

**Airborne eXpendable Buoy
Processing System (AXBPS)
User Manual**

For questions or concerns, please contact Casey Densmore at densmore@alum.mit.edu

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Chapter 1

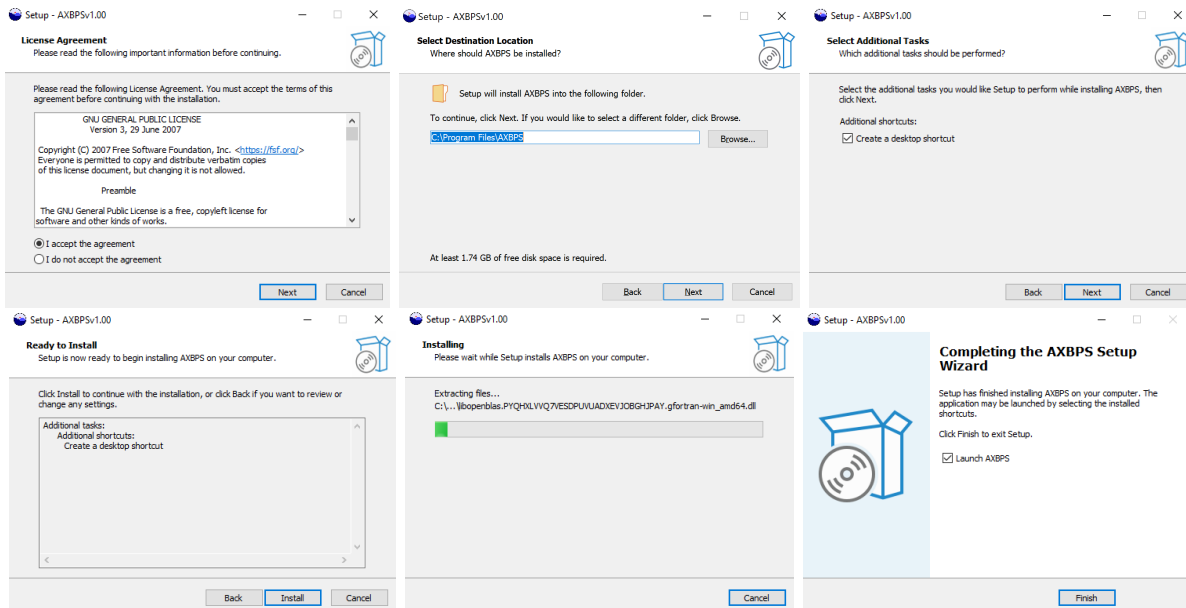
Installation

1.1 Installing AXBPS

AXBPS can be installed by one of two methods: using the executable installer with all supporting libraries bundled together (recommended) or using the Python base and supporting all required Python modules. The steps necessary for each method are described separately in the following subsections.

1.1.1 Installing Via Executable (Recommended)

The executable (.exe) installer file can install AXBPS with minimal work on the part of the user. This file installs a version of AXBPS that has been bundled with the required Python dependencies so it does not require a functional Python installation on the operating computer (and if one exists, AXBPS will operate independently of it). First, run the installer by double clicking and enable administrator access if prompted. Next, follow the user prompts, select where to install AXBPS (if required) or leave the default selection (C:\Program Files\AXBPS). Follow the remaining prompts (shown left to right, top to bottom below) to install AXBPS.



1.1.2 Installing To Use Python Base and Dependencies

Installing AXBPS to operate with Python base and required modules requires the following steps:

1. Install Python Base (version $\geq 3.6.0$)
2. Clone the AXBPS source code from github
3. Download necessary drivers and data dependencies
4. Use pip to install supporting Python modules

Find and download the base module from Python (select a version greater than or equal to 3.6) from <https://www.python.org/downloads/> (the simplest method is to download and install from an executable). Next, clone the AXBPS repository (`git clone https://github.com/cdens/axbps`) to your directory. AXBPS requires source data files that are not included in the repository due to size constraints. These files can be downloaded as a compressed folder from mmmfire.whoi.edu/axbps and extracted to the AXBPS directory as shown on the next page. For brevity, climatology and bathymetry data are abridged to show the general formats of files in each directory. Additional files may exist that are not shown, but are not required to run AXBPS on Windows 10 or 11.

Finally, install all dependencies for AXBPS using pip. This can be accomplished using the included requirements.txt file (via command line) with `pip install -r requirements.txt`. Some modules (namely Cartopy and Shapely) may raise errors on installation due to dependencies. On Windows systems, the simplest workaround is to install affected modules via their respective wheel files (for your computer's architecture and Python version) from <https://www.lfd.uci.edu/~gohlke/pythoAXBPSnlibs>. Download both wheel files from the website, and install them by first installing the wheel module (`pip install wheel`), navigating to the directory with the file, and installing the Shapely module from its wheel file with `pip install WheelFile.whl` (replace `WheelFile.whl` with the name of the downloaded file, and do not rename the file on download as wheel filenames must follow a specific format to avoid raising errors on installation). For example, the Shapely wheel filename should be formatted to follow `Shapely-1.6.4.post2-cp3x-cp3xm-win(32 or _amd64).whl` depending on Python version and windows type (e.g. `Shapely-1.6.4.post2-cp37-cp37m-win_amd64.whl` for Python v3.7, Windows x64-bit). On MacOS or Linux, it is typically simplest to install the required dependencies via your operating system's package manager (for MacOS, install and use HomeBrew).

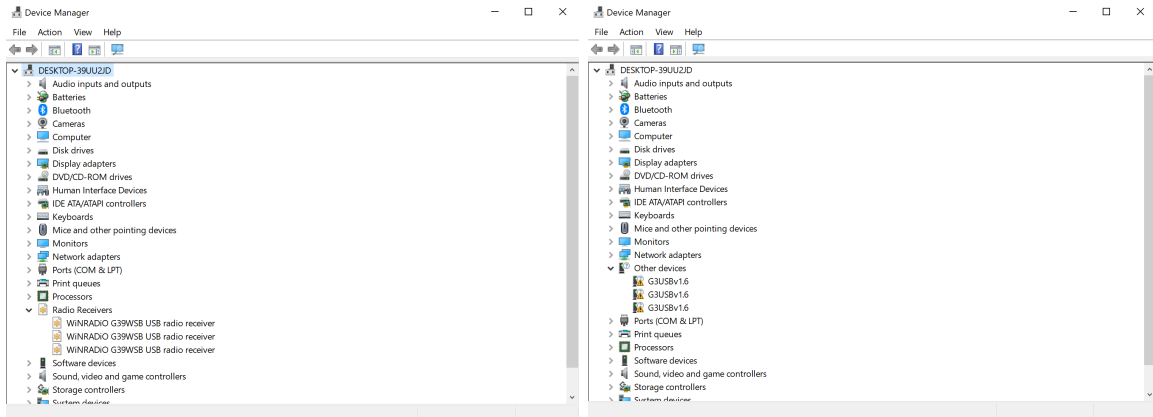
1.2 Installing Necessary Drivers

WiNRADIO drivers are necessary for a computer to recognize and communicate with the WiNRADIO receivers. If these are not automatically installed during the executable installation process, they must be installed manually. Currently, the necessary drivers are only available for windows and thus these instructions are Windows-specific. Future updates to AXBPS may support capabilities for Linux/MacOS, either via WiNRADIO receivers or support for additional software-defined receivers. To check if the necessary drivers are installed, first connect at least one receiver to the computer and then open the "Device Manager" from the Start menu. The receivers will appear in the Device Manager in one of two ways (shown in the following screenshots). If the drivers are already installed, the receiver will appear as in the left image: under the "Radio Receivers" category, named "WiNRADIO G39WSB USB radio receiver". If the drivers are not installed, the receiver will appear as in the right image: under the "Other devices" category, named G3USBv1.6 (in both of the following screenshots, three radio receivers were connected).

AXBPS Program Folder



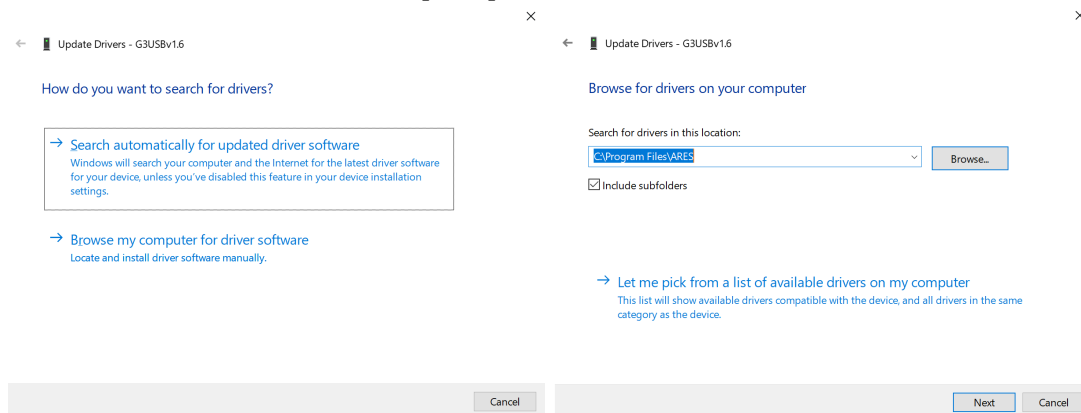
Examples of the Windows device manager with three WINRADIO Receivers connected and the necessary drivers (left) installed and (right) not installed.



If the drivers are not installed (e.g. the right image above), complete the following steps to install them:

1. Right-click on the radio receiver ("G3USBv1.6") and select "Update Driver"
2. Select "Browse my computer for driver software" (left image, below)
3. Select "Browse" and navigate to the AXBPS program folder (right image, below). If AXBPS was installed from the executable installer with default settings, this folder will be C:\\Program Files\\AXBPS
4. Select "Next" and allow the computer to automatically find and install the necessary drivers
5. Upon completion, disconnect and reconnect all receivers. All connected receivers should now appear in the Device Manager as in the above image on the left (this process only needs to be completed once, not individually for each receiver).

Windows prompts for driver installation



Chapter 2

Usage

The Airborne eXpendable Buoy Processing System (AXBPS) can be subdivided into two distinct subsystems with different user interfaces and functions: the Data Acquisition System (which processes data either in realtime from an audio receiver or reprocesses data from a recorded audio file) and Profile Editor (which completes a series of automated checks and corrections on the AXBT, AXCTD, or AXCP profile before displaying it to the user to make additional corrections as necessary). Usage of each of those subsystems are discussed separately in the following two sections.

2.1 AXBPS Data Acquisition System

The Airborne eXpendable Buoy Processing System (AXBPS) Data Acquisition System is designed to receive pulse code modulated (PCM) audio data containing an AXBT, AXCTD, or AXCP signal and return the transmitted profile(s) from that data. AXBPS is compatible with WinRADIO software-defined radio receivers, which demodulate a VHF signal transmitted from a probe and exporting the resulting PCM data to AXBPS for processing. Additionally, previously recorded WAV files can be imported into AXBPS to regenerate temperature, salinity, and/or current profiles from previously launched probes. AXBPS integrates the signal processing capabilities of the MK-21 or similar hardware and audio recorders as software-defined functions, reducing the equipment necessary to launch and process data from air-launched oceanographic probes.

2.1.1 Layout

An AXBPS Data Acquisition System graphical user interface (GUI) tab is opened by default when starting AXBPS. Additional Data Acquisition System tabs can be opened by either selection "Options > New Processor Tab" or using the keybinding ctrl+N. The Data Acquisition System window is divided into three sections (Fig. 2.1):

1. Raw, realtime data-versus-depth profile plot (left)
2. Tabular profile and signal information (lower right)
3. Probe type, data source, VHF, and profile metadata configurations (upper right)

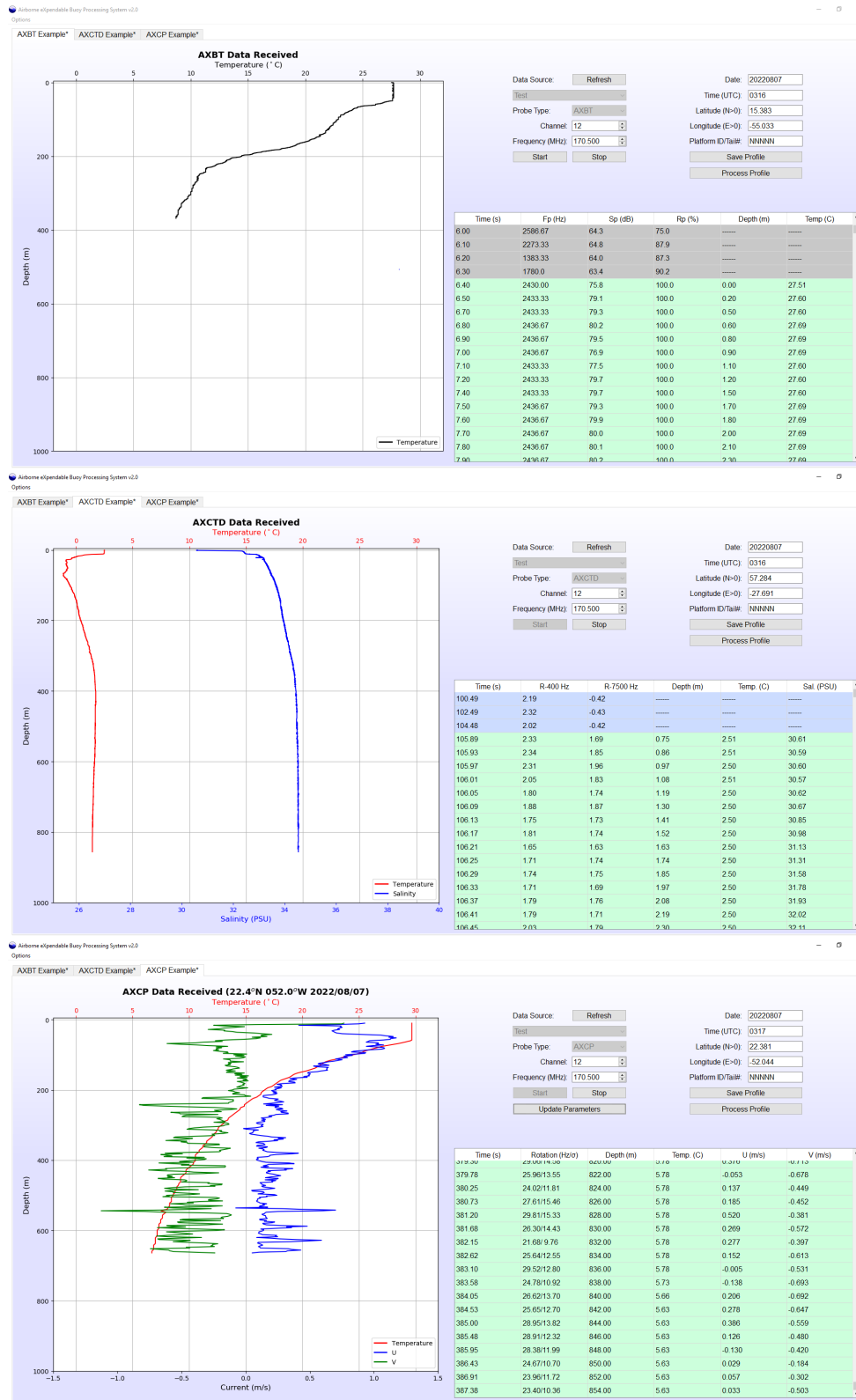


Figure 2.1: The AXBPS Data Acquisition System graphical user interface for AXBTs (top), AXCTDs (middle), and AXCPs (bottom).

The upper-right corner of the GUI provides options for the user to control the Data Acquisition System. There are two columns with user inputs. At the top of the left column, a dropdown menu allows the user to select the data source from which AXBT data is being processed. The datasource selection dropdown menu automatically has two default options: "Test", which processes a test signal (from a raw audio file distributed with AXBPS), or "Audio", which prompts the user to select a raw WAV file to be reprocessed. Additionally, on Windows systems with the WiNRADIO drivers installed, any connected WiNRADIO receivers will be listed by serial number in order to process data in realtime. Because each receiver can only demodulate one channel at a time, AXBPS prevents the user (with a warning message) from selecting the serial number for a WiNRADIO that is actively receiving in a different tab.

The "Probe Type" dropdown menu allows the user to switch between AXBT, AXCTD, and AXCP processing modes. In addition to switching the signal processing method to be used, this selection reconfigures the table and plot to display AXBT (temperature only), AXCTD (temperature and salinity), or AXCP (temperature and current) information.

If a connected WiNRADIO receiver is selected, the two spinboxes immediately below the data-source selection menu (labelled "VHF Channel" and "VHF Frequency") allow the user to select the VHF frequency that the receiver demodulates, either directly by frequencies or by selecting the corresponding sonobuoy VHF channel (selecting a new frequency will update the selected channel, and vice versa). The VHF channel and frequency being demodulated can be changed while a receiver is actively processing data.

Buttons for the user to start and stop data acquisition are located at the bottom of the left column. Data acquisition can be restarted after being stopped (except when reprocessing from audio files), and the time elapsed will be preserved from the initial start selection for AXBTs only, but any data received while the Data Acquisition System was stopped is lost. When processing AXCTD and AXCP profiles, processing in a given tab cannot be restarted after being stopped. After processing has been initiated (by selecting start), the user cannot switch between Test/Audio/Receiver data sources. The selected receiver can be changed if multiple receivers are connected, but to do this the user must stop processing, select a different receiver, and then resume processing.

The right column of text provides inputs to record probe drop information: date, time, latitude, longitude, and platform identifier (e.g. aircraft tail number). For realtime drops (when the selected datasource is a WiNRADIO serial number), the date and time will be autopopulated from the system date and time, and the position will be populated from a connected GPS receiver (if configured in AXBPS preferences, as discussed in the following section). This autopopulation option is configurable in the AXBPS settings. After processing probe data and entering the corresponding drop information, selecting "Process Profile" will first prompt the user to save the raw profile data (this is configurable in AXBPS settings) before loading the raw profile into a Profile Editor tab (discussed in Section 2.2.2)

When in AXCP processing mode, an "Update Position" button will appear directly below the start and stop buttons. This allows the user to update the position and date used to calculate the horizontal and vertical components of Earth's magnetic field and declination (required for accurate current calculations; for more information see Section 4.0.4) used by the AXCP processing routine with the values entered in the date and position input boxes in the right column of text. When a GPS is connected, the latitude and longitude will be autopopulated when "Start" is selected and those values will be relayed to the AXCP processor. If no position or date is provided, the default coordinates in the DAS signal threshold tab of the settings and the current date will be used. To update the date and position to more accurate values while the profile is processing or after it is completed, simply enter the correct values in their respective textboxes and select "Update Position" (this will retroactively correct all previously calculated currents and update the plot, but the table

will not be updated with corrected values). The date and position used in the AXCP processing algorithm are displayed above the plot on the top left side of the window.

While actively processing, the table in the lower-left section of the screen is updated in realtime with incoming data from an AXBT, AXCTD, or AXCP. For an AXBT, the table's columns are (from right to length): time (seconds), frequency (Hz), signal level (dB), signal ratio (%), depth (meters) and temperature (degrees Celsius). The time and frequency fields list the time elapsed since "Start" was selected and the peak frequency of the signal currently being received. If a signal's peak frequency is in the expected range corresponding to realistic temperature values (defined by user settings, default 1300-2800 Hz) and the observed signal level and signal-to-noise ratio (SNR; these values are displayed in the S_P and R_P columns in the table, respectively and described in more detail in Section 4.0.2) meet the required minimum thresholds (which are defined in the user settings as described in the next section), then the temperature and depth are calculated and appended to the profile plot, and the corresponding row in the table will appear green. If the minimum signal level and SNR thresholds are not met, temperature and depth are not calculated or appended to the profile plot, and the corresponding row in the table will appear gray.

When processing an AXCTD, the table's columns are time (seconds), R_{400} (unitless), ΔR_{7500} (unitless), depth (meters), temperature (degrees Celsius), and salinity (PSU). The time, depth, and temperature fields are similar to the AXBT mode, with the addition of a salinity field. R_{400} and ΔR_{7500} are unitless signal-to-noise ratio metrics at 400 Hz and 7500 Hz, respectively. The former is used to identify when the AXCTD begins transmitting 400 Hz calibration tones, and the latter detects when the 7500 Hz tone indicating profile transmission has begun. These are both power levels provided as ratios to the power at a user-selected quiet frequency (default 3000 Hz, adjustable in settings), and must exceed user-selectable minimum thresholds (also adjustable in settings) for their respective tones to be identified. Prior to 400 Hz pulse detection and when bad datapoints are detected during profile collection, table entries appear gray. During the 400 Hz pulse and header calibration transmissions, table entries are blue. Table entries corresponding to valid datapoints will appear green. For more information on underlying AXCTD data transmission format and demodulation/decoding methodology, see Section 4.0.3

When processing an AXCP, the table's columns are time (seconds), rotation rate mean and deviation (Hz; separated by a slash), depth (meters), temperature (degrees Celsius), and zonal and meridional (oriented in degrees True) currents (m/s). The time, depth, and temperature fields are similar to the AXBT and AXCTD modes, with the addition of two current fields. The rotation rate and rotation rate deviation are used to identify when an AXCP probe has "spun up" and begun descending through the water column (as it descends, it rotates at approximately 16 Hz). The rotation rate must be between 12 and 18 Hz for AXBPS to identify probe spinup, and spinup and spindown rotation rate deviation thresholds are adjustable in the DAS signal settings. Table entries before spinup or after spindown are gray, whereas entries containing valid profile data are displayed in green.

2.1.2 Settings

Data Acquisition System Settings

The Data Acquisition System settings are separated into two tabs: DAS General Settings and DAS Signal Thresholds. The DAS General Settings tab includes three sections: autopopulation options, file save formats, and miscellaneous settings. The autopopulation options (top left) control whether AXBPS automatically updates the recorded drop information (in the right column in the Data Acquisition System tab) whenever "Start" is selected for the first time in a tab. Autopopulation

is not used when data is being reprocessed from a raw audio file (when "Audio" is the selected data source). Four file save formats (discussed in Section 4.0.5) are also selectable. Below these options are three additional user settings that control user prompts that appear when attempting to save the raw data and transition to a Profile Editor mode.

The DAS Signal Thresholds tab is divided into three sections by column for AXBT, AXCTD, and AXCP settings. The leftmost column of settings from the right control the windows and thresholds used to process AXBT data. The "FFT Window" is the length of each window of data (in seconds) used to determine peak frequency and corresponding temperature. Increasing this window increases the frequency and temperature resolution (see Δf , Eq. 4.2 in Section 4.0.2) and reduces the effects of transient interference and noise, but also increases computational expense and slows the program, reducing the rate at which data can be processed and decreasing the raw profile's vertical resolution (this effect is compounded when processing multiple profiles simultaneously). The minimum signal level and signal ratio are thresholds used to distinguish valid AXBT data from noise (increasing the thresholds by moving the sliders to the right makes the Data Acquisition System more selective, reducing the amount of data considered valid). These minimum thresholds are applied to the values listed in the S_P and R_P (respectively) columns of the table. They are also discussed in more detail in Section 4.0.2. Finally, the trigger signal level and ratio are additional constraints applied to the minimum signal level and ratio to identify the first datapoint transmitted from an AXBT and trigger the start of the temperature-depth profile. Because AXBT signals typically begin stronger and weaken with depth as the aircraft generally moves away from the buoy, using a higher constraint here can help to prevent weak VHF interference from erroneously triggering data collection prematurely.

The middle column of settings pertain specifically to AXCTD decoding. The minimum R_{400} and ΔR_{7500} sliders allow users to set the minimum threshold for the respective signal-to-noise ratios at 400 Hz and 7500 Hz used to detect AXCTD calibration tone and profile transmission. Below those two sliders, the user can use the quiet frequency field to select a frequency somewhere between 1000 and 7000 Hz that should not contain any noise. The frequency shift key modulated data is transmitted at 400 and 800 Hz, and the profile tone at 7500 Hz, so the default of 3000 Hz is suitable unless known narrowband RF interference is expected in that range. The mark and space bit frequency selectors are used by the demodulation algorithm and should not be adjusted unless there are known discrepancies with the AXCTDs waveform that require compensation. The refresh rate defines the interval at which audio data are relayed to buffers to be demodulated into a bitstream and parsed into temperature and salinity information. Finally, selecting the bottom checkbox allows the user to apply a 100 Hz to 1200 Hz bandpass filter rather than the default (and recommended for most use cases) low pass 1200 Hz filter. The filter is applied to decouple the 7500 Hz profile transmission tone from the bitstream and simplify the demodulation process.

Finally, the rightmost column of settings applies specifically to AXCP decoding. AXCP refresh rate determines the length of PCM data chunks (in seconds) that are processed at a time. One second is recommended for a variety of reasons discussed further in Section 4.0.3. The AXCP quality affects subsampling intervals for the AXCP data, and due to its negligible effects on processing speed it is recommended to keep the highest quality selected. When enabled (recommended), realtime spindown detection automatically detects when the AXCP probe has stopped spinning (and either the probe's cable is severed or the probe has reached the ocean bottom) and terminates profile processing without user intervention. When enabled, AXCP temperature FFT ID uses an FFT (as in the AXBT processing algorithm) to determine the temperature baseline frequency. While slightly slower, the effect on processing speed is fairly small and the alternative method of zero-crossing frequency calculations is much more susceptible to interference, thus this setting is also recommended. The AXCP FFT window determines the window length for the FFT (in seconds),

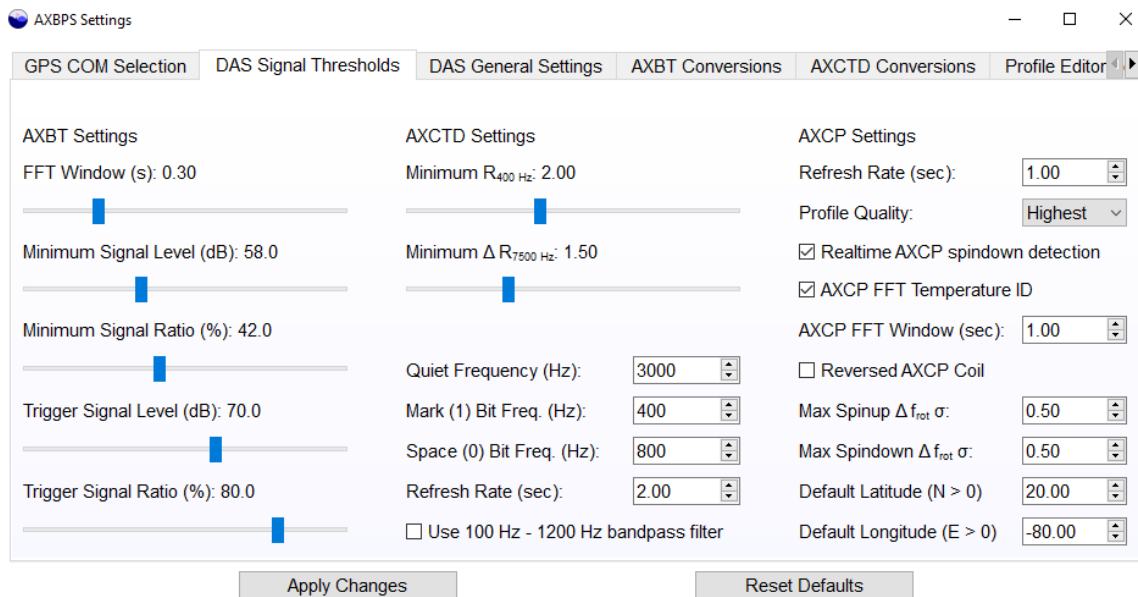
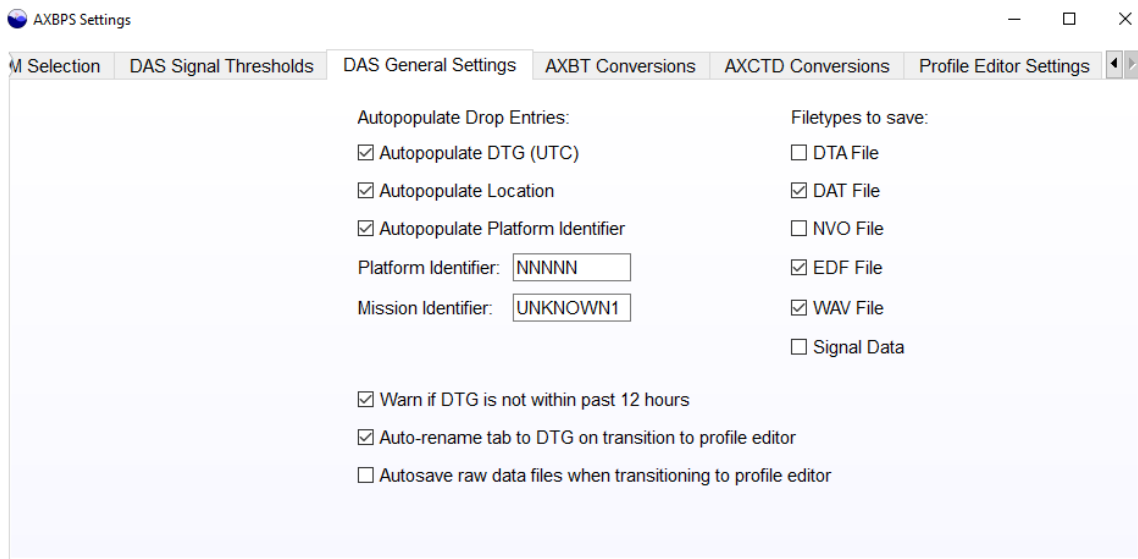


Figure 2.2: The AXBPS Data Acquisition System general (top) and signal thresholds (bottom) settings windows.

and is only used when the corresponding checkbox is selected. Selecting "Reversed AXCP coil" rotates the currents by 180° and shouldn't be done unless you are aware that the launched AXCP falls in this category. The maximum spinup and spindown rotation rate deviations (Hz) are used to identify when the profile starts and stops spinning, respectively. It is recommended to keep both thresholds at 0.5 Hz, with the exception of particularly noisy AXCP profiles where probe spinup is not automatically identified. In that case, the current best practice is to reprocess the profile from audio with spinup and spindown thresholds of 1.0 and 2.0 Hz, respectively. Finally, the default latitude and longitude are the coordinates used to calculate Earth's magnetic field components and declination (for AXCP current calculations) if no coordinates are provided by the user. These settings will not autopopulate in the DAS latitude and longitude entry fields, and are not used for quality control and/or the profile editing system.

AXBT Temperature/Depth Conversion Equation Settings

AXBPS includes the ability to use custom conversion equations for AXBTs. Two columns are provided: one for frequency-to-temperature and the other for time-to-depth conversions. To adjust the conversion equations being used, enter the coefficient for each term in its respective box. The equation at the top of the respective column should update to reflect the coefficients in the boxes. If non-numeric characters are entered, the equation will not update. The equations used by AXBPS will not be updated until "Apply Changes" is selected. Additionally, if the contents of the input boxes do not match their respective equations (e.g. due to a non-numeric character as described above), the coefficients used by AXBPS are based on the equations at the top of each column, not the contents of the input boxes.

Finally, at the bottom of the tab there are two additional inputs to select the valid frequency range. The default range of frequencies AXBPS accepts as valid AXBT signal is 1300 Hz to 2800 Hz, corresponding to approximately -3.9°C to 37°C. However, because AXBPS may be used in locations where only a subset of these temperatures are expected (e.g. an AXBT launched in the Southern Ocean during austral winter would most likely not observe 20°C ocean temperatures), this input can be used to apply more precise constraints on the frequencies (and therefore temperatures) that AXBPS accepts.

AXCTD Temperature, Conductivity, and Depth Conversion Equation Settings

Similar to the AXBT options, AXBPS includes a settings tab where users can specify the default temperature and conductivity calibration equations and the fall rate equation to calculate depth for AXCTDs. AXCTDs should transmit these fields with their header metadata prior to profile transmission (see Section 4.0.3 for more information), but should the AXCTD processing algorithm fail to identify and/or demodulate/parse the header data for a variety of reasons, the default equations will be used instead. Header metadata is saved in the sigdata.txt file and .edf file for each probe (if those file save options are enabled in the DAS settings) for users interested in that information. The AXCTD Conversions tab also includes min and max thresholds for valid temperature and salinity data. These thresholds, particularly the salinity threshold, are the most effective ways of distinguishing good profile data from random noise and interference that occasionally overcome the AXCTD's cyclic redundancy checks.

Due to the complex nature of AXCP conversions (e.g. probe gain and phase angles, nonstandard temperature conversions) and lack of literature and competing conversion equations, an AXCP conversion settings tab is not provided.

AXBPS Settings

M Selection
 DAS Signal Thresholds
 DAS General Settings
 AXBT Conversions
 AXCTD Conversions
 Profile Editor Settings

Frequency to Temperature Conversion:

$$T = -40.0 + 0.02778f + 0.0f^2 + 0.0f^3$$

+
 * f +
 * f² +
 * f³

Time Elapsed to Depth Conversion:

$$z = 0.0 + 1.524t + 0.0t^2 + 0.0t^3$$

+
 * t +
 * t² +
 * t³

Valid Frequency/Temperature Limits:

Minimum Valid Frequency (Hz):
 Maximum Valid Frequency (Hz):
 Minimum Valid Temperature (°C): -3.89
 Maximum Valid Temperature (°C): 37.78

AXBPS Settings

M Selection
 DAS Signal Thresholds
 DAS General Settings
 AXBT Conversions
 AXCTD Conversions
 Profile Editor Settings

Default Time to Depth Conversion:

$$z = 0.72 + 2.76124t - 0.000238007t^2 + 0.0t^3$$

+
 * t +
 * t² +
 * t³

Default Temperature Conversion:

$$T = -0.053328 + 0.994372T_{\text{uncal}} + 0.0T_{\text{uncal}}^2 + 0.0T_{\text{uncal}}^3$$

+
 * T_{uncal} +
 * T_{uncal}² +
 * T_{uncal}³

Default Conductivity Conversion:

$$C = -0.0622192 + 1.04584C_{\text{uncal}} + 0.0C_{\text{uncal}}^2 + 0.0C_{\text{uncal}}^3$$

+
 * C_{uncal} +
 * C_{uncal}² +
 * C_{uncal}³

Temperature Limits:

Minimum Temperature (°C):
 Maximum Temperature (°C):

Salinity Limits:

Minimum Salinity (°C):
 Maximum Salinity (°C):

Figure 2.3: The AXBPS (top) AXBT temperature/depth and (bottom) AXCTDD temperature, conductivity, and depth conversion equation settings window.

GPS Configuration Settings

The GPS settings tab allows the user to select a serial port for AXBPS to open and collect GPS data in order to autopopulate drop latitude and longitude when processing is started (more information on the GPS NMEA stream and serial configuration is provided in Section 4.0.5). The dropdown menu lists all available serial interfaces (it is worth reiterating that all available interfaces are listed, not just those that are transmitting valid GPS NMEA data streams). If multiple COM ports are available, the correct port can be determined by first selecting a port and then selecting "Refresh GPS Info". If an active GPS receiver is connected to the selected port, this will populate the most recent GPS fix from that receiver. Otherwise, a warning message will appear stating that a GPS data stream could not be identified.

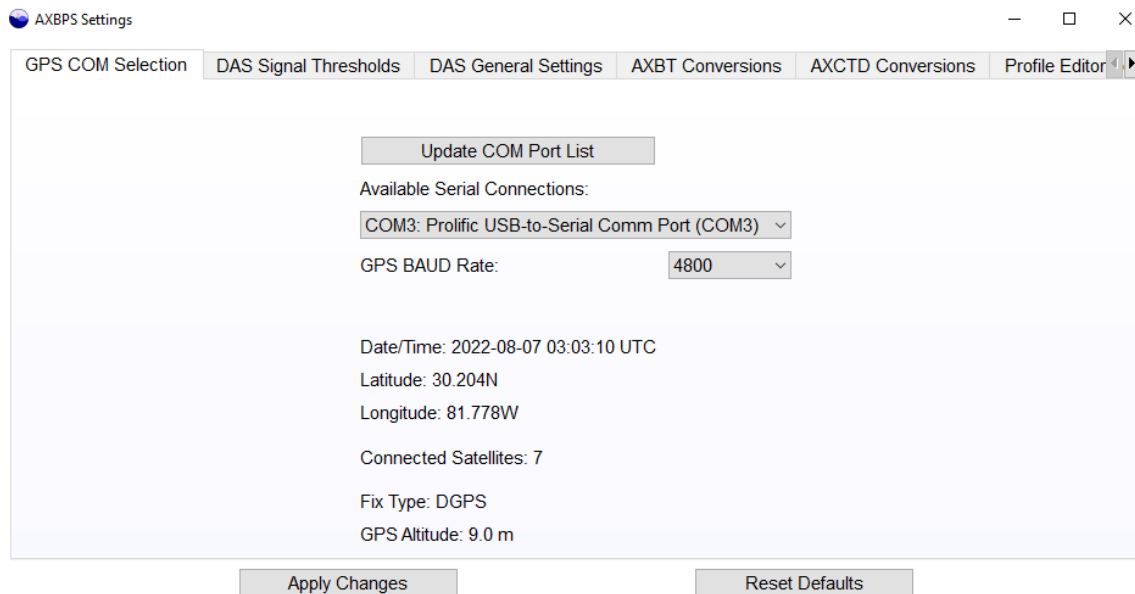


Figure 2.4: The AXBPS GPS configuration settings window.

2.2 AXBPS Profile Editor

The Airborne eXpendable Buoy Processing System (AXBPS) profile editing package is meant to enable users to quality control AXBT, AXCTD, and AXCP temperature, salinity, and current profiles, guided by an automated quality control algorithm and further aided by bathymetry and temperature and salinity climatology data for the region of interest to reduce the background oceanographic knowledge necessary on the part of the user.

2.2.1 Layout

The profile editor interface is divided into three sections (Fig. 2.5):

1. Interactive profile temperature-depth (and salinity-depth for AXCTDs or current-depth for AXCPs) plot (left)
2. Static profile location and bathymetry plot (bottom right)
3. Profile editing tools (top right)

The profile plot(s) overlay(s) three profiles: raw data (black), quality-controlled data (red for temperature, green for salinity or zonal current, blue for meridional current), and a climatological profile (using the Generalized Digital Ocean Model climatology) based on the probe's position and month launched, shaded for uncertainty (light blue; temperature and salinity only). All user edits are made to the quality-controlled (red, green, or dark blue) profiles, which are also the data exported to several output file formats by AXBPS. When the profile editor interface is first loaded, the quality-controlled profile is generated using an automated quality control ("autoQC") algorithm that corrects for common modes of VHF interference and compares the data to climatology and bathymetry. The location plot overlays the probe's recorded position with contoured bathymetric data (1 arcminute resolution data from the NOAA ETOPO1 global relief dataset), to provide the user with additional information about the region in which the probe was launched and the surrounding bathymetry. Color contours are applied over the range 0 m to 4000 m using the cmocean "topo" colormap, and bathymetric features deeper than 4000 m are represented with dashed white contours at a 500m interval.

The top right section of the profile editor interface includes the tools necessary to manipulate and edit the temperature, salinity, and/or current profiles. Along the top of the plot is a toolbar that includes controls to pan and zoom around the temperature-depth plot in order to inspect and edit the profile in greater detail. It is worth noting that the controls in this toolbar do not edit the profile, and only change the user's view (for example, the back and forward arrows do not undo and redo edits to the profile, rather they allow the user to move back and forward to the previous and next views of the profile, respectively). The remaining interactive widgets are organized into two columns. The "Overlay Climatology" button in the left column allows the user to toggle the visibility of the blue climatology shading. All other buttons and spinboxes in the left column allow the user to edit the quality-controlled profile(s) (these are discussed in detail in Section 2.2.3). When editing AXCTD temperature and salinity or AXCP temperature and current profiles, the buttons to add or remove profile points will only be applied to the currently selected profile (temperature, salinity, or current) but changes to the maximum depth, etc. will be applied to both or all three profiles.

The right column includes profile information. The text box includes data such as exact position, ocean depth at that position, and the number of datapoints in the quality-controlled profile. The dropdown menu provides a list of common profile discrepancies that can be used to flag a profile with

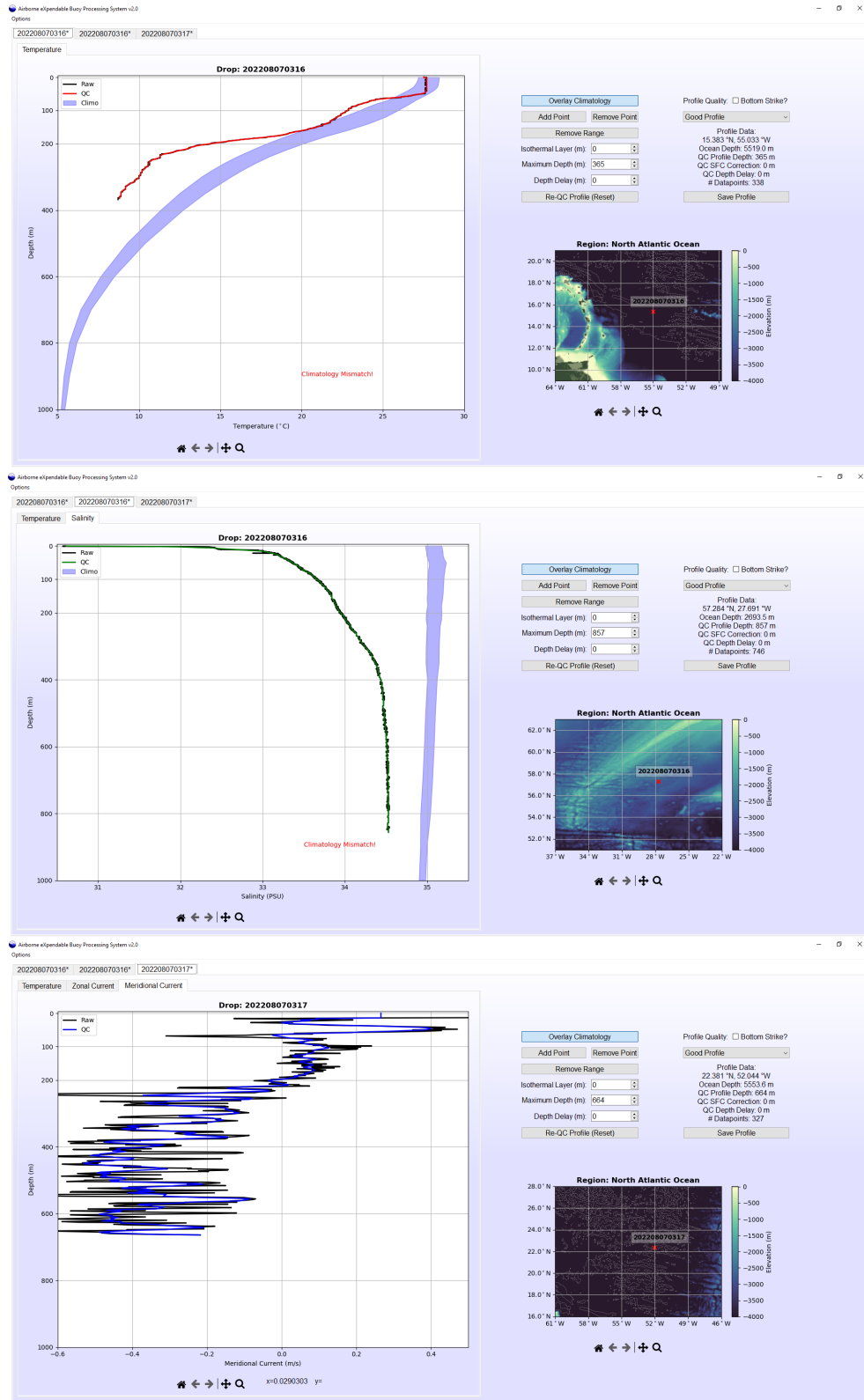


Figure 2.5: The AXBPS profile editing graphical user interface for (top) AXBT profiles and (bottom) AXCTD profiles (salinity plot currently selected).

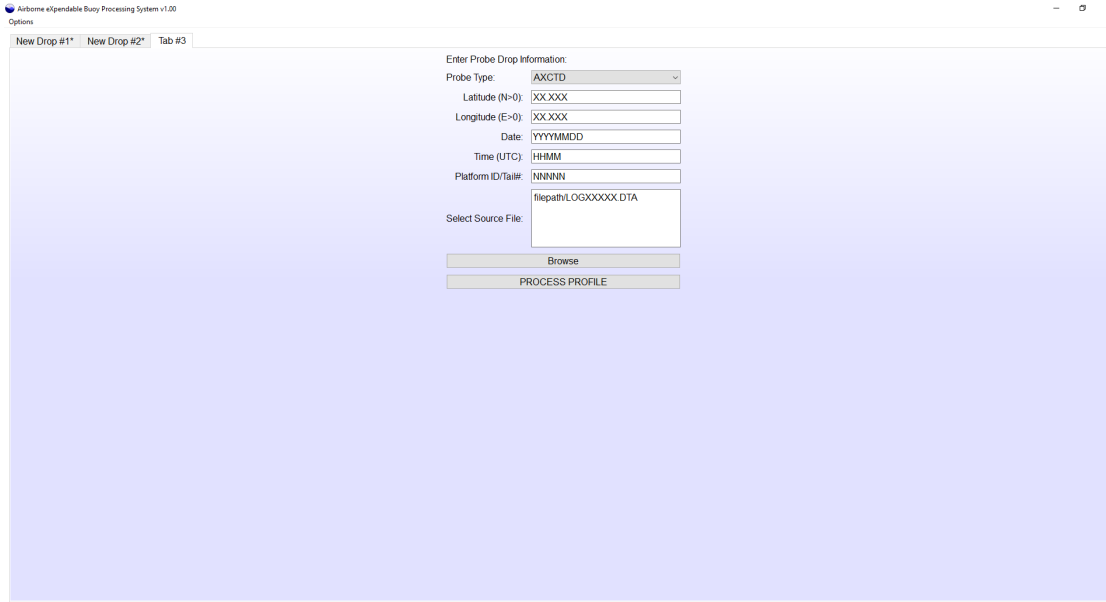


Figure 2.6: The AXBPS profile editor ASCII file selection interface.

uncorrectable features (such as an isothermal profile due to a probe that failed to deploy properly). These quality control flags are further discussed in Section 2.2.4. The "Bottom Strike" checkbox is used to note if it appears that the probe reached the ocean floor (e.g. due to erroneous warning or a profile whose maximum depth exceeds the indicated ocean depth at its position), as this information is incorporated in the output JJVV file (see "Input and Output File Formats", Section 2.2.5).

2.2.2 Opening a Profile Editor Tab

Raw profiles can be loaded into a profile editor interface by one of two means:

1. Loaded directly from the AXBPS Data Acquisition System interface by selecting "Process Profile" after acquiring data in realtime or reprocessing from an audio file
2. Read from an ASCII file format (see supported input ASCII formats in Section 2.2.5) using the AXBPS ASCII file selection interface (Fig. 2.6)

Users can open an ASCII file selection interface tab to load a supported raw text file by either selecting "Options > New Profile Editing Tab" or using the keybinding "ctrl+P". This interface includes user inputs for drop date, time, and position, as some supported file formats (e.g. *.DTA) do not include that information. If a selected raw data file does include position and time, information is not required in those fields, but any valid positions or times entered there will supersede those in the raw data file. Be sure to select the correct probe type; if you select "AXBT" but load an AXCP file, AXBPS will read the file but only allow you to edit and save the temperature profile. If reprocessing data from a temperature-only JJVV file (even if the data was collected via an AXCTD or AXCP), select AXBT as the probe type.

2.2.3 Editing Components

Users can make four categories of edits to the quality-controlled profile (listed in order of appearance on the GUI, from top to bottom):

1. Add or remove individual points or a range of points
2. Specify a surface isothermal region to remove erroneous surface spikes
3. Truncate the base of the profile to correct for bottom strikes or excessive interference
4. Vertically shift the profile to correct for VHF interference

Individually removing points or spikes may be necessary when the autoQC algorithm's spike removal feature fails to identify all erroneous datapoints. This is especially common when there is extreme variability due to VHF interference that saturates the standard deviation filter and increases the deviation necessary to identify a datapoint as erroneous. Additionally, if too many points are truncated and important profile characteristics are missed, adding individual points may be necessary. Individual points can be added and ranges of points can be added or removed with a point selection tool integrated into the AXBPS Profile Editor interface. For AXCTD and AXCP profiles, adding or removing points will only affect the active tab (e.g. if the temperature profile is open, removing points will only remove them from the temperature profile).

Occasionally, surface observations (particularly temperature, associated with a large difference in air and sea surface temperatures) include erroneous spikes due to probe acclimation or interference. The AXBPS Profile Editor provides an option to manually create an isothermal layer at the surface by setting the temperature of all datapoints above a specified depth equal to the observed temperature at that depth. For example, if the surface temperature erroneously starts at 26°C at the surface, but warms to a realistic value of 28°C at 5 m, setting the isothermal layer value to 5 m will change the temperatures of all datapoints above 5 m to 28°C, removing the surface spike. However, care must be taken by the operator to distinguish diurnal surface heating and cooling effects from erroneous features.

In some cases, it is necessary to truncate base of the profile, either to remove data from a bottom strike or to remove excessively variable (strong-interference) data. Finally, excessive VHF interference (either noise or an unexpected signal) that falsely triggers the start of profile collection can be overlooked by the autoQC algorithm if the gap between interference and valid data is less than 5 m or the interference extends without gaps beyond 50 m. If the correct profile surface is easily identifiable, the entire profile can be shifted upward manually. User-specified surface isothermal layer generation and profile truncation are not applied until after the vertical shift, so applying a vertical shift of 200 m and profile truncation at 400 m would first shift the profile upwards by 200 m, and then truncate all data that were below 600 m on the raw profile).

For AXCTD and AXCP profiles, corrections to the surface isothermal layer, VHF depth delay (though these should not be a factor for AXCTDs or AXCPs) or maximum depth fields will be applied to both the temperature and salinity and/or current profiles, regardless of which profile is selected at the time edits are applied.

2.2.4 Quality Control Flags

In addition to profile edits, users can apply quality control flags to note any profile discrepancies. First, a checkbox allows users to note whether the profile was a bottom strike. This information is encoded in the JJVV output file format (described further in Section 2.2.5). Additionally, a dropdown menu allows users to select one of ten quality control (QC) codes depending on the state of the quality-controlled profile (Table 2.1). QC code 1 (Good Data) should be used for a profile that has been successfully quality-controlled (whether edits were necessary or not) and is of sufficient quality to assimilate in models or use for other means. QC code 0 (No QC) should be used when, due to time or other operational constraints, no quality control was conducted on the profile.

Table 2.1: AXBPS quality control codes for post-processed AXBT and AXCTD profiles.

Code	Name	Description
0	No QC	No quality control was conducted
1	Good Data	Any profile discrepancies were corrected
2	No Signal	No signal was received from the probe
3	Spotty/ Interference	Signal was received but was either missing sections of data or was degraded by excessive VHF interference
4	Bad Data	Data was received but was bad quality for a reason not covered by a different code
5	Isothermal	Temperature and/or salinity profile was unexpectedly isothermal/isohaline
6	Late Start/ Hung Probe	Either the probe did not start transmitting on time, or the probe failed to detach from the surface float for some period after the transmission started
7	Slow Falling	Probe sank slowly through the water column, resulting in inaccurate depth recordings
8	Action Required	Profile was reviewed and requires additional corrections
9	Suspect Climo/ Neighbor Mismatch	Profile either does not match climatology for a given region and time or year, or is surprisingly different from other profiles launched nearby

QC code 8 (Action Required) should be used when the profile was reviewed but additional steps (e.g. point removal) are necessary before the profile is accurate. The remaining QC codes describe common issues with air-launched probes. Only profiles with QC codes 1, 3, and 9 (case-dependent for the latter two codes) should be used for other applications.

2.2.5 Output File Formats

In addition to loading data processed either in realtime or from a WAV file using the signal processor interface, AXBPS supports loading data from LOG, EDF, DAT, and NVO ASCII files. It is also possible to read in profiles from JJVV and FIN files (described in the next paragraph), but it is not recommended as these file formats contain lower resolution data that has typically undergone some sort of post-processing already.

AXBPS supports exporting profile data to four ASCII file formats (FIN, DAT, JJVV, and EDF), one binary format (WMO BUFR), and both profile and location/bathymetry plots. FIN files contain drop metadata and a quality-controlled temperature depth profile subsampled and interpolated to a 1m resolution. These files are formatted identically to NVO files (see Section 4.0.5), the only exception being that NVO files include all raw profile information whereas FIN files only include quality-controlled, 1m resolution data. An example of NVO/FIN file format for an AXBT profile is provided in Fig. 2.7a. AXCTD and AXCP profile NVO/FIN files are similar, except each observation includes temperature, depth, and salinity datapoints or temperature, depth, zonal current, and meridional current datapoints (in that order, respectively for AXCTDs and AXCPs). AXCTD and AXCP NVO/FIN files include three observations (with three or four entries each, respectively) per line, whereas AXBT profile NVO/FIN files include five observations with two (temperature and depth) entries each per line. EDF files also contain drop metadata including position and date/time (as well as optional information such as probe serial number and/or conversion coefficients), and

a											
	2017	253	0458	24.054	-82.897	6	6	239	0	0	
201709100458.fjn	28.902	4.0	28.902	5.0	28.912	6.0	28.923	7.0	28.934	8.0	
	28.949	9.0	28.963	10.0	28.977	11.0	28.991	12.0	29.006	13.0	
	29.020	14.0	29.012	15.0	29.003	16.0	28.995	17.0	28.986	18.0	
	28.978	19.0	28.969	20.0	28.961	21.0	28.967	22.0	28.976	23.0	
	28.984	24.0	28.992	25.0	29.000	26.0	29.008	27.0	29.004	28.0	
	28.997	29.0	28.989	30.0	28.982	31.0	28.974	32.0	28.967	33.0	
	28.959	34.0	28.952	35.0	28.944	36.0	28.937	37.0	28.929	38.0	
	28.922	39.0	28.914	40.0	28.907	41.0	28.898	42.0	28.873	43.0	
	28.848	44.0	28.824	45.0	28.799	46.0	28.775	47.0	28.693	48.0	

b											
	JJVV	10097	0458/	724054	082897	88888					
201709100458.jjvv	51099	04289	07289	14290	21290	27290					
	41289	47288	52283	54281	56279						
	57269	59261	61259	64255	68249						
	76243	79237	88233	93228	99901						
	03224	08213	10210	26203	31199						
	35195	40190	46185	48176	56168						
	65163	72158	73155	84144	99902						
	18136	38132	42131	AF302							

Figure 2.7: File formats for AXBT (a) FIN/NVO and (b) JJVV files. Note that the FIN file used in (a) is truncated below 48m, but the same temperature-depth format is continued for the remainder of the file.

data are space or tab-delimited with one depth/temperature (and optionally salinity or zonal and meridional current) datapoint per line.

JJVV files include only the subsampled points from the quality-controlled profile (these typically include only inflection points and critical levels in order to reduce file size). Like FIN/NVO files, JJVV files include a header with drop metadata, but in JJVV files each profile datapoint is encoded as five digits: the first two represent the depth in meters, and the last three represent the temperature to the tenths of a degree Celsius (for example, an observation of 28.3°C at 54 meters would be encoded as '54283'). Temperature-depth observations are listed with increasing depth, and every time depth increases into the next hundreds place, this is denoted by another five digit code: '999', followed by the new hundreds of meters (for example, once depth exceeds 100m, '99901' would be appended to the file, and a subsequent listing of '54283' would now indicate a measurement of 28.3°C at 154m). An example of the JJVV file format is provided in Fig. 2.7b. JJVV files generated by AXBPS will only include the quality-controlled temperature-depth profile, even if generated for an AXCTD or AXCP.

BUFR files are binary files that follow a format outlined by the World Meteorological Organization (WMO) using a large series of tables to specify a common method of encoding large amounts of data from a wide range of sources (e.g. satellites, radiosondes, oceanographic observations) while minimizing file size. BUFR files are divided into six sections, labelled zero through five. Sections 0,1, and 5 contain primarily static data to confirm that the file is formatted correctly, and some basic information such as date and time. Section 2 is optional, used to encode any necessary information without a proper entry in the WMO BUFR tables (this section is unused in AXBPS-generated BUFR files). Section 3 contains F-X-Y descriptors, used to identify the type of data being transmitted (which is encoded in Section 4). The F-X-Y codes used by AXBPS to encode AXBT data encode date and time, latitude and longitude to the hundredth of a degree, and temperature and depth to the tenths place in Kelvin and meters, respectively. Currently AXBPS only supports saving temperature-depth BUFR files; BUFR files can be generated for AX-

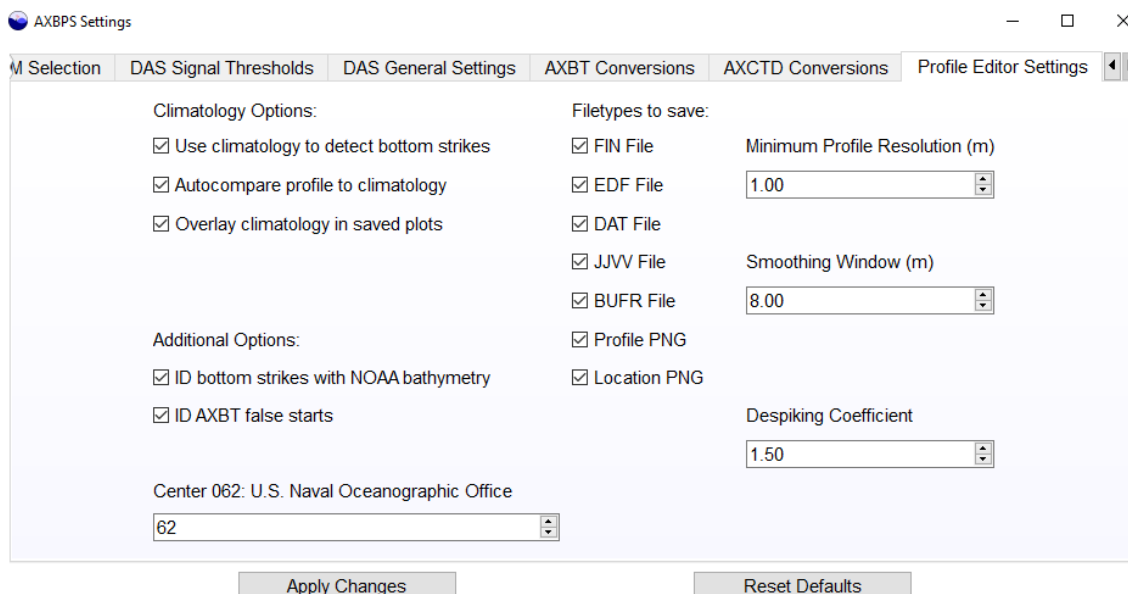


Figure 2.8: The AXBPS profile editor settings window.

CTDs and AXCPs but the resulting files will exclude the salinity and current data, respectively. A guide to the BUFR version used by AXBPS (WMO FM94 BUFR Edition 4) is available at <https://community.wmo.int/activity-areas/wmo-codes/manual-codes/latest-version>.

2.2.6 Settings

The AXBPS profile editor settings (Fig. 2.8) are divided into four sections: climatology options, file save formats, autoQC thresholds, and additional settings. Climatology settings are listed in the top right corner of the settings window. When checked, the "Use climatology to detect bottom strikes" option compares the slope of the quality-controlled profile to the slope of the climatological profile to identify erroneous isothermal or warming features caused by a bottom strike and automatically truncate the profile (this correction is discussed further in Section 4.1). When "Autocompare profile to climatology" is checked, a red "Climatology Mismatch" will appear if less than 50% of the points in the quality-controlled profile are within the blue-shaded climatology region. Finally, "Overlay climatology in saved plots" controls whether the blue climatology shading is included in the output profile plots (discussed in Section 2.2.5).

The "Filetypes to Save" column lists seven different output file formats: four ASCII formats (FIN, DAT, EDF, and JJVV), one binary format (BUFR) and two images (profile and location plots identical to those in the Profile Editor interface). These output files are discussed in Section 2.2.5. The two checkboxes in the bottom left corner of the window control automatic corrections applied by the autoQC algorithm. The "ID bottom strikes with NOAA ETOPO1 bathymetry data" checkbox determines if bathymetry data is used to automatically truncate profiles whose maximum depths are greater than the ETOPO1-indicated ocean depth at the profile location, and the "ID false starts due to VHF interference" checkbox controls whether gaps in data in the upper ocean are identified as signs of VHF interference causing false starts and used to vertically shift the profile. Both of these corrections are discussed further in Section 4.1. Finally, the spinbox in the bottom left is used to identify the center through which data is uploaded to the Global Telecommunications System (GTS), if applicable. This identification is a necessary field for the WMO-formatted BUFR

message, discussed further in Section 2.2.5.

The rightmost column of settings includes three spinboxes that control thresholds used by the autoQC algorithm. The minimum profile resolution is the resolution (in meters) at which points are downsampled following smoothing and despiking. The smoothing window is the length (in meters) of the running smooth filter used to remove high frequency variability before downsampling. Finally, the despiking coefficient adjusts how sensitive the autoQC algorithm is for removing spikes (a higher coefficient results in the inclusion of more data and a lower coefficient results in the exclusion of more data). The mathematical definition of this coefficient and its role in the autoQC algorithm are more clearly defined in Section 4.1.

Chapter 3

Troubleshooting

3.1 Data Acquisition System

Common AXBPS Data Acquisition System (DAS) errors can be subdivided into three categories: (1) errors associated with WiNRADIO VHF receiver integration, (2) errors associated with user-defined settings for the DAS, and (3) errors associated with user inputs. These three categories of errors (and accompanying solutions) are described separately in the following subsections.

3.1.1 WiNRADIO Communication Errors

Errors associated with WiNRADIO receiver communication typically fall into one of two categories: missing hardware drivers or loose connections/loss of power. The former can be resolved by following the driver installation instructions in Section 1.2. To ensure that no connections are loose, check that: (1) the receiver is powered on and receiving power (the blue light is flashing on the receiver) and (2) the serial-to-USB cable is plugged securely into the receiver and the other end is plugged into the computer (if using a USB hub with multiple devices, connect the receiver directly to the computer to confirm that there are no connection or communication issues with the hub). Common error messages or issues connecting to receivers are listed below:

Warning message: "WiNRADIO communications only supported with Windows! Processing and editing from audio/ASCII files is still available.": This message is displayed on non-Windows (e.g. MacOS, Linux) when first opening the program. As of this manual's writing, hardware drivers for WiNRADIO receivers are available for Windows only, and therefore receiver functionality is unavailable for MacOS or Linux. The "Test" case and audio file reprocessing, as well as profile quality control, are still fully functional on MacOS or Linux. In order to process AXBT data in realtime from a WiNRADIO with AXBPS on MacOS or Linux, install AXBPS on a Windows 10 virtual machine (realtime processing with AXBPS has been tested successfully in both VirtualBox and VMWare) running within the host operating system.

A radio receiver is connected to the computer and powered on, but is not appearing in the dropdown menu within an AXBPS Data Acquisition System tab: First, click "Refresh" to force AXBPS check again for any connected devices. Devices plugged into the computer after the tab was opened will not appear unless "Refresh" is selected. If the receiver is still not listed, follow the instructions for driver installation in Section 1.2 to ensure that the computer can properly communicate with the receiver.

Error message: e.g. "Failed to connect to the specified receiver" or "Contact lost with WiNRADIO receiver": This message is displayed when AXBPS recognizes and is able to communicate with a receiver (so the drivers are most likely installed correctly) but fails to begin processing data from that receiver for some reason. The most common cause is intermittent contact with the receiver due to a loose connection between the receiver and the computer or to the receiver's power supply. Check that the WiNRADIO is receiving a constant power supply, and that the serial-to-USB connection between the WiNRADIO and the computer is secure. If the receiver is connected to the computer through a USB hub or similar, try connecting the receiver and computer directly (with a single cable) to ensure that the USB hub was not the cause of the connection issues. Finally, if alternate receivers are available, try connecting to and processing with a different receiver to ensure that the errors are not the result of a hardware issue.

Error message: "The selected WiNRADIO appears to be in use. Please select a different device before proceeding" or similar: Each receiver is only capable of demodulating signal from a probe on one channel at a time. AXBPS prevents users from selecting a receiver from the dropdown menu if that receiver is actively processing a VHF channel in a different tab. To resolve this, find the tab currently processing with the active receiver and either (1) continue using that tab or (2) select "Stop" to stop processing in that tab and free the desired receiver for processing in another tab.

AXBPS crashes whenever the user attempts to start processing data from a WiNRADIO receiver: The most common fix for this issue is to: (1) disconnect the receiver USB cable from the computer, (2) power off all receivers, (3) cut power to the receivers for at least 5 seconds, (4) power on the receivers, and (5) reconnect the USB cable to the computer and restart AXBPS.

3.1.2 User-Defined Setting Related Errors

AXBPS offers a high level of control over Data Acquisition System settings, but some combinations of these settings can result in less-than-ideal performance depending on a number of factors including the computer in use, operational conditions, the ocean features being observed. The following issues can be resolved by adjusting the user settings described in Section 2.1.2. Profiles with any of the following discrepancies can be resolved by:

1. Saving the profile as an audio (WAV) file
2. Opening the preferences window (from the options menu at the top of the screen), selecting the "Data Acquisition System Settings" tab, and making any necessary changes
3. Reprocessing the profile from the WAV file by choosing "Audio" in the "Data Source" drop down menu, selecting "Start", and browsing to the saved WAV file when prompted

The Data Acquisition System begins processing but no valid signal is detected- only gray rows appear on the table (or blue rows for AXCTDs) and no data appears on the plot: This occurs when the received signal is not strong enough to trigger profile collection (the minimum and trigger signal level and signal ratio settings are set too high). The table on the lower right hand side of the Data Acquisition System interface lists the received signal levels and signal-to-noise ratios under the columns labeled S_P and R_P for AXBTs, R_{400} and ΔR_{7500} for AXCTDs, and the rotation rate deviation (σ) for AXCPs. Identify the ideal thresholds for valid probe data by scrolling through the table and distinguishing where the profile started and finished. For AXBTs and AXCTDs, there should be a clear increase and decrease in signal level/ratio both when the probe starts and

finishes transmitting, respectively. For AXCPs, there should be a clear decrease in the rotation rate deviation when the probe spins up and a subsequent increase upon profile termination or probe spindown. Adjust the respective thresholds in the DAS tab of the settings window below these values. For AXBTs, the trigger thresholds must be satisfied for the first observation to be identified, but the minimum thresholds are required for all observations) and reprocess the profile.

For AXCTDs, the observed R_{400} must exceed the preset threshold for the first 400 Hz pulse to be detected and the tabular data to switch from gray to blue, and the threshold for ΔR_{7500} must be exceeded for the profile transmission to be recognized and the tabular data to switch from blue to green, with corresponding points appearing on the profile plot. Additionally, selecting the 100 Hz to 1200 Hz bandpass filter option may improve AXCTD demodulation in some circumstances (this is not generally recommended however as it further degrades demodulation quality in more circumstances than it helps).

For AXCPs, if the profile recording is particularly noisy, increasing the spinup and spindown thresholds to 1.0 and 2.0 Hz respectively may aid in profile processing. Additionally, increasing either threshold above 1.0 activates a noisy profile mode in the processor that increases the likelihood of properly detecting the probe spinup and spindown.

The observed profile begins too soon due to interference, and the entire profile is depth shifted (e.g. the surface temperatures appear at 200m; primarily an issue for AXBTs): This occurs when profile collection is incorrectly initiated ("triggered") by interference or noise. To correct for this, adjust the trigger signal level and trigger signal ratios in the settings to higher values somewhere between the observed signal levels and signal ratios of the interference and the first valid AXBT signal. Observed values of signal level and signal ratios are listed in the S_P and R_P columns (respectively) of the table in the lower right corner of the Data Acquisition System interface. It is worth noting that if the initial interference is more powerful than the AXBT signal, this will not work. In that case (or if reprocessing isn't feasible due to time or operational constraints), false starts can also be corrected using the "Depth Delay" feature in the Profile Editor interface.

The observed profile begins at the correct depth, but excessive interference (erroneous spiking) appears in the profile: For AXBTs, this occurs when the minimum signal level and ratio (vice trigger signal level and ratio) are set too low to distinguish noise from valid AXBT signal. To correct for this, adjust the minimum signal level and ratio in the settings to higher values somewhere between the observed signal levels ratios of the interference and valid AXBT signal. Observed values of signal level and signal ratios are listed in the S_P and R_P columns (respectively) of the table in the lower right corner of the Data Acquisition System interface. If the signal level and ratio of the noise are both greater than that of the valid AXBT signal, then no settings will be able to parse valid signal from the noise. In that case (or if reprocessing isn't feasible due to time or operational delays), the "autoQC" algorithm is designed to automatically identify and remove spikes, and the Profile Editor interface provides user options to remove individual observations or vertical ranges of observations. For AXCTDs, this occurs when interference makes demodulating the audio signal into a bitstream challenging for the AXCTD processing algorithm. Selecting the bandpass filter option in the settings, adjusting the mark and space bit frequencies to be closer together (typically by increasing the mark bit frequency to 500 Hz or 600 Hz), or increasing the refresh rate so more data is processed between GUI refreshes all may improve performance (these settings should not be adjusted when the algorithm is operating optimally as they may also degrade performance). For AXCPs, selecting the "FFT Temperature ID" setting and increasing profile quality may reduce interference.

The computer is lagging and/or processing extremely slowly and recording observations at too low of a vertical resolution: This occurs when the signal processing by the Data Acquisition System becomes too computationally expensive, consumes too much of the computer's resources, and takes too long to process each observation, reducing the frequency with which it can collect observations. While signal processing is inherently a more computationally expensive task, the load on the computer can be reduced for AXBTs by decreasing the value of the "FFT Window" setting. This setting determines the length of the signal (in seconds, ranging from 0.1 s to 1.0 s) the AXBPS Data Acquisition System uses to identify the peak frequency (and corresponding temperature) being transmitted from the AXBT. Shorter windows enable the Data Acquisition System to process faster but will also reduce the temperature resolution in the resulting profile. For AXCTDs, increasing the refresh rate setting and disabling the bandpass filter option (if selected) may improve performance. For AXCPs, disabling the "FFT Temperature ID", reducing the profile quality setting, and adjusting the refresh rate may boost performance. If all else fails, your computer's limitations may require processing only one profile at a time and/or limiting any other open programs in parallel with AXBPS.

The collected AXBT or AXCP temperature-depth profile appears unnaturally discontinuous (e.g. a "stair-stepping" pattern): This can occur when the "FFT Window" setting, which determines the length of the signal (in seconds, ranging from 0.1 s to 1.0 s) the AXBPS Data Acquisition System uses to identify the peak frequency (and corresponding temperature) being transmitted from the AXBT, is too short (although this is also a valid feature common in some regions, e.g. the tropical Atlantic Ocean east of the Lesser Antilles). Low "FFT Window" settings have a correspondingly low temperature resolution, causing the profile to 'jump' from one temperature to the next. Increasing the window size will increase the temperature resolution but also cause the Data Acquisition System to consume more of the computer's resources and possibly reduce the frequency of observations (and corresponding vertical resolution) of the collected profile when processing in realtime. The tradeoff between temperature resolution, processing time, and window length for AXBTs (a similar, but nonlinear, relationship exists for AXCPs) is discussed further in Section 4.0.2.

3.1.3 Input-Associated Errors

AXBPS is configured to raise errors when users attempt to control the program in a way that could result in unexpected behavior. These errors are discussed below.

Error Message: "You cannot switch between Test, Audio, and RF data sources after starting processing.": To prevent multiple profiles from being concatenated together (e.g. starting with the "Test" sequence before processing from audio or in realtime with a WinRADIO), AXBPS does not allow users to switch the datasource (other than switching between multiple receivers) for a tab after "Start" has been selected. In addition, AXBPS only allows users to select "Start" once when processing from audio, to prevent multiple audio files from being concatenated together. To start processing from a different data source, open a new Data Acquisition System tab by either selecting "Options" > "New Data Acquisition System Tab" or typing the keybinding CTRL+N.

Error Message: "Unable to read audio file": This error can be raised in a Data Acquisition System tab where the datasource is set to either Test or Audio (as both of these sources actually reprocess profiles from raw audio). If the datasource is set to test, this is because the required audio file located in the AXBPS program folder under 'data/testdata/AXBT_sample.WAV' for AXBTs, 'data/testdata/AXCTD_sample.WAV' for AXCTDs, or 'data/testdata/AXCP_sample.WAV' for AXCPs is either missing or corrupted. When processing from an audio file, this can occur if the

selected audio file is missing, the program does not have permission to access it, it is corrupted, or it is not a WAV file (the Data Acquisition System is only configured to reprocess audio from WAV files).

Error Message: "Selected audio file is too large!": AXBPS is configured to prevent users from accessing audio files that exceed more than a certain number of datapoints (the current configuration is 2.5×10^8 frames, corresponding to 0.5 GB for 16-bit PCM data and approximately 1 hour and 34 minutes of audio collected at the standard rate of 44.1 kHz) to prevent AXBPS from accessing too much of a computer's random access memory (RAM). A typical profile should be approximately one tenth of this size, so to resolve this error simply make a copy of the audio file to be processed and crop the copy to include only the audio for the profile of interest.

Warning Message: "AXBPS has stopped audio recording as the WAV file has exceeded maximum allowed length.": To prevent AXBPS from accessing too much of a computer's random access memory (RAM), the Data Acquisition System is configured to stop recording audio from a receiver after it has processed 2.5×10^8 frames of data, corresponding to slightly over one hour of recording at the standard 64 kHz sampling frequency for WinRADIO receivers. To start recording again, select "Stop" on the tab that is recording (so the receiver can be accessed by a different tab), open a new Data Acquisition System tab and start processing with that tab.

3.2 Profile Editor

3.2.1 Error loading a profile

Error Message: "Invalid data file format.": This error is raised when the user attempts to load a file containing profile data with an unrecognized extension. The currently supported file types are: log files (.DTA), edf files (.edf), NVO and FIN files (.nvo or .fin), DAT files (.dat) and JJVV (bathy) files, (.jjvv). Formats for NVO, FIN, and JJVV files are described in in 2.2.5).

Error Message: "Failed to read selected file.": This error is raised when the user attempts to load a file with a recognized extension containing a data format that does not match the extension. This can occur if the file is named with the incorrect extension or incorrectly formatted. Formatting for FIN, NVO, and JJVV files is discussed in Section 2.2.5, and example files can be referenced for formatting in the AXBPS program subdirectory 'data/testdata'.

Warning Message: "Profile does not contain any valid data.": This message is provided when the profile editor attempts to load a profile that does not contain any valid data, either from an ASCII file or from the Data Acquisition System. If receiving this message when attempting to transition to Profile Editor mode from the Data Acquisition System, save the raw data as an audio file, lower the minimum signal thresholds, and reprocess from that audio file as described in Section 3.1.2. Should you wish to save an empty quality-controlled file to record drop position and date/time, AXBPS will allow you to select 'Okay' to do so.

Warning Message: "Invalid (latitude, longitude, date, time, etc.) entered": AXBPS is configured to only accept specific formats for date, time, and position. Date should be entered in year-month-day (YYYYMMDD) format and time in hour-minute (HHMM) format (both entries should contain only digits, no hyphens, colons, slashes, letters, or other characters). Latitude and longitude should also be entered as numbers (e.g. 23, 23.0, or 23.56). Latitude and longitude should be entered in

decimal format or comma-delimited (with commas separating degrees, minutes, and seconds), and northern and eastern hemispheres are considered positive and southern and western hemispheres are considered negative (so the longitude 55° 33' 12" W would be entered as either -55.553 or -55,33,12). Additional checks are applied to ensure input is realistic: latitude is constrained between -90 and 90, longitude between -180 and 180, year after 1938 (the year the bathythermograph was invented), month between 1 and 12, and day between 1 and 31.

Error Message: "Unable to find/load (climatology or bathymetry) data" This error is raised when AXBPS is unable to read a supporting climatology or bathymetry data file. If the message is raised when AXBPS is first opened, then the file containing climatology and/or bathymetry positions (named indices.mat) failed to load. If the error appears when attempting to quality control a profile, then AXBPS failed to read the climatology and/or bathymetry data for that profile. In either case, this can be resolved by ensuring that the necessary data files are stored in the AXBPS program folder's qcdata/bathy and qcdata/climo subdirectories, following the layout shown in Section 1.1.2.

3.2.2 Profile editing issues

Quality-controlled profile does not appear on plot (black profile exists but red profile does not): This occurs when the automated quality control checks apply changes that remove all profile data. To correct this, first check that the "Maximum Depth" field is set to zero: drops near land or where the climatology does not match the profile can trigger AXBPS to incorrectly identify a bottom strike. If that does not work, open the Preferences menu (by selecting Options > Preferences), and in the Profile Editor Settings tab, uncheck the fields "Use climatology to detect bottom strikes", "Autocompare profile to climatology", "ID bottom strikes with NOAA ETOPO1 bathymetry data", and "ID false starts due to VHF interference", and then select "Re-QC Profile (Reset)" on the Profile Editor tab to reprocess the profile without any of those quality control checks.

Quality controlled (red or green) profile either has too many spikes or is too smoothed: These features can be corrected by adjusting the "Smoothing Window" and "Despiking Coefficient" features in the Profile Editor Settings (found by opening AXBPS preferences menu by selecting Options > Preferences) and then selecting "Re-QC Profile (Reset)". Decreasing the despiking coefficient causes AXBPS to identify more points as spikes and exclude them from the quality-controlled profile, and conversely increasing it causes AXBPS to include more points. Increasing the smoothing window causes AXBPS to apply a more intense smooth to the profile and filters out more small-scale variability, whereas increasing the window reduces the magnitude of the smooth and results in a profile with more variability.

No climatology is overlaid or the climatology does not extend as deep as (or extends deeper than) the profile: The ocean climatology is stored at a 1/4 degree horizontal resolution, and therefore does not account for sharp changes in ocean depth. Particularly when near land or a sharp change in ocean depth, the climatology can fail to include those changes in ocean depth, and in some cases no climatology data exists for profiles near land or extremely shallow areas.

3.3 Miscellaneous

Error Message: "Unable to communicate with specified COM port" This message occurs when the serial (COM) port selected as the optional GPS receiver is unreachable. Typically, either the device has become physically disconnected or lost power so it is completely unresponsive to the computer. To resolve this, open the "GPS COM Selection" tab of the AXBPS Preferences Menu (Options > Preferences), and select "Update COM Port List" to refresh the dropdown menu of available devices. If the device is not listed, check to ensure it is connected and powered on. If it is, select it and choose "Refresh GPS Info" to test if the computer is able to access the devices measured latitude and longitude.

Error Message: "GPS request timed out" This message occurs when a selected device is connected and responsive but not transmitting valid GPS (NMEA) data to the computer. Typically this is because either the selected device is not a GPS receiver or the receiver is not streaming data. The GPS COM Selection settings tab lists all available serial connections, so it may require some trial and error to select the port associated with a connected receiver (ideally the port's details in the dropdown menu will contain a familiar company name or detail associated with the receiver) by checking all available ports and identifying which successfully reads position data after selecting "Refresh GPS Info". If a selected GPS receiver is causing timeout issues, it may be not streaming data because it is unable to establish a communication link with GPS satellites. To correct this, try moving the receiver (while connected to a computer) outside to a location with an unobscured view of the sky. If all else fails, check the receivers manual to ensure that any necessary drivers or additional supporting software for the receiver was installed and configured correctly.

Chapter 4

Operating Principles and Data Flow

The Airborne eXpendable Buoy Processing System (AXBPS) can be subdivided into two distinct subsystems: the Data Acquisition System and Profile Editor. The data flows for each of those subsystems are discussed separately in the following two sections.

4.0.1 Radio Receiver Integration

External Hardware Configuration

The software-defined radio receiver currently integrated with AXBPS is a WiNRADIO WR-G39WSBe Sonobuoy Receiver (Fig. 4.1; www.winradio.com/home/g39wsbe.htm). It demodulates transmitted signals from standard sonobuoy VHF carrier frequencies between 136 and 173.5 MHz, and outputs analog (SMA) and digital (serial) demodulated data. A single receiver weighs 0.43 kg, measures 16.6 cm x 9.7 cm x 4.1 cm, and requires 12V direct current at 0.5A. The receiver has four connections: power (standard 2.5 mm jack), VHF in (SMA male), analog out (SMA male; unused in this application), and digital out (serial). A serial-to-USB converter for the digital output enables easy integration with most modern computers.

A single receiver can only demodulate one VHF frequency at a time, and thus only process good data from one probe at a time (although there is potential for an advanced system to track multiple peaks in spectral density simultaneously, this is extremely prone to errors and thus limiting operations to one probe per channel at a time is optimal). The time from launch it takes a single probe to fully transmit (for AXBTs, approximately 11.5 minutes from 10,000 feet, including 120 seconds fall time and an approximately 1.5 ms^{-1} descent rate to 850 m), constrains the spatial resolution at which probes can be launched as a function of aircraft ground speed. Thus, AXBPS was configured for the operation of up to six receivers in parallel (though this may be further limited by computer clock rate and random access memory).

An example of an array of WiNRADIO receivers is shown in Fig. 4.2. This array included three radio receivers that connect to a processing computer via a single USB connection with an unpowered USB hub (with a fourth port available for a GPS receiver). The included power adapter converted standard AC current to 2A 12V DC, and thus a single adapter was used with a three-way splitter to provide power to all three WiNRADIOS. Additionally, a BNC splitter was used to connect a single VHF antenna output to all three receivers. SMA-to-BNC converters were used for the VHF input to connect the WiNRADIO's SMA input to this splitter and thus the aircraft's VHF antenna. In testing, no significant drop in signal level or corresponding processor performance was observed when using the BNC splitter. This configuration of three receivers enables deployment of deep-water AXBTs (rated to 850m) every 3-4 minutes, or shallow-water AXBTs (rated to 400m) every 2



Figure 4.1: A WinRADIO G39WSBE software-defined receiver (image from <http://winradio.com/home/g39wsbe.htm>). Ports on the front-left face of the receiver are: (top left) analog audio out (SMA), (top right) VHF in (SMA), (bottom left) power (2.5 mm), and (bottom right) digital audio out (serial).

minutes given an approximately 1.5 m s^{-1} fall rate. For AXCTDs and AXCPs, assuming maximum depths of 1000 m and fall rates of 2.7 m s^{-1} and 4.5 m s^{-1} (respectively), the same configuration enables probe deployment every 2 minutes and 1:30, respectively. The system is capable of achieving even more rapid deployments for users only interested in the upper 100-200 m of the water column, particularly for multichannel buoys that can be programmed via their electronic function select (EFS) interfaces to transmit on one of 99 available RF sonobuoy channels.

Hardware systems accompanying AXBPS (following the design of the example array) require three connections: a standard 60Hz/110V input power supply, a BNC coaxial connection to a VHF antenna for RF signal input, and USB output connected to the processing computer running an instance of AXBPS. VHF signal received by the connected antenna are demodulated by the WinRADIO receiver, which outputs stream of PCM data collected at 64 kHz from a serial port. This data is transferred to the processing computer using a serial to USB converter and appended to a buffer on the computer using the receiver's application-programming interface. This buffer is periodically accessed by the AXBPS Data Acquisition System interface to generate a temperature-depth profile from the received data stream (Fig. 4.3).

WinRADIO API Interaction

In addition to the required proprietary system drivers (which currently exist for Windows only), a dynamic-link library (DLL) provides the application-programming interface (API) necessary for the processing computer to communicate with and control the WinRADIO receivers. This was used in conjunction with the Python ctypes module to handle all receiver communication and control exclusively in Python. This API includes a large range of functions for receiver communication and control (an exhaustive list is available at www.winradio.com/home/g39wsb_sdk.htm). While the exact API functions used by the data acquisition system would vary when integrated with a

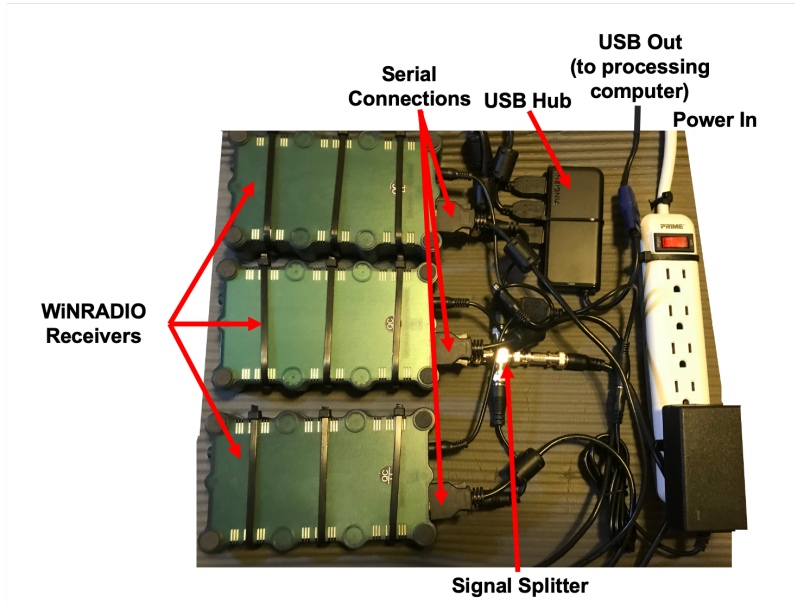


Figure 4.2: The WiNRADIO receiver array used in initial AXBPS evaluations.

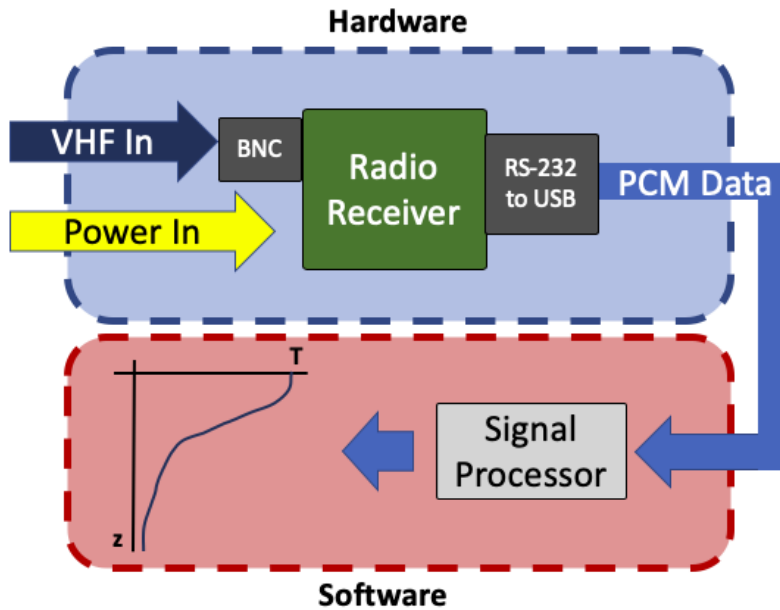


Figure 4.3: Process to demodulate received a AXBT VHF signal and generate the encoded temperature-depth profile. A similar format (with a different signal processor and additional salinity or current profiles) is used for AXCTD and AXCP processing.

different brand of software-defined receiver, the format would be similar and all operations after demodulated PCM data is accessed by the processing computer would be identical.

The WiNRADIO API is accessed by Python using the ctypes module following the syntax in the example below:

```
1 | wrdll = ctypes.windll.LoadLibrary('path-to-DLL-file')
```

Here, wrdll is a class with a library of nested API functions imported from the DLL file. This library includes a large range of functions for receiver communication and control (an exhaustive list is available at http://winradio.com/home/g39wsb_sdk.htm), but the primary functions used in AXBPS are listed in Table 4.1.

Table 4.1: WiNRADIO application-programming interface functions integrated in the AXBPS Data Acquisition System.

Function	Inputs	Output	Purpose
Open	char *SerialNum	int hRadio	Generate handle for a specific receiver using UTF-8 encoded serial
SetPower	int hRadio bool status	bool success	Set receiver power: true=on, false=off
InitializeDemodulator	int hRadio	bool success	Begin demodulating input VHF signal
SetFrequency	int hRadio dword frequency	bool success	Set VHF frequency to demodulate
SetVolume	int hRadio int volume	bool success	Set volume of output PCM data (0-31)
GetSignalStrengthdBm	int hRadio	int sigstrength	Approximate signal strength for current VHF frequency
SetupStreams	int hRadio void *callback	bool success	Direct the stream of demodulated PCM data to a user-written callback function
GetRadioList	Info *RadioList int BufferSize int *InfoSize	int total	Populate a list of structures with info about all connected radio receivers
CloseRadioDevice	int hRadio	bool success	Power off the receiver

Before passing input arguments to functions nested in the library, Python variables must be converted to C-type variables (e.g. 16-bit signed integer, unsigned long integer, character array pointer) using the ctypes module. After these conversions, executing commands from the DLL file is straightforward. The API-defined function "Open" allows AXBPS to access a connected receiver, returning an integer handle used as an input argument for all subsequent commands interacting with that receiver.

In order to control multiple receivers, AXBPS uses the API-defined function "GetRadioList", which provides information about all connected receivers. This function requires a preallocated array of c-type structures (described in detail on the WiNRADIO website), with empty fields to

be populated by the API.

To enable simultaneous processing of multiple probes from multiple receivers in parallel, the AXBPS Data Acquisition System handles the data stream from each radio (and all associated computations) as individual threads, and uses PyQt’s multithreading support to handle processing. Integration of multithreading is discussed further in Section 4.0.5, but it is worth noting here that each thread is a class with nested functions, as shown in Fig. 4.4. The `__init__()` function saves all input variables (e.g. Data Acquisition System settings) to the class, and either opens and initializes the selected radio receiver if processing data live, or opens and reads in PCM data from a selected WAV file if reprocessing from raw audio. The `run()` function starts selecting segments of PCM data either using the most recent data received from the WiNRADIO or sequential segments from a source audio file, and processing them as described in Section 4.0.2. The `changecurrentfrequency()` function (only applicable when processing in realtime from a receiver) changes the VHF channel that the receiver is demodulating while it is actively demodulating data. Finally, `changethresholds()` adjusts the Data Acquisition System settings if the user changes them while the current thread is active and `abort()` allows the user to terminate the current thread and finish processing.

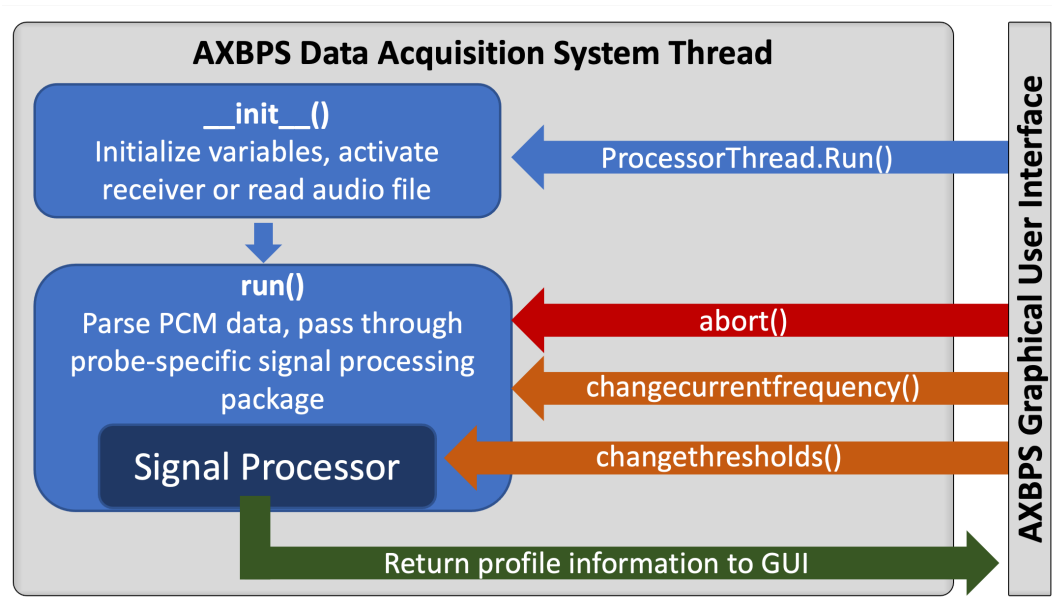


Figure 4.4: Diagram of nested functions in the AXBPS Data Acquisition System thread class, with functions listed on arrows using PyQt signals (arrows out of the Data Acquisition System thread block) and slots (arrows into the thread block) to pass information to and from the AXBPS user interface.

A WiNRADIO API function, ‘SetupStreams’, is used to control PCM data transfer from the receiver to the processing computer. This assigns a callback function that is executed every time a buffer is filled (16-bit PCM data is collected at 64 kHz in a 2 KB buffer, so this occurs at approximately 30 Hz). In AXBPS, this callback function appends the data to both a WAV file and a buffer on the computer from which PCM segments are pulled by the data acquisition system and analyzed, following Fig. 4.5. When processing AXBTs, data is removed from the head of the buffer by the callback function as it is appended to the tail, and segments of data are analyzed by the DAS at a user-defined refresh rate. For AXCTDs and AXCPs, data is still appended to the tail of the buffer by the callback function but removed from the head by the DAS at it is pulled for demodulation and decoding in segments of a user-defined size.

AXBPS was programmed with ease of integration of additional software-defined-radios in mind. To incorporate additional radio receiver types, only two files need to be edited (both in the `lib/DAS` subdirectory): `_processor_functions.py`, and a file with python functions that mirrors the functionality of `winradio_functions.py`. Receivers should be assigned a 2-letter code, excluding TT or AA (the WinRADIO receiver code is WR) that allows AXBPS to keep track of which DLL files and receiver-specific code to use for each datasource.

4.0.2 AXBT Processing

Operating Principles

AXBT operation principles are fairly straightforward: after descending to the ocean surface under a parachute, the probe deploys a small inflatable plastic bag as a surface float and the AXBT's saltwater activated battery begins modulating an empty VHF signal. Water soluble tape attaching the probe to the surface float dissolves, releasing the probe to descend through the water column. A current passes through a thermistor in the probe, which is connected to the surface float via a thin copper wire, and a voltage-controlled oscillator generates an alternating current at a frequency that is a function of the resistance in the probe's thermistor (and therefore the temperature of the surrounding water). It is this frequency that is modulated into a VHF carrier signal and telemetered to the aircraft, and must be converted via an empirical equation back to the observed temperature. Depth is calculated based on an assumed fall rate equation for the probe in the water column given the time elapsed since the AXBT transmission was first detected (when it is assumed that the probe was at the surface).

Whether PCM data are read from a WAV file or accessed realtime from a connected VHF receiver, the subsequent AXBT signal processing sequence is identical. First peak frequency, signal level, and signal-to-noise ratio are determined using a discrete Fourier transform of each segment of tapered PCM data, and then these values are used to infer the temperature-depth profile observed by the AXBT (Fig. 4.5).

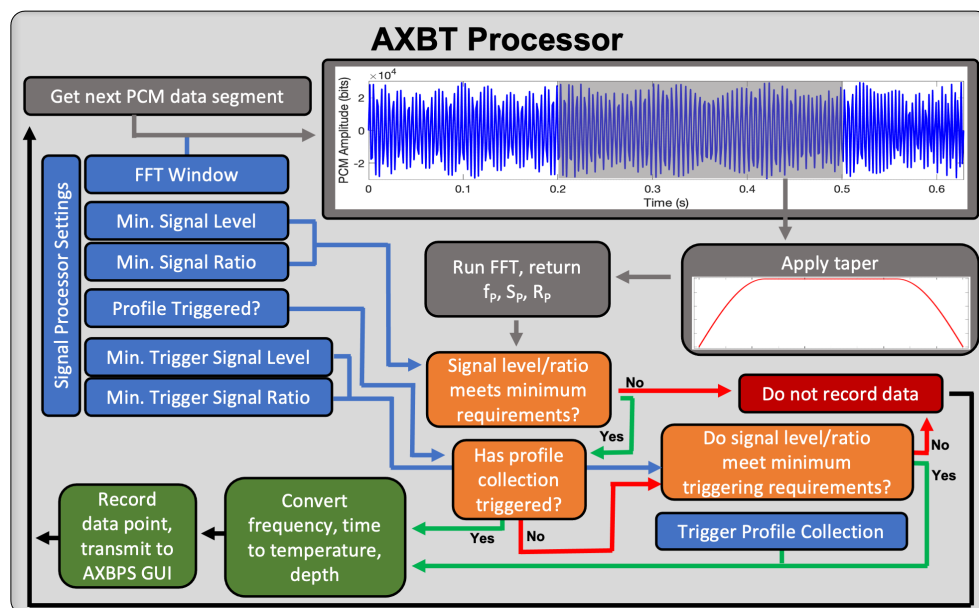


Figure 4.5: Sequence to pull and process segments of PCM data to identify valid temperature-depth measurements transmitted from an AXBT.

Data Flow

Peak frequency, which is empirically related to the AXBT-observed ocean temperature, is determined by applying fast Fourier transforms to small subsets of data. Unless otherwise specified, a window length of 0.3 seconds is used (the effects of this window length are considered in the AXBPS Data Acquisition System evaluation section). Before a data subset is transformed into the frequency domain, a cosine (Tukey) taper is applied to the time series in order to minimize spectral leakage (Eq. 4.1). The taper window (T) is determined by the length of the PCM data subset (L) and a single parameter (α). The alpha parameter is the ratio of the tapered component of the time series to the total length of the time series, and is constrained by $0 \leq \alpha \leq 1$.

$$T[i] = \begin{cases} \frac{1}{2} \left[1 + \cos \left(\frac{2\pi}{\alpha} \frac{i-1}{L-1} - \pi \right) \right], & i < \frac{\alpha}{2}(L-1) + 1 \\ \frac{1}{2} \left[1 + \cos \left(\frac{2\pi}{\alpha} - \frac{2\pi}{\alpha} \frac{i-1}{L-1} - \pi \right) \right], & i > L - \frac{\alpha}{2}(L-1) \\ 1, & \text{otherwise} \end{cases} \quad (4.1)$$

The frequency spectra for a given segment of PCM data are calculated using a fast Fourier transform (requiring only the PCM data subset and corresponding sampling frequency), using the `numpy.fft.fft()` function included in Python's Numpy module. The transform of a discrete time series (s , of length L and sampling frequency f_s) into the frequency domain (S) is described in Eq. (4.2), where m and n are discrete indices corresponding to elements in the time and frequency domains, respectively.

$$S[n] = \sum_{m=0}^{L-1} s_m e^{-i2\pi mn/L}, \quad (4.2)$$

$$n = 0, 1, 2, \dots, \frac{L}{2},$$

$$\Delta f = \frac{f_s}{L}, \quad f = n\Delta f$$

Resulting frequency spectra (S) are collapsed into three characteristic parameters: the peak frequency (f_P) and the corresponding signal level (S_P) and signal-to-noise ratio (R_P ; defined mathematically in Eq. 4.3). Only signals from 1300-2800 Hz, corresponding to a realistic temperature range of -3.88°C to 37.7°C, are considered. The signal level depends on the maximum spectral value in the 1300-2800 Hz band (corresponding to the peak frequency that the AXBT is presumed to be transmitting), and the signal-to-noise ratio (SNR) is the ratio of that maximum spectral value in the 1300-2800 Hz band to the maximum value in the entire band. Thus, the SNR ranges between 0 and 1, where it is 0 if no nonzero values are measured in the 1300-2800 Hz band and 1 if the most powerful received signal is in the 1300-2800 Hz band. These parameters are used to distinguish AXBT signal from noise and to calculate the corresponding temperature if necessary. To be considered a valid AXBT signal, the signal level and SNR must both satisfy pre-set thresholds (appropriate thresholds are considered in the Data Acquisition System evaluation). Because possible maximum values of the signal spectra span several orders of magnitude, the peak signal level is expressed in decibels (dB re 1 bit, referenced in this study hereafter as dB).

$$K = \arg \max S_k, \quad f[k] \in [1300, 2800] \quad (4.3a)$$

$$f_P = f[K] \quad (4.3b)$$

$$S_P = 10 \log_{10} \left(\frac{S[K]}{1 \text{ bit}} \right) \quad (4.3c)$$

$$R_P = \frac{S[K]}{\max S} \quad (4.3d)$$

Temperature-Depth Conversion

For signals that satisfy the minimum signal level, frequency range, and SNR requirements, temperature and depth are determined from the peak frequency and elapsed time between the current observation and first observation. AXBPS uses the general empirical relationship between measured temperature ($^{\circ}\text{C}$) and transmitted frequency (Hz) (Eq. 4.4; noting that the coefficients 1440 and 36 have units of Hz and $\text{Hz } ^{\circ}\text{C}^{-1}$, respectively) and standard fall rate, 1.52 ms^{-1} .

$$f_P = 1440 + 36T \quad (4.4)$$

Thus, given the peak frequency (f_P) and elapsed time (Δt) since the first observation (when it is presumed the probe is at the surface), the corresponding temperature (T) and depth (z , positive down) are calculated as:

$$T = -40 + (2.778 \times 10^{-2})f \quad (4.5a)$$

$$z = 1.52\Delta t \quad (4.5b)$$

Determining time elapsed requires tracking when the first valid signal was recorded. Because AXBT signals are typically stronger when transmission begins and decay over time as distance between the float and the aircraft increases, in order to prevent VHF interference from prematurely triggering the profile, higher minimum signal level and signal-to-noise ratio thresholds are required for a signal to be accepted as the surface value. Thus, AXBT profiles are processed by repeating the six steps below at the data acquisition system's sampling frequency of approximately 10 Hz (this process is represented visually in Fig. 4.5):

1. A subset of PCM data is pulled from the input data stream and tapered.
2. The tapered PCM subset is transformed into the frequency domain.
3. Peak frequency, signal-to-noise ratio, and signal level are calculated.
4. If the signal level and SNR are above the minimum thresholds and profile collection has already been triggered, time elapsed is calculated and the corresponding temperature and depth values are determined and recorded.
5. If profile collection has not been triggered but the signal level and SNR satisfy the trigger thresholds, the observation time is recorded to determine future elapsed times, profile collection is triggered, and the surface temperature is calculated and recorded.

Tapering and FFT Window Optimization

Adjusting the window size (W) of the discrete Fourier transform results in a tradeoff between computational expense and temperature resolution (ΔT , Eq. 4.6). Specifically, as the window size is increased, the window length (L) increases and the frequency step size (Δf , in Hz) in the transformed spectra (Eq. 4.2) decreases, which also decreases the corresponding temperature step size (through Eq. 4.4). This is because the sampling frequency (f_s), which relates window length (L , number of PCM datapoints) to both window size (W , in seconds) and frequency step, cancels out (Eq. 4.6; where the coefficient 36 has units $Hz \text{ } ^\circ C^{-1}$).

$$\begin{aligned} \Delta T &= \frac{\Delta f}{36} = \left(\frac{1}{36}\right)\left(\frac{f_s}{L}\right) = \left(\frac{1}{36}\right)\left(\frac{f_s}{f_s W}\right) \\ &= \frac{1}{36W} \end{aligned} \tag{4.6}$$

This corresponds to a temperature resolution of $0.093^\circ C$ for the standard window size of 0.3 seconds (Table 4.2). To further evaluate the resolution versus computational efficiency tradeoff, ten raw audio files were reprocessed using four different window sizes (0.1, 0.2, 0.3, and 0.5 seconds) both with and without a cosine taper. Performance effects of window size are shown in Table 4.2, with all performance times and standard deviations expressed as ratios to the comparable performance time using a 0.3-second window and no taper. Using window sizes of 0.1, 0.2 and 0.5 seconds, AXBPS processed files in 40%, 70%, and 285% the amount of time it took to process an identical file with a 0.3-second window (respectively). However, the corresponding temperature resolution increased from $0.28^\circ C$ for a 0.1 second window to $0.006^\circ C$ for a 0.5-second window. Based on these results, 0.3 seconds remains a suitable window size as it provides a temperature resolution much less than AXBT instrument error while enabling AXBPS to process multiple profiles simultaneously without consuming all of the processing computer's resources.

Table 4.2: Audio file processing time means and standard deviations for several combinations of FFT windows and taper use. Processing time means and standard deviations (comma-separated) are expressed as the percentage for a given processing time to the corresponding time for the same file using no taper and a window of 0.3 seconds. Temperature resolution ($^\circ C$) is provided in parentheses with each window size.

FFT Window (s)	No Taper	With Taper
0.1 (0.28)	40%, 6%	39%, 7%
0.2 (0.14)	70%, 10%	71%, 11%
0.3 (0.09)	100%, 0%	100%, 3%
0.5 (0.06)	285%, 19%	291%, 11%

4.0.3 AXCTD Processing

AXCTD operation and data transmission principles are comparably significantly more complex than those of an AXBT. The initial deployment of the probe is the same, involving a surface float and a combination of saltwater activated circuitry and water soluble adhesives. The operating principles diverge at this point: the AXCTD's probe measures temperature and conductivity as it sinks through the water column, but these components are connected to analog-to-digital converters,

which output an integer corresponding to the observed temperature and conductivity values. These values are then telemetered to the probe in a frequency-shift-key modulated bitstream, which must first be demodulated to calculate a stream of binary data before being parsed into 32-bit frames, each of which contains one temperature and conductivity observation. Given the time elapsed and an assumed fall rate equation, depth is calculated, and the salinity is subsequently calculated as a function of temperature, conductivity, and depth.

Operating Principles

AXCTDs transmit data via a frequency shift key (FSK) modulation scheme with a symbol rate of 800 Hz, using a mark ('1' bit) frequency of 400 Hz and a space ('0' bit) frequency of 800 Hz. Data are transmitted as a series of 32-bit frames, each of which contains one temperature and salinity datapoint as well as a cyclic redundancy check (described below). Given the bit rate of 800 Hz and frame length of 32 bits, this means the AXCTD transmits 25 datapoints (frames) per second.

An AXCTD transmission begins with approximately 2 seconds of a continuous 400 Hz tone, followed by 72 frames (2.8 seconds) of header data. This data includes probe type ('A000' for AXCTD), serial number, and maximum depth (m), as well as temperature, conductivity, and depth conversion coefficients which may vary between probes. This header is followed by a 5 second period of silence, and the process repeats twice. After the third header, the AXCTD begins transmitting temperature and conductivity data as the probe sits at the surface. When the probe is released, the AXCTD adds a 7500 Hz tone, which continues for the duration of profile collection. Each AXCTD data frame is 32 bits and follows a standard format. An example is shown below:

Header	Conductivity	Temperature	CRC
10	011100100001	001000011111	011110

The frame components are:

1. Header- the first two bits of a frame are always 10
2. Conductivity- the next 12 bits (positions 3-14) contain the conductivity datapoint
3. Temperature- the next 12 bits (positions 15-26) contain the temperature datapoint
4. Cyclic redundancy check- the last 6 bits (positions 27-32) contain a cyclic redundancy check with a 7-bit polynomial divisor (decimal representation 101)

The temperature and conductivity integers conveyed in each frame are translated first into uncalibrated values in degrees Celsius and mS/cm (respectively)- temperatures via a lookup table and conductivity via a simple equation:

$$C_{uncal} = C_{integer} * 60/4096 \quad (4.7)$$

Depth and calibrated temperature and conductivity are calculated from probe descent time and uncalibrated temperature and conductivity (respectively) via a cubic equation using the coefficients transmitted in the AXCTD's header message. For example, given the four depth coefficients D_0 through D_3 , depth (z) is calculated from time elapsed (t) as:

$$z = D_0 + D_1 * t + D_2 * t^2 + D_3 * t^3 \quad (4.8)$$

AXCTD Processor Implementation

Processing an AXCTD audio file presents several challenges:

1. Identifying the 400 Hz pulses and 7500 Hz tones
2. Demodulating the FSK modulated bitstream
3. Decoding the header data
4. Decoding the profile

To identify the 400 Hz and 7500 Hz tones, the AXCTD processor calculates the signal levels at each frequency at a rate of 25 Hz (once per frame). These signal levels are normalized by the signal level at an expected quiet frequency (default 3000 Hz) and smoothed using a 5-point lagging box smooth filter (each point is averaged with the previous 5 points) to calculate the current signal-to-noise ratio. The 400 Hz signal-to-noise ratio R_{400} is compared to user-defined thresholds to identify the start of the first 400 Hz pulse. When the pulse is first detected, the processor calculates the average 7500 Hz signal-to-noise ratio for the period from 4.5 to 5.5 seconds after the pulse was transmitted (when there should be no data being transmitted and the carrier frequency should be relatively silent). This average value is subtracted from all future R_{7500} values to calculate ΔR_{7500} , used to identify the 7500 Hz tone indicating profile transmission. Mathematical representations of this process are presented below, assuming the relatively quiet frequency used is 3000 Hz (the default for AXBPS settings), and k_{400} is the index at which R_{400} first exceeds the user-defined threshold:

$$P_{400_k} = \sum_{n=0}^N \left| PCM_n e^{i2\pi n \frac{400}{f_s}} \right| \quad (4.9a)$$

$$P_{7500_k} = \sum_{n=0}^N \left| PCM_n e^{i2\pi n \frac{7500}{f_s}} \right| \quad (4.9b)$$

$$P_{3000_k} = \sum_{n=0}^N \left| PCM_n e^{i2\pi n \frac{3000}{f_s}} \right| \quad (4.9c)$$

$$R_{400_k} = \log_{10} \left(\frac{1}{5} \sum_{n=k-5}^k \frac{P_{400_k}}{P_{3000_k}} \right) \quad (4.9d)$$

$$R_{7500_k} = \log_{10} \left(\frac{1}{5} \sum_{n=k-5}^k \frac{P_{7500_k}}{P_{3000_k}} \right) \quad (4.9e)$$

$$\bar{R}_{7500} = \sum R_{7500_n}, \quad n \in [k_{400} + 4.5f_s, k_{400} + 5.5f_s] \quad (4.9f)$$

$$\Delta R_{7500_k} = R_{7500_k} - \bar{R}_{7500} \quad (4.9g)$$

The FSK demodulation implemented in the AXCTD Processor is (relatively) simple: first, the PCM data are smoothed via a 1200 Hz low pass filter (or optionally, a 100 Hz to 1200 Hz bandpass filter). Next, all zero-crossing points are identified, and filtered to identify zero-crossing points that match the 800 Hz symbol rate. For each expected bit, the 400 Hz and 800 Hz powers are calculated via as the covariance between the PCM data and a generated complex wave at each frequency over the length of the bit (example equation below for 400 Hz, where PCM is the audio data, n is each index, and f_s is the sampling frequency), and the greater of the two powers (after application of a scaling coefficient) is used to classify each bit as mark or space (1 or 0). This process is demonstrated in Fig. ??, with a small segment of AXCTD PCM data plotted in green, zero-crossing points marked in red (identified as starting mark bits), blue (identified as starting space bits), and black (not corresponding to the start of a bit). Corresponding example 400 Hz and

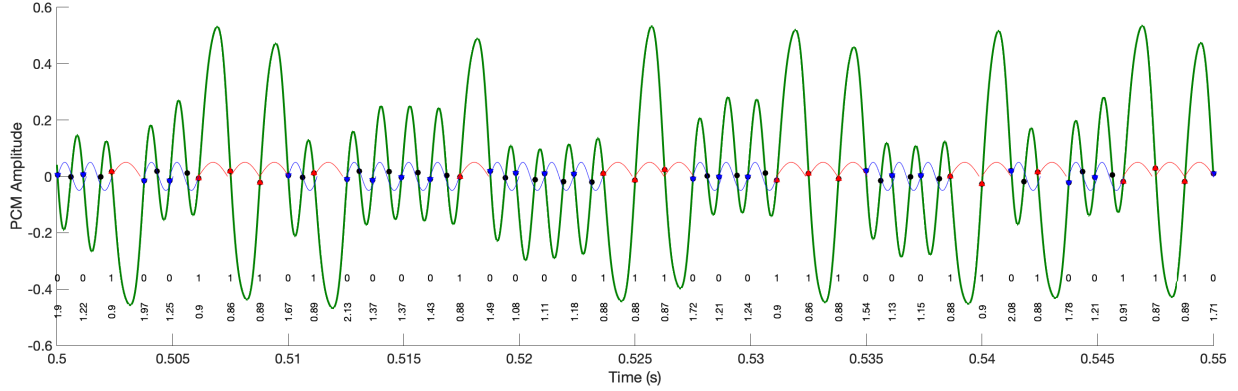


Figure 4.6: Example demodulation of a raw AXCTD signal (green) into bits 1 (red) or 0 (blue), with associated confidences displayed at the bottom of the plot.

800 Hz waveforms are plotted over their respective bits in red and blue, respectively. Finally, the bottom of the figure includes each bit's identification as a 1 or 0 and the associated confidence (less than and greater than 1.0 corresponding to bit 1/400 Hz and bit 0/800 Hz, respectively).

$$P_{400} = \sum_{n=0}^N \left| PCM_n e^{i2\pi n \frac{400}{f_s}} \right| \quad (4.10)$$

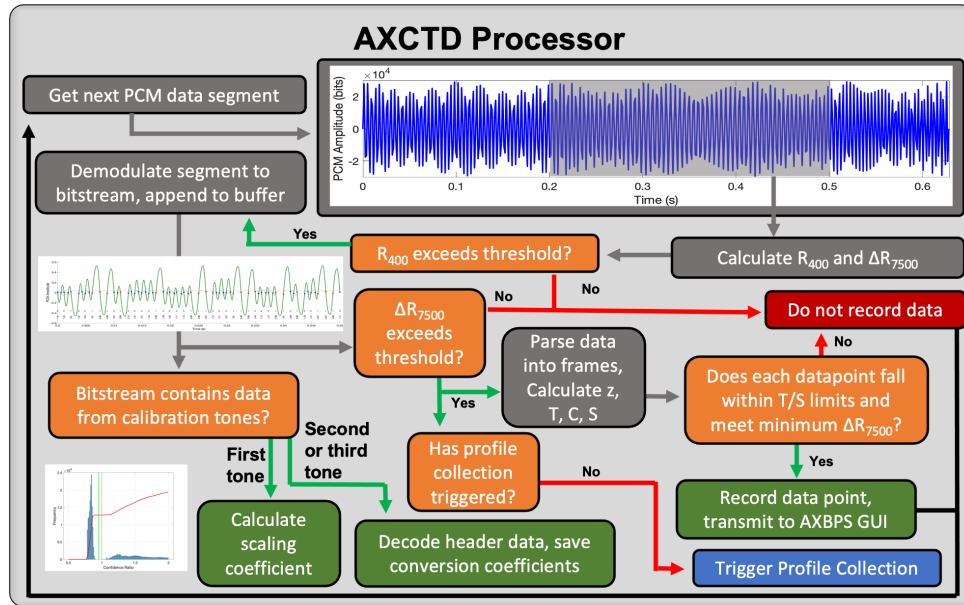


Figure 4.7: Sequence to pull and process segments of PCM data to identify valid temperature-depth measurements transmitted from an AXCTD.

To account for potential differences in amplitude of the 400 Hz and 800 Hz signals due to probe variations or other effects, ratios of 400 Hz and 800 Hz power levels are calculated for each bit in the series of header data following the first pulse (Fig. 4.8). A cumulative probability distribution function is used to split the power ratios into two nearly equal groups (approximately 40% 400 Hz

and 60% 800 Hz signals, based on expected distributions) and the calculated scaling coefficient is applied for all subsequent demodulation. The second and third headers are demodulated and parsed to decode AXCTD metadata such as serial numbers and conversion coefficients, and data from the last two headers are compared so any information missed due to demodulation errors in the second header can be incorporated from the third and vice versa.

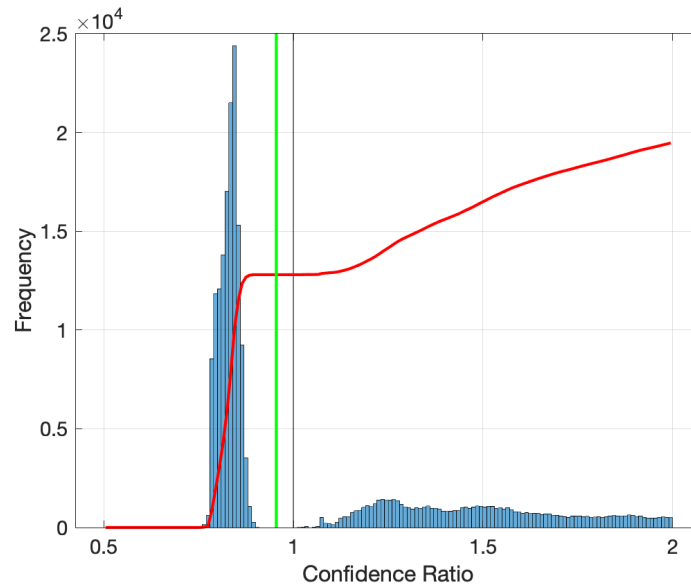


Figure 4.8: Demonstration of scaling coefficient identification. Blue bars and the red line show the 400 Hz to 800 Hz bit identification confidence ratio distribution and cumulative probability distribution function, and the vertical green line denotes the scaling coefficient identified by the AXCTD processing algorithm.

Both header and profile data parsing are accomplished by identifying 32-bit sequences beginning with 10 that have a valid CRC, and converting the data from there. Although some random variations can (and do) pass the CRC, these are rare enough that it does not affect processing success. Error code corrections are not applied in this algorithm; any frames with bit errors are simply ignored.

After each profile frame is parsed, temperature and conductivity are calculated from the frame and the corresponding depth is calculated via the time difference between the start of the frame and the first detection of the 7500 Hz signal. Salinity is then calculated using the temperature, conductivity, and depth for that frame via the TEOS-10 equations from the GSW toolbox. A diagram of the AXCTD processing algorithm’s data flow is presented in Fig. 4.7

4.0.4 AXCP Processing

Operating Principles

Airborne eXpendable Current Profilers (AXCPs) relay temperature and current information via three different frequencies in distinct bands. After reaching the surface, the floats are activated and transmit surface temperatures at the surface as the probe acclimates for approximately 40-60 seconds. After the probe is released, it sinks through the water column and begins rotating as it descends, reaching a steady state rotation rate of approximately 16 Hz within a few meters of the

surface. Temperatures are transmitted via a temperature baseline frequency in the 250 Hz to 500 Hz band. Voltage measured across two electrodes on the probe is transmitted via an electromagnetic forcing baseline frequency in the 1000 Hz to 1500 Hz band. This voltage can be converted into an estimate of the current velocity aligned with the two electrodes, as a function of Earth's horizontal and vertical magnetic field components and several other factors.

The probe's orientation relative to magnetic north is relayed via a compass coil baseline frequency in the 2000 Hz to 2500 Hz band. Probe release and profile initiation are best identified by the development of probe rotation (indicated via oscillations in the compass coil baseline frequency), achieving 8 Hz fairly quickly and steadying at approximately 16 Hz shortly after. The probe fall rate of approximately 4.4 m s^{-1} is used to calculate depth as a function of time since spinup. Finally, profile termination occurs when the probe reaches its terminal depth and the thin cable connecting the probe and surface float separate, or the probe reaches the bottom of the water column. Either ending is characterized by a drop in the probe's rotation rate, as it is either no longer transmitting orientation information or it is stationary and embedded in sediment. This drop in rotation rate can be used to identify profile termination.

AXCP (and XCP/XTVP) operating principles and original data processing methodology are described in greater detail in the following publications:

- Sanford, Drever, Dunlap, and D'Asaro (1982), *Design, Operation, and Performance of an Expendable Temperature and Velocity Profiler (XTVP)*. Technical Report APL-UW 8110. Applied Physics Laboratory, University of Washington
- Sanford, D'Asaro, Kunze, Dunlap, Drever, Kennelly, Prater, and Horgan (1993), *An XCP User's Guide and Reference Manual*. Technical Report APL-UW TR 9309. Applied Physics Laboratory, University of Washington

AXCP Processor Implementation

The Python AXCP Processing algorithm used in AXBPS was adapted from a MATLAB Script (xcpdsp.m) by John Dunlap (University of Washington, APL).

Processing an AXCP also presents unique challenges:

1. Calculating currents requires Earth's magnetic field components, which is a function of the probe's position
2. Three frequencies in distinct bands must be identified, which would be fairly straightforward to accomplish via FFT except:
3. Advanced low and band pass filtering is necessary to extract the mean frequency in each of the three bands from the AXCP signal, and the requisite calculations to determine current speed and direction are arguably more complex than the analogous steps in AXBT or AXCTD processing

Several filters are applied to received PCM data: a 3000 Hz low-pass filter is applied to data before all other filters, and 250-500 Hz, 1000-1500 Hz, and 2000-2500 Hz bandpass filters are applied to isolate the signals associated with each of the three baseline frequencies. PCM data are processed in segments at a user-specified rate (default/recommended setting is 1 second). With each segment, filters are applied to incoming data, which are subsampled twice before probe rotation rate means and standard deviations and baseline frequencies in each of the three discrete bands are calculated. Coarse probe spinup time is identified when (1) probe rotation rate is between 10 Hz and 20 Hz,

and (2) probe rotation rate deviation drops below a user-specified spinup threshold (default/recommended 0.5 Hz, for particularly noisy profiles increasing this threshold to 1.0 Hz may be necessary). Spinup is then refined as the time at which probe rotation first exceeded 8 Hz within the past 5 seconds. Probe temperatures are also optionally calculated (when "AXCP Temperature FFT ID" is enabled) for each segment using a user-specified window length. For this segment, 1.0 seconds is also recommended- the low temperature baseline frequencies compared to AXBTs necessitates a smaller FFT Δf to retain adequate temperature resolution and avoid erroneous "stairstepping" between discrete FFT frequencies as the probe descends and generally cools. The balance of high resolution temperature observations with a large temperature FFT window length (which is limited by the refresh rate) and relatively high resolution probe rotation rate observations (which require lower refresh rates), result in a 1.0 refresh rate being optimal for probe spinup detection and accurate temperature calculations.

Temperature is calculated from frequency, regardless of whether the frequency is identified via FFT or zero crossing analysis, using the same three step process (Eq. 4.11). First, an intermediate coefficient (C_T) is calculated from the temperature baseline frequency (f_T) using calibrated coefficients (C_{rs} and C_{cap}) based on probe calibrated resistances ($R_0 = 16329 \Omega$ and $R_{30} = 4024 \Omega$) and frequencies ($f_0 = 285.3$ Hz and $f_{30} = 449.1$ Hz) at 0°C and 30°C . Second, this intermediate coefficient is converted into a temperature (T_{unc}) in degrees Celsius, and third, the temperature (T) is corrected for depth (z). The AXCP processing algorithm used in AXBPS applies the four nondimensional coefficients $C_0 = 1.73323 \times 10^{-3}$, $C_1 = 8.75509 \times 10^{-5}$, $C_2 = 1.64067 \times 10^{-5}$, and $C_3 = -5.09882 \times 10^{-7}$ in its temperature conversions. The temperature baseline frequency band edges of 250 Hz and 500 Hz correspond to temperatures of -5.0°C and 49.1°C (respectively) at the surface, with depth corrections of approximately 0.1°C at 1000 m.

$$C_{rs} = \frac{f_0 R_0 - f_{30} R_{30}}{f_{30} - f_0} \quad (4.11a)$$

$$C_{cap} = \frac{1}{4.4 f_0 (T_{rs} + R_0)} \quad (4.11b)$$

$$C_T = \ln \left(\frac{1}{4.4 C_{cap} f_T} - C_{rs} \right) \quad (4.11c)$$

$$T_{unc} = \frac{1}{C_0 + C_1 C_T + C_2 (C_T)^2 + C_3 (C_T)^3} - 273.15 \quad (4.11d)$$

$$T = T_{unc} - 0.1 - (7.5 \times 10^{-5})z \quad (4.11e)$$

Once probe spinup is identified, times corresponding to depths of interest are calculated (AXBPS calculates data at a 2 m resolution (over 5 m "chunks", resulting in some smoothing and overlap between depths) starting at 7.5 m (to allow the probe time to spin up and start transmitting accurate data). If "AXCP Temperature FFT ID" is not enabled, the temperature baseline frequency is calculated for each depth chunk using zero crossings within the temperature bandpass (250 Hz to 500 Hz) filtered PCM data. If it is enabled, temperature is interpolated for the current depth/time since spinup from the FFT-calculated temperatures for each segment. Depth (z) is calculated from time elapsed (Δt) since spinup (when probe rotation reached 8 Hz) following Eq. 4.12 from Prater (1991). Meanwhile, zonal and meridional currents are calculated using the zero-crossing identified EF and compass coil baseline frequencies, which are calculated as described in the next paragraph as a function of the rotation frequency. Finally, zonal and meridional velocities in degrees true are calculated from the values in degrees magnetic using the magnetic declination at the probe position.

$$z = 4.68 + 4.377\Delta t - 0.00044\Delta t^2 \quad (4.12)$$

Calculating current velocity at each depth requires extracting the compass coil and EF baseline frequencies over a small depth segment (AXBPS uses a 5 m range) to calculate the mean current direction and speed over that range. First, compass coil zero crossing times (t_{zp}) over that interval are identified. These are times where the compass coil frequency is halfway between its minimum and maximum frequencies (approximately 2070 Hz and 2430 Hz, respectively). From these zero crossing times, probe orientation/phase (θ) is calculated so the phase is 0 or a multiple of 2π at those times. Of note, θ is a $1 \times N$ matrix, with length N corresponding to the lengths of compass coil and EF baseline frequency matrices (f_{cc} and f_{ef} , respectively) for the depth segment of interest.

$$\theta = 2\pi \frac{t_k - t_{zp_j}}{t_{zp_{j+1}} - t_{zp_j}}, \quad k \in t_{zp_j} < t_k \leq t_{zp_{j+1}} \quad (4.13)$$

Next, the compass coil and EF frequencies and probe phase are used to calculate compass coil and EF frequency phase and amplitude estimates for the depth segment via a linear least squares solution (least squares operations are denoted with \backslash):

$$A_{cc} = \begin{bmatrix} \cos \theta_1 & \sin \theta_1 & 1 \\ \cos \theta_2 & \sin \theta_2 & 1 \\ \cos \theta_k & \sin \theta_k & 1 \\ \cos \theta_{N-1} & \sin \theta_{N-1} & 1 \\ \cos \theta_N & \sin \theta_N & 1 \end{bmatrix} \quad (4.14a)$$

$$A_{ef} = \begin{bmatrix} \cos \theta_1 & \sin \theta_1 & 1 & -1 \\ \cos \theta_2 & \sin \theta_2 & 1 & -1 + \frac{2}{N} \\ \cos \theta_k & \sin \theta_k & 1 & -1 + \frac{2j}{N} \\ \cos \theta_{N-1} & \sin \theta_{N-1} & 1 & -1 + \frac{2(N-1)}{N} \\ \cos \theta_N & \sin \theta_N & 1 & 1 \end{bmatrix} \quad (4.14b)$$

$$C_{cc} = A_{cc} \backslash f_{cc}, \quad C_{ef} = A_{ef} \backslash f_{ef} \quad (4.14c)$$

$$\sigma_{cc} = \frac{1}{N} \sum_{k=1}^N (C_{cc_k} - \sum C_{cc}), \quad \sigma_{ef} = \frac{1}{N} \sum_{k=1}^N (C_{ef_k} - \sum C_{ef}) \quad (4.14d)$$

$$a_{cc} = \sqrt{(C_{cc0})^2 + (C_{cc1})^2}, \quad a_{ef} = \sqrt{(C_{ef0})^2 + (C_{ef1})^2} \quad (4.14e)$$

$$\phi_{cc} = \tan^{-1} \left(\frac{-C_{cc1}}{C_{cc0}} \right), \quad \phi_{ef} = \tan^{-1} \left(\frac{-C_{ef1}}{C_{ef0}} \right) \quad (4.14f)$$

Probe gain and phase angles are also calculated as a function of probe rotation rate (f_{rot}) or defined as constants (phase angle coefficients are presented in degrees). These gain and phase angle coefficients include compass voltage (G_{cca} and G_{ccp}), correction voltage (G_{cor_a} and G_{cor_p}), electric field voltage (G_{efa} and G_{efp}), electric field deviation (G_{evfa} and G_{evfp}), and compass deviation (G_{cvfa} and G_{cvfp}), and are defined following John Dunlap's MATLAB xcpdsp script, Horgan et al. (1989), and Kennelly et al. (1989).

$$G_{cc_a} = 1809.877761 - 1.25653911(f_{rot}) + 0.18856556(f_{rot})^2 \quad (4.15a)$$

$$G_{cc_p} = 29.826971133 + 10.265226263(f_{rot}) - 0.176531452(f_{rot})^2 \quad (4.15b)$$

$$G_{cor_a} = 898.89564739 + 0.453188608(f_{rot}) + 0.0717425016(f_{rot})^2 \quad (4.15c)$$

$$G_{cor_p} = 56.552652832 + 7.783581145(f_{rot}) - 0.112472607(f_{rot})^2 \quad (4.15d)$$

$$G_{ef_a} = 23866.12044581 + 107.99111272898(f_{rot}) - 0.905827321(f_{rot})^2 \quad (4.15e)$$

$$G_{ef_p} = -138.158938796 + 9.759010754(f_{rot}) - 0.180878978(f_{rot})^2 \quad (4.15f)$$

$$G_{evf_a} = 494.66, \quad G_{evf_p} = 0 \quad (4.15g)$$

$$G_{cvf_a} = 500, \quad G_{cvf_p} = 0 \quad (4.15h)$$

Given the probe gain and phase angles and compass coil and EF frequency phase and amplitude estimates, several components of current speed and direction estimates (uncorrected for magnetic deviation or field components) are calculated.

$$V_{c0_a} = \frac{(1 \times 10^6)a_{cc}}{G_{cvf_a}G_{cc_a}} \quad (4.16a)$$

$$V_{c0_p} = \phi_{cc} - G_{cvf_p} - G_{cc_p} \quad (4.16b)$$

$$V_{e0_{a1}} = \frac{(1 \times 10^6)a_{ef}}{G_{evf_a}G_{ef_a}} \quad (4.16c)$$

$$V_{e0_{p1}} = \phi_{ef} - G_{evf_p} - G_{ef_p} \quad (4.16d)$$

$$V_{e0_{q1}} = V_{e0_{a1}} \cos V_{e0_{p1}} \quad (4.16e)$$

$$V_{e0_{i1}} = V_{e0_{a1}} \sin V_{e0_{p1}} \quad (4.16f)$$

$$V_{e0_{a2}} = \frac{(1 \times 10^6)G_{cor_a}}{G_{cvf_a}G_{cc_a}G_{ef_a}} \quad (4.16g)$$

$$V_{e0_{p2}} = \phi_{cc} - G_{cvf_p} - G_{cc_p} + G_{cor_p} - G_{ef_p} \quad (4.16h)$$

$$V_{e0_{q2}} = V_{e0_{a2}} \cos V_{e0_{p2}} \quad (4.16i)$$

$$V_{e0_{i2}} = V_{e0_{a2}} \sin V_{e0_{p2}} \quad (4.16j)$$

$$V_{e0_q} = V_{e0_{q1}} - V_{e0_{q2}} \quad (4.16k)$$

$$V_{e0_i} = V_{e0_{i1}} - V_{e0_{i2}} \quad (4.16l)$$

$$V_{e0_a} = \sqrt{(V_{e0_q})^2 + (V_{e0_i})^2} \quad (4.16m)$$

$$V_{e0_p} = \tan^{-1} \left(\frac{V_{e0_i}}{V_{e0_q}} \right) \quad (4.16n)$$

Before current velocities can be calculated, velocity scaling coefficients (s_{fv} , s_{fw} , and s_{fa} ; Eq. 4.17) must be determined as a function of Earth's horizontal and vertical magnetic field components (F_h and F_z , respectively) and declination at the drop position and date. When the user starts processing an AXCP profile, AXBPS will attempt to pull the latitude, longitude, date and time from the user input fields in the DAS. If no values are provided, AXBPS will default to the current date/-time and default coordinates provided in the AXCP signal thresholds settings window. Magnetic field component calculations are accomplished via a python implementation of the GeoMag library. This implementation is adapted from the version available at <https://pypi.org/project/geomag/>,

which is based on a USGS library <https://github.com/usgs/geomag-algorithms>, that uses World Magnetic Model Coefficient files (WMM.COF) containing Gauss coefficients for a five year interval that are updated every five years. The current version implemented in AXBPS is valid for the 2020 to 2025 timeframe. In Eq. 4.17, c_1 and c_2 are probe-related coefficients taken to be 0.97 and -0.02 (respectively), following the `xcpdsp.m` script.

$$s_{fv} = \frac{1}{F_z(5.19 \times 10^{-5})(1 + c_1)} \quad (4.17a)$$

$$s_{fw} = \frac{F_h(1 + c_2)}{F_z(1 + c_1)} \quad (4.17b)$$

$$s_{fa} = \frac{1}{2\pi F_h(1 \times 10^{-5})} \quad (4.17c)$$

Calculating the current velocity at each depth requires an estimate of the area of the probe's copper wire with a surface normal to the horizontal component of Earth's magnetic field. That area, which is a function of time due to the probe's rotation, induces a potential difference which must be compensated in current calculations (for more information, see Sanford et al., 1993). The mean estimate of area (A_{mean}) is approximated while the AXCP profile is calculated in realtime (assuming $A_{mean} = 580 \text{ cm}^2$). This mean area value is refined after the probe's spindown is detected by taking the mean of all calculated areas between probe spinup and spindown and used to update the current velocity calculations for the entire profile.

$$A = \frac{V_{c0a} s_{fa}}{f_{rot}} \quad (4.18)$$

Finally, current velocity (oriented relative to magnetic north) is calculated, given the velocity amplitude and phase estimates, compass coil area, magnetic field coefficients, and a probe fall rate correction factor U_w . The probe fall rate (w) is estimated as a function of time elapsed since spinup using the first derivative of Eq. 4.12. Declination at the probe drop position, calculated by the Geomag implementation, is used to reorient the current velocities relative to true north.

$$\psi = -V_{e0p} + V_{c0p} + \frac{3}{2}\pi \quad (4.19a)$$

$$U_w = w \frac{A}{A_{mean}} s_{fw} \quad (4.19b)$$

$$u_{mag} = (V_{e0a})(s_{fv}) \cos \psi \quad (4.19c)$$

$$v_{mag} = -(V_{e0a})(s_{fv}) \sin \psi + U_w \quad (4.19d)$$

Mean probe rotation rate is calculated at each depth/temperature/current datapoint, and these values are used to identify the probe spindown time. A coarse probe spindown time is identified when the probe rotation rates for the previous 10 segments (corresponding to the user-defined refresh rate) are both below 12 Hz and greater than 18 Hz, and the maximum rotation rate deviation exceeds 1.0 Hz. When these conditions are met, profile processing is terminated and probe spindown is refined using the rotation rates and deviations calculated at each depth datapoint. Specifically, the precise spindown point is identified where the rotation rate deviation increases abruptly, exceeding double the mean deviation for the previous 10 values.

In addition to updating the AXBPS GUI with each new datapoint processed and when an AXCP spinup is detected, the AXCP processor sends and receives updates to and from the GUI when the

user updates the drop position and date (when the user selects the "Update Parameters" button) and when a refined probe spindown time is detected. When probe position and date are updated, the AXCP processor updates its magnetic field parameters (F_h , F_v , declination, s_{f_v} , s_{f_w} , and s_{f_a}), and if probe spinup was detected prior to that point, it also recalculates all previously calculated currents and updates the user interface. Processing is temporarily paused while the magnetic field parameters are updated and current profiles are recalculated to prevent any race conditions resulting in inaccurate current profiles. Additionally, because the spindown point is typically not detected by the AXCP processor until several seconds after spindown occurred, another signal is sent from the AXCP processor to the GUI to update the user interface with the temperature and current profiles truncated at the refined spindown time. This means that the user will typically see either warming temperatures (bottom strike) or erroneous data (copper wire severing) plotted for several seconds before the AXCP processor refines the spindown point and the plotted profiles are truncated at the associated spindown depth. This final profile update also includes currents corrected using a refined mean area (A_{mean} ; Eq. 4.18) calculation. Whenever the AXCP processor updates previously transmitted data, the profile plot and profiles stored in AXBPS memory are updated, but the table is not and will therefore continue to display outdated temperature and current datapoints.

A diagram of the AXCP processing data flow, with user interface interactions, is provided below (Fig. 4.9)

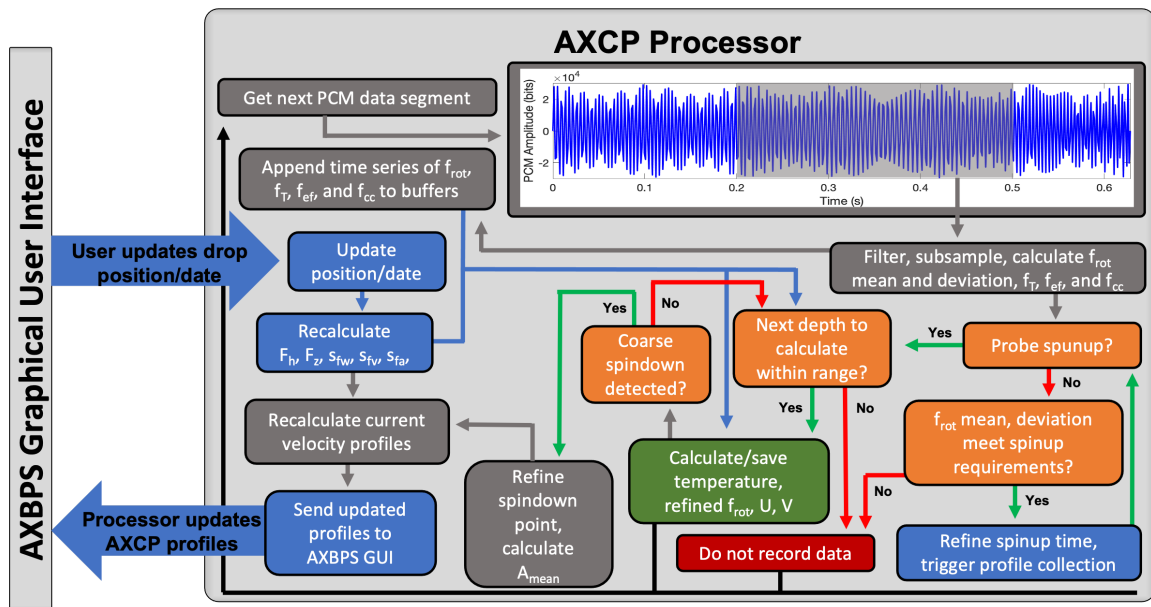


Figure 4.9: Data flow associated with AXCP signal processing.

4.0.5 Additional Features

GPS Integration

In order to reduce potential for error by manual entry, AXBPS was designed to accept input from any GPS receiver that transfers information with a NMEA stream to automatically record position. This is accomplished using Python's pyserial and pynmea2 modules, which were developed to manage serial data connections and parse GPS NMEA-formatted data, respectively. Using pyserial, AXBPS scans for and provides a list of all available serial ports. Given a user-specified port, AXBPS can open the port, parse incoming NMEA data and record latitude and longitude

(as long as the selected port is connected to a GPS with a valid NMEA stream), either when data recording is started or to test the connection to a GPS receiver.

File Types

Raw data from a processed profile can be saved in one of five formats: raw audio (WAV), ASCII signal data, LOG, EDF, and NVO files. WAV files are the most raw form of data available, and recording WAV files is advantageous as it enables reprocessing the profile using different signal processing schemes. However, while some filesystems record creation and 'last modified' datetimes, WAV files cannot store drop metadata such as time and position. In AXBPS, temporary WAV files are generated when a receiver is activated, and PCM data is constantly appended to the file as the WiNRADIO continues passing data to the processing computer.

For AXBTs, the ASCII signal data file records time elapsed, peak frequency, signal level, and signal-to-noise ratios in a comma-delimited format (in that order). This enables profile testing and adjustments (e.g. changes to conversion equations or minimum signal thresholds) without repeating the computationally-expensive signal processing necessary to generate a time series of peak frequencies and accompanying signal levels from a source audio file. For AXCTDs, reprocessing the profile requires demodulation of the raw PCM data and thus the signal data file includes less information- namely processor initialization (start) time, profile 400 Hz pulse and 7500 Hz tone detection times, and the results of any header detection and demodulation/parsing attempts. For AXCPs, coarse and refined spinup and spindown times, segment times and rotation rates/deviations, and detailed profile data are all stored. Like the WAV file, temporary signal data files are created when a receiver is activated and continuously updated as more data is streamed from the receiver. For both the raw audio and signal data files, when the user "saves" the file, they are simply renaming and moving those files from a temporary directory managed by the processing computer's operating system (e.g. Wondershare for Windows 10).

Finally, the LOG, EDF, DAT, and NVO files are all various ASCII file formats for storing the raw data. LOG files are columnar ASCII files including time elapsed, depth, peak frequency, and temperature, but do not include position information. EDF and NVO files include the observed profile(s) as well as time and position information, and the option for additional metadata (e.g. drop number, AXBT type, and additional information). An NVO file format example is provided in Section 2.2.5. When these files are saved by the users, text files are actually generated from the raw profile information stored within the program's primary class.

Multithreading

The Airborne eXpendable Buoy Processing System uses multithreading to facilitate processing data from multiple probes simultaneously (either realtime or from raw audio files). Multithreading and multiprocessing are two methods for handling parallel computations. Multiprocessing requires a central processing unit (CPU) that has multiple cores, each of which are able to run computations simultaneously and separately from one another. Multithreading only requires one core, but instead manages multiple threads (individual tasks) that operate simultaneously from the user's perspective but alternate CPU use at high frequency so each thread receives a requisite of computation time from the CPU.

The PyQt5 library includes multithreading support through several classes: QThreadPool, QRunnable, pyqtSignal and pyqtSlot. The QThreadPool class is initialized with the program to provide a parent to manage a limited number of individual threads (AXBPS currently supports up to six threads) running simultaneously in the background. The QRunnable class is the framework

for the individual threads (e.g. in Fig. 4.4 the "Signal Processor thread" is a QRunnable class). This class contains an initialization function that is executed when the QRunnable class is created and a run function that is called separately by the parent thread after initializing the QRunnable-Class (in AXBPS, these functions are executed consecutively when the user selects the option to start processing on the graphical user interface). Finally, pyqtSignal and pyqtSlot are the PyQt implementation of signals and slots, which enable transfer of information and commands between individual threads and the parent process. In AXBPS, this transfer is between the user interface and individual Data Acquisition System threads. For example, AXBPS supports the user changing the VHF frequency being demodulated and Data Acquisition System minimum thresholds while the Data Acquisition System thread is active, and this is accomplished using signals and slots (labelled changethresholds in Fig. 4.4). Additionally, every time a new segment of PCM data is processed and either converted into a temperature-depth datapoint or identified as a null value, that information is transmitted via a signal back to the parent thread (the user interface), where it is stored with the other profile information and used to update the profile plot and table.

4.1 AXBPS Profile Editor “autoQC” Algorithm

The following VHF interference corrections are applied to raw profiles:

1. Gaps in data due to profile false starts are identified and corrected
2. Spikes from interference are identified using a depth-based running standard deviation filter and removed
3. Profiles are smoothed using a depth-based box filter
4. Profiles are subsampled

Gap detection is most relevant to AXBT profiles, and identifies “false starts” due to strong, typically external signals from a source other than the observed AXBT that trigger profile collection before the AXBT begins transmitting data. These false starts are usually characterized by a brief signal at or near the surface, followed by a several-second gap in data, and then an otherwise valid AXBT profile that is depth-shifted (so the actual surface temperatures from the AXBT are recorded at some subsurface depth). These are identified by searching for a break in data exceeding 10 m in the upper 50 m of the profile (as data gaps due to signal loss are less common near the surface when the AXBT signal is stronger as the aircraft is still close to the float). If such a break exists, the profile is shifted upwards so the surface observation is the first datapoint after the gap, and the gap check is repeated until no such gaps exist in the upper 50 m.

The second step uses a running filter to identify spikes due to VHF interference. This is accomplished by calculating the mean and standard deviation for all profiles within a 10-m window of a point (± 5 m, corresponding to $D_\sigma = 5$ m in Eq. 4.20). If an individual point deviates from the mean by more than the product of a user-specified coefficient (β) and the standard deviation about the mean (such that at any index i , $|T[i] - \hat{T}[i]| \geq \beta\sigma_T[i]$, where $\hat{T}[i]$ and $\sigma_T[i]$ are the mean and standard deviation of the temperatures within the 10-m window of the point $z[i]$ as defined in Eq. 4.20), the datapoint is considered a spike and discarded (for the AXBPS Data Acquisition System evaluation, $\beta = 1$).

$$\hat{T}[i] = \frac{1}{N} \sum_{j=1}^N \hat{T}_n, \quad j \in (z[i] - D_\sigma) \leq z[j] \leq (z[i] + D_\sigma)$$

$$\sigma_T[i] = \left(\frac{1}{N} \sum_{j=1}^N (T_j - \hat{T}[i])^2 \right)^{1/2}$$
(4.20)

After the two primary modes of VHF interference (false starts and profile spikes) are corrected if necessary, each profile is passed through a depth-based smoother using a simple box filter described by Eq. 4.21, where the depth window is determined by D_M , and \bar{T} is the smoothed profile.

$$\bar{T}[i] = \frac{1}{N} \sum_{j=1}^N T_j, \quad j \in (z[i] - D_M) \leq z[j] \leq (z[i] + D_M)$$
(4.21)

Finally, profiles are subsampled to a lower resolution before being displayed to the user for additional edits as necessary and data export. The smoothing window should be at least twice the subsampled resolution in order to prevent aliasing (noting that box smoothers have a relatively poor frequency response compared to more advanced low pass filters). However, the default subsampling resolution is 1 m, and in practice it was observed that a 10-m smoother ($D_M = 5$ m) was necessary to remove high-frequency variability due to remaining VHF interference.

4.1.1 Comparison to Climatology and Bathymetry

After being corrected for VHF interference, smoothed, and subsampled, the temperature (and salinity, as required) profile is compared to bathymetry and climatology data given the probe launch position and date. Ocean depth at the launch position is interpolated from the NOAA ETOPO1 Global Relief Dataset, which provides global topography and bathymetry at a 1-arcminute resolution. The autoQC algorithm automatically truncates profiles at the bathymetry-indicated ocean depth.

Climatological monthly ocean temperature and salinity means and standard deviations are from subset of data from the Generalized Digital Environmental Model (GDEM) climatology, that includes values at a 0.25° horizontal resolution for 29 vertical levels in the upper 1,000 m. The profile climatology comparison has two steps: (1) comparing profile slopes to identify bottom strikes, and (2) comparing the observed profile to climatology to detect possible climatology mismatches (e.g. slow falling probes, late starts, and otherwise faulty probes). Because bottom strikes typically appear as temperature observations that are erroneously isothermal or warming with depth at the base of the profile (coupled with sharp jumps in conductivity and therefore salinity for AXCTD profiles), the slopes of the observed and climatological profiles are calculated and compared. To minimize incorrect identifications due to higher-frequency variability, a fifty-point running mean of the differences between the climatology and observed profile slopes is examined. If this running mean exceeds $0.1^\circ\text{C}/\text{m}$, it is considered a bottom strike, and all data below the depth at which this threshold is exceeded are discarded. The observed profile is then compared to the climatology to identify potential profile discrepancies. If less than 50% of the observed profile falls within the uncertainty range for the climatology (currently one standard deviation), then the profile is flagged as a climatology mismatch.

If either a bathymetry-based or climatology-based bottom strike is identified, the profile is truncated at that depth (priority is given to the climatology-based strike if both are identified).

After a profile has been corrected for both VHF interference and bathymetry- and climatology- indicated discrepancies, it is plotted on the Profile Editor interface. Original and quality-controlled profiles are overlaid in black and red (respectively) on top of blue-shaded climatology (showing \pm one standard deviation). When applicable, a climatology mismatch is noted with red text in the bottom-right corner of the profile window.