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XBT operational best practices for quality assurance

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Since the 1970s, eXpendable BathyThermographs (XBTs) have provided the simplest and most cost-efficient solution for rapid sampling of temperature vs. depth profiles of the upper part of the ocean along ship transects. This manual, compiled by the Ship of Opportunity Program Implementation Panel (SOOPIP) a subgroup of the Global Ocean Observing System (GOOS) Observations Coordination Group (OCG) Ship Observations Team (SOT) together with members of the XBT Science Team, aims to improve the quality assurance of XBT data by establishing best practices for field measurements and promoting their adoption by the global operational and scientific community. The measurement system components include commercially available expendable temperature probes, the launcher, the data acquisition (DAQ) hardware, a Global Navigation Satellite System (GNSS) receiver, an optional satellite transmitter, and a computer with software controls. The measurement platform can be any sea-going vessel with available space for the equipment and operator, and capable of oceanic voyages across the regions of interest. Adoption of a standard methodology in the installation and deployment of the measurement system will lead to data quality improvements with subsequent impact on the computation and understanding of changes in the near surface ocean properties (e.g., heat content), ocean circulation dynamics, and their relationship to climate variability.

KEYWORDS
XBT, techniques, bathythermograph, ocean temperature profiles, best practice , Ocean observation

Introduction

XBT temperature measurements monitor changes of ocean temperature from sub-mesoscale to global scales, deriving key surface and subsurface currents to study meridional heat transport in all ocean basins and also supplement other observational platforms to assess the variability of the upper ocean heat content. Fixed XBT transects are established along regular shipping routes targeted for sampling based on our understanding of how the regional upper ocean dynamics and thermal structure may be linked to long-term climate signals, extreme weather events, ecosystem assessments, and so on. XBT data are archived and distributed by a variety of international data centers and most of the data are made available on the Global Telecommunication System (GTS) within 24 hours of acquisition providing critical input for weather, climate forecast models and other scientific applications.

Since 1980, the Ship of Opportunity Program Implementation Panel's (SOOPIP) primary objective is to fulfill the global XBT upper ocean data requirements established by the international scientific and operational communities. Additionally, SOOPIP is specifically tasked with coordinating the exchange of recommended practices for the XBT network. Now involving 20 agencies from different countries distributing most of the XBT data in near real-time on the GTS, the importance of SOOPIP developing a coherent methodology for XBT data collection is clear. During the 6th International XBT Science meeting in 2018, the participants acknowledged the fundamental need for a set of best practices through an action item with this specific goal (IOC, 2018).

This paper represents SOOPIP recommended XBT operational best practices for quality assurance and is part of a suite of separate companion best practices documents in preparation to include:

- "Vessel Recruiting Best Practices"
- "Delayed Mode XBT Quality Control"
- "XBT Metadata Content and Format"

The XBT measurement system outlined in this document has been adopted for its logistical and financial viability for studies requiring large scale, high density and frequently repeated measurements of upper ocean temperature profiles. Some oceanographic research objectives require highly accurate temperature profile measurements at well resolved depths that the XBT cannot fulfill with its manufacturer-specified accuracy of ± 0.2° C and depths estimated from a fall rate equation based on time. Argo autonomous temperature and salinity profiling floats that reach 2,000 m deep provide a global network of more accurate (± 0.002°C), year-round temperature profiles. The core Argo float mission, which began in 2000, is to maintain a gridded global coverage of over 3,000 of these profiling floats. However, Argo floats are quickly swept out of boundary currents where large-scale mass and heat transport occur and there is less spatial resolution of sampling by Argo floats in dynamic regions. A synergistic approach for understanding circulation in boundary currents and other applications might call for a mix of platforms, including high-resolution XBT transects, as well as gliders, Argo profiles, moorings and remotely sensed measurements.

Equipment

This section discusses types of equipment commonly in use for XBT deployments and provides aids to the best selections. Additional information regarding installation, testing and maintenance of the equipment are discussed later.

XBTs

XBTs provide the simplest and most cost-efficient solution for frequently obtaining temperature profiles along fixed transects of the upper ocean. The XBT contains a precision thermistor located in the nose of the probe and the DAQ card measures the resistance of the thermistor and converts it to temperature. The depth is computed empirically as a function of the time-since-water-contact using a fall rate equation (FRE). There are currently only two major manufacturers of XBTs globally, U.S.-based Lockheed Martin's Sippican and Japan-

Abbreviations: AODN, Australian Ocean Data Network; AOML, Atlantic Oceanographic and Meteorological Laboratory; BUFR, Binary Universal Form for the Representation of meteorological data; CSIRO, Commonwealth Scientific and Industrial Research Organisation of Australia; DAQ, Data acquisition; FRE, Fall Rate Equation is a function for determining probe depth based on time since water contact; FTP, File Transfer Protocol is a simple protocol for transferring files on the internet; GNSS, Global Navigation Satellite System; GOOS, Global Ocean Observing System; GPS, Global Positioning System, a GNSS constellation; GTS, Global Telecommunication System; GTSPP, Global Temperature and Salinity Profile Programme; IMOS, Australia's Integrated Marine Observing System; IOC, the International Oceanographic Commission; IQuOD, International Quality Controlled Ocean Database; NCEI, NOAA's National Centers for Environmental Information; NOAA, National Oceanic and Atmospheric Administration, United States Department of Commerce; OCG, Observations Coordination Group; PPE, Personal Protective Equipment; PPP, Point-to-Point Protocol is a protocol for communication between two nodes; QC, Quality Control; SIO, Scripps Institution of Oceanography at University of California, San Diego; SMTP, Simple Mail Transfer Protocol is a program used for sending emails using an email address; SOOPIP, Ship of Opportunity Program Implementation Panel; SOT, Ship Observations Team; UNESCO, United Nations Educational, Scientific and Cultural Organization; WMO, World Meteorological Organization; XBT, eXpendable BathyThermograph temperature profiling probes.

based Tsurumi-Seiki Company (TSK). The choice of the probe is primarily based on which company the funding institution can access for purchasing. Each manufacturer has a variety of XBT models; the SOOPIP recommends Sippican Deep Blues or TSK T-7s, rated to reach a depth of 760 m at a ship speed of 20 knots. This is one of the most cost-effective probes and though it is only rated to 760 m maximum depth, it is common that they reach nearly ~900 m, depending on the ship speed, with equivalent data quality. The deepest reaching XBT is the Sippican and TSK model T5-15, which are capable of reaching a depth of 1830 m but must be launched at a ship speed of 6 knots.

Launcher

The basic hand-held, manually triggered launcher design for both Sippican and TSK XBTs is the same and commercially available from these XBT manufacturers. A lever compresses 3 sharp electrical contact pins onto the back of the XBT canister with a cable connecting it to the DAQ system The user holds the launcher over the ship side and pulls the pin that secures the XBT inside the canister, releasing the XBT probe to drop overboard.

Manufacturers and different institutions have developed their own launchers capable of holding multiple XBT probes and allowing remote, automated triggering of the XBT launch. Advantages of auto launchers include: a greater percentage of successful profiles, less frequent trips on deck in bad weather, more rest for the field technician when sampling is around the clock, and programmable drop intervals that help avoid missed stations. Disadvantages include: larger weight and volume of equipment for shipping and storage aboard, and more potential for equipment failures due to the increased complexity over hand launchers. The cost of developing an auto launcher has too many variables to estimate here but savings could be achieved by producing an auto launcher developed by another organization with their cooperation.

Ultimately, SOOPIP does not specifically recommend either automated or manual hand launchers; this decision should be based on meeting the needs and budget of the users. However, if an auto launcher is used, a hand launcher should also be available as a valuable troubleshooting tool and backup in case of auto launcher component failure.

Data acquisition hardware

Both Sippican and TSK offer DAQ hardware (proprietary electronic circuit cards with optional enclosures and cables) for processing the XBT signal, that provide results within the prescribed precision and accuracy parameters established for XBT technology. Additionally, DAQ cards can be designed in-house, such as the Turo data recorder which was originally designed for use for the XBT program at the Commonwealth Scientific and Industrial Research Organisation of Australia (CSIRO). Whichever DAQ hardware is used, its performance in combination with the entire XBT system to achieve ± 0.2°C accuracy should be well validated before implementation.

Software and computer

The computer can be quite basic, only needing the correct data cable connectors and system requirements for operating the equipment control software. A suitable laptop-type is recommended to reduce shipping and bench set-up space.

Equipment control software can be obtained from the DAQ hardware manufacturer or custom designed.

The foundation of the software design should be geared toward the users' needs but the following features are recommended to be included:

- Interface with the GNSS receiver – Continuously display the position and capture it for each profile eliminating manual data entry errors. Perform internal checks to alert the user of possible position data errors. An option to manually input positions is recommended in case of primary position source data failure to avoid missed stations.
- Automatically trigger an XBT release or alert the operator when a prescribed data collection point is reached. This can be based on time, distance or position.
- Capture Metadata – Metadata requirements as established by the SOT-10 Task Team on SOOP Metadata (WMO, 2019) and described in the companion document to this best practices suite "XBT Metadata Content and Format" (in prep.), should be captured and attached to each profile data set.
- For each temperature profile, preserve the raw signal data for the profile as well as calculated temperatures and depths.
- Transmit Data – The program should create a data file that is appropriate for transmitting in real time from the ship to the shore. Preferably, the software should be able to interface with the transmitter to automatically send profiles as they are bundled and alert the user of transmission failures.
- Translate and record the XBT signal to 3 decimal places - Although the accuracy of XBTs is significantly lower, noise signals of this magnitude are good indicators to alert the operator of data problems.
- Alert the operator of various system failures such as loss of GPS signal.
- Capture initial quality control (QC) flags either generated from user input or from an automated evaluation.

Global navigation satellite system receiver

An accurate position (latitude and longitude) is required for each XBT profile collected. Global Positioning System (GPS) offers the most globally reliable coverage and accuracy of any single global navigation constellation, so it is best to select a receiver with access to GPS satellites to prevent loss of positioning signal. With many varieties of affordable and accurate GPS devices commercially available, nearly any model which can be interfaced with the implemented computer controls is acceptable. The receiver's position data should be interfaceable with the computer to avoid user-input errors rather than relying on displays and manual input. Many models of transmitters also have integrated GPS, eliminating the need for a separate GPS unit. While a separate display is not required, it is an excellent verification tool to make sure that position data input to the program is correct. Additional features such as outputs for speed and heading may be required depending on the software controls used.

Transmitter

The value of XBT data for climatological applications is increased by making the data widely available to the community in as near real-time as possible. Where budgets and field conditions make it feasible, data transmissions from the ship to shore should be implemented. Near real-time transmission also allows for an additional quality check of the profiles during the cruise. Iridium transmitters are a good transmitter choice because they have low data price rates and can be used as a dial-up modem to establish a PPP connection to the Internet with data files transferred *via* FTP. The use of FTP instead of SMTP is recommended as a cost-saving option due to the ability of FTP connections to resume data upload in case of connection drops, which can be common in remote ocean locations. Because Iridium providers typically price transmissions based on connection time rather than file sizes, several profiles can be bundled together to reduce costs. Iridium Short Burst Data service is costlier and Inmarsat is even more expensive than the Iridium FTP transfer option.

Cabling

Cables, used on deck from the exterior XBT probe connection point to where it connects indoors to the data acquisition system, vary according to application. In any long-term installation, the cable should be durable against damage from wear, weather and ultraviolet radiation. The cable should include shielding from electromagnetic interference often present on ships. Connectors should be low resistance, exterior connectors must be waterproof and, if metal connectors are used, they should not come in contact with the ship's metal hull. A cost-efficient alternative to heavy duty, shielded cabling that does not need to withstand long-term deck installations is CAT6, which employs twisted pairs of wires and a differential amplifier so should not require shielding in most environments. Alternatively, implement a wireless solution.

Power conditioner

A source of clean power is essential to avoid interference with the probe signal, so power protection devices are needed. Sippican recommends the use of an ultra-isolation transformer to isolate the system from the ship's ground. A marine-grade uninterruptible power supply (UPS) is another option for power conditioning.

Test probes

Test probes can be purchased commercially or custom built. Ideally, the test circuit will include all components of the XBT system, except for the XBT probe itself and provide a temperature simulation. Some test probes may only act to test the functioning of the system without providing a temperature profile simulation. While this is better than no test, it is highly recommended to use a temperature test probe. Other test probes may bypass the launcher, thereby testing the electronics only, but this will not reveal if there are any problems with the launcher cables or connectors. Important diagnostic information can be revealed using a mono-temperature simulating test. There is also value in having multiple reference temperature probes between 1-30°C to cover the range of ocean temperatures by using good quality standard resistors to simulate the desired temperature. Verify that temperature test probes perform to an order of magnitude better than the XBT temperature sensor in precision and accuracy by repeatedly recording the simulated temperature reading for the duration of a normal XBT profile.

Platform

With the permission and cooperation of ship owners and operators, the XBT platform can be any sea-worthy vessel with available space for the equipment and operator and capable of oceanic voyages across the regions of interest at the required frequency. Utilizing ships of opportunity, whether they be sporting, military, commercial, research, or fishing, allows for significant savings in data collection because these vessels are already employed on their usual business, eliminating chartering costs. Many ships will volunteer berthing space, while others charge a nominal fee for food and board. The selection, recruitment, and interaction with suitable vessels are explained in great detail in the companion document to this suite of best practices "Vessel Recruiting Best Practices" (in prep.); use that guide for logistics in preparing to meet the selected vessel. Anticipate what equipment, fittings, and tools specific to the vessel's design might be needed in addition to materials specified in this document.

Distance measuring tool

The height of the launch location above the surface of the water should be measured to incorporate in the FRE for improving the profile depth calculation (Bringas and Goni, 2015). A laser distance measuring tool provides the most accurate actual height for a loaded vessel underway.

Spare parts and supplies

If costs, convenience, and space are no barrier, the spares could comprise a complete backup system. In general, the minimum recommended spare parts are those most likely to fail and that cannot be done without, such as: hand launcher, cable connectors, DAQ hardware, computer, and GNSS. Complete the equipment list with additional supplies such as multimeter, flashlight, electrical kit, and toolkit to be prepared for all eventualities and to avoid borrowing ship's tools and office supplies.

Deployment

As previously mentioned, the XBT measurement system is an easily deployed and economical method for obtaining ocean temperature profiles as deep as 1830 m where accuracy on the order of a tenth of a degree Celsius is acceptable. The simplest hand launcher system can be transported in a case the size of a large piece of airline passenger luggage. It can be operated by a single field technician without advanced technical knowledge, requiring about 5 minutes per collected profile. By taking advantage of ships of opportunity and the personnel who work aboard as operators, vessel chartering and field technician costs could be reduced to zero. Typically, for high-density lines (i.e. where an XBT probe is deployed every 10-25 km), a field technician is supplied by the organization and paid at their contracted rate. Additional personnel resources (excluding travel and days spent at sea) are estimated in person-hours as follows: project management including recruiting and scheduling vessels, 8-40 hours per voyage; pre-deployment equipment preparations and packing, 8-40 hours; system installation or removal aboard, 8 hours; data post-processing and quality control 0.5-5 minutes per profile.

Pre-deployment preparation

Careful preparation in advance of the mission is critical for data quality assurance and to avoid failures that result in reduced data collection.

Planning

The critical importance of travel, logistics and schedule planning cannot be overstated. While not included for an in-depth discussion in this document, some example pitfalls include:

- International transportation of equipment is fraught with complexities from the industry and authorities.
- SOOP vessels are often subject to the vagaries of weather, ports, and management that can delay or re-route ships without notice.
- Failure to anticipate or understand travel restrictions and requirements to foreign countries can easily derail all the other careful preparations.

See the companion document "Vessel Recruiting Best Practices" (in prep.) for more tips for creating successful data gathering opportunities.

Testing

Each component of the system including all cables *and* spare parts should be tested in the laboratory immediately prior to sending to the field for deployment. Assemble a complete system in the lab and use a test probe to initiate a series of drops. Do not forget to include in the setup any cable extensions that may be needed on larger ships. Even in the laboratory, power conditions can fluctuate, so performing these drops over days or weeks may reveal otherwise hidden power susceptibilities. Exhaustive repeat testing is important when using new manufacturers or component models which have not been in the field before.

When using a temperature test probe, there should never be any drift in a test profile, even drift and noise an order of magnitude smaller than XBT accuracy are indicative of systemic problems. Noise and drift may not be apparent graphed at full scale, such as 0-25°C, so expand the graph scale of the temperature recording to visually reveal noise signals as small as 0.001°C. Example profiles from a nominal 1.5°C test probe illustrate normal test data, Figure 1A, and abnormal test data that shows decaying drift, Figure 1B. If only viewed at a coarse temperature scale on a small laptop monitor, these indicators would be invisible due to their small magnitude. Learn to recognize the usual characteristics of the expanded scale, well performing test profiles. See the Accuracy and Precision section.

The test probe can also help identify if there is a short in the system which causes data collection to begin before the XBT has entered the water. The test probe should only begin displaying data after it is connected to the ship's ground, if data is displayed without a ground connection, a short is indicated that will cause erroneous data from XBTs known as "false splash".

Identify any components that are faulty or the source of noise or drift outside of accepted parameters and replace or repair them before field deployment. Common noise sources are grounding points, cable connections, power supplies, a failing DAQ card, faulty test probes, and heavy equipment being operated on the same electrical system.

Carefully inspect the integrity of all system components before deploying into the field. Create maintenance schedules that are integrated into checklists and/or cruise reports to include at least the following:

- Verify data quality performance using test probes.
- Verify that the system's mechanical and programmatic components operate without failure.
- Inspect the integrity of cable insulation, connection points and weather exposed seals.
- Operate and lubricate moving parts.
- Provide replacement batteries for computers and peripherals.
- Verify the function of spare components that will be sent into the field.
- Update computer security and create recovery media and disk storage space.
- Verify that the GNSS receiver updates with accurate position, date and time.
- Send test data *via* the transmitter ensuring the settings and subscription service are current.
- Double check software inputs including platform metadata.
- Verify that Personal Protective Equipment (PPE) is present and undamaged.

Prepare a sampling plan

The location and frequency of XBT deployments depend on the region under study, the purpose of the study and the budget. For example, boundary currents are important areas for studying heat transport so these regions would have a higher sampling frequency on a trajectory perpendicular to the current flow while sampling in an open ocean basin could be less frequent. In advance of the trip, develop a sampling plan with these factors in mind in conjunction with the anticipated ship track. Preset sampling locations of latitude *or* longitude (exact locations are impractical due to inevitable course changes) developed for the scientific objective are ideally programmed into the equipment control software to monitor the GPS position and automatically launch a probe or alert the operator to do so. If there are factors making a position sampling plan too complex, alternatively a time or distance plan can be implemented for designated intervals.

Within SOOP, XBT deployment transects are designated as low-density, frequently-repeated, and high-density or high-resolution. "Low-density transects typically target 12 realizations per year, with XBTs deployed at 150–225 km spacing, and are designed to detect the large-scale, low-frequency modes of ocean variability. Frequently repeated [FR] transects typically target 12–18 realizations per year, with XBTs deployed at 100–150 km spacing, and are designed to obtain high spatial resolution observations in consecutive realizations in regions where temporal variability is strong and resolvable with an order of 20-day sampling. High-density (HD) [or high-resolution (HR)] transects target four realizations per year, with XBTs deployed at ~10-25 km spacing, and are designed to obtain synoptic high spatial resolution resolving the spatial structure of mesoscale eddies, fronts, and boundary currents" (Abraham et al., 2013) (Goni et al., 2019).

Exclusive Economic Zones (EEZs) are where coastal nations have jurisdiction over ocean natural resources and so prior

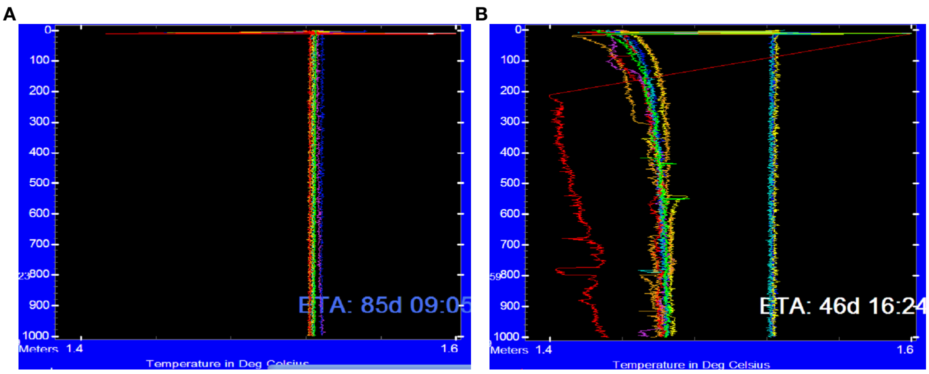

FIGURE 1
XBT Test Data at Expanded Scale. **(A)** Normal Data **(B)** Abnormal Data.

permission may be needed from the nation before sampling is permitted. Before commencing a sampling plan, know the boundaries and rules associated with any EEZs in the region under study. Failure to do so could subject the vessel and the program to serious fines and other consequences. Additionally, consider the locations of Marine Protected Areas and sensitive regions when creating the sampling plan.

Field installation

As discussed in greater detail in the companion document "Vessel Recruiting Best Practices" (in prep.), the three most important aspects of proper ship board installation for all SOOP operations consists of safety, performance, and aesthetics.

- Safety: Equipment must be secured in place in a manner appropriate to the extreme weather and rolling encountered at sea. It should not inhibit the operation of hatches, safety equipment, nor personnel movement. Proper PPE is essential for safety and compliance, including a minimum of a helmet, visibility vest, and safety shoes plus a life vest when at sea. Before working outboard on any deck, secure all tools and equipment with a lanyard so they cannot drop on personnel below or overboard.
- Performance: Selecting the most suitable location for equipment minimizes failures and ensures the best quality data.
- Aesthetics: It is important to project professionalism while working with program partners. Aesthetics matter to avoid a negative impact on the host vessel because not only is an untidy installation visually unappealing, it also looks unprofessional and can attract uncomfortable attention of inspectors who could raise questions for which the officers may be unprepared. Communicating and planning equipment locations with the ship's master and/or Chief Engineer can help avoid violations and inconvenience to the ship.

Equipment placement

XBT Probes

Identify a storage location as close as practical to the launch location. Where possible, XBT storage should be climate controlled to prevent damage from excessive heat, freezing, or humidity. High temperatures can cause the wax, glue, and wire insulation to degrade. With those precautions in mind, XBTs ready for launch should be as close as practical to the sea surface temperature to minimize the time for thermal equilibrium of the temperature sensor upon water contact. Don't store probes for arctic deployment in a heated space, nor those for tropical deployment in an air-conditioned space. (Cook and Sy, 2001). Store XBTs in their packing boxes; a common cause of XBT failures are wire snags which can happen when the wire slips on its spool from too much jostling, vibration or impact. Keep shipping to a minimum and transport on a pallet to reduce handling wherever practical. Proper handling and storage of XBTs ensures fewer failures due to probe quality and therefore, fewer missed data points.

Launcher

The most important aspect of selecting the launcher location is to minimize the possibility of contacting the XBT wire with any part of the ship. The launcher and operator should be out of reach of ocean swells. Position the launcher on what is expected to be the predominantly leeward side for the voyage, keeping in mind that it may need to be moved if unfavorable wind conditions persist. Avoid locations where deck structures could create air flow eddies that pull the light XBT wire on board. The launcher should be on the lowest deck, ideally about 3-4 meters above the water line (Bringas and Goni, 2015). Avoid locations near where solids are discharged overboard, such as garbage chutes.

Auto launchers are typically mounted on the aft railing on the lower-most deck, as far port or starboard as possible to avoid propeller turbulence. Auto launchers are heavy. Make sure that fasteners are secure and appropriately sized for the load and always secure them with a safety tether before mounting and dismounting.

Hand Launchers are also best located on the lowest deck away from turbulence but they do allow for more flexibility in their location. For example, a hand launcher on the bridge deck has the advantage of using the resource of bridge personnel for data gathering. Note that, where the bridge is high above the water line and forward of interfering ship structures, there will be more failures of XBTs launched from the bridge.

Cabling

Safety First! Cabling should be installed to avoid damage, avoid tripping hazards, should not prevent the latching of hatches and portholes, and should not block the overboard access of lifeboats/life rafts, nor personnel access to any lifesaving equipment. For example, do not attach a cable to the light beacon of a life ring, nor string the cable across a rarely used access to the lifeboat boarding area. Take care that cables are not damaged by hatches. Cables should be taut, with frequent attachment points to avoid getting snared by workers' limbs or tools such as lashing rods or fire hoses. Be aware that some spaces are forbidden for cable runs while other spaces require cable attachments to be metal so they do not melt in a fire. Where possible, cables crossing walkways should be routed overhead, otherwise, use a cable ramp. Reinforce chafe points with extra layers of insulation. For long cable runs, leave a service loop of cable at connection points to allow repairs without the need to remove the entire cable.

Control equipment

The system's electronic controls (computer etc.) should be in a climate-controlled space that can be safely accessed in all conditions. Overheating is not only the enemy of computers but has also been shown to cause errors in the DAQ electronics. Secure all components to prevent slipping during rolling in heavy weather. If this is a shared workspace, decrease the bench footprint by securing components that do not need to be accessed on the floor or in a cabinet.

Transmitter and GPS

The antennae of these instruments depend on a clear view of the sky to the horizon to communicate with satellites. Sometimes, a GPS antenna can be set just inside a window and will receive an adequate signal but it is critical that the signal remains consistent because a data profile with a missing or inaccurate position is a useless data profile. Transmitters have fewer satellites available, which can be blocked by deck structures and so are best mounted atop the bridge.

Grounding

The launching system must be grounded to the ocean (referred to as the "seawater ground"), by connecting the system grounding point to the ship's metal hull with a minimum 3.3 mm^2 cross sectional wire. Depending on the system, the grounding point may be at the launcher or the DAQ system, but never both. For non-metal hulls, connect to the rudder shaft or ship's plumbing. Do not use the ship's electrical ground as the system grounding point. A poor ground will cause major flaws in the data and is arguably the most common installation failure. Test the quality of the ground using an ohmmeter with one lead on the system's ground and the other on exposed metal of the ship's hull *other* than the attachment point; the resistance should be less than 5 ohms. Jiggle the ground wire at both ends to make sure there is no major fluctuation in the resistance reading.

Multiple ground points in the system can create ground loops that cause temperature signal interference (Lockheed Martin, 2003). Avoid ground loops by eliminating connections to the ship's electrical ground at the DAQ hardware power supply. This can be accomplished by utilizing a power cable with no grounding pin at the receptacle end. The launcher ground point will function just the same as the DAQ hardware power cord ground pin so long as the launcher ground stays connected to the system. SAFETY NOTE: Establish the system ground first before connecting the system to the power receptacle and do not remove the system ground when the equipment is plugged in. Isolation transformers, surge suppressors and UPS should always be grounded normally with the third pin ground to the ship's electrical ground. Only the DAQ hardware that is connected to these power sources should have the power cord ground pin eliminated while maintaining ground through the system grounding point.

Ground the GNSS receiver to the ship's hull to protect against lightning strikes.

Power considerations

Electrical interference caused by transient imbalances in the ship's active cathodic systems, electrical faults, electromagnetic transmitters, radio communication, and the use of heavy equipment on board can all interfere with the DAQ card, power supplies, or even the XBT probe wire acting as an antenna, sometimes at catastrophic levels (Cook and Sy, 2001). Viewing XBT test data at an expanded scale, as described in Deployment Testing section is a good tool to reveal and diagnose electrical interference. The first line of defense is to use high quality power supplies in the system design. According to Sippican, some ship-induced problems can be remedied by use of an ultra-isolation transformer to isolate the system from the ship's ground. Other problems may benefit from a UPS, but it is essential to select a high quality, *marine-grade* unit. Surge suppressing power strips, if used, must be *marine-grade*. The electronics within UPS and surge suppressors designed for use on-shore are incompatible with ship power and not only can exacerbate the problem but also can be dangerous. Again, always make sure these units are connected to the ship's electrical ground *via* the manufacturer supplied grounded power cable. Sometimes a problem encountered with the power can be remedied by using a different circuit. Other times, the interference is transient and will go away on its own. For example, equipment on board such as cranes, welders, and grinders can cause electrical interference that will disappear when the equipment is not in use. Engaging the ship's electrician and engineers often helps to identify and eliminate ship sources of electrical interference.

Testing

Testing the system *in-situ* before beginning field measurements is just as important as the pre-deployment testing. Test to make sure installation is correct, to check for damage that may have occurred in transit, and also because power conditions on board are different than in the laboratory. Just as in the pre-deployment preparations, use a temperature test probe and expand the graph scale to reveal unusual trace patterns on the order of millidegrees and test for "false splash". Perform a test on each of the auto launcher positions (if used) and the hand launcher. Compare the results from each position to each other and to the results obtained from the pre-deployment tests. The appearance of the trace should be a straight line, no drift, with a maximum, minimum and nominal mean as expected. See the Deployment Testing section for the full discussion.

Field techniques

Monitor the sampling plan

The sampling plan should have been established during the pre-deployment preparations but could require adjustment based on the actual ship's track or local conditions.

- Avoid multiple drops in the same position once a good profile has already been obtained for that position. For example, if the ship is drifting or on anchor, suspend a time-based or position-based plan.
- Monitor course and speed alterations to make sure the sampling plan objectives stay consistent with the new track or speed.
- Monitor the data to change sampling as appropriate. For example, the expected boundaries of an important current can change, so watch the data on the approach and increase sampling density as needed. Also, collect extra data profiles in a location where the data looked bad, questionable, or unusual.
- Monitor EEZs and protected marine parks. Dropping XBTs is permitted in many EEZs but in the case where a known forbidden drop zone is on the route, or the ship diverts to such an area, alter the plan as needed.

Measuring the launch height

The launch height must be recorded and the XBT velocity factored into the FRE depth offset employed in data processing (Bringas and Goni, 2015), i.e. probes launched from the bridge 10 decks up will be moving faster than a probe deployed from the poop deck near the surface. This is most easily and accurately done using a laser distance measuring tool held at the same height and location as the launcher *while underway at the typical speed*. Some technique is required with this tool because if the water is too glassy and clear, the laser will not be reflected off of the surface of the water; in that case try and capture some white water directly below created by turbulence. Ship speed, position on the ship, and ship cargo lading all affect the height of any deck above the water. Therefore, the most accurate estimation of launcher height must be made under *in-situ* conditions by averaging at least 10 measurements. Alternatively, the height can be calculated so long as speed, draught, and squat tables (the ship's change in draught underway) from the vessel are incorporated in the calculation. Don't forget to enter the launch height in the metadata for each drop in case the launcher position is changed.

Launching XBTs

Once released, the XBT probe should enter the water as vertically as possible and its ship-mounted canister should be aligned as closely as possible with the angle of the wire's unspooled trajectory to minimize abrasion against the canister's opening. Fixed-mount launchers at the stern provide the most reliable vertical entry and should be set at a 10-30° angle downward from horizontal. Hand-held launching should release probes away from the ship's hull. While sometimes impossible, try to avoid probes tumbling or making water contact in a more horizontal position because that will reduce the fall rate. After the probe is released, the launcher can be held at the optimum angle for smooth wire unspooling.

Observing data and re-launching

Watch the progress of the data during the launch in real-time using either the commercially available system or a plotting interface capability developed by the user. Plotting the current temperature profile over the previous profile(s) can be an instant visual clue to alert of possible bad data. The profile should be fairly smooth and mostly similar to the previous profile collected nearby with no large temperature offsets, no high frequency noise, nor large, sharp spikes. See the Quality Assessment Methods section and CSIRO's Quality Control Cookbook (Bailey et al., 1994) to identify profile characteristics and failure modes. If there is an unusual feature in the data profile, or when the data is obviously compromised, then another XBT should be launched as soon as possible. The subsequent temperature profile can confirm data features and ensure there is no data gap. If XBT probe costs are a concern, repeat drops can be limited to where suspect data is in the upper 200 m of the profile and/or where the observational area of the study is most critical.

If using an auto launcher, keep the hand launcher at-the-ready so it can be implemented without missing any station data. The more complex auto launcher can take a long time to troubleshoot and repair and might not be repairable in the field.

Weather considerations

Weather conditions causing extreme ship motion, heavy rain, wind, or lightning can all negatively affect the data collection. Do not go on deck if conditions are too dangerous; check-in with the mate on watch and follow the master's safety orders using extra precautions such as taking an escort and wearing a life preserver. Make efforts to ensure that the unspooling wire is not contacting the ship during the drop. At times, wind conditions can make this challenging. Try changing the launch location to a lower deck or more protected area where deck structures are not creating eddies or obstacles. Lightning can cause severe spikes in the data profile for hours after it is no longer observable. Bad weather commonly results in wire stretching or breakage causing both obvious and subtle data errors (see the Quality Assessment Methods for examples). When pre-loading the launcher, it is important to protect the loaded probes from rain. Wet probes may return data before entering the water, causing an observed early water contact or "false splash". Observations and repeat launches should confirm if weather is the source of any bad data. If weather prevents successful launches, then resume launching as soon as possible after conditions improve.

Care and maintenance

During the voyage, all equipment should receive regular maintenance to guard against damage from the harsh environment. Also, collect test data at the beginning and end of every cruise to verify system performance and stability.

Protect the launcher and any exterior equipment from salt and smokestack soot corrosion by rinsing with fresh water every day or two. When not in use, leave the empty probe canister locked in the launcher to protect the contact pins from corrosion. Cover the launcher as appropriate to protect it from severe weather such as ice. Lubricate moving parts with high quality lubricant appropriate to the materials. Lubricate rubber sealing components with a small amount of high-quality silicone lubricant without coating metal electrical contacts. Make sure electrical contacts remain free of salt, soot, dirt and oil. Repair seals that are allowing intrusion of these contaminants. Inspect cabling for kinking, compromised connectors, and insulation damage and reinforce chafe points using additional insulation. Inspect attachment points for signs of loosening and material fatigue which are commonly caused by ship vibration, corrosion, and UV degradation. Protect corrodible parts with anti-corrosion coatings and canvas covers where appropriate. In between cruises, stow equipment off the deck in shipping boxes.

Indoor electronics should be regularly monitored for signs of overheating or moisture. Be aware that as the vessel changes course and position, a once cool location can become exposed to more sun or changes in the climate. Be careful not to dislodge cables and keep the area around the equipment free of dust. Electronics that are deployed for long periods can get clogged with dust inside their enclosures trapping heat, moisture, and corrosive salt from the air. If batteries are used, inspect for corrosion and leakage. Make an inspection schedule part of the cruise report and do not forget to include spare batteries and ancillary tools such as flashlights and multimeters.

Calibration

Individual XBT probes cannot be calibrated before use because any in-water test is destructive. In the past, changes in manufacturer methods or locations have caused changes in performance characteristics and reliability. While manufacturers do perform field and laboratory quality control exercises, it is recommended to do spot tests on a small batch of XBTs to ensure they perform to specifications as time and budgets allow. Refer to "XBT/XCTD Standard Test Procedures" developed for SOOPIP-III (Sy and Wright, 2000), for implementation of independent verification.

When a problematic batch of XBTs is discovered in the lab or in the field, track the probe serial numbers and date of manufacture (DoM) and cross reference against other probes from that time period to see how prevalent the problems are (this is why DoM should always be recorded in the profile metadata). The failure(s) should be documented and summarized for the manufacturer as that could lead to a discovery in factory problems which can be corrected in future batches. Good cooperation addressing quality problems and replacement probes have been obtained from both Sippican and TSK.

The proprietary electronics of Sippican and TSK DAQ cards also are not designed for calibration. An XBT temperature test probe with good quality standard resistors is the best method to ensure the entire system is performing according to specifications.

Accuracy and precision

As stated by the manufacturers, the system accuracy of Sippican's Deep Blue XBT and TSK T-7s for temperature is ± 0.2°C and for depth is 4.6 m or ± 2%, whichever is greater (Lockheed Martin, 2021). Note that under some conditions and with systems that are not well assessed, the accuracy could be worse. The startup transient is the depth at which the initial temperature signal has come to equilibrium with sea water temperature. At depths shallower than that, the temperature is outside of the XBT's stated accuracy and considered unreliable. Startup transient depth is commonly accepted to be <4 m, but has been shown to be DAQ card dependent and could be deeper, an important consideration to avoid systematic bias in sea-surface temperature (Kizu and Hanawa, 2002). The science community has determined that the nominal accuracy of XBT data is suitable for many scientific applications and bias-corrected historical data can be applied for climate research purposes (Cheng et al., 2016). Many studies involving XBT accuracy have been performed on volumes of historical data. For further consideration, a comprehensive list of XBT quality test references compiled by NOAA's National Centers for Environmental Information (NCEI) can be found on their XBT bibliography website (https://www.ncei.noaa.gov/access/world-ocean-database/xbt-bibliography.html). NCEI also offers a list of XBT corrections publications that discuss biases in the temperature data as well as fall rate errors (https://www.ncei.noaa.gov/expendable-bathythermograph-xbt-corrections). In addition, the International Quality Controlled Ocean Database (IQuOD) community (http://www.iquod.org) is actively working to construct a climate-quality temperature database from all collected temperature profile data by developing a consistent quality control standard (Cowley et al., 2021).

At the Scripps Institution of Oceanography SOOP XBT program, test measurements using the Sippican MK21 XBT system with nominal 1.5°C XBT test probes are capable of producing results with noise ranges of ± 0.001 to ± 0.005°C and with ± 0.005°C repeatability. While the results are unpublished, it is a good estimate of observations on precision that span thousands of measurements on dozens of systems performed for over two decades. When DAQ cards that do not perform with this level of precision are identified, they are excluded from use in climate-grade measurements to reduce system bias as much as possible.

Standards

As described in the Test Probes section, XBT test probes provide the standard used for the XBT measurement system. The test canister coupled with the measurement system should perform at least an order of magnitude better than the stated accuracy of the XBT system of ± 0.2°C in precision and accuracy.

Quality assessment methods

This section discusses real-time quality assessment observations and actions to be taken in the field. More rigorous evaluations and expanded QC flags can be applied in post-processing for delayed mode data, which is covered in the companion best practice article "Delayed Mode XBT Quality Control" (in prep.).

The field technician is the first line of offense for great quality assurance, assessment and control. Upon identification of quality problems, the technician should notate data flags, immediately attempt to rectify the cause in order to avoid poor or missing data, and document the observations and steps taken in the cruise report.

Although it might be desirable, at present there is no single universally established QC flagging scheme and it is generally recognized that it is most realistic to accept diverse standards and translate between them (Bushnell et al., 2019). The Intergovernmental Oceanographic Commission (IOC) has proposed a two-level quality flag scheme for the exchange of oceanographic data. The primary level is defined by five flags and applied to any type of data that needs only basic flags. The primary level flags are complemented by the secondary level flags which are created by the group using the flags based on their specific needs and history (Intergovernmental Oceanographic Commission of UNESCO, 2013). The IOC proposal includes cross-references to some data flag schemes for different programs with a plan to keep the references current on the Ocean Data Standards website (https://www.oceandatastandards.org). SOOPIP recommends the use of the Global Temperature and Salinity Profile Programme (GTSPP) flagging scheme. Table 1 compares the two flagging schemes and note the critical difference between IOC primary flags and GTSPP for the description of code 2.

XBT data and metadata to be flagged are date/time, position (latitude and longitude), temperature and depth. Note that the temperature profile could contain multiple flags, e.g., points from 0-250 m flagged as correct data, 251-350 m probably good, and 351-900 m erroneous. Ideally, the XBT software can do an automated data evaluation and QC flagging, or allow the user to input QC flags before any data distribution.

Evaluating XBT profiles for basic failures

The operator is the only observer directly aware of existing field conditions that could be affecting data quality. Experience with temperature conditions in the region and additional data comparisons are excellent tools to help identify erroneous versus real temperature anomalies. In real-time, the operator should examine the temperature plotted against depth for high frequency noise, missing data, large temperature offsets, and sharp spikes. While apparent temperature inversions and constant temperature segments are often real-world conditions, they may also indicate errors caused by wire stretch, wire break or sea floor contact. Compare the current temperature-depth plot to that of the previous profile and if bad data or questionable data is observed, a repeat drop should be made as soon as possible, triggered either by the operator or by the software from its automated QC evaluation. The subsequent repeat temperature profile can confirm data features and ensure there is no data gap. Anomalous features that are present or hinted at in the previous profile and present in the repeat drop or the next profile, lend confidence to the data. In the absence of a repeat drop, neighboring profiles and archived historical data from the same geographical region are invaluable and should be graphed overlapping. Archived data sets can show if features such as large inversions, eddies, or multiple mixed layers are to be expected for the study area.

Examples depicting normal data as well as common failure modes and the descriptive QC flags for labeling them based on CSIRO's Quality Control Cookbook (Bailey et al., 1994) can be found in the Supplementary Materials of XBT Data Profile Features. Although all of the QC flags might not be applied to the data profile in real-time, the examples are a helpful reference to understand XBT temperature profile data.

Metadata verification

It is critical that the field technician takes care that all platform and measurement metadata are accurately recorded and transmitted as outlined in the WIGOS Metadata Standard (WMO, 2019). Ship-ID, DAQ card manufacturer and model, software and version, XBT probe information, drop position (latitude and longitude), date and time of deployment, launcher height, FRE coefficients, and QC flags are all examples of crucial metadata. Because different models of XBTs have different characteristics affecting their fall rate, it is important to not only use the appropriate FRE but also to include the manufacturer

TABLE 1 Flagging Scheme Comparison.

Code	GTSPP Quality Flags (Used by SOOP)	IOC 54:V3 Quality Flags
0	No quality control has been assigned	
1	QC was performed; appears to be correct	Good
2	QC was performed; probably good	Not evaluated, not available or unknown
3	QC was performed; appears doubtful	Questionable/suspect
4	QC was performed; appears erroneous	Bad
5	The value was changed as a result of QC	
9	The value is missing	Missing data

name, model, serial number, and date of manufacture in the metadata reported with each drop (WMO/IOC, 2019). SOOPIP upholds that "no correction scheme is applied to raw XBT data. All archived data should only contain depths calculated from either the manufacturers or the Hanawa et al. (1995) coefficients, and temperatures obtained from the collection system" (Cheng et al., 2016). Additionally, because the profile depth is calculated as a function of time, therefore, time since deployment should be also recorded explicitly or implicitly by knowing the sampling rate of the DAQ card.

When excellent metadata exists, researchers can revisit historical data sets and make improvements using corrections or adjustments based on knowledge enhancements that inevitably come with time, such as done by IQuOD. These adjusted data sets from disparate institutions using different equipment and techniques could be merged effectively creating a comprehensive, coherent, historical record. Indeed, during their Fourth XBT Workshop, the XBT Science Team made the recommendation of the work of Cheng et al. (2014) for historical data corrections and a comprehensive evaluation of errors past and present (Cheng et al., 2016).

Test data comparisons

In addition to testing the operation of the equipment after installation, test data should be collected at the start and the conclusion of every cruise. Re-testing should also be performed each time the DAQ card, launcher, cabling, or power supply is exchanged or repaired. Ensure that the system has remained stable by comparing lab test data to all field test data collected during the cruise. Verify that there are no deviations outside of expected results.

Cruise report

A detailed report for each XBT cruise should be written and at least preserved with the original internal data archive. It should include all the metadata outlined in The Metadata Verification section as well as notations about equipment problems, their causes, equipment changes and repairs. Keep a daily log that includes regular observations of weather that could affect measurements, such as wind speed and direction, lightning, heavy rain, ice, etc. For each launch, note any unusual observations and the reason for profile flags numbered >1 (Table 1). Include statistics for number of drops, probes used, and probe failure rates. List supplies needed for the next voyage and summarize advice for the next technician. Tabulate and summarize the results of all test data. Document what procedural manual and best practices were used. Do not forget to specify the name and identifiers of the scientific project as well as any ancillary project operating at the same time on board, such as Argo or drifter deployments.

Data management

All XBT data collected including paper copies of logs, cruise reports, and test data should be retained and archived by the group collecting it. It is a good practice to keep the data using multiple different storage methods such as: solid state archive, cloud archive and an accessible disk.

SOOP XBT data are additionally archived and distributed through NOAA/NCEI, the Australian Ocean Data Network (AODN) Portal, the institutions conducting the operations, and other regional data distribution centers.

Currently, SOT is working with other organizational task teams establishing the standards and procedures for platform and measurement metadata and also templates for Binary Universal Form for the Representation of meteorological data (BUFR format) for sending data to the GTS. Once this is formalized, there are plans to create the best practices companion document "XBT Metadata Content and Format" (in prep.).

Summary

The measurement of ocean temperature profiles of the upper ocean using XBT probes deployed in a global network of established transects continues to provide important data applicable to climate studies such as changing upper-ocean currents, meridional heat transport and thermosteric sea level rise.

The XBT measurement system in its simplest form is compact, inexpensive, robust, reliable, and easy to operate. The ubiquitous application of XBT probes, first deployed in about 1967, has led to long-term technological support of the product. Permanent components of the system, consisting of the launcher, DAQ hardware, GNSS receiver, computer controls and power, can last in excess of 10 years with careful maintenance and monitoring for stability (e.g. the launchers and DAQ card used by SIO's XBT program have been in service for over 20 years). The low cost of making a large number of closely spaced temperature measurements is the key reason for implementing this surveying technique. Costs can be further minimized by recruiting volunteer ship platforms and employing personnel already working aboard as operators.

The longevity of XBT measurement programs increases their relevance to global ocean circulation studies. While other temperature profiling platforms, such as the Argo core program, now contribute much high-quality data, "they cannot occupy repeated, mesoscale-resolving, trans-ocean basin transects across major currents on the time scales that are regularly sampled using XBTs from fast-moving ships" (Goni et al., 2019). On the other hand, the accuracy limitations and spatio-temporal specialization of XBTs require other techniques to offset the program data's regional biases. Therefore, XBTs and other profiling platforms are complementary and also serve as cross references to identify biases in the Global Ocean Observing System. Because the XBT measurement system will continue to fulfill an important niche, the SOOP community remains active in promoting best practices, advances in the design of XBT probes, and a better understanding of their characteristics that will improve temperature measurement accuracy (Abraham et al., 2013).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

JP, wrote the first draft of the manuscript. FB, RC, CH, LK, JS wrote sections of the manuscript. LC, MC, SC, MG, SK, FR contributed to the design of the best practices. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.991760/full#supplementary-material

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