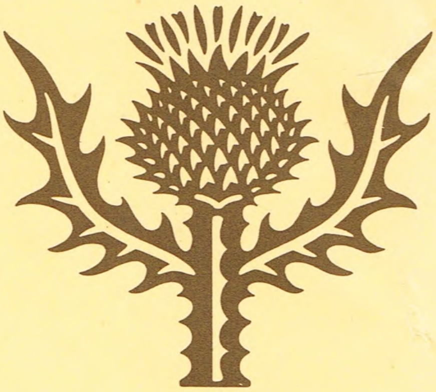

SONAR

by

D. G. Tucker

from the fifteenth edition of ENCYCLOPAEDIA BRITANNICA

HELEN HEMINGWAY BENTON, Publisher

Sonar

Sonar is the name of a technique for detecting the presence of objects underwater by acoustical echo. Having been developed during World War I, it antedates the better known radar, which uses electromagnetic echo. "Active sonar" employs an apparatus for radiating acoustical energy to bounce off underwater objects; "passive sonar" consists merely of the passive reception of acoustical energy generated by another source.

DEVELOPMENT OF THE TECHNIQUE

Interest in a means of detecting underwater objects was originally aroused by the problem of icebergs, dramatized by the sinking of the "Titanic" in 1912. The first proposal was put forward by a British meteorologist, L.F. Richardson, and the first successful application used in iceberg detection was made by the American radio pioneer, R.A. Fessenden. Development was stimulated by the outbreak of World War I and the impact of submarine warfare. A French physicist, Paul Langevin, played the leading role in research in which first British and then American scientists joined. A passive system of submarine detection, operational by 1916, employed a hydrophone (underwater microphone) and amplifier to pick up the noise emitted by submarine engines. By 1918 scientists had developed an active system in which a pulse of sound was transmitted and its rebounding echo used to detect a submarine even when its engines were shut down. The original term, "asdics," is said to have been derived from 'Anti-Submarine Division-ics,' although other explanations have been given. The name was long retained in the United Kingdom; the term sonar, from sound navigation and ranging, a United States acronym from World War II, is now used widely.

In the years between the wars, British and United States researchers refined techniques to such a point that the Allies enjoyed a substantial advantage over Germany in World War II underwater detection. They developed two types of beams, one vertical to bounce off the sea floor for depth determination, the other horizontal and capable of detecting underwater objects and obstacles near the surface. The depth detector, or echo sounder, was in widespread navigational use in the 1930s. A major American wartime contribution was the development of a system that could rapidly scan with a narrow beam either a sector or all around, without mechanical motion of the acoustic transmitters or receivers, making possible swift and methodical search for submarines.

In the years since 1945 a great deal of work has been done in naval acoustics by the United States, the United Kingdom, and the Soviet Union, and other maritime nations, but virtually all of it is secret and so has had little influence on peaceful applications. The most important of these is the use of echo sounders to detect shoals of fish, a potential discovered in the 1930s. By 1950 specialized equipment was being installed on fishing vessels, with notable success.

The echo sounder

In the early 1970s the simple echo sounder remained the basic sonar device used by fishing fleets. A type of sonar has been developed with a horizontal scan that locates fish at a distance of one kilometre (about 1,100 yards), greatly facilitating purse-seining (large net) operations by trawlers. The beam's direction can be changed by mechanical rotation of the underwater transmitting and receiving equipment, permitting a thorough search of a fair-sized area. The technique is slow, owing to the slow rate at which sound travels through water (1.5 kilometres per second).

Another problem in fish sonar is that there is as yet no technique for detecting fish close to the seabed in front of the ship, as the bottom-trawling method of fishing used by the British and other fishermen requires. There are, however, systems that accurately indicate the depth of a net towed behind the trawler, so that adjustments can be made to take advantage of any fish shoals detected on the main sonar.

Known military applications in the 1970s include the detection and location of submarines, control of antisubmarine weapons, sonar-equipped homing torpedoes, and mine hunting.

Detection ranges for civil and military sonar systems vary from 100 metres to 10 kilometres. Wave lengths for the acoustic signal range between 0.5 centimetres and 30 centimetres, corresponding to frequencies of approximately 300 kilohertz and 5 kilohertz.

BASIC PHYSICAL PRINCIPLES

Principles of a simple sonar system. As with most radar systems, sonar systems generally use the transmission and reflection of a pulse of energy as their basis of operation. The arrangement in Figure 1 is typical. Individual systems vary, with some, for example, using a single transducer both for generating the acoustic waves in the water and for detecting the reflected waves. The pulses they send out are always bursts of the transmitted, or carrier, frequency, although the term sonar may also include marine seismic work, using the sound pulses generated by a small explosion.

From B.K. Gazey and D.G. Tucker, *Applied Underwater Acoustics* (1966); Pergamon Press; reprinted by permission

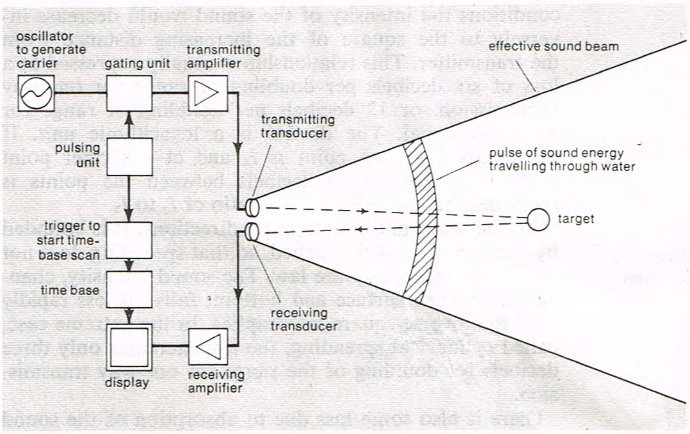

Figure 1: Schematic arrangement of a typical pulsed sonar system.

Display. The distance from the transducers to a reflecting target is indicated by the time elapsing between transmission of the pulse and the reception of an echo. The display, usually a pattern on a moving strip of paper, always includes a time base, the traverse of which is initiated by the transmitted pulse. For simple systems, the commonest display is a chemical recorder which records the received information on sensitized paper by means of a recording stylus drawn across paper. Since the echo actuates the marking mechanism, the position of the mark across the traverse indicates the range of the target. The paper is moved slowly in a direction perpendicular to the traverse of the marking stylus to make successive traverses side by side. If the range of the target in relation to the transducers does not vary, the line produced by the echo is parallel to the direction of motion of the paper. If the range changes (due to the motion of the target or ship), the line slopes with respect to the paper motion.

Resolution. The resolution of the system in range, that is, the fineness of detail it can show in a direction outward from the transmitter, improves as the transmitted pulse is made shorter. The carrier frequency may have to be increased to permit this shortening. Greater bandwidth is then required in the receiving equipment. Improved angular resolution, that is, the ability to distinguish two targets at slightly different angles, is generally obtained by making the beams narrow (more directional).

Doppler sonar. Another sonar method, "Doppler detection," relies upon the relative speed of the target and the observing station to provide an indication of target speed. It employs the Doppler effect, in which an apparent change in frequency occurs when the observed and observer are in motion relative to one another. The classic example is the apparent change in the pitch of a train whistle as the locomotive approaches and passes an observer. Detection by this means requires a long pulse to give an aural recognition of tone. The received signal is mixed with a local signal of slightly different frequency, the frequencies being so arranged that mixing the two produces an audible signal. A shift of pitch between the transmitted and received signals can easily be detected by a trained ear; this method gives not only very sensitive detection but also valuable information regarding the speed of the target.

Doppler detection can be used on fast-moving ocean fish, but most fish move too slowly for the method to be of value for ordinary fishing.

The propagation of acoustic waves in water. If water did not introduce any losses, if it extended indefinitely in all directions, and if it were uniform in all respects, then the spreading of sound would be spherical. Under these conditions the intensity of the sound would decrease inversely to the square of the increasing distance from the transmitter. This relationship is usually expressed as a loss of six decibels per doubling of range for one-way transmission, or 12 decibels per doubling of range for the echo signal. The decibel is a logarithmic unit. If the intensity at one point is I_1 and at a farther point is I_2, then the loss in decibels between the points is ten times the logarithm of the ratio of I_1 to I_2.

Sound intensity in the sea

But the sea is not infinite in all directions. It is bounded by the surface and the seabed, so that spreading does not follow the inverse-square law. The sound intensity, channelled between surface and bottom, falls off less rapidly than the inverse-square law implies. In the extreme case, called cylindrical spreading, the loss increases only three decibels for doubling of the range for one-way transmission.

There is also some loss due to absorption of the sound energy by the water, which converts it into heat. This loss is variable; it is small at low frequencies but rises very rapidly with an increase in frequency. In freshwater, the loss expressed in decibels per kilometre is proportional to the square of the frequency and is about three at 100 kilohertz. In seawater, there is an additional loss at frequencies below one megahertz due to the dissolved salts. Below 100 kilohertz, this additional loss is approximately constant at around 15 decibels per kilometre.

Further propagation effects of importance result from variations of the velocity of sound in seawater. Under normal conditions the velocity is about 1,500 metres per second. The main causes of varying velocity are, in order of their importance: temperature, pressure due to depth, and salinity. The magnitudes of the effects cannot be expressed by any fundamental equation, though several empirical, or rule-of-thumb, equations have been proposed. Increased salinity, temperature, and depth all increase velocity over all normal ranges.

Perhaps the most serious effect of varying velocity is the refraction (bending) of the sound beam, which may cause a beam that is normally horizontal to be deflected to the sea bottom, where it will be reflected upward, then down again, and so on. Along any straight line through the transducer, therefore, there are intervals of range where detection is impossible and others where it is possible. This and similar effects are most serious in low-frequency systems since they have the greatest nominal range.

Effects of varying velocity

Another effect of varying velocity is the general scattering of the sound beam as it passes through turbulent water, leading to rapid fluctuations of signal strength.

INHERENT LIMITATIONS OF SONAR

Noise in water. Acoustic noise in water sets the ultimate limit to the range of detection because it eventually obscures the wanted signal. Noise is defined as power received that is not part of the desired signal and is not produced by the transmitter. Sources of noise can be inherent, can be caused by natural phenomena, or can be produced by man or animals.

Inherent noise. Inherent noise results from motion of molecules, caused by heat. The colder the water the less inherent noise is received. Basically, noise intensity from this source is independent of frequency although, like all noise, it is dependent on the bandwidth of the system.

Sea-state noise. The most important noise produced by natural phenomena is that resulting from wave action. This is called "sea-state noise." Its magnitude is dependent on the height of the waves. Essentially a low-frequency noise, its power diminishes rapidly as the frequency rises, becoming negligible in comparison with thermal noise around 50 to 150 kilohertz.

Animal and man-made noises. Noise-producing aquatic animals include several species of fish and shrimp, encountered frequently in warm waters. Man-made noise, particularly that generated by the ship carrying the sonar equipment, can be more serious. Although difficult to calculate in advance, it poses the main limitation to sonar performance.

Reverberation. When the sonar system must detect small targets, a random background due to "reverberation" can make detection difficult. Reverberation is the sum of all the numerous small echoes produced by reflections from sand and stone particles on the sea bottom, minute air bubbles, and other irregularities in the water. While background noise in the sea limits the maximum range of detection, reverberation may limit performance in all ranges. Since reverberation originates from the signal transmission, it has a power level at any time interval closely related to that of the signal. Consequently, to detect small objects in areas where reverberation level is high (due, for example, to a shallow and rough sea bottom), the beams must be as narrow as possible in the relevant dimension. When reverberation is the limiting factor in detection, increasing the transmitted power does not improve detection over most of the range. Consequently, many sonar systems operate at acoustic powers of fairly low peak level.

Directivity. Sonar is most efficient if the sound energy is confined to a narrow beam on transmission and the receiving transducer responds only to sound coming from a limited angle, or cone. If the transmitter is highly directional, then the sound intensity at any distant point, for a given power source, will be much higher than if the sound had been broadcast uniformly in all directions. Fewer unwanted objects will be illuminated by the transmitted beam. On reception, a high directivity means that the noise will be reduced. If the noise is isotropic (coming almost equally from all directions) the reduction is given by the Directivity Index. Directivity Index is defined for transmission as the ratio in decibels of the intensity at a particular point in the direction of maximum transmission to that which would result at the same point if all the transmitted power were spread uniformly in all directions. On reception, it is the ratio in decibels of the output power developed by a signal in the direction of maximum response to that developed by the same signal power if it were uniformly distributed over all directions. For ordinary transducers, Directivity Index is the same whether the transducer is used for transmission or reception.

The Directivity Index

NEW APPLICATIONS AND TECHNIQUES

Improved sonar techniques are leading to (and often originating from) new applications in various fields of underwater operations. Since naval requirements obviously call for longer ranges of detection, higher powers and larger transducers are being provided, augmented by the sophisticated computer technique of "signal processing," whereby low-level signals can be extracted from a noise background.

Side-scan sonar. In nonmilitary applications, one technique that is increasing rapidly in importance is side-scan sonar. This sonar has a narrow (about 1°) beam in the horizontal plane, but relatively wide (10° or 20°) in the vertical plane, looking sideways from the ship or towed body on which it is mounted. As the ship proceeds along its route, a map of the acoustic scattering from the seabed is built up on recording paper. With experience, these records can be interpreted in geological terms, giving in effect a map of the hardness and roughness of the seabed rocks; it reveals geological faults, sand waves, and ridges. The general arrangement is shown in Figure 2.

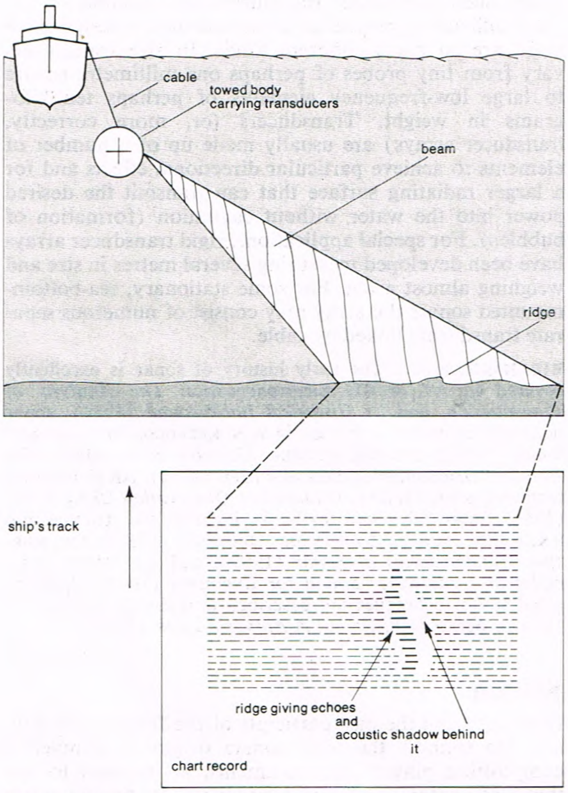

Figure 2: Principle of side-scan sonar with simplified record showing single small ridge with acoustic shadow behind.

Existing equipment for geological applications has a range of about 1,000 metres, but a recent model constructed by the British National Institute of Oceanography has a range of approximately 15 kilometres working at a relatively low frequency, of 6.6 kilohertz. The speed of search is high, but the results are seriously affected by refraction. Smaller, high-frequency, side-scan sonars, operating at 300 kilohertz (or even higher) with a range of about 200 metres, survey an area in finer detail. They can delineate such objects as underwater pipelines, oyster beds, and wrecks.

WPESS sonar. The growing trend towards higher resolution in sonars has led to the development of what is called within-pulse electronic-sector-scanning sonar (WPESS sonar). When very narrow sonar beams are used and it is desired to search a sector rapidly by swinging the beams around, mechanical beam swinging slows the rate of search, making the method unsatisfactory for fish finding and mine hunting when the ship is moving forward. In the WPESS method, a wide sector is covered by each transmitted pulse, and a narrow receiving beam is rapidly swung electronically across this sector. The beam is swung so rapidly that the whole sector width is examined for echoes before the acoustic pulse has travelled its own length through the water. In this way, the whole sector is examined on every transmitted pulse. Thus the search rate is very high, even if very narrow receiving beams are used to provide high resolution. The display is usually a cathode-ray tube giving some kind of plan view of the sector, as illustrated in Figure 3.

From *Underwater Journal* (September 1970)

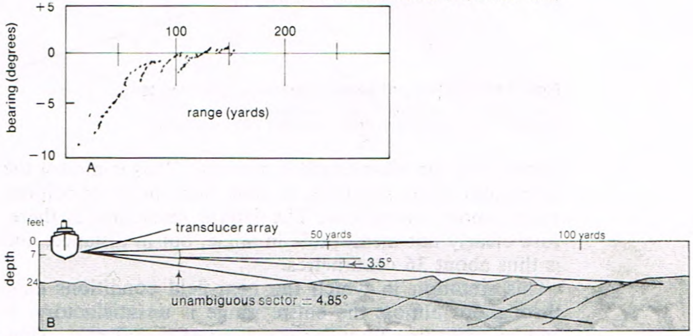

Figure 3: *Scanning sonar used with vertical 'scan' in a shallow reservoir.*
(A) Bearing-versus-range display.
(B) Geometry of bottom of reservoir deduced from A (vertical section).

Applications of WPESS sonar

The use of WPESS sonar is beneficial in the study of fish behaviour, in observing the behaviour of underwater gear, and in monitoring and directing the movements of divers. For some of these applications the acoustic frequency is made high (*e.g.*, 500 kilohertz) so that high resolution (*e.g.*, 0.5° in angle, 7.5 centimetres [three inches] in range) can be obtained using only small transducers. The maximum range is then relatively small, perhaps only 60 metres on 500 kilohertz equipment, or 200 metres in 300 kilohertz equipment. On the other hand, the system can be used equally well at lower frequencies. In early trials, 37 kilohertz was used with a range of detection on small fish shoals of nearly 800 metres.

Because of the trend to higher resolution, sonar can compete with optical methods for underwater viewing. Sonar makes it possible to view objects in muddy and turbid water where optical methods are ineffective. It is thus of great importance in police searches, in civil engineering (*e.g.*, river and harbour works), and in studying fish behaviour. In these applications it is essential to use a sonar that provides high angular (or lateral) resolution as well as high resolution in range. Range resolution can usually be increased by using a short pulse. Lateral resolution, however, raises difficulties.

Beam width considerations. Obtaining a beam of narrow angular width requires a transducer with dimensions equivalent to many wavelengths of the sonar carrier frequency. For example, a beamwidth of half a degree requires transducer dimensions of approximately 120 wavelengths. To keep the transducer small, a high frequency is necessary. Attenuation in water, however, increases rapidly with frequency. For example, at 500 kilohertz, it is in the region of 0.1 decibel per metre, while at one megahertz it is in the region of 0.3 decibels per metre. Thus the frequency cannot be increased indefinitely, and there is a limit to the reduction in size of the transducer. If, for example, the maximum range is to be about 50 metres, then 500 kilohertz would be a reasonable choice of frequency, the wavelength would be 0.3 centimetre, and the transducer length (l) for a 0.5° beam would be 36 centimetres (14 inches).

Far-field beamwidth

The concept of the 0.5° beam is based on the idea that the measuring point is far removed from the transducer from which the beam boundaries are drawn (far-field condition). But at close ranges the concept of angular beamwidth is invalid; if the transducer is straight (*i.e.*, unfocussed) the beam can hardly be narrower than the transducer length l, and the geometry becomes as shown in Figure 4. The far-field beamwidth θ is realized only after a range of about l^2/λ; *i.e.* 40 metres from the trans-

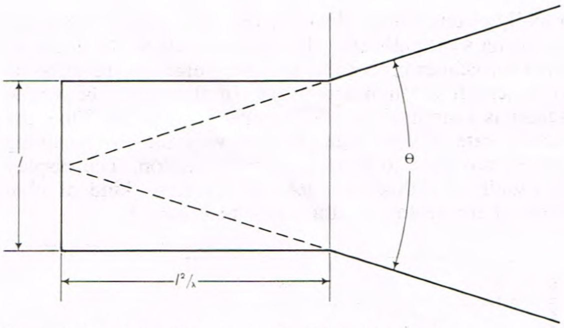

Figure 4: Geometry of beam near transducer (see text).
From B.K. Gazey and D.G. Tucker, *Applied Underwater Acoustics* (1966); Pergamon Press; reprinted with permission

ducer (λ is the wavelength in metres). This is almost the maximum range specified, so that "near-field" conditions exist almost throughout. The lateral resolution is therefore clearly not measurable in angle, but in distance, and is thus about 36 centimetres.

This situation in which the near-field conditions exist throughout almost the entire range is unsatisfactory. It can be overcome by using a system of signal processing, in which the receiving transducer is divided in half, and the signals from the two half-transducers are multiplied together. Thus a target can give a signal output from the receiver only if it lies in the beams of both half-transducers. Moreover, the far-field beamwidth is one-half of that corresponding to the length of the transducer used normally, and is realized at a relatively short distance from the transducer. Thus the near-field beam is extremely narrow, and lateral resolution of one-sixth of the transducer length (or less) is feasible. In the example taken above, the overall length of the transducer would be 18 centimetres, and the lateral resolution is quoted as three centimetres, or 0.5°, whichever is the poorer. This provides an enormous advantage for the multiplicative system.

Influence of modern electronics. Older forms of electronics with thermionic tubes or discrete transistors have been expensive to produce, somewhat unreliable, and costly to maintain. Because of the revolution in electronics that brought forth microelectronics, or integrated-circuit technology, however, it is now possible for a system to be sophisticated and complex and, at the same time, relatively inexpensive and reliable. This change in electronics has influenced sonar design, and already more refined and useful sonars are going into commercial production.

The microelectronic units that first became available were of the digital type; that is, they represented circuits that had switching, or on-off, functions of the type used in digital computers.

Several types of analogue circuits later became available in microelectronic form, and it is possible to make even a complex analogue system such as the WPESS sonar on this basis.

PRINCIPLES OF TRANSDUCERS

The purpose of transducers (strictly, electroacoustic transducers) is to convert an electrical signal into an acoustic signal, or vice versa. Three types of transducer are employed in underwater applications: magnetostrictive, piezoelectric, and electrostrictive.

Magnetostrictive. In a magnetostrictive type, a magnetic field is applied to a piece of suitable magnetic material, causing the dimension of the piece to decrease along the axis parallel to the field. When the field is alternating, application of a steady magnetic field (polarization) is necessary to give the acoustic wave the same frequency as that of the electrical signal. The magnetostrictive effect also operates in reverse: received acoustic signals cause compression of the material, altering the magnetic field, which in turn produces an electromotive force in the electrical winding.

Piezoelectric. Piezoelectric transducers use crystals that change in dimension according to the applied electric field. If the field is alternating, the crystals vibrate and radiate an acoustic wave. Conversely, if the crystals are acted on by acoustic waves, they generate an electric field. Piezoelectric materials used include quartz, ammonium dihydrogen phosphate, tourmaline, and lithium sulfate (see also PIEZOELECTRIC DEVICES).

Electrostrictive. Electrostrictive transducers are becoming the most widely used of the three. Materials used include barium titanate and lead zirconate. The change of dimensions depends on the magnitude but not the polarity of the applied electric field, so polarization is needed as with magnetostrictive transducers. Electrostrictive transducers generally have impedances of a few hundred ohms.

Transducers usually are operated at resonance; that is, the frequency at which they vibrate naturally, to get reasonable efficiency, making their frequency bandwidth rather narrow. When wide-band operation is required, the transducer is operated in such a way that its natural resonances are outside the operating frequency band. Various methods are used to reduce the sharpness of resonance as well as the cost of transducers. In one method, slices of crystal or ceramic material are alternated with plates of metal; such "sandwich" transducers are common.

It is difficult to generalize about transducer design since there are so many different kinds. In size transducers vary from tiny probes of perhaps one millimetre square to large low-frequency elements of perhaps ten kilograms in weight. Transducers (or, more correctly, transducer arrays) are usually made up of a number of elements to achieve particular directional effects and for a larger radiating surface that can transmit the desired power into the water without cavitation (formation of bubbles). For special applications, rigid transducer arrays have been developed measuring several metres in size and weighing almost a ton. For some stationary, sea-bottom-mounted sonars the array may consist of numerous separate transducers linked by cable.

BIBLIOGRAPHY. The early history of sonar is excellently covered in F.V. HUNT, *Electroacoustics: The Analysis of Transduction, and its Historical Background* (1954); sonar occurring in nature is treated in W.N. KELLOGG, *Porpoises and Sonar* (1961); and D.R. GRIFFIN, *Listening in the Dark: The Acoustic Orientation of Bats and Men* (1958). An elementary textbook is D.G. TUCKER, *Underwater Observation Using Sonar* (1966); more advanced textbooks include: D.G. TUCKER and B.K. GAZEY, *Applied Underwater Acoustics* (1966); J.W. HORTON, *Fundamentals of Sonar* (1957); and R.J. URICK, *Principles of Underwater Sound for Engineers* (1967). Sophisticated sonar techniques are described in a simple way in D.G. TUCKER, *Sonar in Fisheries: A Forward Look* (1967).

(D.G.T.)

Sonata

Deriving from the past participle of the Italian verb *sonare*, "to sound," the term sonata originally denoted a composition played on instruments, as opposed to one that was *cantata*, or "sung," by voices. Its first such use was in 1561, when it was applied to a suite of dances for lute. The term has since acquired other meanings that can easily cause confusion. It can mean a composition in two or more movements, or separate sections, played by a small group of instruments, having no more than three independent parts. Most frequently it refers to such a piece for one or two instruments. By extension, sonata can also refer to a composition for a larger instrumental group having more than two or three parts, such as a string quartet or an orchestra, provided that the composition is based on principles of musical form that from the mid-18th century were used in sonatas for small instrumental groups. The term has been more loosely applied to 20th-century works, whether or not they rely on 18th-century principles.

Sonata and sonata form

Quite distinct from all of the preceding, however, is the use of the term in "sonata form." This denotes a particular form or method of musical organization normally used within instrumental sonatas, string quartets, and other chamber music, and symphonies written since the beginning of the Classical period (the period of Mozart, Haydn, and Beethoven) in the mid-18th century.

The first concern of this article will be to establish the