The enhanced XBT probe

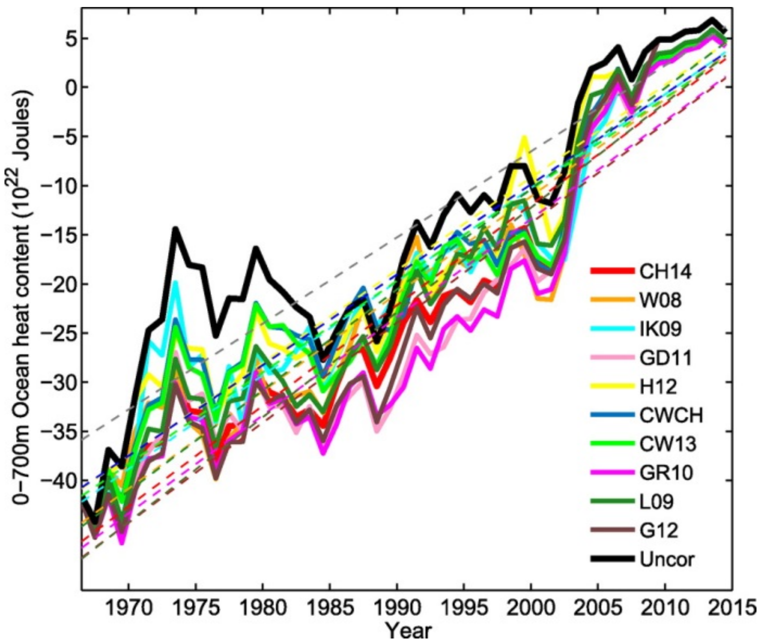
Marlos Goes

Thanks to:

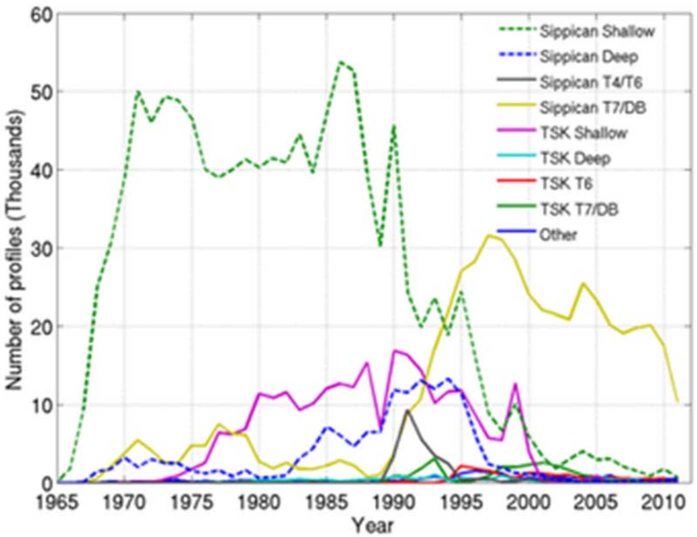
Lockheed Martin/Sippican
XBT Network
NOAA/CPO and NOAA/AOML
AOML engineers
Pirata Northeast extension (PNE)
WBTS project

Japan, 6 Oct 2016

The importance of XBT long-term monitoring



Cheng et al. (2016)

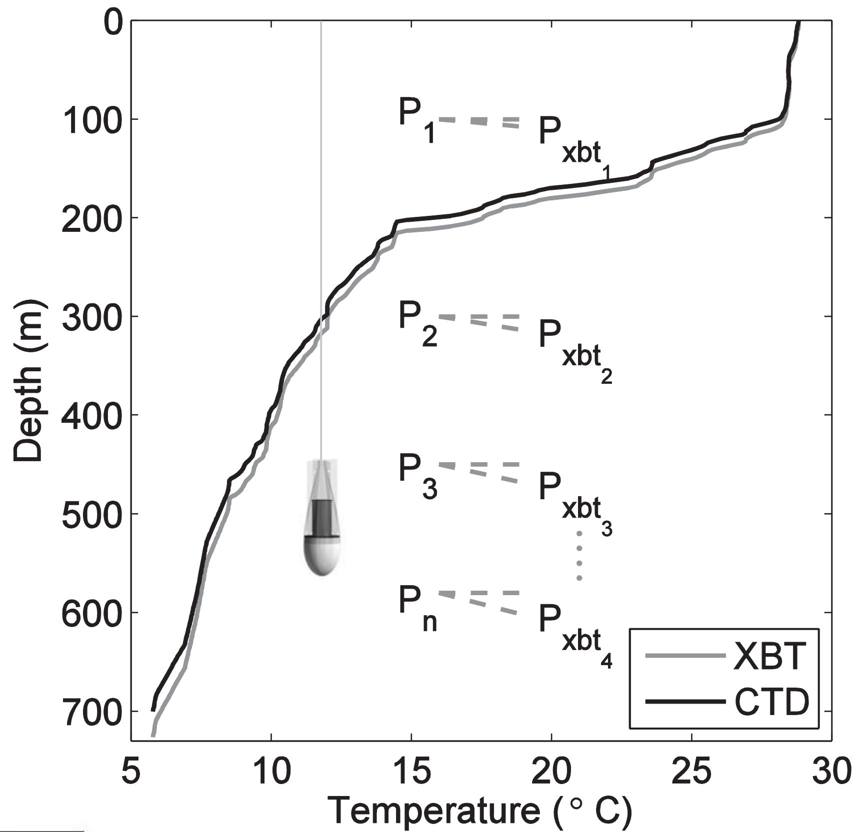


- ❑ XBT temperature profiles provides one of the longest observational records, both globally and at specific transects.
- ❑ It was initially design for navy applications, to be a cheap and reliable estimate of temperature gradients and sound speed.
- ❑ XBT temperatures were found to be positively biased by 0.2 - 0.4°C on global average.
- ❑ Several efforts have been applied to correct biases in the historical record, most of them with focus on the depth correction and rely on CTD x XBT side-by-side comparisons.
- ❑ Most of the probes in use now are the T7 and Deep Blue model.

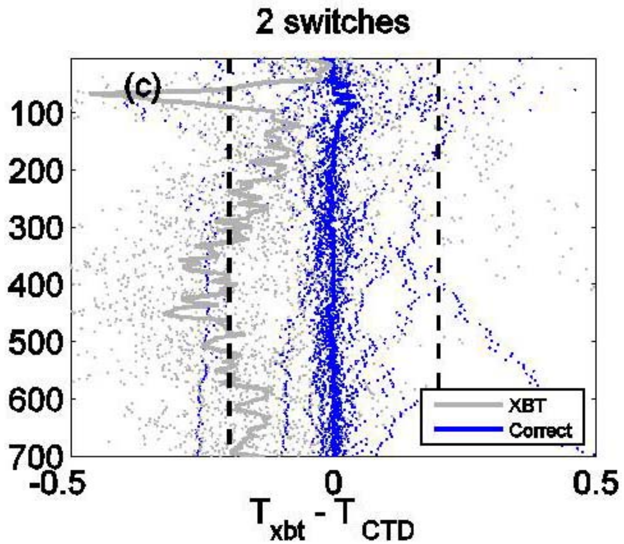
Are there changes to be performed during production that can improve the quality of the XBT data?

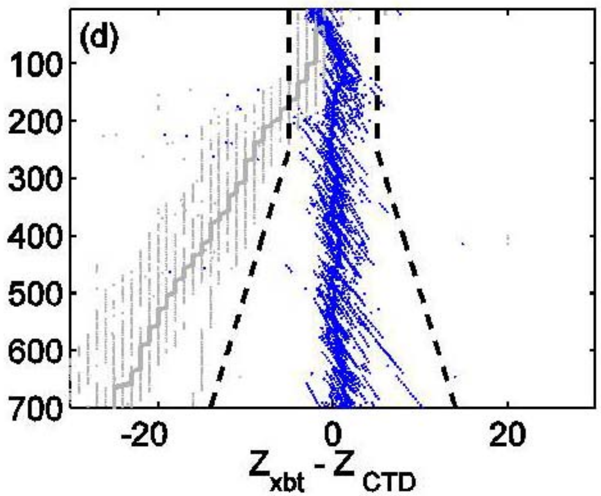
Pressure switches

- Pressure switches are small resistors that are activated at certain depths during the probe descent, marking those depths in the profile with spikes.



Goes et al., 2013





Objectives

- In partnership with LMS, we perform several sea trials, where side-by-side XBT/CTD deployments were carried out.
- We tested improvements in the accuracy of the temperature and depth estimates of XBT probes.
- Results from this study will give recommendations for manufacturing improvements in the XBT probe towards a climate quality XBT probe.

Outline

- Introduction of the XBT measurements
- Description of the AOML/LMS cruises, experiments, and methodology.
- Main results of the side-by-side XBT/CTD comparison.
- Conclusion and future work.

The XBT measurement

Depth: $Z(t)$ in XBTs is estimated using a fall-rate equation:

$$Z(t) = At - Bt^2$$

Where the coefficients A and B are both positive and dependent on the XBT type, and t is the time since the probe hits the water. A is related to the terminal velocity of the probe, and B accounts for probe weight loss due to wire de-reeling.

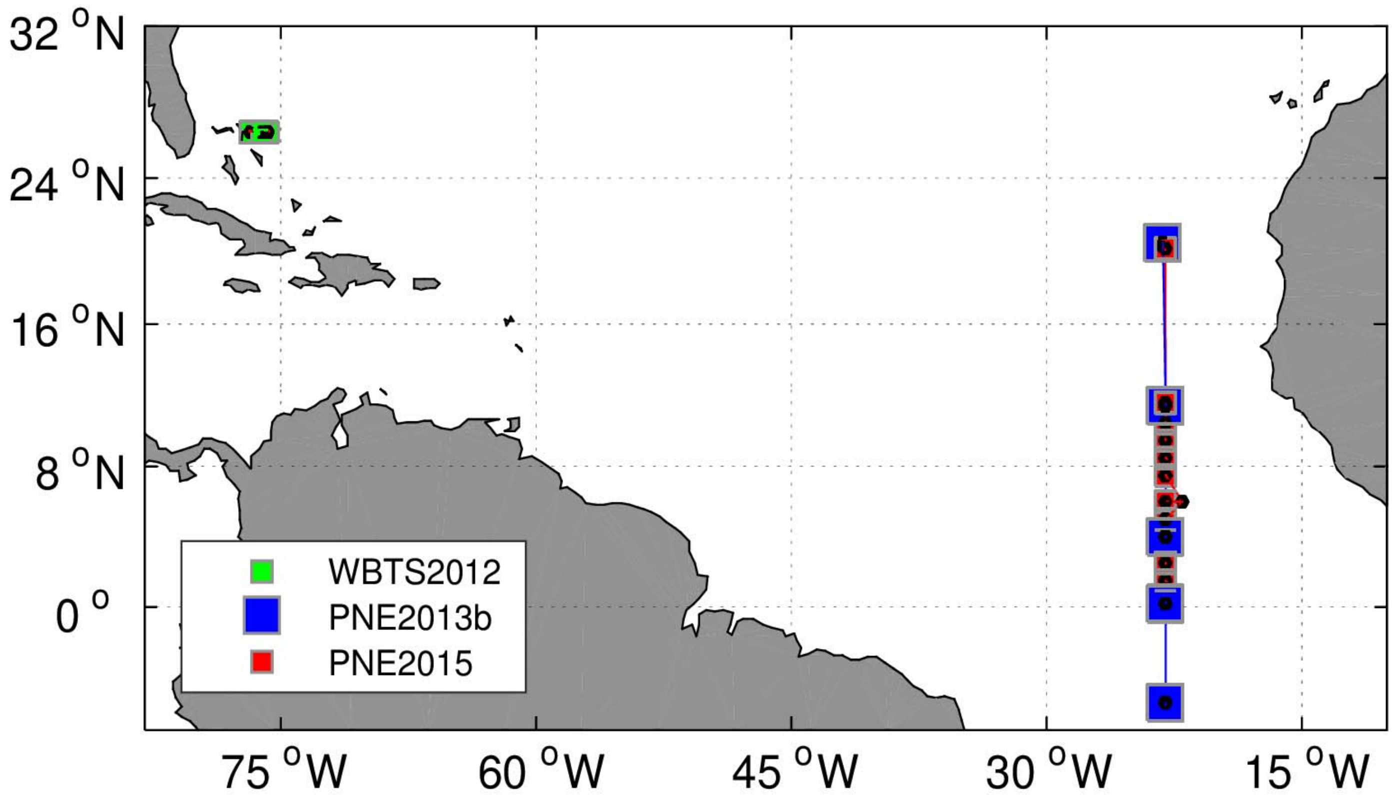
Temperature: $T(t)$ is measured by a thermistor located at the probe's nose. Water passes through the nose, and a resistance value is transmitted to the acquisition system where it is translated into a temperature record.

Typical errors found in XBT measurements

Type of error	Order of Magnitude	Source
Temperature accuracy (T0)	$T0 \approx \pm 0.1°C$ $1\text{-}\sigma \approx 0.12°C$	Probe-to-recording device, **uncalibrated thermistors**, wire resistance.
Depth offset (Z0)	$Z0 \approx \pm 5m$.	Wave height variability, entry velocity, height, and angle of the probe
Depth linear bias (Zd)	$Zd \approx 2\%$ of depth	Pure FRE error. Depends on the water viscosity (temperature), **probe's mass and wire de-reeling**.

How constraining thermistor variability and probe mass influence the temperature and depth errors?

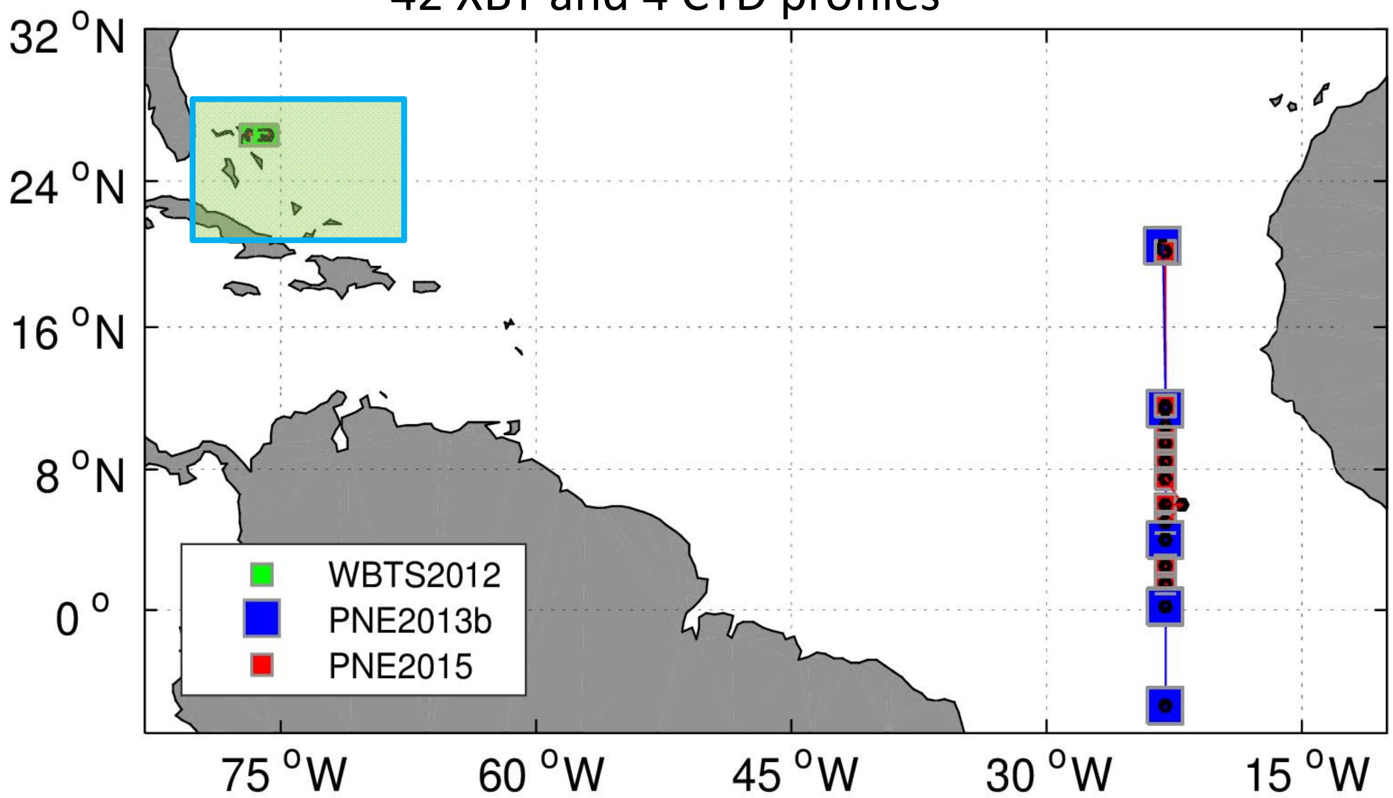
Side-by-side comparisons



Location of the CTD x XBT deployments carried out during the three cruises analyzed here.

Side-by-side comparisons

WBTS2012:
42 XBT and 4 CTD profiles

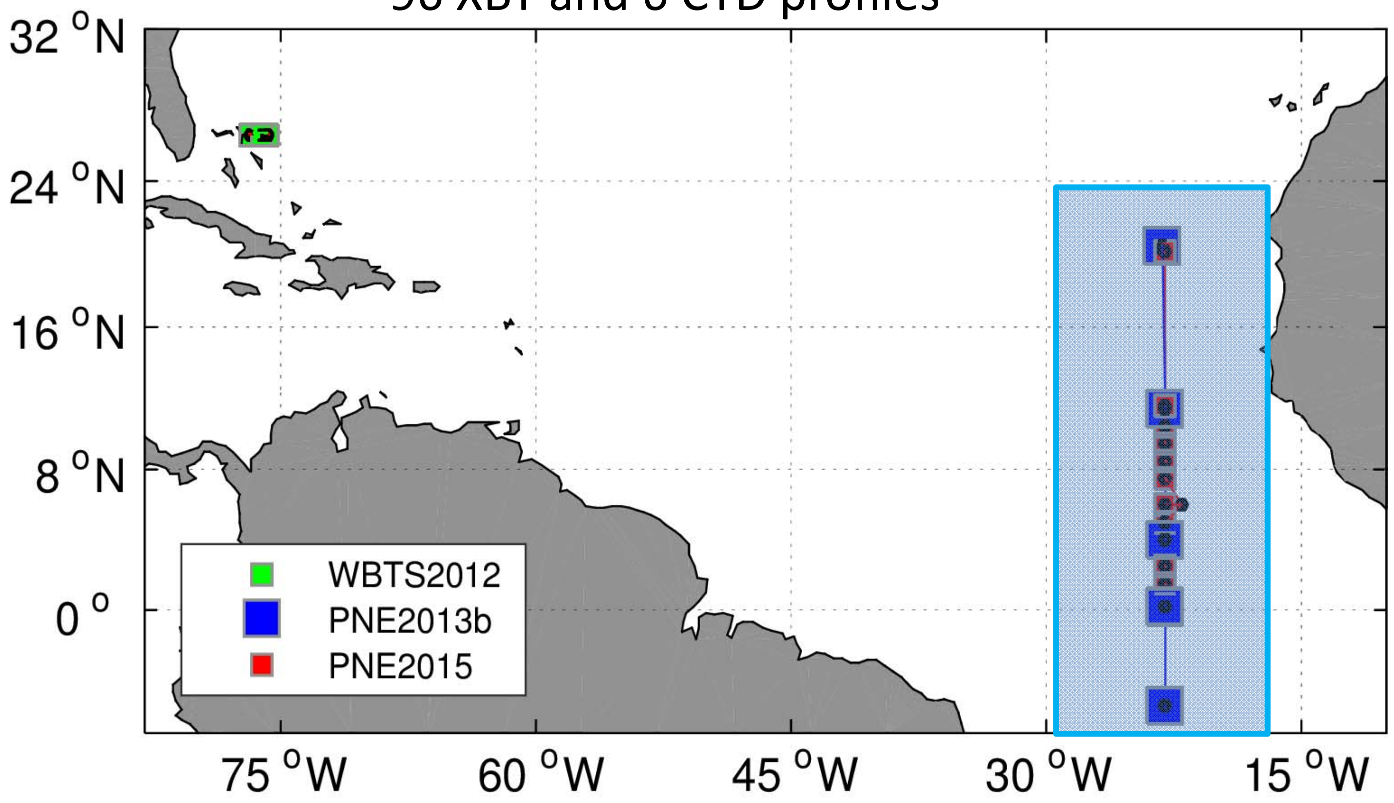


<u>2 probe types</u>:

1. Standard
2. Experimental

Side-by-side comparisons

PNE2013b:
96 XBT and 6 CTD profiles



The corrections:

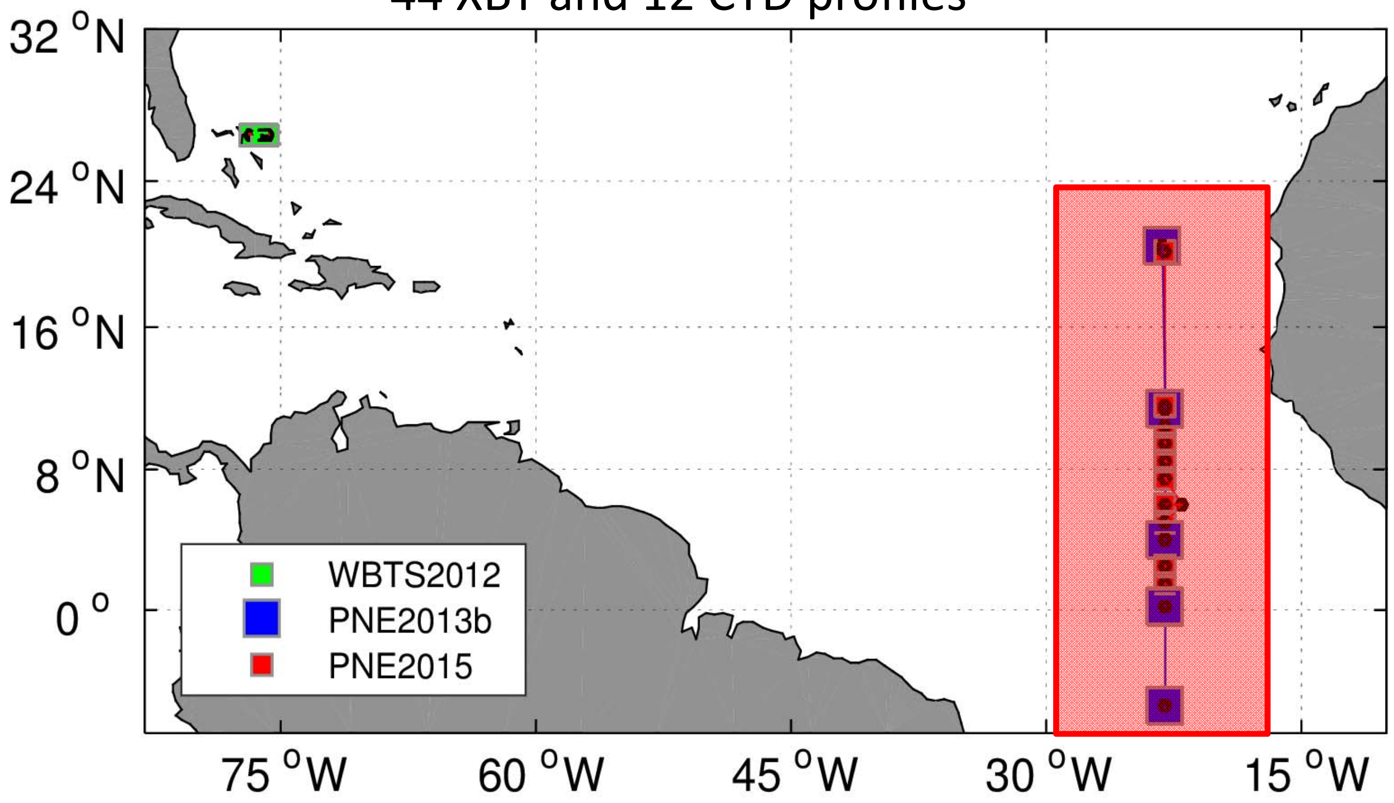
1. Wire imbalance
2. Manufactory thermistor calibration
3. Thermal time constant

3 probe types:

1. Standard
2. Experimental
3. Tight Weight Tolerance (TWT).

Side-by-side comparisons

PNE2015:
44 XBT and 12 CTD profiles



<u>The corrections</u>:

1. Manufactory thermistor calibration

<u>1 probe type</u>:

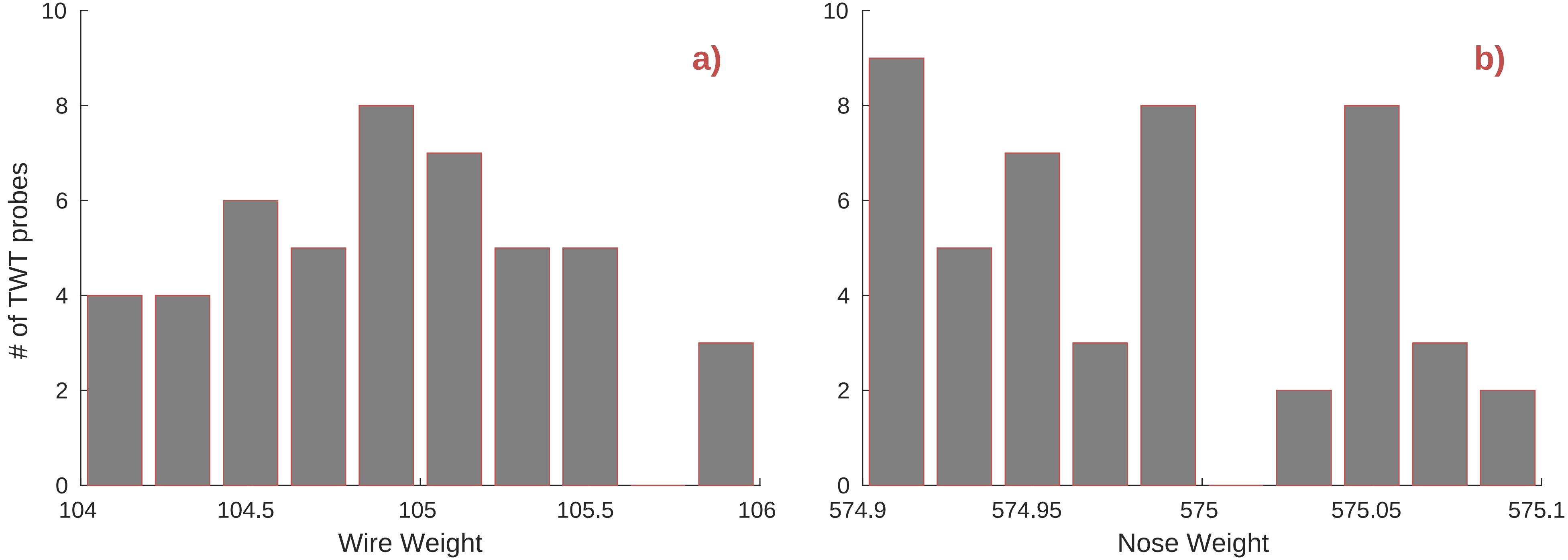
1. Enhanced XBT (Tight Weight Tolerance)

Experimental probe types

- **Standard**: Standard Deep Blue probes.
- **Experimental (screened thermistors):** The thermistors are selected to have a bath temperature within 0.05°C from measured temperature.
- **Tight weight Tolerance (TWT):** Screened thermistors and tighter control of the weight of the probe's nose and wire spool.
- **Enhanced XBT (EXBT):** Similar to Standard (with weight control). Actually we used standard weight instead.

Weight Tolerance

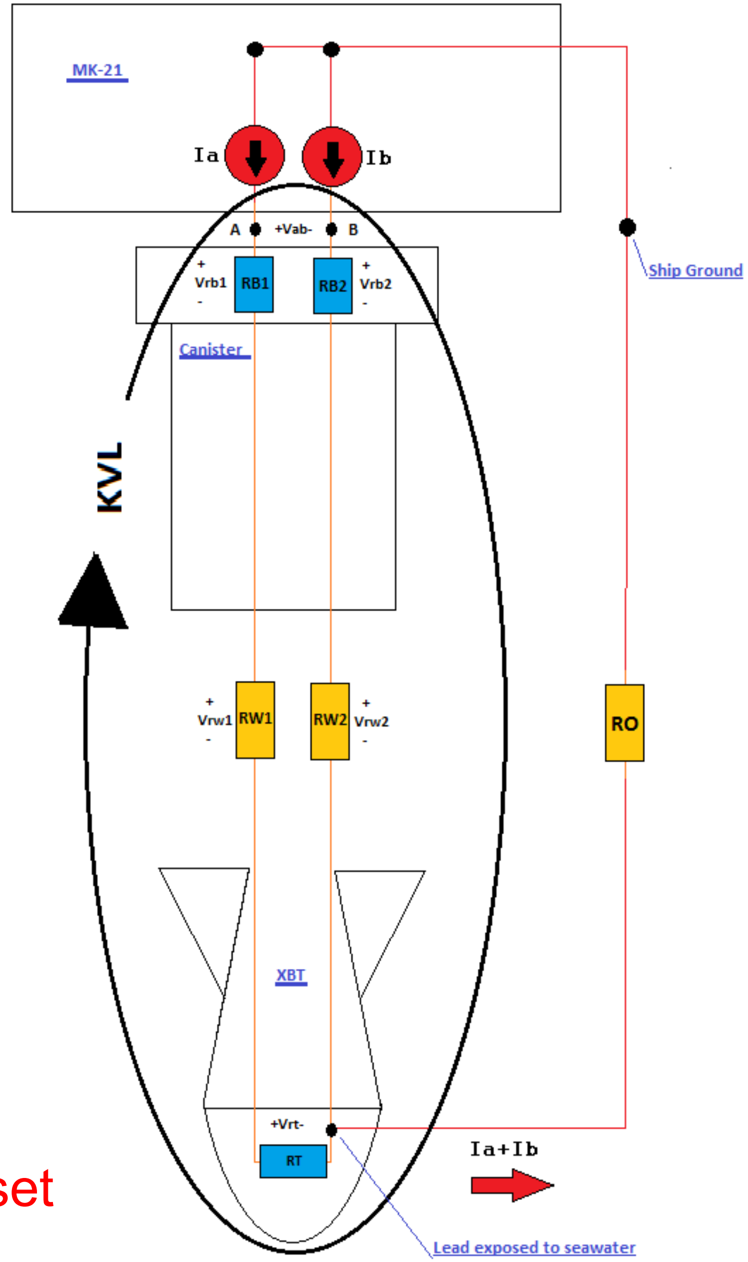
The weight of the probe is mostly defined by:
i) the zinc nose, ii) wire of the probe spool, and iii) plastic body.
The nominal probe weight in the air is 730.9 ± 2.5g (after body is about 51g).
Hypothesis: Reducing the nose and wire weight tolerances would reduce the depth error spread.



Tolerance reduced from ±2.5g to ±1.1g

Probe Wire Imbalance Correction

- The thermistor is located inside the probe's nose, connected to the canister by a two wire system.
- The wires have different resistances, which are balanced by the resistance located in the canister.
- The wire imbalance correction: **Measures the canister "residual" resistance between "A" and "B", and subtracts from the whole profile**



Why? The unbalanced resistance generates one offset in temperature.

Thermistor characterization

- A thermistor characterization is performed by recording the thermistor resistance at a (0°C, 15°C, 30°C) tightly controlled temperature bath.
- The serial number and error measured are labeled outside the launch canister.
- The ratio between the actual and bath resistance values for 15°C is used to correct the whole resistance (temperature) profile.

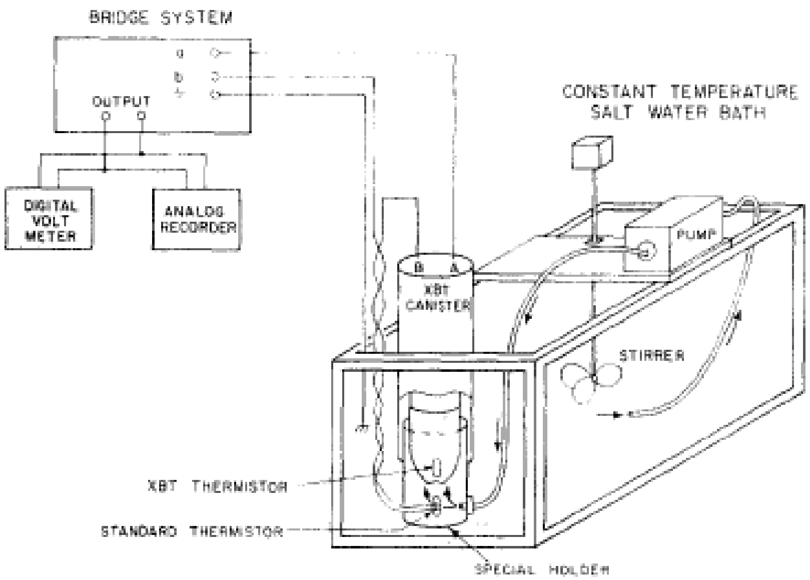


FIG. 1. Block diagram for XBT calibration bridge and bath system.

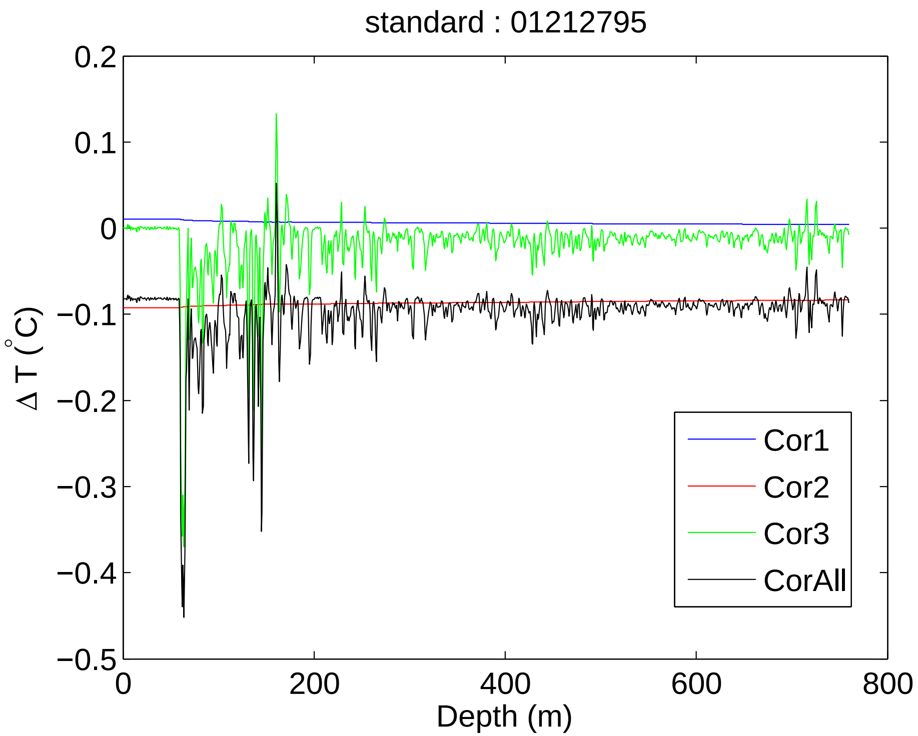
Georgi et al., 1980

Why? The conversion from resistance to temperature is based on a standard thermistor. Biased resistance would bias temperature.

Thermistor Time constant

The thermistor time constant (tau) is the time required to detect 63% of a step thermal signal. It ranges from tau = 0.6 to 0.13 s.
Shifts the temperature or resistance by tau = 0.13s though filtering (< 1 m).

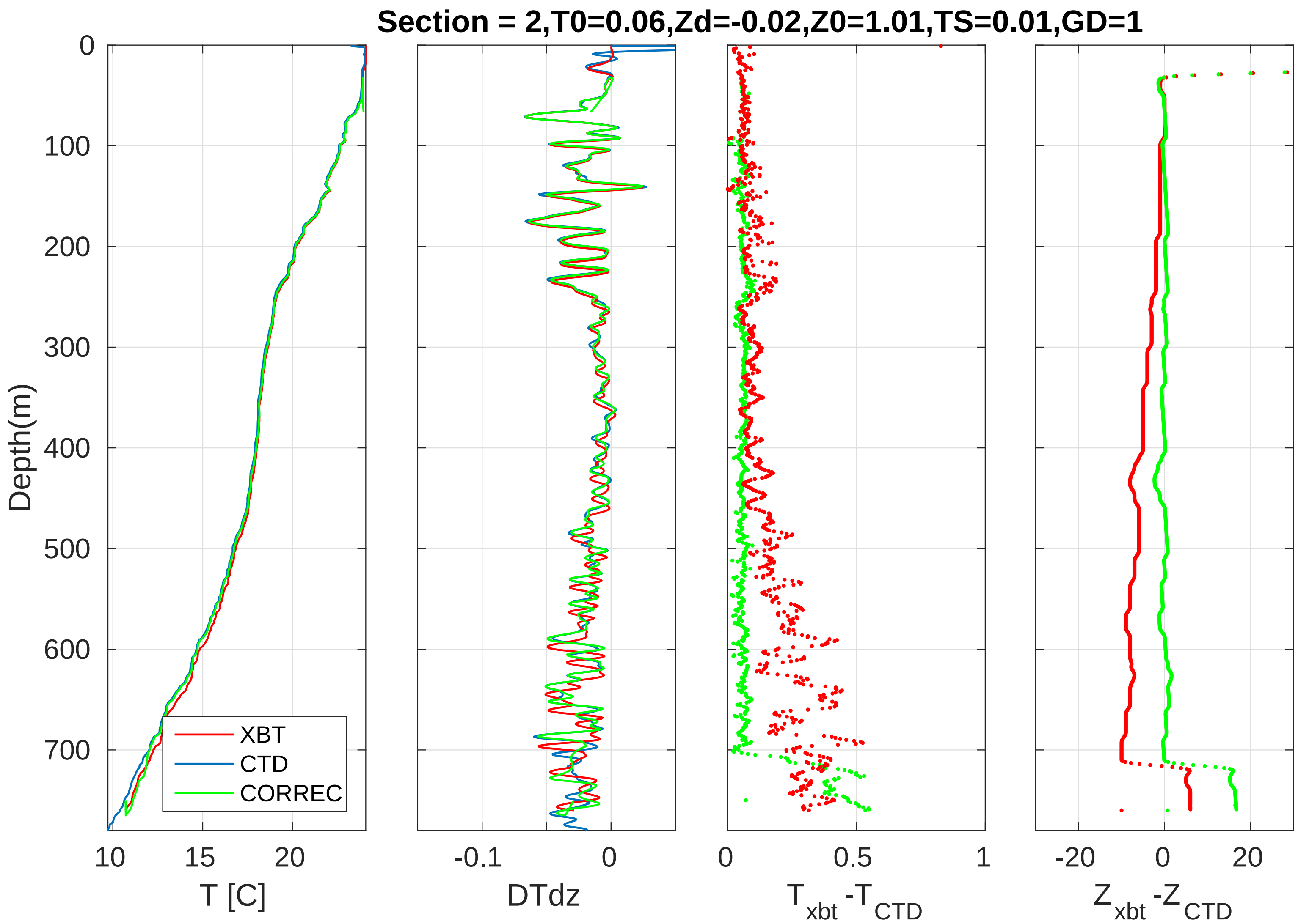
Why? The delayed time to detect a temperature gradient would produce both temperature and depth biases.



Correction 1: Wire imbalance
Correction 2: Thermistor calibration
Correction 3: Time constant
Correction 4: All of the above

Gradient Method

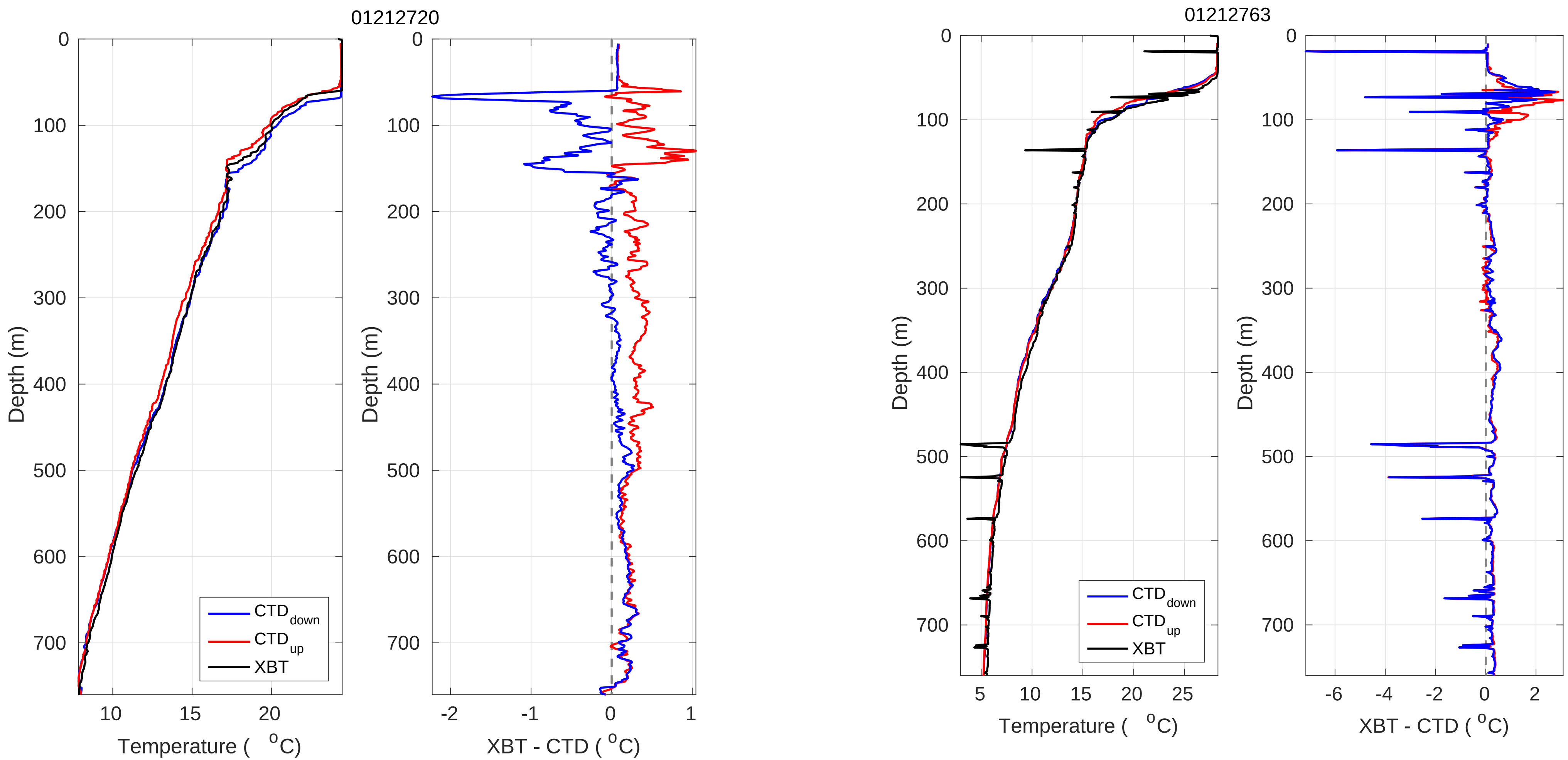
Gradient method: Used to detect depth errors. Compares temperature gradients between XBT and CTD, and locates the depth of the best match.



Error Parameters:

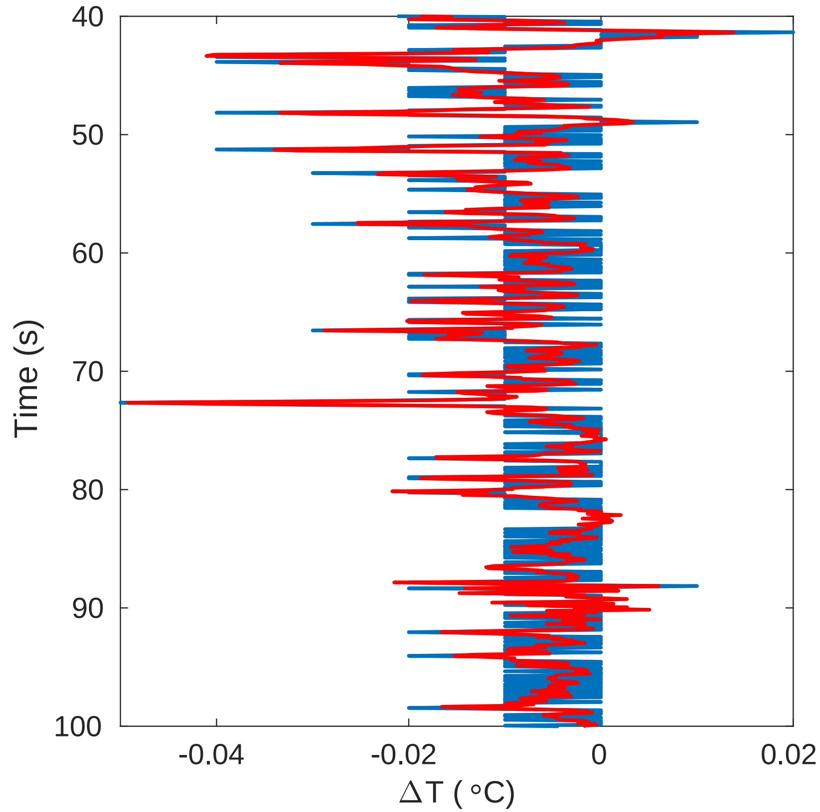
T_0 – Temperature offset (after depth error removal)
Z_0 – depth offset
Z_d – Depth linear bias

CTD x XBT comparison



Conductivity-Temperature-Depth (CTD) profiles collected with a Sea-Bird SBE 911, with a nominal accuracy of 0.001°C.

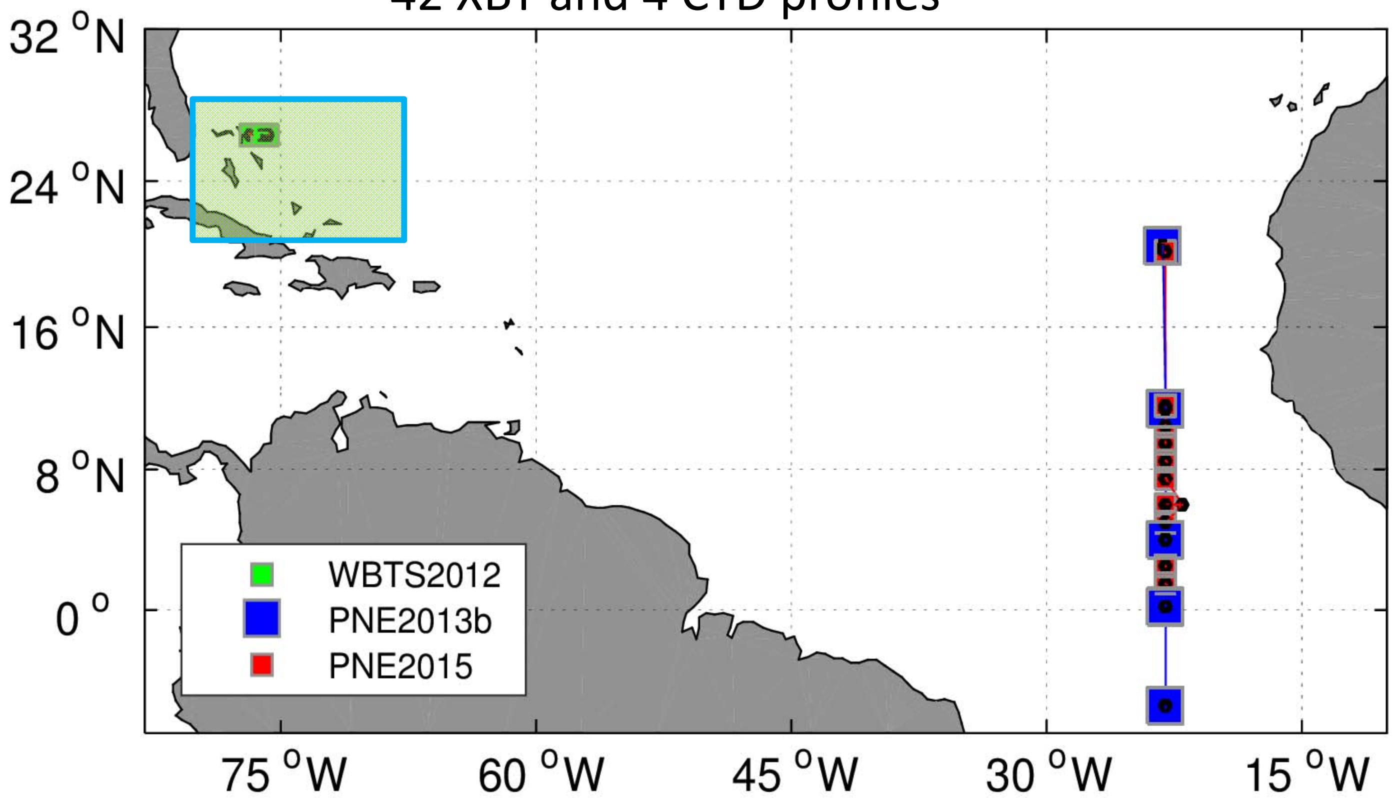
CTD x XBT comparison



- Vertical difference of the temperature gradient over time during the descent of one XBT profile. The resistance vs temperature equation was used using the full precision (red) and the truncated precision common to XBT files.

WBTS2012

WBTS2012:
42 XBT and 4 CTD profiles



<u>2 probe types</u>:
21 Standard
21 Experimental

Experimental Probes

The thermistors are selected for their thermistor physical length, width, and thickness variations.

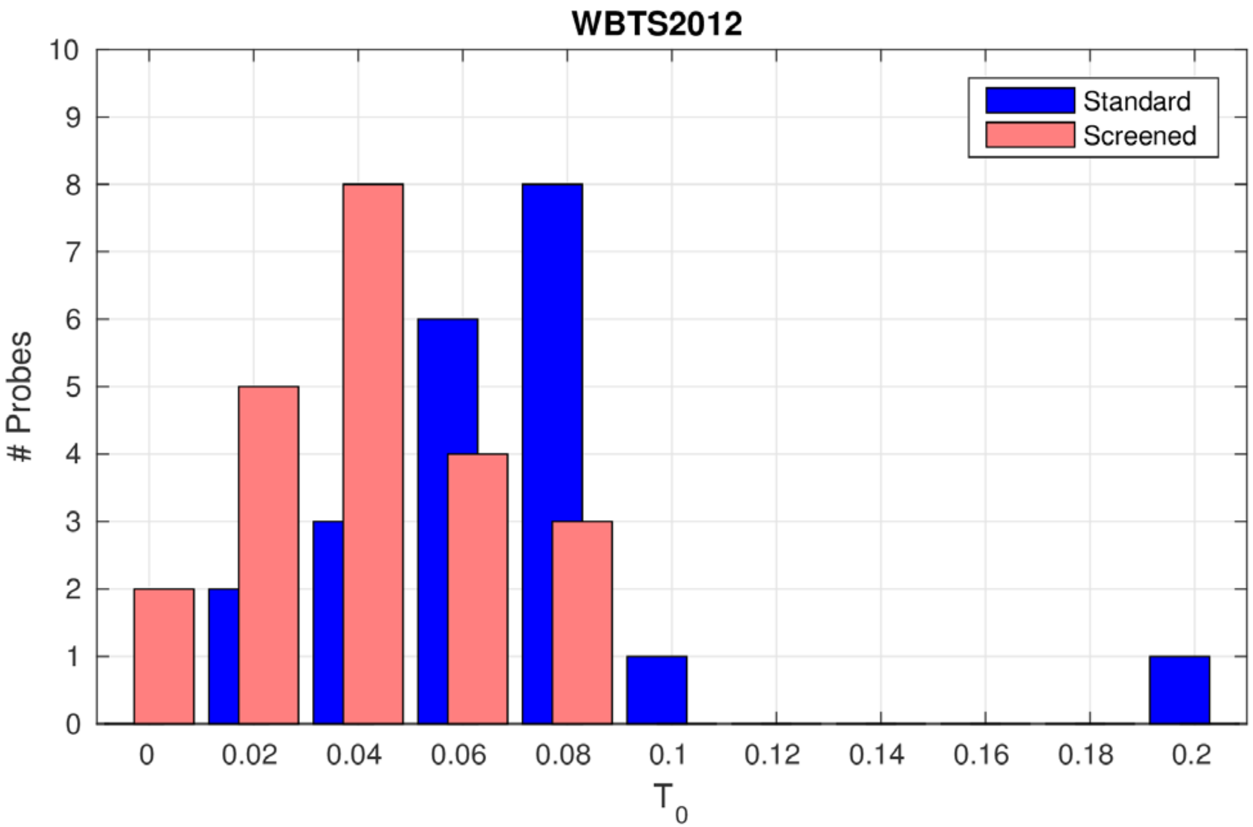


Figure: Histogram of temperature offset (°C) for the probes with standard and screened thermistors.

STANDARD

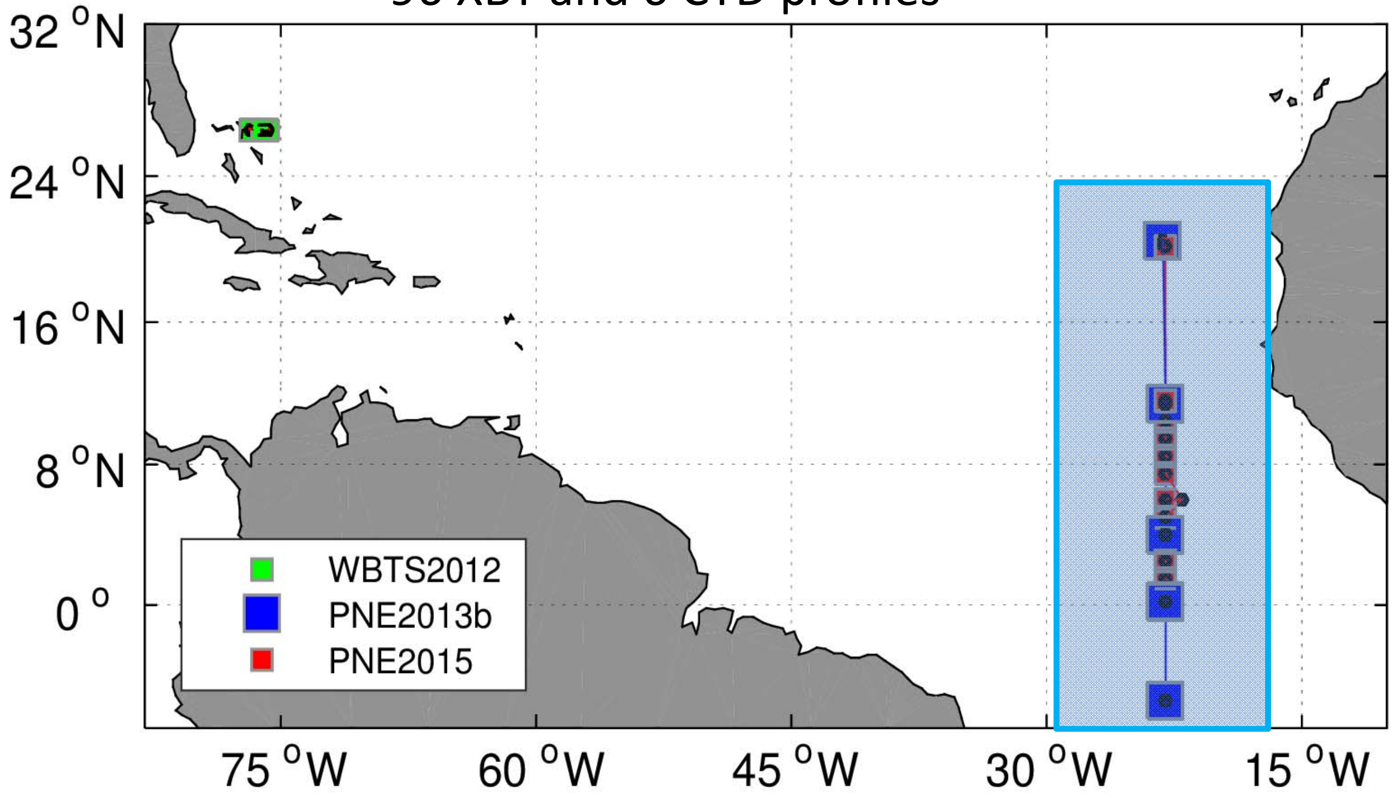
STANDARD
T0 = 0.08 ±0.03
Ts = 0.02± 0.03

SCREENED

SCREENED
T0 = 0.04 ±0.02
Ts = 0.02± 0.01

PNE2013b

PNE2013b:
96 XBT and 6 CTD profiles



The corrections:

1. Wire imbalance
2. Manufactory thermistor calibration
3. Thermal time constant

3 probe types:

20 Standard
23 Experimental
45 Tight Weight Tolerance (TWT).

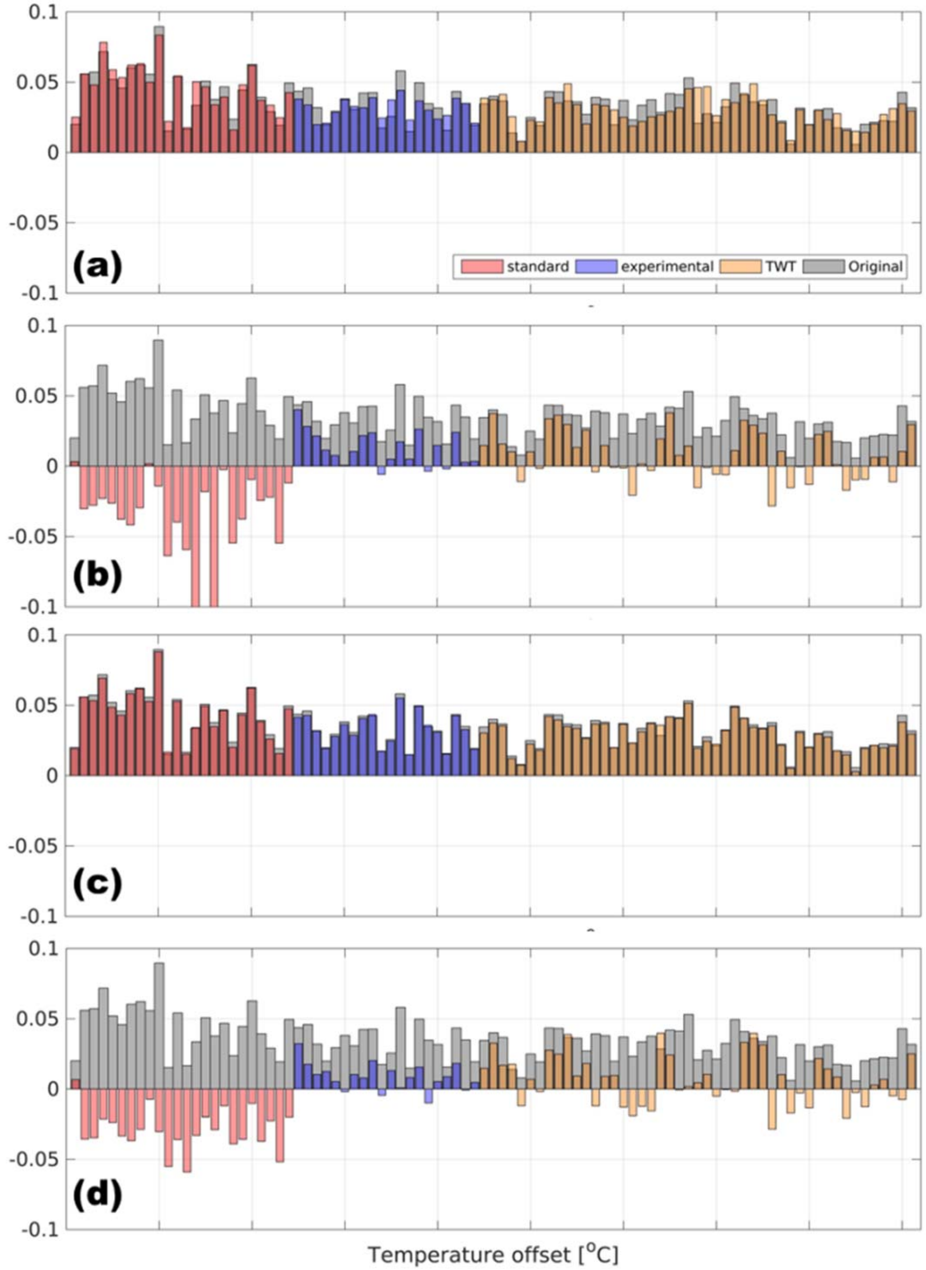
Temperature offset

Wire imbalance

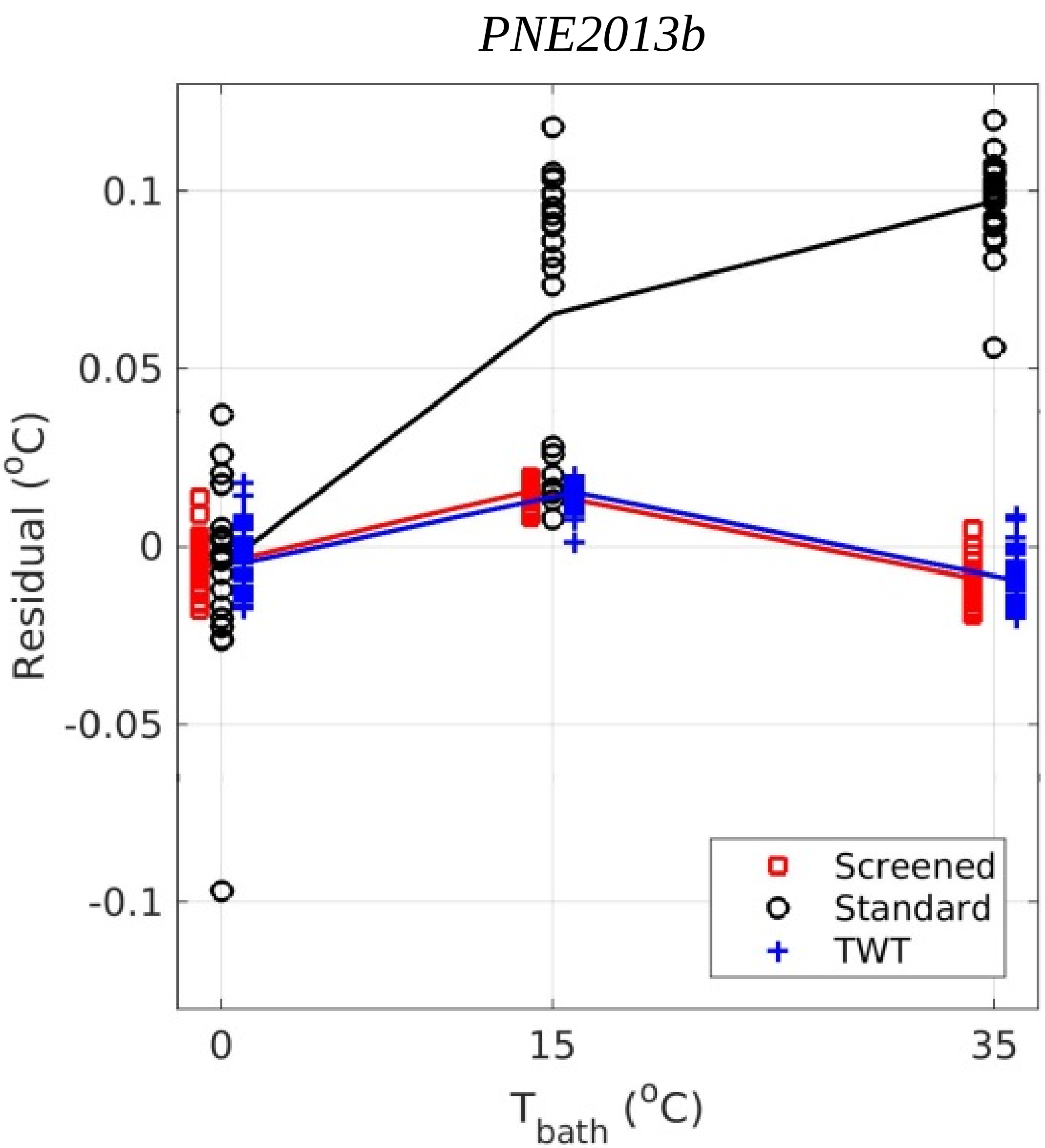
Therm. Cal.

Time constant

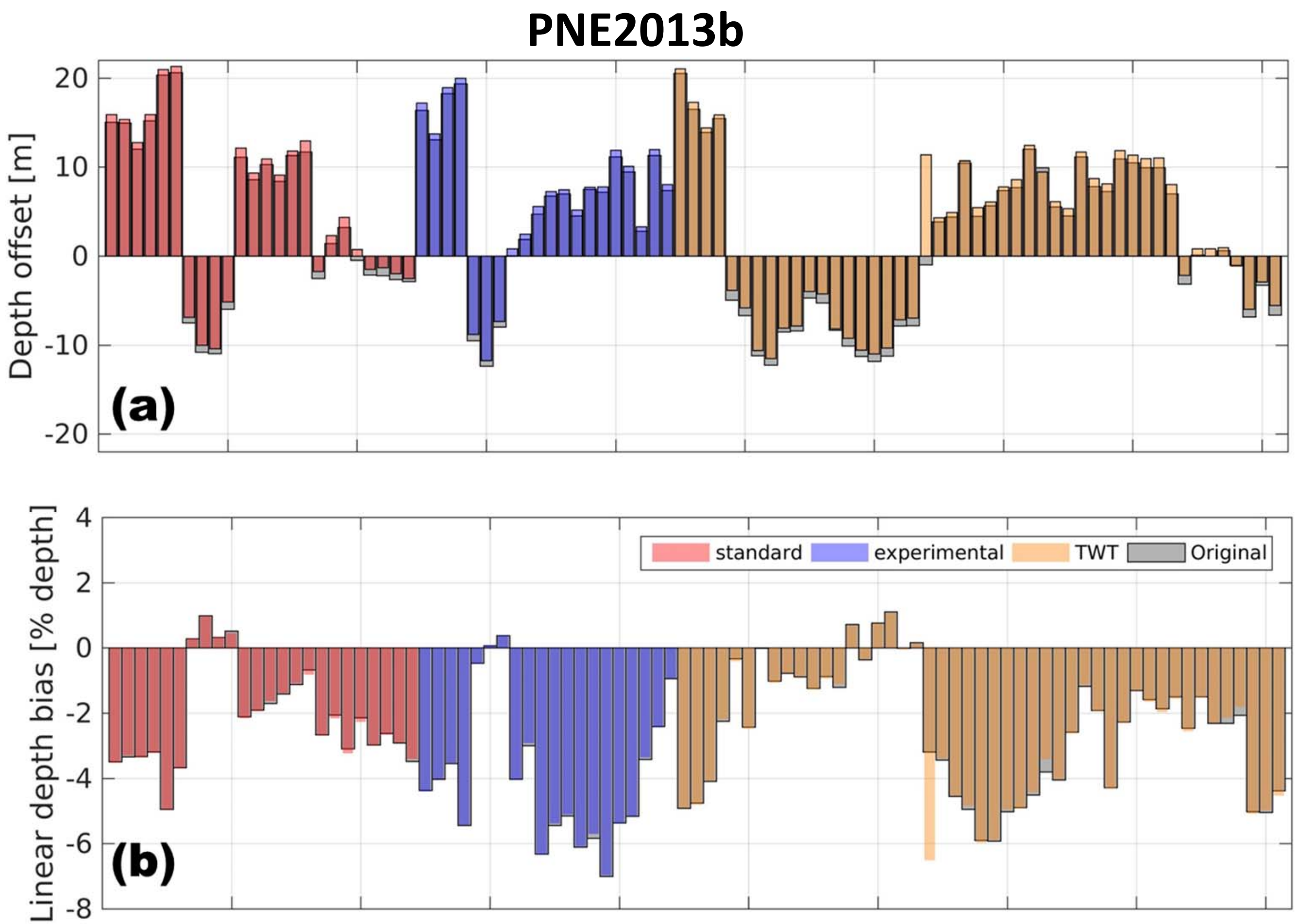
ALL



Thermistor calibration



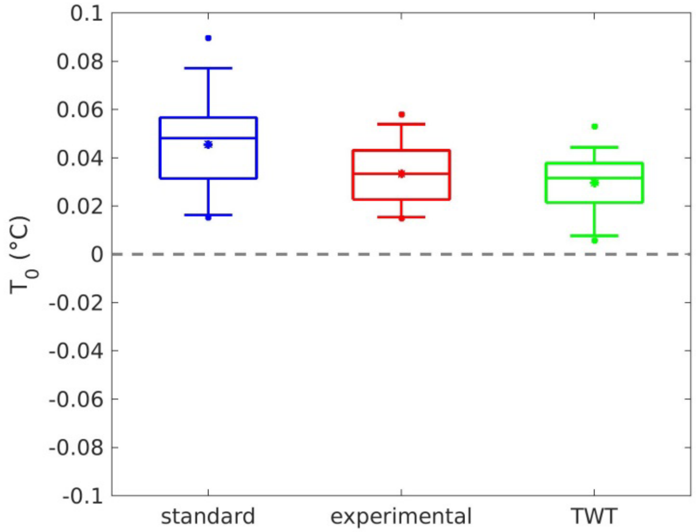
Depth biases

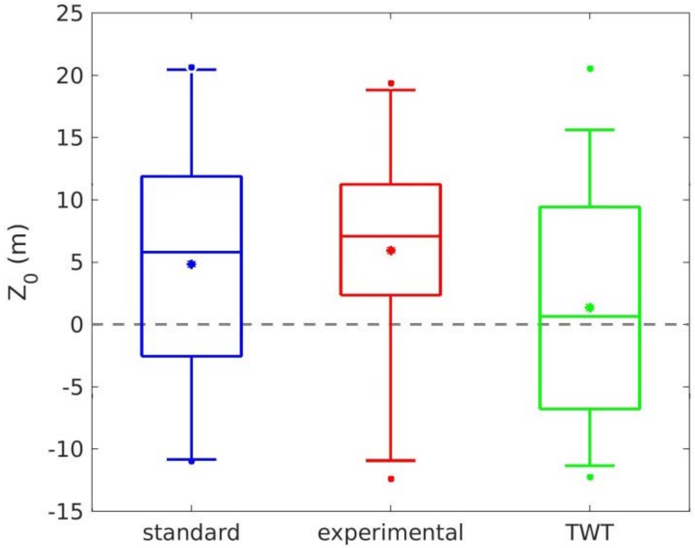


Colors: COR3 (Time constant)

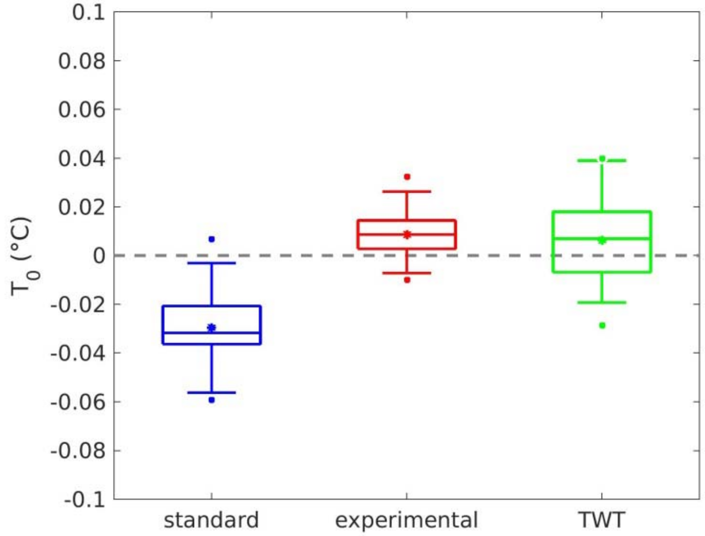
Summary for PNE2013b estimates

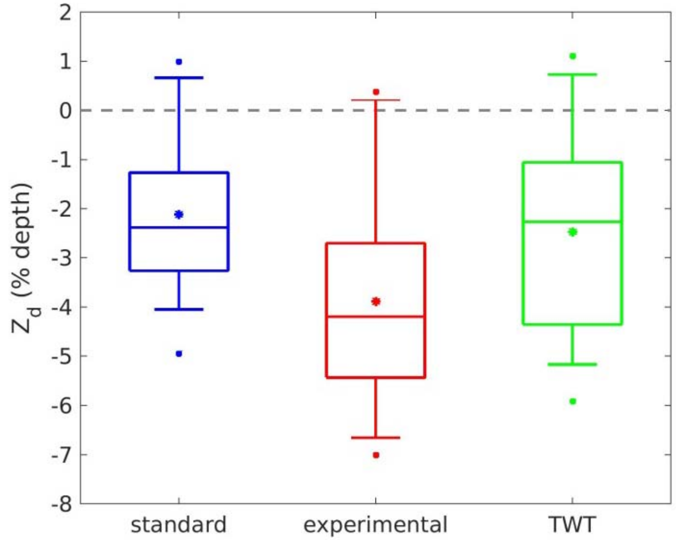
BEFORE CORRECTIONS

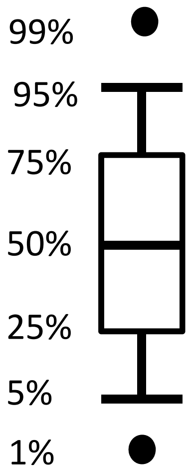




AFTER CORRECTIONS







Analysis of Variance

- ANOVA is typically used to learn the relative importance of different sources of variation in a dataset.

It is modelled as an additive data decomposition, as adding predictors to a linear model:

$$y_i = \mu + \gamma_j[i] + \delta_k[i] + \varepsilon_i$$

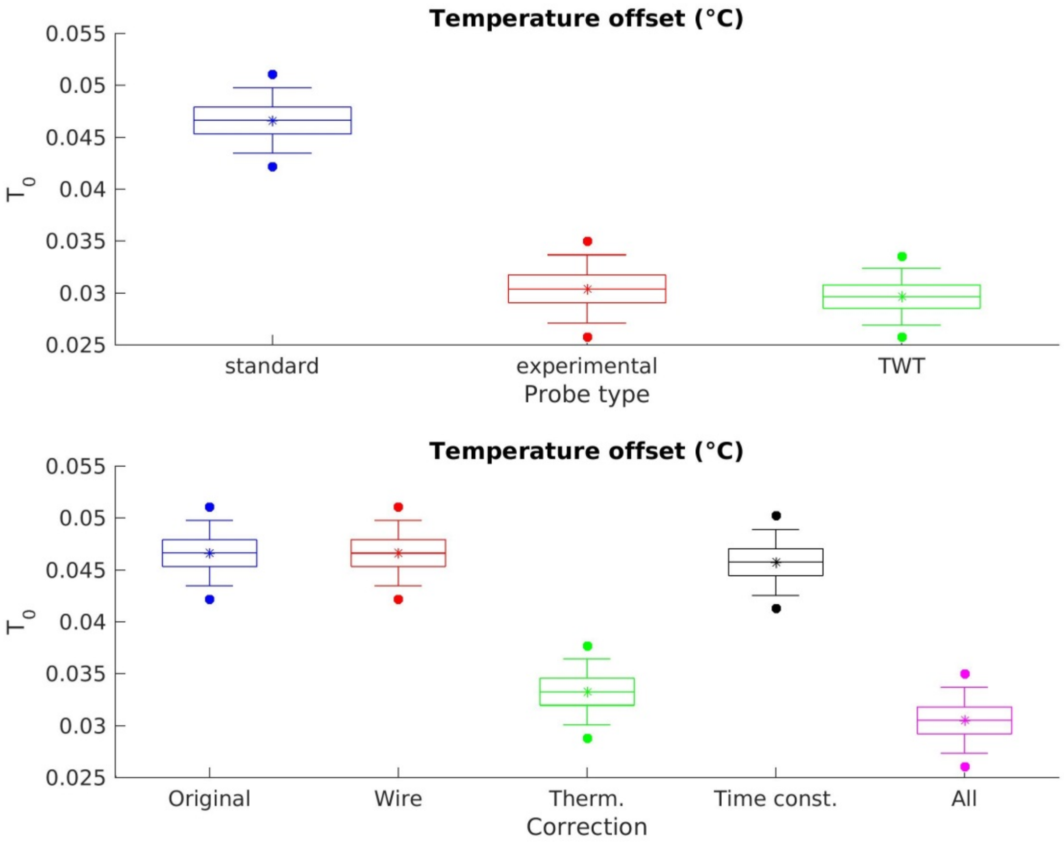
For *j* probes and *k* corrections given *i=1:n* samples.

- Here, we perform a Bayesian 2-way ANOVA, using as predictors the probe type and correction. This is performed using WinBUGS software.
- The mean difference between two populations and treatments can be retrieved, including a probability on error being greater than other.
- We will test 2 main hypothesis:

1 Is the corrected data different than the original?

2 How does each probe compare to the standard?

Temperature offset



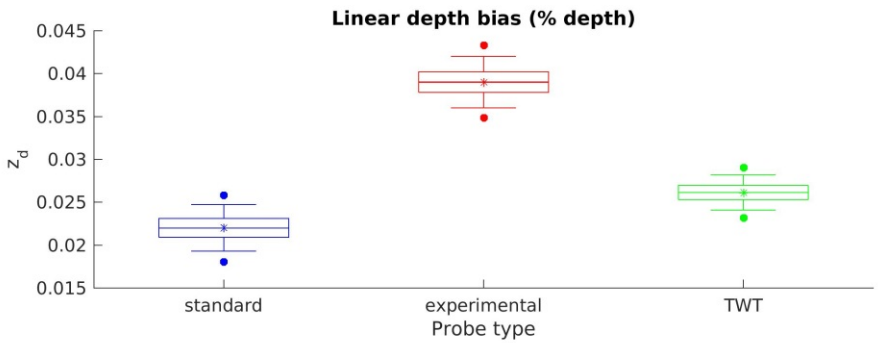
Absolute values $|T_0|$ are plotted

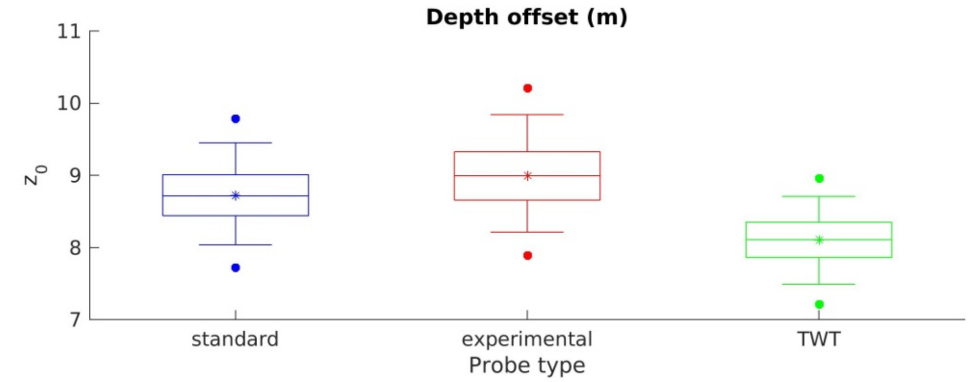
The TWT probes carried screened thermistors as well.

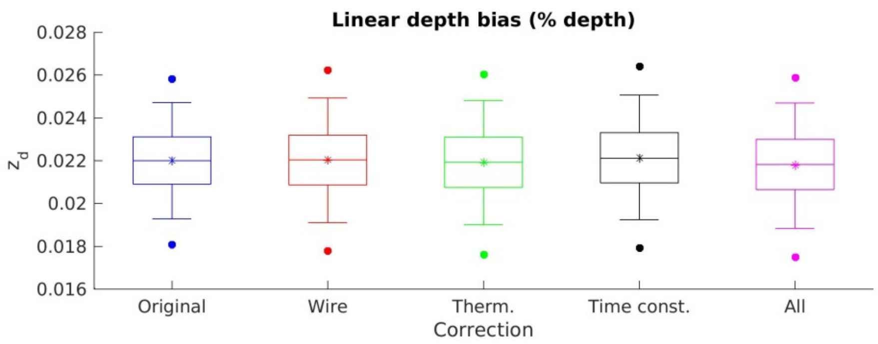
	Mean T0 (1E-2)	SErr
Standard	4.66	0.192
Experimental	**-1.62**	**0.198**
TWT	**-1.69**	**0.165**
COR1	0.0028	0.214
COR2	**-1.33**	**0.217**
COR3	-0.0851	0.215
COR4	**-1.61**	**0.221**

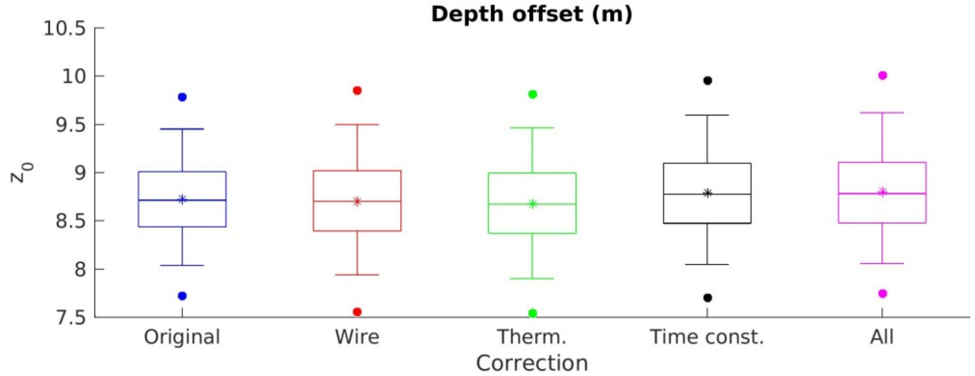
Significantly different than zero

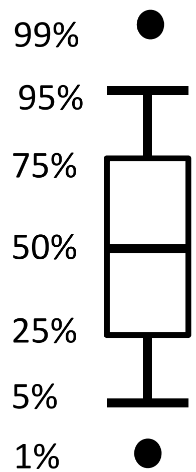
Depth biases





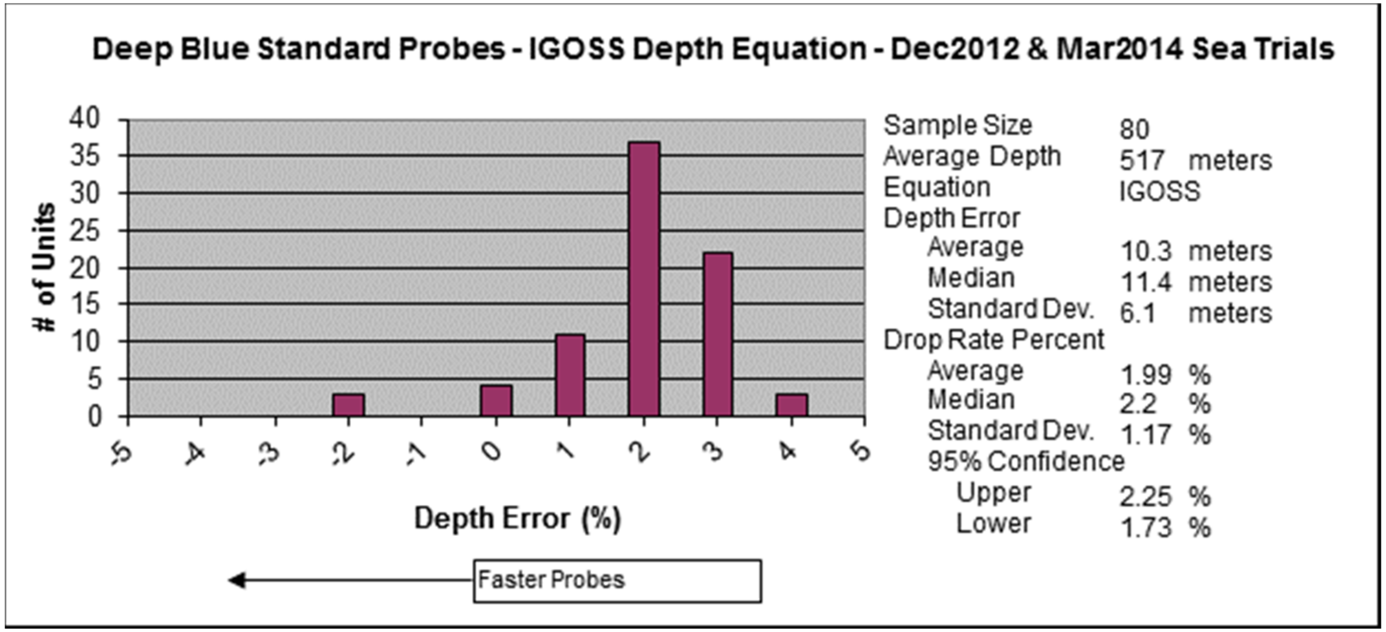


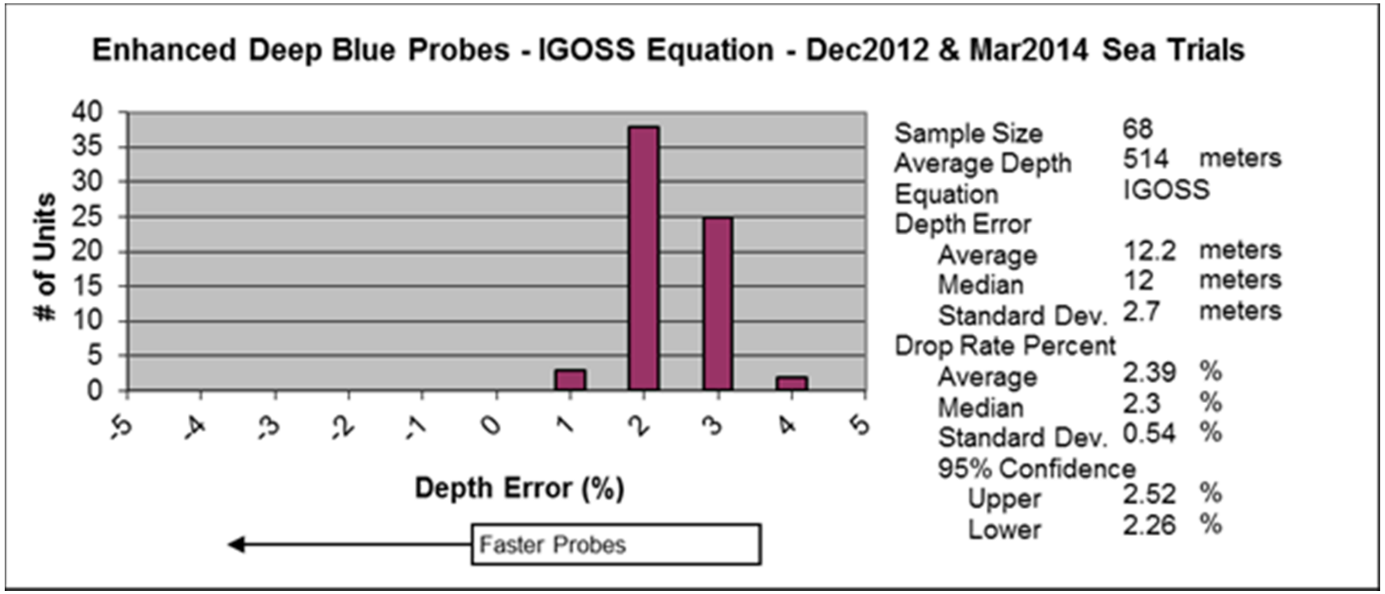




- TWT is not significantly different than Standard.
- TWT has lowest overall mean depth offset.

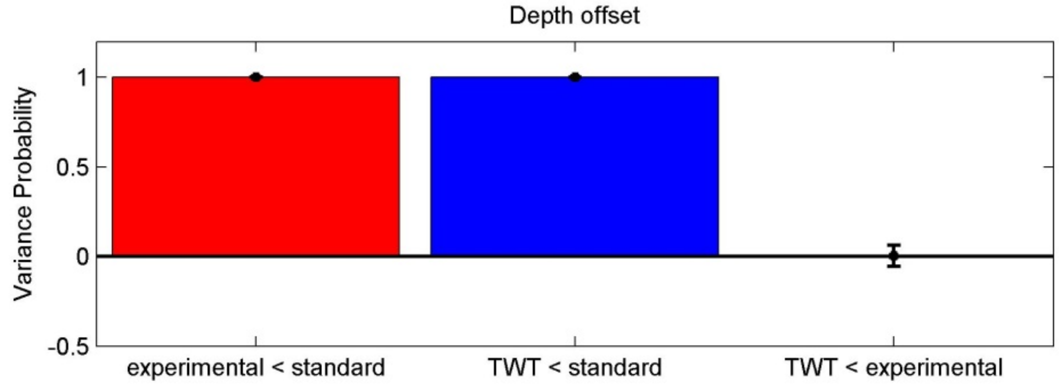
TWT tests from Sippican



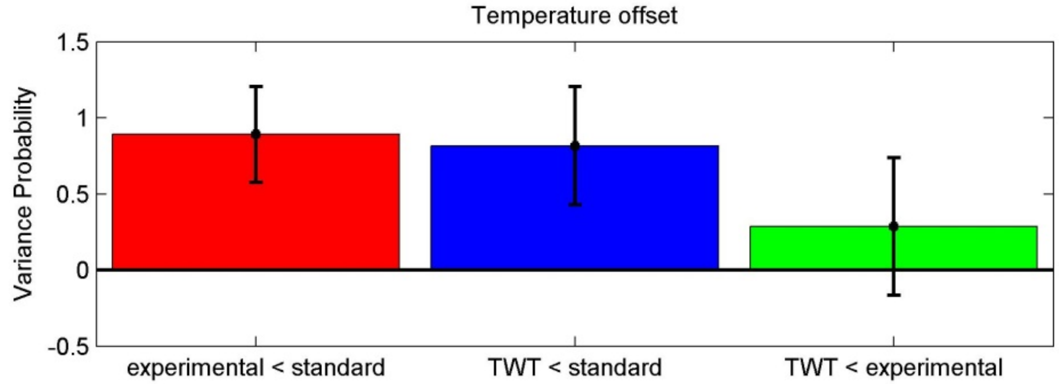


Variance comparison

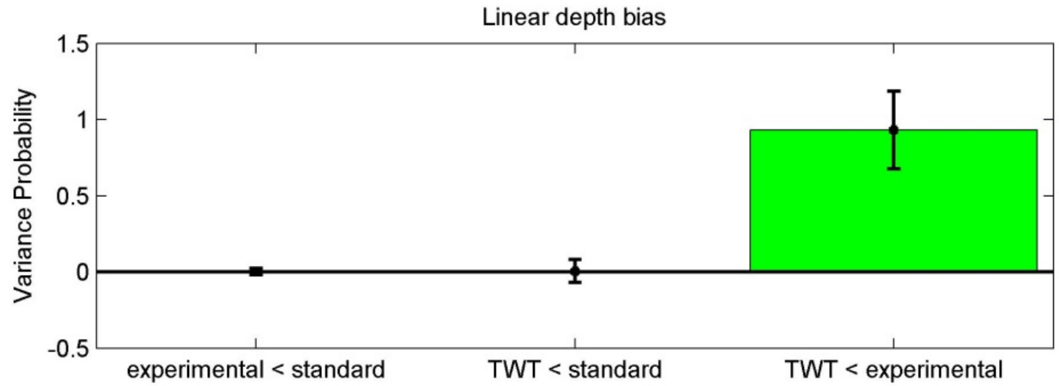
EXP,STD < TWT



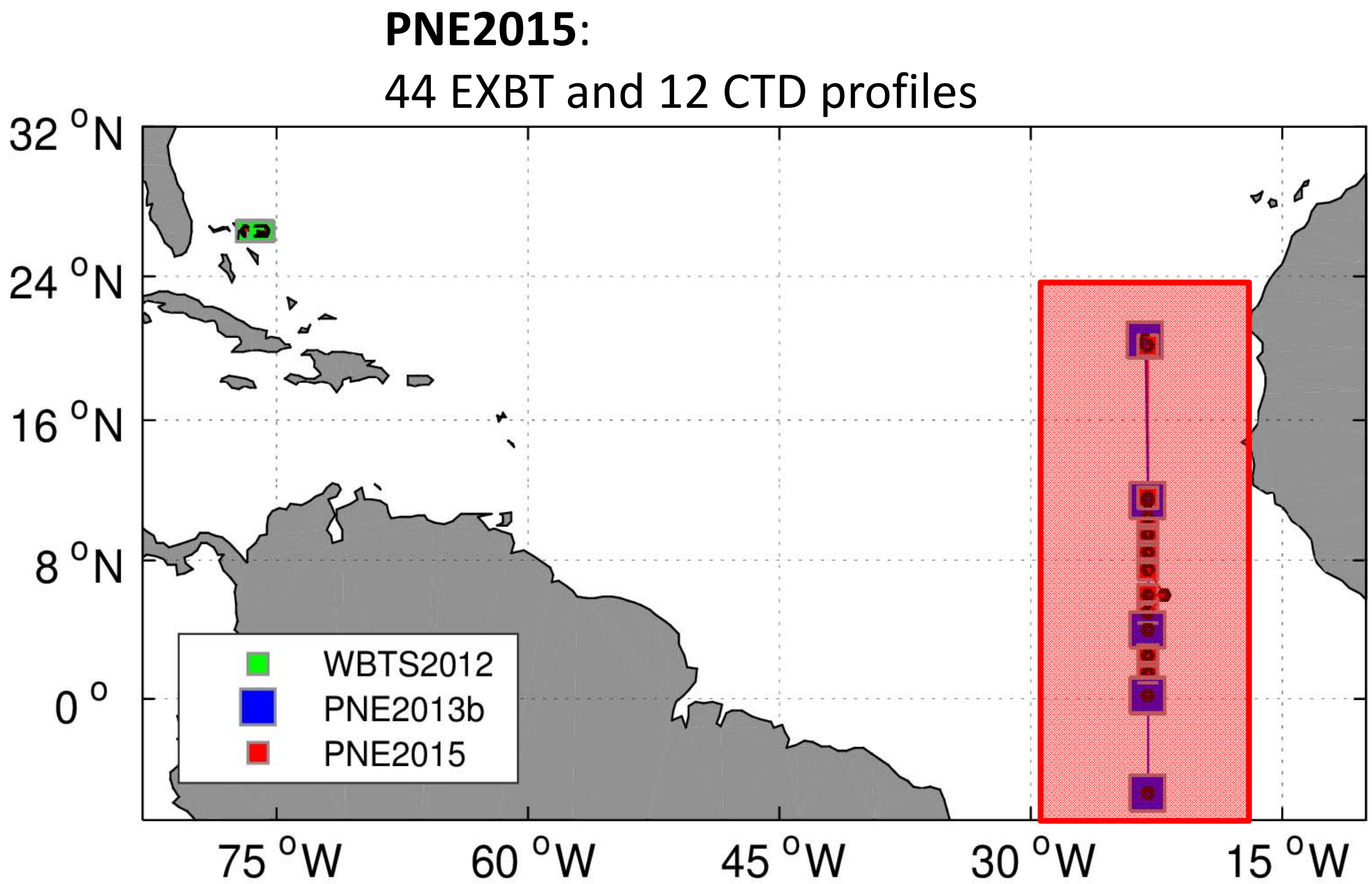
EXP,TWT < STD



STD < EXP,TWT



PNE2015



The corrections:

1. Manufactory thermistor calibration

1 probe type:

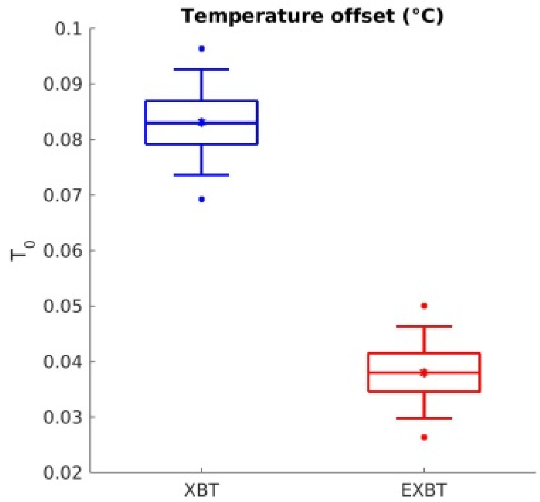
44 EXBTs (actually standard)

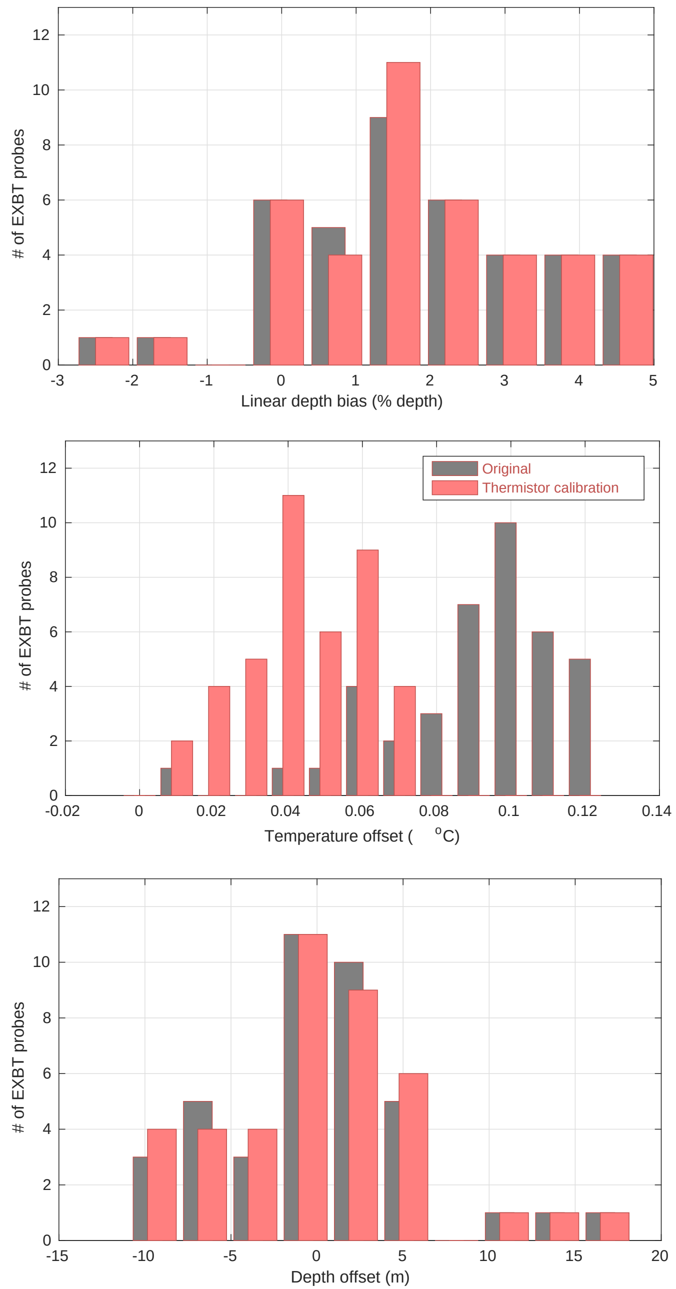
Giving the results obtained in the PNE2013b cruise

Enhanced XBT Probes

Results are similar to WBTS2012 cruise.

PNE2015	Standard	Therm. Calib.
Zd (% depth)	1.88 ± 1.7	
Z0 (m)	0.32 ± 6.1	
T0 (°C)	0.09 ± 0.02	0.04 ± 0.01



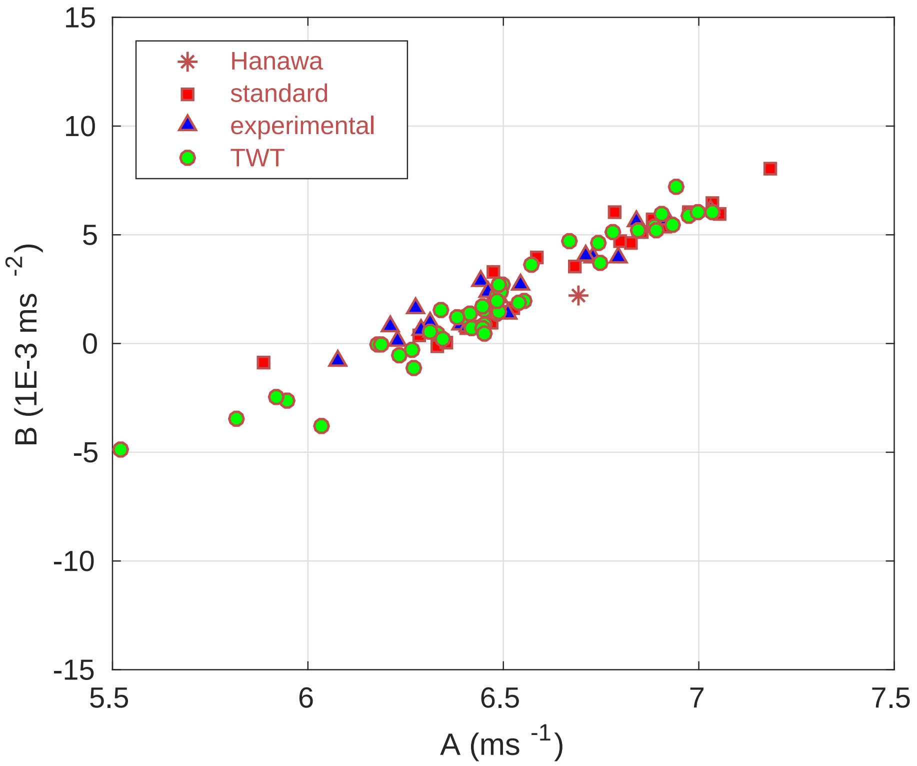


ANOVA results show that only the temperature offset differences are statistically significant.

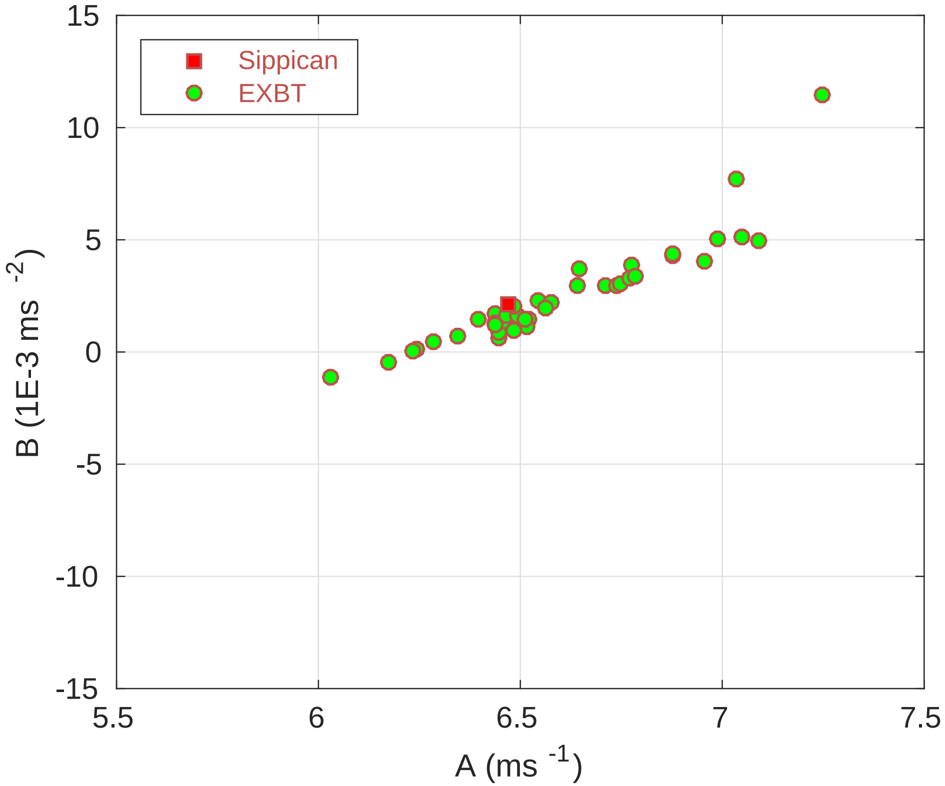
FRE coefficients

$Z(t) = At - Bt^2$

PNE2013b



PNE2015



The FRE coefficients can be retrieved as the gradient of the corrected depth of the profile.
The changes between the probes are not significant, even for TWT.

Summary of experiments

WBTS2012	Standard	experimental
T0(°C)	0.08 ±0.03	0.04 ±0.02

PNE2015	Standard	EXBT
Zd(% depth)	1.88 ± 1.7	
Z0(m)	0.32 ± 6.1	
T0(°C)	0.09 ± 0.02	0.04 ± 0.01

PNE2013b	Standard	experimental	TWT
Zd (%depth)	-2.1 ± 1.5	-3.9 ± 2.2	-2.5 ± 1.9
Z0 (m)	4.8 ± 9.5	5.9 ± 8.6	1.4 ± 8.9
T0 (°C)	0.05 ± 0.02	0.03 ± 0.01	0.03 ± 0.01
T0 (ALLCOR)	-0.03 ± 0.02	0.009 ± 0.01	0.006 ± 0.02

Conclusions (i): Corrections

Thermal Time Constant

- Did not produce significant changes in temperature and (<1m) in depth.
- The probe may need ~0.6s (4m) before a probe detects a step signal (e.g., Kizu and Hanawa, 2002, Reseghetti et al. 2007).

Conclusions (i): Corrections

Wire Imbalance:

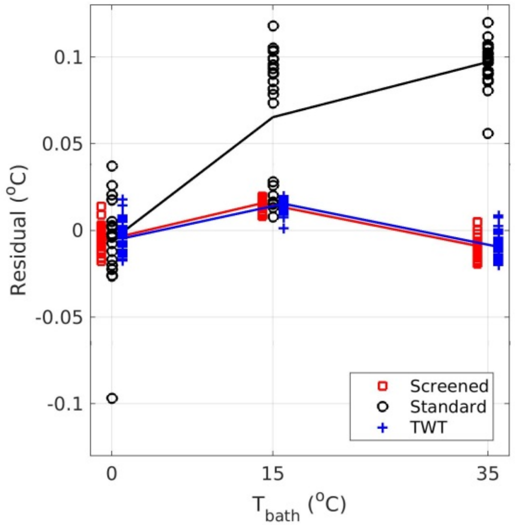
- Did not produce significant changes in temperature. Indeed, resistance residuals due to imbalanced wire resistance are < 1% of the resistance reading in the profile.

Conclusions (i): Corrections

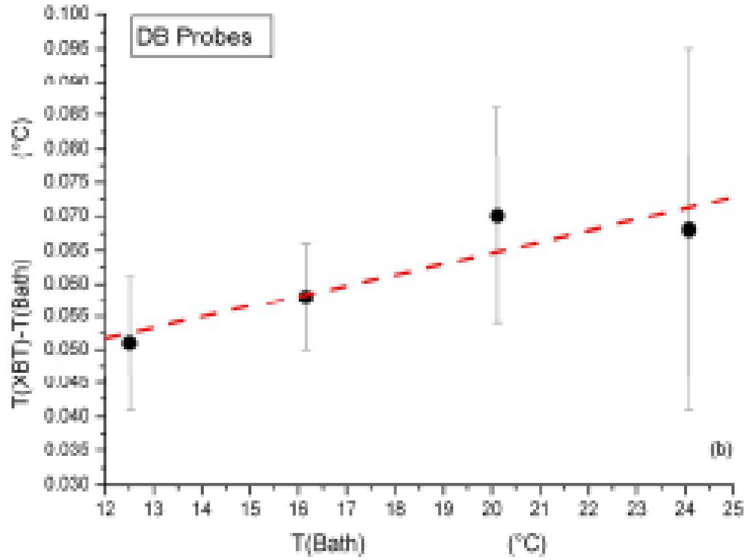
Thermistor calibration

- Has the strongest effect. After its application, the temperature offset is less biased towards positive values. Constrain $T_0 <$ 0.04 °C for experimental probes.
- May overcorrect the standard probe. In this case a linear calibration may be necessary.

PNE2013b



Reseghetti et al., 2007



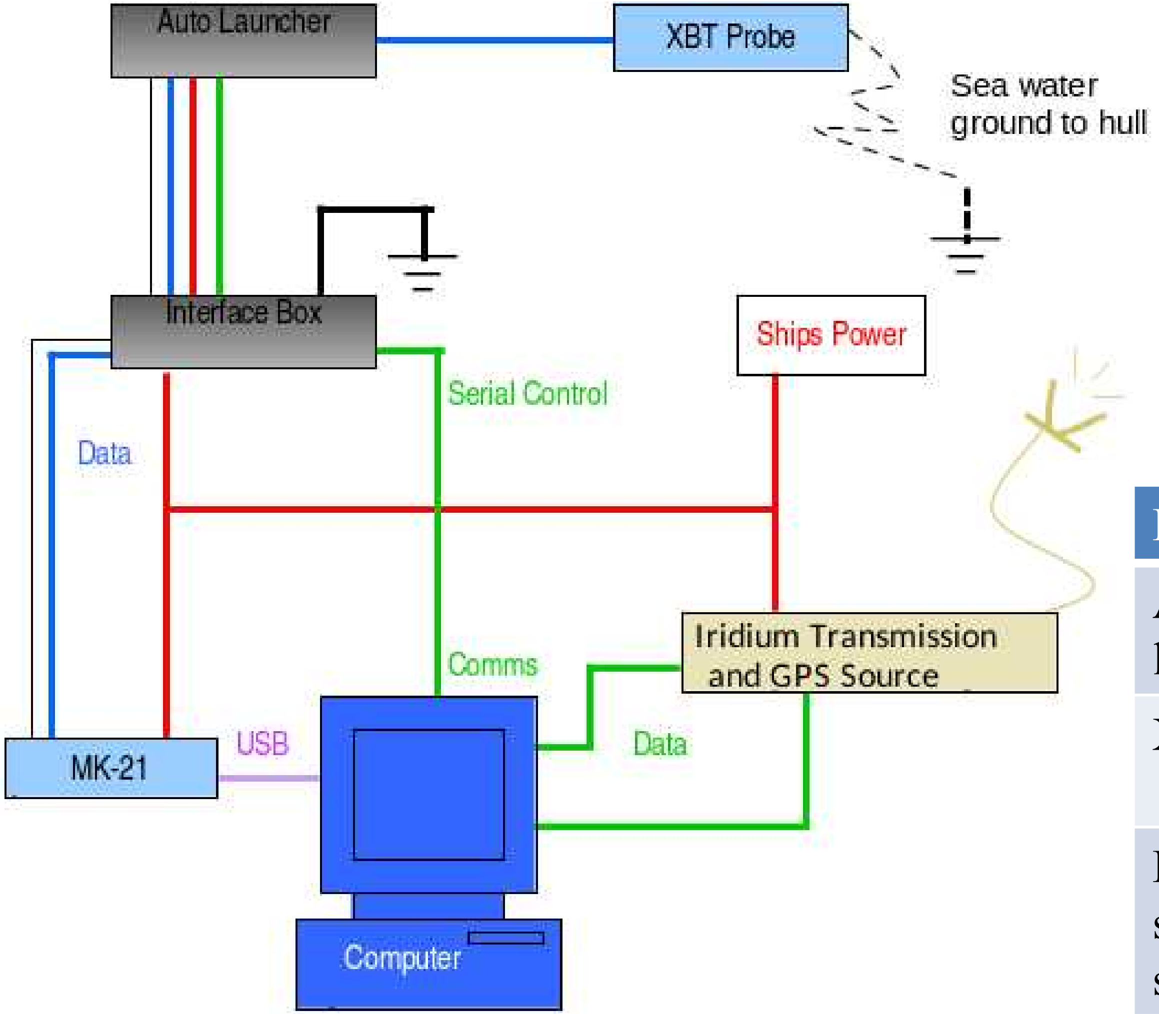
Conclusions (ii): Probes

- **Standard:** Higher $|T_0| < 0.1°C$ than other probes. In PNE2013b overshoot thermistor calibration (left over effect).
- **Experimental**: Shows reduction in T_0 over Standard probes in the WBTS2012 and PNE2013b experiments. Has to be used with thermistor calibration to allow $|T_0| < 0.04°C$.
- **TWT**: Shows same improvement as experimental in T_0. This is because the TWT probes have been screened too. Did not show considerable improvement in depth biases.
- **EXBT**: Shows reduction in T_0 only after thermistor calibration. Needs to include thermistor screening too.

- **Pressure switches and improved parameterization of FRE may be needed to improve depth accuracy.**
- **We will perform more sea trials with EXBT probes to have a more statistically significant population.**

Thank you

The XBT system



Parts	Function
Auto/hand - launcher	Drops the probe from the ship
XBT probe	Includes resistor sensitive to temperature
Data acquisition system + software	Records, processes, and interprets the data the probe collects.