies. These include: measurements based on electronic; acoustic and optic sensing methods; measurements made from volunteer observing ships; images from satellites; and observations from buoys. The data may consist of electrical, optical, acoustic, chemical, and other physical parameters. The timeliness of the measurements, the data volume, and sampling density are obvious factors affecting the scientific utility of the data-acquisition process. Thus, data communications plays an important role in oceanography, so much so that it can limit the sampling density. There has been a distinct trend to improve the density of sampling to better understand the effects of the oceans on world climate and other large scale processes, so that it is fair to conclude that the key to tomorrow's physical oceanography will emphasize oceanographic sensor development, telemetry, and communications.

OCEANOGRAPHIC INSTRUMENT DESIGN CRITERIA

The design of oceanographic instruments is a complex subject. Issues taken for granted in the laboratory may be a luxury aboard ship at the ocean surface. Oceanographic instrument design must take into account a number of parameters, including the poor optical properties of the ocean. Visibility rarely exceeds 30 m (2). Generally, operators of oceanographic instruments cannot see the device they operate, as the instrument packages are generally lowered from the surface and lie at the end of a cable thousands of feet away from the operator. Hence the instruments must be designed to operate unattended. Other problems can be caused by the chemical composition of ocean water and by biological fouling. Any material immersed in the ocean for a long time is vulnerable to corrosion and tends to become an attractive area for many different organisms. The sensor and type of measurement rely on environmental and ambient conditions. Small salt particles present in the humid atmosphere tend to corrode electrical contacts and connections at a much faster rate than is usual on land. Voltage and frequency variations of shipboard power as compared to shore-based power necessitate more stringent electrical specifications. In contrast, submersible sensors and instruments have an entirely different set of requirements. Isolation from continuous power sources requires an energy-conserving design. Very high pressures associated with ocean depths are leading to the use of new materials and new design concepts. Vibration and platform motion associated with ships and buoys can occasionally produce effects that may render even well-designed instruments useless. In summary, most parameters measured in the natural environment are not homogeneous in either time or space and are therefore subject to variability with respect to both frames of reference. The instruments of tomorrow's global observation system will incorporate state-of-the-art technology and the latest knowledge and information in physical oceanography, and they must be capable of interfacing with the best modeling and computing resources.

In addition to the aforementioned design hurdles, the trend to understanding ocean processes has led to increased attention to the scale of measurements. Microstructural effects have been observed and are believed to be important in understanding various ocean processes. The challenge then is to make fine-scale measurements and use them to "ground truth" high-fidelity physical models that are being developed concurrently. Such modeling efforts are now common as a result of the advanced computational technology that is now available.

BASIC INSTRUMENT SYSTEMS

Sensing instruments and/or instrument systems attempt to convert some parameter of interest into a quantity that can be easily interpreted by the user. An instrument system generally is comprised of all or some of the following components.

1. A sensor or transducer that converts a measurand (an environmental parameter) into an electrical, mechanical, chemical or optical signal
2. A translator that converts the signal output of the sensor into a convenient (generally electrical) form
3. A signal processor or analyzer that enhances the information contents of the translator's output by electronically processing it
4. A readout or data display system that converts this output into easily understandable terms

At times, items 2 and 3 are lumped together under the name of *signal conditioner*. Some combination of these four components will render information about the environment in a fashion that can be readily interpreted by the observer or by a computing system. It is necessary to provide a communication link such as a wire, radio, or acoustic link for transmission of the signal information between the components listed.

Instrument Characterization

Every instrument can be characterized in terms of a number of desirable properties and every design attempts to incorporate them. Some of these properties can be summarized as follows:

1. *Accuracy.* The ability of an instrument to reproduce or describe a measurand or an environmental condition within known limits of error
2. *Sensitivity.* The ability of an instrument to detect and measure small changes in the measurand. Sensitivity may depend on the measurand and the environmental characteristics.
3. *Repeatability.* The ability of an instrument to produce consistent output for same set of parameters
4. *Ruggedness.* The ability to withstand shocks and manhandling and be able continue to operate within specifications
5. *Durability.* The ability of an instrument to last a long time with minimum maintenance and still properly perform its intended functions
6. *Convenience.* The ability of an instrument to be fully functional with minimum attention from the operator.
7. *Simplicity.* The ability of an instrument to be easily used and maintained. The instrument should not require a crew of engineers to operate it
8. *Ease of Operation.* The ability of an instrument to be easy to operate and understand, both in terms of the concept and the manner in which output is represented.
9. *Reasonable Cost.* The cost of an instrument to be as low as possible for obvious reasons.

Every instrument design should strive to incorporate as many of the above criteria as possible. There may be cases where the requirements appear to contradict each other. For instance, it may be very difficult to design an instrument that is extremely sensitive and accurate without sacrificing simplicity, ease of operation, and low cost. In such cases the instrument designer has to make trade offs. The designer must decide which characteristics are most important and must be retained and what characteristics are less important and can be sacrificed before finalizing the design.

Oceanographic Instruments

Common oceanographic instruments described in this text include conductivity meters, turbidity meters, salinometers, current meters, thermometers, pressure/depth meters, and acoustic sensors. Most of the sensors can be categorized as either acoustic or nonacoustic devices. Examples of acoustic sensors include hydrophones (underwater microphones), side-scan sonar, passive sonar, and so on, whereas magnetometers, gyroscopes, accelerometers, conductivity meters, and the like, represent the nonacoustic type. Generally, there is a trend to develop instrumentation that is robust for long-term deployment. This is now particularly true for water remote monitoring of nearshore or inland areas that may suffer the effects of pollution from agricultural runoff, pesticide spraying, or fresh water dilution. Therefore, techniques for sensing are being developed that require little maintenance and infrequent calibration. In some cases, the calibration is done unattended under microcomputer control at periodic intervals, in others, calibration is still done by the user prior to deployment.

Research and development activities are emphasizing the detection of fine-scale or low-observable effects, as well as the measurement of new parameters. In this regard, new sensors using the latest technologies are being developed, and in some cases modified, for in-water use. While the trend toward higher sensitivity and accuracy is ongoing, it has become necessary to develop means for sensing new observables such as trace metals, organic chemicals, and so on. The direct adaptation of analytical laboratory instrumentation to in situ sensor suites has been traditional for many oceanographers, and government funding continues to be available to adapt laboratory analytical techniques to in situ instrumentation. The viability of these efforts has been brought about by the rapid advancement of microcomputer processing capability, the miniaturization of electronic components, and the reduction of required energy or power for electronic systems. In some cases it is the sensing technology area itself that becomes viable through breakthrough efforts in other fields. Examples are the use of fiber optics for other uses than communications and the advancements in DNA molecular research that are now allowing specific sensors to be made for certain biologic agents or species.

In the case of fiber optics, novel fiber structures coupled with high-sensitivity detection techniques and negligible signal attenuation make them very attractive for communications, as well as for detection and sensing of many different parameters. As a result, fiber optics is generating tremendous interest among researchers, particularly with the US Navy, which has fully realized this potential and is actively participating and encouraging efforts to study and develop fiber optic sensors. Sensor types have been demonstrated for acoustic pressure waves, seismic activity, electromagnetic radiation, strain and structural failure in composites, linear and rotational acceleration, chemical species, biological agents, and so forth. The motivation for using an all-glass approach (instead of wires) is obvious from the standpoint of electromagnetic interference, thermal operating range and, in some cases, complexity. In navigation, for example, the gyrocompass is a mechanically complex device compared to the fiber optic gyro (FOG). It can be safely predicted that fiber optics will play a major role in the oceanographic instruments of tomorrow.

Some of the classical measurements taken by oceanographers are water conductivity, turbidity, salinity, current, depth (pressure), and temperature. Common systems used at sea employ acoustic transducers, hydrophones, seismometers, magnetometers, accelerometers, gyro and magnetic compasses, as well as camera systems, Light Intensity Detection and Ranging (LIDAR), and other laser imaging systems.

Conductivity Measurement

The electrical conductivity of seawater depends on the temperature of the water and amount of dissolved solids (salts) present. In other words, the electrical conductivity varies as a function of salinity for different temperatures. Unfortunately, this variation is nonlinear, giving different incremental value of conductivity for the same salinity at different temperatures. Therefore, the effects of temperature must be negated if conductivity is to be used as a measure of salinity. The platinum resistance thermometer has a response curve that is highly suited for the compensation of temperature as required by the conductivity to salinity relationship. As a re-

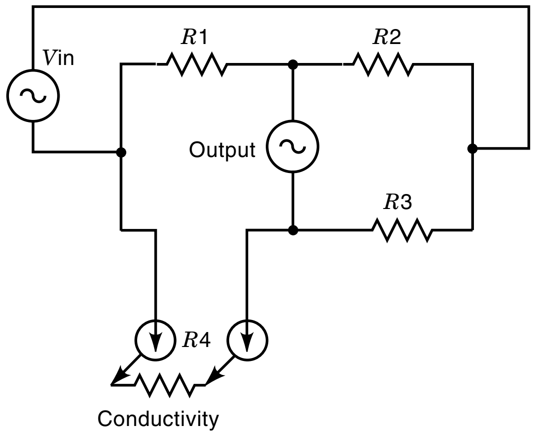

Figure 1. Schematic construction of electrode-type cell.

sult, platinum resistance thermometers are commonly used for compensation.

Traditionally, conductivity measurement instrumentation has been designed according to two different methods. One uses an electrode type cell that forms part of an ac bridge network. Bare-metal electrodes are used to form the basic cell structure that contacts the sample volume. Figure 1 shows the schematic construction of cell type conductivity meter. Changes in cell resistance unbalance the bridge and create a proportional signal across the bridge output. Unfortunately, even small electrode fouling can produce uncertainties on the order of magnitude of the desired accuracy, especially at depth. Cell geometries have been devised that reduce sensitivity to fouling, yet the small diameter tube required for adequate sensitivity leaves this cell susceptible to drift from sediment accumulation and chemical accretions. As a result, the method is not particularly suited for long-term, deep-water oceanography. despite its simpler and comparatively inexpensive design. Still, with proper care, this design is useful for profiling, and for short-term usage in shallow waters.

A preferred method for shallow water deployment in biologically active waters uses an inductively coupled cell in which the seawater forms a single-turn current loop between an excitation coil and a secondary pick-up coil. In this design, electrodes are not necessary and water need not contact any metal surface so that fouling and corrosion are not an issue. Physically, the primary is wound on a toroid that is located in proximity to the secondary. The toroid axes are aligned to allow seawater to create a single-loop coupler as shown in Fig. 2. A change in water conductivity changes the electrical resistance in series with this loop, causing a proportional change in coupled magnetic flux to the secondary signal toroid. The secondary provides an output ac signal that is proportional to the seawater conductivity.

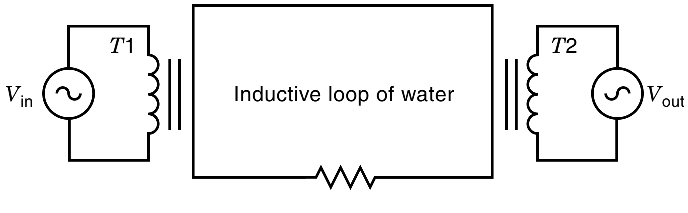

Figure 2. Construction of inductively coupled cell.

A comparison of the two conductivity measurement approaches indicates that polarization effects at the electrodes for the system of Fig. 1 require sine wave excitation frequencies of at least a kilohertz. Furthermore, phase shifts in the bridge network can produce errors. This is particularly true for remote measurements (3). The inductive system of Fig. 2 allows a direct conversion from cell conductance to frequency by making the cell an integral part of the frequency control section of an oscillator. The stability achievable provides some clear advantages for systems intended for high-accuracy measurement and long-term deployment.

Turbidity Meters

Originally, the term turbidity may have been a reference to the effects of turbulence near the sea floor and its effects on the suspension of particulate material. More recently, turbidity has been used as a general term referring to the measurement of the visible optical properties of water. When water is "turbid," it scatters light and makes it difficult to see at a distance. One of the first methods developed to measure water turbidity was the Secchi Disk. The method incorporates a white disk that is lowered to a depth where it seems to disappear. This depth, called the Secchi Depth, is best used as a measure of visibilty, which, in turn, is related to "turbidity." The method was first noted by a ship captain who observed a white dish trapped in a net. The observation was recorded and investigated years later by Commander Cialdi, head of the papal Navy in 1865. Cialdi enlisted the help of Professor C. A. Secchi a year later and together they published a complete report. Although the method seems unexacting, it is able to provide results that are mathematically sound in relation to other more modern measurement techniques

Another means of estimating turbidity used by geologists involves filtering a volume of water and weighing out the remaining solids to develop a mass per unit volume measure. Naturally, the particle size distribution is unknown but is strongly related to the diffractive and scattering properties affecting the visibility characteristics of the medium. Nevertheless, the method is useful in a given geographic area where particle size distribution can remain relatively constant due to suspension from the seabed or from runoff.

Rather than further discuss the many methods used to estimate a general parameter such as turbidity, it is preferable to describe the types of measurements used to characterize the optical properties of water. Understanding the relationships between the many optical properties has been an ongoing research topic that is important to (1) interpretation of satellite-derived images of the sea surface, (2) defense-related detection and reconnaissance systems, and (3) the understanding of radiative transfer processes associated with the ocean itself. Generally, the optical parameters are categorized as either *inherent* or *apparent* types; that is, according to whether the property changes with the radiance distribution at the surface or elsewhere. Inherent properties, those not depending upon radiance distribution, are *attenuation, refractive index, absorption, scattering,* and so on, each having an associated coefficient or parameter.

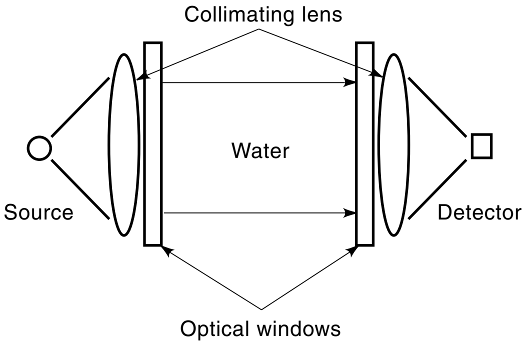

Figure 3. Optical beam transmissometer.

Attenuation is probably the most used optical measure of water clarity. Attenuation can be measured in several ways, according to two definitions. *Beam attenuation* refers to the loss of optical flux as a collimated beam of light is passed through a medium. *Diffuse attenuation* refers to the reduction of light irradiance from a diffusely illuminating light source as observed through the medium with a detector designed to measure irradiance over a 2 π steradian angular field. Although the two definitions appear to be similar, the attenuation coefficient produced by the diffuse method will include a greater amount of scattered flux and will therefore produce a lesser attenuation coefficient. In either case, light lost through the processes of absorption and scattering (both inelastic or elastic) is measured. The most common meter used to measure attenuation is the beam attenuation meter or *transmissometer*. The meter, shown in Fig. 3, consists of a white or monochromatic light source that is collimated to a high degree, usually less than several milliradians, and a detector also having a similarly small angular acceptance.

Usually the transmissometer is designed with a beam diameter sufficient to include a statistically significant number of the largest particles to be included in the measurement over the measurement interval and path length used. Pathlength and beam diameter are typically 25 cm or 1 m and 25 mm, respectively. Transmissometers have been designed using multiple- or single-wavelength lasers, as well as incandescent, arclamp, flashtube, and other white light sources. Beam attenuation coefficients generally range from 0.05/m for the clearest waters to 0.3/m for coastal regimes and to greater than 1/m for estuaries.

An equation describing beam attenuation coefficient c is typically given as follows:

$$I = I_0 \exp(-cz)$$

The term I_0 is the emitted flux or irradiance in the collimated beam and I is the received flux at a distance z through the medium. The units of c are therefore m^{-1}. The beam attenuation coefficient is actually made up of several separate terms.

$$c = c_\mathrm{w} + c_\mathrm{p} + c_\mathrm{d}$$

The subscripts w, p, and d refer to the contributions from water, particulate matter, and dissolved substances, respectively. Each of the terms can be further partitioned into contributions from scattering and absorption according to the definitions for scattering coefficient b, and absorption coefficient a.

$$c = a_\mathrm{w} + b_\mathrm{w} + a_\mathrm{p} + b_\mathrm{p} + a_\mathrm{d}$$

Another useful fact is that, for a given type of particulate material, the attenuation coefficient c_p is directly proportional to the particle concentration expressed as mass per volume. As might be expected, there is no additional scattering term due to the dissolved matter. Due to the difficulty in measuring light scattered over a solid angle of 4 π steradians, it has been customary to measure the absorption coefficient and subtract it from the total attenuation c in order to estimate b—a parameter useful in the prediction of image quality and satellite remote sensing performance. Scattering meters have been designed, but are usually cumbersome to use and calibrate. They are typically designed for operation at a *fixed angle* (small forward angles or 45°), *free angle* (separate angles over the entire angular range), or *integrating* (over an angular range suited for measurement of b directly). In addition to the aforementioned issues, there exists no exacting standard for "clear water," so that the user of the beam transmissometer must rely partially on computed relationships from theory for calibration or from constants provided by the manufacturer.

The Secchi Depth Z_D is related to the beam attenuation coefficient in an approximate manner independent of scattering.

$$Z_\mathrm{D} \approx 7c$$

A Secchi disk is generally white (reflectance unspecified) and about a foot in diameter.

The relationship defining the *diffuse attenuation coefficient* is obtained from successive measurements of irradiance at different distances from the source. The diffuse attenuation coefficient K is defined in terms of the irradiance I_z and I_z measured at two depths Z_1 and Z_2 with a submersible radiometer. Often, solar radiation is used as a source, although other methods using lamps have been devised.

$$I_{Z1} = I_{Z2} \exp(-Kz)$$

A challenge in making this measurement is to obtain a physically stationary depth and a temporally stationary irradiance measure as the radiometer is relocated. Measurements are therefore sometimes made with a surface-located solar reference radiometer that is used to normalize the readings taken at depth. In addition, the effects of surface waves create a disturbance in the readings when the radiometer depth is less than several attenuation lengths. A depth gauge is usually added to the instrument suite to allow a more precise estimate of the measurement depth and a profile is taken against depth to allow measurement of the radiance slope versus depth.

Another relationship suggested by physical principles is the proportionality of light backscattered from the propagating light field to the concentration of suspended solids. A *backscatter meter* is designed to provide an illumination source and a sensitive detector arranged to view the illuminated volume from the source location. Care must be taken in the design to reduce the light backscattered from surfaces such as windows and foreign objects in the volume. Novel designs using infrared semiconductor sources and synchronous detectors are now available. Measurement range is substantially better than for the transmissometer if suspended particle mass is of interest. Mass per unit volume ranges from 20 μg/L for very clear water to over 10 mg/L for extreme turbidity conditions associated with floods and storms.

Recent studies of optical parameters have concentrated on the development of models to describe the relationship of backscattered light at multiple wavelengths to biological and physical processes. These models have been refined and used to interpret satellite data for the purposes of monitoring temperature, ocean circulation, bioactivity (chlorphyll content), water depth, and so on. Instruments have been designed to measure the absorption, elastic scattering (at the same wavelength), inelastic scattering (wavelength shifted Raman and Brouillin processes) (4).

Salinity Measurement

In 1901, *salinity* was initially defined as the gram weight of dissolved solids in 1000 g of seawater. Shortly thereafter, new definitions arose defining salinity in terms of *chlorinity* or the amount of chloride ion in parts per thousand (ppt). Later, this definition was changed to relate chlorinity to salinity measured by means of electrical conductivity. Salinity can range from near zero per thousand for fresh water to 36 parts per thousand for seawater. Required measurement accuracy is determined by the application and is usually specified to be better than 0.02 ppt for oceanic density studies. The measurement of salinity can be performed in a number of ways, as follows:

- Chemical titration
- Density
- Index of refraction
- Velocity of sound
- Conductivity

The first two are uncommon, as they do not lend themselves readily to direct measurement (5). Density and refractive index are quite sensitive to the environmental effects of temperature and pressure, but the latter is useful for high-resolution measurement of microstructural salinity layering. Measurements can exceed 0.01 ppt using refractive index measurement techniques over spatial scales of 1 cm or less. Required resolution in refractive index is approximately 2 ppm (parts per million) for salinity resolution of 0.01 ppt. Chemical titration techniques are difficult to use in situ. Acoustic and sound velocity sensing devices lack the accuracy needed to properly resolve changes in salinity. Similarly, density is of little practical use for the measurement of salinity as it has only a second-order effect on these variables. The classical method of measurement is with a CTD (conductivity, temperature, and depth) meter.

Electrical conductivity has a first-order effect on salinity and therefore it is much more sensitive than any other quantity for measurement of salinity. It should be noted that the electrical conductivity is sensitive to the effects of temperature and to a lesser degree to those of pressure, but these effects are no worse than other methods of sensing salinity. Furthermore, electrical conductivity can be measured directly by electrical means; therefore it is considered as the most appropriate method. The use of a single inductively coupled conductivity sensor, together with a temperature and pressure sensor connected in a single electrical bridge configuration, was demonstrated to produce an accurate salinity readout as early as the late 1960s. Empirical equations relating seawater salinity, temperature, pressure, and electrical conductivity started evolving during the same time period with the original development of Ribe–Howe equation (6). It was found that a resolution of 0.01 S/m in conductivity and 0.01°C in temperature were required for salinity resolution of 0.01 ppt. Even today, this accuracy is difficult to achieve for long periods in moored sensor arrays without frequent calibration, but is easily achievable for short-term measurements.

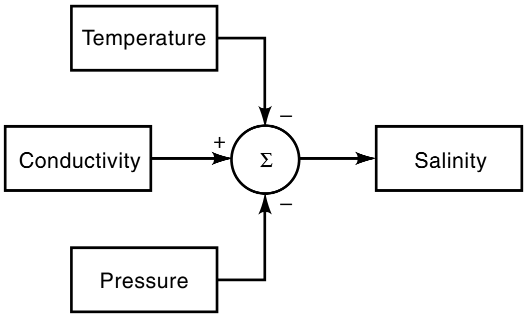

Figure 4. Use of conductivity to obtain salinity.

Ocean-going instrumentation often use two approaches for computing salinity. The first separately records conductivity, temperature, and pressure, and then computes salinity from these variables. The second method combines the outputs of conductivity, temperature, and pressure sensors electronically, such that the output registers salinity alone. Figure 4 illustrates the basic concept of using conductivity to obtain salinity. The second approach can reduce the accuracy requirement if a telemetry link is used and reduces the number of telemetry channels from three to one.

The relationship between salinity and chlorinity is given by

$$S = 1.80665 \cdot Cl$$

where each quantity is measured in units of parts per thousand (ppt). Since World War II this definition has been abandoned in favor of that in terms of electrical conductivity:

$$\begin{aligned} S = & -0.08996 + 28.2972R + 12.80832R^2 - 10.67869R^3 \\ & + 5.98624R^4 - 1.32311R^5 \end{aligned}$$

The parameter R is defined as the ratio of conductivity of the sample at 15°C and 1 atm to that of water at 15°C and 1 atm with salinity of 35 ppt.

In an attempt to observe fine-scale salinity distributions, novel instrumentation has been developed using refractive index methods. The relationship between refractive index n of seawater and parameters such as wavelength, pressure, and temperature is determined by the equation of state. Although there has been considerable controversy over the determination of the best form, the approximate relationships are as follows:

$$\begin{aligned} \partial n/\partial\lambda &\approx -4\times 10^{-5}/\text{nm, visible}\\ \partial n/\partial P &\approx +1\times 10^{-5}/\text{bar}\\ \partial n/\partial T &\approx -6\times 10^{-5}/{}^{\circ}\text{C}\\ \partial n/\partial S &\approx +2\times 10^{-1} \end{aligned}$$

Developmental techniques for measuring refractive index to the required part per million level have reached varying levels of performance. The following is a list of demonstrated refractive index measurement techniques that have been used for high-resolution refractive index determination (7).

Abbe Half-Sphere	10^{-6}	1982
Differential Michelson	$<10^{-6}$	1984
Critical Wavelength Refraction	2×10^{-5}	1987
Pellin Broca Prism refractometer	2×10^{-5}	1983

CURRENT MEASUREMENT

An important goal of physical oceanography is to understand the physical properties and movement of seawater and its interactions with the surroundings. Hence the quantization of water movement or currents is important. Traditionally a mechanical sensor that rotates due to mechanical drag or lift caused by the moving water measures water current. This rotation is proportional to the water velocity. Unfortunately, mechanical sensors become unreliable when water velocity approaches a few centimeters per second and they can disturb the hydrodynamic conditions of the fluid. Furthermore, they may not be suitable for fast turbulence studies due to their limited bandwidth of less than 1 Hz.

Classical methods of measuring current have been by either indirect or direct means. The equations of motion provide a means for determining current under the *geostrophic approximation,* where only the pressure gradient force per unit mass and the coriolis force per unit mass are in balance. In this case it is only necessary to measure density or pressure gradients.

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = 2\Omega v\sin\varphi$$

Here ρ is the medium density, Ω is the rotational speed of the earth, v is the speed along the y-axis, φ is the latitude, and p is the pressure. The pressure gradient can be converted to a density gradient, which provides enough information to compute the speed.

Another indirect method relies upon the earth's magnetic field to determine current. From Maxwell's equations, an electrostatic field will be created for charges flowing through the earth's magnetic field B at speed v. If the vertical field component is H_z, the electrode separation is l, and the potential is V, the relationship is given by the force balance.

$$V/\ell = v\times B = kvH_z \approx 1.1vH_z\times 10^{-8}\,\text{V}$$

Since all units are in the cgs system, the produced voltage is small and is affected by contact potentials at the electrodes, which are often as much as 1 mV. This method is therefore better at establishing current direction rather than absolute speed. Electrochemical half-cells can be unintentionally produced at each electrode. (When designed to do so, these half-cell reactions may be used to detect hydrocarbons in sediments as a result of bacterial activity, producing potentials of several millivolts or more.)

Direct methods of current measurement include the so-called Lagrangian and Euler-based approaches. The former uses drifting objects such as buoys or dyes. Although seemingly primitive, modern drifting buoys may use the global positioning system (GPS) for position updates and may employ satellite communication for data transfer providing exceptional data. Subsurface buoys may be tracked acoustically and fluorescent dye plumes may be detected at low concentration at great distance. Euler methods consist of dynamic and static sensors; for example, rotating vane devices such as the propeller and Savonius rotor, or static devices like the pressure plate, arrested rotor, and pitot tube. The Savonius rotor is preferable over propeller-type rotors, since it is sensitive to water flow in only one direction. The pitot tube uses the pressure differential principle and is commonly employed for aircraft air speed sensors.

Although the aforementioned current-sensing techniques are common, development of electronics and advances in transducer technologies have made it possible to measure fluid velocities by exploiting the interaction between a moving fluid and either an acoustic wave or electromagnetic field. A number of instruments have been designed and built using nonmoving sensors. They include electromagnetic current meters, laser Doppler current meters, and acoustic or ultrasonic current meters.

The electromagnetic flow sensor contains a coil to produce a magnetic field. A set of electrodes is used to measure the voltage gradient across the face of the coil. A voltage gradient is induced in water when it flows through the field. According to the principle of induction, the induced voltage field is the vector product of the velocity and the magnetic field. The magnetic field of the coil depends on the current and the number of turns. But the magnetic field varies with the square of the power. Therefore, with a typical 100 mW dc-powered coil, the resulting field reacts to produce a potential difference of 10 μV to 15 μV for a flow of one knot. A flow of 0.01 knot will result in an output electrode potential of $\sim$0.1 μV. Due to chemical uncertainties at the electrode surface, it is nearly impossible to get two electrodes to remain within a few microvolts potential. Stray currents and electrochemical effects resulting from fouling of the electrode surface may produce two to three orders of magnitude larger static offset. However, if the magnetic fields are periodically reversed, the polarity of the electrode potential due to water flow will change but the static offset will remain constant. The electrode voltage can be detected in synchrony with the reversal of the field. The magnitude of field is a function of the velocity of flow. Electrode errors and amplifier dc offset and drift become insignificant with this approach, allowing large ac voltage gain to be used without saturation from dc potentials. It is important for stability that the dc bias potentials remain constant during the field cycle. Furthermore, after each field reversal the measurement of the electrode voltage has to be delayed until the field becomes stable.

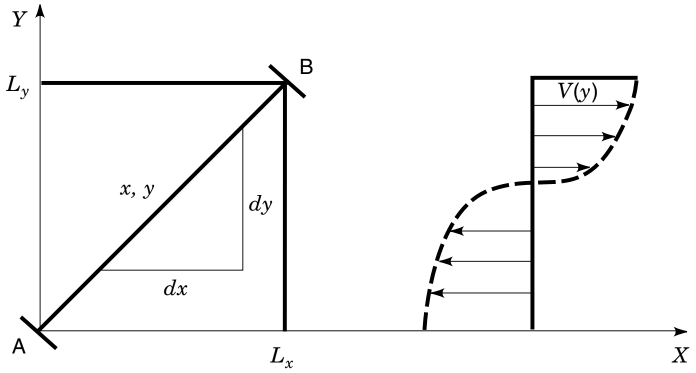

Figure 5. Travel time arrangement to determine current velocity.

All acoustic and ultrasonic current-measurement instruments are based on the principle that the net velocity of an acoustic wave propagating in a moving fluid is the vectorial sum of the fluid velocity and the velocity of sound in the fluid at rest. Ultrasonic current measurement is mostly made with the help of two piezoelectric transducers placed in a moving fluid in a unidirectional field arrangement. Although a number of different signal processing techniques are available, the following three systems are generally used—(1) the "travel time" or the "leading edge" system, (2) the "sing around" system, and (3) the "phase difference" system. In the travel time or leading edge system, voltage steps of few hundred volts at a fixed repetition rate excite the two piezoelectric transducers simultaneously. Each excitation produces a burst of exponentially damped acoustic oscillations at the surface of the two transducers. These acoustic wave trains travel toward the opposite transducer. As a result the travel time of the leading edge of the signal can be determined and can be correlated to the current speed, assuming the speed of sound is known and remains fixed. In order to compensate for changes in sound velocity, the average travel time for both the piezoelectric transducers are simultaneously measured and computed.

Figure 5 illustrates the travel time arrangement to determine current velocity. It comprises two transducers A and B, pointed toward each other in a one-dimensional flow field $v(y)$. The sound path between the two transducers is at an angle θ to the x-axis that coincides with the direction of flow. The transit time difference, Δt, for ($v^2 \ll c^2$), can be given as

$$\Delta t = \frac{2L\bar{v}}{c^2} \cos \theta$$

In other words, the travel time difference (Δt) is a function of the mean fluid velocity ($\bar{v}$), the velocity of sound (c), and the projected length (L) of the path followed by the sound.

The sing-around method is basically a pulse technique in which each new pulse in one direction is triggered by the arrival of the previous. After a number of repetitions the sound direction along the length is reversed. The difference in the pulse repetition rate then provides the time difference. The instrument is consisting of two sing-around velocimeters. The velocimeters are arranged in such a fashion that the transmission paths in the liquid are equal and adjacent but the directions of travel of the pulses are opposite. One velocimeter measures the sum of the speeds of sound and current flow while the other is used to determine the difference between the two speeds. Hence by taking the difference of the sing-around frequencies of two the velocimeters, we obtain an output signal that has its frequency proportional to current flow. The ideal velocimeter has an output frequency (f) given by

$$f = c/L$$

where c is the velocity of propagation and L is the distance between the two transducers. Since the transducers send pulses in opposite direction and if v is the current flow, then the two sing-around frequencies are

$$f_1 = \frac{c+v}{L} \qquad \text{and} \qquad f_2 = \frac{c-v}{L}$$

Taking the difference of the two frequencies and assuming n repetitions at an angle θ (for $v^2 \ll c^2$), we get

$$f_v = f_1 - f_2 = \frac{2v\cos\theta}{nL}$$

Hence the difference of the two sing-around frequencies (f_v) is proportional to the current flow, and in this ideal case, the velocity of sound does not effect the measurement of flow and currents. It can be noted that small individual differences in time intervals are accumulated, by n repetitions, to make a larger and more easily detectable difference signal.

Using similar physical principles, Acoustic Doppler Current Profilers (ADCP), acoustic Doppler single-point current meters, and correlation sonars are now reaching maturity and dominate research and development in current sensing. They are true beneficiaries of advances in technology and computing that employ state-of-the-art signal processing, high-performance acoustic transducers, and large data rates. The operating principle generally relies on return and processing of Doppler-shifted acoustic signals from a remote volume of water to assess fluid flow. Acoustic Doppler sensors have also driven technological advancement. Broadband techniques have enhanced the sample frequency, speed resolution, and range product limit as compared to the earlier incoherent ADCPs, permitting custom application to turbulence measurements where fast sampling and high resolution are necessary to resolve turbulent spectra. Another advantage of ADCPs has been the reduction in mooring cost of bottom-mounted instruments. This is particularly true in shallow waters where the profile of an entire water column is possible, except for an approximate of 15% ambiguous region near the surface.

Finally, remote satellite imagery is used for remote determination of oceanic currents. When current systems are composed of waters whose characteristics are slightly different from the surrounding water, it is possible to locate these currents by exploitation of slight differences in relative motion in the same direction or different directions. Sensing methods used include temperature, texture, solar glint, back-scattered light radiance, and Doppler radar. These techniques are best described under the classification "remote sensing."

Ocean current sensors have employed a variety of measurement techniques and are continuing to develop. Rotor-and-vane or impeller-type sensors are now giving way to acoustic Doppler-type measurements. Mechanical sensors continue to be used but are being upgraded with digital and more advanced electronic readouts and interfaces. There has also been an emphasis on the use of airborne or air-operated Doppler instruments for numerous applications. Radar backscatter at multiple frequencies provides current maps as well as directional wave spectra. The number of such instruments and their acceptance are increasing with demand for remote sensing. Acoustic travel time current meters continue to be employed for in situ applications. The implementation of Electromagnetic and Laser Doppler Velocimeter (LDV) current measurements is complicated by cost and size constraints, although three-dimensional measurements and miniaturization for in situ deployment are currently of interest to some users. Indirect means, including drifters, altimeters, and hydrographic means, are still popular and remain as important as they were. Historically, sensors are getting smaller and are measuring a wide variety of current-related flows including boundary layers, heat flux, and vorticity. It is projected that development in current meters will remain an important and active process.

PRESSURE

Most of the physical quantities like conductivity, salinity, and depth measurement are closely related to pressure. Like any other process, pressure measurement is critical to physical oceanography. A classical method employs two mercury filled thermometers, one *protected* and the other *unprotected,* to perform deep-sea measurement of pressure. The unprotected thermometer is similar to that used for measuring atmospheric temperatures. The protected thermometer is encased in a second glass housing with a mercury chamber designed to allow better heat transfer from the surrounding water. The two thermometers are lowered together and measurements are taken simultaneously. The unprotected thermometer will be subject to the effects of pressure more so than the protected one, and will therefore read higher. If the readings are standardized, the difference in temperature will allow estimation of the hydrostatic pressure.

With the advent of electrical measurement technology, a variety of new pressure-measurement techniques were devised. These methods were somewhat different in construction from the mercury-filled thermometers and generally used a mechanically deformable sensing element. The most common of these is the spring bellows or the aneroid element. This is made with the help of a compressible waterproof chamber that acts against a spring, forming a bellows type structure. As the pressure is increased the bellows experiences inward motion due to compression, and vice the versa. This motion may be used to drive an electrical transducer or mechanical indicator. Another way of translating the increase in pressure to mechanical motion is achieved using a Bourden tube. The Bourden tube is a fluid filled, curved tube that changes its curvature and tends to straighten with an increase in pressure. Readout is achieved with a mechanical indicator. Another transducer, the Vibratron, uses a vibrating wire as its sensing element. The vibrating wire is attached to the two tines of a fork. Hence the frequency of vibration of the wire depends on the tension exerted by the fork. When pressure is applied to the fork, the wire tension changes, producing a different fundamental oscillation frequency of the wire. The oscillation is sensed by a magnetic pickup located near the wire.

A more modern mechanical method uses a piezoelectric element to sense the pressure directly. The capacitance change is converted to frequency by allowing it to parallel the tank circuit capacitance in a relaxation or other oscillator. The physical configuration consists of an inner cylindrical quartz element coated with a platinum film that is fused to an outer section of a precision bore quartz tube. This tube is also coated on the inside with platinum film. Together, these two electrodes form a capacitor. As pressure acts on the outside tube, the diameter of the tube decreases, reducing the spacing between the elements, lowering the capacitance. Quartz is a material of choice to its high stability, availability, construction, and relatively small temperature coefficient of expansion.

Pressure transducers also use materials whose resistance tends to vary with pressure. A common example is carbon. Carbon granules are used in some pressure sensors in the same manner. An increase in pressure reduces the bulk resistance of a package of carbon granules. Some semiconductor devices also utilize this mode; for example, the tunnel diode is an example of a device that changes resistance with pressure.

Pressure may also induce mechanical strain in certain structures, allowing strain sensors to be used for measurement. Electronic bathroom scales often use a strain gauge to observe deformation of cantilevered beams as weight is applied. Strain may also be sensed using different transducers; for instance, the current flowing through a semiconductor varies exponentially with strain, and electrical strain gages exhibit a change in resistance under varying strains. Similarly, fiber optic sensors are extremely sensitive to changes in strain, providing resolution of several microstrain or less. All of these techniques have been used in one form or the other to determine pressure.

ACOUSTIC TRANSDUCERS/HYDROPHONES

The ocean is virtually opaque to light in the infrared and ultraviolet spectral regions. Visible light is also attenuated with attenuation coefficients of 0.05/m in the blue-green spectral region under the best conditions. Practical transmission distances, therefore, are always less than several hundred meters. Therefore, except for short-range examination, photography and video, optical techniques are of little use for long-range detection, communication, and sensing. Conversely, the ocean is a good conductor of sound energy. Acoustic waves travel readily in water whereas all but the lowest frequency (VLF) electromagnetic waves are rapidly attenuated. Acoustic or pressure waves, therefore, offer an opportunity to see the interior of the ocean. For all practical purposes, hydrophone arrays serve the dual purpose of underwater eyes and ears of the oceanographer.

The bandwidth associated with underwater acoustics is good, varying from the millihertz to the megahertz range. This allows the use of sound as a probe of objects and processes whose scales can vary from millimeters to ocean basin scales. The ocean is especially transparent to low frequencies where it offers comparatively low attenuation. At high frequencies, attenuation is increased, but the wavelength is much shorter as determined by the speed of sound c.

$$\lambda \cong \frac{c}{f} = \frac{1500\text{ m/s}}{f} = 0.1\text{ m at }15\text{ kHz}$$

Because angular resolution is determined by the diffraction limit, which, in turn, is dependent upon wavelength, higher frequencies are suited to the development of imaging sonar and narrow beamforming arrays. The attenuation coefficient in fresh water α_F is generally a function of the square of the frequency f, as well as the density-speed of sound product $\rho_F c_F$, and shear/bulk viscosities, $\mu_F \mu_F$. Attenuation in seawater α_s is a little more than an order of magnitude greater, having contribution from magnesium sulfate and boric acid relaxation terms.

$$\alpha_F \approx 4\pi^2 \frac{4.34}{\rho_F c_F^3} \left[\frac{4}{3}\mu + \mu\right] f^2 \Rightarrow 4.9 \times 10^{-2}\,\text{dB/km at 10 kHz}$$

$$\alpha_s \approx 0.1 \frac{f}{1+f^2} 40 \frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 (kyd^{-1})$$

Therefore, only short-range performance is available when the wavelength is suitable for locating objects at centimeter resolution. Examples of various high-frequency systems include current profilers, active and passive sonar, doppler-velocity logs, and communications systems. Continuous measurement of ocean currents is possible from shipboard acoustic sensors known as acoustic doppler current profilers (ADCPs) can provide a two-dimensional record to several hundred meters. Active sonar includes multibeam types capable of imaging at ranges from 10 m to 1000 m or more, depending on the frequency of operation. Passive sonar, aside from having proven advantages for detection, is still the object of advanced development for source localization, bioacoustic characterization, and imaging. Doppler logs use spatial correlation principles to assess platform movement (velocity) for acoustically obtained seafloor signatures, whereas communications systems use various modulation and receiver design methods to obtain maximum channel utilization for a given range/frequency.

In spite of these proven application areas, sound is still an underemployed tool in oceanography. Significant developments are being made in this area by thoughtful application of acoustic principles and techniques for direct probing of the ocean and information transfer through it. Some of the applications of underwater acoustics are simple. Others may require complex and improved signal processing techniques and instrumentation. Coverage of the many signal processing advancements and system configurations are beyond the scope of this text, but many good references exist.

All underwater acoustic observations are made with the help of transducers that convert part of the energy of the acoustic wave to an electrical signal. Some appropriate electronic circuit processes this signal to provide the output. The output devices can range from an audio recorder or oscilloscope to computer waterfall displays of power spectrum (sonagrams) and other signal processing constructs. The transducer used for reception is called the hydrophone and is generally made of ceramic or quartz crystal. It is a broad band device operating well below the resonant frequency of its active elements. Its construction resembles that of the piezoelectric microphones, where a ceramic or quartz crystal is either linked with a diaphragm or is directly exposed to acoustic waves. Stresses in the crystal, resulting from the acoustic or sound wave, generate an output voltage that is proportional to the acoustic pressure. Some designs incorporate a built-in preamplifier next to the crystal to reduce electrical noise and output impedance. The elements of construction are well sealed and can operate over a wide range of frequencies. Sometimes a transducer similar to the hydrophone is used as a generator or *projector* of acoustic signals. The *projector* often requires thousands of volts of excitation to achieve a large acoustic signal output.

Fiber optics and piezofilms are two of the new candidate technologies for hydrophones that are gaining rapid recognition. The piezofilm consists of an electrically active fluoropolymer that has piezoelectric properties. It exhibits both parallel and transverse piezoelectric effects, but due to its physical characteristics, the parallel, or thickness mode is commonly used. This is generally known as PVDF or PVD due to its chemical name Polyvindylidene Fluoride, and it has found application in noise-canceling hydrophones. It is stable and operable at temperatures over 120°C, in addition to withstanding application of voltage stresses of several thousand volts or accelerations to several hundred times without becoming depolarized. It can be laminated to form multilayered bimorphs or multimorphs that result in multiplication of transducer response levels, but like many hydrophones, is not good for applications requiring power-handling capability. It is suited for low-power-emissive transducers and in hydrophone or microphone applications. Due to its pliability, it can be directly attached to almost any structure to form transducers of almost any shape. This and similar materials are suited for large array fabrication and for high-frequency use in imaging sonar applications.

Fiber optics also lends itself well to wet area applications and is used extensively for undersea communications due to its high bandwidth capability, low weight per unit length, and low loss. Perhaps surprisingly, optical fibers are also a viable means for constructing hydrophones and seismic sensors. Acoustic pressure tends to change the characteristics of optical fibers which can, in turn, be sensed by changes in the propagating light field in terms of light intensity, phase, polarization, spectral distribution, or allowed spatial mode. Interferometric phase sensors are particularly sensitive, since changes of fractional wavelength dimensions can be measured. Over the last ten years, fiberoptic sensors have been built to demonstrate measurement of many parameters, including strain, temperature, force, electromagnetic field intensity, vibration, shock, pH, refractive index, and some chemical species. Practical fiber optic devices, including hydrophones, are now commercially available. Fiber optic sensors have a number of inherent advantages over traditional techniques with respect to electromagnetic interference and detection, mainly because they are photon based, not electron based, and transmission is therefore in dielectric materials instead of conductive wires.

Aside from the obvious advantages of electromagnetic interference, optical fibers also exhibit low cross-talk, light weight, compact size, large bandwidth, resistance to corrosion, ability to operate safely in wet, hazardous, and explosive environments, multiplexing capability, and remote real-time operation. Their small mass and submillimeter size allow embedding and in situ operation. The sensitivity of the fiber optic sensors to the measurand is measured in terms of the induced phase shift of light. The phase shift ψ, for light of wavelength λ_0, propagating in a single-mode fiber of gauge length L, and refractive index n_1, can be written as

$$\varphi = \frac{2\pi L n_1}{\lambda_0}$$

In operation as a hydrophone, the fiber is wound on a complaint mandrel, where acoustic pressure will result in a force F that will predominantly change the length L. The induced change, ΔL, depends on the Young's modulus, E, of the material. Mathematically it can be represented as

$$\Delta L = \frac{FL}{AE}$$

where A is the cross-sectional area of the fiber. The Young's modulus for quartz glass is 2×10^{11} Pa. Hence the resultant change of phase $\Delta\varphi$ due to an axial force F will be

$$\Delta\varphi = \frac{2\pi n_1 LF}{\lambda_0 AE}$$

Similarly if the same fiber sensor is subjected to a uniform radial pressure P, then the gauge length L of the sensor will also increase due to the Poisson effect. If ξ is the Poisson's ratio of the material ($\xi = 0.2$ for quartz glass) then the increase in length can be represented (8) as

$$\Delta L = \frac{2\xi PL}{E}$$

and the change in phase of the sensor becomes

$$\Delta\varphi = \frac{4\pi n_1 \xi LP}{\lambda_0 E}$$

Two light signals, one from a reference arm and one from the sensor, interfere at the detector to produce an output electrical signal that changes proportion to variations in the optical path. Generally fiber optic hydrophones utilize the Michelson or the Mach–Zhender interferometers. Coherent light from the source is split into the two paths using a fiber optic coupler. One path is fed to an isolated reference arm and the other to the sensing arm. The acoustic energy applied to the sensing arm produces a change in the optical path length, and is detected as an sinusoidal intensity change. Signal-to-noise performance with this approach exceeds that available from hydrophones using piezoelectric transduction, and its use is, therefore, becoming more widespread.

There are many applications where a single transducer cannot provide the performance required for signal detection and analysis. In such cases more than one transducer can be used. An assembly or group of more than one transducer is called an array. It is basically a series of transducers, which are driven together in case of a projector, and their outputs are integrated in some prearranged fashion in case of a detector, to enhance the received signal-to-noise ratio. The *array gain* (AG) is used to measure the enhancement of signal-to noise-ratio. The arrays could be two- and three-dimensional as well.

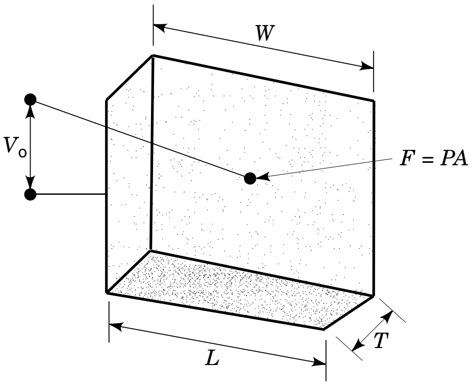

Figure 6. Piezo crystal produces output voltage with changing pressure.

$$\text{ArrayGain} = 10 * \log_{10}\left[\frac{(S/N)\text{Array}}{(S/N)\text{SingleHydrophone}}\right]\text{dB}$$

Basic hydrophone construction is shown in Fig. 6. The hydrophone element(s) are usually backed with materials having specific acoustic properties. Computer programs are now available for individual hydrophone design. External coatings are selected for low loss, low bubble content, durability, and speed of sound similar to that of the water. Acoustic impedance matching mandates selection of ρc products close to that of the medium. Certain rubber compounds and urethanes meet these requirements and are typically used.

The array gain may be used to determine the link performance of any acoustic transmission and reception system. When the signal transmitted is a plane wave and the noise is isotropic, the array gain reduces to the directivity index (DI). The source level (SL) is defined in terms of decibels relative to 1 μPa (1 N/m^2 pressure).

$$SL = 171.5 + 10\log P + DI$$

The term P is the emitted power in watts. Once SL is known, the transmission loss TL can be used to determine the signal level at a distance R in meters. Generally, the source is considered to follow an inverse square reduction as a function of R for deep water.

$$TL = 20\log R + \alpha R \times 10^{-3}$$

Here the attenuation α is given in units of kilometers^{-1}. In shallow water the loss is cylindrical, following an inverse R relationship where the factor of 20 in the equation is halved. The sound level at a hydrophone located at a distance R is given by the difference SL − TL. At the hydrophone array with directivity index (DI), the signal level can be compared to the ambient noise (NL to establish the signal-to-noise margin or detection threshold (DT).

$$DT = SL - TL + DI - NL = SL - TL - 15 + 20\log f$$

The noise is computed for a deep-sea location devoid of other than thermal sources. In the case of sonar, where the path is two-way, TL is doubled and the target strength is added to the right side of the equation. Target strengths are computed for different target types and may be found elsewhere, but generally these equations provided here are adequate to assess hydrophone performance. The actual electrical signal produced by the hydrophone is obtained by conversion of SL − TL + DI to an open-circuit voltage using the OCV response for the hydrophone in units of dB re:1 V/μPa.

MAGNETOMETERS

Magnetic flux density sensors provide an electrical output that is proportional to the magnetic field strength. The most common device for measuring flux density is the Hall effect sensor, where the excitation current is kept constant and a semiconductor crystal, placed in the field, produces voltage along the axis perpendicular to the direction of the field and current flow. This voltage is proportional to the flux density. Hall effect sensors are designed as small-size probes and can contain one, two,or three crystals in a single package to measure one, two, or three mutually orthogonal transverse directions.

Another common type of magnetic sensor is the *inductive magnetometer,* made of iron core or other inductor. According to Faraday's law, the induced voltage in a coil that is placed in an alternating magnetic field is proportional to the measured flux density. Steady-state magnetic fields can be measured by spinning the coil and measuring the induced ac voltage.

The *nuclear magnetic resonance flux meter* is also used to measure magnetic fields and field anomalies. It is based on the dependence of the sensitivity of nuclear resonance frequencies, of certain substances, under magnetic field strength. The transduction element generally consists of a coil wound around a small container of deuterium or lithium. The coil is excited by a high-frequency current. The resonance frequency is detected by a sharp increase in the power consumption of the system due to the characteristic energy absorption of the material. The frequency is related to the desired magnetic signature.

The *flux gate magnetometer* is also a very sensitive device and it is used to measure extremely small magnetic signals. It consists of several saturable reactors that are excited by an ac signal. The ac drive signal ensures that the induction in core of the reactors is kept close to saturation. Under the influence of steady external fields, components of second harmonic current are induced in the reactor circuit. The second harmonic signals provide measure of the flux density. These components are not detected in the absence of any external fields. Three mutually orthogonal reactors can be used to measure the flux density along the three axes.

NAVIGATIONAL SENSORS

The most common navigation instruments include the "compass" and the "gyro compass". Compass construction may be mechanical, magnetic, or electromagnetic (flux-gate). The gyrocompass includes electromechanical, laser, and fiber optic types.

A basic mechanical compass consists of a permanent magnet dipole magnetic and a graduated indicator. In the simple case, the magnetic dipole is a magnetized bar or needle that pivots on a bearing and is installed so that it is free to move about an axis aligned approximately with the gravitational pull. If properly positioned, the needle points toward magnetic north established by the magnetic field structure of the earth's core. The graduated or marked disk is fixed to the vessel structure. The relative displacement between the needle and the disc indicates the deviation of the vessel course from magnetic north. The top of the compass has a small look-through window onto which is painted a straight line known as the lubber's line. A compass is a standard part of almost any undersea vehicle and is used by the operator to guide the vessel until the desired direction is opposite the mark. Directions of travel are generally given in degrees. North is assigned zero degrees. As the circle has 360°, moving clockwise through 90° will lead to an easterly course. South is at 180° and moving clockwise through 270° will lead to west. Generally, the marine compass is marked in 5° increments.

A magnetic compass may be affected by ferrous material on the vessel on which it is mounted. This error is known as magnetic deviation. *Deviation* keeps the compass from pointing to the magnetic north. *Declination* keeps it from pointing to geographic north. Usually, a compass is installed on a well-selected location and, if inaccuracies are still detected, small magnets are placed in special slots within the compass to correct the inaccuracy and compasses must be checked frequently. Compass readings are generally made when on a straight course at a steady speed. Generally they are not used during turns because of the inertial effects of the damping fluid on the indicator. Before making a turn the navigator notes the compass reading and then sets the *directional* (inertial) *gyro* to that reading. Then the turn is made and the *directional gyroscope* indicates the direction of the turn. Some time after completing the turn and after resuming the straight course, the compass readings are checked again to make sure of the exact direction being followed.

The directional gyro does not replace the magnetic compass but it is valuable in making precise turns and maintaining a straight course. It is a practical necessity, even in ordinary voyage conditions. It is a gyroscope that is mounted in such a way that it can move in any direction. When the gyroscope wheel is set in a certain position it will remain in that position according to the law of conservation of momentum, in spite of inertial forces observed in the vessel frame of reference due to motion. The property of the gyroscope that allows it to hold a fixed position is known as rigidity. The rigidity of a mechanical gyroscope wheel in the directional gyro is tremendous because the gyroscope wheel is massive and travels at high rotational speeds—nominally hundreds of miles per hour at the circumference. Thus, the angular momentum and energy are large compared to frictional losses. Like most other gyros, the wheel of the directional gyro does not stay indefinitely in the direction in which it was started. It tends to drift of slowly off position because of the rotation of the earth. At the North Pole the gyro would drift nearly 15° per hour. On the contrary, at the equator, there would be no drift at all. Anywhere in the United States, the drift is such that the operator should adjust the gyro after about every 15 to 20 min.

Modern high-precision gyroscopes are sometimes optical rather than mechanical. A higher degree of accuracy can be obtained with proper design. Laser and fiber optic gyros are the dominant types. The optical gyro is basically a type of interferometer that is used to detect rotation by the Sagnac effect. Consider a circular coil of fiber wound around an axis of rotation. Alternatively, a square, or triangularly shaped ring laser may be used. The idea is to divide the light beam into two equal-amplitude clockwise- and counterclockwise-rotating beams. If the vessel containing this structure is not rotating, the optical transit time is same for both the beams. If the plane of the ring starts rotating in a clockwise direction, at any rate, then the clockwise beam will have to cover a slightly longer path as compared to the counter clockwise beam, before the two optical beams meet and interfere with each other. This will cause a difference in the propagation times of the two counterpropagating optical beams. The change in phase due to this time delay can be detected and processed to obtain very high-resolution information regarding rotation. The laser gyro has been used for many years now and can provide low drift rates and circular error performance (CEP) when used as part of an inertial navigation system (INS). The performance of the Sagnac interferometer improves with the area of the ring per loop. For this reason, the fiber gyro is becoming more practical for small, high-performance applications. Many turns of fiber can be used to increase the delay for a given rotational rate, thereby improving sensitivity. The optical fiber gyro is insensitive to most of the unwanted environmental effects on the fiber, as both the counterpropagating beams travel along the same path. Fiber gyros have proven performance for short-duration operation of ten to fifteen minutes, while laser gyros have established performance for long-mission undersea operations. *Fiber gyros,* (FOGs) are still being improved, but several commercial models are low cost (several thousand dollars) and provide rotational linearity of 1% and drift rate of 2° per hour, respectively.

The fiber optic gyro is basically a type of fiber optic sensor that is used to detect rotation. The primary principle of operation for the fiber optic gyro uses the Sagnac effect. Consider a circular coil of fiber wound around an axis of rotation and a fiber optic coupler at the input separates, the input transmitted beam, into two equal amplitude clockwise- and counterclockwise-rotating beams. If the vessel containing this fiber is not rotating the optical transit time τ, is same for both the beams and it is given as

$$\tau = \frac{2\pi R}{c}$$

where R is the radius of the loop of fiber and c is the speed of light. If the plane of the fiber starts rotating in a clockwise direction, at a rate of Ω radians per second, then the clockwise beam will have to cover a slightly longer path as compared to the counterclockwise beam, before the two optical beams meet and interfere with each other. This will cause a difference in the propagation times ($\Delta\tau$), of the two counterpropagating optical beams that can be given as

$$\Delta\tau = \frac{4\pi R^2\Omega}{c^2}$$

The change in phase ($\Delta\phi$), due to this time delay can be detected and processed to obtain very high-resolution information regarding rotation. If v is the operating frequency of light then the change in phase can be given (9) by

$$\Delta\phi = \frac{8\pi^2 R^2 v}{c^2}\Omega$$

The optical fiber gyro is insensitive to most of the unwanted environmental effects as both the clockwise- and counterclockwise-propagating beams travel the same path. These gyros are excellent for applications that involve short duration of time, (e.g., few tens of minutes). They are still in developmental stage and have just started penetrating the market. Continuing research on behalf of industry and academia to produce lower-cost, high-performance units is ongoing.

Accelerometers are also an essential part of any inertial navigation system. Both optical and mechanical types are common. The most common type uses piezoceramics. They are mostly designed on the spring and mass concept. A mass connected to a spring-loaded system will react to every acceleration due to its inertia. As a result, a force that is proportional to the acceleration will be exerted on the piezo crystal. This force on the crystal causes an output voltage that can be correlated to acceleration. In addition to single-axis accelerometers, biaxial and triaxial accelerometers are also available. Currently the fiber optic and beryllium Hopkinson bar accelerometers are state of the art (10). Other methods of sensing acceleration employ p–n junctions, MEMs, and capacitive transducers.

POSITIONING, TRACKING, AND SURVEY SYSTEMS

Although surface vessels continue to use magnetic and inertial navigational aids, as described in the previous section, these are rapidly being supplanted by systems incorporating the Global Positioning System (GPS) capability. GPS receivers operate in the 1.575 GHz (L1) and 1.22 GHz (L2) spectral regions and utilize concurrent and precision timing information from a constellation of up to 12 satellites at a time to establish geodetic position by differential timing. A minimum of four satellites must be received to compute latitude, longitude, and altitude (with respect to mean sea level). The satellites orbit at an altitude of 10, 898 miles in six 55° orbital planes with four satellites in each plane. The system incorporates a network of up to 24 satellites including four spares. The stand-alone accuracy is purposely reduced to the above approximate values for nonmilitary personnel due to security and defense, rather than technological, concerns. In reality, the global positioning system (GPS) has a much better resolution but errors are intentionally built in to ensure that this system may not be abused in a manner that it causes concern for the national security. This is done by sending a spread spectrum coded sequence containing two codes, a precision P-code and a coarse acquisition C/A code, on the L1 frequency. The L2 carrier contains the P-code and is made available to the military and authorized civilian users. The department of defense is able to achieve pinpoint accuracy with the P-code—about 17.8 m horizontal and 27.7 m vertical. This technology is immediately available to surface vessels and to any vehicle that can support a hand-size microwave antenna. The system can also be used with an auxiliary fixed location receiver, the so-called “differential” DGPS mode, to provide resolution of centimeters at close range. Shallow water submersible vehicles have already been designed to use DGPS for underwater navigation via a tightly tethered surface buoy containing the GPS receiver. Soon most vehicles including automobiles will be using the GPS navigation for unheard-of navigational ease and accuracy.

In addition to the aforementioned navigational methods, there are acoustic (sonar) and optical aids for positioning, tracking, and survey applications. These are only very briefly discussed here. Since there are many activities associated within offshore work, there are over ten different systems that can be employed to various degrees of utility. For tracking and positioning, the use of directional hydrophones has been abandoned in favor of more advanced sonar systems, such as ultrashort, short, and long baseline transponders. In operation, several tansponders are deployed at known locations, if possible. The distance to each transponder is determined by the acoustic travel time and therefore establishes a reference for location of the inquiring platform. The transponders can be deployed without knowledge of their exact position and, in that case, the ship or other platform must move to find the minimum range (depth) from which the surface position is then known. All transponders are treated in the same fashion until all coordinates are located. The use of “smart” transducers having depth measurement capability allows computation of slant ranges and therefore position without using the search procedure. Long-range navigation at low frequencies of 8 kHz to 16 kHz provides an accuracy of up to 1 m to 2 m at 10 km range. A positional accuracy of 0.1 m can be obtained at higher frequency of 40 kHz to 80 kHz, but at a reduced range of 1 km.

The short baseline system uses three or more hydrophones attached to a vessel at known position. The principle of operation is similar to the long baseline system with the exception that all the transducers are aboard the surface vessel. Only one seabed transponder or pinger is required for this type of system. The ultrashort baseline system is again similar to the short baseline system, with the added advantage that only one hydrophone/transducer is required. All timing information is determined from within the one transducer head. Accuracy for these systems is about 0.5% to 0.75% of the slant range.

Scanning sonar, either mechanical or by array electronic scanning, is used for forward imaging in obstacle avoidance, surveillance, vehicle navigation, or survey work. Narrow-beam mechanical scan, phase comparison, side scan, synthetic aperture, and multibeam are just a few sonar types. Usually, narrow-beam sonar has a thin beam of 1° to 2° in the horizontal direction and scans over a multisecond period. CTFM (continuous transmission frequency modulation) is a subset of this category. Phase comparison sonar uses the phase information to determine bearing on two or more wide beams at a time. Data rate is improved over mechanical scan systems, but bearing resolution is proportional to SNR. Side-scan sonar uses a line array to produce a narrow (1°) horizontal beam and a wide (30 to 70°) vertical beam. The system operates by observing the interruption of the acoustic reverberation caused by an object in the beam. Images are difficult to interpret for the untrained observer. Multibeam sonar either steers a multiplicity of single beams or duplicates angular sectors to arrive at a complete image in the time it takes one pulse to travel to the target and back. Thus information rate is high. Many different configurations are possible and beyond the scope of this discussion. Synthetic aperture techniques rely upon coherently summing many returns from a sonar system as it passes a target area. The resolution of the system is increased by the synthetic size of the aperture that is formed by many data records put together to make a much larger time record. Angular resolution from diffraction theory is related inversely to the aperture width.

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