NOAA Technical Memorandum OAR PMEL-128

CALIBRATION PROCEDURES AND INSTRUMENTAL ACCURACY ESTIMATES OF NEXT GENERATION ATLAS WATER TEMPERATURE AND PRESSURE MEASUREMENTS

H.P. Freitag[1]
T.A. Sawatzky[2]
K.B. Ronnholm[3]
M.J. McPhaden[1]

[1]Pacific Marine Environmental Laboratory
Seattle, WA

[2]Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
University of Washington, Seattle, WA

[3]ITS Corporation
Bremerton, WA

Pacific Marine Environmental Laboratory
Seattle, WA
August 2005

UNITED STATES DEPARTMENT OF COMMERCE

Carlos M. Gutierez
Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

VADM Conrad C. Lautenbacher, Jr.
Under Secretary for Oceans and Atmosphere/Administrator

Office of Oceanic and Atmospheric Research

Richard D. Rosen
Assistant Administrator

NOTICE

Contribution No. 2817 from NOAA/Pacific Marine Environmental Laboratory
Contribution No. 1142 from Joint Institute for the Study of the Atmosphere and Ocean (JISAO)

For sale by the National Technical Information Service, 5285 Port Royal Road
Springfield, VA 22161

Contents

List of Figures

List of Tables

Calibration Procedures and Instrumental Accuracy Estimates of Next Generation ATLAS Water Temperature and Pressure Measurements

Freitag, H.P.[1], T.A. Sawatzky[2], K.B. Ronnholm[3], and M.J. McPhaden[1]

Abstract. This report describes instrumentation that measures and records water temperature and pressure from taut-line surface moorings of the TAO/TRITON Array in the tropical Pacific and the PIRATA Array in the tropical Atlantic, with primary focus on calibration methods. The analysis includes estimates of calibration repeatability, calibration accuracy, initial instrumental accuracy, and calibration drift over time. The overall accuracy of temperature (pressure) measurements made from these moorings is estimated to be ±0.0181°C (±0.98 dbar).

1. Introduction

The Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) array of moored buoys spans the tropical Pacific Ocean and is a major in situ component of the El Niño/Southern Oscillation (ENSO) Observing System, the Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS) (McPhaden *et al.*, 1998). A similar, but smaller scale array, the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) spans the tropical Atlantic (Servain *et al.*, 1998). The majority of TAO/TRITON and all PIRATA sites are occupied by Autonomous Temperature Line Acquisition System (ATLAS) moorings (Hayes *et al.*, 1991), which are designed, manufactured, and maintained by the National Oceanic and Atmospheric Administration's (NOAA's) Pacific Marine Environmental Laboratory (PMEL). Standard measurements from all ATLAS moorings include wind speed and direction (WSD), air temperature (AT), relative humidity (RH), sea surface temperature (SST), and subsurface temperatures (T) down to 500 m depth. Additional measurements at all PIRATA moorings and selected TAO/TRITON sites include rainfall, downwelling shortwave radiation (SWR), and conductivity. In addition, ocean currents, downwelling, longwave radiation, and barometric pressure are measured at selected TAO/TRITON sites.

Water temperature measurements on TAO and PIRATA moorings are presently made with NextGeneration (NX) ATLAS modules. This memorandum describes the calibration procedures for these instruments, and quantifies their calibration accuracy and drift characteristics. The original ATLAS systems (aka Standard ATLAS), which were used from the beginning of the TAO Array in 1984 until replaced by NX ATLAS systems over the period 1996 to 2001, are described by Freitag *et al.* (1994).

[1]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115

[2]Formerly at Joint Institute for the Study of Atmosphere and Ocean (JISAO), University of Washington, Box 354235, Seattle, WA 98195-6349

[3]ITS Corporation, 4040 Wheaton Way, Suite 215, Bremerton, WA 98310

2. NX ATLAS Temperature Modules

NX ATLAS modules may be configured to measure temperature alone (T modules), temperature and conductivity (TC modules), or temperature and water pressure (TP modules), and may also interface with Sontek Argonaut-MD Doppler current meters (TV and TCV modules). Daily mean data and hourly SST are telemetered to shore in real time via NOAA satellites and Service Argos. High temporal resolution (typically 10-min sample rate) data are stored internally, and retrieved when the moorings are recovered. Modules placed nominally at the surface (1-m depth, SST or SSC modules) provide daily mean and hourly data via direct cable. Modules placed deeper in the water column (Table 1) provide daily mean data via inductive modem along the mooring line.

Sea surface conductivity (SSC) is presently measured at 1 m on about half of the ATLAS moorings in the Pacific Ocean (TAO) and on all ATLAS moorings in the Atlantic (PIRATA). PIRATA moorings also measure subsurface conductivity at three depths (20 m, 40 m, and 120 m). For specific research studies, such as the Eastern Pacific Investigation of Climate (EPIC), TAO moorings have been deployed with up to six subsurface TC modules.

TP modules are typically deployed on ATLAS moorings at 300 m and 500 m only. Water pressure measured at these depths is used as a data quality diagnostic, indicating times when the module's depth is significantly different from their nominal depth. The design of the taut-line ATLAS mooring is such that naturally occurring variations in sensor depth are greatest at the deeper modules.

NX ATLAS modules were designed by PMEL's Engineering Development Division (EDD) and are assembled and maintained at PMEL. Temperature is measured by a model 46006 thermistor from Yellow Springs Instruments of Dayton, OH. The manufacturer's nominal sensor accuracy is 0.2°C. Pressure is measured by a model 211-30-660-01 pressure transducer from Paine Electronics, LLC, of Seattle, WA. The manufacturer's nominal sensor accuracy is 0.25% of full scale (1000 psi) or 2.5 psi (1.7 dbar. 1 psi = 0.68947 dbar. Pressure in dbar is equivalent to depth in meters to within 1%). When coupled with PMEL digital electronics temperature sample resolution is 0.001°C or less and pressure resolution is 0.03 psi (0.02 dbar).

When first introduced, NX ATLAS modules had thermistors within the plastic pressure case. It was found that temperature measurements from instruments placed within 75 m of the sea surface could have positive daytime biases of up to order 0.1°C due to solar heating (A'Hearn *et al.*, 2002).

Table 1: Standard depths (meters below sea surface) for temperature modules in TAO and PIRATA moored arrays. The sensor depths were chosen to optimally define the thermocline structure.

Western Pacific (165°E to 155°W)	1	25	50	75	100	125	150	200	250	300	500
Eastern and Central Pacific (140°W to 95°W) and Atlantic	1	20	40	60	80	100	120	140	180	300	500

Instruments deployed directly below the buoy at 1-m depth were not biased because they were shaded by the buoy. Since 2001 all NX ATLAS modules have been modified to reduce solar heating to 0.01°C or less by shielding the thermistor from direct sunlight and improving the transfer of heat between the thermistor and sea water.

3. NX ATLAS Module Calibration Procedures

All NX ATLAS modules are calibrated before and after (typically 1-year) deployments at sea. Most temperature calibrations are performed at PMEL. Modules that measure conductivity (SSC, TC, and TCV) are calibrated for both temperature and conductivity by Sea-Bird Electronics, Inc. (SBE), in Bellevue, WA. The TAO temperature calibration facility presently has three baths; the first two (aka Bath1 and Bath2, present before the development of the NX ATLAS modules) are model 5010 fluid baths manufactured by Guildline Instruments, Inc. of Lake Mary, FL, and a third (Bath3, installed at PMEL in 1999) was manufactured by SBE. Calibrations in Bath1 and Bath2 typically contain nine NX modules. Bath3, which is larger and similar to that used by Sea-Bird for their in-house T and C calibrations, typically contains 18 NX modules. PMEL baths use bath standard sensors manufactured by SBE (model SBE03), which are in turn calibrated annually by the manufacturer. Model SBE03 frequency outputs are measured using a model HP3457A Multimeter manufactured by the Hewlett Packard Company. More information on the calibration equipment is given in Table 2. Bath3 is a limited production model for which no manufacturer's specifications are available.

Modules without conductivity cells are typically calibrated once between deployments. Thus the post-deployment calibration for one deployment serves as the pre-deployment calibration for the next deployment. Conductivity cells can drift significantly, mainly due to biofouling or scouring,

Table 2: Manufacturer's specifications for test equipment used in calibrations.

Instrument	Specifications
HP3457A Multimeter	Frequency Accuracy = ±0.01% of reading, from 400 Hz to 1.5 MHz
	Frequency Resolution = 0.1 Hz, from 2000 Hz to 19000 Hz
Sea-Bird SBE-03 Thermometer	Range = −5°C to +35°C
	Accuracy = ±0.001°C
	Stability = ±0.002°C per year, typical
SBE-03 Thermometer and	Temperature Accuracy* = ±0.005°C
HP3457A Multimeter System	Temperature Resolution* = 0.0005°C
Guildline Model 5010	Range = −9.90 to +65.00°C
Programmable Fluid Bath	Resolution = 0.01°C
	Stability = ±0.002°C
Ruska Model 7250xi Digital	Range = 0 to 1000 psi
Pressure Controller	Precision = 0.005% of reading (at 5% to 100% FS)
	Accuracy = 0.011% of reading (at 5% to 100% FS) for 1 year

*When combining specifications for two instruments, manufacturer's specifications listed as % reading values were converted to physical units using the scales and readings appropriate for the calibrations.

and are cleaned and replatinized between deployments. Modules with conductivity cells are calibrated at least twice between deployments, once in the "as recovered" condition, and once after cleaning and replatinization. Thus each deployment of a SSC, TC, or TCV module has unique pre-deployment and post-recovery calibrations. Comparisons of pre-deployment and post-recovery calibrations, along with shipboard CTD measurements, are used to correct for sensor drift (Freitag *et al.*, 1999).

Most temperature calibrations performed at PMEL are presently conducted in Bath3, because of its greater capacity. The main exception to this are TP modules, which are simultaneously calibrated for temperature and pressure in Bath1. Since July 2003, the pressure standard used in Bath1 is a model 7250 Digital Pressure Controller manufactured by Ruska Instrument Corp., of Houston, TX, and is calibrated on a 1- to 2-year schedule. Previous to July 2003, the pressure standard was a model 6010-1660-C Pressure Gauge and model 6005 Pressure Controller, also from Ruska Instrument Corp. Additional information on the older pressure standard is available in Lake *et al.* (2003). Bath2 is used primarily for air temperature sensor calibration, and infrequently for NX module calibration.

Calibrations at PMEL are automatically performed by a Windows-based computer program (created by Software Engineering Associates, Everett, WA) which controls the bath temperature (and pressure for TP calibrations), records the sensor output in real time via the inductive modem, and computes the sensor calibration coefficients. Nominal temperature calibration set points are 6°C, 8°C, 11°C, 14°C, 17°C, 20°C, 23°C, 26°C, 29°C, and 32°C. Once the bath reaches the set point temperature (after an equilibration time of 2 hours or more) 10 samples are recorded at a 1-min rate.

Temperature calibrations at Sea-Bird Electronics are performed at nominal set points of 1°C, 4.5°C, 15°C, 18.5°C, 24°C, 29°C, and 32.5°C, while the modules record data internally at 2-min intervals. Calibration coefficients are computed from the internally recorded data after return of the modules to PMEL.

NX module raw data are reported as digital counts, N. The mean sensor output at each calibration set point is least squares fit to the calibration standard values using the following equation:

$$T(^\circ\mathrm{C}) = (A + B * \log R + C * (\log R)^3)^{-1} - 273.15 \qquad (1)$$

where

T = mean bath temperature,
R (nominal resistance in ohms) = $(N_T + 10000)/2.5$,
A, B, C = computed calibration coefficients,
N_T = Sensor mean temperature counts.

Pressure sensor accuracy is improved by calibration over a range of temperatures. PMEL pressure calibrations are performed at pressure set points of 400 psi, 500 psi, 600 psi, 700 psi and 800 psi, at temperature set points of 6°C, 11°C, 17°C, 23°C, and 29°C. At each temperature set point the pressure sensors are exposed to 0 psi, and then allowed to equilibrate at each pressure set point in ascending order. To measure and compensate for pressure sensor hysteresis, the sensors are then exposed to 850 psi, after which the pressure set points are repeated in descending order. The mean sensor output (from 10 values recorded at a 1-min rate) at each calibration set point (at both ascending and descending pressure values) is least squares fit to the calibration standard values using the following equation:

$$P(\text{psi}) = D + E * N_P + F * T \tag{2}$$

where

P = mean pressure of the standard,
D, E, F = computed calibration coefficients,
T = measured bath temperature (°C),
N_P = sensor mean pressure counts.

Note that while pressure is calibrated in units of psi, TAO data are reported in dbar. The pressure calibration set points are equivalent to 276 dbar, 345 dbar, 414 dbar, 483 dbar and 552 dbar.

At each set point the difference between the bath temperature (or standard pressure) and that predicted by the calibration equations above was computed. Modules were considered to have passed calibration if the absolute value of the maximum calibration residual was $\leq$0.006°C for temperature calibrations or $\leq$2.5 psi (1.7 dbar) for pressure calibrations. A second calibration pass/fail criteria is whether a minimum of 6 (of 10) samples were obtained at each set point. This second criteria is generally an issue only for calibrations performed at PMEL for which some data may have been lost during communications via the inductive modem. This type failure was unrelated to module calibration performance, but due to interference with the inductive loop from electromagnetic noise in the calibration room. Instruments which fail either test are recalibrated and most pass the second calibration. Those that do not pass the second calibration are repaired or removed from the inventory of actively used modules.

4. Calibration Repeatability and Temperature Bath Intercomparisons

A series of tests were conducted to quantify the repeatability of ATLAS temperature module calibrations, and also to intercompare calibrations made in any of the four temperature baths in which TAO calibrations are performed. Bath1 and Bath2 hold up to nine modules per calibration, arranged horizontally in a 3 × 3 honeycomb rack. Bath3 holds up to 18 modules, arranged radially around the cylindrical bath in 3 racks of 6 modules each. Each rack holds the modules vertically in a three across by two down arrangement. Each of the temperature calibration standard sensors was calibrated in May 2003 and again in July 2004. The test runs between baths at PMEL were performed in December 2003 and January 2004.

A series of nine calibration runs were performed on the same T modules to determine the repeatability of PMEL temperature calibrations. The tests are designed to determine both the combined precision of the sensors and baths, as well as to identify any differences between baths. The first five runs were conducted in Bath3, and runs six through nine were conducted in Bath1 and Bath2.

For the first 3 runs, 18 T modules were placed in Bath3 and 3 consecutive calibrations were performed without changing the placement of the modules between runs. For the fourth run, modules remained within the racks, but the racks were rotated one position counter-clockwise within the bath. For the fifth run, racks were returned to their original radial positions and modules were swapped from the top to bottom row and vice versa.

For Runs 6 through 9, the same 18 T modules were split into 2 groups of 9 modules each, named Group A and Group B. Two calibration runs (Runs 6 and 7) were performed with the Group A in Bath1 and Group B in Bath2, with no change in module placement between runs. For the last two runs (Runs 8 and 9), the groups were switched so that Group A was placed in Bath2 and Group B in Bath 1. Once again, the two calibration runs were performed on the modules without changing the module placement between runs.

For each run of each module a set of calibration coefficients were computed per equation 1 above. Temperatures were calculated for each module at each set point for each run, using the coefficients from the respective runs and nominal sensor count values, N_T. The nominal count values were chosen to approximate the calibration set point values: 6°C, 8°C, 11°C, 14°C, 17°C, 20°C, 23°C, 26°C, 29°C, and 32°C. The use of the same nominal counts for all modules and calibration runs, rather than using the actual sensor counts recorded, removes any influence from bath variability between runs. To estimate repeatability, the calculated temperature from one run for a given sensor and set point was subtracted from the calculated temperature of the following run for the same sensor and set point. Several arrays of these consecutive-run differences were compiled. The first created was an ensemble array containing the differences computed over all 9 runs, for a total of 1440 differences (8 differences between runs, 18 sensors, 10 set points). The mean, standard deviation, and root mean square (RMS) were calculated at each set point, and over the entire array (Table 3). The mean difference over all was 0.35×10^{-3} °C, and ranged between 0.16×10^{-3} °C and 0.43×10^{-3} °C over the 10 temperature set points, with the smallest mean difference at the 32°C set point. The RMS difference over all sensors was 1.54×10^{-3} °C, and ranged between 1.26×10^{-3} °C at the 29°C set point and 1.80×10^{-3} °C at the 6°C set point. These statistics are comparable to or smaller than the manufacturer's specified accuracy of the baths and bath standard sensors.

The next analysis focused on the characteristics of individual baths, by computing similar statistics for each bath individually. Each module was calibrated twice in Bath1 and then again in Bath2 for a total of 180 temperature differences (18 sensors, 10 set points) in each bath. Mean (-0.16×10^{-3} °C) and RMS (0.56×10^{-3} °C) differences in Bath1 (Table 4) were

Table 3: Statistics of temperature differences between 9 calibration runs in 3 PMEL baths on 18 NX ATLAS temperature modules. Units of temperature differences are m°C (°C × 10^{-3}).

	Temperature Set Point										
	All	**6°C**	**8°C**	**11°C**	**14°C**	**17°C**	**20°C**	**23°C**	**26°C**	**29°C**	**32°C**
Mean	0.35	0.37	0.40	0.42	0.43	0.43	0.41	0.37	0.31	0.24	0.16
Standard Deviation	1.50	1.76	1.70	1.64	1.59	1.54	1.47	1.38	1.29	1.24	1.30
RMS	1.54	1.80	1.74	1.69	1.65	1.60	1.52	1.43	1.33	1.26	1.30

Table 4: Statistics of temperature differences between 2 calibration runs in Bath1 and Bath2 on 18 NX ATLAS temperature modules. Units of temperature differences are m°C (°C × 10^{-3}).

	Temperature Set Point										
	All	**6°C**	**8°C**	**11°C**	**14°C**	**17°C**	**20°C**	**23°C**	**26°C**	**29°C**	**32°C**
Bath1											
Mean	−0.16	−0.02	−0.06	−0.12	−0.17	−0.20	−0.22	−0.22	−0.21	−0.19	−0.15
Standard Deviation	0.53	0.51	0.41	0.45	0.57	0.66	0.69	0.66	0.57	0.43	0.34
RMS	0.56	0.50	0.41	0.46	0.58	0.67	0.71	0.68	0.59	0.46	0.38
Bath2											
Mean	−0.29	−0.46	−0.47	−0.46	−0.44	−0.39	−0.33	−0.25	−0.15	−0.04	0.10
Standard Deviation	0.74	1.39	1.13	0.81	0.58	0.43	0.36	0.35	0.37	0.44	0.58
RMS	0.79	1.43	1.20	0.91	0.71	0.57	0.48	0.42	0.39	0.42	0.57

smaller than ensemble statistics over all three baths (Table 3) by factors of 2 and 3, respectively. Mean (-0.29×10^{-3} °C) and RMS (0.79×10^{-3} °C) differences in Bath2 were also smaller than ensemble statistics over all 3 baths, but larger than for Bath1. Mean and RMS differences for Bath2 had larger temperature dependence than for Bath1, with the largest differences occurring at the lowest temperatures.

For Bath3 the effect of module placement within the bath was also considered. A total of 5 calibration runs with 18 modules were conducted. Modules were kept in the same locations for the first three runs, then moved within the bath for the fourth and fifth runs as described above. Statistics were then computed over the first three runs, and then again over the third, fourth, and fifth runs. Statistics were computed over a total of 360 temperature differences (2 differences between runs, 18 sensors, 10 set points). Mean and RMS differences between runs were smaller for Bath3 than for either Bath1 or Bath2. Mean differences were -0.09×10^{-3} °C when modules remained in the same location for each run, and 0.03×10^{-3} °C when modules were rearranged between runs (Table 5). RMS differences were nearly identical between runs when modules were stationary vs. when they were rearranged, 0.37×10^{-3} °C and 0.34×10^{-3} °C, respectively. Therefore there was no indication that location within the bath affected calibration stability. The change in sign in the mean difference when modules remained stationary vs. when they were rearranged may be attributed to small ($<0.1 \times 10^{-3}$ °C) random uncertainty in the repeatability of calibrations. RMS differences in Bath3 were smallest at set points near the middle of the calibration range (17°C to 23°C).

Table 5: Statistics of temperature differences between 3 calibration runs in Bath3 on 18 NX ATLAS temperature modules, and 3 calibration runs in Bath3 on 18 NX ATLAS temperature modules with module locations varied between runs. Units of temperature differences are m°C (°C × 10^{-3}).

	Temperature Set Point										
	All	**6°C**	**8°C**	**11°C**	**14°C**	**17°C**	**20°C**	**23°C**	**26°C**	**29°C**	**32°C**
Bath3											
Mean	−0.09	0.06	0.04	−0.01	−0.04	−0.08	−0.11	−0.14	−0.17	−0.19	−0.22
Standard Deviation	0.36	0.51	0.35	0.38	0.32	0.29	0.27	0.27	0.28	0.31	0.36
RMS	0.37	0.51	0.44	0.37	0.32	0.30	0.29	0.30	0.32	0.36	0.42
Bath3 Locations Varied											
Mean	0.03	0.07	0.07	0.06	0.05	0.04	0.03	0.02	0.01	0.00	−0.01
Standard Deviation	0.34	0.54	0.44	0.33	0.24	0.19	0.17	0.19	0.26	0.36	0.49
RMS	0.34	0.53	0.44	0.33	0.25	0.19	0.17	0.19	0.25	0.35	0.48

Table 6: Statistics of temperature differences between mean temperatures computed from three calibration runs in Bath3 subtracted from mean computed from two calibration runs in Bath1, and subtracted from two calibrations runs in Bath2. Units of temperature differences are m°C (°C × 10^{-3}).

	Temperature Set Point										
	All	**6°C**	**8°C**	**11°C**	**14°C**	**17°C**	**20°C**	**23°C**	**26°C**	**29°C**	**32°C**
Bath1 minus Bath3											
Mean	2.19	2.33	2.63	2.93	3.05	2.99	2.76	2.35	1.76	1.00	0.06
Standard Deviation	1.40	1.08	0.97	0.80	0.65	0.56	0.60	0.80	1.10	1.47	1.91
RMS	2.59	2.56	2.79	3.03	3.11	3.04	2.82	2.47	2.06	1.75	1.86
Bath2 minus Bath3											
Mean	3.95	4.61	4.66	4.66	4.58	4.41	4.16	3.83	3.41	2.91	2.32
Standard Deviation	1.19	0.70	0.61	0.48	0.39	0.41	0.55	0.78	1.07	1.40	1.77
RMS	4.13	4.66	4.70	4.68	4.59	4.43	4.19	3.90	3.56	3.21	2.89

Table 7: Statistics of temperature differences between mean temperatures computed from three calibration runs in Bath3 subtracted from a single run at SBE. Units of temperature differences are m°C (°C × 10^{-3}).

	Temperature Set Point										
	All	**6°C**	**8°C**	**11°C**	**14°C**	**17°C**	**20°C**	**23°C**	**26°C**	**29°C**	**32°C**
SBE minus Bath3											
Mean	1.28	1.63	1.53	1.41	1.31	1.23	1.18	1.14	1.12	1.13	1.16
Standard Deviation	1.21	1.04	1.08	1.19	1.28	1.32	1.31	1.26	1.18	1.14	1.22
RMS	1.76	1.93	1.87	1.84	1.82	1.80	1.75	1.69	1.62	1.60	1.67

Each bath exhibited better stability (smaller RMS differences) than the ensemble over all baths, indicating that there may have been some mean bias between baths. To confirm and quantify this bias, mean temperatures from each bath were compared. The means were computed from the first three runs (between which modules were not moved) in Bath3 and subtracted from means computed over two runs each in Bath1 and Bath2. The mean differences between baths, $2.19 \times 10^{-3}\,°C$ between Bath1 and Bath3, and $3.95 \times 10^{-3}\,°C$ between Bath2 and Bath3, were 3 to 10 times larger than individual bath RMS differences (Table 6), implying a bias between baths, rather than random differences. In both cases the mean differences were larger at colder temperatures, with a range of about $2 \times 10^{-3}\,°C$ between 6°C and 32°C. The differences between baths were within the computed combined nominal accuracy of the SBE-03 temperature standard and HP3457A Multimeter ($5 \times 10^{-3}\,°C$, Table 2).

Temperature differences between PMEL and SBE calibrations were also examined. Eighteen TC modules which had been calibrated for both temperature and conductivity at SBE were recalibrated at PMEL. Each module had been calibrated once at SBE in calibration runs between March and June 2004. All 18 were then calibrated together in Bath3 at PMEL for 3 separate runs in June 2004. Differences between each PMEL calibration and the SBE calibration were computed and summary statistics are shown in Table 7. The mean difference of $1.28 \times 10^{-3}\,°C$ was less than that between Bath3 and the other two PMEL baths. Differences were somewhat larger at colder temperatures, but these differences were less than half that between Bath3 and the other PMEL baths.

5. Pressure Calibration Repeatability Tests

A series of three calibration runs with nine TP modules was conducted in Bath1 in January 2004 to determine the repeatability of the pressure sensor calibrations. Sensor locations were not changed between runs, so variability introduced by sensor position was not addressed with this test. During the first run, one module did not return data at the 29°C temperature set point. A second module did not return data at both the 23°C and 29°C temperature set points. The loss of data was due to telemetry problems, rather than sensor malfunction. If these had been normal production runs the calibrations would have been considered failed and rerun. For this exercise, calibration coefficients were computed without the missing data. Pressure values computed from these coefficients at the missing temperatures may be less accurate than in typical circumstances, since the coefficients would be computing values at conditions beyond the range of the calibration. Thus the results of this exercise can be considered as a conservative estimate of repeatability.

Similar to the method for temperature calibration repeatability, a set of nominal pressure frequency counts (chosen to best fit the pressure and temperature set points of the sensor ensemble) were applied to equation 2, using the calibration coefficients for each run and for each sensor. Nominal

Table 8: Statistics of pressure differences between three calibration runs on nine NX ATLAS TP modules.

Ensemble Pressure Differences (psi)

	Mean	Standard Deviation	RMS
	−.16	0.19	0.24

Pressure Differences (psi) vs. Temperature (°C)

Temperature	Mean	Standard Deviation	RMS
6	−0.14	0.19	0.23
11	−0.14	0.17	0.22
17	−0.15	0.16	0.22
23	−0.17	0.19	0.25
29	−0.18	0.23	0.29

Pressure Differences (psi) vs. Pressure

Pressure	Mean	Standard Deviation	RMS
400	−0.15	0.25	0.29
500	−0.15	0.21	0.26
600	−0.16	0.18	0.24
700	−0.16	0.15	0.22
800	−0.16	0.13	0.21
800	−0.16	0.13	0.21
700	−0.16	0.15	0.22
600	−0.16	0.18	0.24
500	−0.15	0.21	0.26
400	−0.15	0.25	0.29

temperature values (6°C, 11°C, 17°C, 23°C, and 29°C) were also used. Pressure differences were then computed at each temperature and pressure set point, and for each module; first between calibration runs 1 and 2, and then between calibration runs 2 and 3. Thus, stability statistics were computed from 900 pressure differences (2 run differences, 9 sensors, 5 temperature set points, 5 ascending and 5 descending pressure set points).

The mean pressure difference (Table 8) computed between the three calibration runs and over all temperature and pressure set points was −0.16 psi (−0.11 dbar) and the RMS difference was 0.24 psi (0.17 dbar). Mean and RMS differences varied by about 25% over the calibration temperature range, with the larger differences occurring at higher temperature. Mean differences over the calibration pressure range did not vary by more than 0.01 psi. RMS differences varied by about 25% over the calibration pressure range, with larger differences occurring at lower pressure.

6. Pre-Deployment Calibration Statistics

Ensemble statistics for 7212 temperature calibrations performed at PMEL and at SBE between April 1996 and June 2004 are shown in Table 9. A total of 7374 temperature calibrations were available in the TAO module calibration data base, from 2485 individual modules. Failed calibrations (162, which represented 2% of the total) were omitted from the ensemble statistics: most had maximum residuals (the largest absolute value of the bath temperature minus that computed by application of the calibration equation to the sensor output) within ±0.006°C, but failed due to loss of some inductive data during the calibration. Most modules were successfully recalibrated without the need for repair. Only 38 calibrations (0.5%) had maximum residuals whose absolute value exceeded 0.006°C. Of these 38, some passed their next calibration without repair, some required repair before passing, and some were set aside from the active module inventory.

Most (73%) of the 7212 calibrations were performed at PMEL, with 43% in Bath3, 25% in Bath1, and 4% in Bath2 (Appendix A). The remainder of PMEL calibrations (2% of the total and all calibrations in 1996) were conducted in a bath used only during the initial development of the modules. This bath was not used after 1996. Modules with conductivity cells, which were calibrated at SBE, made up 27% of the 7212 temperature calibrations.

The RMS of the 7212 calibration maximum residuals was 0.0009°C, thus the typical maximum residual was nearly an order of magnitude smaller than the threshold criteria for passing calibration. Note that the standard deviation of the A, B, and C calibration coefficients were about 2 orders of magnitude smaller than their means, indicating small differences between individual modules.

Ensemble statistics for 1132 pressure calibrations performed between February 1997 and June 2004 are shown in Table 10. A total of 1178 pressure calibrations were available in the TAO module calibration data base, from 395 individual modules. Failed calibrations (46, which represented 4% of the total) were omitted from the ensemble statistics; about 30% had maximum residuals within ±2.5 psi, but failed due to loss of some or all inductive data

Table 9: Statistics for 7212 temperature module calibrations. Coefficients are from equation (1).

RMS Maximum	Coefficient A		Coefficient B		Coefficient C	
Residual	Mean A	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
0.0009°C	1.0124×10^{-3}	6.1093×10^{-6}	5.5861×10^{-4}	1.7564×10^{-6}	1.7254×10^{-6}	3.1570×10^{-8}

Table 10: Statistics for 1132 pressure module calibrations. Coefficients are from equation (2).

RMS Maximum	Coefficient D		Coefficient E		Coefficient F	
Residual	Mean A	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1.20 psi	1.5176×10^{2}	8.0286	2.7538×10^{-2}	4.15171×10^{-4}	6.0333×10^{-2}	4.6066×10^{-2}

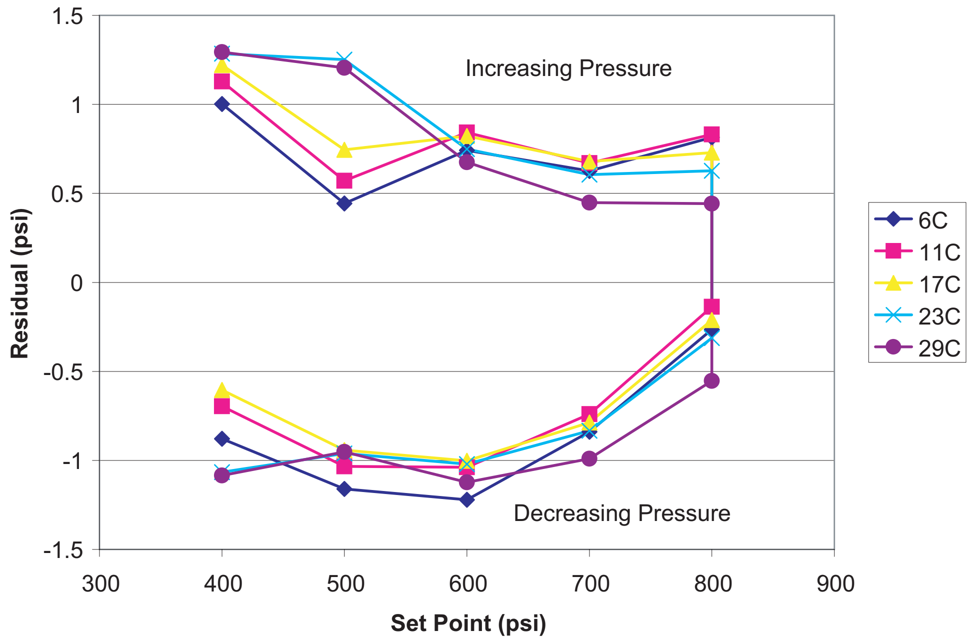


Figure 1: Calibration residuals for an NX ATLAS pressure module. Residuals >0 were experienced when pressure was increasing. Residuals <0 were experienced when pressure was decreasing.

during the calibration procedure. Of the other failed calibrations, some were unrelated to the pressure sensor calibration itself, e.g., problems with the calibration apparatus, or improper installation of the pressure transducer in the module body. A few required repair to the module circuitry. All modules which failed calibrations passed later calibrations or were removed from the active sensor inventory.

The RMS of the calibration maximum residual was 1.20 psi (0.83 dbar). Thus the typical maximum residual was half the threshold criteria for passing calibration. Note also that the standard deviation of the D and E calibration coefficients were about 2 orders of magnitude smaller than their means, indicating small differences between individual modules. The standard deviation of the F calibration coefficient was about equal to its mean. The F coefficient applies a correction for temperature dependence of the pressure sensor. At typical deployment temperatures (8°C to 12°C) the mean adjustment is about 0.5 psi to 0.7 psi (0.3 dbar to 0.5 dbar).

Pressure calibration residuals indicate that hysteresis is a major contributor to the residuals (Fig. 1). In the case shown, the maximum calibration residual was 1.29 psi, similar to the RMS of 1132 maximum residuals shown in Table 9. Residuals when pressure set points were incremented in ascending order were positive, while residuals when pressure set points were incremented in descending order were negative. Residual differences between ascending and descending modes were much larger than differences between temperature or pressure set points. The hysteresis is a characteristic of strain gauge pressure sensors like that used in the NX ATLAS module. The calibration standard employs Bourdon Tube technology for which hysteresis of this magnitude is not an issue.

7. Sensor Calibration Drift

While the pre-deployment calibration statistics presented above quantify measurement accuracy when first deployed, the standard practice of calibration after recovery provides the opportunity to quantify calibration drift while deployed at sea. Ensemble statistics from 3012 pre-deployment, post-recovery temperature calibration pairs are presented in Table 11. Pre-deployment calibrations were conducted between February 1997 and April 2003. Post-recovery calibrations were conducted between January 1998 and April 2004. The mean time deployed at sea was 308 days and the mean time between calibrations was 481 days. The distribution of the number of days deployed at sea was bimodal (Fig. 2) with a majority (54%) being between 330 and 420 days and an additional 26% being between 120 and 270 days. Most ATLAS moorings are scheduled to be deployed for 1 year, but each site in the TAO Array is routinely visited twice a year. The spread about the annual and semiannual modes was due mainly to variations in annual cruise schedules. The semiannual secondary mode was the result of moorings being replaced early due to vandalism, major sensor failure or mooring failure. Also, a few sites are routinely scheduled for 6-month deployments when new or modified instruments are tested. The longer deployment periods (up to 742 days) were due to changes in ship schedules that prevented an annual replacement or due to redeployment of sensors at sea.

The distribution of the number of days between calibrations (not shown) was also somewhat bimodal, but more widely varying than the deployment days. A large portion (43%) was between 420 and 540 days. Longer times between calibrations were generally related to longer deployment times, but a few were due to unusually long periods between the mooring recovery and the return of equipment to PMEL, which has been particularly true for some PIRATA moorings.

The sensor calibration drift was computed as the temperature (or pressure) computed using post-recovery calibration coefficients minus that computed using pre-deployment calibration coefficients. Temperature was computed at 10 levels over the calibration range (1°C to 32°C) by applying a

Table 11: Ensemble calibration drift statistics for NX ATLAS temperature and pressure. N_{Cal} is the number of module calibration pairs. D_{Dep} is the mean number of days deployed at sea. D_{Cal} is the mean number of days between pre-deployment and post-recovery calibrations.

				Difference		
Sensor Type	$\mathbf{N_{Cal}}$	$\mathbf{D_{Dep}}$	$\mathbf{D_{Cal}}$	**Mean**	**Std. Dev.**	**RMS**
Temperature	3012	308	480	−0.0095°C	0.0154°C	0.0180°C
Pressure	533	322	496	−0.14 psi	0.68 psi	0.69 psi

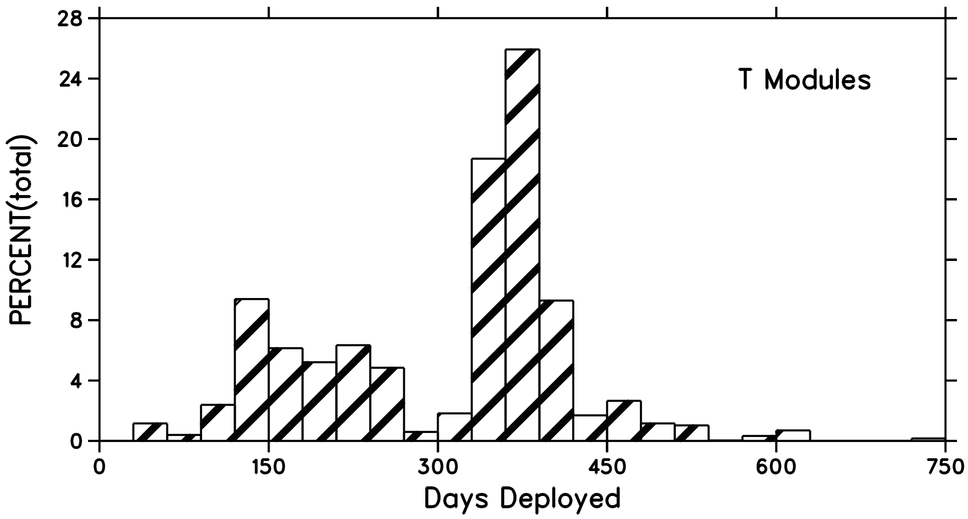


Figure 2: Distribution of the number of days 3012 modules were deployed at sea.

set of 8 sensor counts N_T into equation (1) above. Pressure was similarly computed at a combination of 5 temperature levels and 5 pressure levels over the calibration range (6°C to 29°C and 400 psi to 800 psi) using a set of 25 N_P, T pairs to equation (2). Ensemble statistics of the differences computed for all calibration pairs and all calibration check points are presented in Table 11.

The ensemble mean temperature drift was −0.0095°C; thus on average, temperature modules were reporting slightly warmer temperature when recovered than they would have at the beginning of the deployment. About 86% of the mean (over the calibration temperature range) drifts between calibration pairs were negative (Fig. 3). The magnitude of the ensemble mean drift was an order of magnitude larger than the ensemble RMS residual for pre-deployment calibrations (0.0009°C). In addition, the standard deviation of 0.0154°C implies that the true mean drift is non-zero at a confidence level of more that 99%. The ensemble RMS temperature drift was 0.0180°C, about twice the mean. About 86% of RMS differences (over the calibration temperature range) between calibration pairs were less than or equal to 0.020°C.

The mean temperature drift and time between calibrations were somewhat correlated (R^2 = 0.08, significant at the 95% confidence level), with mean drifts becoming more negative as the time between calibrations increased (Fig. 4). A similar relationship was found between mean temperature drifts and number of days deployed.

The ensemble pressure calibration drift statistics (Table 11) were computed from 533 calibration pairs over essentially the same time period as for temperature calibration drift. The smaller number of pressure calibration pairs compared to temperature calibration is due to the fact that a typical NX ATLAS mooring has 2 modules measuring pressure and 11 modules measuring temperature. The ensemble mean pressure calibration drift was

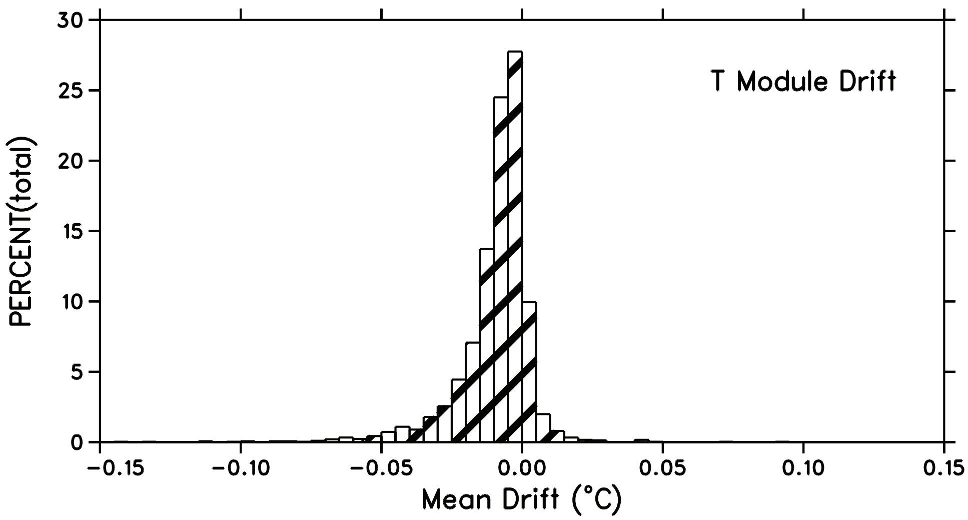


Figure 3: Mean module temperature drift between 3012 NX ATLAS calibration pairs.

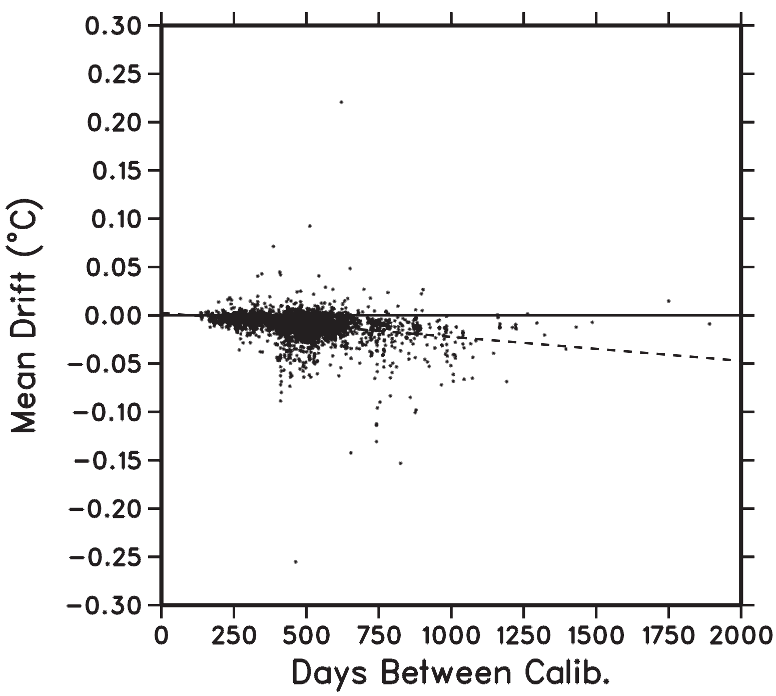


Figure 4: Scatter plot of the mean temperature drift vs. the number of days between calibrations for 3012 NX ATLAS module calibration pairs.

−0.14 psi (−0.10 dbar), nearly an order of magnitude smaller than the RMS maximum residual for all individual calibrations (1.20 psi). The ensemble RMS drift of 0.69 psi (0.48 dbar) was also smaller than the RMS maximum residual for individual calibrations. Thus it can be concluded that NX ATLAS pressure modules drift very little over a typical mooring deployment, compared to their initial accuracy.

8. Discussion and Summary

Surface (1 m) and subsurface (down to 500 m) water temperature measurements on moorings within the TAO and PIRATA moored arrays are made using NX ATLAS temperature modules. Most module temperature calibrations are performed at PMEL, with the exception of modules that also measure conductivity, for which both temperature and conductivity are calibrated at SBE. PMEL has three temperature baths, identified as Bath1, Bath2, and Bath3. Most calibrations are conducted in Bath3. The percentage of calibrations conducted between April 1996 and June 2004 in each bath were 27%, 25%, 4%, and 43%, for the SBE bath, Bath1, Bath2, and Bath3, respectively. Bath1 is used primarily for calibration of modules which measure both temperature and pressure. Bath2 was used for a small percentage of ATLAS temperature module calibrations, but none since early 2002. The number of calibrations performed in each bath per year is shown in Appendix A.

8.1 Accuracy at the time of calibration

The repeatability of temperature calibrations performed at PMEL was estimated via a series of 9 calibrations (2 in Bath1, 2 in Bath2 and 5 in Bath3) on 18 NX ATLAS modules. Bath1 had a repeatability of 0.0006°C (RMS). Bath2 had the largest variation, with a repeatability of 0.0008°C (RMS). Temperature calibrations in Bath3 (in which most calibrations are presently conducted) were repeatable to within 0.0004°C (RMS). Note that as estimated in this experiment, the repeatability reflects uncertainty in both the temperature bath and the NX ATLAS modules. The repeatability of ATLAS temperature module calibrations performed at SBE was not investigated in this study. SBE estimates the repeatability of calibrations in their bath to be 0.0002°C (Dick Guenther, SBE, personal communication). Calibration repeatability in any of the baths is 2 to 3 orders of magnitude smaller than the manufacturer's nominal accuracy for the thermistor used in NX ATLAS temperature modules and an order of magnitude better than the accuracy of the calibration standard (Table 2). Given that relatively few calibrations were performed in Bath2, a conservative estimate of NX ATLAS temperature calibration repeatability within a bath in general is 0.0006°C or better.

Although the repeatability in any of the baths was <0.001°C, differences between baths were larger. The mean bias relative to Bath3 was found to be 0.0022°C for Bath1, 0.0040°C for Bath2, and 0.0013°C for calibrations performed at SBE. It is encouraging that mean differences between the two baths in which most (70%) ATLAS temperature calibrations are conducted

(Bath3 and SBE) are of order 0.001°C. A source of the bias between Bath3 and the other PMEL baths may be calibration differences between the model SBE03 sensors used for the PMEL baths. These calibration standards are calibrated on a nominal yearly basis at SBE. The two most recent standard calibrations were performed in May 2003 and July 2004, about 7 months before and after the repeatability tests were performed at PMEL in December 2003, respectively. Annual calibration drift rates for the standards between May 2003 and July 2004 were +0.0022°C $year^{-1}$ for S/N 559 (which was in Bath1), −0.0036°C $year^{-1}$ for S/N 728 (which was in Bath2), and −0.0009°C $year^{-1}$ for S/N 1698 (which was in Bath3). Negative bias values imply a sensor was reporting low at the time of the latter calibration. Assuming that the standards drifted linearly in time, these rates would predict a bias of +0.0018°C for Bath1 relative to Bath3 at the time of these tests, and a bias of −0.0016°C between Bath2 and Bath3. Thus the calibration drift of the standards measured by SBE is consistent with bias between Bath1 and Bath3 measured at PMEL. The same relationship does not hold for bias between Bath2 and Bath3, as it was of larger magnitude and of opposite sign to the standards calibration drift.

A complete history of PMEL standard calibrations since 1996 and the baths in which they were used is given in Appendix B. The RMS of the annual drift rates computed over four sensors and 8 years was 0.0021°C $year^{-1}$. The RMS annual drift for individual sensors ranged from 0.0002°C $year^{-1}$ to 0.0026°C $year^{-1}$. The RMS annual drift computed over all sensors, weighted by the number of calibrations conducted for each sensor, was 0.0018°C $year^{-1}$.

Another possible source of bias between baths may be thermal stratification within a bath, i.e., a mean temperature difference between the location of the standard sensor and the location of the modules being calibrated. This possibility was not investigated in this study.

The largest bias between baths (0.0040°C) found between Bath2 and Bath3 had only a minor impact on overall accuracy estimates, because Bath2 has been used in relatively few calibrations (4% of the total). Bath2 has not been used for ATLAS module calibrations since early 2002, and less than 1% of calibrations conducted that year were in Bath2 (see Appendix A).

Based on the RMS of the annual drift rate for the calibration standard sensors used in PMEL temperature baths from 1996 to 2004 (0.0018°C $year^{-1}$), the mean bias between Bath1 and Bath3 (0.0022°C), and the mean bias between SBE and Bath3 (0.0013°C), a reasonable estimate of the accuracy of ATLAS module temperature calibrations is ±0.0020°C. This estimate can be considered conservative if it is assumed that the calibration standard sensor drifts are linear in time, and thus a standard sensor is typically in error by this magnitude only after a year of use.

The RMS of maximum residuals from 7212 individual calibrations between April 1996 and June 2004 was 0.0009°C, which is about twice the calibration repeatability found for Bath3. This confirms that equation (1) is a good approximation of the NX ATLAS temperature module transfer function.

The overall accuracy of a temperature module at the time of calibration (E_{INI}) can be considered to be the result of three factors; the error of the calibration standard (E_{STD}, estimated by the standard sensor accuracy), the calibration uncertainty (E_{CAL}, estimated by the repeatability of calibrations), and how well the calibration equation fits the sensor response (E_{SEN}, estimated by the RMS calibration residual). Assuming that these factors are independent, the overall accuracy can be estimated as

$$E_{INI} = (E_{STD}^2 + E_{CAL}^2 + E_{SEN}^2)^{1/2} \quad (3)$$

Using the values determined above for E_{STD}, E_{CAL}, and E_{SEN}, (0.0020°C, 0.0006°C, 0.0009°C) we estimate that a recently calibrated NX ATLAS module has a temperature accuracy of ±0.0023°C.

The manufacturer's accuracy specification for the pressure standard used at PMEL is 0.011% of the reading for 1 year, which corresponds to 0.09 psi at 800 psi (0.06 dbar at 552 dbar). Shortly after the PMEL pressure standard was replaced in July 2003, eight TP modules were calibrated using both the older and newer pressure standards. The mean difference between calibrations was 0.24 psi (0.17 dbar) and the RMS difference was 0.26 psi (0.18 dbar). A conservative estimate of the pressure standard accuracy, E_{STD}, is the RMS of the differences between old and new standards. The repeatability of pressure calibrations at PMEL, estimated as the RMS difference over a series of three calibrations on nine TP modules, was 0.24 psi (0.17 dbar), which can be used to estimate the calibration uncertainty, E_{CAL}. The RMS of the maximum residual for 1132 calibrations was 1.20 psi (0.83 dbar), which can serve as an estimate of how well the calibration equation fits the sensor response (E_{SEN}). Assuming that the errors are independent and combining them as for temperature in (3) above, we estimate that a recently calibrated NX ATLAS module has an initial pressure accuracy, E_{INI}, of ±1.25 psi (±0.86 dbar).

8.2 Accuracy while deployed at sea

The accuracy of NX ATLAS modules while deployed has been estimated by analyzing the sensor calibration drifts defined by the difference between calibrations before and after deployment at sea. For temperature, 3012 pre-deployment vs. post-recovery calibration pairs were considered. The RMS difference for this ensemble was 0.0180°C. For pressure, 553 pre-deployment vs. post-recovery calibration pairs were considered. The RMS difference for this ensemble was 0.69 psi (0.48 dbar).

A estimate for the overall calibration accuracy, E_{TOT}, of NX ATLAS module data may be obtained by combining the accuracy of the initial pre-deployment accuracy, E_{INI} (as estimated in (3) above), with the estimate of sensor calibration drift, E_{DFT}. This is a conservative estimate in that it assigns the level of sensor drift measured typically after a year or longer to the entire deployment period, while in reality the accuracy of data from the beginning of the deployment is presumably better. Assuming that the initial accuracy and sensor drift are uncorrelated over the ensemble of all sensors and calibrations, the overall accuracy can be estimated as

Table 12: NX ATLAS temperature and pressure data accuracies based upon ensemble calibration statistics.

	Temperature	**Pressure**
Initial Accuracy, E_{INI}	±0.0023°C	±1.25 psi (±0.86 dbar)
Sensor Drift, E_{DFT}	±0.0180°C	±0.69 psi (±0.48 dbar)
Overall Accuracy, E_{TOT}	±0.0181°C	±1.43 psi (±0.98 dbar)

$$E_{TOT} = (E_{INI}^2 + E_{DFT}^2)^{1/2} \qquad (4)$$

Application of (4) to the values of temperature error estimated as $E_{INI} = \pm 0.0023$°C and $E_{DFT} = \pm 0.0180$°C yields an overall temperature calibration accuracy of ±0.0181°C. Application of (4) to the values of pressure error estimated as $E_{INI} = \pm 1.25$ psi (±0.86 dbar) and $E_{DFT} = \pm 0.69$ psi (±0.48 dbar) yields an overall calibration accuracy of ±1.43 psi (±0.98 dbar). The initial accuracy, sensor drift, and overall sensor calibration accuracies of NX ATLAS temperature and pressure modules are summarized in Table 12.

The accuracy estimates for temperature and pressure derived here are intended to be applied to the ATLAS mooring data served from the TAO web pages (`www.pmel.noaa.gov/tao/`). These data will be accompanied by quality indices which may have one of the following values:

1—Highest Quality. Pre-deployment and post-recovery calibrations agree to within sensor accuracy. In most cases, only pre-deployment calibrations have been applied.

2—Default Quality. Pre-deployment calibrations only or post-recovery calibrations only applied. Default value is used for sensors presently deployed and for sensors which were not recovered or were not calibratable when recovered, or for which pre-deployment calibrations have been determined to be invalid and post-recovery calibrations were applied.

3—Adjusted Data. Pre/post calibrations differ, or original data do not agree with other data sources (e.g., other in situ data or climatology), or original data are noisy. Data have been adjusted in an attempt to reduce error.

4—Lower Quality. Pre/post calibrations differ, or data do not agree with other data sources (e.g., other in situ data or climatology), or data are noisy. Data could not be confidently adjusted to correct for error.

Individual sensors which have calibration drifts exceeding twice the values in Table 12 will be assigned a quality value of 4, unless the data have been adjusted, in which case the quality value will be 3. Sensors whose drift is less than or equal to twice the values in Table 12 will be assigned a quality value of 1. Missing data are given a quality value of 0 and data determined to be bad are given a quality value of 5.

9. Acknowledgments

We would like to thank Pat McLain, design engineer of the NX ATLAS system, who provided valuable information on the function and characteristics of the instrumentation described here. We are also grateful to Jim Illman, Dan Dougherty, Brian Lake, and Patrick A'Hearn for the design and development of software used in the calibration procedures, data processing, and analysis performed in this work. Patrick A'Hearn also reviewed the manuscript and provided valuable editorial suggestions. This publication is partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution #1142.

References

A'Hearn, P.N., H.P. Freitag, and M.J. McPhaden (2002): ATLAS module temperature bias due to solar heating. NOAA Tech. Memo OAR PMEL-121 (NTIS PB2003-101593), NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 24 pp.

Freitag, H.P., Y. Feng, L.J. Mangum, M.J. McPhaden, J. Neander, and L.D. Stratton (1994): Calibration procedures and instrumental accuracy estimates of TAO temperature, relative humidity and radiation measurements. NOAA Tech. Memo. ERL PMEL-104 (PB95-174827), NOAA, Pacific Marine Environmental Laboratory, Seattle, WA, 32 pp.

Freitag, H.P., M.E. McCarty, C. Nosse, R. Lukas, M.J. McPhaden, and M.F. Cronin (1999): COARE Seacat data: Calibrations and quality control procedures. NOAA Tech. Memo. ERL PMEL-115 (PB99-146144), NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 89 pp.

Hayes, S.P., L.J. Mangum, J. Picaut, A. Sumi, and K. Takeuchi (1991): TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bull. Am. Meteorol. Soc.*, *72*, 339–347.

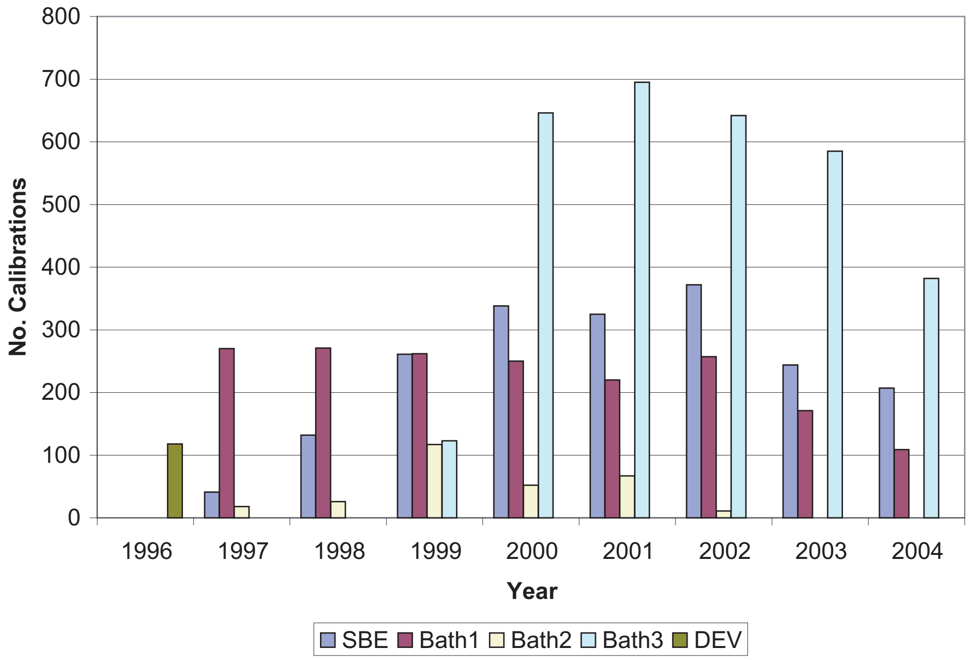
Lake, B.J., S.M. Noor, H.P. Freitag, and M.J. McPhaden (2003): Calibration procedures and instrumental accuracy estimates of ATLAS air temperature and relative humidity measurements. NOAA Tech. Memo. OAR PMEL-123, NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, 23 pp.

McPhaden, M.J., A.J. Busalacchi, R. Cheney, J.-R. Donguy, K.S. Gage, D. Halpern, M. Ji, P. Julian, G. Meyers, G.T. Mitchum, P.P. Niiler, J. Picaut, R.W. Reynolds, N. Smith, and K. Takeuchi (1998): The Tropical Ocean Global Atmosphere observing system: A decade of progress. *J. Geophys. Res.*, *103*(C7), 14,169–14,240.

Servain, J., A.J. Busalacchi, M.J. McPhaden, A.D. Moura, G. Reverdin, M. Vianna, and S.E. Zebiak (1998): A pilot research moored array in the tropical Pacific (PIRATA). *Bull. Am. Meteorol. Soc.*, *79*(10), 2019–2031.

Appendix A

Number of NX ATLAS module calibrations performed at Sea-Bird Electronics, Inc., (SBE) and in PMEL baths (DEV, Bath1, Bath2, Bath3) from April 1996 to June 2004. DEV was a bath used during the early development of the modules.



Appendix B

This table contains the history of calibrations, performed by Sea-Bird Electronics, Inc., of four model SBE03 sensors which were used as calibration standards for NX ATLAS module calibrations performed at PMEL. The table includes the SBE03 serial number (S/N), the total number of NX ATLAS modules calibrated using that SBE03, the annual drift rate (°C $year^{-1}$) since the previous calibration, the time period over which the calibration was used, and the PMEL bath in which the SBE03 was used.

Standard Cal Date	Annual Drift Rate	Module Cal Dates		Bath
Standard S/N 559 (898 module calibrations)				
1/7/1997	0.00078	2/12/1997	2/12/1997	2
2/14/1998	0.00225	5/5/1998	1/11/1999	1
		3/4/1998	6/10/1999	2
1/19/1999	0.00562	7/9/1999	3/27/2000	2
4/27/2000	0.00264	9/6/2000	10/3/2000	1
		8/1/2000	1/29/2001	2
4/16/2001	0.00249	1/15/2002	3/6/2002	2
4/17/2002	−0.00056	4/22/2002	5/8/2003	1
5/28/2003	−0.00089	5/30/2003	7/7/2004	1
7/25/2004	0.00219	6/30/2004		1
Standard S/N 728 (1213 module calibrations)				
10/21/1995	NA	4/4/1996	8/19/1996	DEV
2/11/1997	−0.00010	2/8/1997	1/31/1998	1
2/14/1998 and	−0.00102	2/18/1998	2/16/1999	1
3/5/1998		11/23/1998	11/23/1998	2
4/3/1999	−0.00254	4/22/1999	3/21/2000	1
4/27/2000	−0.00221	5/18/2000	3/6/2001	1
4/16/2001	−0.00332	4/18/2001	4/18/2002	1
4/27/2002	−0.00163			
5/28/2003	−0.00373			
7/25/2004	−0.00356			
Standard S/N 1698 (2844 module calibrations)				
3/16/1999	−0.00053	2/26/1999	4/19/1999	1
4/27/2000	−0.00090	6/2/2000	3/3/2001	3
5/8/2001	−0.00094	7/19/2001	7/30/2001	2
		5/24/2001	5/2/2002	3
5/15/2002	−0.00091	5/31/2002	4/30/2003	3
5/28/2003	−0.00054	6/13/2003	5/28/2003	3
7/25/2004	−0.00093	7/30/2004		3
Standard S/N 2561 (337 module calibrations)				
3/17/1999	NA	8/4/1999	5/9/2000	3
6/3/2000	−0.00025	5/13/2002	5/13/2002	3
5/31/2002	0.00015	5/29/2003	5/29/2003	3
8/6/2003	−0.00018			
7/25/2004	−0.00015			