NOAA Technical Memorandum OAR PMEL-150
doi: 10.25923/bn0n-3g25

GLOBAL TROPICAL MOORED BUOY ARRAY: WIND DIRECTION ACCURACY REVISITED

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Pacific Marine Environmental Laboratory
Seattle, Washington
November 2019

UNITED STATES DEPARTMENT OF COMMERCE
Wilbur Ross
Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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Office of Oceanic and Atmospheric Research
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NOTICE from NOAA

Contribution 4903 from NOAA Pacific Marine Environmental Laboratory

Contribution 2019-1032 from Joint Institute for the Study of the Atmosphere and Ocean (JISAO)

Also available from the National Technical Information Service (NTIS)

(http://www.ntis.gov)

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Global Tropical Moored Buoy Array: Wind Direction Accuracy Revisited

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Abstract. Wind direction measurement accuracy for Global Tropical Moored Buoy Array (GTMBA) moorings deployed by Pacific Marine Environmental Laboratory (PMEL) was estimated by analysis of pre-deployment and post-recovery calibrations of compasses and anemometer vanes. The results of more than 4000 pre-deployment and post-recovery calibrations of Next Generation Autonomous Temperature Line Acquisition System (NX-ATLAS) compasses and anemometer vanes were compiled. More than 300 compass and vane calibrations of a newer PMEL mooring system (known as T-Flex) were also analyzed. NX-ATLAS ensemble wind direction accuracy was estimated to be 2.1° when moorings were first deployed, increasing to 6.6° when recovered due to calibration drift of both the compasses and vane. Three types of compasses were employed in NX-ATLAS moorings over the past two decades. Systems with the three compass types had nearly equal pre-deployment wind direction accuracy. Root-mean-square differences in compass calibration drift resulted in post-recovery wind direction accuracy ranging from 5.1° to 8.4° for the three compass types. T-Flex wind direction accuracy was estimated to be 2.7° at deployment and 3.4° when recovered, although the number of post-recovery calibrations was relatively small: 32 compass calibrations and 22 vane calibrations. The present composition of PMEL-deployed GTMBA moorings is about half NX-ATLAS systems and half T-Flex systems, with the number of T-Flex systems expected to increase in the future.

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1. Introduction

The Global Tropical Moored Buoy Array (GTMBA) provides high-quality moored time series and related data throughout the global tropics for improved description, understanding, and prediction of seasonal to decadal time scale climate variability (McPhaden et al., 2010). The program is a contribution by NOAA and its partners to the Global Ocean Observing System, the Global Climate Observing System, and the Global Earth Observing System of Systems. Components of the array, which occupy each of the three tropical oceans, are supported by international cooperation and resource sharing between the United States, Japan, France, Brazil, India, Indonesia, and China. The Tropical Atmosphere Ocean (TAO) array in the Pacific was initiated in 1984 by NOAA's Pacific Marine Environmental Laboratory (PMEL) and transferred to the National Data Buoy Center (NDBC) of NOAA's National Weather Service in 2005, although PMEL continued to contribute NX-ATLAS systems to NDBC until 2012. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) operates the Triangle Trans-Ocean Buoy Network (TRITON) in the western Pacific. The Prediction and Research Moored Array in the Atlantic (PIRATA), begun in 1997, is the Atlantic Ocean component of GTMBA (Bourlès et al., 2008). It is operated by NOAA, France's Institut de Recherche Scientifique pour le Développement en Coopération (IRD), Meteo-France, and Brazil's Instituto Nacional de Pesquisas Espaciais (INPE) and Diretoria de Hidrografia e Navegacao (DHN). The Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA) is the tropical Indian Ocean component of the GTMBA (McPhaden et al., 2009). It is presently maintained by NOAA, JAMSTEC, India's Ministry of Earth Sciences (MoES), Indonesia's Agency for Meteorology, Climatology and Geophysics and Agency for the Assessment and Application of Technology (BMKG), and China's First Institute of Oceanography/State Oceanic Administration (FIO).

ATLAS (Autonomous Temperature Line Acquisition System) moorings have been the predominant mooring systems deployed in the GTMBA since 1984. The present NX-ATLAS (Next Generation ATLAS) was used extensively in all three tropical ocean basins beginning in 2000; it continues as a significant component of the Atlantic and Indian ocean arrays. Obsolescence of some components, technological advancements of commercially available instruments, and a new, more capable satellite telemetry system led PMEL to design and implement a replacement for the NX-ATLAS system. The new system, known as Flex, was first deployed by PMEL's Ocean Climate Stations (OCS) project beginning in 2007 at moorings in the Kuroshio Extension (KEO) and the Gulf of Alaska (PAPA). OCS moorings are designed for higher wind, current, and wave conditions than those typically found near the tropics. Beginning in 2011, a tropical version of the system, known as T-Flex (Freitag et al., 2018), was tested in PIRATA and RAMA. Flex and T-Flex share the same sensor suites, control electronics, firmware, and telemetry. At this time (2019), T-Flex systems occupy 61% of PIRATA sites (www.pmel.noaa.gov/gtmba/pirata-t-flex-implementation) and 39% of PMEL's RAMA sites that are currently implemented (www.pmel.noaa.gov/gtmba/rama-t-flex-implementation).

This work follows a previous analysis of ATLAS wind direction accuracy (Freitag et al., 2001). Wind direction is measured by two sensors (**Table 1**): a compass measuring the orientation of the anemometer base relative to magnetic north and a vane measuring the wind direction relative to the base of the anemometer. Two compass types had been used in NX-ATLAS systems at the time of the 2001 analysis, the EG&G model 63674 (referred to hereafter as the EG&G) and the KVH model LP101 (referred to hereafter as the KVH). At that time, the EG&G compass was no longer available from the manufacturer, but these compasses were being transferred from older, standard ATLAS systems to the NX-ATLAS. NX-ATLAS pre-deployment ensemble error statistics were found to be comparable for the two compass types, with mean errors of 0.04° for the EG&G (computed from 135 calibrations) and 0.33° for the KVH (106 calibrations). RMS errors were 1.42° and 1.45°, respectively, which were comparable to the ATLAS system resolution. The RMS error of the EG&G was well below the manufacturer's specified accuracy (5°) and the KVH slightly higher than its specified accuracy (1°). While not always clearly stated, manufacturer's specifications often refer to newly calibrated instruments and may not reflect drift over time. Post-recovery errors for 111 EG&G compass calibration checks were 0.61° in the mean and 2.38° RMS, within the specified accuracy. There were only a few post-recovery calibration checks available for KVH compasses in 2001, but it was noted that errors appeared to be somewhat larger than those of the EG&G. A third compass was added to the NX-ATLAS inventory in 2004, the KVH model C100 (referred to hereafter as the C100).

Freitag et al. (2001) documented the calibration accuracy of the NX-ATLAS anemometer (R.M. Young model 05103) vane. The propeller/vane anemometer swivels such that the propeller orients into the wind. The orientation of the vane is determined by measuring the output of a circular potentiometer, of which PMEL checks the calibration in the laboratory as described in Freitag et al. (2001). The physical structure of the circular potentiometer results in there being a nominal 5° "dead zone" near the 0° vane orientation. The potentiometer and related components (e.g., rotating shaft and bearings) are subject to wear and/or calibration drift and are checked both before and after deployment at sea. Errors in the vane alignment and calibration procedure were found to cause a mean bias of 6.8° in the vane reading. The RMS wind direction error (computed from compass and vane errors) was determined to be 7.8° for NX-ATLAS systems. Beginning in November 2000, corrections were made to the vane alignment and calibration procedure as well as improvements to system circuitry and firmware. The 2001 report suggested that

Table 1. Specifications for wind direction sensors as used on NX-ATLAS and T-Flex mooring systems.

Sensor	System	Manufacturer	Model	System Resolution	Manufacturer's Specified Accuracy
Compass	NX-ATLAS	EG&G	63764	1.4°	5°
	NX-ATLAS	KVH	LP-101	1.4°	1°
	NX-ATLAS	KVH	C100	1.4°	0.5°
	T-Flex	Sparton	SP3004D	0.1°	0.5°
Vane	NX-ATLAS	R.M. Young	05103	1.4°	3°
	T-Flex	Gill	Windsonic	1°	2°

wind direction error was expected to be about 5° for systems with these modifications. Henceforth, we refer to this as the target wind direction accuracy.

Flex and T-Flex systems employ the Sparton Navigation and Exploration model SP3004D compass, which has a resolution of 0.1° (compared to 1.4° for NX-ATLAS compasses). PMEL integrated the Sparton compass into the Gill Instruments, Ltd. Windsonic wind sensor and also into the Vaisala Corporation WXT series Weather Transmitter. The Gill instrument, deployed on all T-Flex moorings, has become the Flex standard anemometer. The Vaisala was used on some Flex moorings as a secondary sensor and on an experimental standalone real-time wind system using short burst data telemetry (SBD) developed at PMEL. Sparton compass calibrations analyzed here include those used in both the Gill and Vaisala instruments.

The ATLAS database now contains sufficient numbers of post-recovery calibrations from all compass types; this report details our reanalysis of the data for the EG&G and KVH compasses and the addition of the C100 compass to the analysis. We also provide an initial analysis of the Sparton compass, although the number of post-recovery Sparton calibration checks available was relatively small (32). The present analysis was based on NX-ATLAS calibration information within the project database in April 2018. The NX-ATLAS inventory had 98 systems available, of which 8% had EG&G compasses, 32% had KVH, and 60% had C100. The OCS, PIRATA, and RAMA databases were composed of calibrations of 75 Sparton compasses (as of June 2018). The databases contained calibrations made between April 1996 and March 2018 (**Figures 1** and **2**). Variations in annual numbers of calibration and differences between compass types reflect the evolution of the tropical arrays and commercial availability of specific compasses. Lower numbers after 2012 were due to PMEL no longer providing NX-ATLAS systems to NDBC for deployment in TAO. The increase in Sparton compass numbers tracks the implementation of T-Flex systems into PIRATA and RAMA. The decline in the numbers of EG&G and KVH compasses were due to the compasses no longer being in production by their manufacturers.

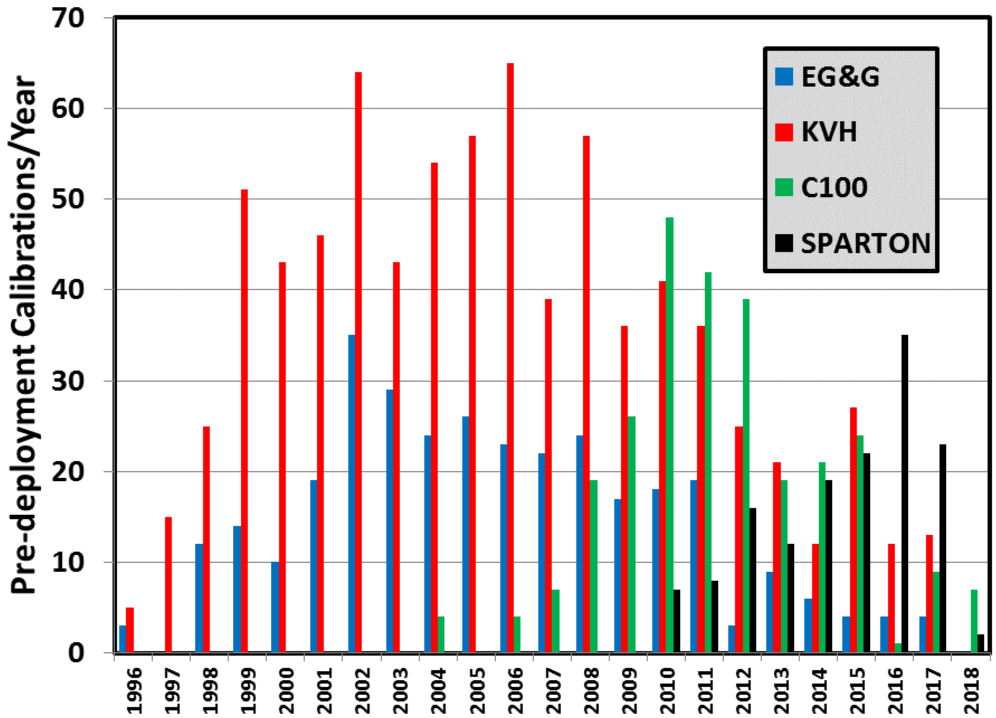

Figure 1. Number of pre-deployment compass calibration checks performed by year and compass type.

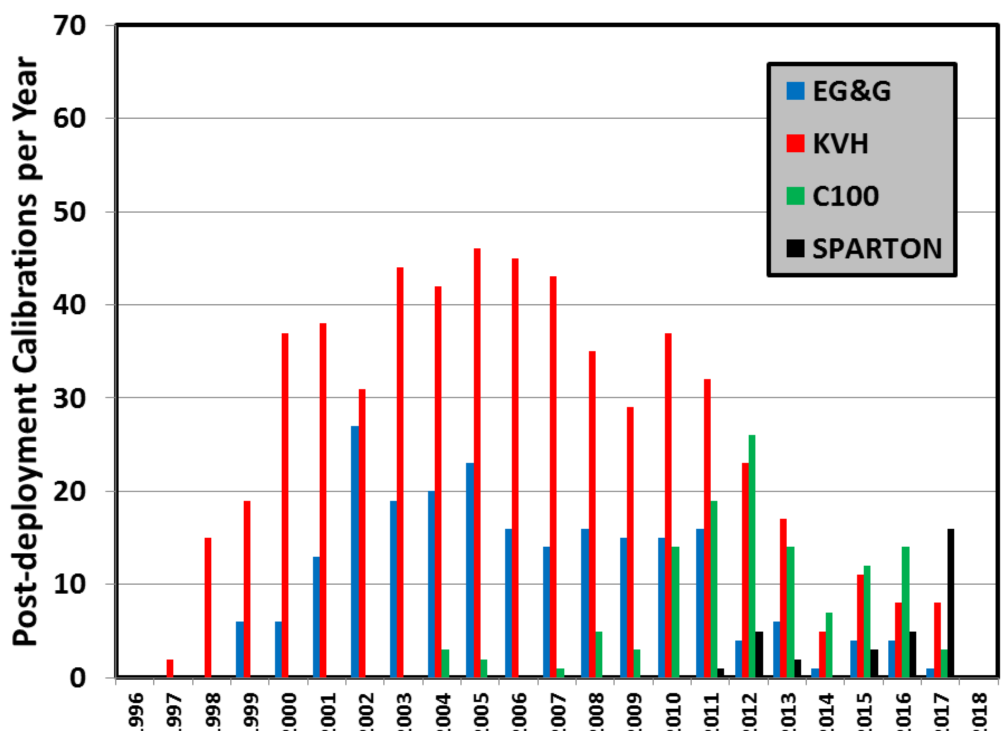

Figure 2. Number of post-deployment compass calibration checks performed by year and compass type.

2. Data Analysis

Pre-deployment and post-recovery calibrations of compasses and vanes were first analyzed independently. Wind direction accuracy was then estimated by combining the compass and vane results.

2.1 Compass

As described in Freitag et al. (2001), NX-ATLAS compasses are calibrated at PMEL prior to deployment and again after recovery from sea (if functional). This protocol is also applied to Flex and T-Flex systems (subsequent reference to T-Flex statistics will include Flex as well). Compasses are deemed to fail their calibration test if the error exceeds ±5° at any of 24 compass set points (0° to 345° at 15° increments).

Some editing was required before analyzing the calibration data. Several of the data records were incomplete and/or had errors. The NX-ATLAS database is populated by automated scanning of text files created during the calibration check procedure. If the text files have irregular or unexpected structure, large error values followed by missing data may result. When these and other errors were encountered during this analysis, the text files were manually checked and the record corrected if possible. In many cases the correction caused the test results to change from Fail to Pass. Records with 1 or 2 missing calibration points or where the tests were performed over a full 360° but at intervals >15° (e.g., 45°) were included in the analysis without modification.

Some calibration checks found in the database were omitted from the analysis. Reasons for the omissions included: compasses or NX-ATLAS systems were not functioning properly (typically these were post-recovery calibrations); entries were duplicated; calibration checks failed (absolute maximum error >>5°), after which the compass was removed and replaced in the instrument; or calibration checks failed but only by a few degrees and at only a few check points, after which the test was repeated and the compass passed (typically pre-deployment calibrations). Omissions of pre-deployment calibration checks were limited and only occurred for KVH compasses (2% of all KVH pre-deployment checks) and C100 compasses (1%). Omissions of post-recovery calibration checks were more frequent: 2% of EG&G, 3% of KVH, and 8% of C100 compasses. (No Sparton post-recovery calibration checks were omitted, which may have been due to the small number of calibrations available.) The more frequent omission of post-recovery checks compared to pre-deployment checks reflects the failure of instruments while deployed at sea, but not solely those caused by a failure of the compass (e.g., leakage of an NX-ATLAS system housing could cause the compass to fail). The higher frequency of the omission of C100 post-recovery compass checks compared to other compass types suggests a higher failure rate for the C100. A comparison of the number of pre-deployment to post-recovery calibrations in the database (**Table 2** vs. **Table 3**) may also reflect differences in performance between compass types. The number of post-recovery calibration checks for EG&G and KVH compasses is about 70% of their pre-deployment calibration checks (226 of 326 and 567 of 787, respectively). The lower number of post-recovery checks is due to moorings being lost, systems/instruments being damaged, and instruments failing. For the C100 compass this statistic is 46% (123 of 270). Lost and damaged systems should not be affected by compass type, so it can be inferred that the C100 compasses themselves failed more often than the EG&G and KVH compasses.

Pre-deployment ensemble mean errors (**Table 2**) were 0.02° for the EG&G, 0.11° for the KVH, 1.36° for the C100, and 0.61° for the Sparton. RMS errors were 1.13°, 1.28°, 1.77°, and 1.47°, respectively. The EG&G and KVH errors are comparable to those reported in Freitag et al. (2001). The C100 and Sparton RMS errors were 3–4 times their manufacturer's specified accuracy of 0.5°.

Table 2: Pre-deployment errors by compass type (°). N Calib is the number of calibrations in the database used in the analysis. N Pass and N Fail are the numbers of calibrations used that passed or failed, respectively. N Omit is the number of calibrations found in the database not used in the analysis. Compass error statistics (°) include minimum, maximum, mean, standard deviation, RMS (computed over all 24 calibration set points), and the standard error (SE) of the mean. The two right-most columns contain percentages of calibrations in which the mean error and RMS errors were ≤5° in magnitude.

Compass Type	N Calib	N Pass	N Fail	N Omit	Min	Max	Mean	Std. Dev.	RMS	SE of Mean	Mean ±5°	RMS ±5°
EG&G	326	326	0	0	–5.0	5.0	0.02	1.13	1.13	0.02	100%	100%
KVH	787	784	3	17	–6.0	8.0	0.11	1.28	1.28	0.01	100%	100%
C100	270	270	0	3	–3.7	5.0	1.36	1.15	1.77	0.07	100%	100%
Sparton	144	143	1	0	–5.2	4.5	0.61	1.34	1.47	0.07	100%	100%

Table 3: Post-recovery errors by compass type (°). N Calib is the number of calibrations in the database used in the analysis. N Pass and N Fail are the numbers of calibrations used that passed or failed, respectively. N Omit is the number of calibrations found in the database not used in the analysis. Compass error statistics (°) include minimum, maximum, mean, standard deviation, RMS (computed over all 24 calibration set points), and the standard error (SE) of the mean. The two right-most columns contain percentages of calibrations in which the mean error and RMS errors were ≤5° in magnitude.

Compass Type	N Calib	N Pass	N Fail	N Omit	Min	Max	Mean	Std. Dev.	RMS	SE of Mean	Mean ±5°	RMS ±5
EG&G	226	180	46	5	–22.0	18.0	0.58	2.47	2.53	0.13	97%	96%
KVH	567	223	344	18	–27.0	28.1	3.82	4.02	5.54	0.15	68%	66%
C100	123	42	81	10	–38.0	32.0	1.50	7.13	7.28	0.21	95%	53%
Sparton	32	30	2	0	-4.4	5.2	0.85	1.72	1.92	0.14	100%	100%

While it is not standard practice, a few instruments were deployed with compasses that had marginally failed their pre-deployment calibration (with maximum errors ≤8° and at only a few of the 24 calibration points). These were three KVH (0.4% of the total number of calibrations) and one Sparton (0.7% of the total number of calibrations). The three KVH compasses, deployed early in the development and implementation of the NX-ATLAS system (1996–1999), may have been deployed due to low inventory at the time. Mean errors for these three ranged from –1.8° to 0.9° and RMS errors from 2.8° to 3.8°. The one failed pre-deployment Sparton compass had a mean error of –0.3° and RMS error of 3.1°. This compass was used on a test deployment of PMEL's Vaisala SBD instrument.

Post-recovery ensemble mean errors (**Table 3**) were 0.58° for the EG&G, 3.82° for the KVH, 1.50° for the C100, and 0.85° for the Sparton. RMS errors were 2.53°, 5.54°, 7.28°, and 1.92°, respectively. While post-recovery errors were larger than pre-deployment errors for all four compass types, the KVH and C100 exhibited the largest calibration drifts. Absolute maximum errors (at a given compass heading) of up to 22° occurred in the EG&G ensemble, with larger maximum errors occurring for the KVH (28°) and C100 (38°). The largest post-recovery errors for the Sparton compasses were comparable to those for the pre-deployment ensemble, i.e., within ±5°. The EG&G errors are comparable to those reported in Freitag et al. (2001). There was a marked difference in post-recovery compass test failure rates. The Sparton compasses had the lowest occurrence of failures (6%), although the sample size was relatively small compared to the other compass types. The EG&G failure rate was 20%. Over half the KVH and C100 compasses failed their post-recovery calibration checks: 61% (344 of 567) and 66% (81 of 123), respectively.

There was a marked difference between compass types in terms of post-recovery mean and RMS errors relative to the target accuracy of 5°. The percentage of compass checks with mean errors ≤ ±5° was 97% for the EG&G, 68% for the KVH, 95% for the C100, and 100% for the Sparton (**Figure 3**, **Table 3**). The percentage of compass checks with RMS errors ≤5° was 96%, 66%, 53%, and 100%, respectively (**Figure 4**, **Table 3**). Nearly all (96–100%) mean and RMS errors of EG&G and Sparton compasses were within the target accuracy. While nearly all (95%) of C100 compasses also had mean errors within the target, nearly half of the C100 RMS errors exceeded the target. The mean and RMS errors of about one third of recovered KVH compasses exceeded the target accuracy.

Although small (0.11° to 1.36°), the pre-deployment mean errors for the KVH, C100, and Sparton compasses were significantly different from zero, based on the standard error of the mean (**Table 2**). (This error analysis assumed Gaussian distribution of the mean errors, which was not strictly the case.) Several factors may have contributed to the statistical significance of the mean errors: uncertainty in the calibration procedure, resolution of the data, and nominal accuracy of the compasses. Uncertainty in compass checks at PMEL is the sum of several factors, e.g., alignment of the compass within the instrument, transfer of the compass

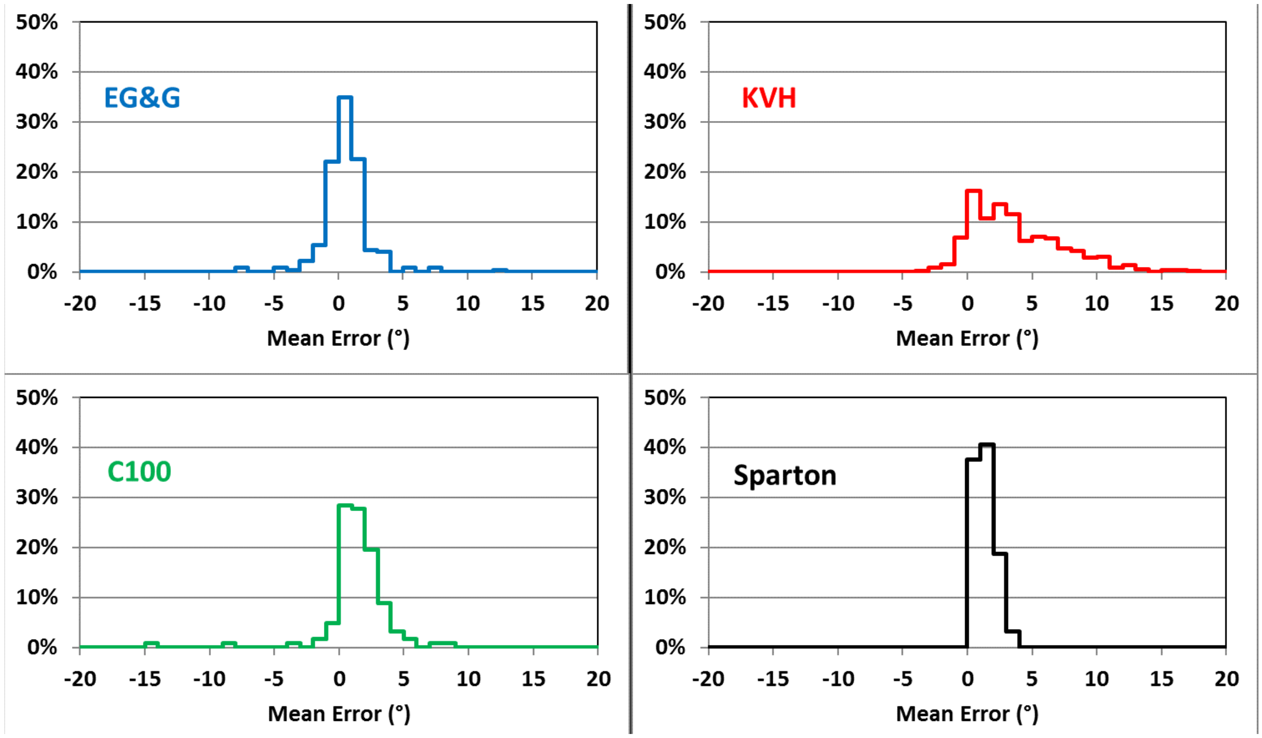

Figure 3. Distribution of mean errors of post-recovery compass calibration checks by compass type.

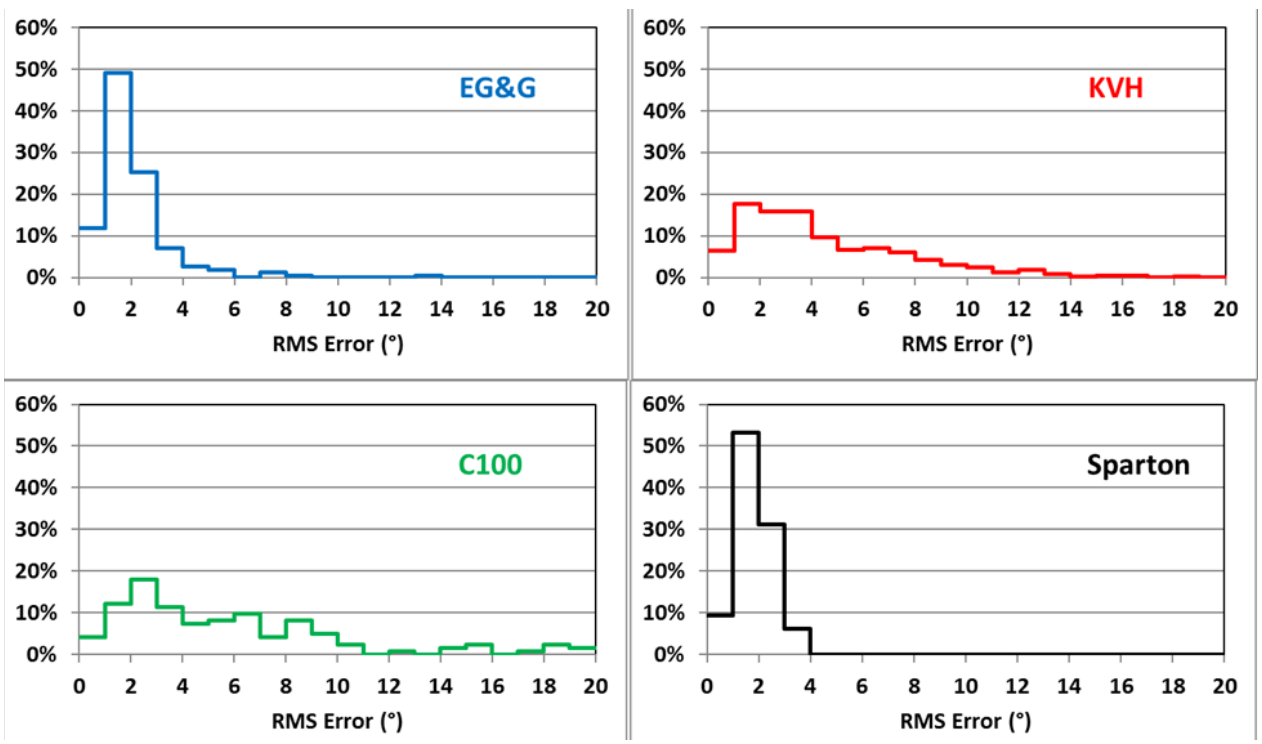

Figure 4. Distribution of RMS errors of post-recovery compass calibration checks by compass type.

alignment to the outside of the instrument case, alignment of the instrument on the compass stand, orientation of the compass stand to magnetic north, etc. While not precisely quantified, we expect the accuracy of the calibration procedure to be about 1 degree, comparable to the mean errors themselves. The ATLAS mean errors were all less than the resolution of the ATLAS system (1.4°), but the Sparton mean error was larger than its resolution (0.1°). The KVH mean error was less than its specified accuracy and the Sparton mean error exceeded the manufacturer's specified accuracy by only 0.11° (comparable to its resolution). The C100 mean error was 3 times larger than the manufacture's specification. Post-recovery mean errors were larger than pre-deployment mean errors and statistically different than zero, from which we conclude that all the compass types experienced calibration drift over time.

2.2 Vane

Analysis of the NX-ATLAS vane accuracy after the modifications mentioned above was based on 1510 pre-deployment calibration checks made after December 2000 and 653 post-recovery calibration vane checks made after December 2001 (where we have assumed that post-recovery checks made in 2001 would have been on unmodified systems.) Originally, the NX-ATLAS vane alignment procedure attempted to orient the dead zone (defined above) within a heading of 355° to 0°. As part of the modifications, an attempt was made to center the dead zone nearer to 0°. The protocol (both before and after the modification) was to measure the range of the dead zone when rotating in both the clockwise and counterclockwise directions. The average midpoint of the post-modification dead zone for pre-deployment checks was –1.2° clockwise and –0.7° counterclockwise, with 97% of midpoint values within ±2.5°. The average midpoint for post-recovery checks was nearly the same: –1.1° clockwise, –0.5° counterclockwise, although the percentage within ±2.5° declined to 78%. The average width of the pre-deployment dead zone was 5.8°, somewhat larger than the nominal value of 5°. Half (51%) of the pre-deployment dead-zone widths were within the nominal value. Post-recovery, the dead-zone average width was nearly identical at 5.9°, with 48% within the nominal value.

A small percentage of vane calibration checks in the database were omitted from the analysis: 1.6% of pre-deployment checks and 3.3% of post-recovery checks (**Table 4**). Reasons for omitting pre-deployment calibrations included: checks that nearly passed initially and did pass when rechecked (in which case the first check was omitted); vanes that were replaced before being deployed; and database errors (e.g., post-recovery checks mislabeled as pre-deployment checks, incomplete or empty records). Included in the analysis were two pre-deployment checks noted as having passed but with maximum errors slightly larger than 5° (5.1° and 5.6°). Post-recovery checks that were omitted from the analysis included database errors and those that had failed to function or had errors so large that the wind direction data during the deployment had been flagged as bad.

The mean vane error was –0.39° for pre-deployment vane calibration checks and –0.80° for post-recovery vane calibration checks. RMS errors were 1.64° and 4.55°, respectively. As was the case for compass calibration, vane calibration checks were deemed to have failed if the error at any check point was greater than 5°. Fifteen percent (100 of 653) of post-deployment vane checks failed (i.e., had at least one check point with an error greater than 5°). The pre-deployment and post-recovery mean errors were significantly greater than zero at the 95% confidence level, but less than the manufacturer's specified accuracy (±3°) and the ATLAS resolution (1.4°). The mean errors of pre-deployment calibrations were all < ±5° as were 94% of post-recovery calibrations.

T-Flex sonic anemometers do not have a physical vane, directly measuring wind components from orthogonal wind speed sensors, which are fixed in the instrument housing. They have no moving parts and no vane dead zone. Presumably the orthogonal orientation of the sensors is not subject to change. PMEL checks the calibration of the relative direction (RDir) accuracy of the sonic anemometer by rotating the instrument in a wind tunnel at constant speed. The sonic RDir reading is computed from the vector wind components, both before and after deployment at sea. As of July 2018 the database contained 111 pre-deployment and 22 post-recovery RDir checks from Gill anemometers performed between August 2012 and June 2018 (**Table 5**)[1]. Mean errors were 0.49° for pre-deployment checks (significantly greater than zero at the 95% confidence limit) and 0.29° for post-recovery checks (not significant). Both are smaller than the manufacture's specified resolution (1°) and accuracy (±2°) and comparable to mean vane errors for NX-ATLAS anemometers. RMS errors were 2.10° for pre-deployment checks and 2.74° for post-recovery checks. Compared to the NX-ATLAS vane, there was less difference between pre-deployment and post-recovery checks in the Gill RDir RMS accuracy, supporting the presumption that the orthogonal orientation of the Gill wind velocity sensors is stable with time. The mean and RMS error for all calibrations were ≤± 5°. There are no Pass/Fail criteria for these checks. For comparison to the 5° target accuracy of the compass and NX-ATLAS vane, 7 of 111 (6%) pre-deployment and 6 of 22 (27%) post-recovery checks had errors >5° at one or more of the 24 check points. In percentage terms, the Gill "failure" rates are higher than those for the NX-ATLAS vanes, but recall that the NX-ATLAS vanes are not deployed until they either pass when recalibrated or are repaired. In addition, the magnitude of Gill post-recovery maximum errors (8°) were an order of magnitude smaller than those for the NX-ATLAS (83°). The higher percentage of Gill anemometers with relatively small maximum errors may indicate that PMEL's Gill RDir calibration check methodology (turning the sensor in a wind tunnel) may

1 As mentioned above, a very small number of Vaisala anemometers were initially deployed as secondary or test sensors on OCS moorings, but their use was discontinued. Vaisala wind data were rarely publically distributed and the limited number of Vaisala vane accuracy checks available are not included in this analysis.

Table 4: Pre-deployment and post-recovery NX-ATLAS vane errors. N Calib is the number of calibrations in the database used in the analysis. N Pass and N Fail are the numbers of calibrations used that passed or failed, respectively. N Omit is the number of calibrations found in the data base not used in the analysis. Compass error statistics (°) include minimum, maximum, mean, standard deviation, RMS (computed over all 24 calibration set points), and the standard error of the mean. The two right-most columns contain percentages of calibrations in which the mean error and RMS errors were ≤5° in magnitude.

	N Calib	N Pass	N Fail	N Omit	Min	Max	Mean	Std. Dev.	RMS	SE of Mean	Mean ±5°	RMS ±5°
Pre-deployment	1510	1510	0	25	−5.6	4.7	−0.39	1.59	1.64	0.03	100%	100%
Post-recovery	653	553	100	22	−83.4	58.1	−0.80	4.48	4.55	0.15	94%	93%

Table 5: Pre-deployment and post-recovery Gill relative direction (RDir) errors. N Calib is the number of calibrations in the database used in the analysis. Compass error statistics (°) include minimum, maximum, mean, standard deviation, RMS (computed over all 24 calibration set points), and the standard error of the mean. The two right-most columns contain percentages of calibrations in which the mean error and RMS errors were ≤±5°.

	N Calib	Min	Max	Mean	Std. Dev.	RMS	SE of Mean	Mean ±5°	RMS ±5°
Pre-deployment	111	−6.0	8.0	0.49	2.05	2.10	0.17	100%	100%
Post-recovery	22	−8.0	6.0	0.29	2.73	2.74	0.47	100%	100%

be less precise than the bench testing performed on the NX-ATLAS vanes. Modifications to improve the Gill procedure are being considered. The relatively small sample size (22) for Gill post-recovery RDir checks may also be a factor.

2.3 Wind direction

Using the methodology of Freitag et al. (2001), the wind direction RMS error was computed by combining mean and standard deviation errors of the compass and vane ensembles. The mean wind direction error was estimated as the sum of the mean compass and mean vane/RDir error. The fluctuating wind direction error was estimated as the square root of the sum of the squared compass and squared vane/RDir error standard deviations (which assumes they are uncorrelated). The RMS wind direction error was estimated as the square root of the sum of the mean wind direction error squared and the wind direction error standard deviation squared. Using RMS error as a metric, the pre-deployment wind direction accuracy of the three NX-ATLAS compass/vane combinations was between 2.0° and 2.2° (**Table 6**). Initial wind direction accuracy for T-Flex systems using a Gill anemometer and Sparton compass was 2.7°. Post-recovery NX-ATLAS wind direction accuracy ranged from 5.1° (EG&G compass) to 8.4° (C100 compass). NX-ATLAS wind direction accuracy computed from an ensemble of all compass types was 6.6°.

As a conservative estimate of wind direction we use the post-recovery values. For the NX-ATLAS systems we use the ensemble value of 6.6°, noting that the systems with C100 compasses and the largest error of 8.8° made up only 13% of the compass calibration database. The target accuracy of 5° suggested by Freitag et al. (2001) was not realized due to the KVH and C100 compasses being less accurate than the original EG&G.

Post-recovery T-Flex wind direction accuracy was 3.4°. Unfortunately, the Sparton compass used in Flex/T-Flex systems is no longer available. PMEL has tested alternate compasses and has chosen the OceanServer Technology, Inc. (now owned by L3 Technologies) model OS-4000-T as its compass for new systems. As these new systems are deployed their performance and calibration stability will be reviewed.

Table 6: Summary compass and vane/RDir error statistics and resultant wind direction errors for pre-deployment (Pre) and post-recovery (Post) calibration checks. Error units are degrees. Ensemble (Ens.) values are based on data from all three NX-ATLAS compass types (EG&G, KVH, and C100). NX-ATLAS system vane is part of the R.M. Young anemometer. T-Flex system RDir is computed from orthogonal wind components measured by Gill anemometer.

		Compass		Vane/RDir		Wind Direction		
Compass	**Status**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**RMS**
EG&G	Pre	0.0	1.1	–0.4	1.6	–0.4	2.0	2.0
	Post	0.6	2.5	–0.8	4.5	–0.2	5.1	5.1
KVH	Pre	0.1	1.3	–0.4	1.6	–0.3	2.0	2.1
	Post	3.8	4.0	–0.8	4.5	3.0	6.0	6.7
C100	Pre	1.4	1.1	–0.4	1.6	1.0	2.8	2.2
	Post	1.5	7.1	–0.8	4.5	0.7	8.4	8.4
Ens. (EG&G, KVH, C100)	Pre	0.3	1.3	–0.4	1.6	–0.1	2.1	2.1
	Post	2.7	4.5	–0.8	4.5	1.9	6.4	6.6
Sparton	Pre	0.6	1.3	0.5	2.0	1.1	2.4	2.7
	Post	0.9	1.7	0.3	2.7	1.1	3.2	3.4

3. Summary and Conclusions

The GTMBA was first implemented in the tropical Pacific beginning in 1984 and was primarily composed of PMEL's ATLAS system of moorings. It has since expanded into the Atlantic and Indian Ocean, while keeping pace with technological advancement in oceanographic instrumentation through modification of the ATLAS system and development of the newer T-Flex system. We have documented the accuracy of one of the GTMBA's primary observations, wind direction, for the sensors that make this measurement. Our target has been to measure wind direction to within 5°. When first deployed the target was well met, with RMS error of 2.1° for NX-ATLAS systems and 2.7° for T-Flex systems. Calibration drift of some NX-ATLAS sensors while deployed at sea resulted in the target not being met, with an ensemble RMS error of 6.6°. The target was exceeded primarily due to a combination of larger drift of KVH and C100 compasses, which replaced the original EG&G sensor, and drift of the R.M. Young anemometer vane. Based on relatively few calibration checks (32 compasses and 22 RDir), we estimate T-Flex systems meet the target with an RMS error of 3.4°.

At present, half the GTMBA is composed of T-Flex systems. NX-ATLAS wind direction error may increase with time as fewer of the more accurate EG&G compasses are available for deployment, but GTMBA ensemble error should improve as more sites are occupied with T-Flex systems.

4. Acknowledgments

This publication is contribution 4903 from NOAA Pacific Marine Environmental Laboratory, and is partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington under NOAA Cooperative Agreement No. NA15OAR4320063, JISAO contribution 2019-1032.

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