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EXPENDABLE SENSORS

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Introduction

Expendable sensors represent an approach to ocean measurement in which some degree of measurement precision may be sacrificed in the interests of lower costs and operational expediency. Two requirements of physical oceanography have driven their development: the problem of achieving adequate spatial sampling of the ocean on timescales commensurate with temporal variability; and the requirement by naval forces for under-way assessments of sonar propagation conditions – the first (and still the dominant) application of *operational oceanography*.

The naval requirement first arose in the area of physical oceanography, in the need to know the depth variation of water temperature. In practice, of the three parameters that determine sound speed – temperature, salinity, and pressure – it is temperature that predominates. Pressure is normally deducible with adequate precision from depth, and salinity is normally sufficiently constant to be neglected or simply 'modeled' using an archived (T,S) relation. However, salinity may be important near ice, in fiords, and estuaries, and in regions of freshwater influence (ROFIs). The naval requirement is normally for the vertical sound speed profile, and it is the *shape* of this profile that is important, rather than its mean value.

The expendable measurement facility was quickly taken up by the civilian oceanographic community. It gives a means of tackling the problem of how to make synoptic ocean structure measurements where features are likely to move significantly during a survey. A survey with spatial scales small enough to capture interesting features is seriously degraded by their movement and development. Particularly at mid- to high latitudes, a survey using conventional profiling instruments – such as the conductivity-temperature-depth (CTD) probe – cannot be carried out in a time that is small compared with the timescales of motion and development of features such as frontal boundaries and eddies.

Surveys are severely limited by deployments that require a vessel to be regularly stationary for casts with a profiling speed of $\sim 1\,\mathrm{m\,s^{-1}}$. Expendable probes allow use at ship speeds up to 20–30 knots, and air-dropped expendables can clearly outstrip even this.

The technique also provides standard results, and the expendable bathythermograph, or XBT, is now considered a central component of global climate monitoring programs such as the Global Ocean Observation System (GOOS). Near-real-time transfer of these data from ships under way is now also an important input to global meteorological forecasting.

The XBT was originally intended to improve on the (nonexpendable) *mechanical* bathythermograph

(MBT) which was the principal operational naval device up to the mid-1970s. The MBT was lowered into the water from a vessel, and it *inscribed* a temperature-depth trace, with a sharp stylus on a small coated glass slide. The temperature-sensing element was a xylene-filled copper tube, whose (temperature-dependent) pressure moved the stylus across the slide via a Bourdon tube. Stylus movement along the slide was determined by a copper bellows, compressed by the increasing water pressure. Data were read from the trace using an optical projector and scale.

The XBT was a major advance, allowing operation while under way and dispensing with the intricate measurement routine of the MBT, with the need for a deployment/recovery winch and with the need for calibration. It uses a pre-calibrated thermistor measurement, read onboard in real time. Inference of its depth uses knowledge of its rate of fall through the water. There are now several manufacturers, although the originators. Sippican Inc. (Marion, MA, USA), still lead in the number of available probe types.

Current expendable probe capabilities include, in addition to temperature, the measurement of sound speed, conductivity, ocean current, optical properties, and (recently) seabed properties. This review of expendables summarizes the variety of measurable parameters and then outlines the available deployment options. A number of examples are then given of their use in oceanographic research. Expendables specific to naval activities, such as noise-measuring (sonobuoy) systems, will not be covered here, although in some cases they have a limited ocean measurement capability. Air-deployed drifting systems are also omitted.

Expendable Sensor Types

Expendable Bathythermograph (XBT)

The purpose of the XBT is to provide a vertical profile of temperature, from the surface to as great a depth as required, if possible to the seabed. A thermistor measures temperature as the probe descends, and the depth for each measurement is deduced from time of descent using an empirical equation. A number of variants are available with different depth capabilities, the deepest (the T5) reaching 1830 m, which may necessitate data extrapolation in deeper water. Apart from expense, which increases with depth capability, operational constraints become more restrictive for the deeper probes. Whereas the T-7 (760 m) can operate at platform speeds up to 15 knots, a T-5 is limited to 6 knots.[1,2] Other probe types are (or have been) available,[3] but T-7 and T-5 types are in most regular use.

The stated accuracy of all probe types is $\pm$ 0.15°C and $\pm$ 2% of indicated depth, with a depth resolution of 0.65 m.

Operational effects of finite depth Various approaches have been adopted to overcome the limited depth capability of XBTs. The best means of doing this is generally accepted to be extrapolation with the help of relevant (same survey) full-depth CTD casts. This has the added advantage of allowing a check on the XBT depth data. In naval operational terms, however,[4] this is rarely an option. In conditions where the measured temperature has stabilized at the maximum depth, extrapolation to the seabed using the data trend may be reasonable. A second approach uses extrapolation using archived data, although if these are mismatched, this may be a problem.

Probe design The standard XBT has two main parts: a protective 'shell' which remains on the vessel after launch, and the probe itself, which falls through the water and passes data along the connecting wire. Electrical contact with the probe is achieved when the unit is loaded into the launcher, allowing initialization of the onboard electronics before the probe is released by withdrawal of a 'firing pin' from its tail section.

Throughout the operation of the device the probe remains connected to its shell, and thence to the onboard electronics, by two-strand wire. This wire is arranged in two coils, one within the shell, dispensing wire horizontally as the vessel moves away from the launch location, and one within the probe body, which dispenses wire upwards as the probe falls. Data are collected until wire breakage, either

[1] The 450 m T-4 (460 m, 30 knots), with a rated ship speed of 30 knots, used to be the routine choice for operational use, but this generally gave way to the deeper T-7 at the end of the 1980s.

[2] The specified maximum may be exceeded, but premature breakage of the wire will then limit the depth of data collected.

[3] The T-7, T-5, and T-4 are complemented by the T-6 (460 m, 15 knots), T-10 (200 m, 10 knots), and T-11 (460 m, 6 knots), the latter giving a 0.18 m vertical resolution). A T-7 variation called 'Deep Blue' (760 m, 20 knots) was developed for (faster moving) Volunteer Observing Ships.

[4] The naval application differs significantly from purely oceanographic applications. At great depth the sound speed increases slowly with depth (pressure), providing weak upward refraction of sound and decreased seabed interaction. Even small temperature gradients may negate this effect, and small errors in the extrapolation may have disproportionate effects.

when the probe reaches the seabed or (in deeper water) when the wire has been expended without the bottom being reached. If the deploying vessel travels faster than the design speed, the upper coil of wire may be exhausted first.

The success of XBT is the result of a number of critical design features. One of these is the small compartment in the shell that contains the electrical contacts, which is designed to avoid the problem of making good instant electrical contacts between a probe, which may have spent many months awaiting use, and a launcher normally sited on an exposed ship deck. In the compartment, the probe contacts are embedded within a thick gelatinous insulator, which is penetrated by the pointed launcher contacts as the breech closes. The material cleans the launcher contacts as they penetrate, and maintains their clean state by the practice of leaving the spent shell in the launcher between probe launches.

The free-falling probe itself involves three principal components: the thermistor element, making the temperature measurement; the two-strand wire that connects the thermistor circuit to the onboard electronics; and a weighted, hydrodynamically shaped body. Each of these components plays a vital part in the remarkable success of the instrument as a whole. The thermistor, of course, is indispensable, this small fragment of temperature-sensitive semiconductor providing the measurement capability of the unit. This is positioned in an aperture at the probe tip.

The connecting wire may represent a technical achievement at least as great as any of the other XBT components. Two thin strands of copper wire are covered by a thin insulating lacquer which binds them securely but which is sufficiently non-sticky to avoid the problem of self-attachment within the coils, in which hundreds of meters are compactly wound.

The probe body consists of a weighty metal nose cone attached to a lightweight faired hollow plastic tail, equipped with fins to ensure vertical travel, and an even metering of wire from the contained coil. The metal cone acts as a 'sea electrode' to complete the measurement circuit with the (effectively grounded) vessel. The final part of the instrument is a soft plastic cap, removed before use, which restricts the movement (and possible damage) of the probe in its packaged state.

Probe operation Operation of the XBT involves five stages (1) removal of the shell of the previous probe from the launcher; (2) unpacking and insertion of the fresh probe into the launcher, completing the electrical circuit by closing the breech; (3) initialization of the onboard electronics to recognize the probe and to prepare for data acquisition; (4) launch, by withdrawing the 'firing pin'; and (5) following data acquisition, completion of the data file closure procedure. Data acquisition begins when the probe completes the earth–loop circuit on reaching the water, and continues until the wire breaks. Acquisition may be ended before this if, for example, the probe is known to have reached the seabed. This process is common to all ship-launched probes.

Expendable Sound Velocity Probe (XSV)

In the XSV the active sensor, instead of the XBT's thermistor, is a small sound speed sensor using the 'sing-around' principle. In this, an ultrasonic transmitter/receiver pair are arranged with a fixed separation in an electrical circuit with strong feedback. The circuit's 'resonance' ('sing-around') frequency is determined mainly by the time acoustic path, and its measurement allows inference of the sound speed.

XSVs are almost solely limited to military use,[5] principally by operational submarines, and both air-launched and submarine-launched variants are available for this reason. For naval operations, they offer an improvement over the XBT in regions such as Arctic, Mediterranean, and coastal waters where salinity variations may cause significant sound speed changes.

The probes have a specified precision of $\pm 0.25\,\mathrm{m\,s^{-1}}$, and they are available with two main depth options: the XSV-01 (850 m, 15 knots) and the XSV-02 (2000 m, 8 knots). Both give depth resolution of 0.32 m. A higher resolution, slower-falling XSV-03 (850 m, 5 knots) is available, giving 0.1 m depth resolution. Depth precision is quoted as $\pm$ 4.6 m or $\pm$ 2% of indicated depth, whichever is greater.

Expendable Conductivity-Temperature-Depth Probe (XCTD)

The XCTD is one of the newer expendable probes, measuring conductivity as well as temperature. This is not a simple extension of capability, since precision conductivity measurement is acknowledged to be particularly difficult, and first-time operation must be assured, even following a lengthy unattended shelf-life. A four-electrode configuration is used in a resistive measurement of conductivity,

[5] An important exception is their potential use in precision hydrographic surveying, to assess the mean sound speed of the water column.

with a thermistor for the temperature measurement. As with other probes, depth is inferred from the fall rate of the probe. In the XCTD the measuring system converts basic C, T data into frequency-modulated signals for transmission along the standard two-wire connection. Each unit is calibrated in a three-saltwater-bath procedure following manufacture, with the resulting calibration coefficients stored in nonvolatile memory in the probe canister.

Expendable Current Profiler (XCP)

The Sippican XCP is the first expendable technique for ocean current measurement. Its measurement of current velocity utilizes measurements of the weak[6] electrical current generated by the motion of conducting sea water through the Earth's magnetic field, which is directly proportional to the velocity at any given depth. The falling probe interrupts this current and measures the electrical potential thus produced. The probe spins at a prescribed rate, converting the potential seen by separated electrodes into a sinusoidal signal whose orientation is deduced from a co-rotating 'compass' coil. This allows resolution of the measured current into north and east components; the third measurement made is that of temperature, by the thermistor mounted in the usual probe nose position. The data are passed along the wire as three frequency-modulated signals.

The XCP is available only as a stand-alone instrument using a radiofrequency (rf) link, similar to that used for air-launched versions of the XBT and XSV. It may therefore be used from either ship or aircraft, and reception need not be from the deploying platform. An aircraft allows greater reception range, particularly in high sea states. A time interval is allowed between launch and probe release, to allow a deploying ship to move away, reducing its electromagnetic disturbance. Operation involves only the removal of a number of a few items of protective packaging before the unit is dropped into the sea. Energizing of the seawater battery, deployment of the rf antenna, operation of the probe, and eventual scuttling all take place without intervention. The probes have a 1500 m capability, and the 16 Hz (rotation rate determined) sampling rate allows 0.3 m vertical resolution, with a specified velocity resolution of $\pm 10\,\mathrm{mm\,s^{-1}}$ rms and $\pm 3\%$ rms horizontal shear current accuracy. The specified temperature resolution is $\pm 0.2^{\circ}\mathrm{C}$.

[6] In the measurement, a water velocity of $1\,\mathrm{m\,s^{-1}}$ corresponds to about $5\,\mu\mathrm{V}$ at mid-latitudes.

Expendable Optical Irradiance Probe (XKT)

The XKT, another relatively recent innovation, is used to measure the vertical profile of light penetrating the upper layer of the ocean, allowing an estimate of the optical diffuse attenuation, K, in addition to temperature. The upward-looking probe has a cosine spatial response and is sensitive to the wavelength band $490 \pm 10\,\mathrm{nm}$, operating down to 200 m with about $0.15\,\mathrm{m\,s^{-1}}$ vertical resolution. Irradiance is measured over a dynamic range of 10^5 within 5% log conformity and 10^6 within 10%. An air-dropped version is available.

A second variety of optical properties probe, the XOTD/AXOTD, measuring suspended particle concentrations in addition to temperature, has been reported as 'under development'. This operates using the scattering of light from an included source and is intended for the particle concentration range $5\,\mu\mathrm{g\,l^{-1}}$ to $3\,\mathrm{g\,l^{-1}}$ in the depth range to 500 m.

Expendable Bottom Penetrometer Probe (XBP)

The XBP is the most recent addition to the armoury of expendables, and it is currently still at the development stage, available by special arrangement for evaluation. The requirement which it fulfils is, once again, driven by military operations, and relates to the need to know certain seabed properties, particularly in shallow water ($< 200\,\mathrm{m}$). Sonar behavior in shallow water is often determined by the geoacoustic properties of the seabed, and aspects of mine counter-measures, particularly relating to the probability of mine burial, are sensitively dependent on the properties of seafloor sediments.

The sensor carried by the XBP in place of the XBT's thermistor is an accelerometer, whose purpose is to monitor the deceleration of the probe on impact with the seabed. Hard or rocky seabeds involve rapid deceleration, whilst sediments allow a smoother, longer period of retardation.

Normal (Surface Ship) Deployment

The standard deployment of all probes is from a surface vessel, normally from the stern, so that the wire emerges freely behind the vessel as it moves away from the launch point. Two types of launcher are normally available: a robust (heavy) military standard deck launcher, usually mounted permanently on deck, and a much smaller hand-held unit which may be used even from small craft. Care is required with either type in strong wind conditions, as the thin wire may be 'caught' by the wind and may become entangled with parts of the vessel's superstructure. (Through-hull launchers are an option used by some military vessels, allowing operation in adverse weather conditions.)

Since vessel heading is normally set by survey or operational demands, rather than by wind direction, it is often found that having a pair of launchers, mounted on the port and starboard quarters of the vessel, allows greater flexibility in cross-winds. A hand-held launcher is sometimes used to complement a single deck-mounted launcher for this reason. A less conventional way of addressing this problem is to apply mild restraint to the emerging wire – such as loosely guiding the wire through the fingers. This can reduce the effect of the wind on pulling excess wire from the dispenser within the shell, although care must be taken not to impede its normal flow.

Successful use of expendables may also be limited if the vessel is towing equipment, since the XBT wire streaming aft can become fouled by tow cables.

The only processing of the data normally needed involves the removal of values from the top 3–5 m, influenced by transient effects as the probe adjusts to the water temperature, and the removal of values obtained after the probe has reached the seabed, an event frequently denoted by a sharp spike in the data.

Deployment Variations

The XBT and XSV are available with additional deployment options – air-launched and submarine-launched, – developed mainly for military use. As was noted above, the XCP is suited to both ship and airborne deployment.

The Air-Launched XBT and XSV (AXBT, AXSV)

The measurement parts of the AXBT and AXSV are substantially the same as for the standard probes, including the sensor, the wire attaching the falling probe to the surface unit, and the weighted probe body. In this case, however, the only wire coil used is that within the probe, connecting the sensor to a buoyant electronics package which conditions the temperature signal and communicates it via an rf transmitter link to the launch aircraft. AXBTs and AXSVs are packaged in the standard-size canister used for sonobuoys – the 'A-size', 914 mm × 124 mm – and they may be launched at air speeds up to 370 knots and altitudes up to more than 9000 feet. Descent is controlled by a parachute, deployed when the buoy leaves the aircraft, and operation begins after a short delay in which the probe reaches temperature stability and the seawater battery (for the rf transmitter) becomes energized.

Each unit has a user-selectable rf frequency, which allows simultaneous monitoring of a number of probes. Although as many as 99 channels may be available, the number of probes being deployed is also limited by the number of channels available for simultaneous monitoring by the aircraft. Although transmissions cease when the probe has reached its maximum depth, and the scuttling mechanism is initiated, another probe using the same frequency cannot be launched until this has occurred. The receiver used for AXBTs is a standard unit normally fitted only to military (Maritime Patrol) aircraft.

Two types of AXBT are available, designed for maximum depths of 302 m and 760 m. Their spatial resolution is rather better than that of the standard XBT, at about 0.15 m. Specified depth accuracy is 2% of indicated depth, and temperature accuracy is $\pm 0.18^{\circ}$C. The standard AXSV operators to 760 m, with vertical resolution of about 0.15 m, 2% accuracy, and a specified sound speed accuracy of $\pm 0.25\,\mathrm{m\,s^{-1}}$.

In practice, although AXBTs allow rapid deployment over substantial horizontal scales, it is difficult to simultaneously achieve high spatial sampling, because of the combined effect of the finite reload time and the finite number of available receiving channels. To achieve a probe spacing smaller than about 30 km along a single track it is normally necessary to make at least two passes along the track, the second interleaving dropping probes between the stations covered on the first. Despite the operational difficulties, and the relative inaccessibility of such activities to nonmilitary agencies, AXBTs are the only means of executing large-area surveys (hundreds of kilometers) of dynamic regions for which the synoptic requirement requires a time-spread of < 1 day.

The Submarine-Launched XBT and ASV (SSXBT and SSXSV)

These variants of the XBT and XSV satisfy the uniquely military requirement for a submerged submarine to assess the sonar propagation characteristics of its environment. Without it, a submarine would need either to surface for a conventional deployment or to move vertically, making measurements with onboard sensors.

The technique is related to that of the AXBT, in that the temperature profile is measured by a probe falling from a buoyant package which floats at the surface. In this case, however, the package rises to the surface under its own buoyancy following its submerged launch from a signal ejector probe, and remains connected by wire to the submarine. As might be imagined from its requirement to pass probes through the pressure hull of a submarine, this technique involves expensive technology, and is unlikely to be used for purely oceanographic, as opposed to operational, purposes.

An equivalent version of the XCTD is understood to be imminent.

Data Recording and Handling

Current practice for the recording of data normally involves a PC, with a dedicated electronic interface unit which checks the continuity and integrity of the individual probe electronics before launch and then transfers data only after it has detected the probe reaching the water. Data display options exist using either dedicated display programs or standard data handling routines. As in many oceanographic applications, PCs have dramatically simplified the data recording process. In the years between the emergence of the XBT and the eventual prominence of the PC there was a period in which a dedicated inboard electronic unit was necessary for acquisition and data display using a paper trace. Digital recording on magnetic media (long-since obsolete) was also an option, although the practice of digitization from the paper trace persisted operationally into the 1980s. This inboard equipment frequently tended to be temperamental – a feature that is difficult to forgive when linked to the use of expendable probes.

The operational context of XBT data (for meteorological and military purposes) has led to the establishment, by the World Meteorological Organization (WMO) of a standard data exchange format, known as the JJYY format (formerly JJXX the format was officially changed from JJXX to JJYY by the WMO on November 8, 1995), following the alphabetical code used to prefix each 'bathy report'. Details such as date, time, location, probe type, and recorder type are included in these reports. This format involves reduction of the XBT data to a small number of 'inflection points', or 'break points', which are intended to capture the main features of the temperature profile whilst minimizing the data transfer requirement.

Measurement Precision

Assessment of the precision of an expendable device is necessarily limited by the expected loss of the probe following use. However, practical experience normally indicates performance within specified tolerances for the measured variables. Experience is considerably greater for the XBT than for the other probe types, as this is used much more widely for routine purposes.

The growing importance of XBTs in the population of global databases has led to some detailed consideration of their precision in the scientific literature. This has centered principally on the derivation of probe depth using the fall-rate equations provided by the manufacturers. Direct verification for individual probe types is not possible because of the large vertical distances involved, and the inappropriateness of attaching verification sensors. The best available means of checking the depth data of expendables, of any kind, is to carry out parallel measurements with a temperature-measuring instrument, such as a CTD, which has a direct pressure-measuring capability. Distinctive individual temperature features in the water column may then be used to indicate a depth correction for the region of the survey.

A number of surveys, several of them involving dense sampling of XBT and CTD casts, have found significant systematic errors greater than the quoted tolerances, the manufacturer's equation always underestimating the fall rate. A number of alternative fall-rate equations have been proposed, and it appears that a consensus is steadily being reached on the optimum equation.

The calibration issue is particularly significant for assessing trends in climate change, and it is acknowledged to be particularly important to follow an agreed standard procedure for handling the known depth errors in databases. Use of a variety of fall-rate equations would lead to major confusion in interpretation of ensembles of data. It is now accepted that only data using the manufacturer's equation should be used for archived data, and that it should be left to subsequent analysis to make whatever adjustments are felt necessary.

It is generally found that temperature errors are within the bounds indicated by the manufacturer. However, it has been indicated that performance may be improved by calibrating each probe against a secondary standard before use. Although this method can realistically assess only one temperature, giving an error to be applied as an offset to the subsequent launch, it is a reasonably practical means of improving confidence in the data.

Use for Ocean Surveying

Although XBT use for purely oceanographic survey purposes is probably still dominated by naval requirements this is an effective way of enhancing a traditional survey using CTD casts. Without impact on survey time it is possible to increase the spatial sampling rate by a factor of two or more by interpolating XBT launches between CTDs. Another common use is in the support of surveys undertaken with towed undulators or instrument chains, XBTs allowing a degree of downward extrapolation of the detailed upper-layer data that these collect. A third common use of XBTs is as a 'fall-back' option for use when weather conditions are unsuitable for other equipment.

AXBTs, and their deployment, are considerably more expensive, and tend to be used only when rapidity is essential. For example, the use of repeated large-scale AXBT surveys of the highly dynamic Iceland-Faroes frontal zone has been reported. AXBTs have also been used to give near-synoptic sections using aircraft underflights of satellite altimeter tracks, to validate the use of residual height data for ocean monitoring.

The viability of these techniques depends on the proportion of budget available for expendable items, and the expense of the probes must be seen in the context of the high basic cost of trials.

The other main contribution made to ocean science by expendables relates to deductions made from data archives. These are frequently dominated by XBT data and they often allow spatial and temporal coverage of regions that would otherwise have insufficient coverage for reliable deductions to be made.

None of the other probe types described here comes close to the XBT in its contribution to the science. Perhaps the most detailed and intensive use of the other expendables has involved the XCP, whose data (drawn from a number of different ocean regions) have been used to draw conclusions about the horizontal shear environment of the ocean.

See also

Acoustics, Deep Ocean. Acoustics, Shallow Water. CTD. Data Assimilation in Models. Inherent Optical Properties and Irradiance. Ships. Sonar Systems.

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