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Calibration Procedures and Instrumental Accuracy Estimates of ATLAS Air Temperature and Relative Humidity Measurements

Brian J. Lake[1], Sonya M. Noor[2], H. Paul Freitag[1], and Michael J. McPhaden[1]

[1]Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle, WA 98115-6349

[2]Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
University of Washington
Box 354235
Seattle, WA 98195-4235

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Brian J. Lake[1], Sonya M. Noor[2], H. Paul Freitag[1], and Michael J. McPhaden[1]

Abstract. Calibration procedures for sensors measuring air temperature and relative humidity from NextGeneration Autonomous Temperature Line Acquisition System (ATLAS) moorings are described. Sensor accuracy when first deployed and calibration drift are quantified. Modifications to sensors and procedures since a previous report (Freitag *et al.*, 1994) are documented. Instrumental error for air temperature measurements is estimated to be 0.22°C, nearly equal to that from the previous report. Instrumental error for relative humidity (RH) measurements is estimated to be 2.73 %RH, smaller than the previously reported value of 4.1 %RH. The decrease in relative humidity is due to improvements in instrumentation and calibration procedures.

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, shortwave radiation (SWR), and conductivity. In addition, ocean currents, longwave radiation, and barometric pressure are measured at selected TAO/TRITON sites.

Calibration procedures and instrumental accuracy of ATLAS WSD measurements were described by Freitag *et al.* (2001) and ATLAS AT, RH, SWR, and T calibrations and accuracy were documented by Freitag *et al.* (1994). In the latter, the method of RH calibration (described below under "Humidity Calibration Procedures") was characterized as time consuming, requiring significant manual interaction and subjective interpretation of sensor stability by laboratory technicians. Moreover, RH sensor drift was estimated to be 4 %RH over the sensor deployment duration (nominally 1 year), which was significantly larger than that specified by the manufacturer (2% accu-

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

[2]Joint Institute for the Study of the Atmosphere and Ocean (JISAO), University of Washington, Box 354235, Seattle, WA 98195-4235

racy and 1% drift per year, for the Rotronic MP100 model deployed at the time). It was speculated that some of the difference between expected and estimated sensor drift could be the result of inaccuracy in the calibration procedure. As a result, PMEL has developed an automated, computer controlled RH calibration procedure, to improve upon RH sensor calibration efficiency and accuracy.

This memorandum documents the new RH calibration procedure and provides a revised estimate of instrumental accuracy for ATLAS RH measurements that reflect improvements in the calibration method at PMEL and improvements in the sensors by the manufacturer. Calibration and accuracy of AT, which is measured by the same sensor as RH, are also revisited. ATLAS mooring electronics were updated over the period 1996 to 2001, during which an evolution toward use of the NextGeneration ATLAS system occurred in the Pacific. PIRATA moorings have been NextGeneration ATLAS systems since the inception of the array in 1997. Differences in circuitry and sampling from the earlier Standard ATLAS system are described.

2. Instrumentation

Relative humidity and air temperature are presently measured on ATLAS moorings by model MP101A combined humidity and air temperature probes manufactured by Rotronic Instrument Corporation of Huntington, NY. Within the probe, relative humidity is measured by a Rotronic Hygromer C94 thin film capacitive sensor that is protected beneath a Teflon foam filter cap, while temperature is measured by a Pt100 RTD (Resistance Temperature Detector). Manufacturer specifications regarding the accuracy of the MP101A are listed in Table 1. Sensor output is an analog DC voltage that is a linear function of either RH or AT expressed in engineering units. RH sensor output in the range 0 V to 1 V represents values of 0 %RH to 100 %RH. AT sensor voltage in the range from −0.4 V to +0.6 V represents temperature from −40°C to 60°C. The nominal calibration equations for the sensors are thus

$$\begin{aligned} \mathrm{RH}(\%) &= B_{\mathrm{rh}} V_{\mathrm{rh}} \\ \mathrm{AT}(^\circ\mathrm{C}) &= B_{\mathrm{at}} V_{\mathrm{at}} \end{aligned}$$

where V_{rh} and V_{at} are the output in volts for the RH and AT sensors, respectively, and B_{rh} and B_{at} are calibration coefficients with nominal values of 100 each.

ATLAS RH and AT measurements described in Freitag *et al.* (1994), were made with a Rotronic model MP100 sensor. The manufacturer updated this sensor to the MP101A, which included modifications to the circuitry, the humidity sensor, and its protective filter. Modifications listed below are based upon comparison of the manufacturer's published specifications and/or personal communications with representatives of the company. Surface-mount technology (the method of attaching components without leads in feed through holes) was applied to the circuitry. The electronics-imposed operating temperature limits were increased from [−20 – +55°C] to

Table 1: Manufacturer's specifications for Rotronic Instrument Corp. model MP101A air temperature (AT) and relative humidity (RH) sensors used on NextGeneration ATLAS moorings.

Sensor	Specifications
AT	$\pm$0.2°C accuracy 0.2°C drift/year $\pm$0.1°C repeatability
RH	$\pm$1.0 %RH accuracy* $<$1.0 %RH drift/year $\pm$0.3 %RH repeatability

*RH accuracy when calibrated with a high quality standard.

[−40−60°C]. The Pt100 RTD thermistor's linearity was improved and the temperature accuracy improved from 0.5°C to 0.2°C. The humidity sensor was upgraded from a C80 to a C94, which improved the nominal accuracy from 2 %RH to 1.5 %RH and halved the %RH repeatability specifications from 0.6 %RH to 0.3 %RH. The specified nominal accuracy is applicable to factory or field calibrations. When calibrated with a high quality standard, such as the Thunder Scientific chamber, Rotronic specifies accuracy of the MP101A as 1 %RH. Modifications to the electronics improved the linearity and temperature compensation of the sensor. The humidity sensor's electrodes were also improved to better resist contaminants. PMEL found that some cases enclosing the MP100 and MP101A sensors leaked in the ocean environment. Sensors purchased by PMEL now use watertight enclosures which are designed and provided by PMEL to Rotronic for instrument assembly. One of the most substantial modifications by the manufacturer was an improvement in the current drain, a specification vital to PMEL's battery-operated, low-power moorings. The current drain was reduced during several successive versions of the MP101A model. The current drains of MP100 and early MP101A versions exceeded 10 mA, while the newer versions of MP101A are typically 4 mA. All NextGeneration ATLAS moorings use the newer, lower-current MP101A sensors.

Digitization of the analog voltages is performed by electronic circuitry designed and built at PMEL. The present NextGeneration ATLAS system employs a 12-bit analog-to-digital (A/D) converter with RH resolution of 0.024 %RH over a range of 0 %RH to 100 %RH and AT resolution of 0.01°C over a range of 0°C to 40°C. For real-time telemetry and during calibration, RH data are reduced to 8 bits or 0.39 %RH resolution, for compatibility with telemetry buffers and data processing of the older ATLAS systems. After mooring recovery, the full 12-bit resolution is obtained from internal memory. The earlier Standard ATLAS systems used 10-bit A/D converters, which gave 0.04°C resolution for AT. RH data in the older system were truncated to 8 bits (0.39 %RH resolution) for both real-time and delayed modes.

In the course of this investigation it was found that the reduction of RH data from 12 to 8 bits during calibration was done via truncation, rather than the more accurate method of rounding, which is used during real-time telemetry of data. Assuming an even distribution of data, truncation would bias the data by about 1/2 the reduced resolution or about 0.2 %RH. This bias is not reflected in drift estimates presented below as it is present in both pre-deployment and post-recovery calibrations. Modifications to the next version of NextGeneration ATLAS firmware will eliminate this small bias.

Temporal resolution has also increased in the present NextGeneration ATLAS system. AT and RH sensors are sampled at 2 Hz for 2 min every 10 min. Two-minute means are computed at each 10-min interval and stored in internal memory. Daily means and the 2-min mean at the most recent hour are telemetered in real time. The earlier Standard ATLAS systems computed and stored hourly average data, based on spot samples measured at 10-min intervals.

When deployed on a buoy the MP101A sensor is shielded from direct sunlight by a naturally aspirated, multi-plate radiation shield (supplied by the R.M. Young Co., Traverse City, Michigan), the effectiveness of which increases with wind speed. The manufacturer specifies that at a radiation level of 1080 W m^{-2}, temperature bias is 0.4°C at 3 m s^{-1} wind speed, 0.7°C at 2 m s^{-1}, and 1.5°C at 1 m s^{-1}. The present study focuses on instrumental calibration errors and does not address errors associated with factors such as radiant heating. Typical (mode) wind speeds measured within the TAO Array are about 6 m s^{-1} and values below 3 m s^{-1} compose about 12% of the data. Wind speed statistics are similar in the PIRATA Array. Thus bias due to radiant heating of air temperature measured in TAO or PIRATA is presumably limited to a small portion of the data.

3. Humidity Calibration Procedures

Rotronic recommends that RH calibration be verified on a 6- to 12-month basis for maximum accuracy. ATLAS moorings are typically deployed for 1 year. Calibrations of sensors are performed before and after every mooring deployment, thus the calibration frequency recommended by the manufacturer is roughly met.

The manufacturer-specified calibration procedure involves connecting each probe to a calibration receptacle containing a humidity standard (non-aqueous salt solution). The method includes measuring sensor output after the recommended 1-hour equilibrium period, followed by adjustment to the correct value by use of a potentiometer in the sensor circuitry. Rotronic recommends this procedure be performed at 35 %RH and 80 %RH, plus either 0 %RH or 10 %RH. After this procedure, the RH sensor is assumed to follow the nominal calibration equation given above, within the nominal accuracy. The low-humidity calibration point is not performed at PMEL, since tropical ocean humidity is rarely less than 50 %RH. This procedure to bring the sensors into nominal performance is performed routinely by PMEL technicians before sensors are deployed in the field.

In an additional procedure developed at PMEL, the sensor linearity and calibration accuracy is confirmed, and individual sensor calibration coefficients are computed by measuring the sensor output at additional levels, as described below. Individual sensor coefficients are computed from a linear least square fit to the equation

$$\mathrm{RH}(\%\mathrm{RH}) = A_{\mathrm{rh}} + B_{\mathrm{rh}} V_{\mathrm{rh}}$$

which allows for individual bias (A_{rh}) and gain (B_{rh}) calibration coefficients for each sensor. This process is performed and coefficients computed before deployment and again after recovery in an "as is" state. Before subsequent deployment, the sensor filter cap is cleaned or replaced, the sensor brought back into nominal accuracy (using the procedure recommended by Rotronic described above) and a new calibration performed and coefficients computed. Thus for each deployment a sensor has unique pre-deployment and post-recovery calibration coefficients.

As described in Freitag *et al.* (1994), the previous method of checking sensor output for accuracy and linearity employed standard salt solutions between 50 %RH and 95 %RH at 15 %RH intervals. This procedure was relatively labor intensive and time consuming. In addition, our experience was that the 1-hour equilibration time recommended by the manufacturer was often not sufficient, and determining when the sensor had equilibrated was subjective and thus could vary between calibrations. Therefore, a more automated and less subjective procedure was designed at PMEL to improve both the efficiency and accuracy of calibrations. In the new calibration procedure a Model 2500 Benchtop Two-Pressure Humidity Generator (manufactured by Thunder Scientific of Albuquerque, New Mexico) provides a humidity source while under the direction of a PC computer program. Up to 10 Rotronic probes are connected via a multimeter and monitored simultaneously by the computer. Temperature stability, vital to the accuracy of calibrations, is maintained in the chamber to within 0.1°C. The humidity generator itself is calibrated on a yearly basis, according to manufacturer recommendations. Specifications of the humidity generator and its calibration are given in the Appendix.

Sensor output is recorded at set points of 55 %RH, 65 %RH, 75 %RH, 85 %RH, and 95 %RH, with measurements taken after allowing for sensors to come to equilibrium within the chamber. The length of the equilibrium period is a function of the humidity set point. Based upon past experience, the following equilibrium periods (T_{eq}) are used for all calibrations: 1.5 hours at 55 %RH, 65 %RH, and 75 %RH levels, 2.5 hours at 85 %RH, and 3.5 hours at 95 %RH. Subsequent analysis of calibration data (described below) has confirmed that these times are sufficient for equilibration in most cases.

In a typical calibration, 6 to 10 sensors are placed into the humidity generator's chamber, taking care to avoid blocking the chamber's ventilation. From that point, the calibration is completely under computer control. Temperature in the chamber is held at 21°C and the humidity initially set at

45 %RH. After a half-hour period for temperature equilibration, the chamber is brought to the first set point (55 %RH). The sensor output (volts) is monitored during the equilibrium period at 1-min increments. After equilibrium a mean of the next ten 1-minute samples is computed and archived for use in the computation of calibration coefficients. The humidity level is then increased to the 65 %RH set point, and the process continued until finished with the 95 %RH set point. The computer program then computes the calibration coefficients (B_{rh} and A_{rh}) using a linear least-square fit to the five mean sensor voltages and chamber humidities. Calibration residuals (differences between humidity computed from the calibration coefficients and the chamber reading) are computed and displayed. For pre-deployment calibrations, if any residual exceeds 1.0 %RH, sensors are set aside for adjustment or repair and recalibration. The maximum acceptable residual was initially set at 2 %RH, based on the manufacturer's original accuracy estimate for the MP100 sensor. Experience with the improved MP101 sensors and automated calibration procedure indicated that this criterion could be lowered to 1 %RH with only a small number of sensors failing predeployment calibration.

4. Air Temperature Calibration Procedures

The ATLAS air temperature (AT) sensor calibration procedure as described in Freitag *et al.* (1994), has remained unchanged. Sensors are calibrated before deployment and again after recovery. Adjustment or repair of the temperature circuitry is rarely necessary, thus in most cases a post-recovery calibration for one deployment serves as the pre-deployment calibration for the next. Calibrations are performed in a computer controlled water bath, with a model SBE 03 temperature sensor from Sea-Bird Electronics, Inc. (calibrated on a yearly basis by the manufacturer) used as a standard. The Rotronic sensors are placed in protective rubber gloves before immersion in the bath. The output of the Rotronic sensors and the calibration standard are measured at set points ranging from 14°C to 32°C at 3°C intervals. An equilibration period of 1.5 hours is used for all set points, which has been confirmed to be adequate for sensor and bath equilibrium. After the equilibration period, the sensors and standard are sampled for ten minutes, with one reading per minute, and a mean value for each computed. Calibration coefficients are produced from a linear least-square fit between the Sea-Bird standard temperature and Rotronic voltages

$$\mathrm{AT}(^{\circ}\mathrm{C}) = A_{\mathrm{at}} + B_{\mathrm{at}} V_{\mathrm{at}},$$

where A_{at} and B_{at} are unique bias and gain calibration coefficients, respectively, for each sensor.

5. I/O Board Calibration Procedures

In the NextGeneration ATLAS system electronics, AT and RH sensor outputs first pass through individual signal-conditioning hardware interface circuitry. Digitization of humidity and air temperature sensor outputs is then performed by a common 12-bit A/D converter. The Input/Output (I/O) board calibration procedure is nearly unchanged from that described by Freitag *et al.* (1994). Each board is calibrated twice, once over the range of voltage output by the humidity sensor, then again over the range of voltage for temperature. For humidity the voltage range is 0.4 V to 0.99 V, at roughly 0.1 V increments. For temperature the voltage range is 0.1 V to 0.4 V, at 0.05 V increments. Previously, the calibration range for air temperature I/O boards was 0.0 V to 0.4 V and for relative humidity boards it was 0.0 V to 0.9 V. It was noted in the 1994 report that maximum residuals occurred predominantly at the 0.0 V set point, presumably due to error in the voltage source at this level, and/or a zero bias in the I/O circuitry. Because tropical air temperatures and relative humidity never reach these levels (0°C, 0 %RH) the 0.0 V calibration point was dropped from the calibration procedure.

I/O board calibration coefficients are produced from a linear least square fit between voltages and output counts

$$\begin{aligned} V_{\mathrm{rh}} &= C_{\mathrm{rh}} + D_{\mathrm{rh}} N_{\mathrm{rh}} \\ V_{\mathrm{at}} &= C_{\mathrm{at}} + D_{\mathrm{at}} N_{\mathrm{at}} \end{aligned}$$

where N is the I/O board output in counts and C and D are the calibration coefficients.

6. Relative Humidity Equilibration

Freitag *et al.* (1994) noted that an equilibrium period of 1-hour during humidity calibrations (as suggested by the manufacturer) did not appear to be sufficient to insure stability of the sensor output. It was proposed that a lack of stability could be responsible for a portion of the measured residual error and/or sensor drift. The automated humidity calibration procedure described above presented an opportunity to determine appropriate equilibration periods.

To quantify equilibrium times, 183 sensor calibrations (both pre-deployment and post-recovery) performed in 2001 were analyzed. For each of five calibration set points, sensor output voltage (V_{data}) measured at 1-minute intervals throughout the equilibration period (T_{eq}) was fit to the exponential equation

$$V_{\mathrm{t}} = V_{\mathrm{eq}} + \Delta V e^{-kt}$$

Where V_{t} is the predicted voltage at time t, V_{eq} the predicted voltage at equilibrium, ΔV the difference between V_{eq} and $V_{\mathrm{t=0}}$, and k^{-1} the sensor time constant. An example of the exponential fit for a calibration set point is shown in the upper part of Fig. 1. In this and most other cases, the exponential fit was reasonably representative of the data. For the 915 calibration set points, 97% of the maximum residuals from the fits ($V_{\mathrm{data}} - V_{\mathrm{t}}$) fell within ±0.005 V, or 0.5 %RH, the accuracy of the humidity chamber

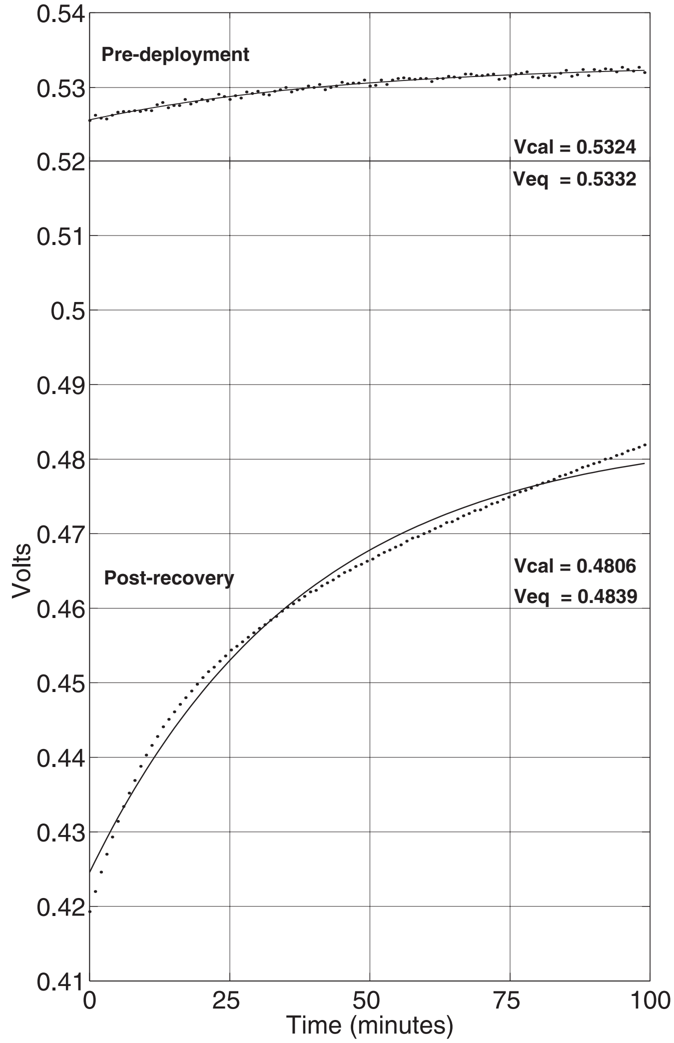

Figure 1: Sample RH sensor output (dots) during pre-deployment (upper) and post-recovery (lower) calibration at the 55 %RH calibration set point. Solid lines are exponential fits to the data. Units are volts. V_{cal} is the mean of the last 10 points in the time series. V_{eq} is the equilibrium value predicted by the exponential fit.

(Fig. 2a). With the exception of a limited number of outliers, computed time constants ranged from 5 to 180 minutes, with typical (median) values of about 30 minutes for the three lowest set points, 60 minutes for the 85 %RH set point, and 90 minutes for the 95 %RH set point. A scaled equilibrium time, $T_{\mathrm{eq}}/(k^{-1})$, was calculated for each fit, which provided a comparison of the chosen equilibrium period to the actual sensor equilibrium characteristics. The median scaled equilibrium time was greater than 3 for the 55 %RH, 65 %RH, and 85 %RH set points, 2.7 for the 75 %RH set point, and 2.5 for the 95 %RH set point. Thus, 2.5 or more sensor time constants were encompassed by the chosen equilibration times for typical calibrations.

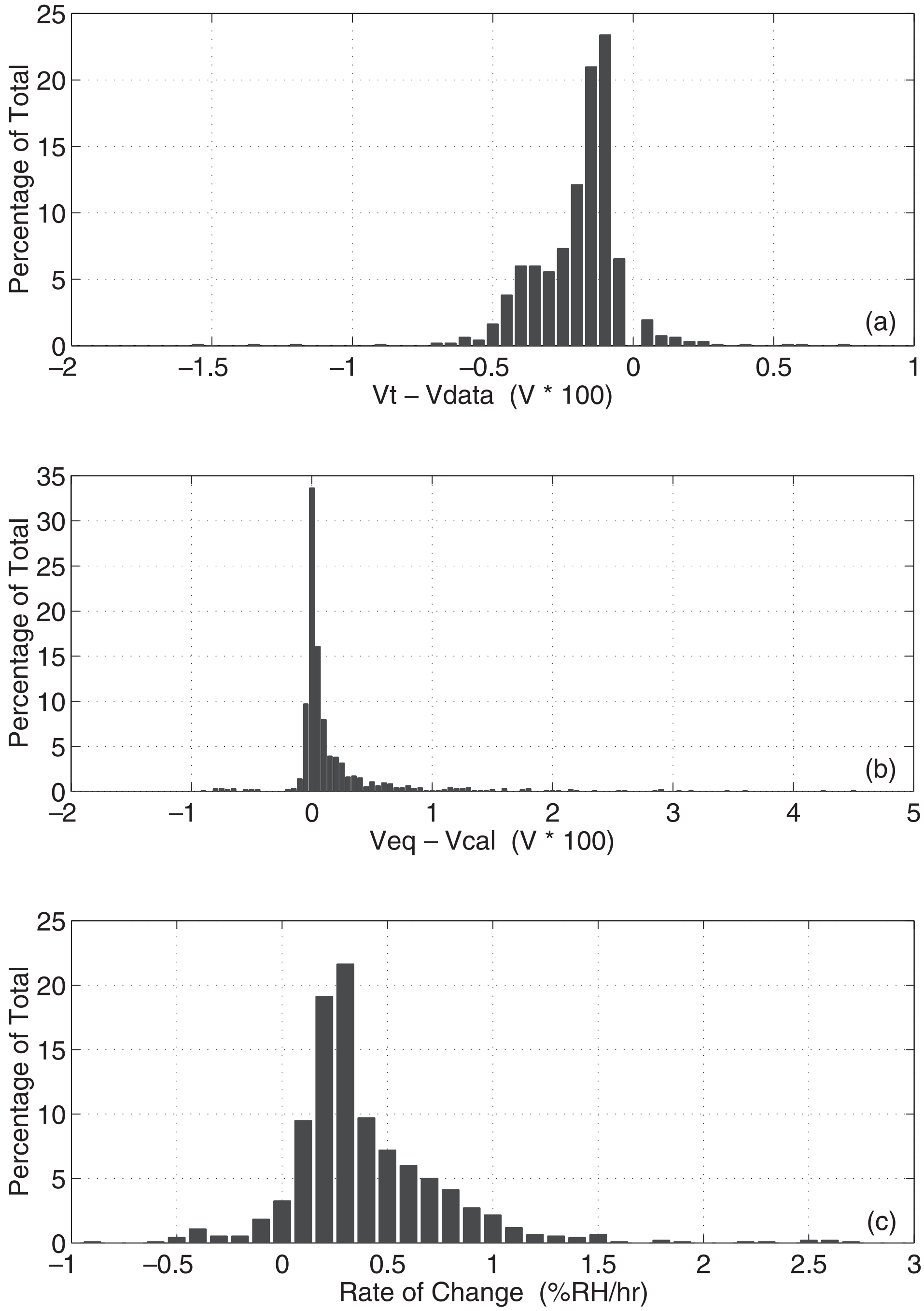

Figure 2: Ensemble distributions from 183 calibrations (915 set points). (a) Maximum difference between measured calibration data and exponential fit (as in Fig. 1). Units are nominally %RH (Volts*100). (b) Difference between the sensor output at equilibrium as predicted by the exponential fit, V_{eq}, and the mean of the last 10 points in the time series, V_{cal}. Units are nominally %RH (Volts*100). (c) Rate of change of sensor output computed from a linear least-squares fit to last 10 points of the time series. Units are nominally %RH (Volts*100) per hour.

In 87% of cases, the 10-minute mean sensor outputs used for computing the calibration coefficients, V_{cal}, fell within 0.5 %RH (the specified accuracy of the humidity chamber) of the equilibrium value, V_{eq}, predicted by the exponential fit (Fig. 2b). As another measure of the degree to which the sensors equilibrate during calibration, the rate of change over the 10-minute averaging period (estimated by the trend of a linear least-squares fit) was less than 0.5 %RH hr^{-1} in 71% of cases (Fig. 2c). Thus, changes in sensor output would generally be small compared to the accuracy of the humidity generator, even if equilibrium times were lengthened by as much as an hour.

The analysis above was for the combined set of 535 pre-deployment and 380 post-recovery calibration set points. When the analysis was separated by calibration type, there was strong indication that some post-deployment sensors took longer to equilibrate. The data shown in the upper part of Fig. 1 was from a pre-deployment calibration. When the same sensor was calibrated after recovery, the rate of change of the sensor output after the equilibration period was an order of magnitude larger than that for the pre-deployment calibration (Fig. 1, lower part). In addition, the sensor output during post-recovery calibration did not fit the exponential equation as well. Most significantly, the mean of the final 10 samples (V_{cal}) was 0.05 V (5 %RH) lower for the post-deployment calibration. Presumably some sensor drift occurred between calibrations, but the estimated drift would have been smaller had the sensor equilibrated during the post-deployment calibration. Comparisons of ensemble statistics for pre-deployment vs. post-recovery calibrations indicate that a significant portion of post-recovery sensors exhibited slower time response. The percentage of cases in which $V_{\mathrm{eq}} - V_{\mathrm{cal}}$ was within $\pm$0.5 %RH was 95% for pre-deployment calibrations, but 76% for post-recovery calibrations; and the rate of change over the 10-min averaging period was less than 0.5 %RH hr^{-1} in 91% of pre-deployment calibrations, but this statistic was only 43% for post-recovery calibrations.

7. Humidity Calibration Repeatability

To quantify the repeatability of PMEL RH calibrations, five sensors were calibrated nine times over the course of a month and the resultant calibration coefficients compared. Prior to the study, the multimeter had been calibrated according to manufacturer specifications and all sensors had been pre-calibrated and adjusted. The sensors' locations within the chamber remained unchanged, and normal calibration procedures were used consistently throughout the study. Calibration residuals (%RH$_{\mathrm{chamber}}$ − %RH$_{\mathrm{calculated}}$) were typically in the range $\pm$0.3 %RH (Fig. 3). Residuals tended to be negative at the 55 %RH, 65 %RH and 95 %RH set points, and positive at the 75 %RH and 85 %RH set points, indicating a small (0.1 to 0.2 %RH) non-linearity in the sensor output.

Resultant calibration coefficients were applied at nominal set point voltages (i.e., .55 V, .65 V, .75 V, .85 V, .95 V) to calculate sensor %RH values for each calibration (Fig. 4). Computed in such a manner, differences in %RH values reflect the combined stability of sensor output and calibra-

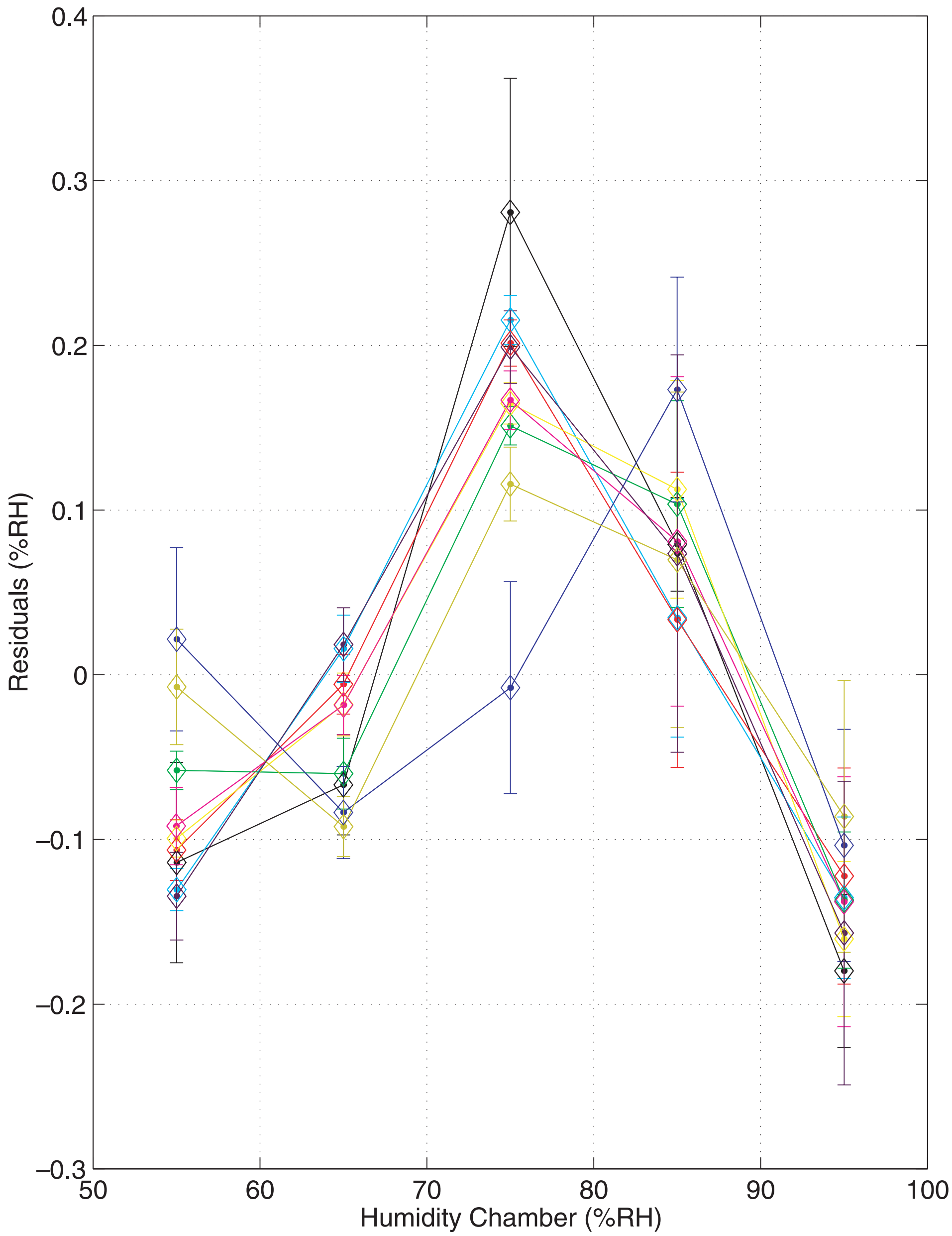

Figure 3: Residual error (in %RH) for five sensors calibrated nine times. Each color represents one of the nine calibrations. The mean (diamond) and standard deviation (vertical lines) of the residuals computed over the five sensors is shown vs. the humidity chamber setting.

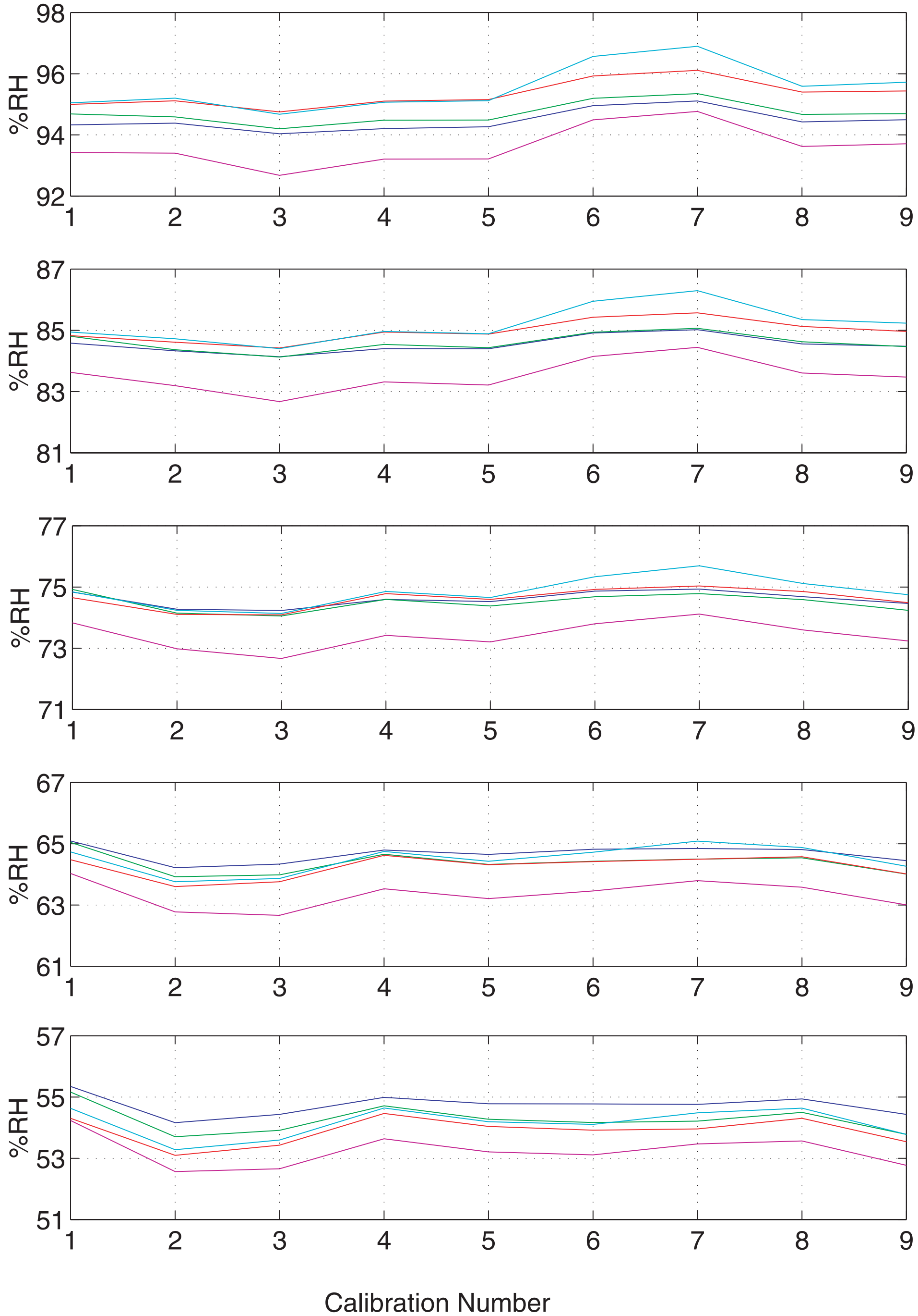

Figure 4: Sensor output (in %RH) computed using individual calibration coefficients from each of nine calibrations. Each color represents one of five sensors. Computations were made at each of the five calibration set points from 55 %RH to 95 %RH.

tion uncertainty, while accounting for small (∼0.03 %RH) humidity chamber variability during the nine calibrations. The maximum deviation in relative humidity was about ±1 %RH for a given sensor and calibration set point.

The standard deviation of calibrated sensor output computed over the nine calibrations for a given sensor ranged from 0.25 %RH to 0.75 %RH (Fig. 5). Variations in the deviations reflected both differences between sensors (deviations for two sensors were larger than for the other three sensors) and general stability characteristics of the sensors and/or calibration system (deviations were generally lower at the 65 %RH and 75 %RH set points relative to the other set points). The RMS of standard deviations computed over all set points and sensors was 0.42 %RH. These deviations were a measure of both the repeatability of the sensors, and of the calibration system itself, including the humidity chamber and associated instrumentation. As such, the RMS value of 0.42 %RH compares favorably with the manufacturer's specified sensor repeatability of 0.3 %RH.

8. Individual Sensor and I/O Board Calibrations

A large number of calibrations (1111 RH sensors, 848 AT sensors, and 394 I/O boards) were analyzed to determine the instrumental accuracy of NextGeneration air temperature and relative humidity measurements. Previous ATLAS analysis (Freitag *et al.*, 1994) considered a much smaller ensemble (200 or fewer sensor and I/O board calibrations). As in the previous study, the root-mean-square (RMS) of the maximum residuals (the largest difference between the calibration standard and the sensor or I/O board output, as calculated using the calibration coefficients) was used as an estimate of sensor or board accuracy at the time of calibration.

8.1 Relative Humidity Sensor

A total of 1111 RH sensors were calibrated during the study period (1996–2002). The RMS maximum residual (expressed in humidity units) of 0.56 %RH (Table 2) is roughly half the manufacturer's specified accuracy of 1 %RH (Table 1). Freitag *et al.* (1994) reported a RMS maximum residual of 2.6 %RH for ATLAS RH sensors. Thus the new, automated RH sensor calibration procedure (along with the RH sensor's improved electronics) has led to improved calibration results. Sensor gain (coefficient B in Table 2) remained about the same as in the previous study at 6% above the nominal value of 100. The difference in nominal vs. measured gain is compensated by the measured offset ($A = -3.8$) and is due in part to the fact that PMEL calibrations are limited to the range 55 %RH to 95 %RH.

The RH sensor and filter can become fouled during deployment, which can affect sensor performance. Therefore, the RH sensors are calibrated in both pre-deployment (pre-cal) and post-recovery (post-cal) conditions. The RMS maximum residual for 693 pre-deployment calibrations was 0.37 %RH (Table 2). For 418 post-recovery calibrations, the value was roughly double (0.78 %RH), but remained less than the manufacturer's specified accuracy. Pre-deployment calibration sensor gain was 4% higher than the nominal

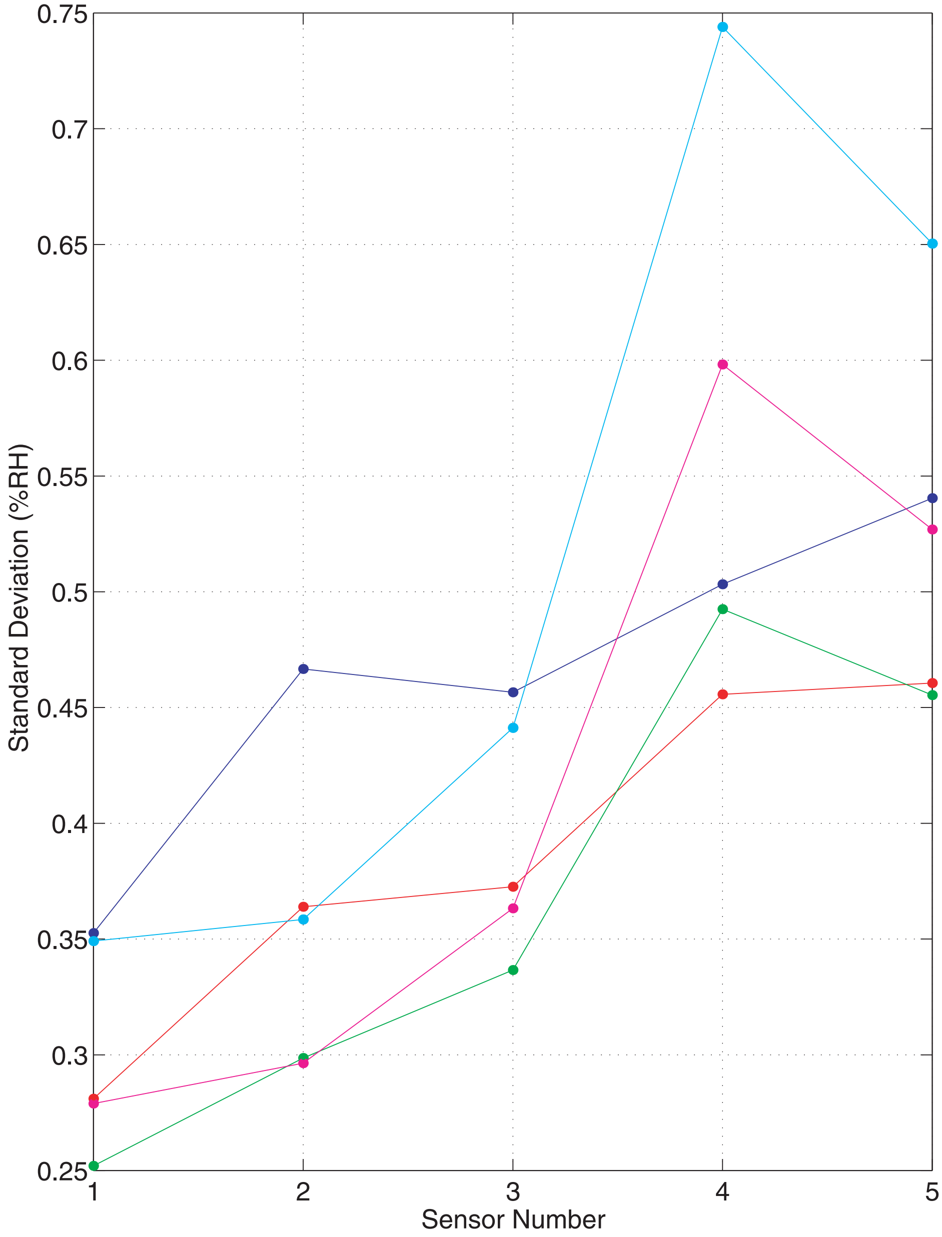

Figure 5: Standard deviation (in %RH) of calibrated sensor output computed over nine calibrations for each of five sensors. Colors represent chamber set points from 55 %RH to 95 %RH.

Table 2: Statistics for NextGeneration ATLAS air temperature (AT) and relative humidity (RH) sensor calibrations. M is the number of sensors calibrated.

		RMS Max	Coef. A		Coef. B	
Sensor	**M**	**Residual**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
AT (all)	848	0.022°C	0.024	0.482	100.12	1.34
RH (all)	1111	0.56 %RH	−3.803	9.70	105.65	7.24
RH (pre-cal)	693	0.37 %RH	−2.110	3.02	103.51	4.28
RH (post-cal)	418	0.78 %RH	−6.608	14.94	109.20	9.42

Table 3: Statistics for NextGeneration ATLAS I/O board calibrations. M is the number of sensors calibrated. Residuals have been scaled to the same units as sensors, by application of the nominal sensor gain of 100. The resolution listed for RH is for internally recorded data. Data telemetered in real time and calibration data have a resolution of 0.39 %RH.

	1-bit		RMS Max	Coef. C		Coef. D	
Board	**Resolution**	**M**	**Residual**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
AT	0.01°C	394	0.082°C	0.006	0.057	0.0230	0.012
RH	0.024%RH	394	0.18%RH	0.00206	0.00198	1.003	0.006

value of 100 whereas the post-cal gain was 9% higher than the nominal value. Differences between pre- and post-cal statistics are presumably due to fouling of the filter, sensor drift, and electronic drift during deployment. Sensor and electronic drift are examined in more detail below.

8.2 Relative Humidity I/O Board

As noted above, RH calibration data are reduced to 8-bit resolution, to produce coefficients for use with real-time telemetered data which also have 8-bit resolution. This procedure decreases the precision of RH I/O board calibrations and induces a small (∼0.2 %RH) positive bias, but does not have a significant effect on overall accuracy as the truncation bias and measured drift of the I/O boards are an order of magnitude smaller than the RH sensor calibration drift (see below). Field data stored in internal memory have the full 12-bit resolution.

The RMS maximum residual for 394 RH I/O board calibrations was 0.18 %RH, about half the resolution of RH calibration data (0.39 %RH, Table 3). This value is also about half that for pre-cal RH sensors (Table 2). It is somewhat less than the value reported previously (Freitag *et al.*, 1994) of 0.26 %RH for ATLAS RH I/O boards. The improvement may be due to the reduction in calibration range (now 40 %RH to 99 %RH compared to 0 %RH to 95 %RH previously). RH board gain values were consistent with the previous study.

8.3 Air Temperature Sensor

Statistics from the calibration of 848 air temperature sensors (Table 2) were similar to those reported in Freitag *et al.* (1994). The RMS of the maximum residual was 0.022°C, an order of magnitude smaller than the manufacturer's stated accuracy of 0.2°C. Sensor gain, 100.12, and offset, 0.024, were nearly identical to the manufacturer's nominal values of 100 and 0, respectively.

8.4 Air Temperature I/O Board

The RMS maximum residual for 394 air temperature I/O boards was 0.082°C (Table 3), about half that reported previously (Freitag *et al.*, 1994). The improvement is presumably due to the reduction in calibration range (now 10°C to 40°C compared to 0°C to 40°C previously).

9. Sensor and I/O Board Drift

Instrumentation recovered in working condition is returned to PMEL for post-recovery calibration before being reused on future deployments. After post-recovery calibrations are completed, the resultant coefficients are compared to the pre-deployment coefficients. First, a set of output values is computed by application of the calibration equation using pre-deployment coefficients to a set of nominal input values. Input values are chosen so that the output values span the standard calibration range. A second set of output values is generated by application of the calibration equation using post-recovery coefficients to the same set of input values. Sensor drift is calculated by subtracting the first set of output values from the second set of output values. This method of calculating sensor drift is identical to that employed by Freitag *et al.* (1994). Mean and RMS differences for sensor calibration pairs are given in Table 4. Mean and RMS differences for I/O board pairs are given in Table 5.

ATLAS moorings are nominally deployed for 1 year, but due to the replacement of failed, damaged, or questionable sensors the actual mean deployment length was about 9 months. The mean time between calibrations was about 16 months. RMS drift normalized to 1 year (by the ratio of 365 over the mean number of days between calibrations), appear in parentheses in Tables 4 and 5. Normalization in this manner assumes that the drift occurred linearly throughout the time between calibrations and decreases unnormalized drift estimates. Normalization by the mean time between mooring deployment and recovery (assuming that sensor drift occurs primarily while in the field) would increase drift estimates. Freitag *et al.* (1994) suggested a correlation between the magnitude of calibration drift and the length of the deployment at sea. The data used in this study indicate very little correlation between the size of calibration drift and either the time between calibrations or the time deployed at sea (Fig. 6). Other factors, such as environmental conditions while deployed, or handling and conditions before or after deployment, may be important in some cases. Because the factors affecting drift rates are not well known, we have opted to

Table 4: Differences between pre- and post-deployment sensor calibrations. RMS differences in parentheses are normalized to 1 year based on days between calibrations assuming linear drift with time.

Sensor	Number of Calibration Pairs	Mean Days Between Calib.	Mean Deployment Days	Range	Mean Difference	RMS Difference
AT	225	506	272	14–32°C	0.025°C	0.157°C(0.113)
RH	201	476	262	55–95 %RH	1.04 %RH	2.72 %RH(2.09)

Table 5: Differences between pre- and post-deployment I/O board calibrations. RMS differences in parentheses are normalized to 1 year based on days between calibrations assuming linear drift with time.

Board	Number of Calibration Pairs	Mean Days Between Calib.	Mean Deployment Days	Range	Mean Difference	RMS Difference
AT	211	461	274	5–35°C	−0.057°C	0.146°C(0.115)
RH	223	462	272	40–100 %RH	−0.02 %RH	0.21 %RH(0.16)

use non-normalized drift values as our primary estimate of sensor and I/O board accuracy.

9.1 Relative Humidity Sensor

In computing the sensor drift estimate, 21 calibration pairs (9 percent of the total) with RMS drifts ranging from 6 %RH to 13 %RH were rejected as outliers. Two criteria were considered in rejecting these data. In some cases the sensor did not reach equilibrium during the post-deployment calibration, but would have reached values closer to those of the pre-deployment calibration if the equilibration time were increased substantially (Fig. 1, lower part). The longer response time of these sensors was probably due to fouling of the sensor or filter cap while at sea. If these sensors exhibited similar performance while at sea, then their data would not necessarily be biased, but would lag fluctuations by periods of up to several hours. A second criteria used to reject some large drift estimates was to apply post-recovery calibrations to the data at the time of recovery and compare these to the data from the next sensor deployed at that site. In many cases the application of the post-deployment calibrations resulted in large discontinuities between deployments, or values that were unreasonably high or low. Under these circumstances it was concluded that the post-recovery calibrations did not accurately reflect the condition of the sensors while deployed. The majority of cases with RMS drift between 6 %RH to 13 %RH were rejected because they met one or both of these criteria. A few cases with large drift did not clearly meet these criteria and remain in the ensemble over which the drift estimate was computed.

RMS difference between 201 RH sensor calibration pairs (Table 4) was 2.72 %RH, about seven times greater than the RMS of sensor pre-cal residuals. Thus, significant sensor drift had occurred between calibrations. Mean

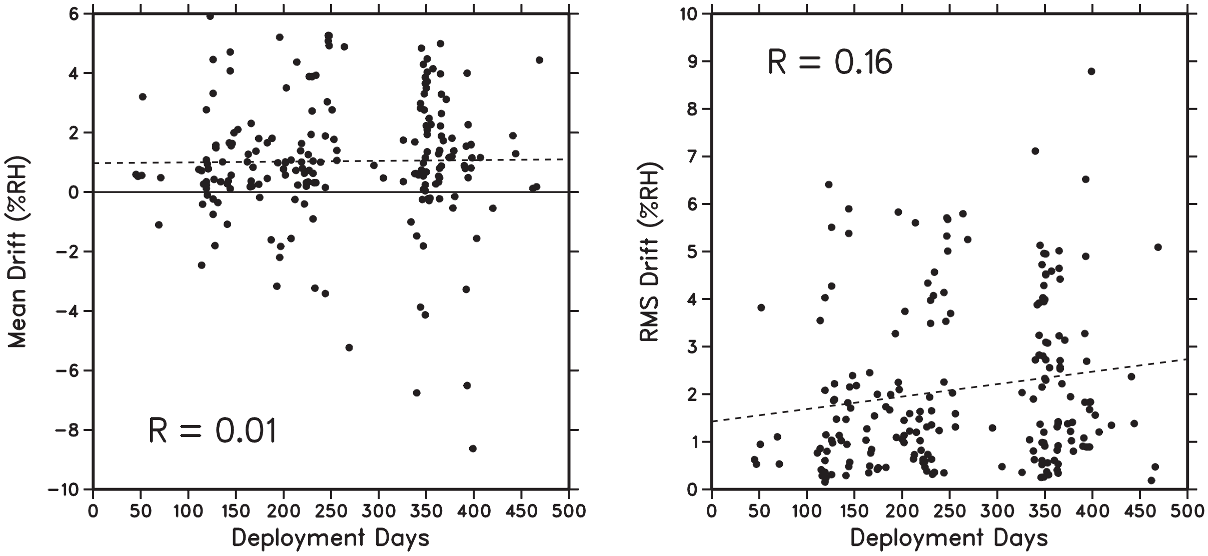

Figure 6: Mean (left panel) and RMS (right panel) differences between pre-deployment and post-recovery calibration of humidity sensors plotted versus the number of days each sensor was deployed at sea. The dashed lines represent a linear, least-squares fit to the data. R is the correlation coefficient.

differences were about 1/3 of RMS differences and positive, indicating that on average the sensors were reading about 1.0 %RH low when recovered. Based on a much smaller number of calibrations, Freitag *et al.* (1994) estimated relative humidity sensor RMS drift to be 4 %RH. Modifications to the sensors combined with improved sensor calibration techniques have decreased the error estimate by more than 1 %RH.

9.2 Relative Humidity I/O Board

The mean difference between 223 RH I/O calibration pairs was −0.02 %RH and the RMS difference was 0.21 %RH (Table 5). The mean difference being near zero indicated that there was no preferred direction of drift. The RMS was about one half the resolution of the calibration data. This indicates that there was little or no measurable drift in RH boards between calibrations.

9.3 Air Temperature Sensor

RMS difference between 225 AT sensor calibration pairs was 0.157°C (Table 4), nearly an order of magnitude larger than the RMS maximum residual for AT sensors (Table 2), indicating that measurable drift had taken place. The observed RMS difference is comparable to the manufacturer's nominal drift rate of 0.2°C (Table 1). Mean AT difference was 0.025°C, indicating little or no preferred direction to the drift.

9.4 Air Temperature I/O Board

In computing drift statistics, a small number of calibration pairs (10 or about 5% of the total) were omitted as outliers. The pre-deployment calibrations

Table 6: Combined (sensor and I/O board) instrument error for NextGeneration ATLAS air temperature and relative humidity measurements based on unnormalized data in tables 4 and 5.

Sensor	Instrument Error
AT	0.22°C
RH	2.73 %RH

for all these cases were performed between January 1998 and January 1999, and had drifts between 0.5°C and 1.1°C, larger than any observed before or after. The majority of boards with pre-deployment calibrations during 1998 had drifts comparable to the overall ensemble. Beginning in 1998 and continuing throughout 1999, NextGeneration ATLAS electronics were upgraded by replacement of boards which included the sensor IO A/D components. It was intended that post-deployment calibrations would be performed before board replacement, but in several of the outlier cases it was found that the calibration pairs were not performed on identical electronics. In other cases the date of electronic upgrades was not documented. It was concluded that the large drifts in these cases were not representative of the true electronic performance and were not included in the computation of ensemble statistics.

RMS difference between 211 AT I/O board calibration pairs was 0.146°C (Table 5), less than twice the RMS maximum residual for individual AT I/O boards (Table 3), indicating that the drift in AT boards between calibrations was measureable and comparable to the sensor drift. The mean drift was –0.057°C, indicating little or no preferred direction to the drift.

10. Combined Instrument Error

The combined effect of I/O board and sensor drifts (i.e., instrument error) was computed as $(\mathrm{RMS}^2_{\text{board drift}} + \mathrm{RMS}^2_{\text{sensor drift}})^{1/2}$, which assumes that sensor and I/O board drifts were independent of one another. Using unnormalized data, instrumental error estimates for the RH sensor improved from 4.07 %RH in 1994 to 2.73 %RH in the present investigation (Table 6). We conclude that the lower instrument error estimate is due to the improved RH calibration procedure at PMEL and modifications to the sensor by the manufacturer.

AT instrument error estimates remained virtually unchanged from the previous study—0.20°C in 1994 compared to 0.22°C for the present study.

11. Summary

TAO air temperature and relative humidity sensor calibrations have been analyzed to estimate both their instrumental accuracy when first deployed and the calibration drift over time. Both air temperature and relative humidity are measured by the same sensor package, presently the model MP101A from Rotronic Instrument Corp. This study updates Freitag *et al.* (1994), which was repeated because the previous work was based on a fairly limited number of calibrations. In addition, since the publication of Freitag *et al.*, the sensors were upgraded by the manufacturer, the electronics were modified by PMEL, the calibration method for relative humidity was automated, and a new calibration standard was used.

The manufacturer's modifications to the air temperature sensor included improved nominal accuracy (from 0.5°C to 0.2°C) and lower power consumption. The PMEL circuitry was modified to increase resolution from 0.04°C to 0.01°C. The present PMEL estimate of combined (sensor and circuitry) instrumental error for TAO air temperature measurement is 0.22°C, virtually unchanged from the previous value. The fact that the previous PMEL estimate (0.20°C) was better than the manufacturer's nominal sensor accuracy at that time was because the manufacturer's estimate was based on nominal calibration coefficients and applicable to a wider temperature range, whereas PMEL sensors are individually calibrated over a reduced temperature range.

The changes to the relative humidity portion of the sensor included improved linearity and temperature compensation which lead to an improved nominal accuracy of 1% (when individually calibrated with a high accuracy standard). The PMEL circuitry was modified to increase resolution from 0.39 %RH to 0.02 %RH (for internally recorded data). A major modification to the PMEL calibration method was the replacement of saturated salt solutions for the calibration standard by a humidity chamber, plus automation of the procedure which standardized and increased sensor equilibration times. The combined (sensor and circuitry) error estimate for TAO relative humidity measurements is 2.73 %RH, which is an improvement of over 1 %RH from the 1994 estimate.

This PMEL error estimate is larger than the manufacturer's nominal value because the latter does not reflect environmental issues such as contamination of the sensor or its filter by salt. Analysis of calibration data has confirmed that after deployment at sea the time constant of these sensors can increase significantly, which results in overestimation of calibration drift estimates. Moreover, in some cases the post-recovery calibrations were found to not accurately reflect the sensor condition when recovered. This could be due to changes between recovery and calibration, e.g., drying and precipitation of salts on the sensor or filter.

A small (about 0.2 %RH) error due to the PMEL circuitry calibration firmware was discovered during the course of this study. This error will be eliminated in future versions of the firmware.

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Appendix: Specifications and Calibration of the Humidity Generator

The Thunder Scientific Humidity Generator uses a "two-pressure" method to humidify its chamber. It first saturates an air stream with water vapor at a set pressure and temperature, and then isothermally expands the stream into the chamber. The resulting chamber humidity is equivalent to the ratio of final to initial pressures. Corrections are applied both for minor temperature differences between the air stream and chamber, and for an "enhancement factor ratio" that takes into account the dependence of the effective saturation vapor pressure upon the absolute pressure as well as temperature (Thunder Scientific Humidity Generator manual).

The humidity generator is calibrated annually, alternately by the manufacturer or by PMEL. Calibrations at PMEL follow a procedure recommended by the manufacturer. The humidity generator's thermistors are calibrated by immersion in a water bath at three temperature set points that encompass the range of operating temperatures used at PMEL during RH sensor calibrations. Typical set points of 11°C, 26°C, and 40°C are controlled by a model 5010 Programmable Fluid Bath by Guildline Instruments, Ltd. A model SBE-03 temperature sensor from Sea-Bird Electronics, Inc. (calibrated annually by the manufacturer) is used as a temperature standard, and its frequency output is counted by an HP3457A Multimeter, manufactured by Hewlett-Packard Company. Depending on the range of operating pressure, calibration of the humidity generator's pressure gauges is performed by the application of either a high (0–150 psi) or low (0–50 psi) static pressure source of nitrogen gas. Three set points per source are chosen which span the full range of operating pressures. Typical set points are 15 psi, 30 psi, and 50 psi for the low-pressure source, and 30 psi, 100 psi, and 150 psi for the high-pressure source. A 0 to 1000 psi, model 6010-1660C Direct Reading Pressure Gauge and 6005 Pressure Controller, from Ruska Instrument Corp., are used as the pressure standard and source controller. A Digiquartz Barometer, model MET1-2, from Paroscientific, Inc. measures atmospheric pressure, for conversion of the Ruska standard's psi readings to psia. The Ruska standard is calibrated bi-yearly by the manufacturer. The accuracies of the temperature standard, the pressure standard/controller, the temperature bath and other associated test equipment (tabulated below) are comparable to or exceed those required by Thunder Scientific for humidity generator calibrations. For each transducer, the generator's circuitry produces three raw counts and solves three quadratic equations, internally making any needed adjustments to the transducer and iterating the process until the desired tolerances are attained. Following this calibration procedure, the generator is specified to have an accuracy of ±0.5 %RH over the operating range 10–95 %RH.

Table A1: Test equipment accuracy standards.

Instrument:	**Specifications:**
Thunder Scientific 2500 Two-Pressure Humidity Generator	RH Range = 10% to 95% RH Resolution = 0.02% RH Accuracy = ±0.5% at the chamber pressure and temperature Temperature Range = 0 to +70°C Temperature Resolution = ±0.02°C Temperature Uniformity = ±0.1°C Temperature Accuracy = ±0.06°C
HP3457A Multimeter	Voltage Accuracy = ±0.00254% of reading, from 0 to 1 V 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 = −5.0 to +35°C Accuracy = ±0.001°C Stability = 0.002°C per year, typical
SBE-03 Thermometer & HP3457A Multimeter System	Temperature Accuracy* = ±0.005°C Temperature Resolution* = 0.0005°C
Guildline Model 5010 Programmable Fluid Bath	Range = −9.90 to +65.00°C Resolution = 0.01°C Stability = ±0.002°C
Ruska 6010-1660C Pressure Gauge and 6005 Pressure Controller	Range = 0 to 1000 psig Resolution = 0.01 psia Accuracy* = ±0.027 psia from 0 to 136 psi (14 to 150 psia) Stability (control mode noise) = 0.01 psia Repeatability ≤ ±0.02 psia
Paroscientific Digiquartz Barometer, Model MET 1-2	Range = 11.5 to 16 psia Accuracy = ±0.01% of reading Stability (drift) <0.00145 psia per year Repeatability = ±0.003% of reading

*When combining specifications from two instruments, manufacturer specifications listed as % reading values were converted to physical units using the scales and readings appropriate for the calibrations. The Ruska Pressure Gauge specifications were calculated using the typical 11 ppm error in the standard that was used to calibrate the gauge in year 2001.