Mooring Motion Bias of Point-Doppler Current Meter Measurements

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Abstract—Upper-ocean current measurements have been made for more than 20 years from taut-line surface moorings deployed in the equatorial Pacific by NOAA's Pacific Marine Environmental Laboratory (PMEL). Until 1998 the moorings were instrumented with mechanical current meters (MCMs, either Vector Averaging Current Meters (VACM) or Vector Measuring Current Meters (VMCM)). Comparison with nearby subsurface 150 kHz Acoustic Doppler Current Profilers (ADCP) indicated that differences between the two measurement systems were generally small (i.e., mean differences of 5 cm s^{-1} or less). By the early-1990's, maintenance of the aging MCMs (designed in the 1960s and 1970s) was difficult, time consuming and expensive. Early tests of the Sontek Argonaut-MD current meters by PMEL indicated that it was a good candidate for replacement of the MCMs. Subsequent comparisons between Argonaut-MD data and nearby ADCPs revealed significant bias between the two, with the Argonaut-MD reporting lower horizontal current speed. Further investigation, including the analysis of high-frequency output from the Argonaut-MD compass/tilt-sensor (Precision Navigation model TCM2), found that the source of the bias was the inability of the compass/tilt-sensor to function properly in response to extreme lateral and rotational accelerations experienced by the instruments in high current speed regimes. A solution to this problem was to reduce the acceleration of the current meters by attaching vanes to each instrument. Since PMEL introduced this modification, differences between Argonaut-MD and ADCP data are comparable to those found previously between MCM and ADCP.

I. INTRODUCTION

The Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) Array is comprised of surface moorings at about 70 sites covering the equatorial Pacific from 137°E to 95°W and 8°S to 8°N [1]. Primary measurements within the array are surface meteorology (wind speed and direction, air temperature, relative humidity) and surface and upper ocean (1–500 m) temperature, in support of research, monitoring and prediction of climate variability such as El Niño Southern Oscillation (ENSO). Upper-ocean currents are routinely made from five equatorial locations within the TAO/TRITON Array (Fig. 1), with measurements at the first site in the array, 0° 110°W, beginning in 1979. Data from the array are available at www.pmel.noaa.gov/tao .

Current measurements were originally made with E.G. & G. Vector Averaging Current Meters (VACMs) and Vector Measuring Current Meters (VMCMs) which were deployed as an integral component of the taut-line moorings. Beginning in 1990, 150 kHz Acoustic Doppler Current Profilers (ADCP) were added to the moorings in a downward-looking orientation from the surface buoy. It was found that the taut-line surface moorings attracted large pelagic fish to such an extent that the ADCP measurements were significantly biased by the fish population at these sites [2]. In 1995 the ADCP measurements were moved to separate upward-looking subsurface moorings located 5 to 15 nm from the surface moorings to remove the fish bias. In this deployment scheme the ADCP and VACM/VMCM current data were essentially equal. For example, over a 27-month period at 0° 140°W the mean speed difference between a VACM at 45 m and a nearby ADCP was 0.3 cm s^{-1} and the RMS difference between daily mean data was 5.7 cm s^{-1} (Fig. 2). The VACM/VMCM measurements are essentially at a single point, while the ADCP computes a weighted mean over a vertical distance of 16 m and horizontal distances of tens of meters. Differences of these magnitudes are to be expected, given the different measuring techniques and spatial separation of the moorings. Although it was confirmed that the two measurement systems gave similar results, VACM/VMCMs

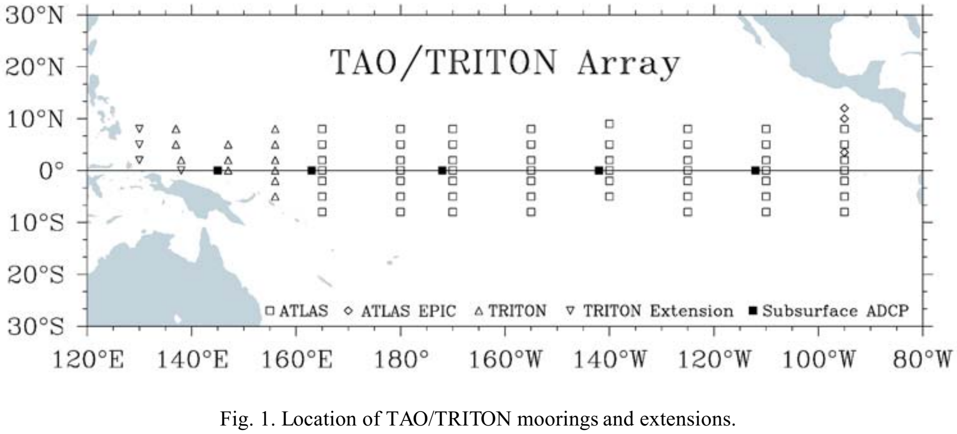

Fig. 1. Location of TAO/TRITON moorings and extensions.

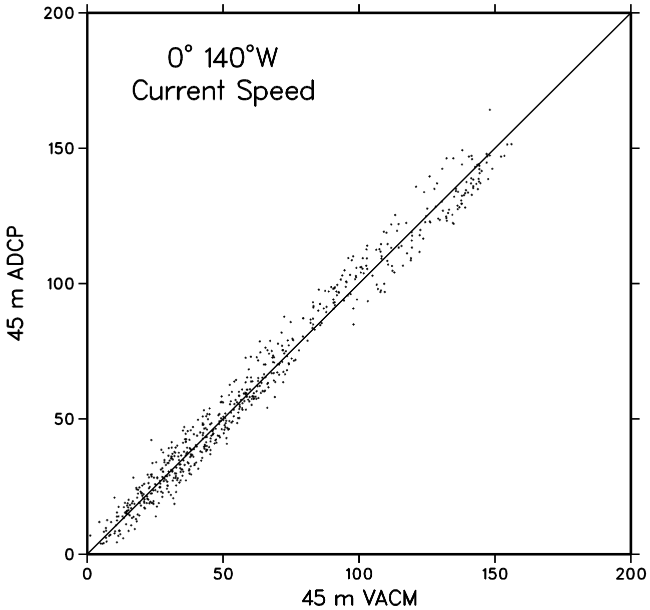

Fig. 2. Scatter plot of 45 m daily mean current speed from VACMs and ADCPs measured from October 1996 to February 1999. Units are cm s^{-1}.

continued to be deployed for two reasons: first, as a backup to the ADCP, and second, to measure near the surface, as the subsurface ADCP cannot accurately measure within about 30 m immediately below the surface due to side-lobe interference.

The VACM was designed in the late 1960's and the VMCM about a decade later. By the mid-1990's production and support by the manufacturer had long ceased. The current meters were becoming difficult to maintain due to obsolete mechanical and electronic parts, and new technology was required to continue the PMEL observations.

Also in the mid-1990s, PMEL began the design and testing of the NextGeneration ATLAS mooring (Fig. 3), with subsurface inductive data telemetry via the main mechanical mooring cable [3]. It was planned that by the end of the decade all surface moorings in the array would be of this type. With this telemetry method, the mooring cable could no longer be easily segmented for insertion of current meters, providing another reason for replacement of the VACM/VMCM current meters. Desirable features in the replacement instruments were small size and weight, reliability, accuracy and endurance comparable to previous technology, and lower cost. An additional feature that was considered was the ability to purchase only critical components (transducer head, electronics, and data storage) of the instrument so that they could be integrated with the NextGeneration instrument and data telemetry system.

Obtaining accurate current measurements from taut-line surface moorings in the equatorial Pacific is challenging. Velocity within the Equatorial Undercurrent and South Equatorial Current is typically over 100 cm s^{-1}, with a maximum of over 250 cm s^{-1} and shears 100 cm s^{-1} or more over a vertical distance of 50 to 100 m. An instrument's past performance in other less energetic regimes could not necessarily be used to predict its applicability for use in TAO/TRITON. Thus PMEL planned a series of tests in the equatorial Pacific to examine the performance characteristics of new, commercially available current meters.

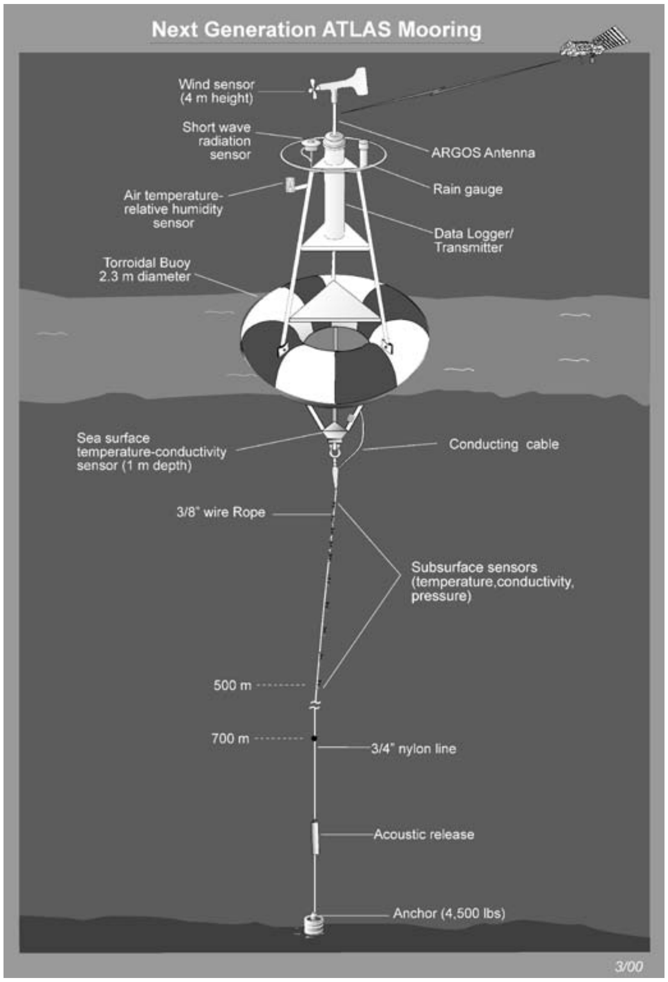

Fig. 3. Schematic drawing of NextGeneration ATLAS mooring.

II. INITIAL EVALUATION OF ACOUSTIC CURRENT METERS

In 1997 a traditional (instrumented with VACM/VMCM current meters inserted between sections of mooring cable) current meter mooring deployed at 0° 140°W was used to test two newer current meters; a 3D-ACM (Falmouth Scientific, Inc., Cataumet, MA) and an Argonaut-MD (Sontek, Inc., San Diego, CA). The 3D-ACM was deployed within its manufacturer supplied cage as an integral part of the mooring (similar to the VACMs) about 2 m below the rotor of a VACM which was 25 m below the sea surface. The upward-looking Argonaut-MD was clamped to the mooring wire about 3 m below the 3D-ACM. Unfortunately, the VACM failed to return any current data during this test deployment. Comparison of the two acoustic current meters indicated that their respective data were comparable for much of the deployment period, but during the period of strongest currents (up to 125 cm s^{-1}) the Argonaut-MD reported values up to 75 cm s^{-1} below the 3D-ACM. Velocity profiles from a nearby subsurface ADCP intermittently reached 30 m depth and the partial data returned from this depth indicated that the Argonaut-MD was in error. Closer comparison of the ADCP and Argonaut-MD data indicated that in addition to the large bias at the highest current levels, the Argonaut typically reported current speed lower by about 20%. After further analysis of the data, PMEL and Sontek, Inc., concluded that the underestimation of strong currents was due to inaccuracy of the compass/tilt-sensor (model TCM2, Precision Navigation, Inc., Santa Rosa, CA) when subjected to energetic mooring motion. The prototype Argonaut-MD used in this test sampled the compass at 1 Hz, which appeared to be insufficient. The tilt sensors in the TCM2 are free surface electrolytic sensors that cannot differentiate between actual tilts and horizontal accelerations (or vertical accelerations if actually tilted).

The 3D-ACM recorded data for only 121 days of the 188-day deployment due to battery failure. The manufacturer had predicted that the battery capacity was insufficient for this deployment period, so a 50% duty cycle was chosen (sampling for 15 min every 30 min), but it appeared that a larger reduction was necessary. While VACMs and VMCMs had sufficient battery capacity for 100% duty cycles over 6-month to 1-year deployments, most new current meters we have considered (including the Argonaut-MD) require a reduction of duty cycle to meet power requirements.

Although the data from the 3D-ACM was in agreement with the ADCP, it was decided to not continue testing it for use on TAO moorings for several reasons. In addition to the power requirements noted above, the method of mounting the instrument did not compliment the inductive telemetry of the NextGeneration ATLAS mooring. Furthermore, the design of the sensor heads presented concerns about possible damage to them from commercial fishing near the moorings and their suitability in the biologically active equatorial upwelling zone. In some cases, VACMs recovered from TAO moorings were fouled with gooseneck barnacles to the point that the rotors did not turn. While biologic growth on the 3D-ACM sensor heads may be acoustically transparent, it could decrease the effective distance between sensors through which water flowed, and possibly bias the velocity measurement.

In a second test in 1998, an upward-looking Argonaut-MD was clamped to the mooring cable 4 m below the rotor of a VACM which was 45 m below the sea surface. In this case the TCM2 was set to burst sample and the Argonaut used mean compass and tilt values computed over 0.5 s during velocity sampling. A more viscous fluid was also used in the electrolytic tilt sensor. Unlike the previous test deployment, there was no indication of a problem with the compass/tilt-sensor. Current conditions were similar to those during the previous year, with maximum speeds of about 175 cm s^{-1}. Mean speed difference between the 45 m VACM and 49 m Argonaut was 1.5 cm s^{-1} and mean speed difference between the Argonaut and the 50 m ADCP bin was 3.1 cm s^{-1}. RMS differences were 6.2 cm s^{-1} between 30-min Argonaut-MD and VACM data and 9.8 cm s^{-1} between hourly Argonaut-MD and ADCP data. Thus it appeared that the Argonaut-MD and ADCP made comparable measurements under these conditions.

III. ARGONAUT-MD PERFORMANCE ON NEXTGENERATION ATLAS MOORINGS

Given this positive result, it was decided to go forward with design plans for replacement of TAO VACMs and VMCMs with Argonaut-MDs and to integrate the Argonaut sensor with Next Generation ATLAS subsurface temperature and inductive telemetry components. While the integration was under development, standard Argonaut-MDs were deployed on NextGeneration ATLAS moorings at some of the traditional current meter sites, with the first deployment at 0° 110°W in fall 1998. On recovery of these moorings it was found that the underestimation of current velocity by the Argonaut was still a problem (Fig. 4). Comparisons with nearby ADCP data for this and most subsequent deployments varied in detail, with the bias variable in space and time, but in general the Argonaut-MD was found to underestimate currents compared to the ADCP, by about 30%. Other characteristics which made the Argonaut-MD data suspect were unusually large vertical velocity, O (50 cm s^{-1}), and high compass heading variability. In many cases, the standard deviation of the compass heading over a few minutes'

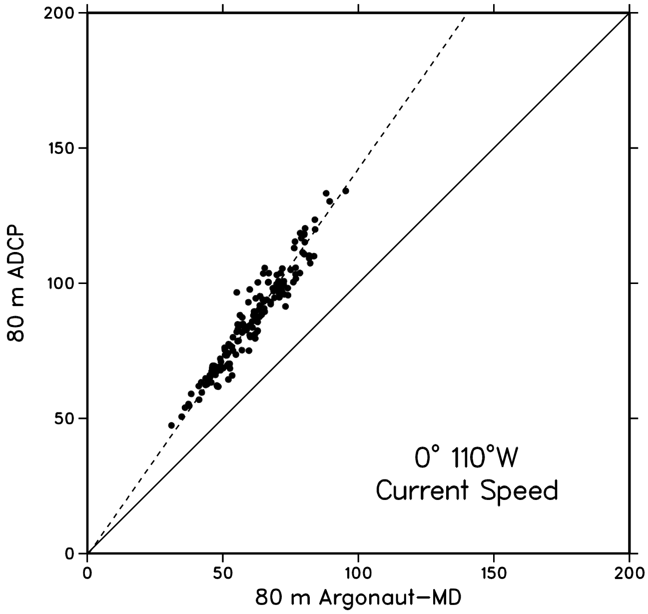

Fig. 4. Scatter plot of 80 m daily mean current speed from an Argonaut-MD and an ADCP from October 1998 to April 1999. The dashed line shows the orthogonal least-squares regression of the two. Units are cm s^{-1}.

time routinely exceeded the instrument's maximum recordable value for compass heading standard deviation of 25°.

In May 1999 a prototype instrument that integrated the Argonaut-MD sensor head and electronics with an ATLAS temperature module and inductive telemetry was deployed. The instrument was comprised of three separate cylindrical pressure cases joined by a single end plate through which connecting wires passed. This prototype design proved to be problematic in terms of hardware integrity and cost to machine. It was therefore abandoned in favor of a simpler system in which a complete Argonaut-MD was cabled to a separate ATLAS temperature module attached to the mooring wire above. An unexpected result from the prototype system was that there was no underestimation of current speed. This suggested that the shape of the prototype system damped the acceleration experienced on the mooring.

In a November 1999 deployment, an Argonaut-MD, provided and modified by Sontek, Inc., recorded 1 Hz data to better quantify the scale and frequency of instrument motion. The raw magnetic flux data indicated that the instrument was at times rotating by as much as ±70° over a time period of several seconds. From this, it became apparent that simply damping the TCM2 response would not eliminate the problem, as the damped compass heading and tilts would not be synchronized with the actual motion experienced by the acoustic sensors.

Since the problem appeared to be in the tilt response of the TCM2, a new firmware version was created by Sontek which ignored the tilt sensor when computing velocity components from the raw acoustic and compass data. Compass heading was computed directly from the horizontal components of magnetic flux. If actual instrument tilts were relatively small, this method would not significantly bias the data. If the magnitude of the current was correctly measured in this manner, then the true tilt of the instrument could be inferred by the size of the vertical velocity component recorded by the instrument, since true vertical velocities in the equatorial Pacific are only 10^{-3} to 10^{-4} cm s^{-1}. In addition, if the vertical velocity component recorded was large enough to bias the horizontal velocity components, corrections could be computed based on a simple combination of the two. This firmware version was first deployed in September 2000.

The effect of this firmware change was apparent in the vertical velocity data, which had previously been recorded as large as 50 cm s^{-1} and always as negative. Vertical velocity data from instruments with the modified firmware were typically in the range ±20 cm s^{-1}. Values in this range would be expected if instrument tilts were about 10°. Unfortunately, this firmware change reduced the magnitude of horizontal current underestimation by about a factor of 2 at best, but did not eliminate the problem.

It was therefore decided that the best solution may be to decrease the amount of motion to which the instruments are subjected. The cause of the motion was assumed to be vortex induced motion around the cylindrical instrument. In high current conditions, vortices develop which are shed alternately from either side of the cylinder and lift and drag forces excite forced oscillations of the cylinder around the mooring line. The proposed PMEL solution was to dampen the forced oscillations by providing a more hydrodynamic shape to the instrument. A small vane (14 cm by 50 cm) was designed to dampen the oscillations at the expected currents, yet be robust enough to survive mooring deployments and possible interaction with fishing gear. Several vane cross section aspect ratios (length:width) were tested in Lake Washington by towing a cable under tension over various speeds with an Argonaut-MD clamped to the wire. A vane with aspect ratio of 2.5:1 (Fig. 5 inset) was found to have acceptable dampening performance yet was small enough to have minimal impact on mooring deployment operations and low potential for being fouled by fishing nets or lines. The low-cost, all-plastic vanes are fixed to the existing clamps which attach the instrument on the mooring wire (Fig. 5). In the first deployment with this modification, instruments with and without the vane were positioned within 3 m of each other (42 m for the instrument without a vane and

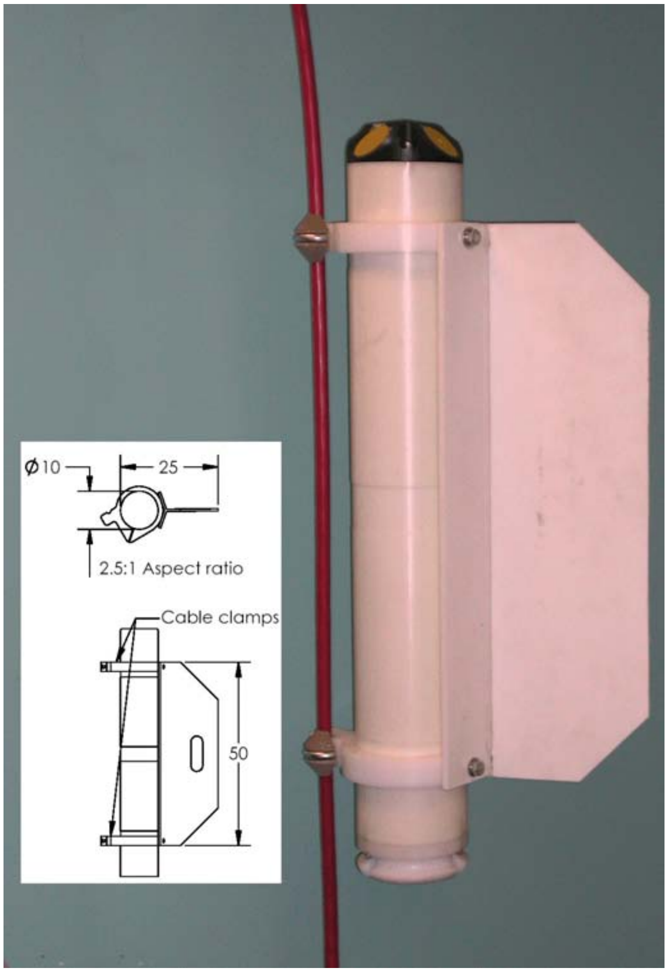

Fig. 5. Argonaut-MD with PMEL designed vane. Inset: Schematic diagram of vane with dimensions (cm).

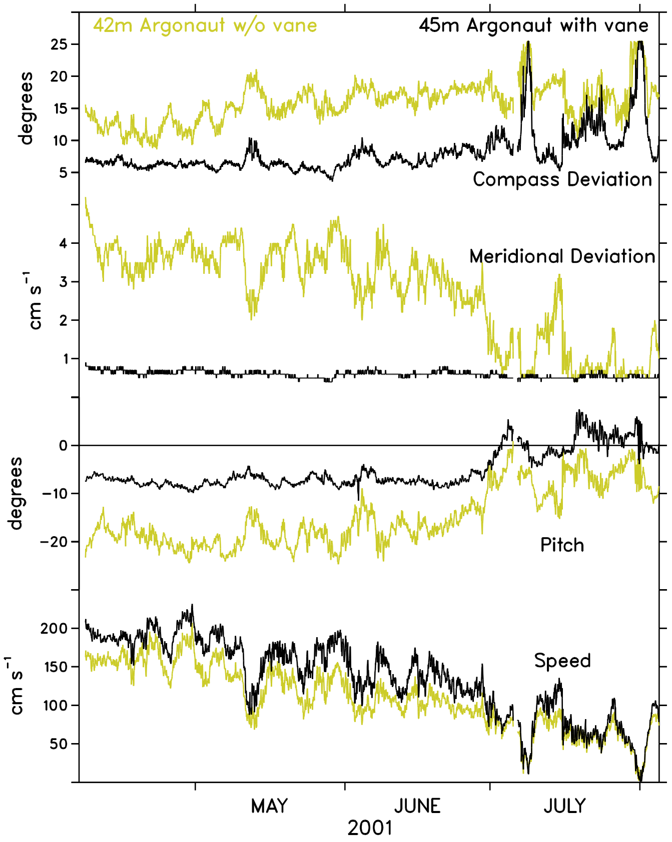

Fig. 6. Compass heading standard deviation, meridional velocity standard deviation, mean pitch and mean horizontal speed from an Argonaut-MD deployed without a vane at 42 m depth (grey) and from an Argonaut-MD deployed with a vane at 45 m (black). Statistics were computed over a 3-min period at 10-min intervals.

45 m for the instrument with a vane). Comparison of data from the two indicated a significant reduction in instrument motion as evidenced by a reduction in the standard deviation of compass heading and tilt from the instrument with the vane (Fig. 6). Since the instruments were in close proximity, the actual tilts should have been comparable. However, the mean tilt reported by the instrument with the vane was about half that of the instrument without a vane, indicating that the decrease in sensor motion improved the accuracy of the tilt sensor. More importantly, the Argonaut-MD equipped with the vane reported substantially larger horizontal current speeds than that from the instrument without the vane. Differences between the Argonaut-MD without a vane and the ADCP were comparable to those of previous deployments (e.g., Fig. 4), while differences between the Argonaut-MD with a vane and the ADCP current speed were small and comparable to those previously observed between ADCPs and VACM/VMCMs (e.g., Fig. 2). The mean difference between the 45 m vaned Argonaut-MD shown in Fig. 6 and the nearby ADCP was −2.4 cm s^{-1} (sign implies Argonaut-MD > ADCP) and the RMS difference between daily mean data was 5.3 cm s^{-1} (Fig. 7).

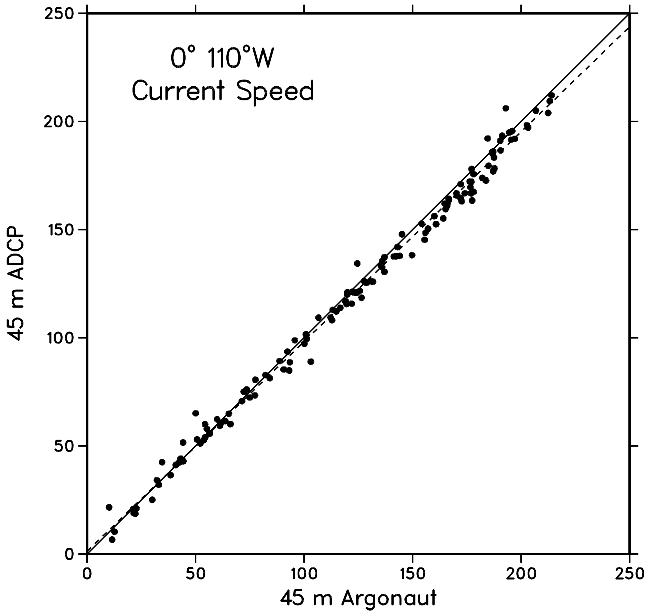

Fig. 7. Scatter plot of 45 m daily mean current speed from an Argonaut-MD deployed with a vane and an ADCP from April to August 2001. The dashed line shows the orthogonal least-squares regression of the two. Units are cm s^{-1}.

The use of these vanes is now standard practice on all equatorial TAO moorings deployed with Argonaut-MD current meters. At present Argonaut-MDs mounted with the vane have been deployed and recovered from five moorings, and in most cases the velocity data are comparable to the ADCP currents with no significant bias toward lower values. Argonaut-MD and ADCP data compare most favorably at more shallow (25 m to 80 m) depths. Somewhat larger differences (up to 15 cm s^{-1} in the mean) have been found for some observations at 120 m. While the reason for this has not been determined at this time, a possible source may be lower signal strength deeper in the water column. In the eastern equatorial Pacific, 120 m is below the biologically productive surface mixed layer, and thus the density of acoustic targets is lower. Signal strength reported by instruments at 120 m are typically 20% to 40% lower than from those at shallower depths. Increasing the signal strength of the Argonaut-MD may provide better data at this depth.

IV. SUMMARY

Argonaut-MD current meters may significantly underestimate current flow when deployed on taut-line surface moorings in strong current regimes. The source of the error is the inability of the compass/tilt sensor to adequately differentiate between acceleration of the instrument and inclination of the instrument from the vertical. A solution to the problem is to reduce the acceleration and magnitude of instrument motion by attachment of a suitably designed vane. Mean current speed differences between ADCPs and Argonaut-MD current meters deployed with vanes and at depths of 80 m and shallower are a few cm s^{-1} or less. Differences at deeper depths are larger, possibly due to decreased signal strength resulting from a lower density of acoustic targets.

Obtaining accurate current measurements on taut-line surface moorings in a strong current regime is challenging. In less energetic situations (e.g., off-equatorial sites within the TAO array, or mid-ocean sites in general) the problem discussed here may not be significant. It should be noted that without in situ comparison data, the bias may have gone undetected, as the Argonaut-MD velocity data by themselves appeared qualitatively reasonable. Whenever new systems are developed a thorough comparison with previous technology is required to ensure that no systematic biases are introduced into the time series.

Acknowledgments—We are grateful to Ramon Cabrerra, Sontek, Inc., for providing modifications and enhancements to the instruments and for analysis of the data which proved invaluable in diagnosing and correcting the problem described here. PMEL contribution 2539.

V. REFERENCES

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