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Calibration procedures and instrumental accuracies for ATLAS wind measurements

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Contents

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Abstract. We describe calibration procedures and instrumental accuracies for wind speed and direction on Autonomous Temperature Line Acquisition System (ATLAS) buoys deployed in the tropical Pacific and Atlantic Oceans. Accuracy of wind speed measurements over a range of 1 m s^{-1} to 20 m s^{-1} is estimated as 0.3 m s^{-1} or 3% of the speed, whichever is greater. A conservative estimate for root-mean-square (RMS) wind direction error for sensors deployed before November 2000 is 7.8°, of which 6.8° is a mean error in a counterclockwise direction. Beginning in November 2000, wind sensors on ATLAS moorings were modified to correct for this direction bias. Wind direction errors from modified sensors are expected to be reduced to about 5° RMS with minimal bias.

1. Introduction

The Tropical Atmosphere Ocean (TAO) Array was initiated as an in situ observing system contribution to the Tropical Ocean-Global Atmosphere (TOGA) Program, a 10-year (1985–1994) study of climate variability on seasonal to interannual timescales, the most pronounced mode of which is the El Niño/ Southern Oscillation (ENSO) phenomenon (McPhaden *et al.*, 1998). The array consists of approximately 70 deep-ocean moorings spanning the equatorial Pacific Ocean between 8°S and 8°N from 95°W to 137°E and typically separated by 2–3° latitude and 10–15° longitude (Fig. 1a). The majority of moorings are ATLAS moorings (Hayes *et al.*, 1991). The array has continued after TOGA as a major component of the ENSO Observing System under the auspices of the international Climate Variability and Predictability (CLIVAR), Global Ocean Observing System (GOOS), and Global Climate Observing System (GCOS) programs. As of January 2000, the westernmost portion of the array is maintained by Japan Marine Science and Technology Center (JAMSTEC), which deploys Triangle Trans-Ocean buoy network (TRITON) moorings between 138°E and 156°E. The TAO/TRITON array, as it is now known, is supported primarily by the United States (NOAA) and Japan (JAMSTEC) with contributions from France via the L'Institut de Recherche pour le Développement (IRD). TAO collaboration with France (through IRD) and Brazil (through the Instituto Naçional de Pesquisas Espaçiais or INPE) led to the development of the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), a similar array of ATLAS moorings in the tropical Atlantic (Fig. 1b) (Servain *et al.*, 1998).

ATLAS moorings were developed by NOAA's Pacific Marine Environmental Laboratory (PMEL). Standard ATLAS measurements include surface wind, air temperature, relative humidity, sea surface temperature, and subsurface temperature to a depth of 500 m. Recent development of Next

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Table 1: Manufacturer's specifications for TAO wind speed and direction sensors.

Measurement	Sensor type	Manufacturer/Model	Specifications
Wind speed	Propeller	R.M. Young/05103	Maximum Speed: 60 m s^{-1} Threshold: 1.0 m s^{-1} Accuracy: $\pm$0.3 m s^{-1}
Wind direction	Vane	R.M. Young/05103	Range: 0–355° Threshold: 1.1 m s^{-1} Accuracy: $\pm$3°
	Fluxgate compass	EG&G/63764 or KVH/LP101-5	Range: 0–360° Accuracy: 5°

Generation ATLAS moorings added the option to measure rainfall, short- and long-wave radiation, barometric pressure, salinity, and ocean currents. Data are transmitted daily to shore via NOAA polar-orbiting satellite by Service Argos and made available on the World Wide Web at `http://www.pmel.noaa.gov/tao/`. Data are also submitted to the Global Telecommunications System (GTS) by Service Argos. Moorings are generally designed for a nominal 1-year deployment.

Calibration techniques and estimated accuracy for TAO temperature, relative humidity, and short-wave radiation measurements are described by Freitag *et al.* (1994). This report covers the calibration techniques and estimated accuracies of wind speed and direction measurements from TAO moorings as performed at PMEL by TAO technicians. Calibrations of sensors are performed both prior to deployment and after recovery, unless lost or damaged.

Wind speed and direction relative to the buoy are measured with an R.M. Young Co. model 05103 propeller/vane wind monitor on both Standard and Next Generation ATLAS moorings. Buoy orientation relative to magnetic north is measured by a fluxgate compass, either EG&G model 63764 or KVH model LP101-5. Manufacturer's specifications are listed in Table 1. The electronics hardware and firmware components that digitize and record sensor outputs and transmit averaged data were designed by PMEL's Engineering Development Division (EDD) and constructed by TAO Project technicians.

2. Sensor Operation and Calibration

2.1 Wind speed

Wind speed is measured with a four blade, 18 cm diameter $\times$ 30 cm pitch helicoid propeller anemometer (Fig. 2), manufactured by R.M. Young of Traverse City, Michigan. Rotation of a magnet on the propeller shaft produces an AC sine wave with output frequency proportional to the wind speed. The output signal is induced in a centrally mounted coil by a six-pole permanent magnet attached to the propeller shaft; thus for every rotation of the propeller, there are three complete cycles of output.

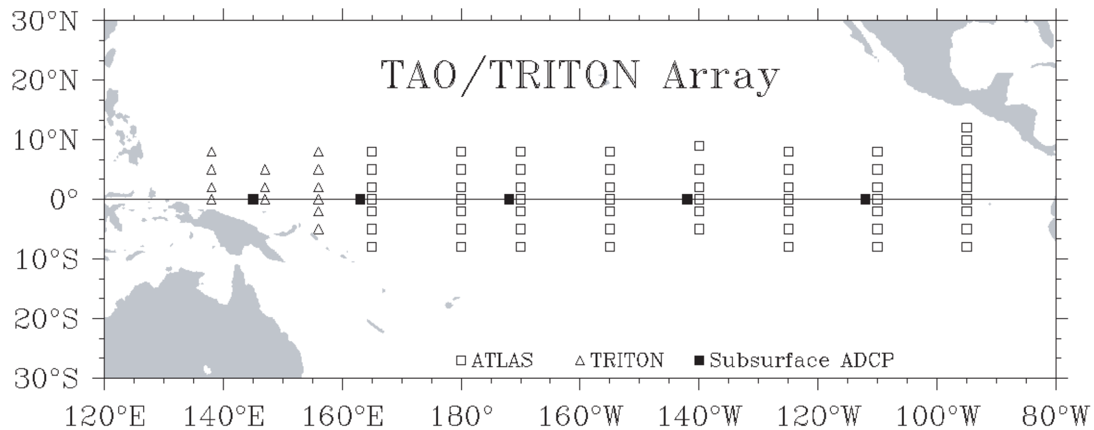

Figure 1a: Map of the TAO/TRITON Array. In addition to the ATLAS and TRITON moorings there are 5 subsurface ADCP (Acoustic Doppler Current Profiler) moorings deployed along the equator.

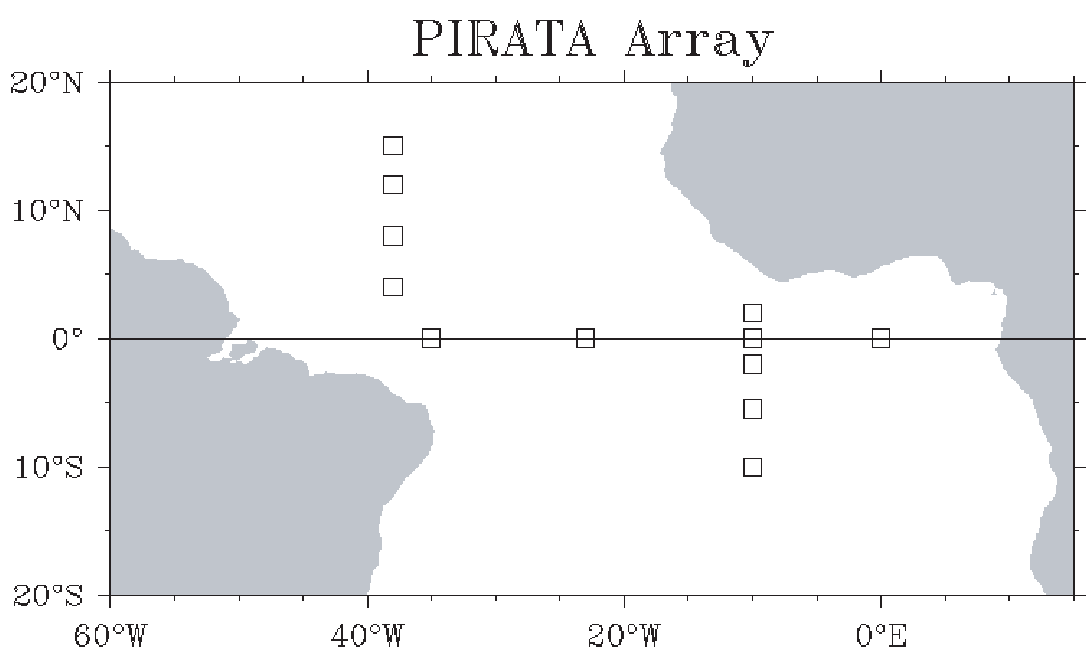

Figure 1b: Map of the PIRATA Array.

Figure 2: Repairing sensors on an ATLAS Mooring.

Speed calibrations are performed in an on-site wind tunnel. The PMEL standard anemometer is an R.M. Young model 27106T propeller anemometer, which is calibrated by R.M. Young on an annual basis by comparison to an identical model calibrated by the National Institute of Standards. The wind tunnel has a 1.08 square meter rectangle closed test section 8 m long with straight walls and an open return. The test instrument and a standard are attached on side-by-side stands in the wind tunnel test section. The two are monitored for 90 s at each of 8 settings from approximately 1 to 20 m s^{-1}. A software program reads the voltage output from the standard and the frequency output (expressed in counts) from the test instrument. The frequency output of the test instrument is digitized by circuitry identical to that used on the moorings. Voltage from the standard is converted to speed using a calibration transfer function as determined by R.M. Young. Calibration coefficients for the test instrument are computed from a linear least-squares fit between the wind speed from the standard and the counts from the test instrument. Residual differences between the speed of the standard and that predicted by the linear least-squares fit to the test sensor output are used to evaluate the test sensor performance. Generally a sensor fails the calibration and is not used on a mooring if the residual at any test point is greater than 0.2 m s^{-1}. A sample calibration is shown in Figs. 3a and 3b and included in Appendix A.

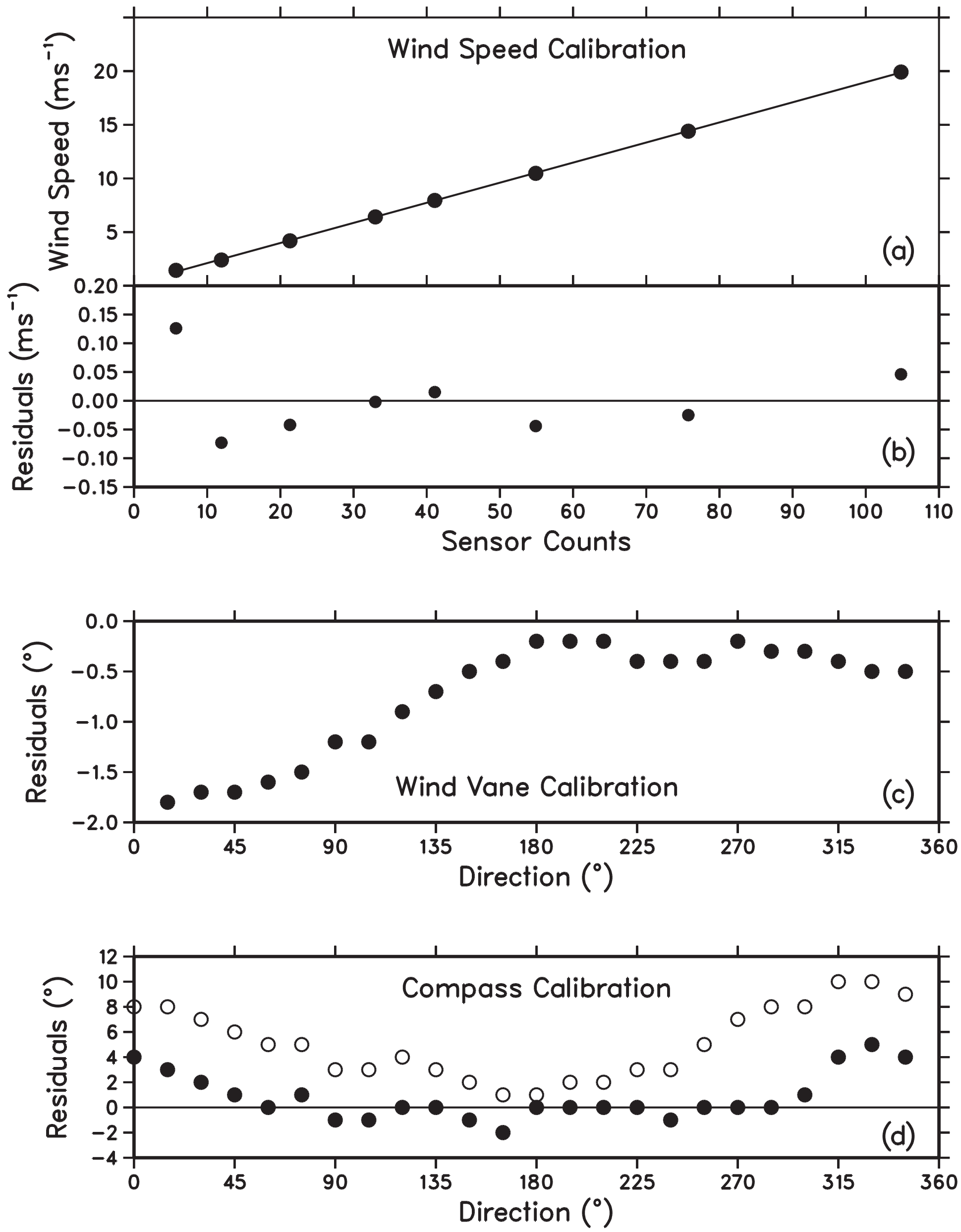

Figure 3: Sample pre-deployment calibrations. (a) Wind speed versus sensor counts (solid circles) and computed calibration equation (line). (b) Residual difference between calibration fit and measured wind speed. (c) Residual between wind vane set point and sensor output. (d) Residual between compass set point and sensor output. Open circles are uncorrected. Solid circles are corrected.

2.2 Wind vane

The vane measurement is made with a potentiometer within the anemometer assembly. The vane assembly rotates freely on a vertical shaft and is coupled to the middle arm of a 10 kΩ precision potentiometer. A regulated constant voltage is applied to the ends of the potentiometer and the resulting output voltage from the middle arm is directly proportional to the angle of the vane. The potentiometer has an open section resulting in a dead zone of nominally 5° which is near the 0° orientation.

Prior to deployment, calibration checks are performed by TAO technicians, during which a voltage of 3.55 V is applied across the potentiometer. The orientation of the potentiometer is then adjusted such that an output reading of 1.8 V from the middle arm corresponds to a vane orientation of 180°. The output voltage is then read at 15° intervals through its entire range. In general, if the error at any test point is greater than 5° the sensor fails the calibration and is not used until it is repaired. For sensors that pass pre-deployment tests and are subsequently deployed, the calibration check is repeated after the sensor is recovered. If a wind sensor has been deployed for more than 6 months the potentiometer is replaced when returned to the lab and its calibration rechecked before re-deployment. A sample vane calibration check is shown in Fig. 3c and included in Appendix B.

Vane calibrations as described above check the accuracy of the vane potentiometer alone. In this regard, vane calibrations differ from those of the compass which combine sensor and digitization electronics. Analog to digital (A/D) converters and their related electronic components were designed to be linear to within 1 bit ($\sim$1.4°). For Standard ATLAS systems, individual A/Ds were not routinely checked for accuracy. On Next Generation systems, however, each A/D circuit is checked for accuracy and RMS errors have been confirmed to be within the 1 bit design criteria.

While documenting the vane calibration procedures for this report, it was found that the potentiometer polarity was reversed during calibrations relative to that during field measurements. The effect of this error was such that the dead zone, which was thought to be near the range 355° to 0°, was in fact near 0° to 5°. This rotation introduced a counterclockwise bias when deployed, i.e., the vane output would be about 5° lower than the true orientation. We refer to this as the alignment error.

An error in the digitization of the vane output was also found during the preparation of this document. When computing vector components of wind velocity (see section 3) the instrument software assumed that each vane count represented approximately 1.4°, so that the full range of values (360°) was represented by counts from 0 to 255. In actuality, the digitization did not account properly for the 5° dead zone, so that the full range of counts (255) was output over a range of 355°. This firmware error, which was only present in Next Generation ATLAS systems, caused vane values to be high by about 1%.

It was also found that modification of a component in the vane digitization circuitry would improve its accuracy. The circuitry employs a pulldown resistor to force the vane output to zero when in the 5° dead zone. The value of the resistor caused vane values to be low by about 1% when outside the dead zone. By changing the value of the pulldown resistor, this circuitry error was decreased to about 0.2%. This circuitry error was in both Standard and Next Generation ATLAS systems. Both firmware and circuitry errors are gain errors and theoretically range from negligible values for vane orientations near 0° to a maximum of 3.6° at an orientation of 355°. Note also that firmware and circuitry errors are of opposite sign, and in theory would compensate each other on Next Generation systems.

In late 2000, modifications were made to the vane alignment, firmware and circuitry to correct for these errors. The calibration procedure was also modified so that the vane output is now digitized with circuitry identical to that used on the moorings, as opposed to the previous method of only recording the analog output of the sensor.

2.3 Compass

The compass bearing of the buoy is measured with a magnetic flux gate compass. Standard ATLAS buoys were typically equipped with model 63764 compasses manufactured by EG&G of Herndon, Virginia. EG&G stopped the manufacture of this compass around 1996, just as the Next Generation ATLAS was being developed. New Next Generation buoys were typically equipped with model LP101-5 compasses manufactured by KVH of Middletown, Rhode Island. However, the different compasses can be used interchangeably in either type of ATLAS buoy, and EG&G compasses are used in Next Generation buoys as Standard ATLAS systems are retired.

Primary coils in the compass are driven with a 400 Hz square wave excitation signal. Secondary coils produce an 800 Hz square wave output with a phase shift proportional to the direction of the ambient magnetic field. The phase shift is measured by a counter which measures the time between the leading edges of the 400 Hz excitation signal and the 800 Hz sensing signal. More details on the general operation of fluxgate compasses can be found in Watson (1992).

The fluxgate compass is housed in an aluminum tube with sensor I/O boards, memory, and batteries. To account for the field created by other electronics within this tube, the compass is calibrated after assembly of the tube is complete. Calibrations are performed prior to deployment and are checked again after recovery.

To calibrate the compass, the tube is attached to a compass calibration stand and aligned to magnetic north. The area near the calibration stand was surveyed for magnetic anomalies before installation and the stand was carefully orientated relative to local magnetic north. An independent check of the stand in April 2001 indicated that its orientation was correct to within 0.25° (Capt. Keith Sternberg, Sternberg Compass Adjusting and Nautical Instrument Repair, personal communication).

During the compass calibration, the tube is rotated in 45° increments through 360° clockwise then repeated counterclockwise. An average of the clockwise and counterclockwise readings are made for each increment. From differences between the raw compass output and its known orientation, firmware internal to the tube (based upon a method outlined in Defense Mapping Agency Publication No. 226) then creates a table of corrections to reduce the size of the raw compass errors. Using the table, the compass is retested at 15° increments. Residual errors (differences between the set orientation and that reported by the corrected compass) are recorded to the nearest degree. Prior to deployment, the maximum residual error allowed at any test point is 5°. Instruments with residuals larger than 5° are generally not deployed. In a few rare cases, compasses with pre-deployment errors of up to 8° at one or two calibration points, but with mean errors less than 1° and RMS errors less than 4° were deployed when no other compass was available. A sample calibration is shown in Fig. 3d included in Appendix C.

3. Data Acquisition

Anemometer and compass outputs are measured simultaneously at a 2-Hz rate and converted to vector-averaged orthogonal wind components. Mean wind components are recorded over averaging periods of 6 min once per hour on standard ATLAS moorings and 2 min every 10 min on Next Generation ATLAS moorings.

The onboard processing of the wind velocity components is a multi-stage process. First, the sensors sample the environment and generate an analog signal. Next, input/output (I/O) boards, designed at PMEL, convert the analog signals to digital counts. The analog signal from the wind speed sensor is digitized by a frequency counter, reporting the number of cycles counted in a 0.5 s interval. Resolution is approximately 0.2 m s^{-1} per count. At the same 2-Hz rate, voltage from the anemometer vane is passed through an A/D converter, and stored in memory, with a resolution of approximately 1.4° per count. The phase shift of the compass is likewise digitized to a value with resolution of approximately 1.4° per count. Compass and vane are summed to give wind direction relative to magnetic north. Orthogonal components of the wind direction are obtained from a set of trigonometric lookup tables which are then applied to the wind speed to give zonal (east–west) and meridional (north–south) wind components. These components are accumulated at the 2-Hz rate, averaged, and stored.

Wind direction as reported by the mooring is relative to magnetic north. Rotation to true north is performed after the data are telemetered to shore, by applying the magnetic variation for the specific location of the buoy.

4. Estimation of Sensor Accuracy

Accuracies are estimated from an ensemble of pre-deployment and post-recovery calibrations performed on each of the three types of sensors; wind speed, wind vane, and compass. Calibration residuals of pre-deployment calibrations are used to estimate expected instrumental errors when moorings are first deployed. Differences between pre-deployment and post-recovery calibrations are used to estimate calibration stability while deployed.

Table 2: Wind sensor calibration statistics. Coefficients A0 and A1 are the y-intercept and slope of the linear calibration equation. The maximum residual for a given calibration is the largest absolute difference between the wind tunnel speed and that predicted by the calibration equation. N is the number of instruments calibrated over which the statistics are computed. Units of A0 and maximum residual are m s^{-1}, and m s^{-1} per count for A1.

	N	**Minimum**	**Maximum**	**Mean**	**Standard deviation**	**RMS**
Pre-deployment A0	856	–0.11	0.57	0.21	0.11	0.23
Pre-deployment A1		0.179	0.206	0.195	0.004	0.195
Pre-deployment maximum residual		–0.26	0.33	0.05	0.13	0.14
Post-recovery A0	240	–0.13	0.75	0.08	0.10	0.13
Post-recovery A1		0.183	0.206	0.197	0.004	0.197
Post-recovery maximum residual		–0.32	0.69	0.02	0.14	0.14
All A0	1096	–0.13	0.75	0.18	0.12	0.21
All A1		0.179	0.206	0.195	0.004	0.195
All maximum residual		–0.32	0.69	0.04	0.14	0.14

4.1 Wind speed

A total of 1096 wind speed calibrations performed between 1991 and 1999 were analyzed, of which 856 were pre-deployment calibrations and 240 were post-recovery calibrations (Table 2). Wind sensor calibration coefficients consist of a y-intercept (A0) and slope (A1) of the linear calibration equation. Most of the calibration statistics were not significantly different between the pre-deployment and post-recovery calibrations. The RMS of maximum calibration residuals (0.14 m s^{-1}) did not vary between pre-deployment and post-recovery calibrations. The mean slope coefficient, A1, increased by only 1% between pre-deployment and post-recovery calibrations and the standard deviation of A1 did not differ between the two. The mean y-intercept coefficient, A0, for post-recovery calibrations was less than half the pre-deployment value (0.08 m s^{-1} vs. 0.21 m s^{-1}). However, the difference (0.13 m s^{-1}) is small in absolute terms. Mean differences in A0 and A1 compensate each other, so that computed wind speeds, if based on either pre-deployment or post-recovery mean values, would be nearly the same. At wind speeds of 1 m s^{-1}, values computed from mean pre-deployment coefficients are about 0.1 m s^{-1} larger than values computed from mean post-recovery coefficients; at 10 m s^{-1} differences are near zero, and at 20 m s^{-1} speeds computed from pre-deployment values are about 0.1 m s^{-1} smaller.

From the 1096 calibrations above, 168 pre-deployment/post-recovery calibration pairs were analyzed for individual sensor calibration drift. For each calibration pair, differences in wind speed from application of pre-

Table 3: Wind speed difference between pre-deployment and post-recovery calibrations, normalized to one-year. Percent differences are RMS differences divided by the nominal wind speed.

Nominal wind speed ($m\ s^{-1}$)	Mean difference ($m\ s^{-1}$)	Standard deviation difference ($m\ s^{-1}$)	RMS difference ($m\ s^{-1}$)	Percent difference
1	−0.20	0.19	0.27	27.4
2	−0.18	0.17	0.25	11.7
3	−0.17	0.15	0.23	7.4
4	−0.15	0.15	0.22	5.3
5	−0.14	0.15	0.21	4.1
6	−0.13	0.17	0.21	3.5
7	−0.11	0.18	0.21	3.1
8	−0.10	0.21	0.23	2.8
10	−0.07	0.26	0.27	2.7
12	−0.04	0.32	0.32	2.7
14	−0.01	0.39	0.39	2.8
16	0.02	0.45	0.45	2.8
18	0.04	0.52	0.52	2.9
20	0.07	0.59	0.59	3.0

deployment vs. post-recovery calibration coefficients were computed at nominal speed values between 1 m s^{-1} and 20 m s^{-1}, at 1 m s^{-1} to 2 m s^{-1} increments. Typically, moorings are deployed for about 1 year, so differences have been normalized to annual values, based on the actual number of days deployed at sea (Table 3). It is presumed that sensor drifts result from mechanical wear and/or corrosion occurring over the time that a sensor was in the field.

Annual drift rates (based on RMS differences) ranged in absolute terms from 0.2 m s^{-1} to 0.6 m s^{-1}, with larger values at higher wind speeds. Alternately, we can characterize the drift as being less than or equal to 0.3 m s^{-1} or 3% of the measured value, whichever is larger. The sense of the mean differences implies that, on average, recovered sensors are slightly overestimating low wind speeds and slightly underestimating high wind speeds.

4.2 Wind vane

The vane error was first evaluated by considering a large number of calibrations made over several years, but before the alignment, firmware and circuitry problems described in section 2.2 were discovered. These early calibrations are reported here since they provide important information related to error variance and stability over time. A second, smaller set of calibrations were performed recently to measure the total error including combined firmware, circuitry, and alignment biases.

A total of 303 anemometer vane calibration checks performed in 1997 through 2000 were examined, of which 188 were pre-deployment calibration checks and 115 were post-recovery calibration checks (Table 4). The mean

Table 4: Vane calibration error statistics for calibration checks made before firmware, circuitry, and alignment errors were discovered. N is the number of instruments calibrated. Negative values imply that measured orientation is clockwise, or to the right, of the true orientation.

Type	N	Minimum (deg.)	Maximum (deg.)	mean (deg.)	Standard Deviation (deg.)	RMS (deg.)
Pre-deployment	188	–5.7	5.8	−0.28	1.13	1.16
Post-recovery	115	−22.5	14.0	−1.01	3.19	3.23
All	303	−22.5	14.0	−0.56	2.14	2.19

error was small (−0.28°) for pre-deployment calibration checks, and only slightly larger (−1.01°) for post-recovery calibration checks. Thus the mean error did not change appreciably during deployment. Since mean errors were small, standard deviation and RMS error were nearly the same. The error standard deviation was 1.13° for pre-deployment calibration checks with a range of maximum errors of about ±6°. As would be expected, errors were larger for recovered sensors, with an error standard deviation of 3.19° and range from −22° to +14°. The error standard deviation was 2.14° for the combined set of pre-deployment and post-recovery instruments.

The location of the wind vane dead zone was also checked before deployment and after recovery of the sensors. The values presented here (Table 5) have been adjusted to reflect the alignment bias described in section 2.2. On average, the width of the dead zone was 3.9° for both pre-deployment and post-recovery checks, compared to a nominal value of 5° as specified by the manufacturer. The location of the dead zone typically rotated counterclockwise about 1° during deployment, which is consistent with the change in mean error in Table 4.

When in the dead zone, the vane orientation is reported as 0°. Therefore, on average, errors when in the dead zone would range from about −1° to +3° at deployment and about ±2° at recovery. These values are comparable in magnitude to ensemble errors outside the dead zone (given in Table 4).

Once the errors due to firmware, circuitry, and alignment errors were discovered, we checked 23 vanes by recording their digitized output with the alignment correctly measured. Of these, 21 had not been used in the field, and two had been used for a 2-month long test on land at the Woods Hole

Table 5: Average location of the vane dead zone. N is the number of instruments tested.

Type	N	Start (deg.)	End (deg.)	Width (deg.)
Pre-deployment	188	359.1	3.0	3.9
Post-recovery	115	358.2	2.1	3.9
All	303	358.8	2.7	3.9

Table 6: Vane calibration error statistics for calibration checks made after measurement errors were discovered. N is the number of instruments calibrated. Negative values imply that measured orientation is counterclockwise, or to the left, of the true orientation.

Type	N	Minimum (deg.)	Maximum (deg.)	Mean (deg.)	Standard deviation (deg.)	RMS (deg.)
Uncorrected	23	0.0	10.8	−6.8	2.0	7.1
Corrected for alignment	10	−0.9	9.8	−4.1	2.2	4.6
Corrected for alignment, firmware, and circuitry	20	−2.3	5.6	−1.0	1.3	1.6

Oceanographic Institution, near the seashore. The mean error for these vanes is clearly larger than that presented in Table 4 and is a better indication of true mean error characteristics. The mean error was $-6.8°$ (Table 6), the sign of which implies that vane readings were biased in the counter clockwise direction. For example, if the reported direction was 90°, the true direction would have been 96.8°. The error standard deviation was 2.0°, only 1° larger than the error standard deviation for pre-deployment calibration checks made previously (Table 4). This suggests that the combined firmware, circuitry, and misalignment errors can be characterized mainly as a mean bias.

Beginning in fall 2000 the vane alignment method, firmware, and circuitry were modified to improve the accuracy of the vane measurement. First, ten vanes were realigned and checked with the original firmware and circuitry. Compared to the uncorrected vanes, the mean and RMS error of this group decreased by 2.7° and 2.5°, respectively. Four anemometers from this group were deployed on moorings in October–November 2000. Soon after, a group of 20 vanes were evaluated using corrected alignment, firmware and circuitry. These modifications reduced the mean error for the ensemble to 1.0° and the RMS error to 1.6°, values that are comparable to the resolution (1.4°) of the digitization circuitry. Most moorings deployed in November 2000 and all moorings deployed thereafter had or will have vanes corrected for alignment, firmware, and circuitry.

4.3 Compass

A total of 355 compass calibrations performed in 1997 through 1999 were examined. Of these 244 were pre-deployment calibrations and 111 were post-recovery calibration tests. Pre-deployment calibrations for the two types of compass were similar with an overall RMS error of 1.44° for 244 calibrations (Table 7).

The RMS error for 111 EG&G post-recovery calibration tests was 2.38°. Note that while the mean error is small (0.61°), its sign is opposite to the mean vane error in Table 6. At the time of this analysis the number of recovered KVH compasses was much smaller and did not allow the compu-

Table 7: Compass calibration error statistics. N is the number of instruments calibrated. Positive values imply that measured orientation is clockwise, or to the right, of the true orientation. Note that the manufacturer of three compasses included in the "All Pre-deployment" group could not be identified and thus were not included in the EG&G or KVH groups.

Type	N	Minimum (deg.)	Maximum (deg.)	Mean (deg.)	Standard deviation (deg.)	RMS (deg.)
EG&G re-deployment	135	−7	7	0.04	1.42	1.42
KVH Pre-deployment	106	−6	8	0.33	1.41	1.45
All pre-deployment	244	−7	8	0.18	1.43	1.44
EG&G post-recovery	111	−10	10	0.61	2.31	2.38

tation of stable error statistics. However, preliminary indications are that the KVH post-recovery errors are somewhat larger than those of the EG&G. As more KVH calibrations become available their performance will be evaluated quantitatively.

4.4 Wind direction

The wind direction error, ϵ_{dir}, is the combined error of the compass, ϵ_{v}, and vane, ϵ_{c}. The mean direction error is given by

$$< \epsilon_{\text{dir}} >=< \epsilon_{\text{v}} > + < \epsilon_{\text{c}} >$$

where $< >$ designates ensemble means. In general, post-recovery sensors have larger errors, so use of post-recovery calibration statistics gives a more conservative (larger) error estimate. For the wind vane, most pre-deployment calibrations and all post-deployment calibrations available at this time are known to underestimate mean error due to the recently discovered errors in alignment, firmware, and circuitry. Therefore, we use the ensemble mean of $-6.8°$ from Table 6 as an estimate of $< \epsilon_{\text{v}} >$. As indicated in Table 4, the mean vane error differed by less than $1°$ between pre-deployment and post-recovery, thus use of the pre-deployment value from Table 6 is a reasonable choice. Mean compass errors (Table 7) are of opposite sign compared to mean vane errors and thus tend to compensate for vane errors. However, mean compass errors are small and only marginally different from zero. Therefore as a conservative estimate for mean direction error we assume a mean compass error of zero, so that the mean direction error, $< \epsilon_{\text{dir}} >$, is estimated to be $-6.8°$. The negative sign implies that the measured direction is counterclockwise, or to the left, of the true direction.

Assuming that the fluctuating components of the compass and vane errors are uncorrelated, an estimate for the standard deviation of wind direction errors may be computed as

$$\sigma = < {\epsilon'}^2{}_{\text{dir}} >^{\frac{1}{2}} = \left[< {\epsilon'}^2{}_{\text{v}} > + < {\epsilon'}^2{}_{\text{c}} > \right]^{\frac{1}{2}}$$

where $< \epsilon'^2{}_{\mathrm{v}} >$ is the standard deviation of the vane errors about its mean, and $< \epsilon'^2{}_{\mathrm{c}} >$ is the standard deviation of the compass errors about its mean.

A conservative estimate is obtained by using post-recovery values since, at the beginning of a deployment and for some time thereafter, errors would be smaller. Thus, we use 3.2° as the standard deviation for vane errors (Table 4) and 2.3° as the standard deviation of compass errors. This leads to an overall standard deviation of direction errors of 3.9°. Combining the mean and fluctuating components of the wind direction error then gives a conservative estimate of total direction error of

$$\text{RMS Wind Direction Error} = ((6.8)^2 + (3.9)^2)^{\frac{1}{2}} = 7.8^\circ$$

As noted in section 3.2, most sensors deployed in November 2000 and all thereafter have improved vane alignment, firmware, and circuitry. Initial calibrations of these modified systems indicate that post-recovery RMS vane errors should be reduced to around 3° with little or no mean bias. In the future, therefore, we expect that wind direction errors will be around 5° or less.

5. Summary

The RMS error estimate for wind speed measured on Standard and Next Generation ATLAS moorings was found to be less than or equal to 0.3 m s^{-1} or 3% of the speed, whichever is greater. This is a conservative estimate of overall instrumental error, as it was based upon the sensors' recovered state. When first deployed, the RMS error is estimated to be 0.14 m s^{-1} over wind speeds from 1 m s^{-1} to 20 m s^{-1}.

The RMS error estimate for ATLAS mooring wind direction was found to be 7.8°, most of which was due to a mean wind direction error of –6.8° (counterclockwise, or to the left, of the true direction). This bias was primarily due to a misalignment of the vane and a bias in the vane digitization firmware and circuitry. Calibration procedures and firmware versions have changed with time since the first ATLAS mooring was deployed in 1984. However, we believe that some mean direction bias has been present in the majority of historical ATLAS data, even though the time history of the error is not exactly known. Given the uncertainty in mean bias for older data, no correction will be made to archived data from Standard ATLAS systems.

On the other hand, calibration procedures and firmware versions for Next Generation ATLAS systems have been consistent with regard to vane processing. For this reason we plan to apply a mean direction correction to all data from Next Generation moorings. These moorings began entering the TAO Array in 1996 and will comprise 100% of the array after fall 2001. All moorings in PIRATA have been Next Generation systems. The 6.8° correction to be applied (Table 6) will be a significant improvement to data obtained from systems deployed before new alignment procedures and firmware were developed. It is estimated that the new alignment procedures and firmware will essentially eliminate the directional bias and lower RMS wind direction errors to about 5° or less in future deployments.

Direction bias between buoy winds and NSCAT satellite observations have been reported to be of order 8° (Dickinson *et al.*, 2001; Wentz and Smith, 1999). This bias is of similar magnitude and sign as that found in this study, indicating that a significant amount of the satellite-buoy bias reported previously may be due to the vane errors reported here. To our knowledge, however, no scientific study has been compromised as a result of biases in ATLAS wind directions.

6. Acknowledgments

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Appendix A: Sample wind speed calibration

The results of a wind speed calibration of a TAO anemometer. A0 and A1 are the calibration coefficients computed from a linear least-squares fit of the sensor output (counts) to the wind tunnel speed reported by a standard anemometer. Units (other than the sensor counts) are m s^{-1}.

```
Sensor serial number: 28510

A0 =  2.3924703e-01
A1 =  1.8729044e-01
```

Counts	Tunnel Speed	Sensor Speed	Residual
5.734	1.439	1.313	0.126
11.941	2.402	2.476	-0.073
21.311	4.188	4.231	-0.042
32.983	6.415	6.417	-0.002
41.095	7.951	7.936	0.015
54.896	10.477	10.521	-0.044
75.747	14.401	14.426	-0.025
104.812	19.916	19.870	0.046

```
MAXIMUM RESIDUAL =   0.1257
```

Appendix B: Sample wind vane calibration check

In the upper half of the form the sensor output (volts) is checked at 15° increments as recovered after use. In the lower half the sensor is rechecked after replacement and reorientation of the potentiometer. The location of the potentiometer dead zone is also measured.

Wind Sensor Data Sheet

Serial Number	08135	**Field Status**	
Configuration	Standard ATLAS ☒	Next Generation ☐	
Pot Scheduled for Replacement ?		(Yes, if deployed more than 6 months)	

Post Deployment

Speed Cal	Pass	**Date**	1/14/99	**Tech**	RL
Pot Check	Fail	**Date**	1/14/99	**Tech**	RL

Dead Zone	**Start**	**End**
CW	358	002
CCW	001	357

Degrees	**0**	**15**	**30**	**45**	**60**	**75**
Volts		0.127	0.276	0.424	0.573	0.723
Degrees	**90**	**105**	**120**	**135**	**150**	**165**
Volts	0.873	1.021	1.171	1.319	1.467	1.619
Degrees	**180**	**195**	**210**	**225**	**240**	**255**
Volts	1.769	1.918	2.069	2.215	2.361	2.489
Degrees	**270**	**285**	**300**	**315**	**330**	**345**
Volts	2.665	2.818	2.967	3.116	3.265	3.413

Maximum Residual	-0.023	**RMS**	19.692

Pot Replaced?	Yes	**Date**	6/18/99	**Tech**	RL

After Adjustments or Replacement

Date	7/9/99	**Tech**	DVK

Dead Zone	**Start**	**End**
CW	358	002
CCW	001	357

Degrees	**0**	**15**	**30**	**45**	**60**	**75**
Volts		0.132	0.283	0.433	0.584	0.735
Degrees	**90**	**105**	**120**	**135**	**150**	**165**
Volts	0.888	1.038	1.191	1.343	1.495	1.646
Degrees	**180**	**195**	**210**	**225**	**240**	**255**
Volts	1.798	1.948	2.098	2.246	2.396	2.546
Degrees	**270**	**285**	**300**	**315**	**330**	**345**
Volts	2.698	2.847	2.997	3.146	3.295	3.445

Maximum Residual	-0.002	**RMS**	2.052

Propeller Bearings Replaced?	Yes	**Date**	6/18/99	**Tech**	RL
Pre-Deployment Speed Cal	Pass	**Date**	6/18/99	**Tech**	RL

Other Maintenance

New needle, circuit board and bottom vane bearing 6-18-99

Comments

Appendix C: Sample compass calibration

Firmware in the ATLAS electronics leads the technician through the calibration procedure. The compass is first rotated 360° clockwise and its output recorded at 45° increments. The procedure is then repeated in the counterclockwise direction.

```
CAL.COMP
08/31/1999 20:36:04
Compass calibration
enter any comments desired.
end with <cr><cr>

PRECRUISE CAL OF TUBE 424T 31 AUG 99


Align the instrument to the angle
requested.  Type <CR> when ready,
<CONTROL-Z> to quit.


align the instrument to   0 degrees
Compass reading was   8 degrees   is this ok? Y
align the instrument to  45 degrees
Compass reading was  51 degrees   is this ok? Y
align the instrument to  90 degrees
Compass reading was  94 degrees   is this ok? Y
align the instrument to 135 degrees
Compass reading was 138 degrees   is this ok? Y
align the instrument to 180 degrees
Compass reading was 181 degrees   is this ok? Y
align the instrument to 225 degrees
Compass reading was 228 degrees   is this ok? Y
align the instrument to 270 degrees
Compass reading was 276 degrees   is this ok? Y
align the instrument to 315 degrees
Compass reading was 325 degrees   is this ok? Y
align the instrument to 360 degrees
Compass reading was   8 degrees   is this ok? Y
align the instrument to 315 degrees
Compass reading was 325 degrees   is this ok? Y
align the instrument to 270 degrees
Compass reading was 276 degrees   is this ok? Y
align the instrument to 225 degrees
Compass reading was 228 degrees   is this ok? Y
align the instrument to 180 degrees
Compass reading was 181 degrees   is this ok? Y
align the instrument to 135 degrees
Compass reading was 136 degrees   is this ok? Y
align the instrument to  90 degrees
Compass reading was  94 degrees   is this ok? Y
align the instrument to  45 degrees
Compass reading was  51 degrees   is this ok? Y
```

Next the firmware calculates a table of corrected compass values for each of the 256 possible raw compass output values. This table is stored onboard the instrument and corrects the compass in real time. The coefficients, P0 through P4 may be used to rebuild the table, should it be corrupted in the firmware.

```
Calculating table...
P0=  -312
P1=  50
P2=  -100
P3=  50
P4=  75
```

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
F10000	FD	FD	FF	00	01	02	03	04	05	06	07	08	09	0A	0B	0C
F10010	0D	0E	0F	10	11	12	13	14	15	16	17	18	19	1A	1B	1C
F10020	1D	1E	1F	20	21	22	23	24	25	26	27	28	29	2A	2B	2C
F10030	2D	2E	2F	30	31	32	33	34	35	36	37	38	39	3A	3B	3C
F10040	3D	3E	3F	40	41	42	43	44	45	46	47	48	49	4A	4B	4C
F10050	4D	4E	4F	50	51	52	53	54	55	56	57	58	59	5A	5B	5C
F10060	5D	5E	60	61	62	63	64	65	66	67	68	69	6A	6B	6C	6D
F10070	6E	6F	70	71	72	73	74	75	76	77	78	7A	7B	7C	7D	7E
F10080	7F	80	81	82	83	84	85	86	87	88	89	8A	8B	8C	8D	8E
F10090	8E	8F	90	91	92	93	94	95	96	97	98	99	9A	9B	9C	9D
F100A0	9E	9F	A0	A1	A1	A2	A3	A4	A5	A6	A7	A8	A9	AA	AB	AC
F100B0	AD	AE	AE	AF	B0	B1	B2	B3	B4	B5	B6	B7	B8	B9	BA	BB
F100C0	BC	BD	BE	BE	BF	C0	C1	C2	C3	C4	C5	C6	C7	C8	C9	CA
F100D0	CB	CC	CD	CE	CF	D0	D1	D2	D3	D4	D5	D6	D7	D8	D9	DA
F100E0	DB	DC	DD	DE	DF	E0	E2	E3	E4	E5	E6	E7	E8	E9	EA	EB
F100F0	EC	ED	EE	EF	F0	F1	F2	F3	F4	F5	F6	F7	F8	FA	FB	FC
F10100	08	31	19	99	00	00	7F	69	FF	FF	FF	FF	FF	FF	FF	FF

The compass is rotated again. This time the corrected compass output is recorded at 15° increments. Angles are computed from the compass output (counts) by application of the factor 360/256.

```
do you want a cal test? Y
08/31/1999 20:39: 27
Compass calibration
enter any comments desired.
end with <cr><cr>

TEST 424 31 AUG 99

Enter the test angle value, then <enter>.
The system will respond with the calibrated
value for that angle.
TO QUIT enter an angle value of 999.
```

TEST ANGLE	CORRECTED ANGLE	RAW ANGLE	CORRECTED CNTS	RAW CNTS
0	4	8	3	6
15	18	23	13	16
30	32	37	23	26
45	46	51	33	36
60	60	65	43	46
75	76	80	54	57
90	89	93	63	66
105	104	108	74	77
120	120	124	85	88
135	135	138	96	98
150	149	152	106	108
165	163	166	116	118
180	180	181	128	129
195	195	197	139	140
210	210	212	149	151
225	225	228	160	162
240	239	243	170	173
255	255	260	181	185
270	270	277	192	197
285	285	293	203	208
300	301	308	214	219
315	319	325	227	231
330	335	340	238	242
345	349	354	248	252
360	4	8	3	6
999				

```
done testing
```