Towing Basin Speed Calibration
of
Acoustic Doppler Current Profiling Instruments

H. H. Shih (1), C. Payton (2), J. Sprenke (3), and T. Mero (4)
Center for Operational Oceanographic Products and Services
NOAA/ National Ocean Services
1305 East West Highway
Silver Spring, MD 20910-3281
PH (301) 713-2897; FAX (301) 713-4465
email: (1) eddie.shih@noaa.gov, (2) charles.payton@noaa.gov,
(3) james.sprenke@noaa.gov, (4) tom.mero@noaa.gov

Abstract

With new development in technologies, proliferation of manufacturers, and expanded applications of acoustic Doppler current profiling instruments, the need for proper sensor calibration procedures becomes increasingly important. This paper describes a towing basin speed calibration procedure that NOS has adopted for the past decade and a summary of calibration results of twenty-eight sensors. These sensors include twelve RD Instruments ADCP's (seven 600 and four 1200 KHz units) and fourteen SonTek ADP's (three 500 and fourteen 1500 KHz units). ADCP and ADP were calibrated repeatedly at the same speed and on different dates. Tow carriage speeds varied from 5 cm/sec to 2 m/sec and were used as references for comparison. The speed differences between sensor readings and carriage references are expressed in terms of mean, standard deviation, and percentage of reference speed. Overall, RDI 1200 KHz ADCP has smaller standard deviation and rms of speed differences and SonTek 500 KHz ADP has the largest. RDI 600 KHZ ADCP and SonTek 1500 KHz ADP are similar. Except for SonTek 500 KHZ, the standard deviation and percentage error of the tested sensors were slightly larger than manufacturer's specifications. The parameters affecting the calibration results, such as error sources and back scatter materials are also discussed.

1. Introduction

The technology of acoustic Doppler current profiling instruments has made significant advances during the past decade. Several products are available on the market and they have been widely used by researchers and engineers in a variety of applications. However, the need of a practical and effective calibration procedure for routine checks of the instrument's speed measurement performance still exists.

The National Ocean Service (NOS) methodically deploys these instruments for use in the Physical Oceanographic Real-Time Systems (PORTS^{TR}) program to monitor currents in navigation channels at several major harbor and bay systems in the U.S. The instruments are also used in a circulation survey program to verify NOS' tidal current prediction products. Data quality control has been a major requirement in these programs. One of the data quality assurance measures is to test the acoustic Doppler current profiling instruments in a towing basin facility to verify its speed measurement performance (Appell, et al, 1988). The facility utilized by NOS is located at the David Taylor Model Basin (DTMB) of the Naval Surface Warfare Center in Carderock, MD.

The sensors tested to date consisted of RD Instruments (RDI) 600 KHz (7 units) and 1200 KHz (4 units) Acoustic Doppler Current Profilers (ADCP), mostly Broadband Workhorse products, and SonTek 500 KHz (3 units) and 1500 KHz (14 units) Acoustic Doppler Profilers (ADP). Both products measure the velocity of water using the Doppler shift principle. However, the transducer design, operation and signal processing techniques vary between the manufacturers.

2. Sensors

The sensors calibrated to date are the RDI ADCP and SonTek ADP types. Some of the common characteristics, major differences, and calibration setup configurations of these sensors are described below.

The RDI ADCP (RD Instrument, 1989, 1993, 1994) transducer assembly consists of four transducers, equally spaced at 90 degree relative azimuth angles and each has a 20-degree beam angle off the vertical axis. Each transducer is used both as a transmitter and receiver (monostatic Doppler system). All RDI ADCP's tested are of the Workhorse model which is a miniaturized version of RDI's Broadband ADCP. It uses a broadband signal processing technique to obtain higher precision and resolution as compared to conventional narrowband signal processing.

For standard narrowband ADCP using 20 degree beams, the standard deviation is approximately $(2.4 \times 10^5) / (FDN^{1/2})$ m/sec, where F is the transmitted frequency (Hz), D is the depth cell size (m), and N is the number of pings averaged together to get the velocity estimate. In Broadband processing, the standard deviation becomes $(1.5V_a / \ )[(R^{-2}-1)(2C)(\cos \ )/FD]^{1/2}$ m/sec, where $V_a = \ \ C/(4FT_L)$ is the ambiguity velocity, T_L is lag time between two pulses, C is speed of sound (m/sec), F is the transmitted frequency (Hz), is beam angle, and R is the correlation at lag T_L (0.5 for a two-pulse system). Note that the frequency dependence now becomes $1/F^{3/2}$ vs. 1/F for the standard narrowband ADCP.

The SonTek ADP (SonTek, 1996, 1997) transducer assembly consists of three transducers, equally spaced at 120-degree relative azimuth angles, and has a 25-degree beam angle off the vertical axis. It is also a monostatic Doppler system. ADP uses the narrowband technology and the standard deviation of its horizontal velocity measurement is proportional to $1 / (FDN^{1/2})$.

For both ADCP and ADP the depth cell (or bin), size affects both range and accuracy. A small cell collects more detailed water current profiles but needs more pings (or longer sampling intervals) to reach a given level of velocity accuracy. Following typical NOS field deployment configurations, it was set to 1 m during the calibration of all sensors. Cell velocities are the weighted averages of the neighboring two depth cells.

Also true for both sensor types is that more pings per ensemble (or profile for ADP) will smooth the data and decrease the standard deviation. The ping rate was set to 1 Hz for RDI ADCP and maximum ping rate (2 to 8 Hz, automatically adjusted based on the range and signal- to- noise level) for SonTek ADP.

Most of the transducer's acoustic energy for ADCP and ADP is concentrated in a narrow beam. However, some energy is transmitted in all directions. Part of this energy (sidelobe energy) will take a direct path to the bottom and the reflections will contaminate the main beam measurement (sidelobe interference) in the near-boundary region. This shortens the velocity measurement range approximately by [1-cos]D, where is a transducer beam angle, D is distance from a center of transduced face to bottom of the basin. This amounts to about 6% and 10% reduction of profiling depth for ADCP and ADP, respectively. The actual profiling depth affected by the sidelobe is a function of boundary condition (strength of reflection), scattering return strength from water, and acoustic properties of transducers, and may be more than [1-cos]D.

In addition to the velocity information at each depth cell, the sensor outputs several data quality indicators. These include: signal strength (for each beam), standard deviations (of each velocity component), and signal-to-noise ratios (for each beam) for ADP; and echo intensity (for each beam), correlation value (for each beam), percent-good pings, and status flag for ADCP.

3. Calibration Facility and Procedure

Sensor speed calibrations were conducted using either DTMB carriage 1 or carriage 2 at the deep water basin. Carriage 1 was operated over a basin section with a width of 15.5 m, depth of 6.7 m, and length of 271 m. Carriage 2 was operated over a basin of same width and depth but with an available length of 575 m. Both carriage designs and their driving systems are similar. While it appears to be a two rail system, each carriage is really a monorail structure with two outrigger idle wheels supporting the lighter side of the carriage frame. Four drive wheels and four pairs of horizontal guide wheels operate in tandem on the main rail. The carriage tows equally well in either direction. The drive system consists of electro-hydraulic drive and a regenerative braking system with four drive wheels. Maximum speed is 9.3 m/sec for carriage 1 and 10.3 m/sec for carriage 2.

The speeds of both carriages were calibrated in the past by DTMB using various methods, including a gear wheel magnetic pulse counter, reflective tape photo cell time gate, and stop watches. The uncertainty is reported to be within $\pm$ 0.15 cm/sec (Day, 2000).

As shown in Fig. 1a and 1b, the base of ADCP or ADP is fastened evenly to the end of a 122 cm long by 15.24 cm diameter Schedule 80 PVC cylinder. For the ADCP, the sensor is oriented such that the tow direction is at 45 degrees with the acoustic beams. For the ADP, one of the acoustic beams is aligned with the tow direction. The PVC cylinder was then clamped to a vertical strut on the carriage with transducers looking downward. The transducers are about 0.5 m below the water surface.

The combined effects of sidelobe interference (6% or 10% of depth plus additional loss), the transducer submergence (~0.5 m), the transducer blanking distance (0.4 m, 0.44 m , or 1 m), and the weighted cell velocity averaging configuration (cell spatial extend of 2 cell sizes or 2 m) limited the number of bin velocities to a maximum of four. Note that the fourth bin velocity averaging depth extends down to about the basin bottom when using a 1 m blanking distance. This will make the fourth bin velocity susceptive to contamination by sidelobe returns from the basin bottom.

Sensors were calibrated at several tow carriage speeds from 5 cm/sec up to 2 m/sec. Data were recorded for 1.5 to 3 minutes depending on the tow speed. Using an ensemble (or profile) averaging interval of 10 sec, a minimum of 9 ensembles (or profiles) were recorded for each velocity data. Carriage speeds are determined by counting the magnetic pulses from the pick-up on the geared wheel that runs on the rail. The counter measures for 0.7 sec and the speed is recorded every second. The speed measurement resolution is about 0.3 mm/sec.

The basin contains filtered natural stream waters and the acoustic back scatter property was poor. To improve the acoustic back scatter strength, two 50-lb bags of pulverized limestone were spread in the water over a tow path of about 150 m before the test. The limestone powder has a particulate size of about 55 micrometer and dispersed rapidly along the tow path and through the water column. The echo amplitudes throughout the calibration speed runs (typically lasting for 20 to 40 minutes) did not change significantly. The echo amplitudes were monitored frequently during the test. To ensure adequate signal return, we use 27 dB (about 60 counts) as a lower limit for calibration.

Two PC's (generally Laptops) were used as data collection platforms, one to record carriage speed and the other to record sensor outputs. The manufacturer's data acquisition software (RDI's Transact Version 2.72 and SonTek's Version 5.2) was used for sensor setup, testing, and data recording.

4. Data Processing and Analysis

RDI ADCP. The raw binary data file from each sensor calibration was converted to ASCII data files using the RDI's data conversion software BBLIST.EXE and a user defined format files. Typical outputs consist of ensemble profile data of velocity components (mm/sec, in XYZ coordinate), echo intensity (for each beam, in counts where each count is about 0.45 dB), correlation value (for each beam, with typical range of 0-255 where 255 is perfect correlation reflecting from a solid boundary), percent-good pings, status flag, and other header information consisting of ensemble number, date and time. A report file for each ASCII data file is also generated documenting the ADCP information, user setup configuration, and processing parameters.

SonTek ADP. The raw binary data file from each sensor calibration was converted to ASCII data files using SonTek's data conversion software modules (GADPSPDR.EXE, GADPSTD.EXE, GADPAMP.EXE, GADPSNR.EXE, GADPHDR.EXE, GADPCTL.EXE). Typically, these ASCII files provide profile data of velocity components (cm/sec, in XYZ coordinate), velocity component standard deviations (along each beam), acoustic back scatter amplitude (along each beam, in counts), and signal-to-noise ratios (along each beam), header information containing profile number, dates and time, number of samples averaged for the profile, sound speed, heading, pitch, roll, temperature and pressure, and control file documenting the file name, date and time, serial number, ADP hardware configuration and ADP user setup parameters.

Useful sensor data were marked when the carriage was run at steady state speed, signaled by the carriage operator. To match the 10-sec sample averaged sensor data (ensemble or profile data) with 1-sec carriage speed data, we used two approaches. The first was to compute 10-sec block averages of carriage speed data set and match it to the sensor data. The second is to compute the average carriage speed over the sensor data period and apply it to the sensor data set. Since the carriage speeds remained fairly uniform during each test run, the latter approach was used in most of the analysis. Typical standard deviation of carriage speed over the calibration speed range is within 0.15 cm/sec which is within the uncertainty of the carriage speed measurement.

For each sensor, the analysis included the computation of vector averaged sensor speeds, differences between sensor speeds and carriage speeds, and associated statistical parameters such as mean and standard deviation of speed differences for each bin and speed group.

5. Results and Discussions

Individual Sensor Performance. Samples of mean speed difference of individual sensors (600 and 1200 KHz ADCP's, and 500 and 1500 KHz ADP's) versus carriage speed are shown in Fig. 2. Note that in these results, the speed differences at lower speeds (less than 50 cm/sec) for most sensors show greater speed errors than at higher carriage speeds. ADP's consistently read lower than reference for both 500 KHz and 1500 KHz units, and ADCP's mostly read higher for 600KHz and varies between for 1200 KHz). Appell (Appell 1988) attributed this error to possible alignment error of the acoustic beam pointing angle.

Variation among Bins. Sample (at carriage speed of 103 cm/sec) bin to bin variations in mean speed difference are shown in Fig. 3, where the frequency in the horizontal axis corresponds to a unique sensor calibrated. Bins 1, 2 and 4 tend to scatter more. Variations are also stronger for the low frequency instruments (500 KHz ADP's and 600 KHz ADCP's). It is suspected that this may be due to threshold frequency response to limestone back scatterers (e.g., longer acoustic wave length relative to the size of the limestone particulate size), or basin echo and reverberations. Stronger wake turbulence associated with the larger 500 KHz ADP transducer head could also be a factor causing large bin variations, especially for Bins 1 near the free surface.

Variation among Sensors. Fig. 3 also shows the variation of mean speed difference among sensors. In general, there are more sensor to sensor variation among ADP's (both 500 KHz and 1500 KHz) than among ADCP's.

Mean Variation among Sensor Types. The statistical parameters of the mean speed difference of all calibrated sensors are shown in Fig. 4 for representative Bin 3 at speed of 103 cm/sec (performances at other speeds are similar). It can be seen that ADP's tend to read slightly lower than reference speed and the ADCP's a little higher. ADCP's have lower standard deviations values compared with ADP's in similar frequency range. Fig 4 also shows the larger sensor to sensor variations among ADP's.

Repeatability. A couple of sensors had repeated runs at same speed during their calibration. Several others also were calibrated more than once at different dates. The repeated speed runs in the same calibration date show a maximum spread of less than 1 cm/sec (mostly are well within 1% of speed), which is an indication of stable calibration environment (assuming high precision sensors). Fig. 5 shows excellent stability of sensors calibrated at different dates. Among the four ADP's and one ADCP calibrated for repeatability, only SN 4032 (not shown) and SN 4033 (both are 1500 KHz ADP units) show a trend of changing performance, in the order of 1 to 2% of speed, which was latter corrected by a firmware change.

Zero Offset. Velocity readings under zero carriage speed were collected in several calibrations. They vary mostly between 0.5 to 1 cm/sec (ADCP 600 and 1200 KHz) and 1 to 2 cm/sec (ADP 1500 KHz units), except higher value of about 6 cm/sec for ADP 500 KHz (SN 104). These are higher than typical sensor bias given by RDI (0.2% $\pm$ 0.5 cm/sec) and SonTek (none). The mean zero offsets are proportional to their corresponding standard deviation values. The temperature distributions in the basin are stable and there is no strong indication of disturbances induced by the tow. This phenomenon was also observed previously (Appell 1988) and causes are currently under investigation.

Back Scatter Strength, Correlation, Percent-Good Pings, and Signal-to-Noise Ratio. Among the data quality parameters output by both ADP and ADCP, signal strength of echo returning from scatterers (echo intensity or signal amplitude) is most indicative. It is used to verify that there is sufficient particulate matter in the water so that the return signal is stronger than the ambient noise level. For each depth cell there is one value for each acoustic beam, and it varied from about 27 dB to 95 dB (mostly at 45-90 dB). A field test at Tampa, FL (Appell et al, 1995) showed values of 67-76 dB (90-99 dB at top two bins).

ADCP also outputs correlation values at each bin and along each beam. Correlation is a measure of the pulse-to-pulse correlation in a ping for each depth cell, indicating the validity or confidence of the data. Low values will increase noise level or increase variability in velocity data and reduce the measurement accuracy. However, it does not correlate directly with the echo intensity and therefore, is not under users' control. The value varied from 120-130 in the calibration. Low value such as 20 was found to associate with large scattering of velocity data.

The Percent-Good Pings output by ADCP represents the percent of pings having good data based on a signal-to-noise threshold. This output was mostly available for beam 4, indicating a four-beam solution used in the velocity computation.

Signal-to-noise ratio is another output parameter from ADP's. Typical starting value near a transducer is SNR 40-60 dB. Value greater than 15 dB is recommended and 3-5 dB is the lower limit for good profile measurement. Most of the calibrations, SNR are greater than 20 dB.

Uncertainty and Error Sources. The uncertainty of velocity measurements depends on many factors such as: Sensor design - transducer beam angles (larger beam angle decreases the standard deviation or increases the accuracy), beam width, pulse length, transmit power and frequency; sensor setup configurations - depth cell size, ping rate, number of pings per ensemble; ambient noise - flow turbulence, salinity and temperature variations; data processing technique - such as narrowband vs. broadband processing, coherent vs. incoherent.

The error sources affecting the accuracy of measurements include: Sensor hardware induced systematic error (bias) - bias due to transducer alignment error could be up to $\pm$ 1% of measured (RD Instrument 1989); biases from calibration procedure errors - such as sensor alignment, reference speed error; random errors from external sources - such as turbulence in the water generated by flow blockage and wake turbulence from transducer head and sensor housing, and non-uniform back scatter particle distribution.

The speed of sound in water is mainly dependent on temperature and salinity. However, it requires significant changes in water temperature and salinity to affect the sound speed (For example, a temperature change of 5 degrees or a salinity change of 12 ppt results in sound speed of 1%). The basin water properties remain relative constant throughout each calibration and no velocity corrections are necessary.

It is not known if the performance differences between 500 KHz ADP's and 600 KHz ADCP's are related to sensor design, signal processing technique, transducer size difference (i.e., associated intensity of flow disturbance), the threshold frequency response to limestone back scatterers, or basin echo and reverberations.

6. Conclusions

The following conclusions can be drawn from the calibration results:

a. Among the sensors calibrated, the performance in speed measurement for 1500 KHz ADP is comparable to those of 1200 KHz and 600 KHz ADCP. Their accuracy and standard deviations are close to the specifications. The 1200 KHz ADCP has the lowest standard deviation and rms of speed differences, while 1500 KHz ADP, and 600 KHz ADCP are about the same. 500 KHz ADP is much nosier in all statistical performance parameters, but its mean accuracy and standard deviation are still close to the specifications.

b. There are larger performance variations among ADP's than ADCP's.

c. The bin-to-bin speed variation is higher in lower frequency sensors.

d. The small variability in duplicated speed runs qualitatively demonstrated the stability of the calibration environment. The repeatability of properly designed ADP's and ADCP's is very good.

e. Back scatter strength is a good data quality indicator. Values below 9 dB in any beam was found to result in bad bin velocity measurement. Limestone seeding in the basin yielded an intensity range of t 27-95 dB. Field test in Tampa, FL showed an intensity range of 67-99 dB in natural waters.

f. Some large deviations in velocity measurements were observed in Bins 1 and 2. Flow disturbances due to the presence of sensor transducer/housing are potential causes.

g. Speed readings of about 0.5 to 1 cm/sec (ADCP 600 and 1200 KHz), 1 to 2 cm/sec (ADP 1500 KHz), and about 6 cm/sec (ADCP 500 KHz) were observed at zero carriage speed. These are larger than the specified sensor bias. It is not known if these are due to large scale basin turbulence generated by the sensor housing and transducer head, threshold frequency response to limestone back scatterers, basin echo and reverberations, or other causes.

REFERENCES

Appell, G. F., J. Gast, R. G. Williams, and P. D. Bass. 1988 "Calibration of Acoustic Doppler Current Profilers," Proceedings of Oceans'88 Conference, IEEE/MTS.

Appell, G.F., J.L. Chapin, L. Gordon, 1995. "Preliminary tests of a prototype Workhorse ADCP," Proceedings of Oceans'95 Conference, IEEE/MTS.

Day, W., 2000. Naval Sea Systems Command, Naval Surface Warfare Center, Carderock Division, 2000. Personal communication.

RD Instruments, 1989. Acoustic Doppler Current Profilers: Principles of Operation: A Practical Primer.

RD Instruments, 1993. Direct-reading Broadband Acoustic Doppler Current Profiler, Technical Manual.

RD Instruments, 1994. Transect: User's Manual for Broadband Acoustic Doppler Current Profilers.

RD Instruments, 1997. DR/SC Acoustic Doppler Current Profiler: Technical Manual.

SonTek, 1996. SonTek ADP Acoustic Doppler Profiler: Technical Documentation.

SonTek, 1997. Acoustic Doppler Profiler (ADP) Principles of Operation.

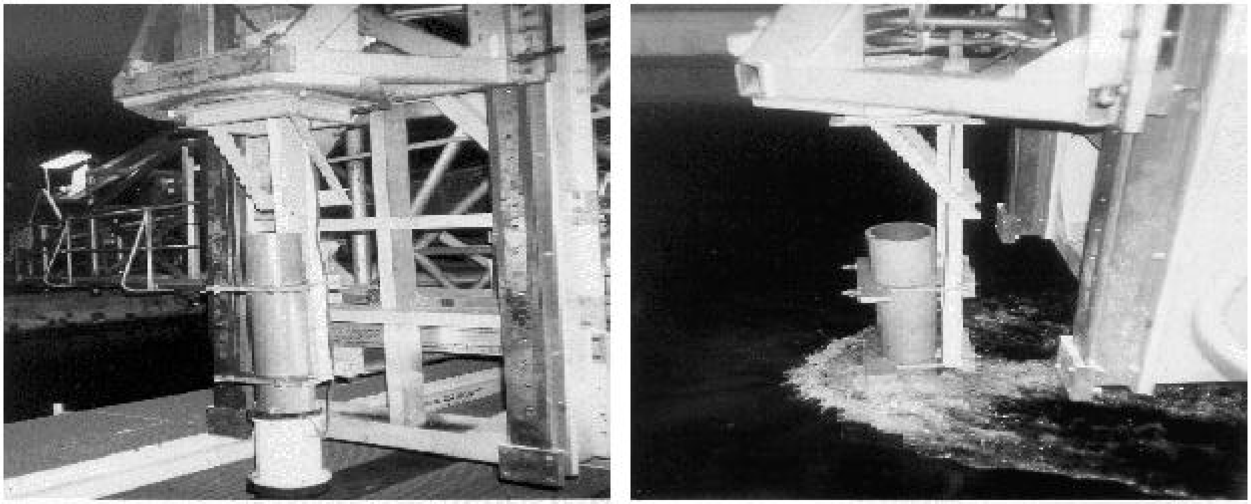

Figure 1. Calibration Setup: Sensor mounting fixture (left), Sensor under tow (right).

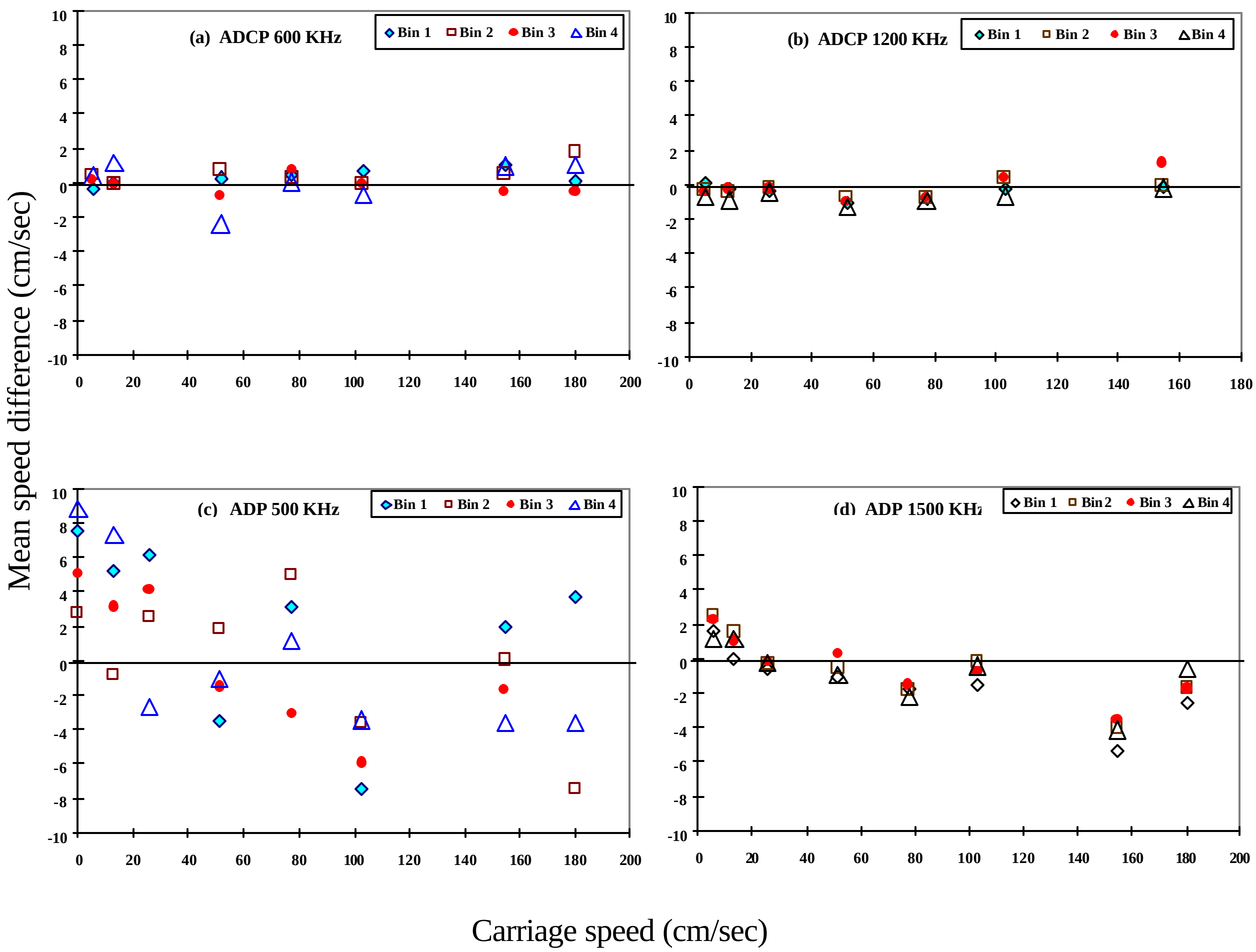

Figure2. Sample results of individual sensors.

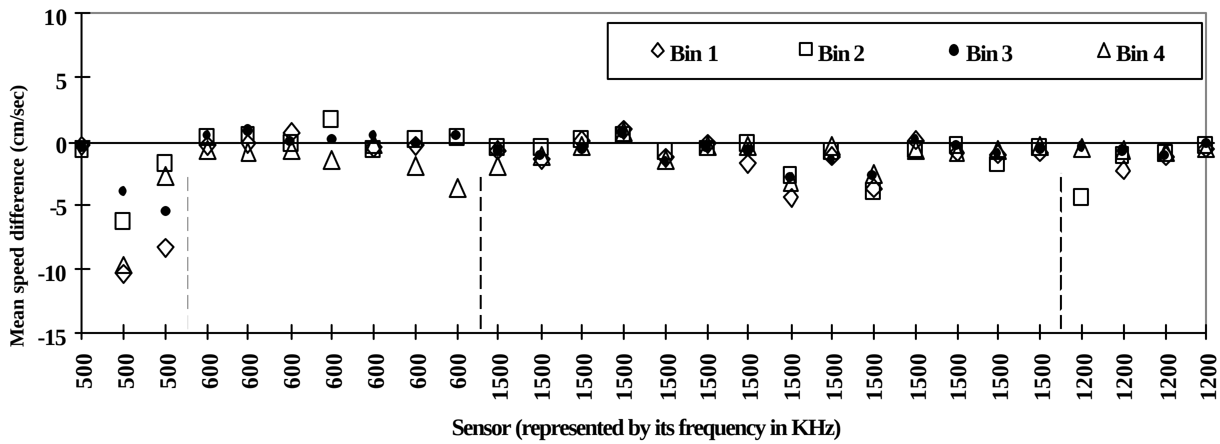

Figure 3. Bin Variations among sensors (103 cm/sec)

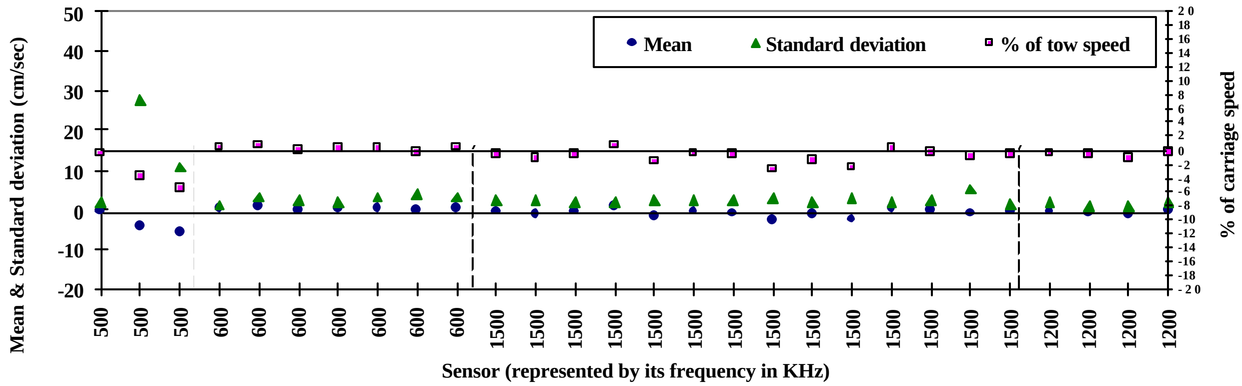

Figure 4. Performance among sensors (Bin3, 103 cm/sec)

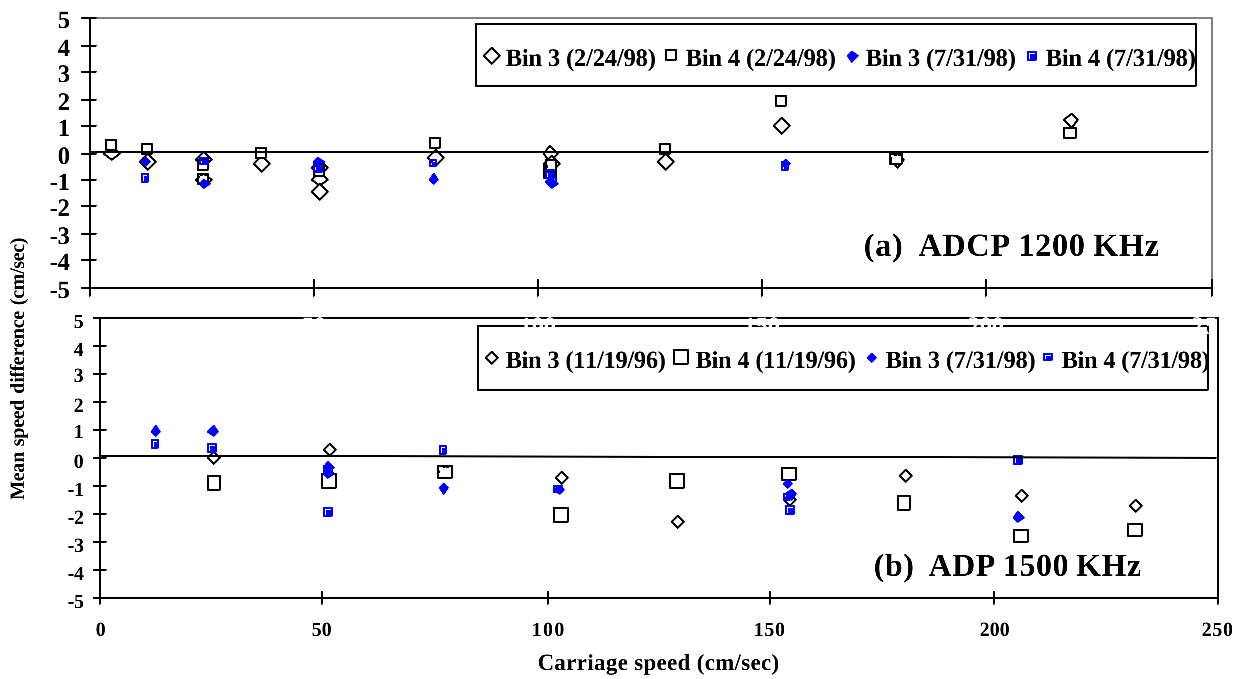

Figure 5. Sample results of sensors calibrated at different dates.