NOAA Technical Report NOS CO-OPS 033

Towing Basin Speed Verification of Acoustic Doppler Current Profiling Instruments

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U.S. DEPARTMENT OF COMMERCE
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Towing Basin Speed Verification of Acoustic Doppler Current Profiling Instruments

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Abstract

With new development in technologies, proliferation of manufacturers, and expanded applications of acoustic Doppler current profiling instruments, the need for proper sensor test procedures becomes increasingly important. This report documents a towing basin speed measurement verification procedure that NOS has adopted for the past decade and a summary of verification results of forty-one cases consisting of twenty-nine individual sensors. These sensors include fourteen RD Instruments acoustic Doppler current profiler (ADCP) units (seven 600 and seven 1200 KHz units) and fifteen SonTek acoustic Doppler profiler (ADP) units (three 500 and twelve 1500 KHz units). Some of these sensors were tested repeatedly on different dates prior to deployment. Tow carriage speeds varied from 5 cm/s to 200 cm/s 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 ADCPs have smaller mean speed differences and standard deviations compared with SonTek ADPs of similar frequencies. There is a larger sensor-to-sensor variation among SonTek units, especially among the 500 KHz ADPs. Except for the SonTek 500 KHz units, the standard deviation and percentage error of the tested sensors were close to manufacturer's specifications. Small zero offsets, on the order of 1 cm/s for ADCPs, 2 cm/s for 1500 KHz ADPs, and 5 cm/s for 500 KHz ADPs, were measured. The test results of both sensor types repeat well over time. To aid in the discussing of test procedure and results, a brief review of related ADCP and ADP design and operational parameters are also included in this report.

1. INTRODUCTION

1.1 Objectives

The technology of acoustic Doppler current profiling instruments has made significant improvements during the past decade. Several products are available on the market and they have been widely used by researchers and practitioners in a variety of applications. However, the need for a practical and effective test procedure for routine checks of the instrument's speed measurement performance exists. This report documents a speed verification method used by the National Ocean Service (NOS) in support of its data quality assurance program.

NOS methodically deploys these instruments for use in the Physical Oceanographic Real-Time Systems (PORTS®) program to monitor currents in navigation channels at several major harbor and bay systems in the U.S. The instruments are also used in the National Current Observation program to verify and update NOS tidal current prediction products. Data quality control is a major requirement in these programs. One of the data quality control measures is testing of the acoustic Doppler current profiling instruments prior to deployment 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.

1.2 Scope

The instruments tested to date consist of RD Instruments' (RDI) 600 KHz (7 units) and 1200 KHz (7 units) ADCPs, mostly broadband Workhorse products, and SonTek's 500 KHz (3 units) and 1500

KHz (12 units) ADPs. Both products measure the velocity of water using the Doppler shift physical principle. However, the transducer design, operation and signal processing techniques vary between the manufacturers. Some of these sensors were tested at different dates separated up to 54 months.

2. SENSORS

To aid in the discussion of test procedure and results, some of the common characteristics, major differences, and test setup configurations of these sensors are described below.

2.1 RDI ADCP

The ADCP transducer assembly consists of four transducer elements, equally spaced at 90-degree relative azimuth angles, and each has a 20-degree beam angle off of the vertical axis. Each transducer is used both as a transmitter and receiver (monostatic Doppler system). All four transducers ping at the same time. The along-beam velocity ensembles are computed and are combined with other beams to compute the resultant horizontal velocity at each depth bin. (three-beams solution or four-beam solution for a better fit). The ensemble velocity is the mean estimate of water velocities determined from all pings over the ensemble interval. The RDI ADCPs tested are of the Workhorse model which is an updated and scaled down version of RDI broadband ADCPs. The systems use a patented broadband signal processing technique which produces higher precision and resolution as compared to conventional narrowband signal processing. Depending on the operating environmental conditions, user of the broadband systems has options to select profiling mode. The mode number defines the types of pings to be transmitted (i.e., combination of ambiguity-resolving and profiling pings) to obtain optimal velocity measurements. Mode 1 is best for dynamic sea state environment and is most robust [RDI 1997]. It is used in both NOS field deployment and towing basin tests.

For standard narrowband ADCP using 20-degree beams, the standard deviation is approximately [RDI 1989]:

$$\text{std.dev. (m/sec)} = K / (FDN^{1/2}) \qquad (1)$$

where K = conversion constant = $2.4 \times 10^5\ (m/s)^2$,
F = the transmit frequency (Hz),
D = the depth cell size (m),
N = the number of pings averaged together to get the velocity estimate.

In broadband processing, the standard deviation becomes [RDI 1993]:

$$\text{std.dev. (m/s)} = (1.5V_a/\pi)[(R^{-2}-1)(2C)(\cos\theta)/FD]^{1/2} \qquad (2)$$

where $V_a = \pi C/(4FT_L)$, the ambiguity velocity,
T_L = lag time between two pulses,
C = speed of sound (m/s),
F = the transmit frequency (Hz),
θ = beam angle,
R = 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 configuration and performance specifications of typical RDI Workhorse [RDI 1994, 1997] sensors are shown in Table 1. Note that the bracketed standard deviation values are estimates based on equation (2) and other manufacturer specified values.

Table 1. RDI ADCP Workhorse Specifications

	Bin size (m)	Blank zone (m)	Profiling range (m)	Ping rate (Hz)	Single ping standard deviation (cm/s)	10-sec averaging standard deviation (cm/s)	Accuracy
300	1	2	130-160	>2	15	[5] at 6 pings/s	± 0.5 % ± 5 mm/s
	2				6	[1] at 6 pings/s	
600	1	0.5	60	>2	6	[1] at 6 pings/s	± 0.25% ± 2.5 mm/s
	2				3	[0.5] at 6 pings/s	
1200	1	0.4	20	>2	3	Frequency (KHz)	± 0.25% ±2.5 mm/s
	2				2	[0.5] at 16 pings/s	

Note: Long-term accuracy: ± 0.2% ± 0.2 cm/s
Max. ping rate (pings/s): lesser of 1/(0.002N + 0.07), or 1/(0.003R +0.07)
Where N=number of depth cells, R= profiling range (m)
Disabling internal compass measurement reduces ping interval by 0.05 sec.

2.2 SonTek ADP

The ADP transducer assembly consists of three transducer elements, equally spaced at 120-degree relative azimuth angles, and a 25-degree beam angle off of the vertical axis. It is also a monostatic Doppler system. Acoustic pinging is carried out one transducer at a time in a rotating sequence among the three transducers. Horizontal velocity profiles are computed from the along-beam velocities of three beams. SonTek uses the term “profile velocity” at each depth bin to refer to the mean velocity estimate computed from all pings over the “profile interval” (similar to ADCP’s “ensemble velocity”). The ADP uses narrowband technology and the standard deviation of its horizontal velocity measurement follows equation (1), using K = 140C [C is the sound speed in water, SonTek 1997]. Typical ADP configuration and performance specifications [SonTek 1996] are shown in Table 2. Note that the bracketed standard deviation values are estimates based on equation (1) and other manufacturer specified values. Standard autonomous deployment sampling scheme (with no waiting time) is used in both NOS field operation and towing basing tests.

Table 2. SonTek ADP Specifications

Frequency (KHz)	Bin size (m)	Blanking distance (m)	Profil-ing range (m)	*Ping rate (pings/s)	Standard deviation (cm/s)		Averag-ing time for sigma<= 1 cm/s)	Accuracy
					Single ping	10-sec average		
500	[1.0]	1	75-125	2	[42]	[9]	[880 s]	± 1% ± 5mm/s
	2				21	[5]	240s	
	4				11	[3]	60s	
1500	0.5	0.4	15-25	9	28	[3]	100s	
	1				14	[2]	25s	
3000	0.25	0.2	3-6	20	28	[2]	40s	
	0.5				14	[1]	10s	

* Ping rate is determined by the propagation time of the acoustic pulses

2.3 General Sensor Information

For both ADCP and ADP, the depth bin size (or cell size) affects both range and accuracy. A small bin collects more detailed water current profiles but requires more pings (or longer sampling intervals) to reach a given level of velocity accuracy. The bin size was set to 1 m during the tow basin tests for all sensors, which is the typical NOS field deployment configuration. Bin velocities are the weighted averages of the neighboring two depth bins.

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

Most of the ADCP and ADP transducer's acoustic energy is concentrated in a narrow beam. However, some energy is transmitted in other directions. Part of this energy (sidelobe energy) will take a direct path to the bottom/surface and the reflections will contaminate the main beam measurement (sidelobe interference) in the near-boundary region. This shortens the velocity measurement range approximately by $[1-\cos\theta]D$, where θ is a transducer beam angle off the vertical, D is distance from the center of transduced face to bottom/surface of the basin. It 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 $[1-\cos\theta]D$. The effect of this is illustrated in Fig. 4a (together with Fig. 4b, a schematic diagram of velocity bins discussed in section 3.2).

In addition to the velocity measurements at each depth bin, the sensor outputs several data quality indicators. For the ADP, these include: signal strength (for each beam), standard deviations (of each velocity component), and signal-to-noise ratios (for each beam). For the ADCP these include echo intensity (for each beam), correlation value (for each beam), percent-good pings, and error velocities.

3. VERIFICATION FACILITY AND PROCEDURE

3.1 Towing Basin

Sensor speed tests were conducted using either DTMB Carriage 1 or Carriage 2 on the deep water basin (Fig. 1a and 1b). Carriage 1 is operated over a basin section with a width of 15.5 m, depth of 6.7 m, and length of 271 m. Carriage 2 is operated over a basin section of the 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 actually 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 forward or backward direction. The drive system consists of electro-hydraulic drive and a regenerative braking system with four drive wheels. Maximum speed is 9.3 m/s for Carriage 1 and 10.3 m/s for Carriage 2.

The speeds of both carriages have been calibrated 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/s (Day, 2000). Fig. 2 shows typical carriage speed standard deviations obtained from one of the verification tests.

3.2 Procedure

As shown in Fig. 3a and 3b, the base of ADCP or ADP housing is fastened evenly to the end of a 122 cm long , 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 installed approximately 0.5 m below the water surface.

With 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 bin sizes or 2 m) limit the number of usable bins to a maximum of four. Note that the fourth velocity bin extends down to about the basin bottom when using a 1 m blanking distance. In this case, the fourth bin velocity is possibly contaminated by sidelobe returns from the basin bottom. Fig. 4b illustrates the general elevations of the transducer and velocity bins, and Table A1 (in the Appendix) lists the sensor Serial Number, operating frequency, test date, and bin size, blank distance, sampling scheme, and profiling mode.

Sensors were tested at several tow carriage speeds from 5 cm/s up to 200 cm/s. 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/s.

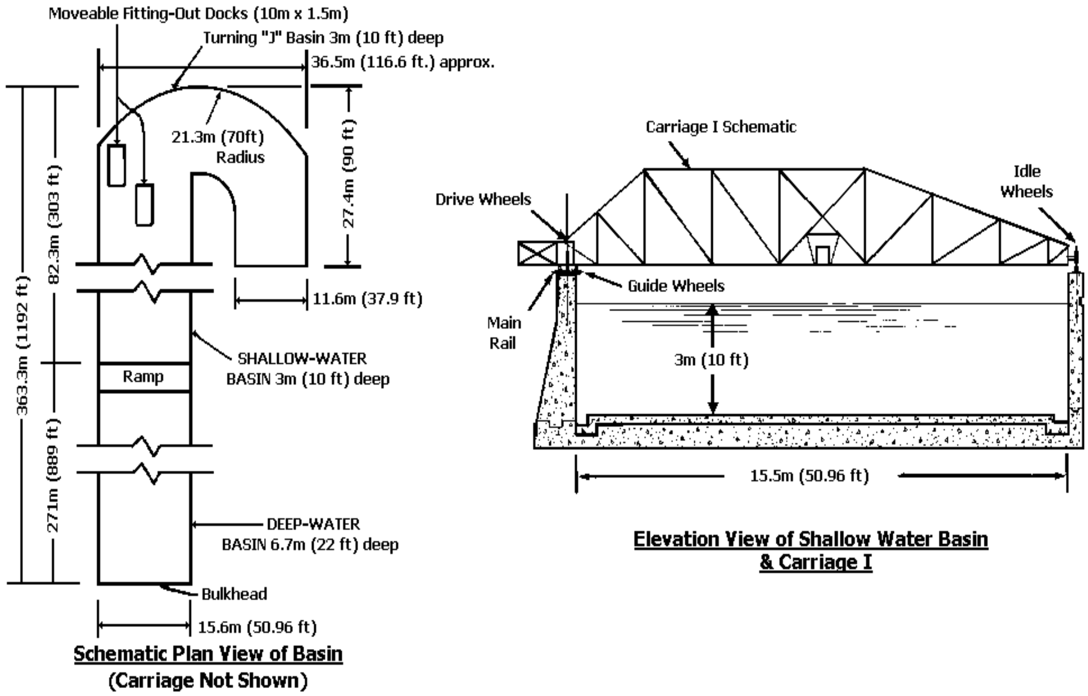

Fig. 1a Towing basin and carriage 1

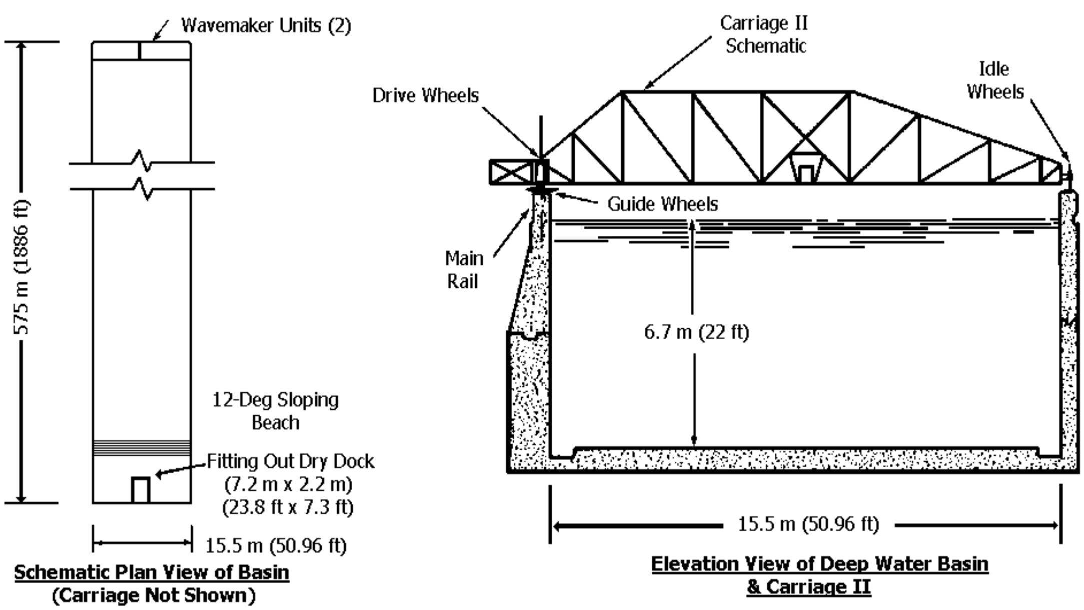

Fig. 1b Towing basin and carriage 2

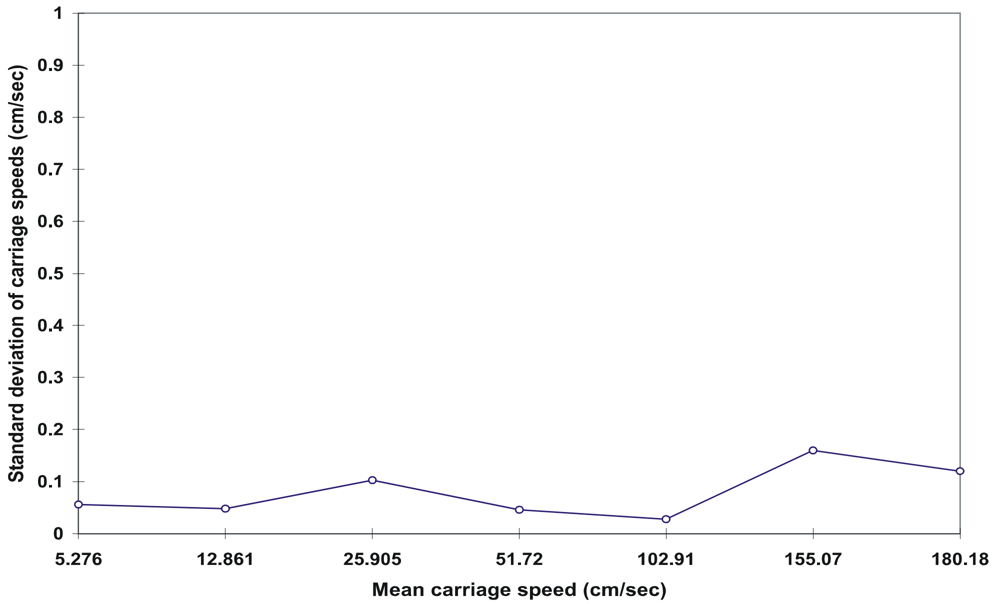

Fig. 2 Typical accuracy of carriage speed

Fig. 3a Mounting of sensor on the carriage

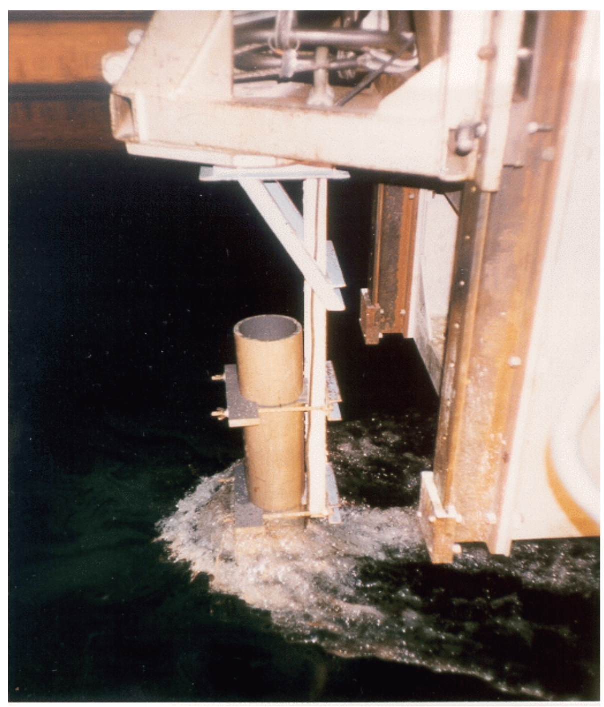

Fig. 3b Sensor in tow

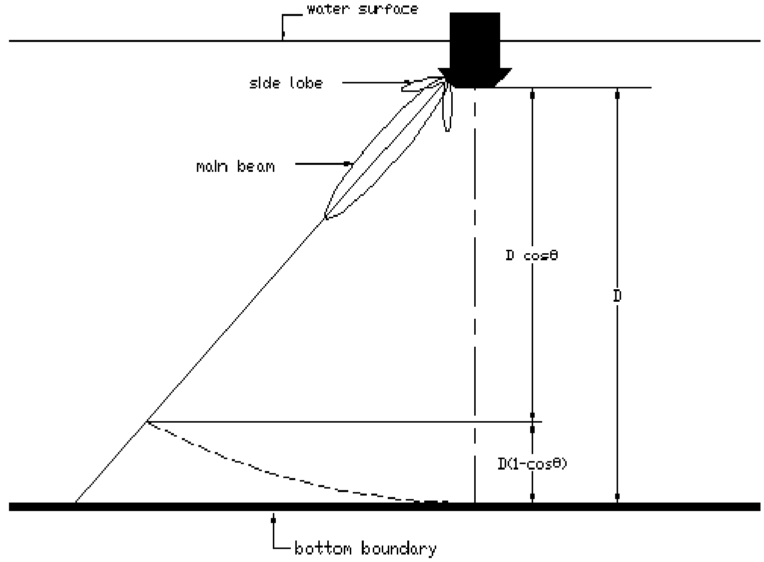

Fig. 4a Profile depth lost due to sidelobe contamination near the boundary

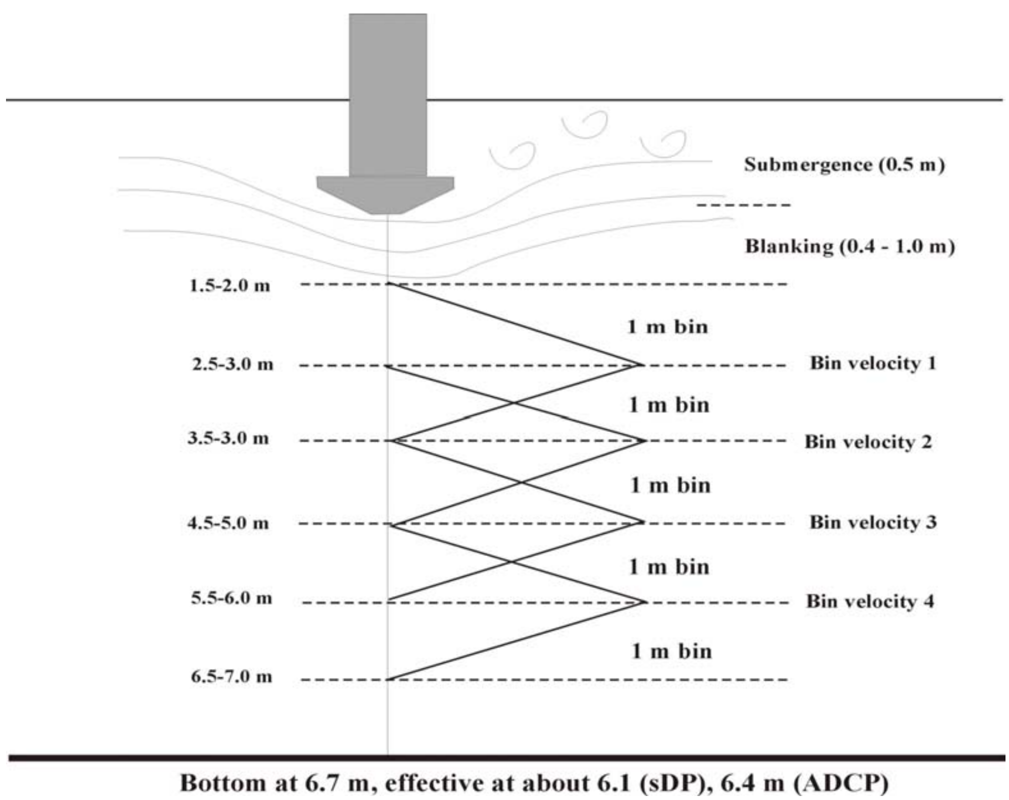

Fig. 4b Schematic diagram of velocity bins

The basin contains filtered natural stream water and the acoustic backscatter properties are poor. To improve the acoustic backscatter strength, two 50-lb bags of pulverized limestone are spread in the water over the tow path before the test. The limestone powder has a particulate size of about 55 μm and dispersed rapidly over the tow path and through the water column. The echo amplitudes throughout the test 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 in all tests. The backscatter strength for most estuary systems is typically high due to suspended sediments, bubbles, zooplankton and other biological matters in the water column.

Two PCs (generally laptops) were used as data collection platforms, one to record carriage speed at one second intervals and the other to record sensor outputs at ensemble intervals (typically 10 seconds). Carriage speed record was typically a large continuously data file over the whole duration of the test. It included calibrated speeds for all sensors tested and speeds when carriage was in transient motion or idling. While the ADCP/ADP record contains only the data over the individual sensor's speed runs (including transient motion between constant speeds). The manufacturer's data acquisition software (RDI Transact Version 2.72 and SonTek Version 5.2) were used for sensor setup, testing, and data recording.

4. DATA PROCESSING AND ANALYSIS

4.1 Binary to ASCII Data Conversion

RDI ADCP data - The raw binary data file from each sensor test was converted to ASCII data file using the RDI's data conversion software BBLIST.EXE and user defined format files. Each format file allows the user to extract the specified data in a desired format. Typical outputs extracted consist of ensemble profile data of velocity components (mm/s, in instrument XYZ Cartesian coordinates), echo intensity (measured signal strength of the returning echo for each beam, in counts where each count is 0.45 dB), correlation value (for each beam, with range of 0-255), percent-good pings, vertical and error velocities, 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, ASCII file format, and processing parameters.

SonTek ADP data - The raw binary data file (ASCII data file output is another option, but requires user defined processing code) from each sensor was converted to ASCII data files using SonTek's data conversion software modules (GADPVEL.EXE, GADPSTD.EXE, GADPAMP.EXE, GADPSNR.EXE, GADPHDR.EXE, GADPCTL.EXE). These ASCII files provide profile data of velocity components (cm/s, in instrument's XYZ Cartesian coordinate), velocity component standard deviations (along each beam), acoustic back scatter amplitude (along each beam, in counts, at 0.43 dB per count), 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.

Samples of ADCP report file and ADP control file are shown in Tables A2a and A2b in the Appendix.

4.2 Velocity averaging and Analysis

During each tow, the starting and ending time for each constant speed (as signaled by the carriage operator) were recorded in a notebook. Since the time between the two speed data loggers (PCs) were synchronized manually and the two speed records (carriage and ADCP/ADP) were of different length, these notes help to identify the corresponding data segments. An iteration procedure which computes the ensemble averages of the carriage speed and the value of correlation coefficient between the two speed records was prepared to determine matching time and the time offset.

Sensor speeds for each constant carriage speed were computed in two ways: one is the speed for each ensemble and the other is the vector averaged speed of all ensembles. These are expressed as follows:

The speed of an ensemble for each bin is:

$$V_i = (V_{ix}^2 + V_{iy}^2)^{1/2} \qquad (3)$$

where i indicates ensemble number i, and V_{ix} and V_{iy} are the x and y velocity components for ensemble i. Fig. 5a and 5b show sample plots of ensemble speeds of sensor and carriage.

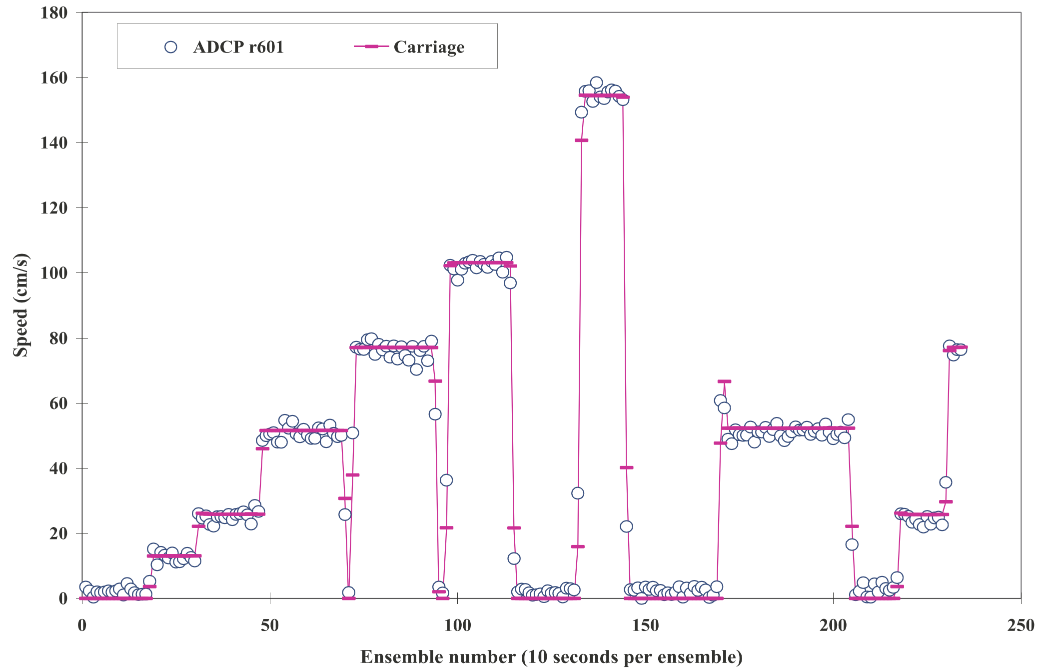

Fig. 5a Sample plot of carriage and sensor ensemble speeds (ADCP r601, Bin 3, 5/11/01)

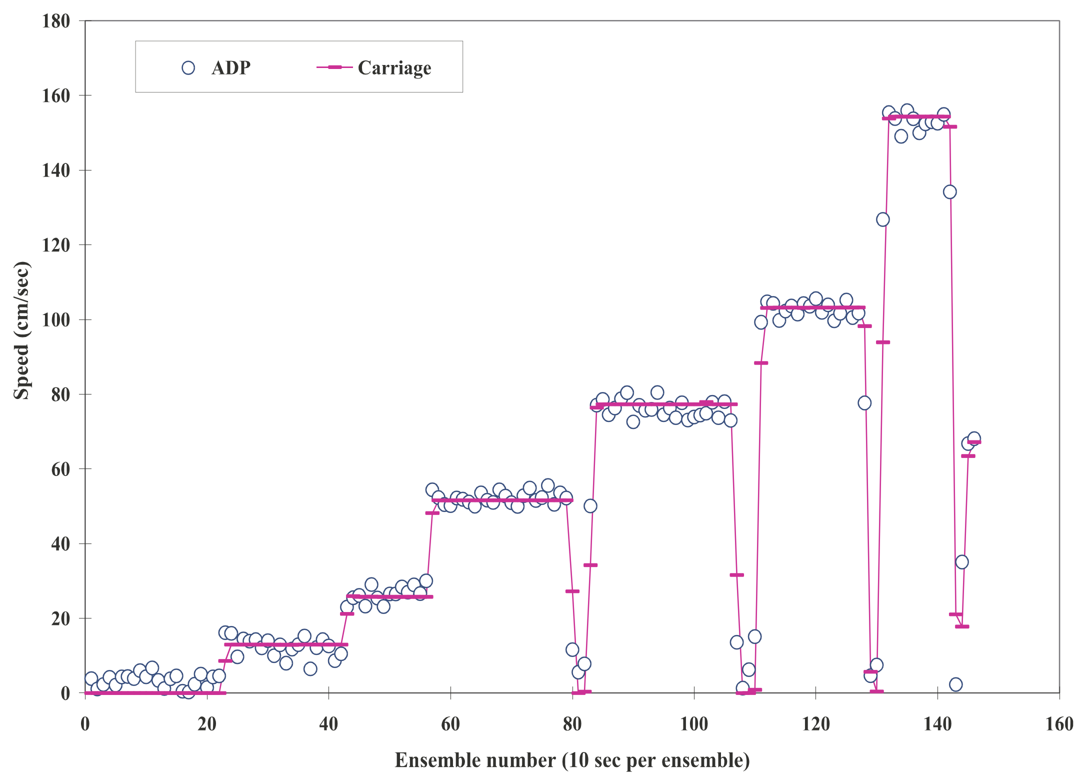

Fig. 5b Sample plot of carriage and sensor ensemble speeds (ADP s4033, Bin 3, 5/11/01)

The vector averaged speed for each bin is:

$$V_m = (\langle V_x \rangle^2 + \langle V_y \rangle^2)^{1/2} \tag{4}$$

where $\langle V_x \rangle$ and $\langle V_y \rangle$ are mean value of x and y velocity components of all ensembles (or profiles) over a constant carriage speed.

The mean speed differences are computed as:

$$\Delta V = V_m - V_{mc}$$

where V_{mc} is the mean carriage speed.

For each bin, the standard deviations of velocity components of all ensembles under a constant carriage speed are also computed.

The use of sensor's vector averaged speeds significantly reduces the mean speed differences for lower speed cases. As an example, for the ADP sensor, the reduction which compares to a non-vector averaging (mean of ensemble speed differences) is in the order of 4 cm/s at zero speed (zero speed offset) and about 1 cm/s at 15 cm/s. For speeds above 50 cm/s, the reduction becomes insignificant.

5. RESULTS AND DISCUSSIONS

5.1 Individual Sensor Performance

To illustrate the relative performance of sensors in terms of operating frequencies, sample results of ADP 500 KHz, ADCP 600 KHz, ADCP1200 KHz, and ADP 1500 KHz are shown in Figs. 6a to 6d (mean speed difference as percentage of carriage speed vs. carriage speed) and Figs. 7a to 7d (standard deviation of X velocity component vs. carriage speed.). Results for other sensors in the same frequency order are included in the Appendix (Figs. A1 to A32). Many sensors in the same frequency group have similar performance characteristics. For briefness, results in standard deviations that are very similar to the cases shown in Figs. 7a to 7d are noted but not presented. The values of standard deviation of Y velocity components are also close to that of the X velocity components and therefore are not shown.

The results showed that the ADP 500 KHz unit has a much larger mean speed percentage differences and standard deviations than ADCP 600 KHz unit, while the ADCP 1200 KHz and ADP 1500 KHz units are about the same in this respect. Overall, ADCP units have lower standard deviations than ADP units. Since the mean speed deviations are about the same over all speeds, the percentage differences for lower speeds (less than 50 cm/s) becomes higher. The ADP speed measurements also tend to be lower than the carriage reference for both 500 KHz and 1500 KHz units.

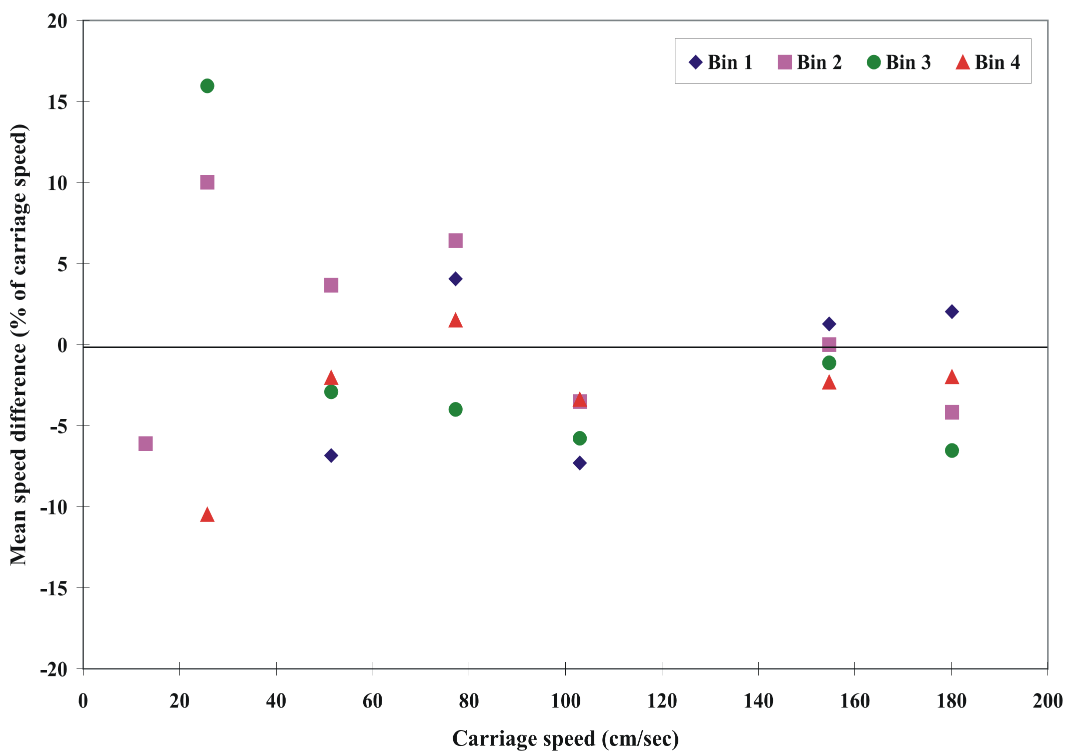

Fig. 6a Mean speed differences of ADP s104/500 KHz unit (9/14/99)

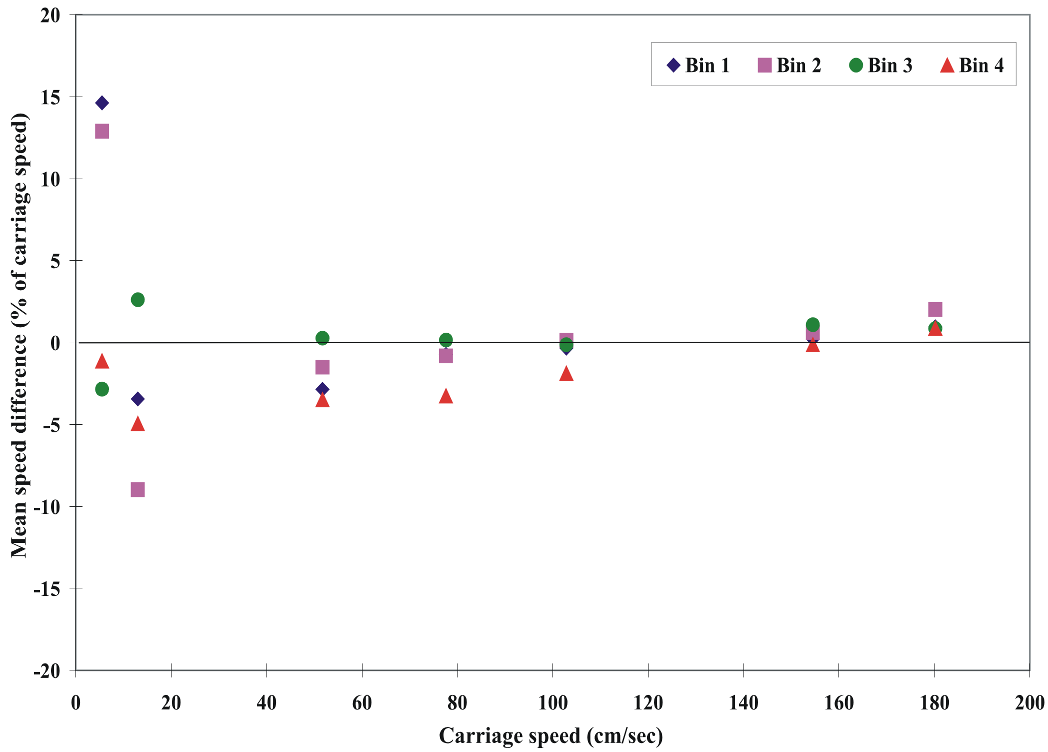

Fig. 6b Mean speed differences of ADCP r948/600 KHz unit (6/17/99)

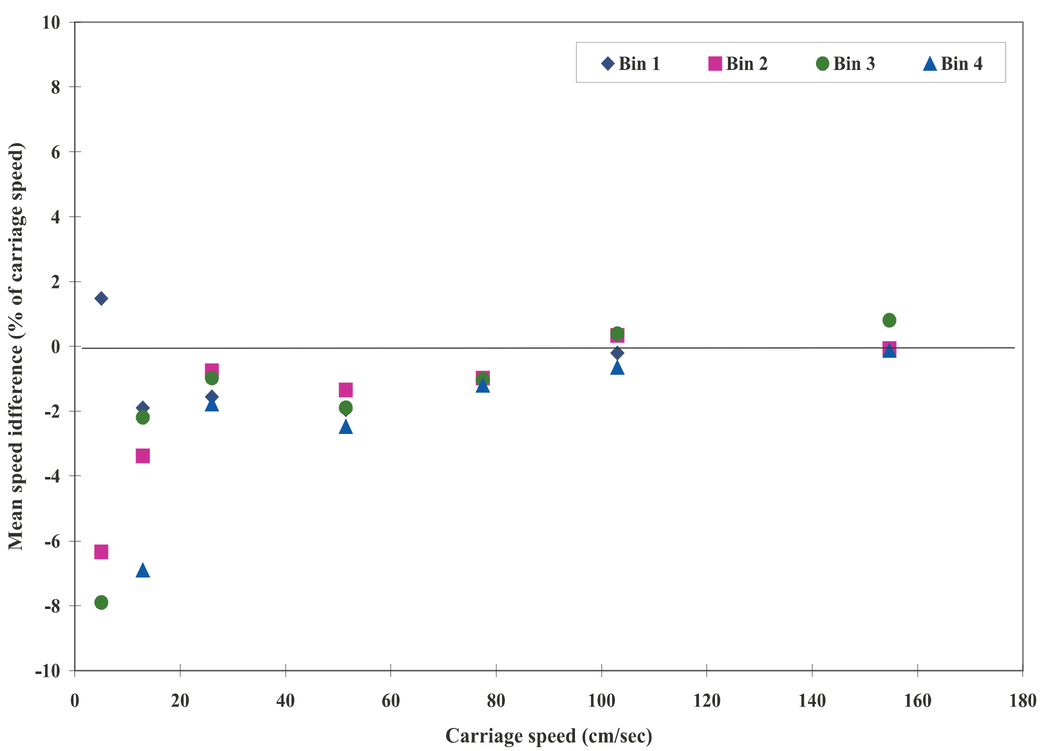

Fig. 6c Mean speed differences of ADCP r238/1200 KHz unit (6/17/99)

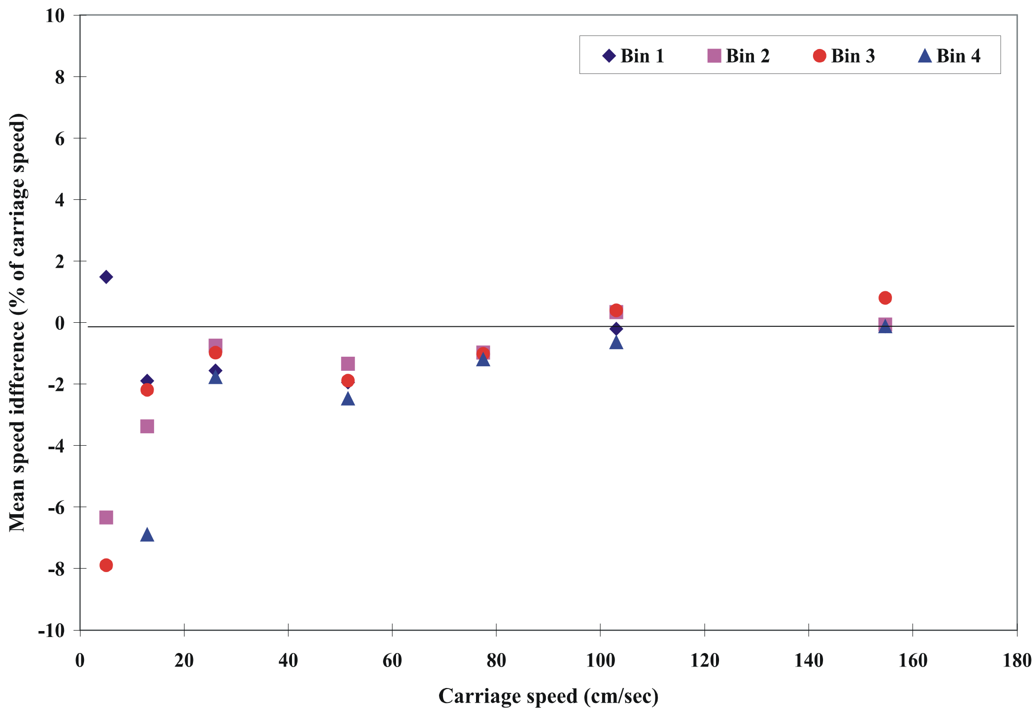

Fig. 6d Mean speed differences of ADP s20/1500 KHz unit (9/8/97)

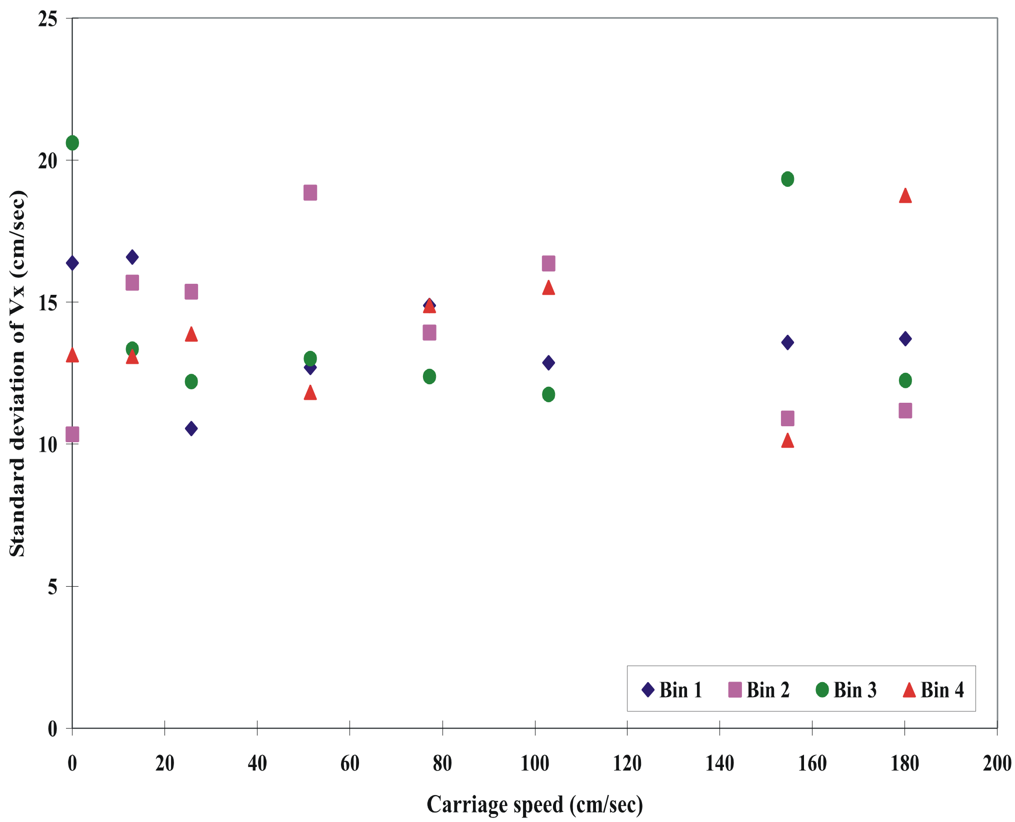

Fig. 7a Standard deviation of velocity component for ADP s104/500 KHz unit (9/14/99)

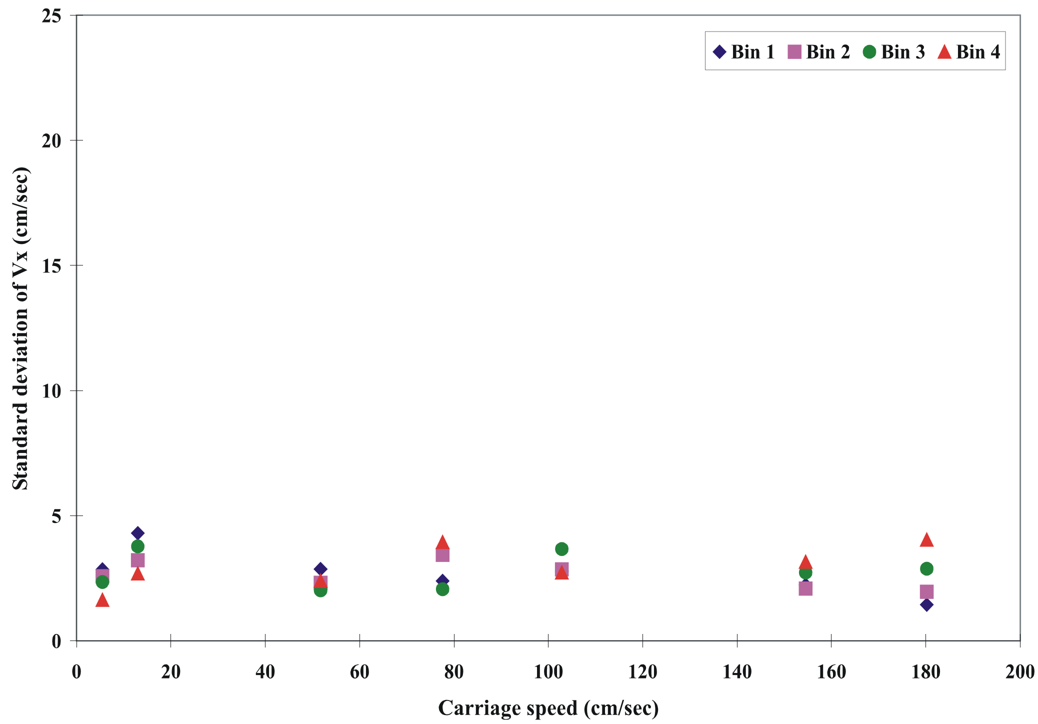

Fig. 7b Standard deviation of velocity component for ADCP r948/600 KHz unit (6/17/99)

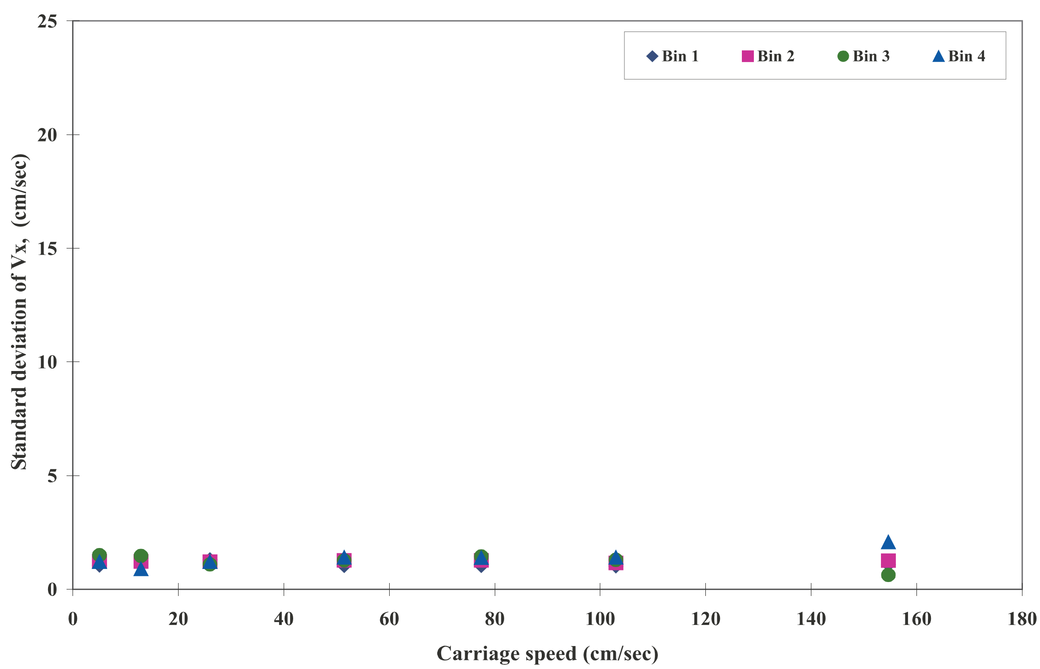

Fig. 7c Standard deviation of velocity component for ADCP r238/1200 KHz unit (6/17/99)

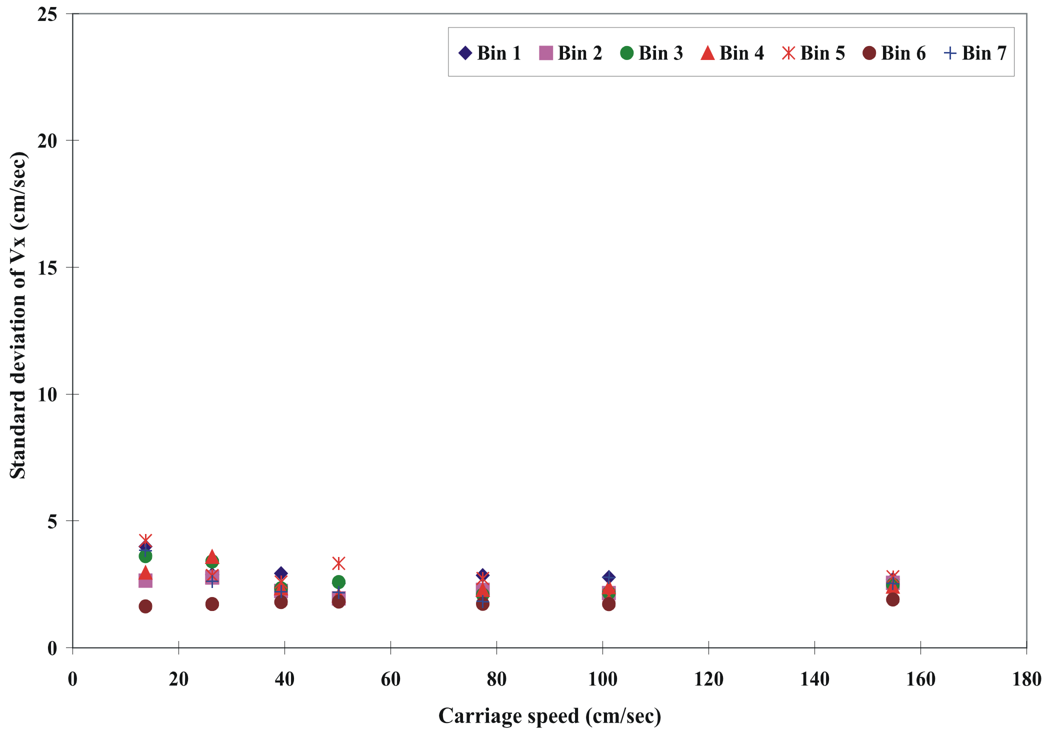

Fig. 7d Standard deviation of velocity component for ADP s20/1500 KHz unit (9/8/97)

5.2 Variation among Bins

Sample bin-to-bin variations in mean speed difference are shown in Fig. 8a for the case of carriage speed of about 103 cm/s. In this graph, sensors tested are represented by an index number and are grouped by their frequency. It is seen that Bins 1, 2 and 4 tend to scatter more than Bin 3. This could be likely caused by the near surface flow disturbances induced by the transducer housing and head (for Bins 1 and 2), and contamination from bottom reflections (for Bin 4). Stronger flow disturbances associated with the large transducer head of 500 KHz ADP could be a factor for its larger variation.

5.3 Variation among Sensors

Fig. 8b shows the mean speed differences and associated standard deviations of all tested sensors for a representative Bin 3 at speed of about 103 cm/s. It can be seen that ADPs (500 and 1500 KHz units) tend to read slightly lower (up to 3%) than reference speed and the ADCPs (600 and 1200 KHz units) a little higher (up to 1 %). The ADCPs have lower standard deviations values compared with ADPs in similar frequency range (about 10 vs. 3 in the 500 and 600 KHz groups, and 1 vs. 3 in the 1200 and 1500 KHz groups). There are more sensor-to-sensor variation among ADPs (-1 to 7 % for 500 KHz group and 1 to -3 % for 1500 KHz group) than among ADCPs (0 to 1 for 600 KHz group and 1 to -1 for 1200 KHz group).

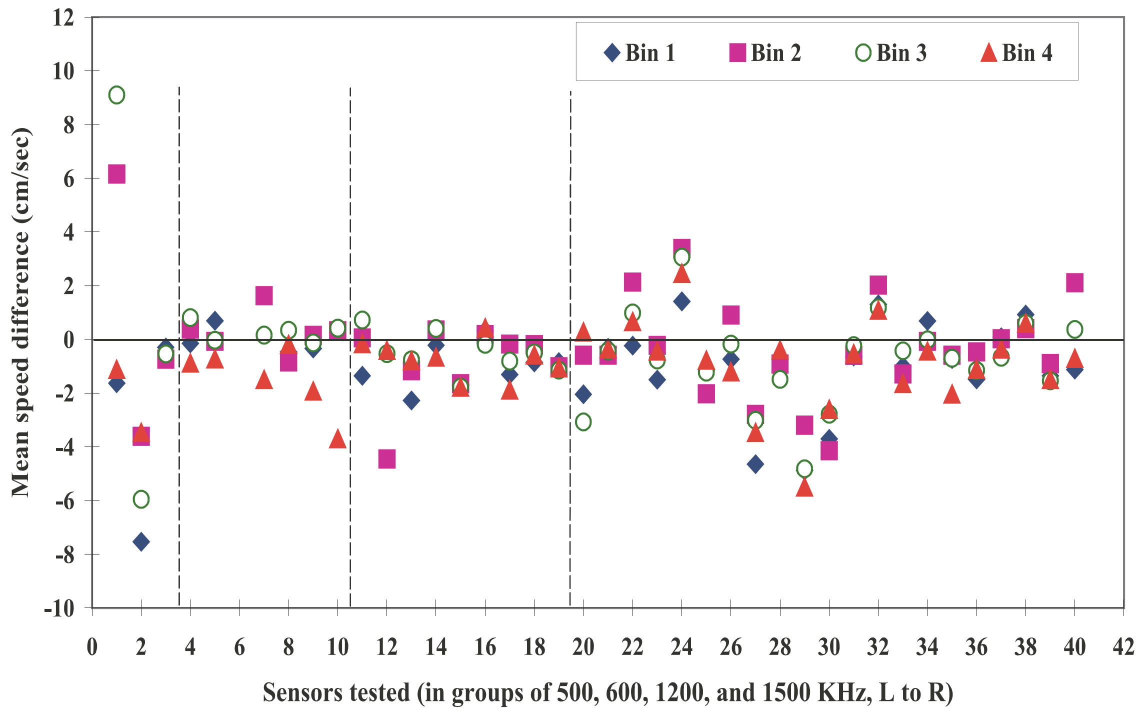

Fig. 8a Summary plot of mean speed differences in Bins 1 to 4
(at speed of approximately 103 cm/sec)

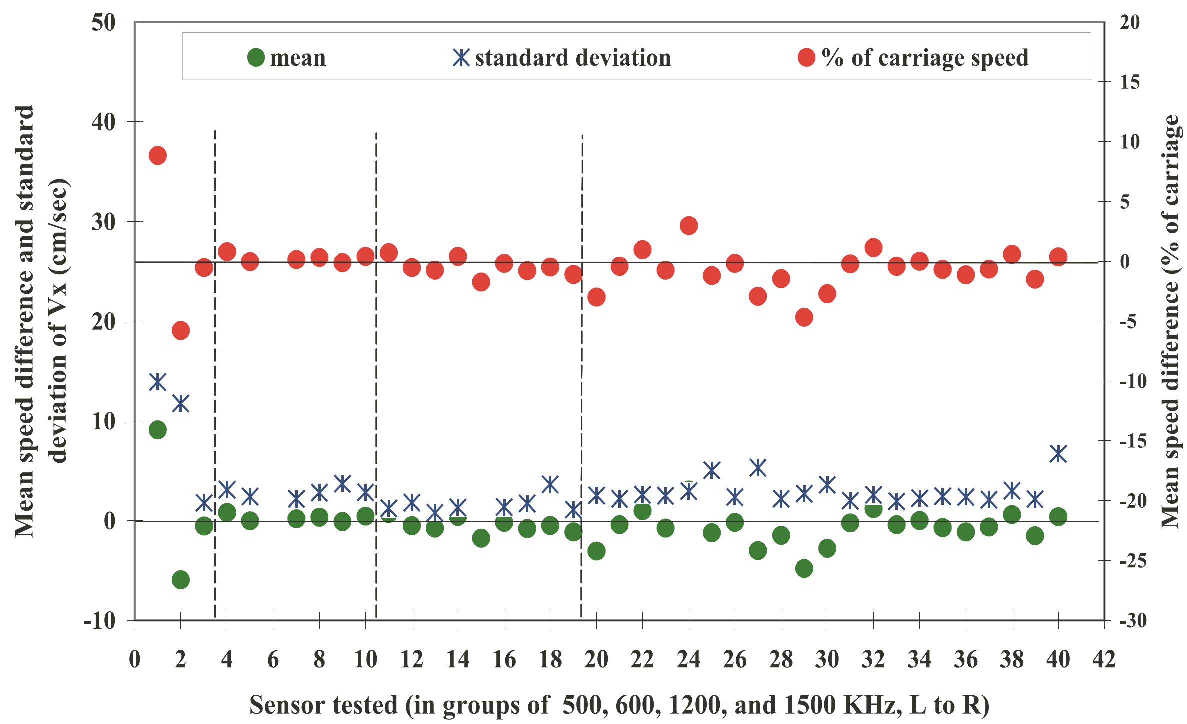

Fig. 8b Summary plot of mean speed differences and standard deviation of Vx
(Bin 3, at speed of approximately 103 cm/sec)

5.4 Repeatability

Most of the sensors had repeated runs at the same speed during their tests. Some also were tested more than once on different dates prior to their deployments. The repeated speed runs on the same test date show a maximum spread of less than 1 cm/s (mostly are well within 1% of speed), which is an indication of stable test environment (assuming high precision sensors). As shown in Figs. 9a to 9i, the stability of sensors over time are also fairly good; the differences are mostly less than 2% of speed and are within the variability of bin velocities. Among the seven ADPs and two ADCPs tested for repeatability, s4032 and s4033 exhibit some shift between the 1998 and 1999 tests. It is not known if this is related to a manufacturer's firmware modification occurred between them.

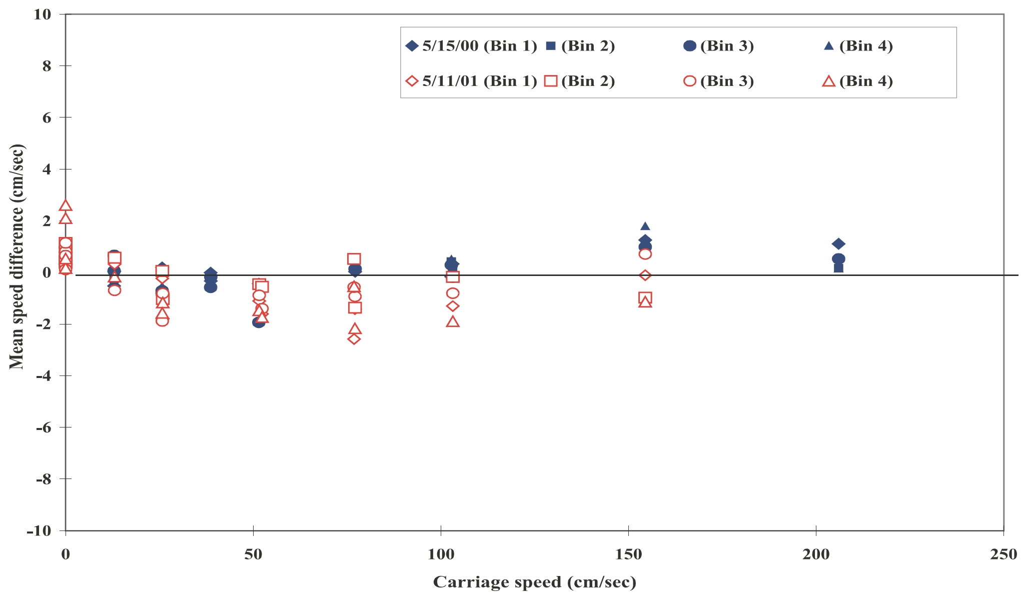

Fig. 9a Repeatability of ADCP r601/1200 KHz unit

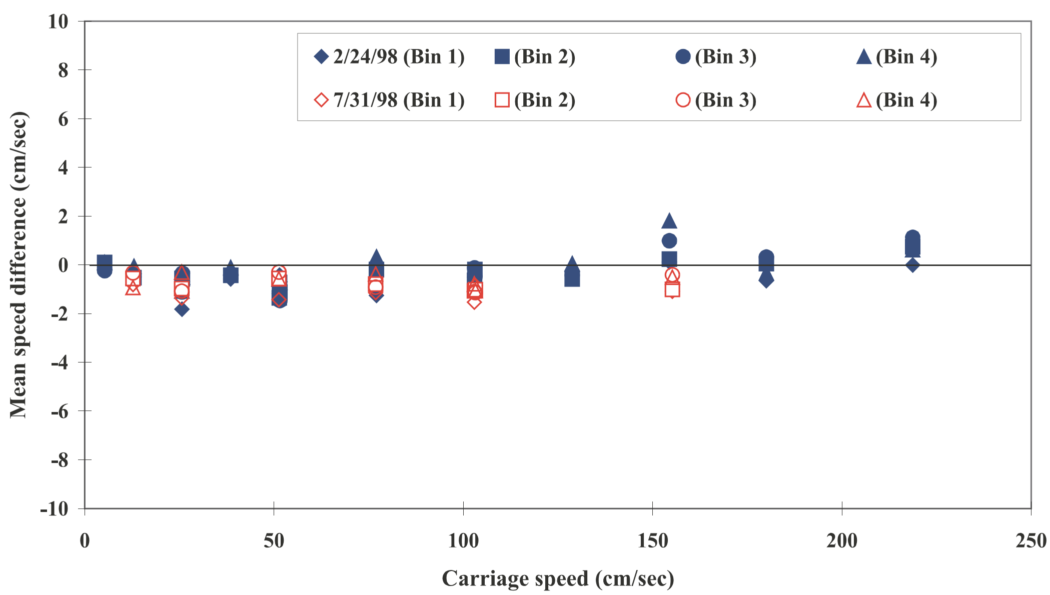

Fig. 9b Repeatability of ADCP r604/1200 KHz unit

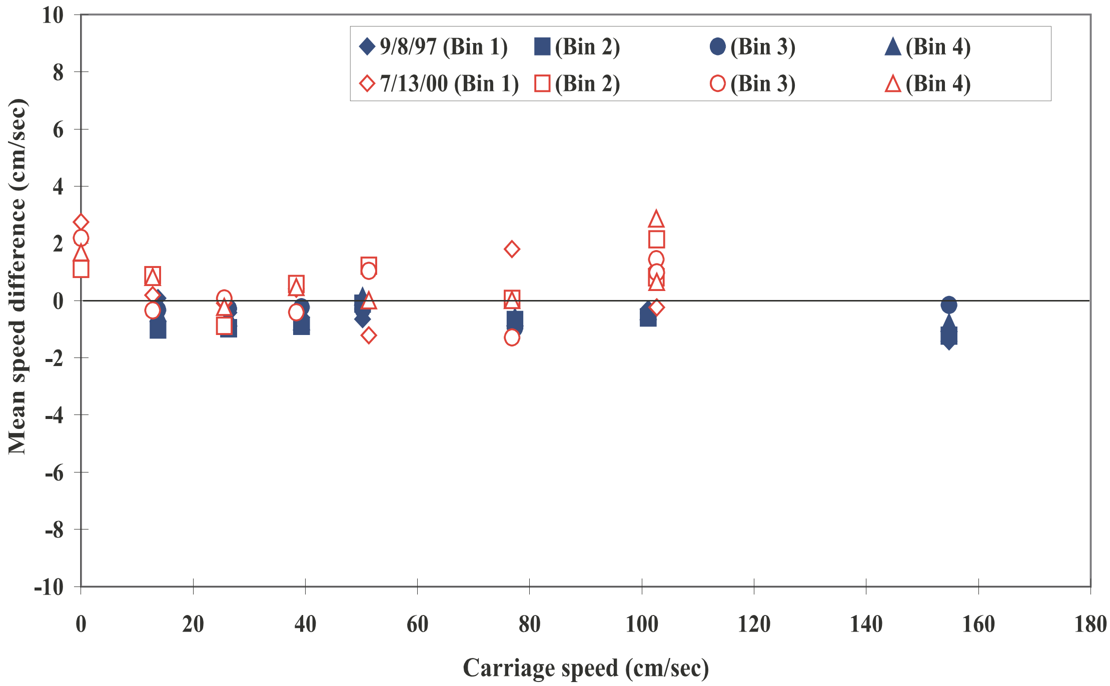

Fig. 9c Repeatability of ADP s20/1500 KHz unit

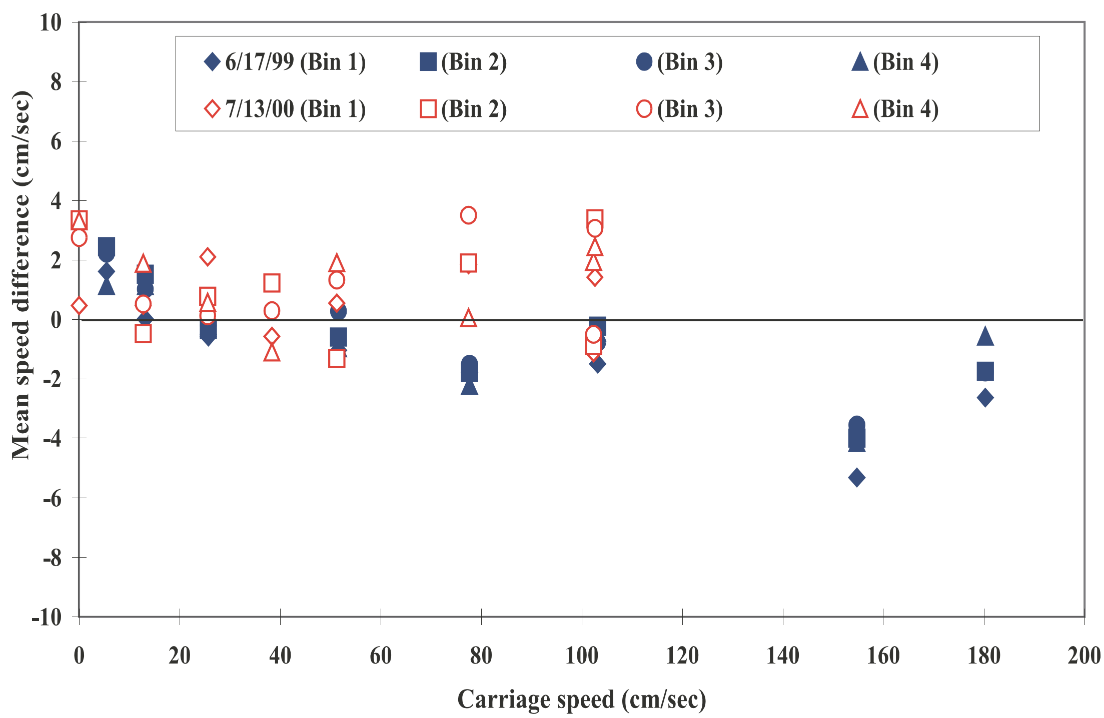

Fig. 9d Repeatability of ADP s21/1500 KHz unit

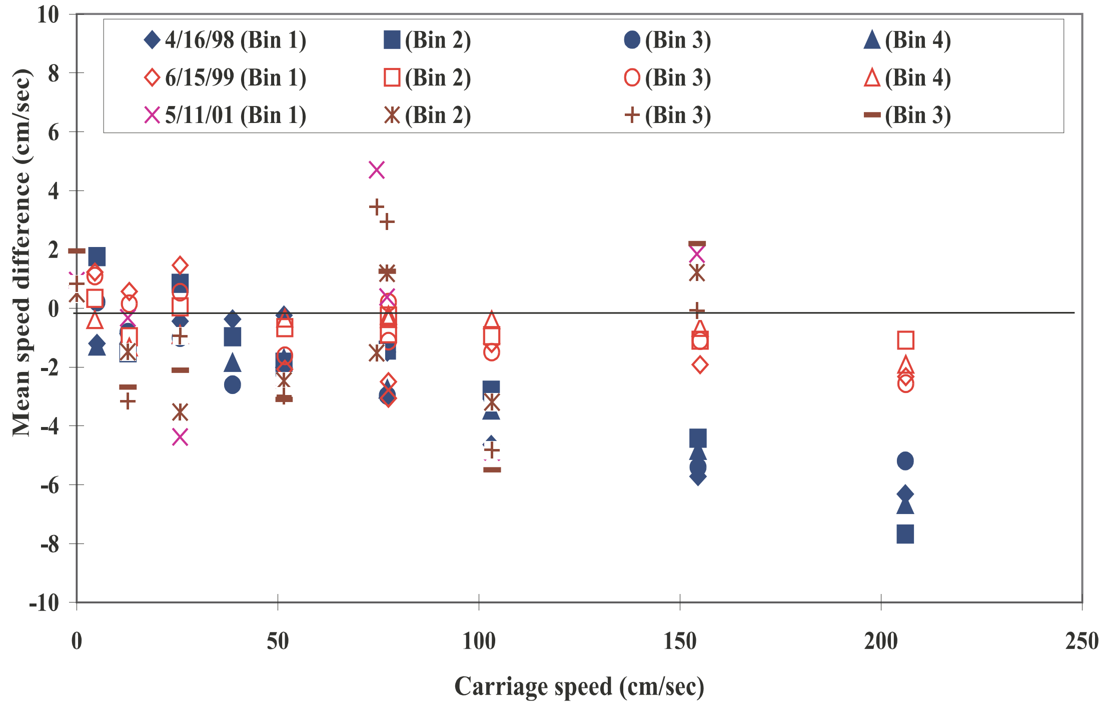

Fig. 9e Repeatability of ADP s4032/1500 KHz unit

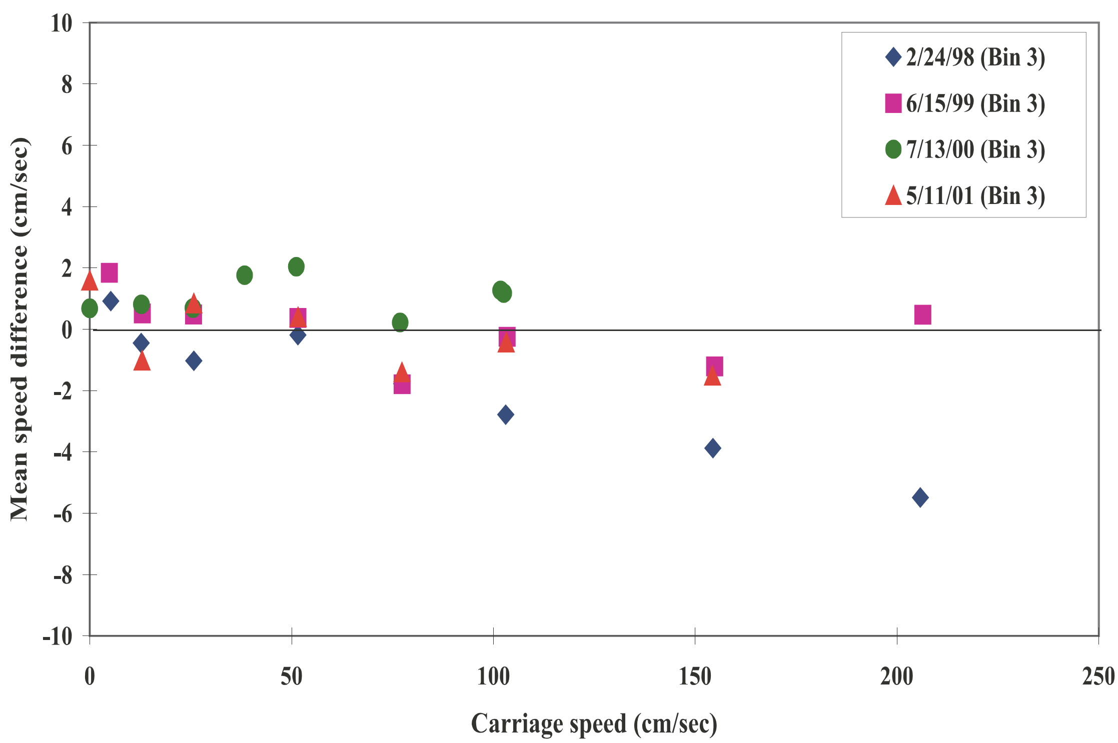

Fig. 9f Repeatability of ADP s4033/1500 KHz unit

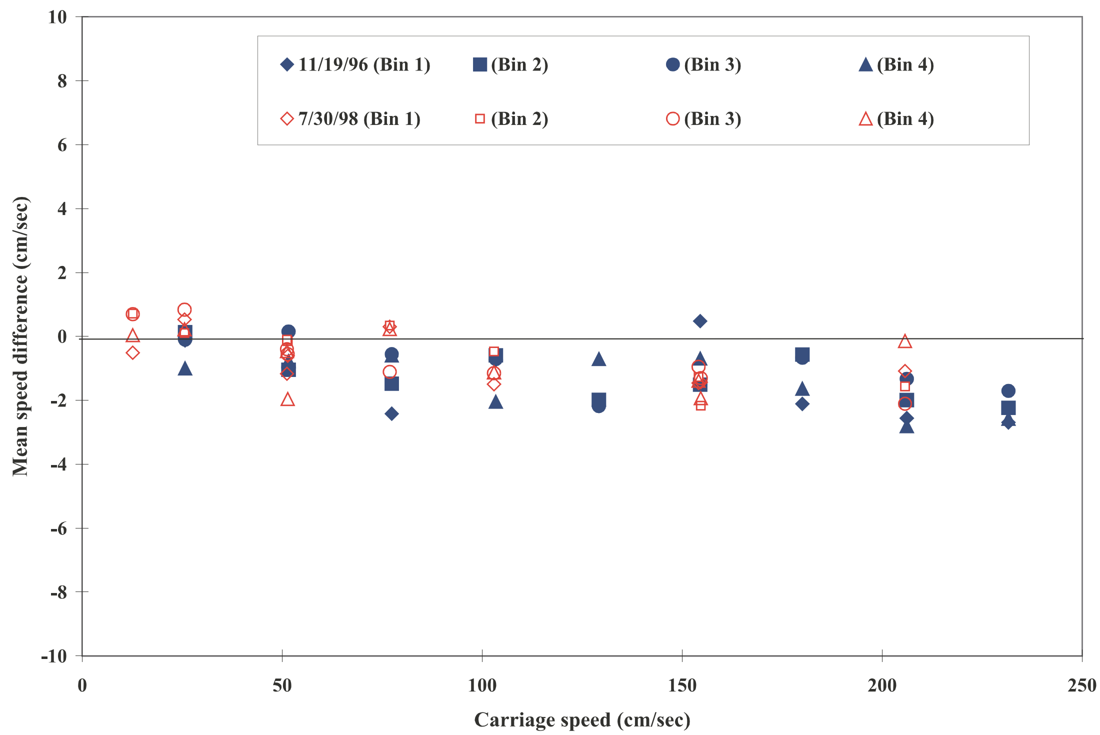

Fig. 9g Repeatability of ADP s4123/1500 KHz unit

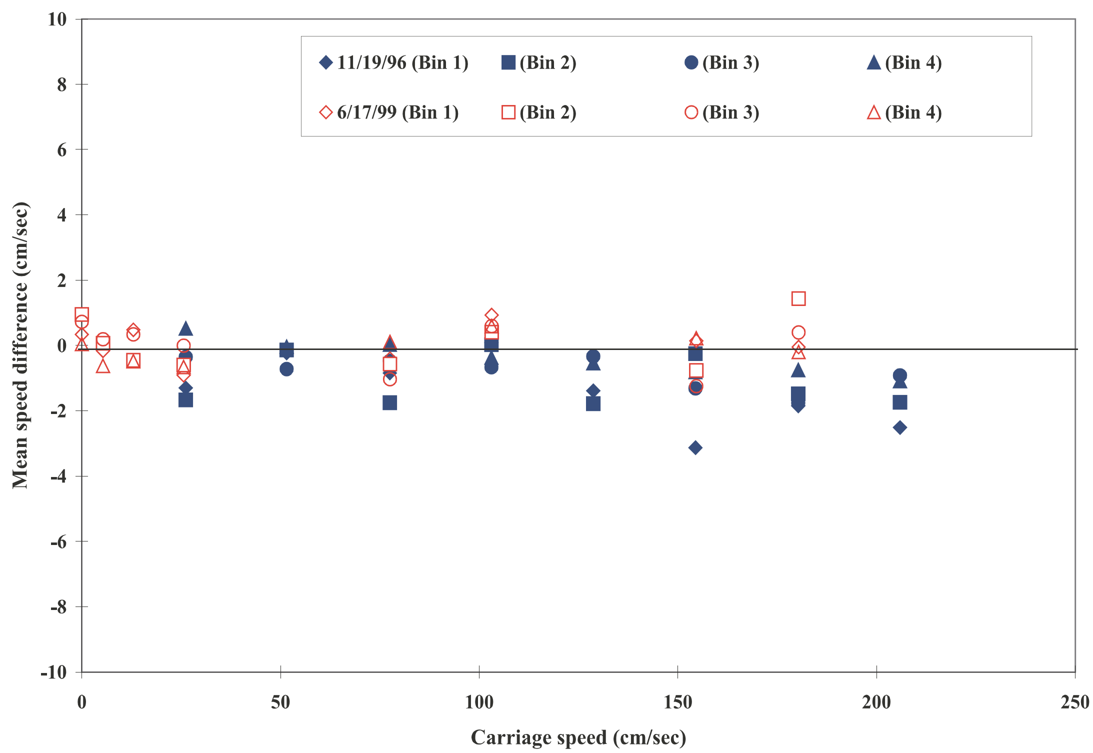

Fig. 9h Repeatability of ADP s4125/1500KHz unit

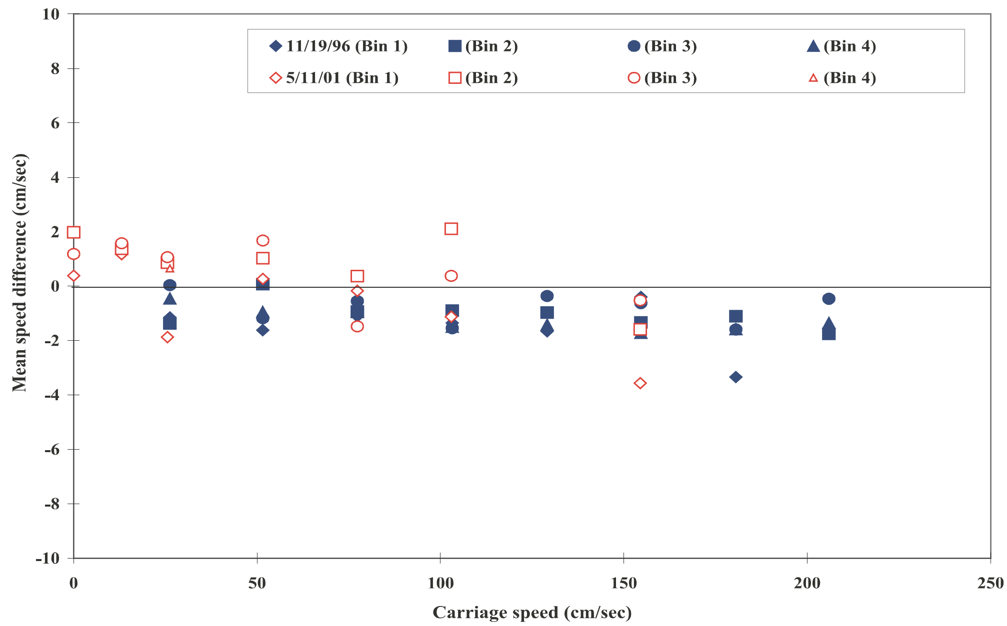

Fig. 9i   Repeatability of ADP s4126/1500 KHz unit

5.5 Zero Offset

Velocity readings at zero carriage speed were collected in several tests. They vary mostly between 0.5 to 1 cm/s for ADCPs (600 KHz and 1200 KHz units) and 1 to 2 cm/s for ADPs (1500 KHz units), except higher values of 3 to 9 cm/s for ADP 500 KHz (Fig. 10a). These are higher than the typical sensor bias given by RDI (0.2% $\pm$ 0.5 cm/s) and SonTek (none). As shown in Fig. 10b, the mean zero offsets are proportional to their corresponding standard deviation values. The temperature

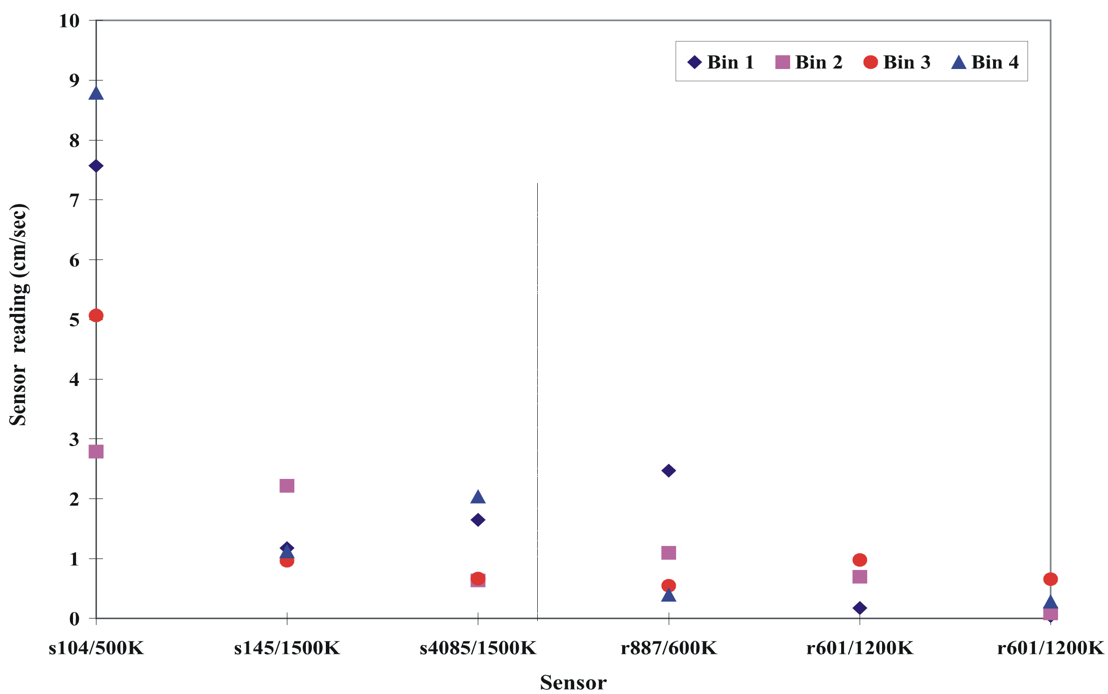

Fig. 10a Sensor readings at zero carriage speed

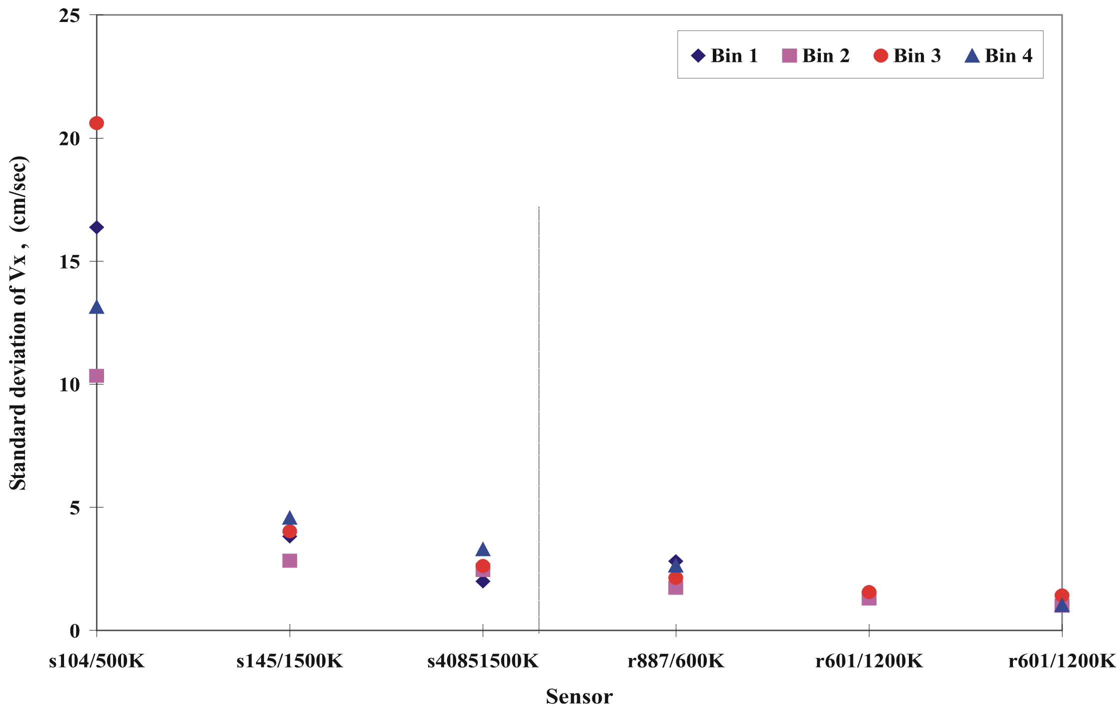

Fig. 10b Standard deviation of sensor readings at zero carriage speed

distributions in the basin are stable (Fig. 11), and there is no significant sign of disturbances induced by the tow. This phenomenon was also observed previously (Appell 1988).

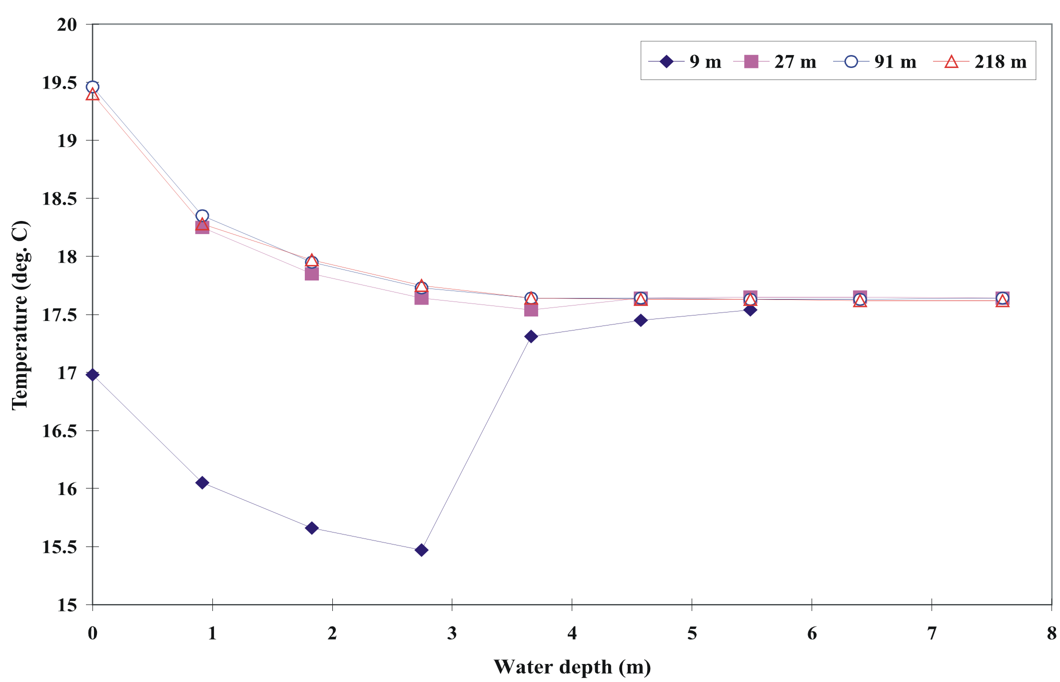

Fig. 11 Sample temperature distribution in the tow basin

5.6 Data Quality Parameters

Among the data quality parameters output by both ADP and ADCP, strength of echo returning from scatterers (echo intensity or returned signal amplitude) is most indicative of measurement quality. It is used to verify that there is adequate particulate matter in the water so that the return signal is sufficiently above the ambient noise level. For each depth cell, there is an echo amplitude value for each acoustic beam, and it varied from about 27 dB to 95 dB (mostly at 45-90 dB). The variation is due to uneven spreading of limestone powder and settling with time. Fig. 12 shows typical echo intensity vs. data ensemble number (at 10 s per ensemble). Also shown in this figure are constant carriage speed segments when sensor data were collected. Fig. 13a shows an example of data drop (in Bin 1) due to low level of backscatter (along Beam 1 and 3 where echo intensities are below 11 dB). Most estuarine waters contain zooplankton which tends to migrate between near surface layer and deeper depth during a day. This appears to be reflected in the semi-diurnal variation in echo intensity data at PORTS® sites (for example Tampa Bay, FL by Appell et al, 1995; and Oakland, San Francisco Bay by Bourgerie, 2001). The echo intensity varied from 67 to76 dB (90 to 99 dB at top two bins near the surface) in Tampa Bay and from 34 to 54 dB in Oakland.

The Percent-Good Pings information from ADCPs is also a useful data quality indicator. It represents the percent of pings having good data based on a signal-to-noise threshold. Most of the tests had a four-beam solution in the velocity computations (i.e., 100% good pings in 4-beam solutions), which represents an optimal solution with minimum uncertainties in the velocity determination. When the value drops to 90% or less it often indicates lower data quality such as the case shown in Fig. 13b where a 3-beam solution is required and most of the speed runs had about 90% good pings.

The ADCP's Correlation is a measure of the pulse-to-pulse echo auto-correlation in a ping for each depth cell, indicating the validity or confidence of the data. It ranges from 0 to 255 counts (255 represents a perfect correlation from a solid target). Low values will increase noise level or increase variability in velocity data and reduce the measurement accuracy. Typical default threshold value for bad data is 64 counts. The value varied from 120-130 in the tow basin tests. Low values such as 20 are found to be associated with large scattering of velocity data. However, as shown in Fig. 13c (same case as Fig. 13a and 13b), this data quality indicator is not as robust as echo intensity or percent-good pings.

Signal-to-noise ratio (SNR) for each beam is another parameter in the ADP output. Typical initial values near a transducer are 40-60 dB. Values greater than 15 dB are recommended, and 3-5 dB is the lower limit for good profile measurement. In most of the tow basin tests, the SNR are greater than 20 dB.

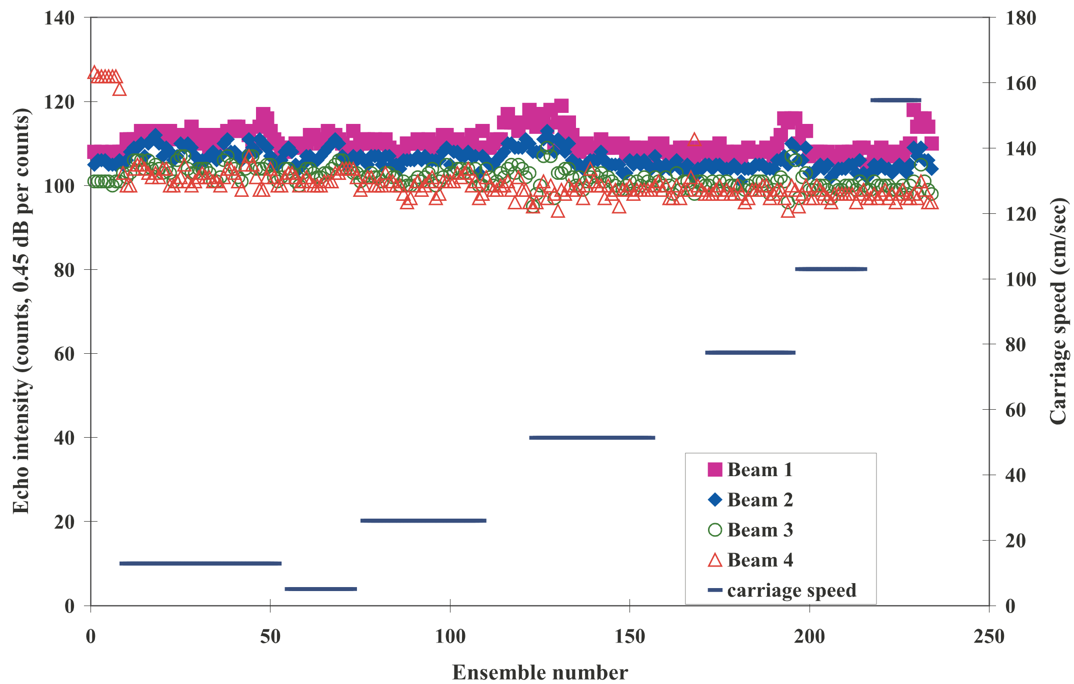

Fig. 12 Typical echo intensity data (ADCP r238/1200 KHz, 6/17/99)

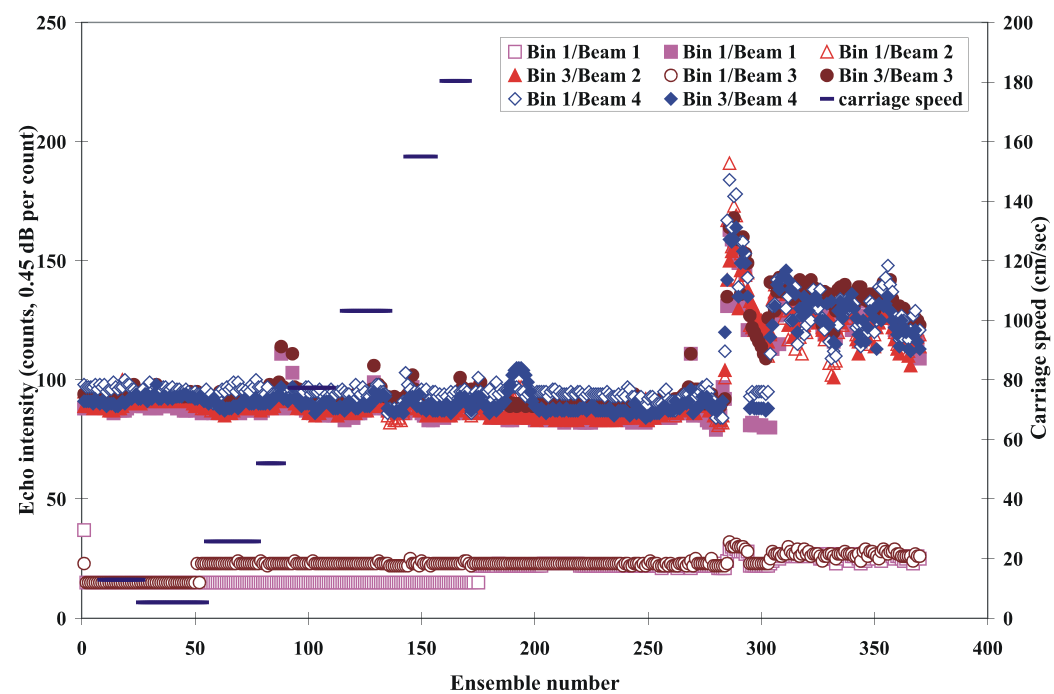

Fig. 13a Example of echo intensity affected by non-uniform backscatter distribution (ADCP r949/600 KHz, 6/16/99, Bin 1 empty)

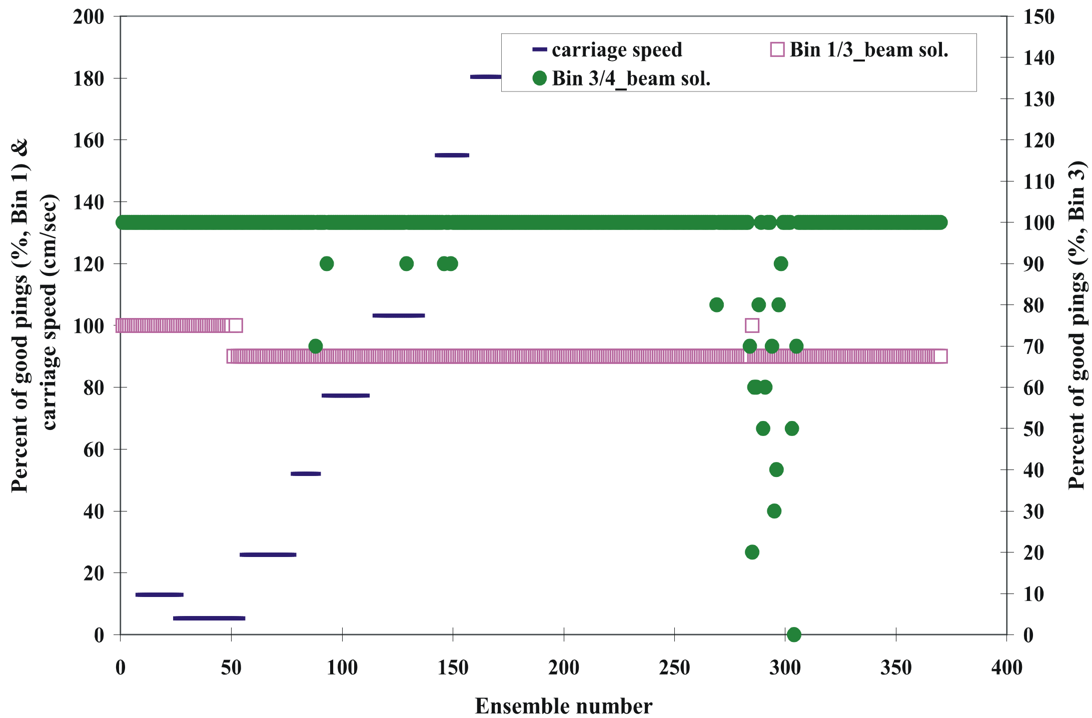

Fig. 13b Example of percent of good pings associated with non-uniform backscatter distribution (ADCP r949/600 KHz, 6/16/99, Bin 1 empty)

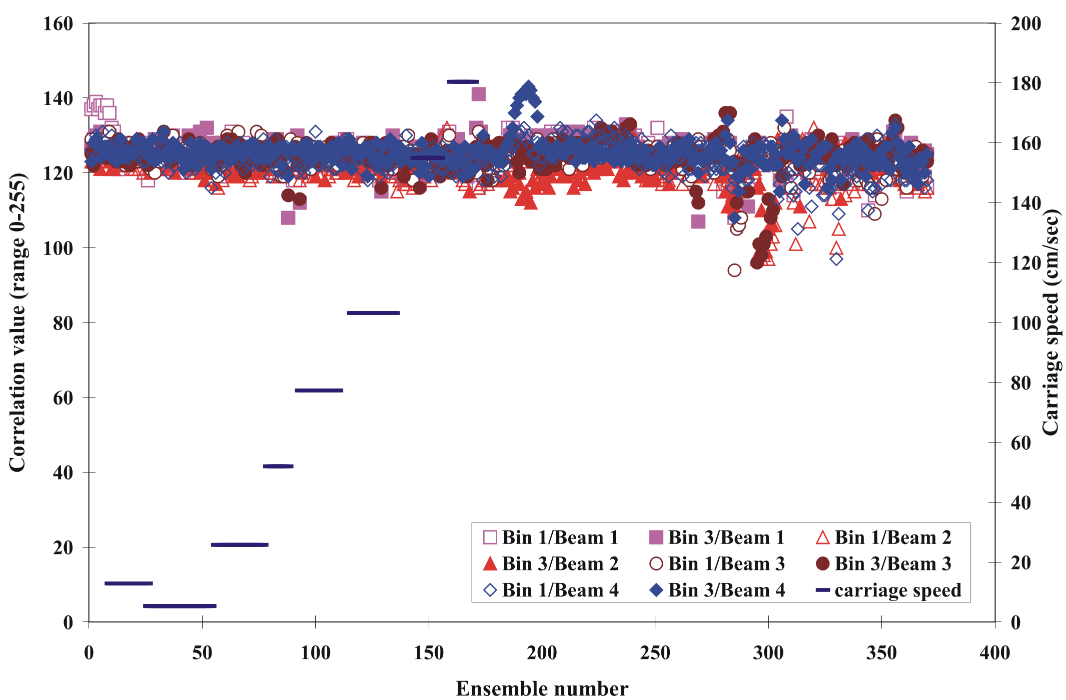

Fig. 13c Example of correlation value associated with non-uniform backscatter distribution (ADCP r949/600 KHz, 6/16/99, Bin 1 empty)

5.7 Uncertainty and Error Sources

As shown in Figs. 14a and 14b, Bins 1 through 4 are indeed good velocity bins, while sensor speed data in other bins were affected by the basin boundaries (bottom and side walls for Bin 5 through 7).

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.

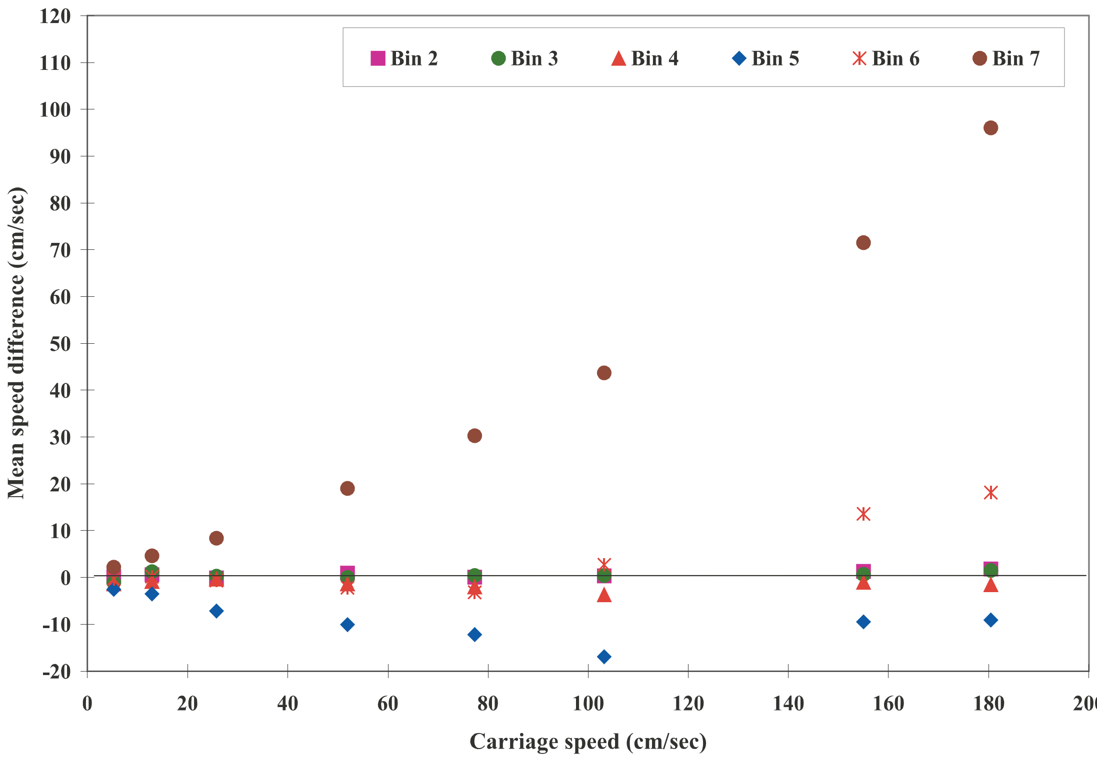

Fig. 14a Example of bin velocities affected by bottom boundary (ADCP 600 KHz)

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 test 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 will require 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 change of 1%). The basin water properties remain relatively constant throughout each test, hence the error associated with sound speed changes in the tow basin tests is negligible.

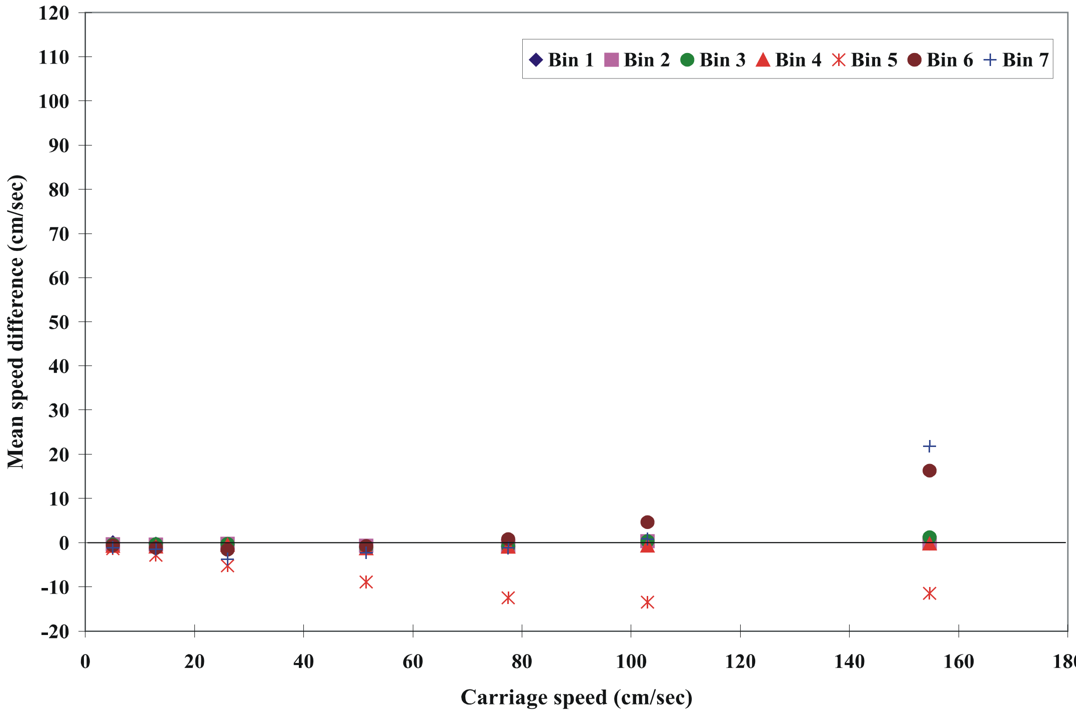

Fig. 14b Example of bin velocities affected by bottom boundary (ADCP 1200 KHz unit)

Since the frequencies of 500 KHz ADP and 600 KHz ADCP are close (wave length of 3 mm vs. 2.5 mm) the large mean speed differences and standard deviations of 500 KHz ADPs are believed to be associated with its signal processing technique and large transducer size (i.e., flow disturbances).

6. CONCLUSIONS AND RECOMMENDATIONS

Since the same test conditions and procedures were applied to all sensors, relative performances of the sensors can be drawn. However, the limited number of sensors tested does not support a more precise statistical interpretation of these results. The following general remarks are drawn from the test results:

A. Among the sensors tested, 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 manufacturer specifications. The 1200 KHz ADCP has the lowest standard deviation, while 1500 KHz ADP, and 600 KHz ADCP are about the same. The 500 KHz ADP is much noisier in all statistical performance parameters, but its mean accuracy and standard deviation are still close to the manufacturer specifications.

B. ADPs have larger sensor-to-sensor performance variations than ADCPs.

C. The bin-to-bin speed variation is higher in lower frequency sensors, especially the ADP 500 KHz units.

D. The small variability in duplicated speed runs qualitatively demonstrated the stability of the test environment. The repeatability of both ADPs and ADCPs is very good. Thus, a malfunctioned instrument can be easily detected through this test procedure.

E. Back scatter strength is a good data quality indicator. Values below about 10 dB in any beam were found to result in bad bin velocity measurement. Limestone seeding in the basin yielded an intensity range of 27-95 dB. Field data from PORTS® sites showed an intensity range of 67-99 dB and 34-54 dB at Tampa Bay, FL and Oakland, San Francisco Bay, CA, respectively. The ADCP percent-good pings value is also a useful indicator.

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/s (ADCP 600 KHz and 1200 KHz), 1 to 2 cm/s (ADP 1500 KHz), and about 6 cm/s (ADP 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 basin turbulence generated by the sensor housing and transducer head, threshold frequency response to limestone back scatterers, basin echo and reverberations, or other causes.

Recommendations:

A. Adequate and uniform distribution of backscatter materials (limestone) is important. The current method of manual spreading by hand should be replaced by mechanical spreading equipment. Sensors should be kept above the water during spreading to minimize flow disturbances.

B. Sensor readings at zero carriage speed are good background information about the sensor and the basin, and should be collected at the beginning, during, and at the end of the test.

C. Larger number of ensembles (or profiles) per velocity data (20 or greater) will improve the quality of statistical analysis. Carriage 2 has longer towing length and is preferred. Whenever possible, a waiting period of 5-10 minutes is recommended before the carriage reverses its direction.

D. All instruments should be tested prior to their field deployment (Present CO-OPS policy for systems used in real-time application is to test before deployment and again at least every 2 years). The test results should be reviewed with the user.

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Several colleagues at the Center for Operational Oceanographic Products and Services have contributed to this report; Michael Connolly, Richard Bourgerie, and Jerry Appell (retired) provided some historical data sets; Brenda Via and Gina Stoney edited and finalized the figures; Stephen Gill, Michael Connolly, Peter Stone, and Richard Bourgerie reviewed the manuscript and provided valuable comments; and Brenda Via coordinated the review process and prepared the final document for publication. To each one, the authors express their gratitude.

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APPENDIX

Appendix

Table A1 Sensors tested and their setup parameters
Table A2a Sample ADCP report file
Table A2b Sample ADP control file
Fig. A1 - A32 Test results of other sensors(s33, s4114, r849, r886, r887, r942, r944, r949, r113, r134, r135, r523, r601, r604, s17, s20, s21, s53, s145, s312, s4032, s4033, s4085, s4123, s4125 and s4126)

Note: The velocity standard deviations that are very similar (in values at corresponding carriage speeds) to those shown in Figs. 7a-7d for the same frequency group are not presented in this report. These sensors are:
ADP 500 KHz group - s33 and s4114;
ADCP 600 KHz group - r886, r942, r944, r949;
ADCP 1200 KHz group - r113, r135, r523, r601(all), r604(all);
ADP 1500 KHz group - s17, s20(7/13/00), s21(6/17/99), s53, s145, s4032 (6/15/99, 5/11/01), s4033(6/15/99, 7/13/00, 5/11/01), s4085, s4123(all), s4125(all), s4126(all).

Table A1. Sensors tested and their setup parameters (Sensors are listed in the order of manufacturer's serial number)

Sensor (SN/KHz)	Date	Binl size (m)	Blank dist. (m)	Profiles /or ensembles per velocity data	Profile/or ensemble interval (sec)	Profiling mode
r113/1200	36326	1	0.44	9-20*	10 (1 s per ping)	mode 1
r134/1200	35312	1	1	10	10 (1 s per ping)	mode 1
r135/1200	9/5/96	1	1	10	10 (1 s per ping)	mode 1
r238/1200	36327	1	1	11-42*	10 (1 s per ping)	mode 1
r523/1200	4/5/95	?	?	5-20*	10 (1 s per ping)	mode 1
r601/1200	36660	1	1	6-28*	10 (1 s per ping)	mode 1
r601/1200	37021	1	1	4-32*	10 (2 s per ping)	mode 1
r604/1200	35849	1	1	9-31*	3.8 (8 pings at 0.47 s per ping)	mode 1
r604/1200	36006	1	0.44	8-17*	9.4 (20 pings at 0.47 s per ping)	mode 1
r849/600	6/22/99	1	1	10-20*	10 (1 s per ping)	mode 1
r886/600	36326	1	1	9-18*	10 (1 s per ping)	mode 1
r887/600	36291	1	0.44	12-39*	9.4 (20 pings, at 0.47 s per ping)	mode 1
r942/600	36326	1	1	6-35*	10 (1 s per ping)	mode 1
r944/600	6/16/99	1	1	9-18*	10 (1 s per ping)	mode 1
r948/600	36327	1	1	9-19*	10 (1 s per ping)	mode 1

r949/600	36326	1	1	8-27*	10 (1 s per ping)	mode 1
s17/1500	36719	1	0.4	9-33*	10	N.A.
s20/1500	9/8/97	1	0.4	21-33*	10	N.A.
s20/1500	36719	1	0.4	4-17*	10	N.A.
s21/1500	36327	?	?	10 to 23*	10	N.A.
s21/1500	36719	1	0.4	9-29*	10	N.A.
s33/500	36327	?	?	13 to 22*	10	N.A.
s53/1500	36332	1	1	8 to 24*	10	N.A.
s104/500	36416	1	1	10-24*	10	N.A.
s145/1500	36416	1	0.4	9-24*	10	N.A.
s312/1500	37021	1	0.4	4-15*	10	N.A.
s4032/1500	35900	1	0.5	8 to 25*	10	N.A.
s4032/1500	36325	?	?	8 to 25*	10	N.A.
s4032/1500	37021	1	0.4	5-23*	10	N.A.
s4033/1500	35849	1	0.5	9 to 21*	10	N.A.
s4033/1500	36325	?	?	6 to 22*	10	N.A.
s4033/1500	36719	1	0.4	4-15*	10	N.A.
s4033/1500	37021	1	0.4	9-22*	10	N.A.
s4085/1500	36162	1	0.5	17 to 68*	10	N.A.
s4114/500	11/19/96	2	1	10	10	N.A.
s4123/1500	35387	1	0.4	10	10	N.A.
s4123/1500	36005	1	0.5	16-53*	10	N.A.
s4125/1500	11/19/96	1	0.4	10	10	N.A.
s4125/1500	36327	?	?	10 to 31*	10	N.A.
s4126/1500	11/19/96	1	0.4	10	10	N.A.
s4126/1500	37021	1	0.4	10-36*	10	N.A.

Notes: * Lower ensemble number at higher speeds.
SonTek sampling scheme: standard deployment sampling with zero waiting time.
Beam angle: 20 degrees for RDI sensors, and 25 degrees for SonTek sensors.

Table. A2a Sample ADCP report file

REPORT FOR ASCII DATA CONVERSION
----

1. ADCP INFORMATION:

Frequency 1200 kHz
Beam angle 20 deg
4 beam system
Down-looking orientation
Convex beam pattern
Transducer head connected
CPU firmware 8.32

2. ADCP SETUP:
Number of bins 8
Bin length 100 cm
Blank after transmit 100 cm
Distance to first bin 207 cm
Transmit length 103 cm
Pings per ensemble 5
Time per ping 2.00 s
Profiling mode 1

3. ASCII FILE DATA FORMAT:

Line 1: Recording date string, Recording time string, Time of the day in seconds, Ensemble number, Velocity 1 , 2, 3, 4

4. PROCESSING PARAMETERS:

Velocity units: ADCP
Velocity reference: ADCP
Depth units: ADCP
Bins: From 1 to 8 skip 0 bin
Magnetic variation 0.00 deg
Do not mark data below bottom

END OF REPORT

Table. A2b Sample ADP control file

```
File ----------------------> DT0105\SCB5BC40.ADP
File Size (bytes) ---------> 29908
Number of profiles --------> 146
Time of first profile -----> 2001/05/11  12:40:10
Time of last  profile -----> 2001/05/11  13:04:21

ADP Hardware Configuration
----------------------------
CPUSoftwareVerNum ---------> 6.4
DSPSoftwareVerNum ---------> 4.0
BoardRev ------------------> D
SerialNumber --------------> 4033
AdpType -------------------> 1500 kHz
Nbeams --------------------> 3
BeamGeometry --------------> 3_BEAMS
SlantAngle ------ (deg) ---> 25.0
SensorOrientation----------> UP
CompassInstalled ----------> YES
RecorderInstalled ---------> YES
TempInstalled -------------> YES
PressInstalled ------------> YES
PressOffset (dbar) --------> -3.388050
PressScale  (dbar/count) --> 0.001349
PressScale_2 (pdbar/c^2) --> 543.000000
ExtSensorInstalled --------> NO
ParosSensorInstalled ------> NO
CtdSensorInstalled --------> NO
TransformationMatrix ----->    1.577  -0.789  -0.789
                               0.000  -1.366   1.366
                               0.368   0.368   0.368

ADP User Setup
----------------
DefaultTemp ----- (deg C) -> 20.00
DefaultSal ------ (ppt) ---> 0.00
DefaultSoundSpeed (m/s) ---> 1481.60
Ncells --------------------> 10
CellSize -------- (m) -----> 1.00
BlankDistance — (m) -----> 0.40
SensorDepth ----- (m) -----> 0.00
TempMode ------------------> MEASURED
AvgInterval ----- (s) -----> 10
ProfileInterval - (s) -----> 10
```

```
PingInterval ---- (s) -----> 0.00
BurstMode -----------------> DISABLED
BurstInterval — (s) -----> 1200
ProfilesPerBurst ----------> 1
CoordSystem ---------------> XYZ
OutMode -------------------> AUTO
OutFormat -----------------> BINARY
RecorderEnabled -----------> ENABLED
RecorderMode --------------> BUFFER
DeploymentMode ------------> OFF
DeploymentName ------------> BOLIV
Comments:
```

Cell #	Depth Range (m) (relative to sensor)
1	1.40
2	2.40
3	3.40
4	4.40
5	5.40
6	6.40
7	7.40
8	8.40
9	9.40
10	10.40

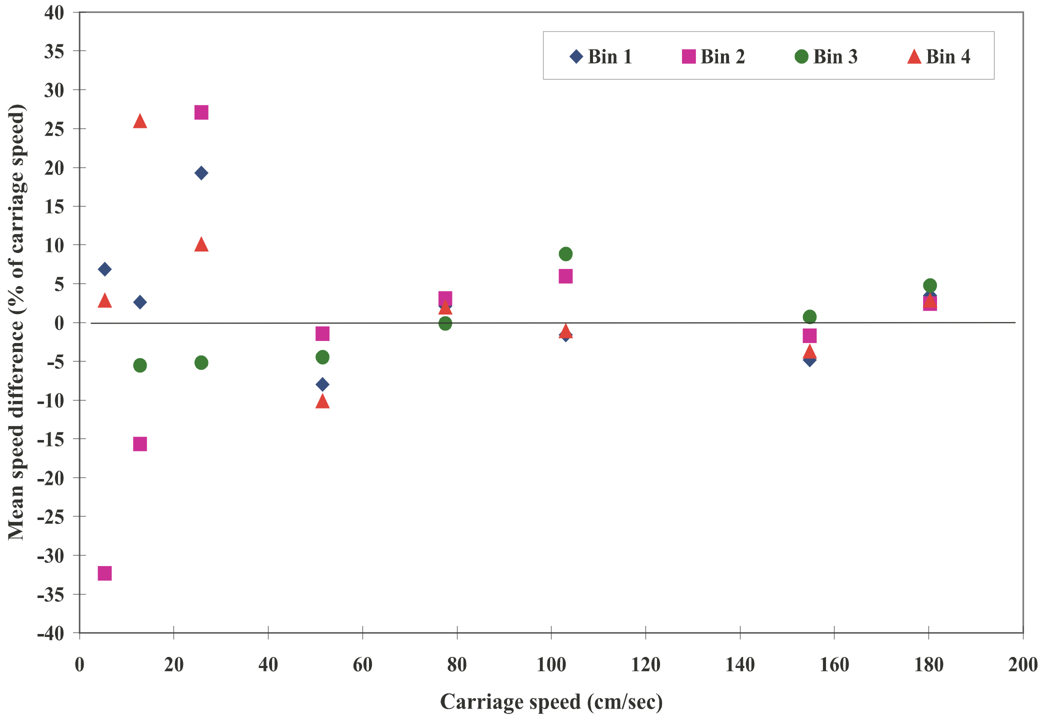

Fig. A1 Mean speed differences of ADP s33/500 KHz unit (6/17/99)

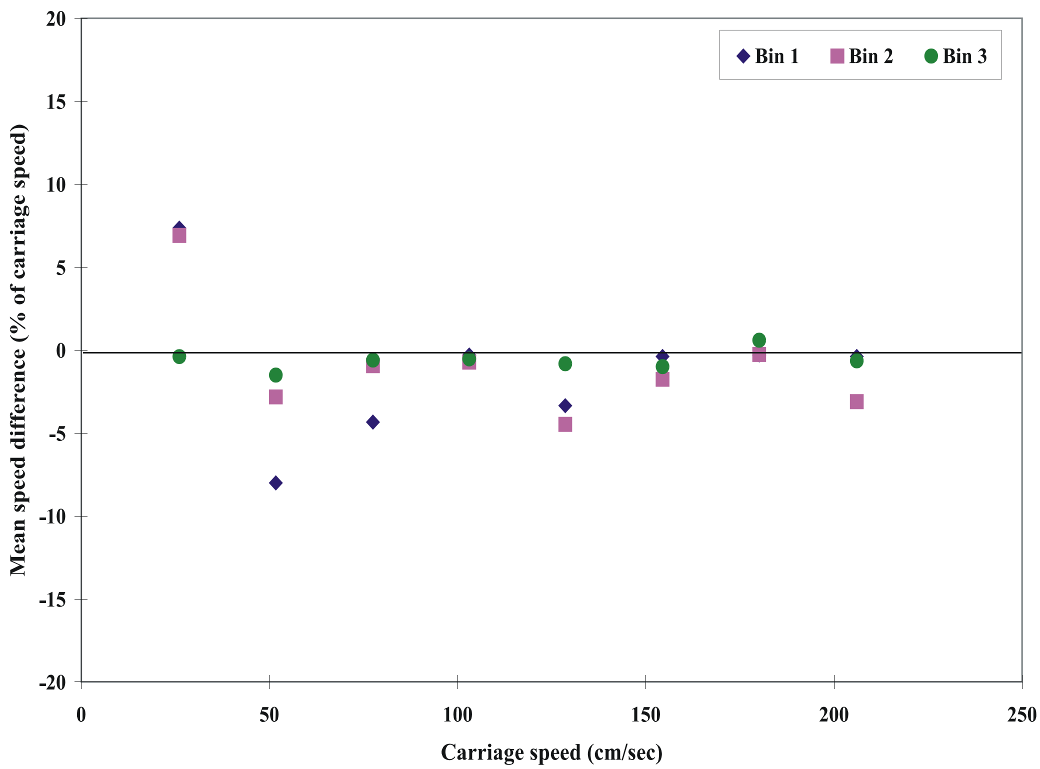

Fig. A2 Mean speed differences of ADP s4114/500 KHz unit (11/19/96)

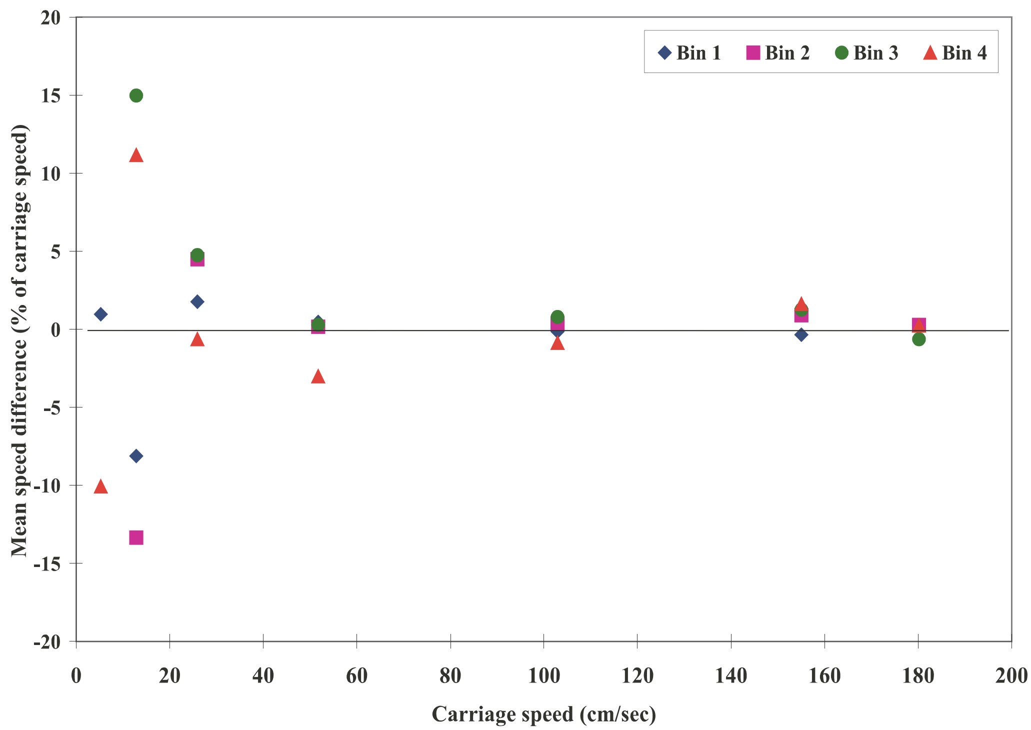

Fig. A3 Mean speed differences of ADCP r849/600 KHz unit (6/22/99)

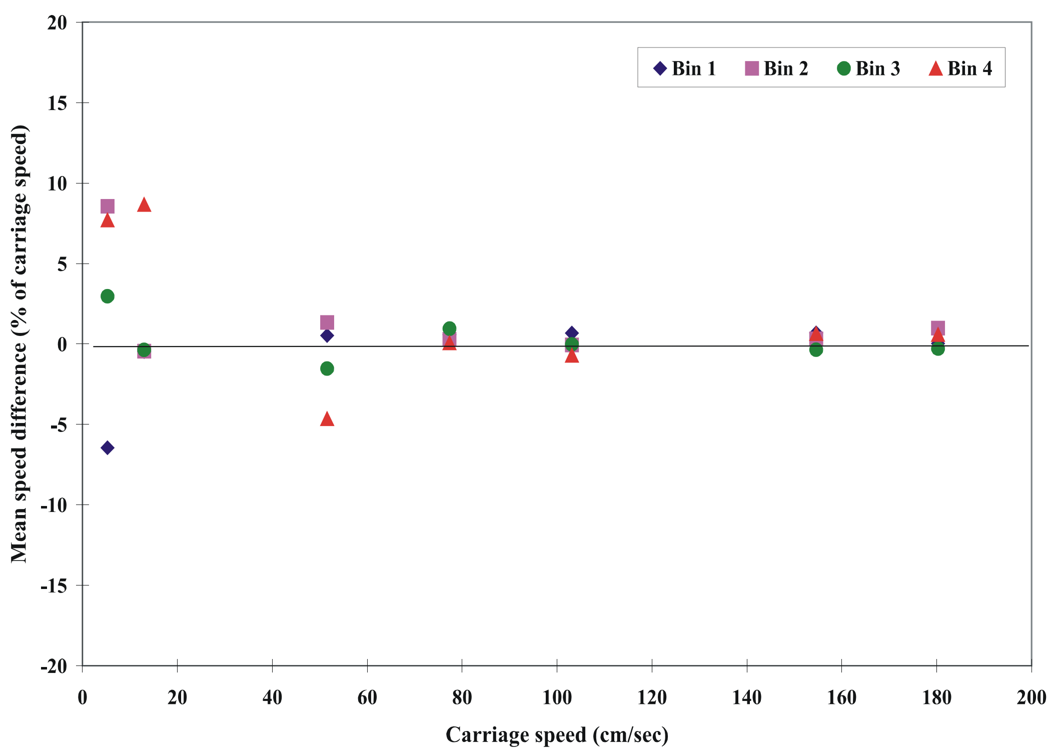

Fig. A4 Mean speed differences of ADCP r886/600 KHz unit (6/16/99)

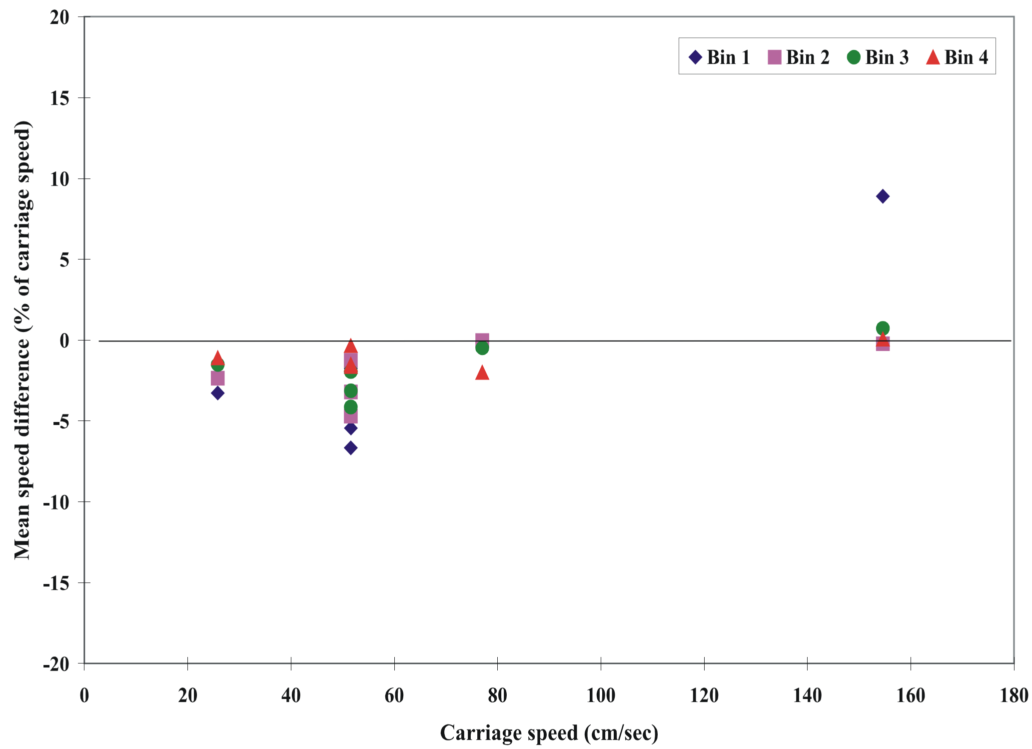

Fig. A5 Mean speed differences of ADCP r887/600 KHz unit (5/12/99)

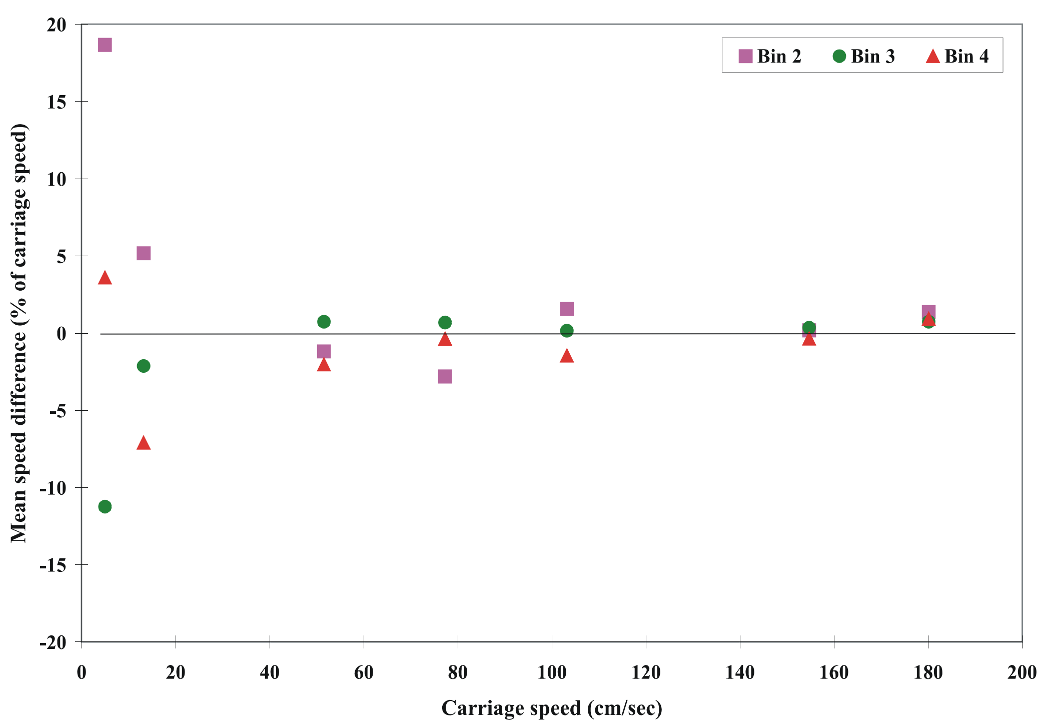

Fig. A6 Mean speed differences of ADCP r942/600 KHz unit (6/16/99)

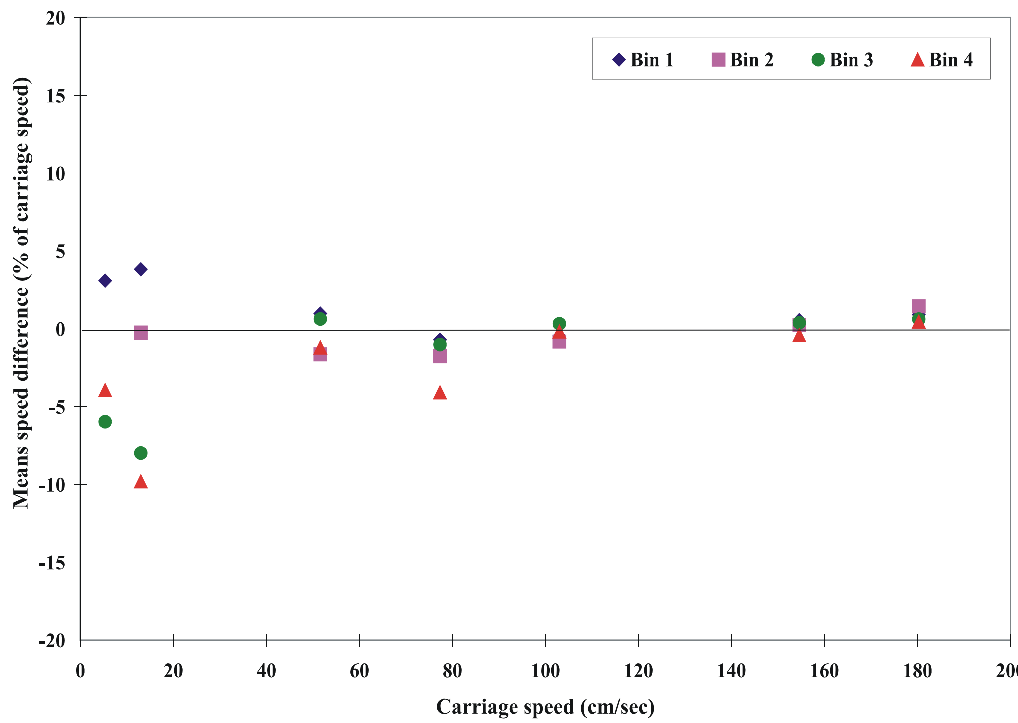

Fig. A7 Mean speed differences of ADCP r944/600 KHz unit (6/16/99)

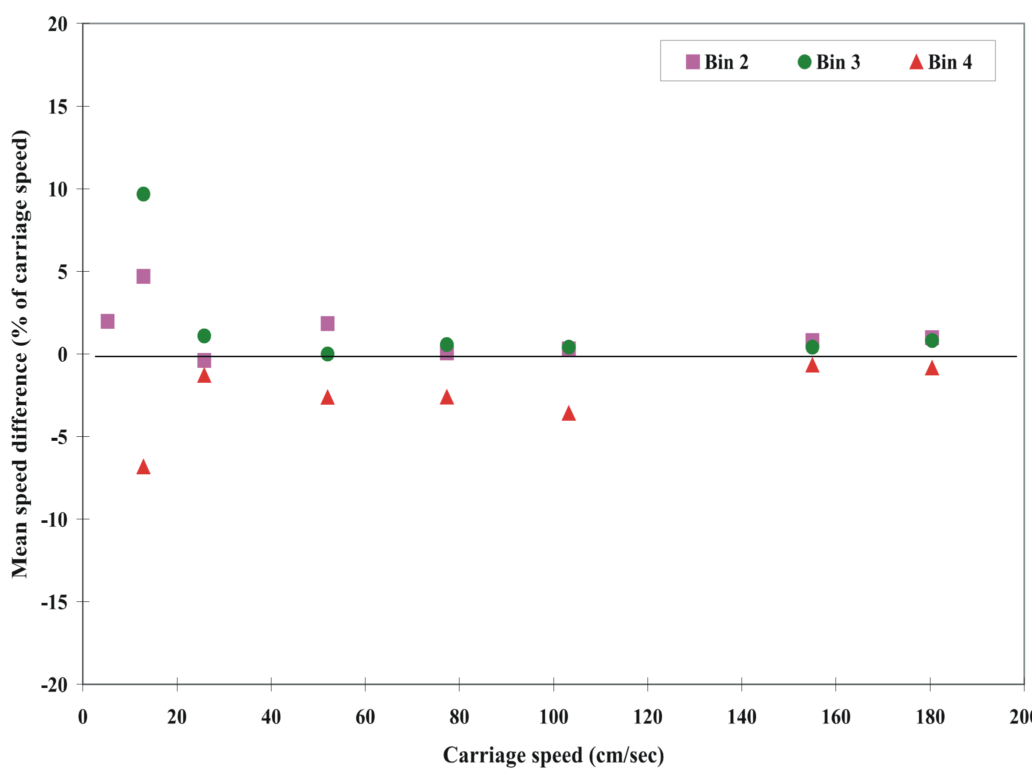

Fig. A8 Mean speed differences of ADCP r949/600 KHz unit (6/16/99)

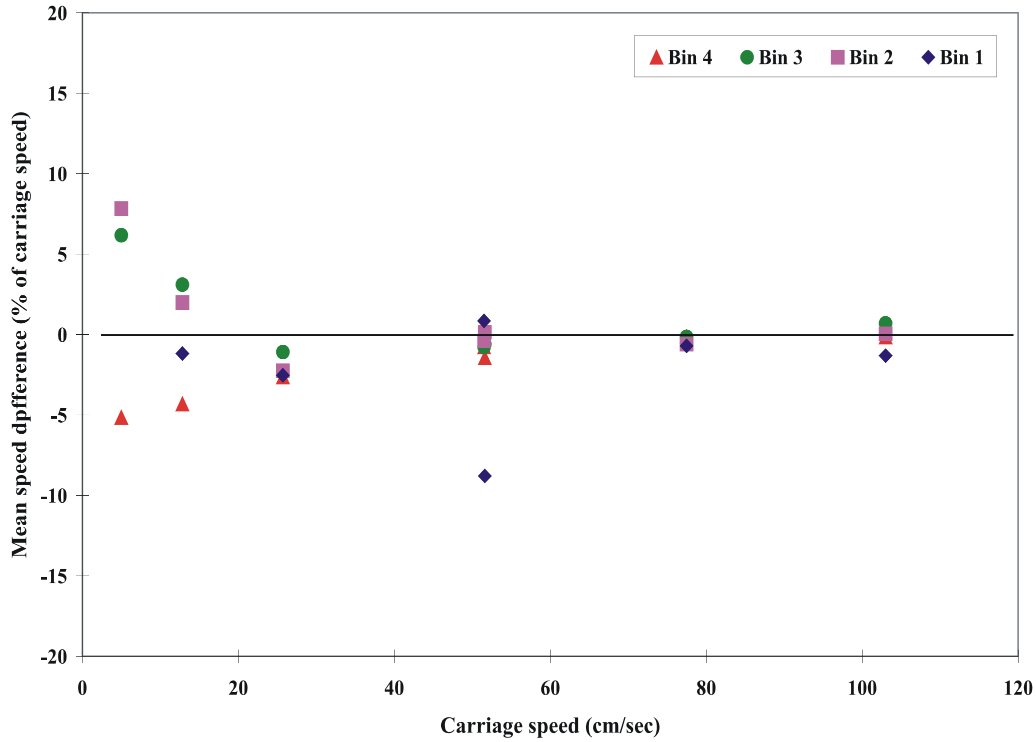

Fig. A9 Mean speed differences of ADCP r113/1200 KHz unit (6/16/99)

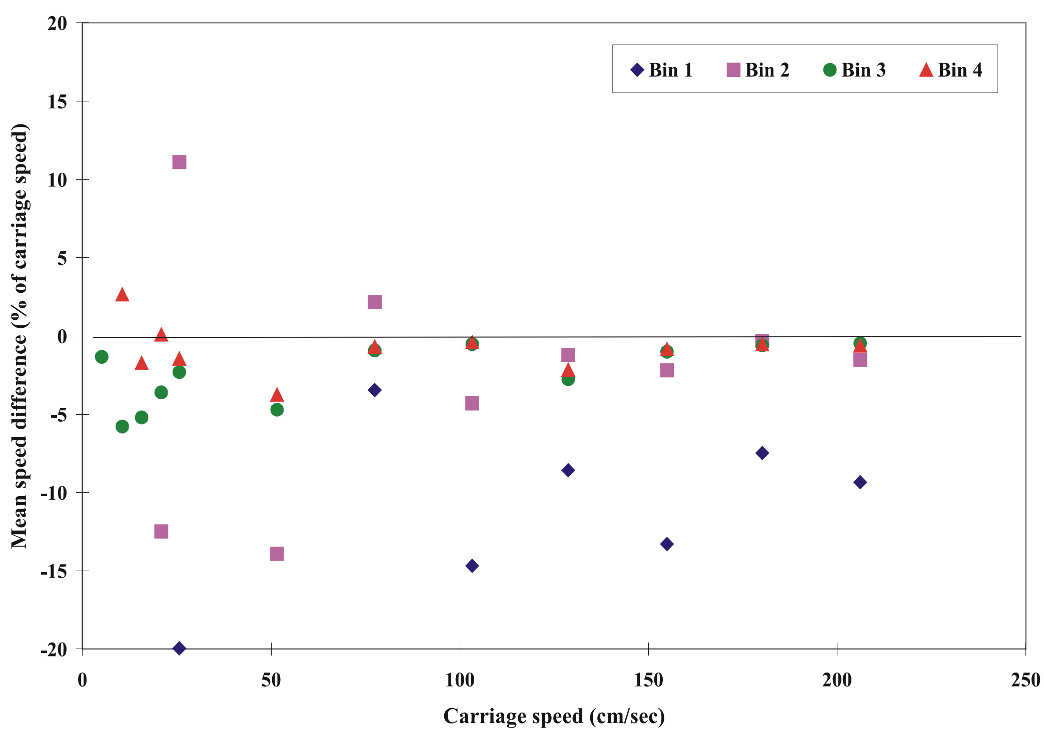

Fig. A10 Mean speed differences of ADCP r134/1200 KHz unit (9/5/96)

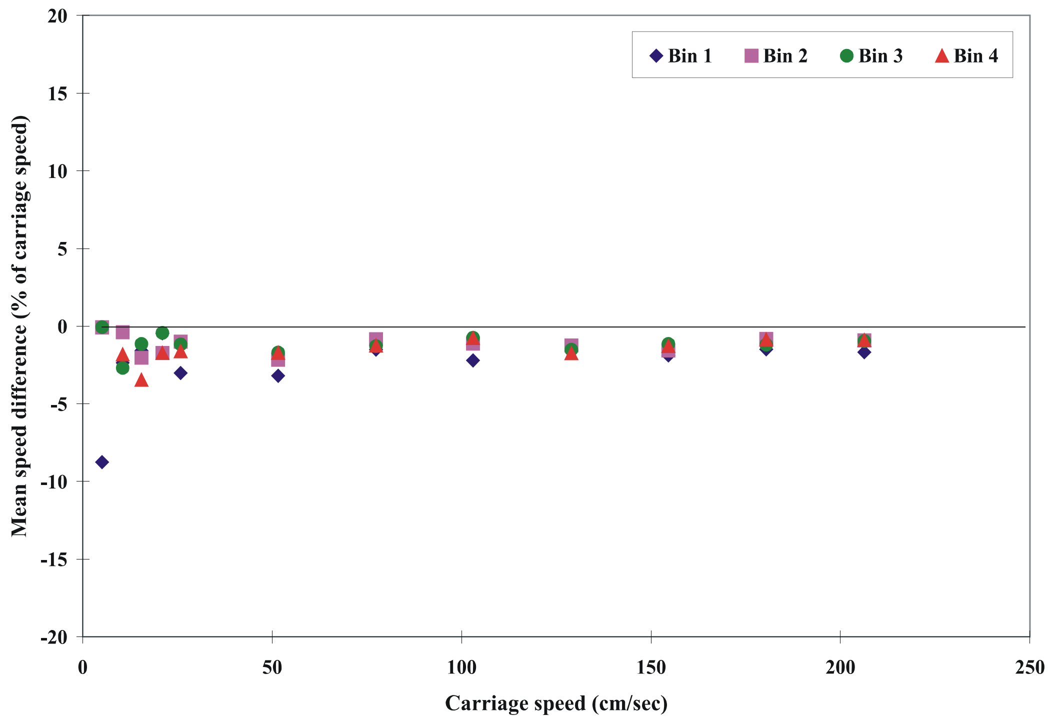

Fig. A11 Mean speed differences of ADCP r135/1200 KHz unit (9/5/96)

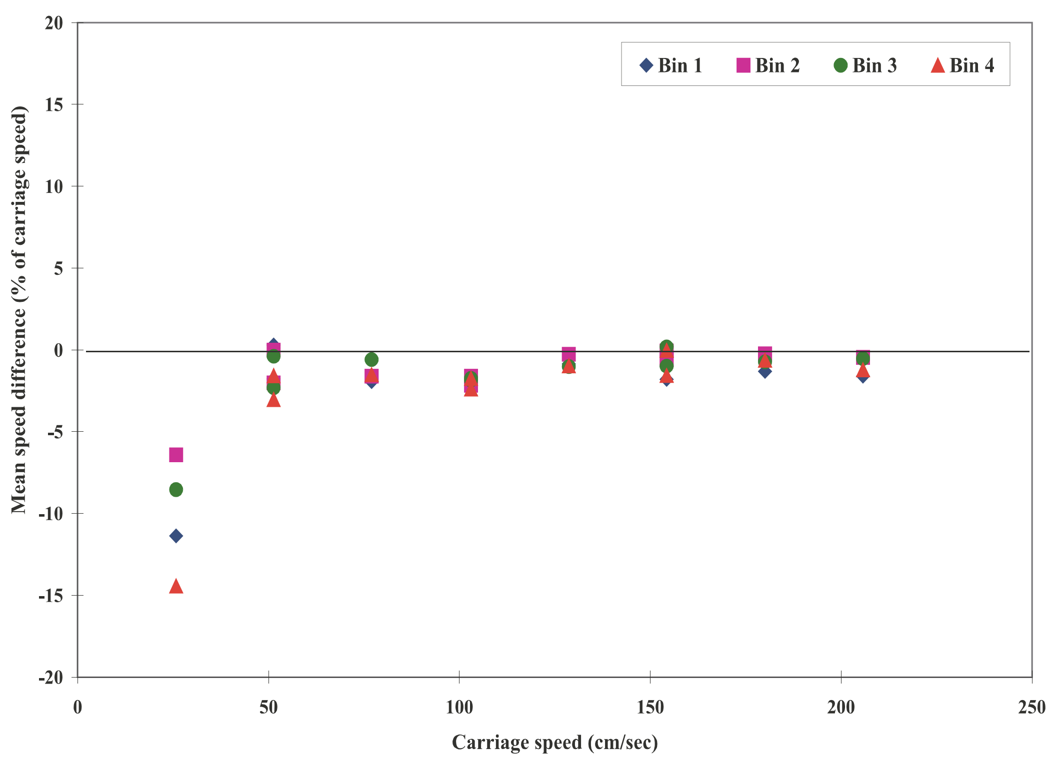

Fig. A12 Mean speed differences of ADCP r523/1200 KHz unit (4/6/95)

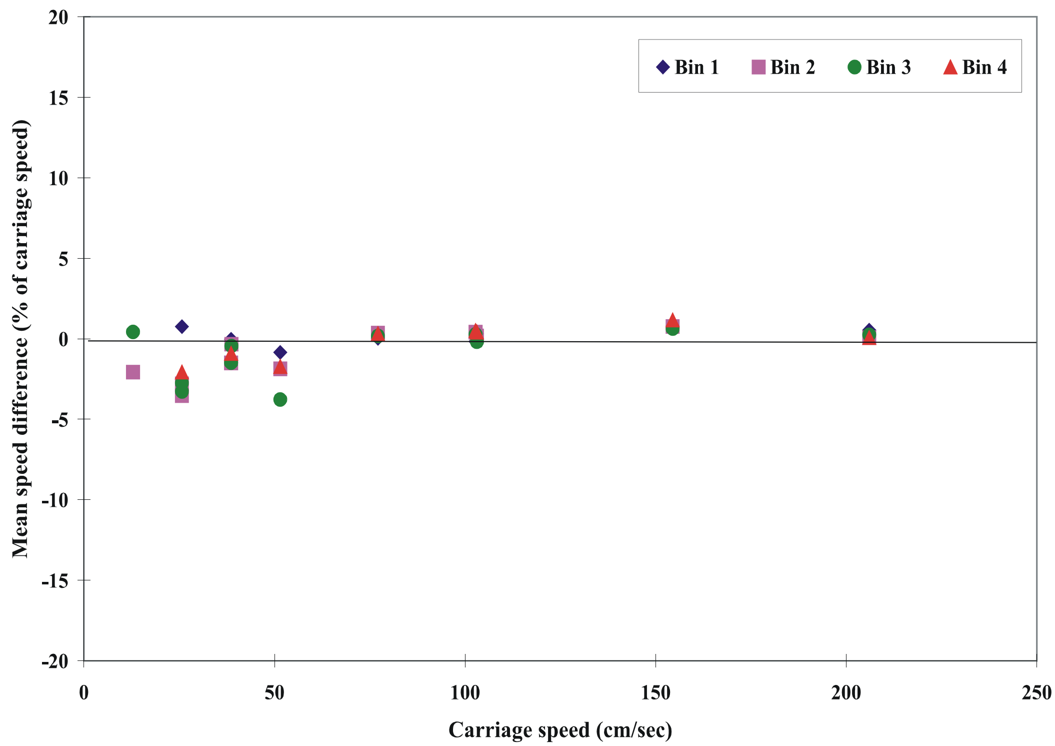

Fig. A13a Mean speed differences of ADCP r601/1200 KHz unit (5/15/00)

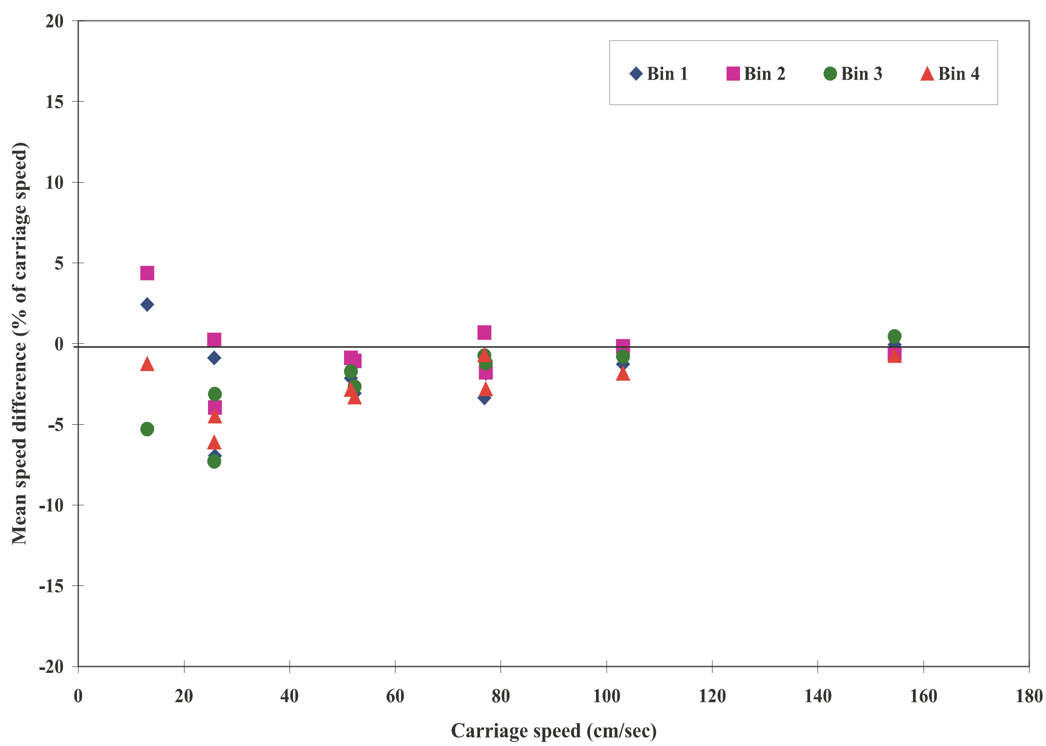

Fig. 13b Mean speed differences of ADCP r601/1200 KHz unit (5/11/01)

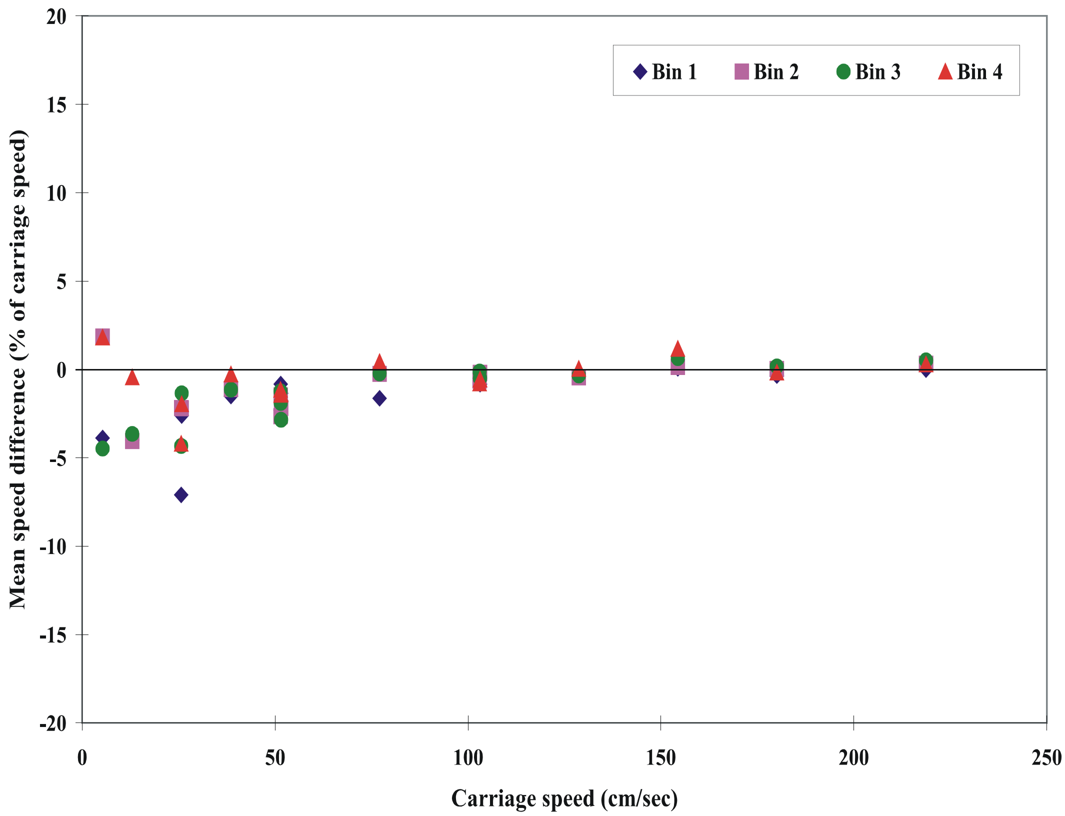

Fig. A14a Mean speed differences of ADCP r604/1200 KHz unit (2/24/98)

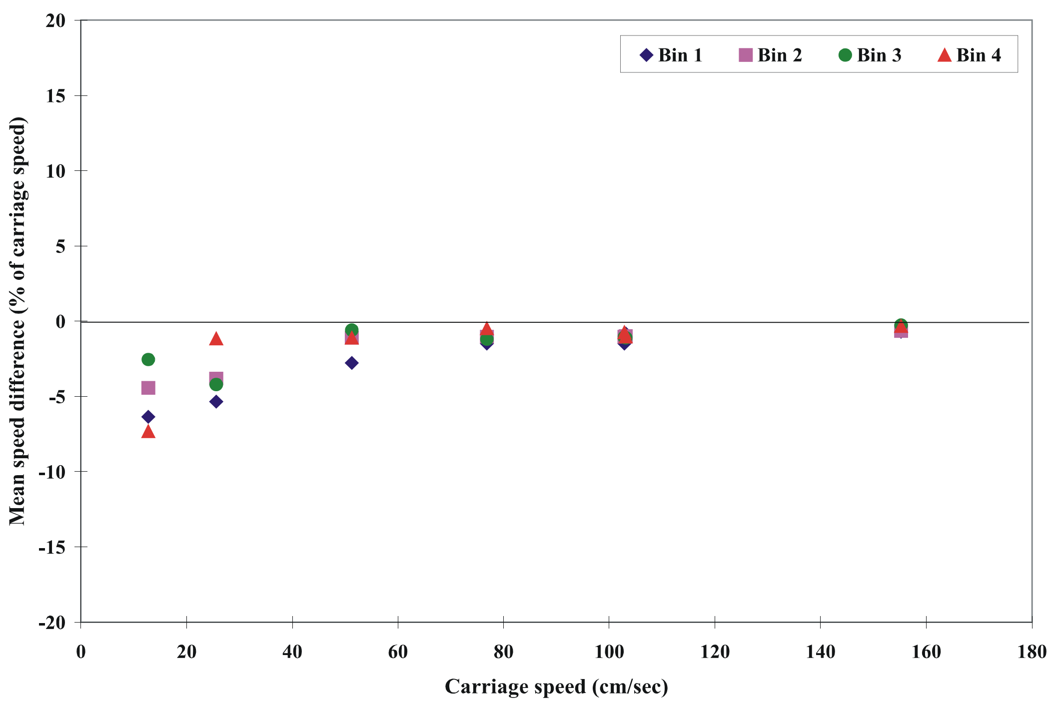

Fig. A14b Mean speed differences of ADCP r604/1200 KHz unit (7/31/98)

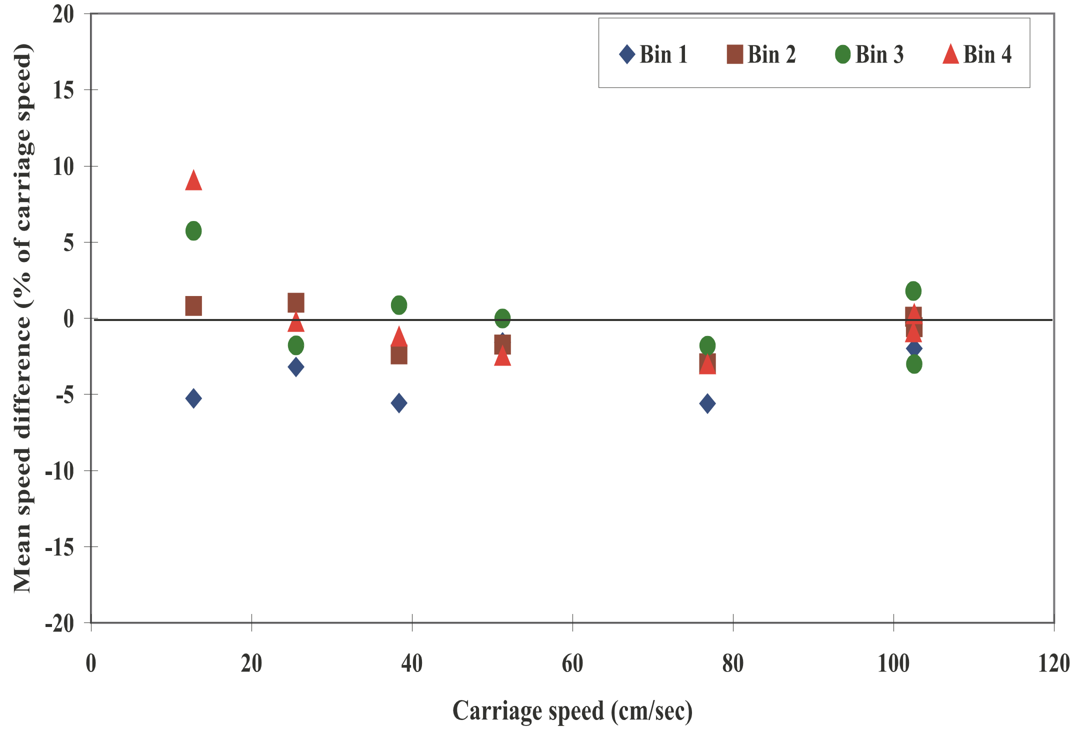

Fig. A15 Mean speed differences of ADP s17/1500 KHz unit (7/13/00)

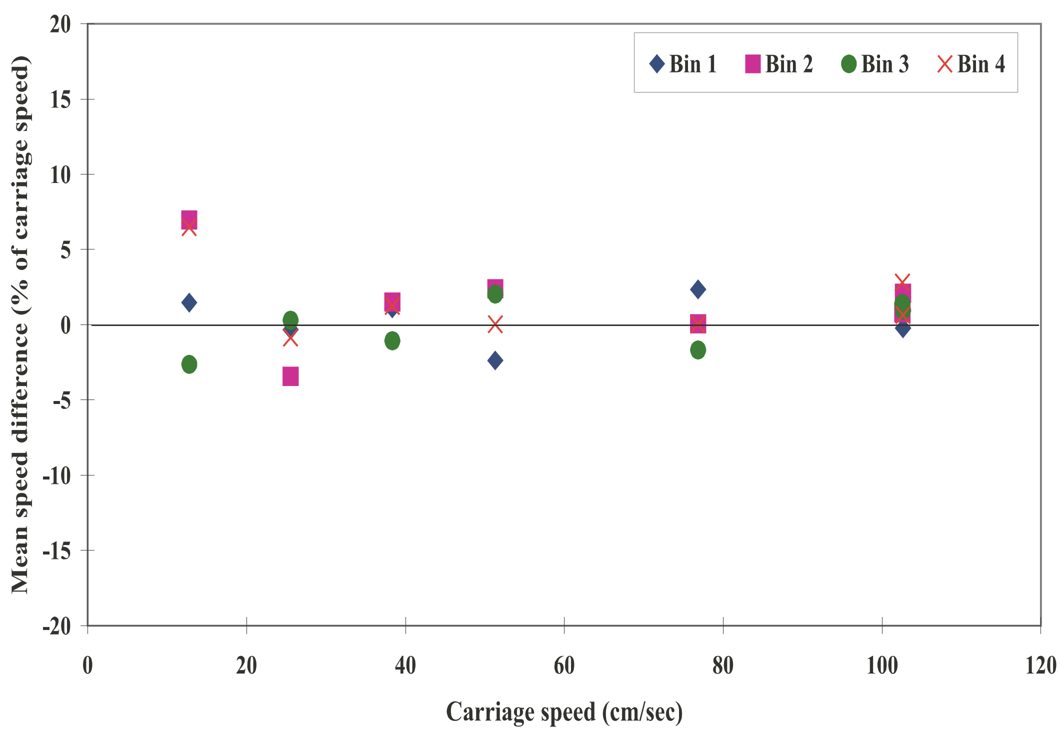

Fig. A16 Mean speed differences of ADP s20/1500 KHz unit (7/13/00)

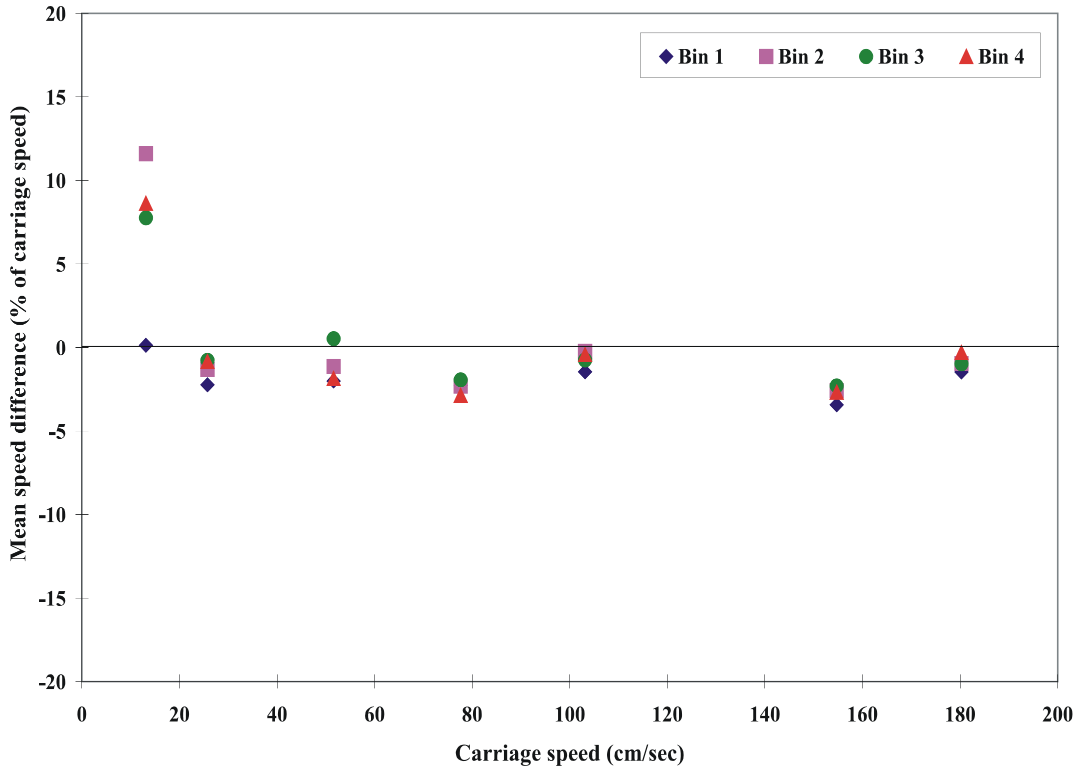

Fig. A17a Mean speed differences of ADP s21/1500 KHz unit (6/17/99)

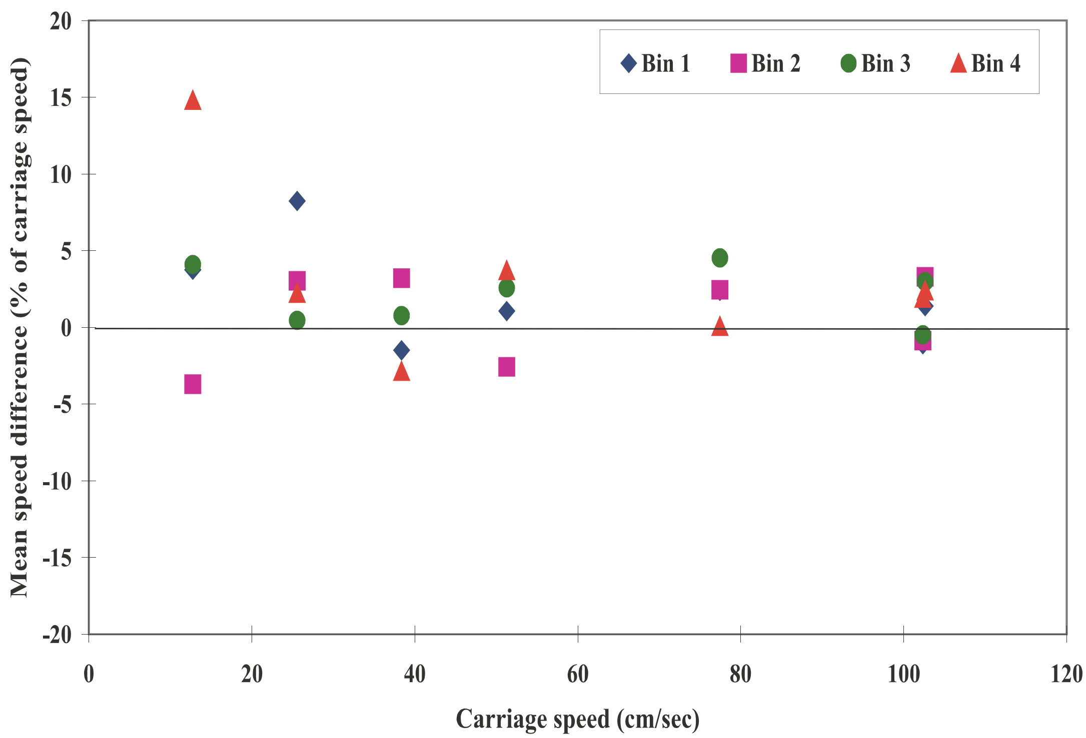

Fig. A17b Mean speed differences of ADP s21/1500 KHz unit (7/13/00)

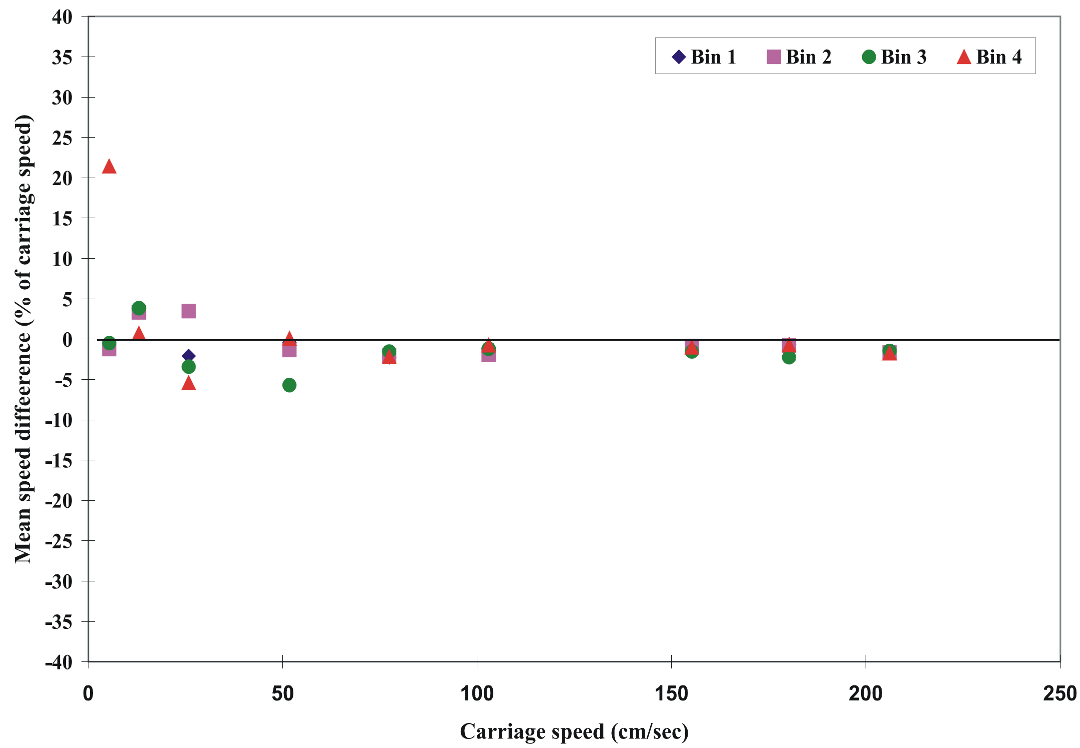

Fig. A18 Mean speed differences of ADP s53/1500 KHz unit (6/22/99)

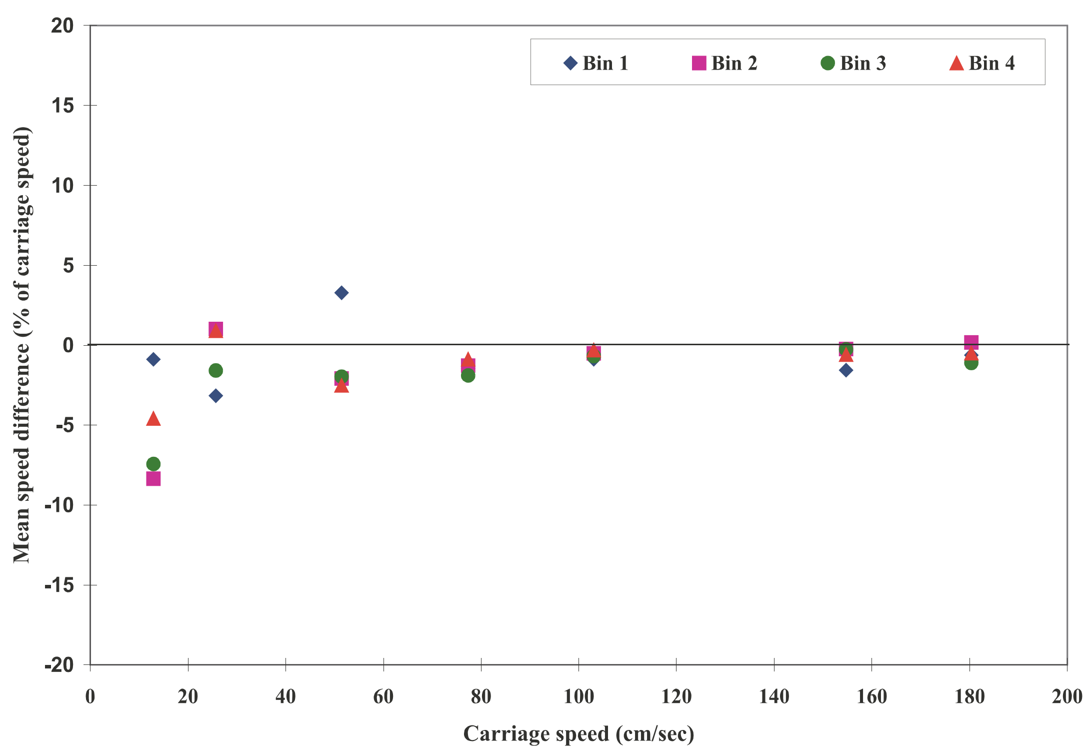

Fig. A19 Mean speed differences of ADP s145/1500 KHz unit (9/14/99)

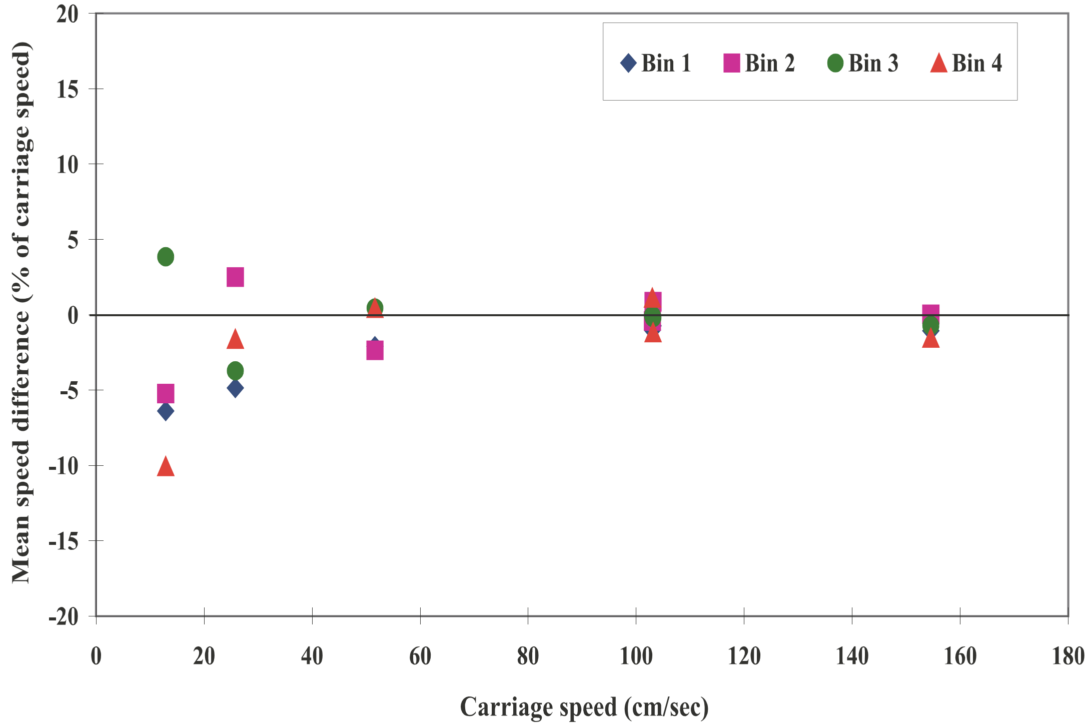

Fig. A20 Mean speed differences of ADP s312/1500 KHz unit (5/11/01)

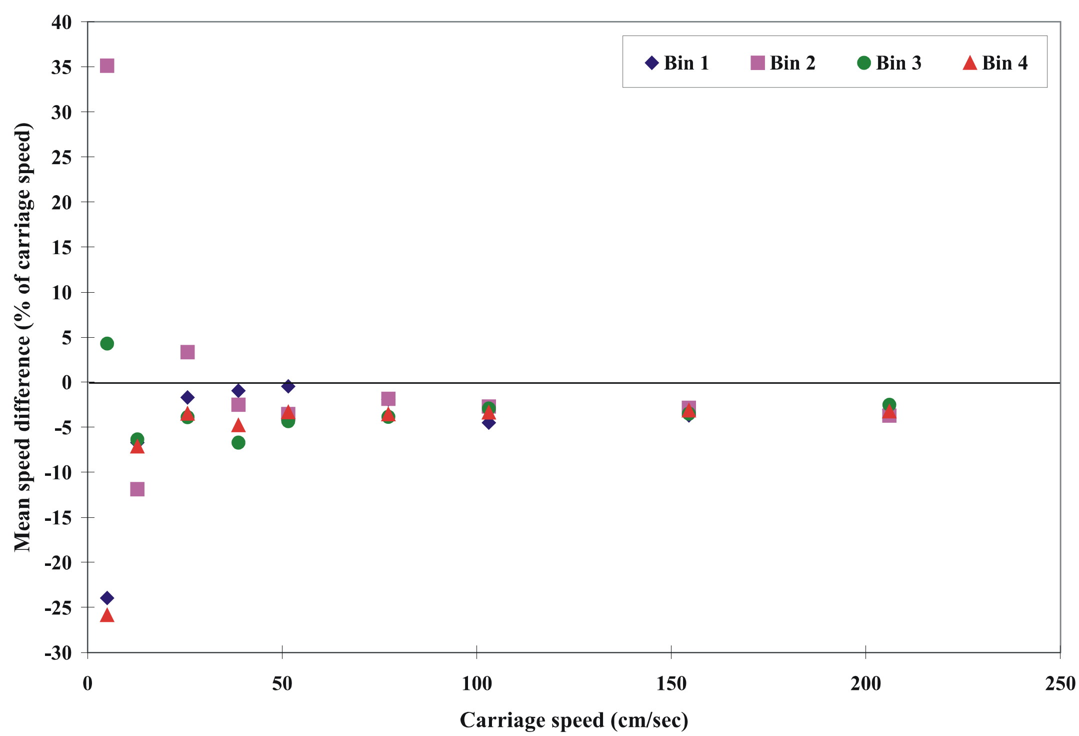

Fig. A21a Mean speed differences of ADP s4032/1500 KHz unit (4/16/98)

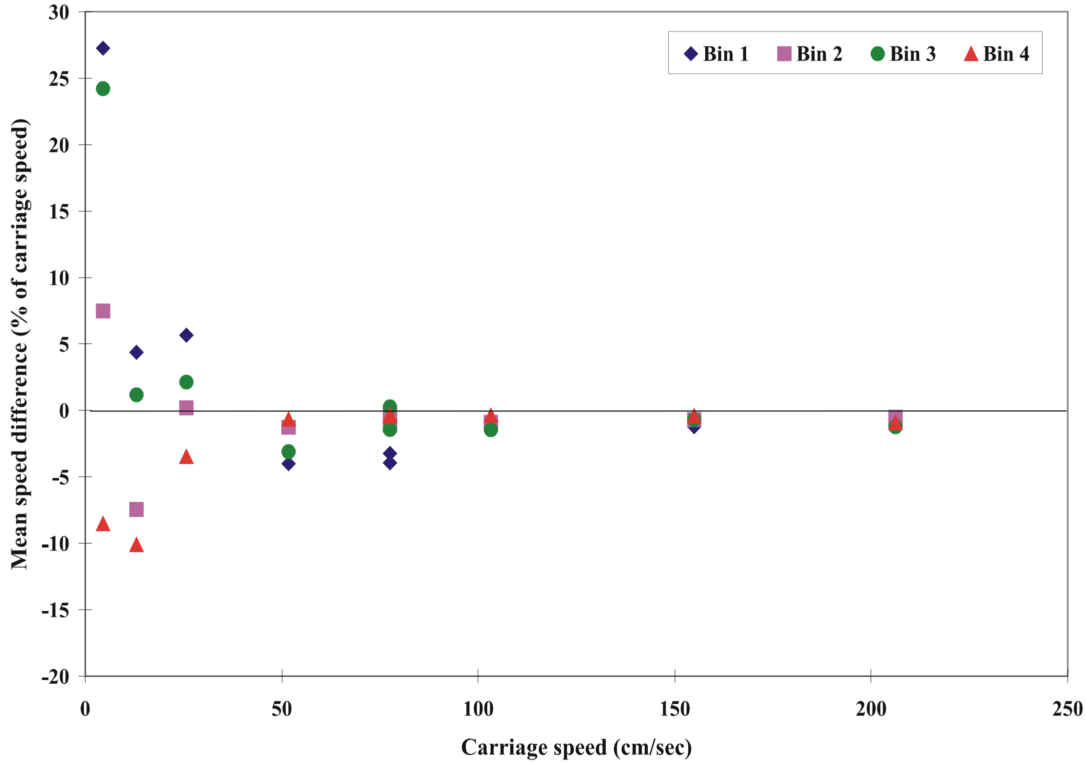

Fig. A21b Mean speed differences of ADP s4032/1500 KHz unit (6/15/99)

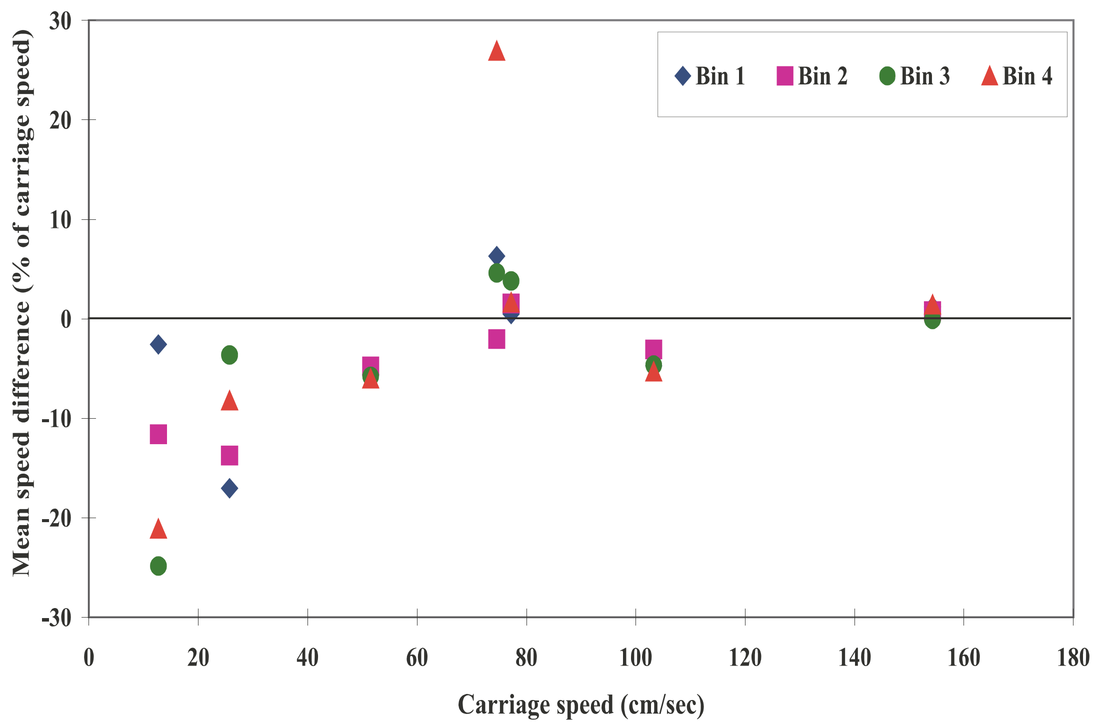

Fig. A21c Mean speed differences of ADP s4032/1500 KHz (5/11/01)

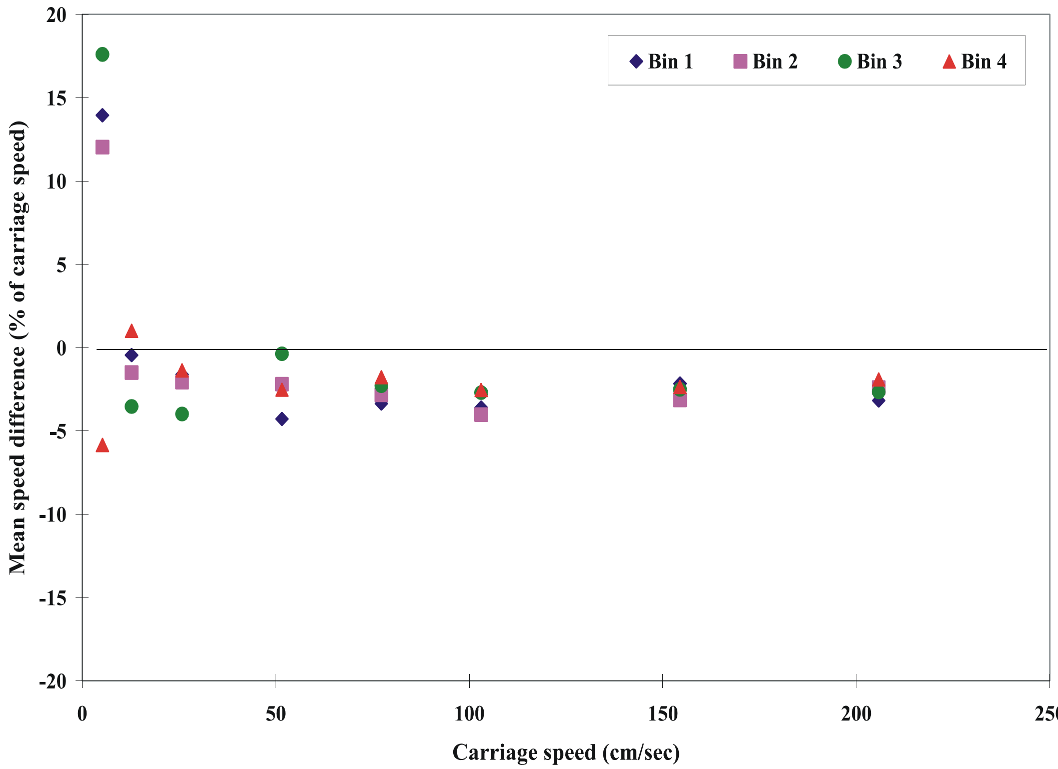

Fig. A22a Mean speed differences of ADP s4033/1500 KHz unit (2/24/98)

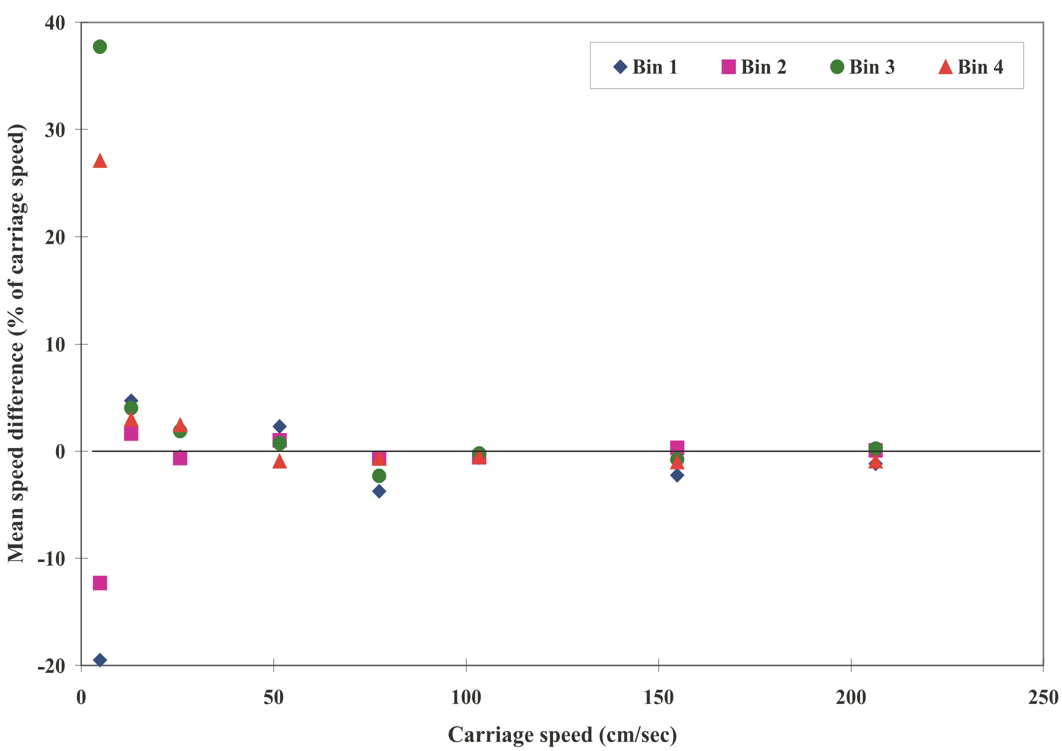

Fig. A22b Mean speed differences of ADP s4033/1500 KHz unit (6/15/99)

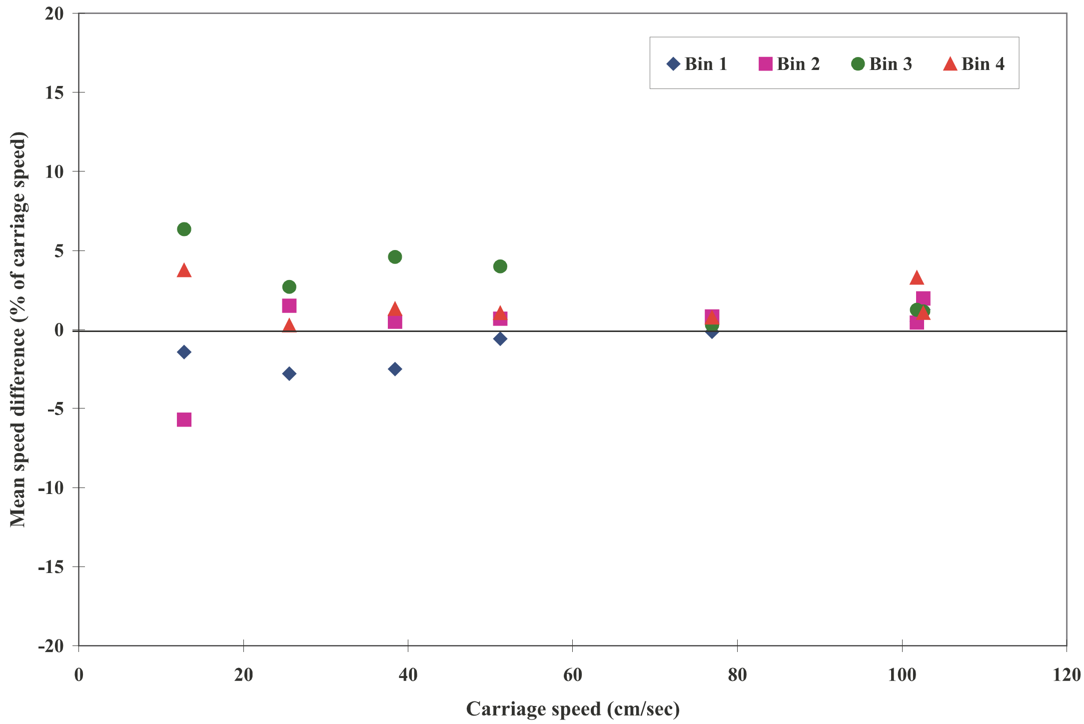

Fig. A22c Mean speed differences of ADP s4033/1500 KHz unit (7/13/00)

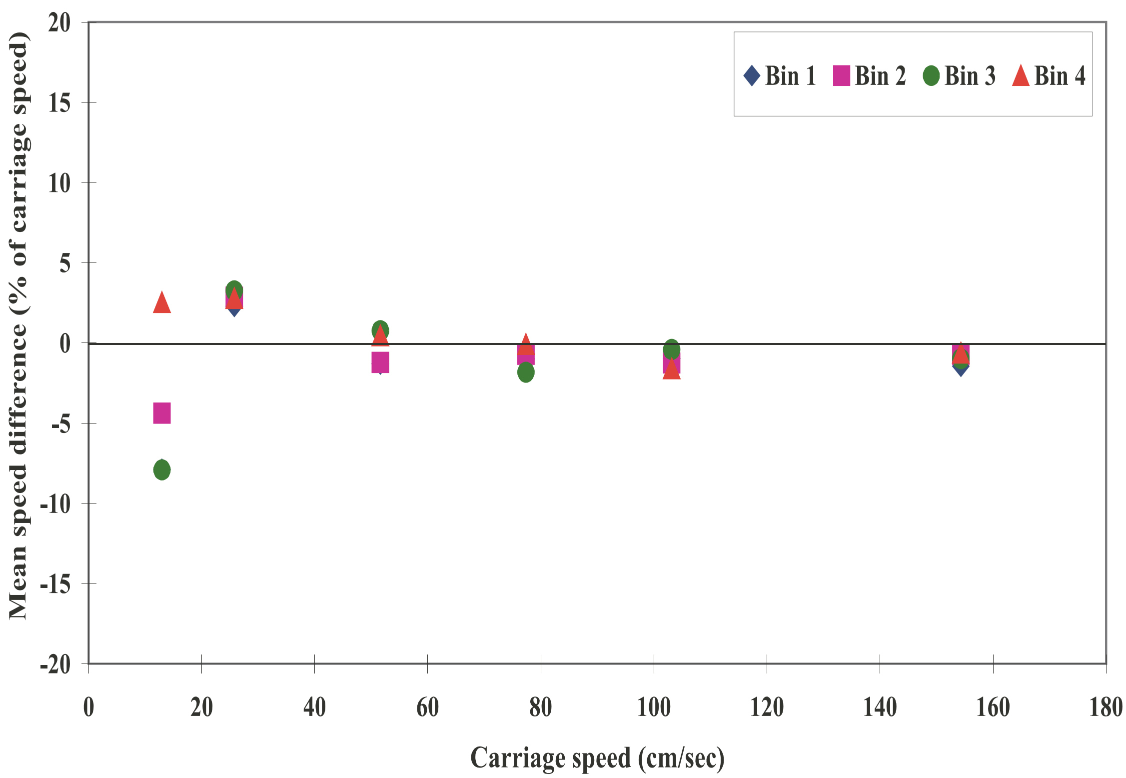

Fig. A22d Mean speed differences of ADP s4033/1500 KHz unit (5/11/01)

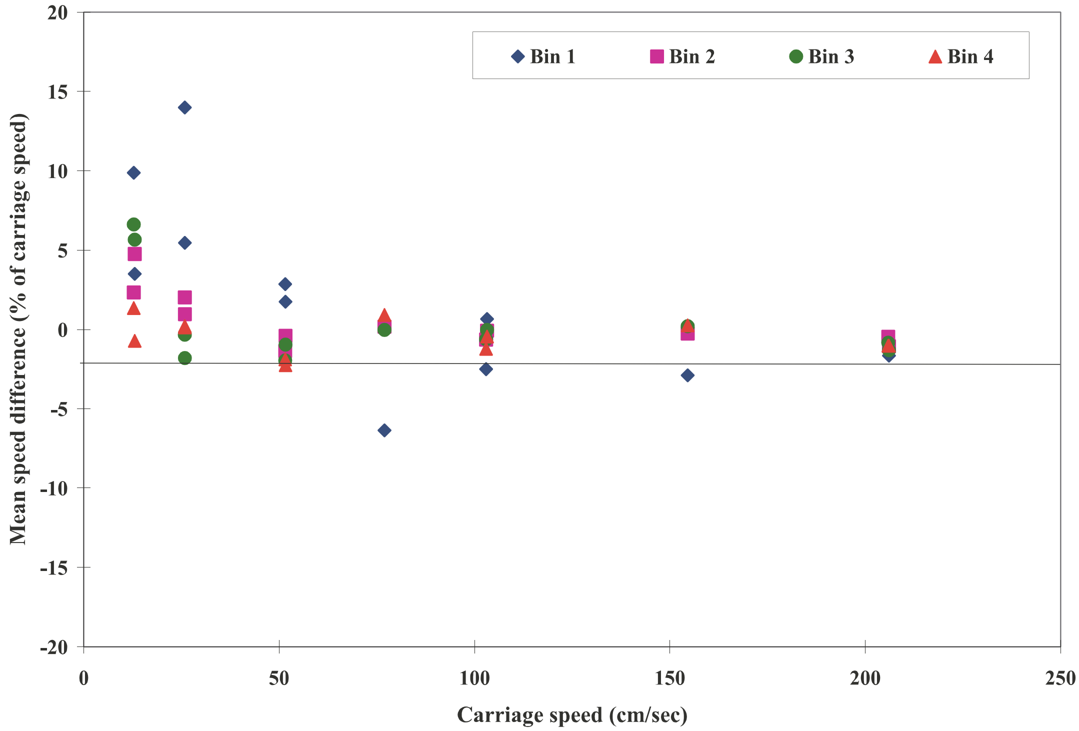

Fig. A23 Mean speed differences of ADP s4085/1500 KHz unit (1/3/99)

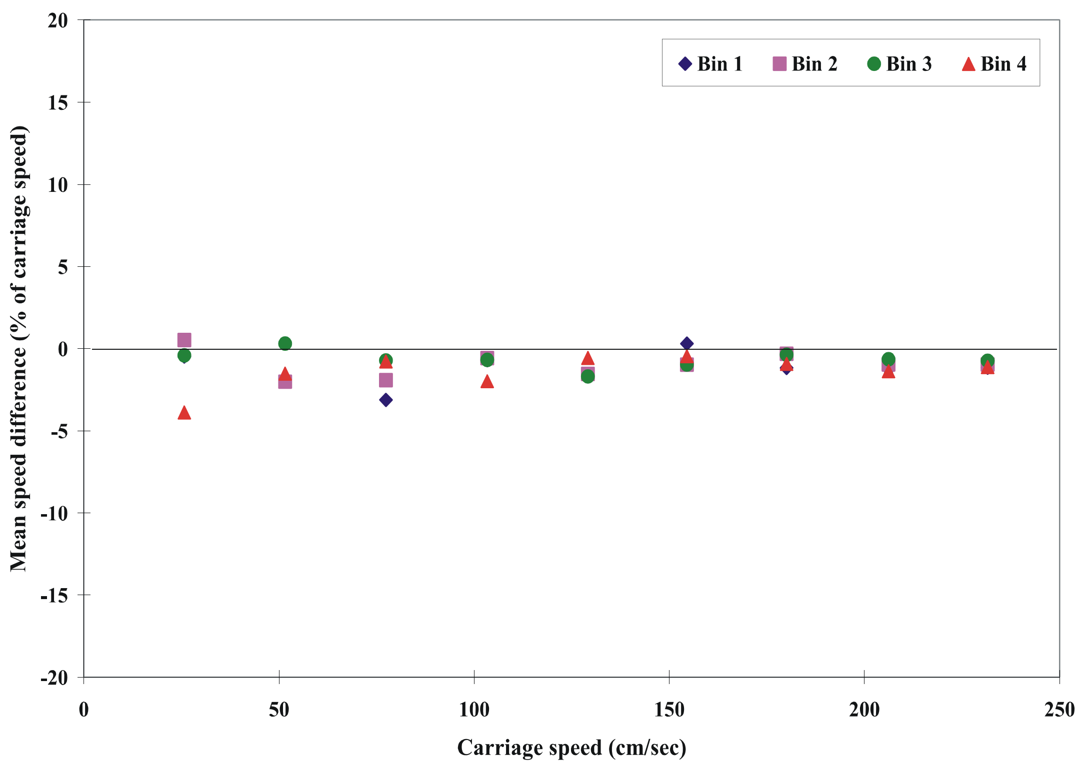

Fig. A24a Mean speed differences of ADP s4123/1500 KHz unit (11/19/96)

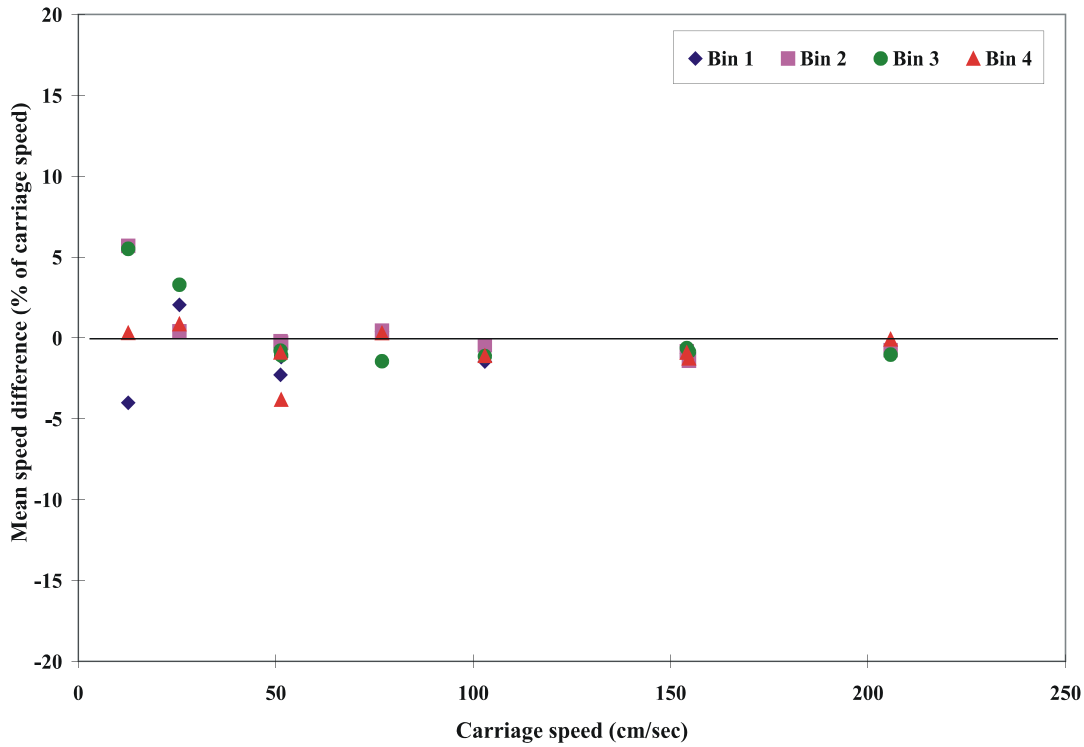

Fig. A24b Mean speed differences of ADP s4123/1500 KHz unit (7/30/98)

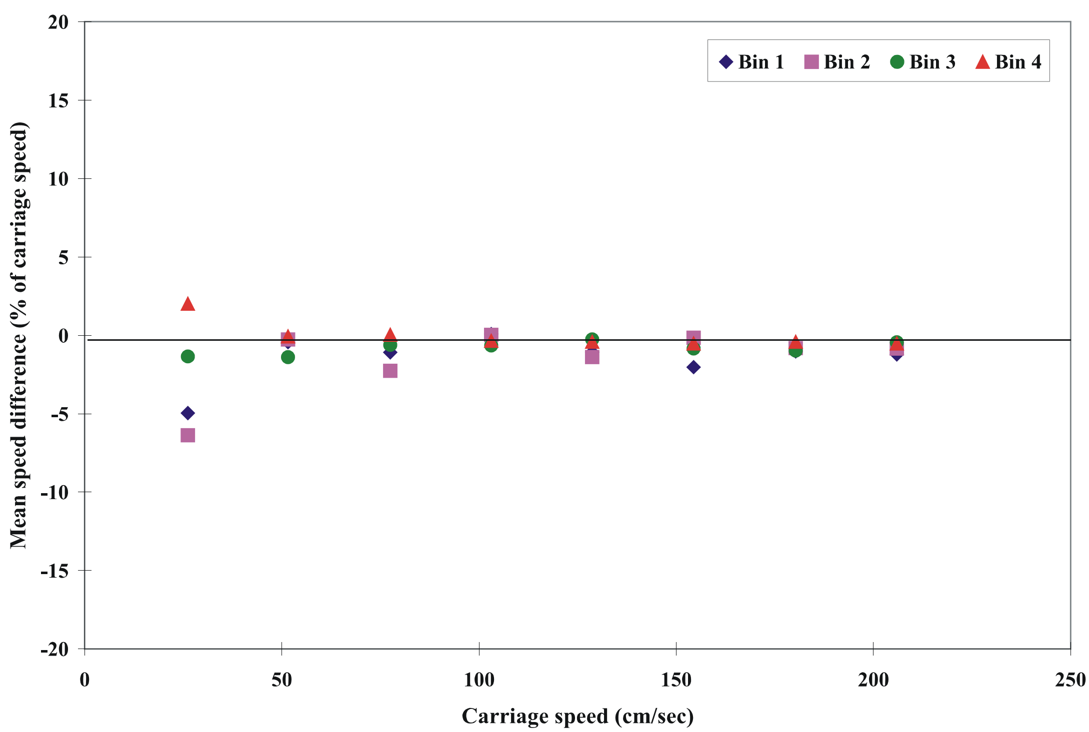

Fig. A25a Mean speed differences of ADP s4125/1500 KHz unit (11/19/96)

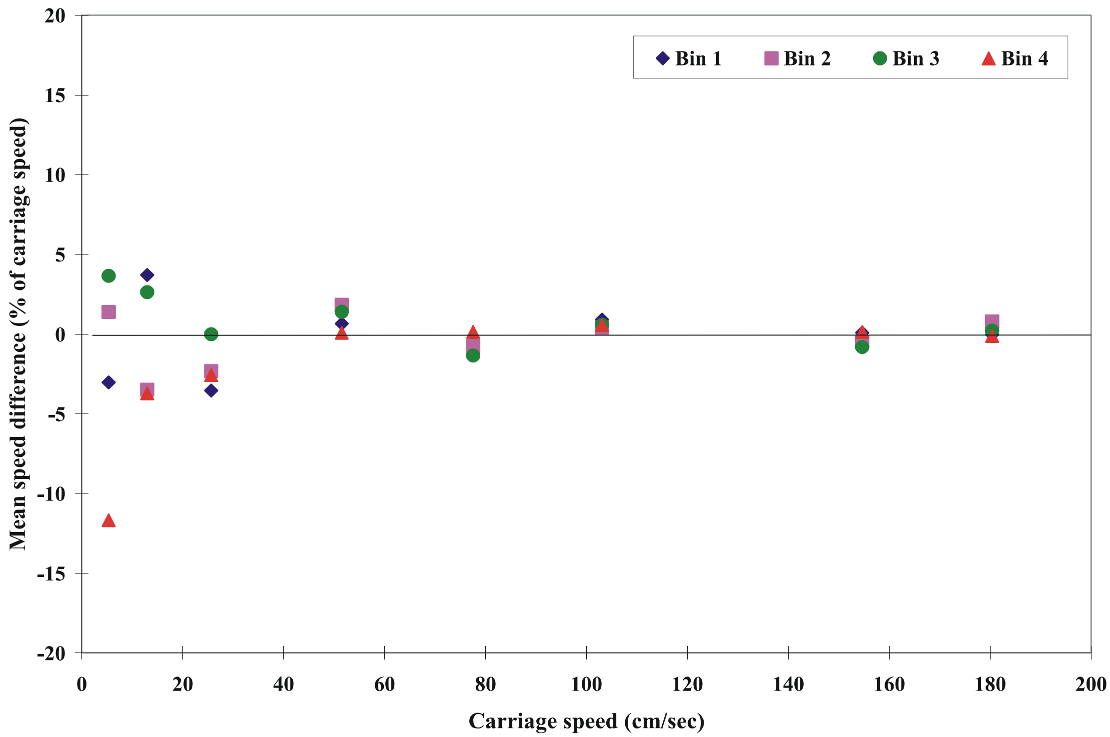

Fig. A25b Mean speed differences of ADP s4125/1500 KHz unit (11/19/96)

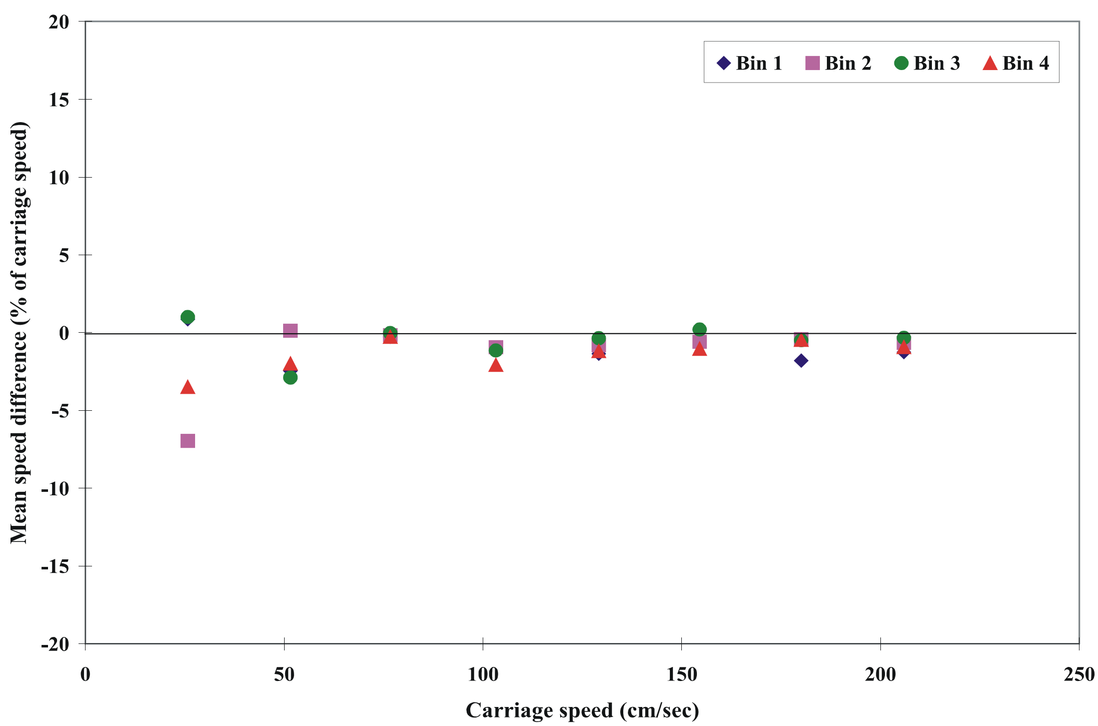

Fig. A26a Mean speed differences of ADP s4126/1500 KHz unit (11/19/96)

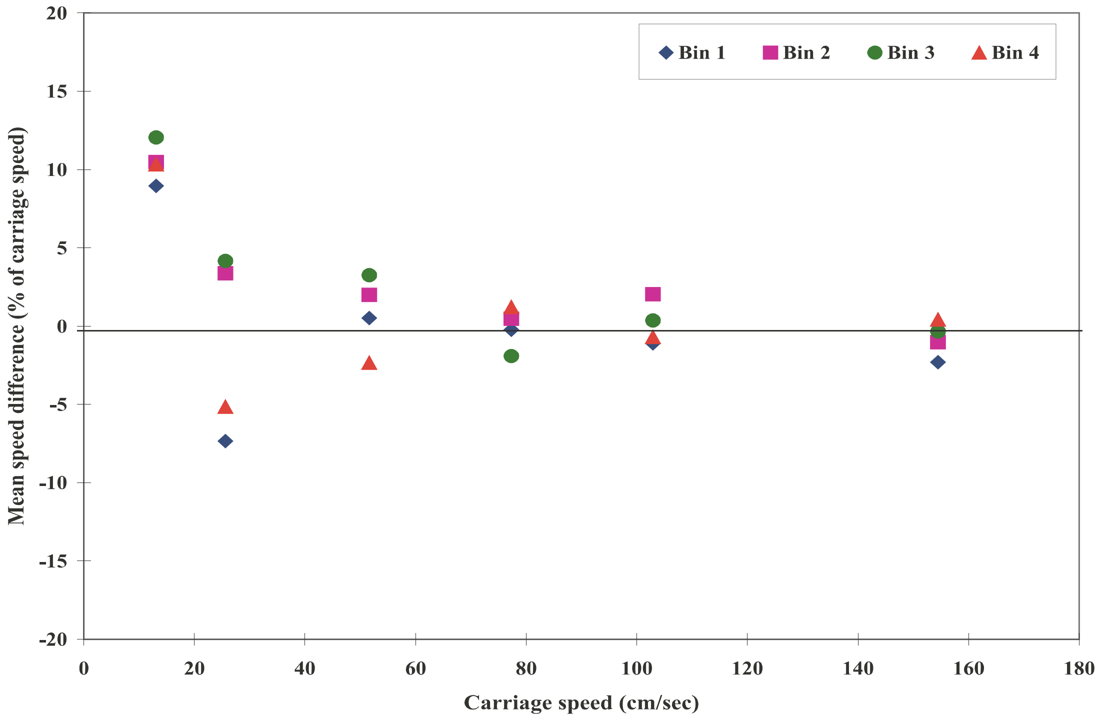

Fig. A26b Mean speed differences of ADP s4126/1500 KHz unit (5/11/01)

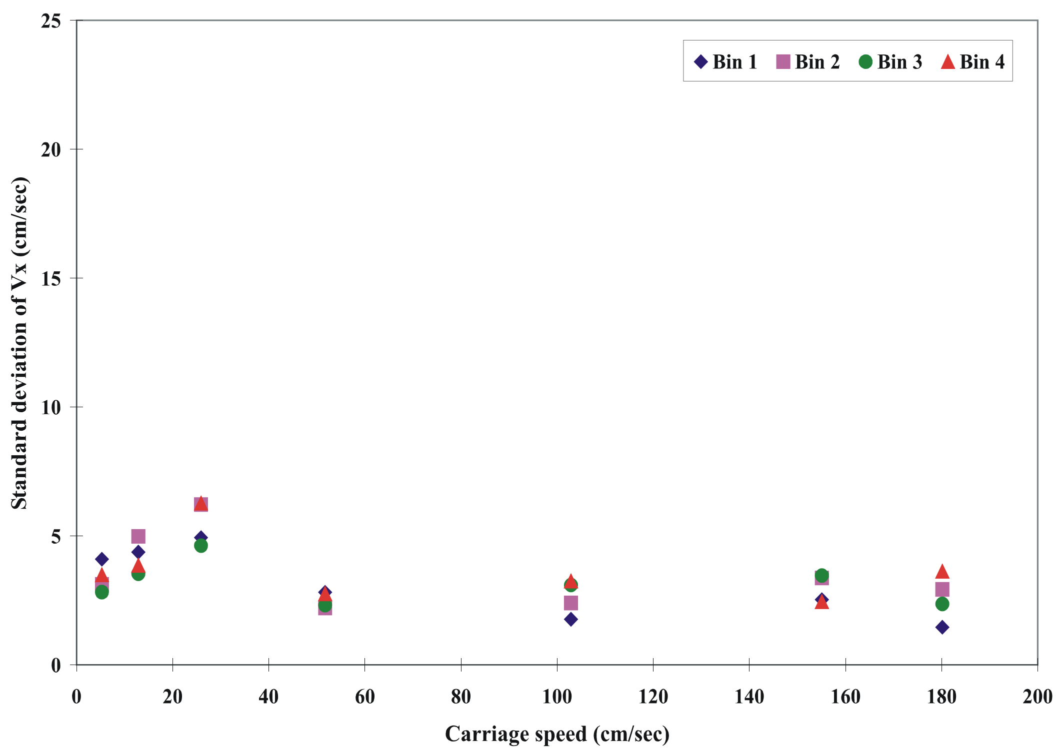

Fig. A27 Standard deviation of velocity component for ADCP r849/600 KHz unit (6/22/99)

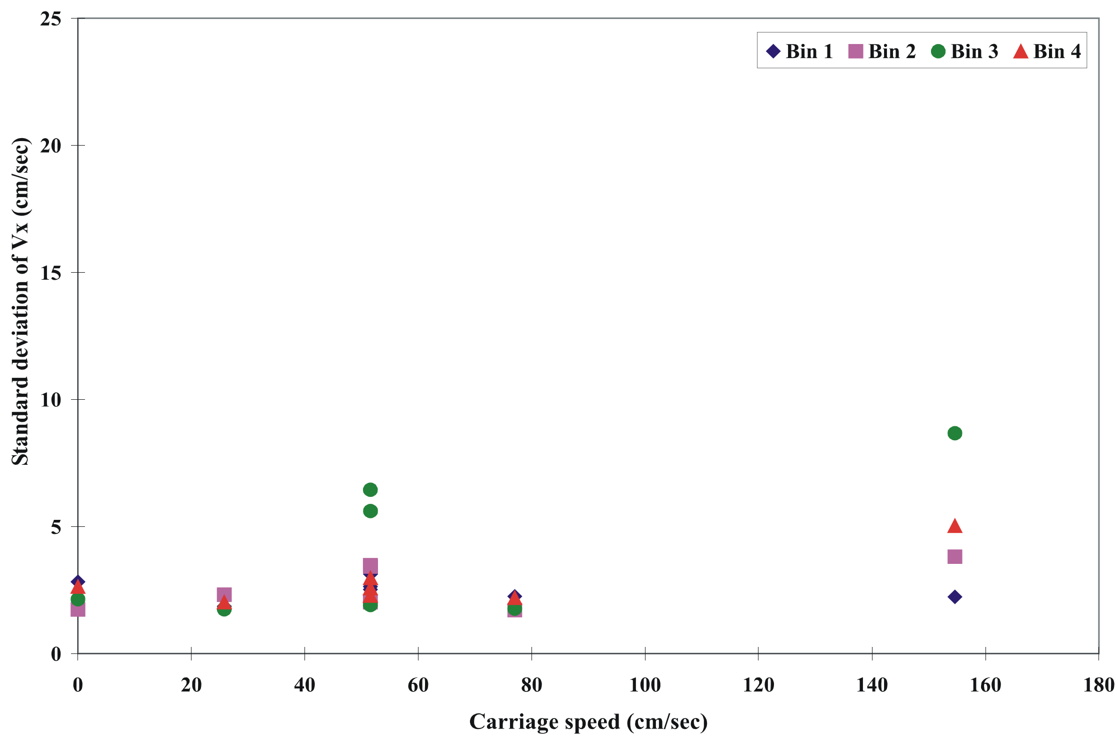

Fig. A28 Standard deviation of velocity component for ADCP r887/600 KHz unit (5/12/99)

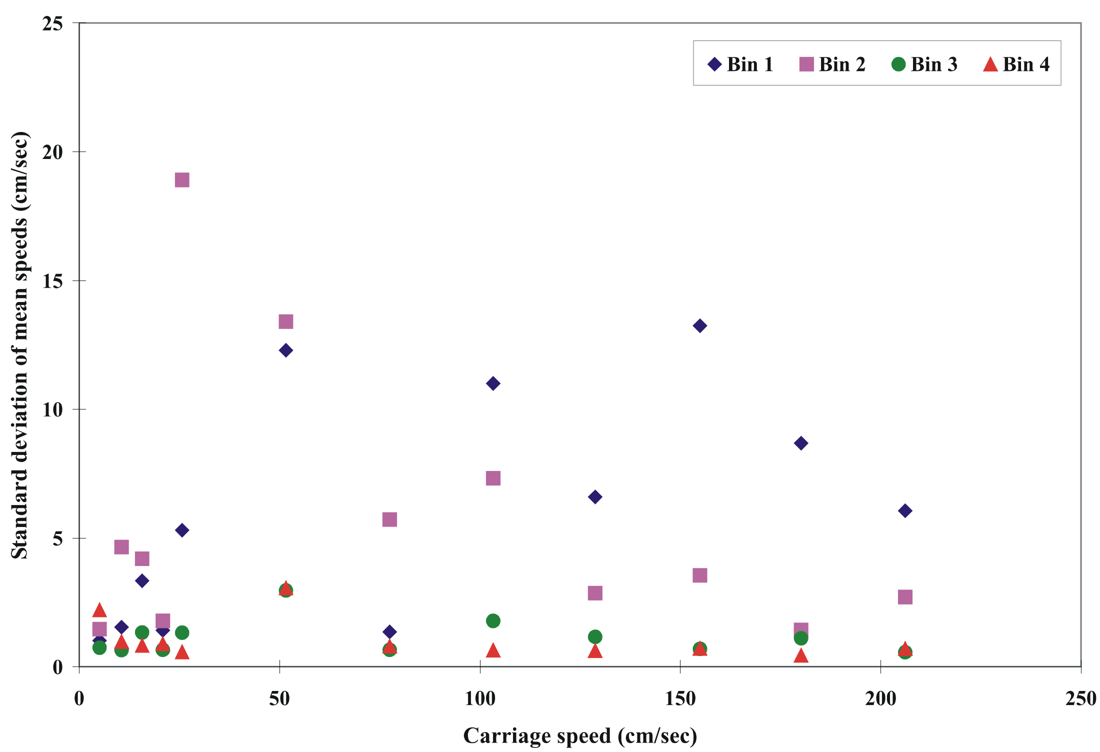

Fig. A29 Standard deviation of speeds for ADCP r134/1200 KHz unit (9/5/96)

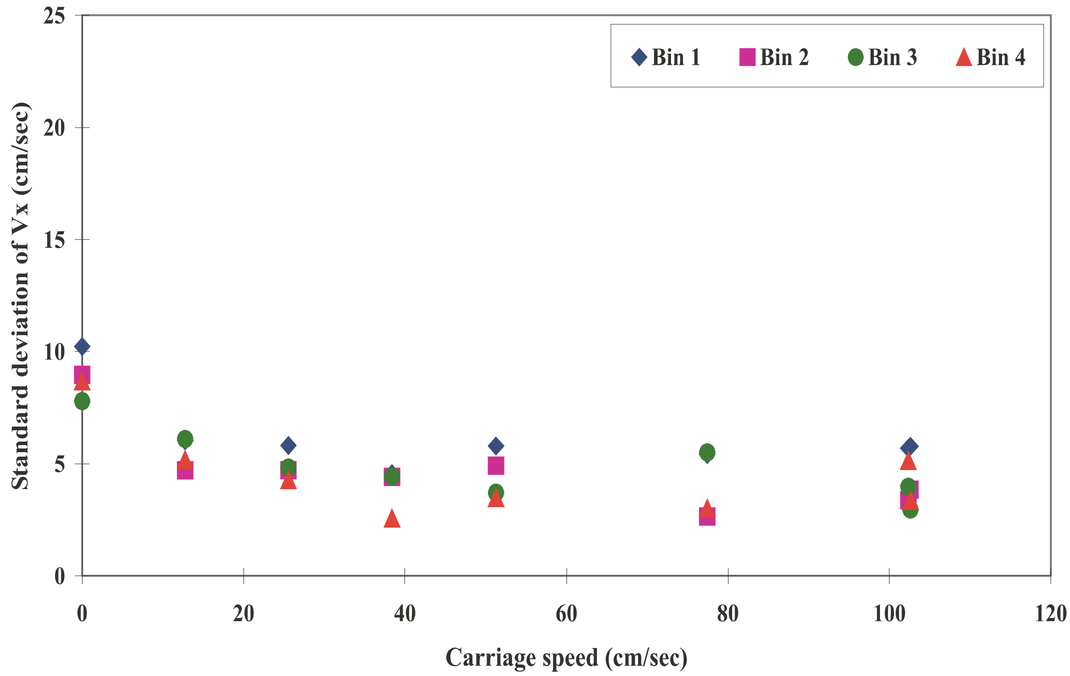

Fig. A30 Standard deviation of velocity component for ADP s21/1500 KHz unit (7/13/00)

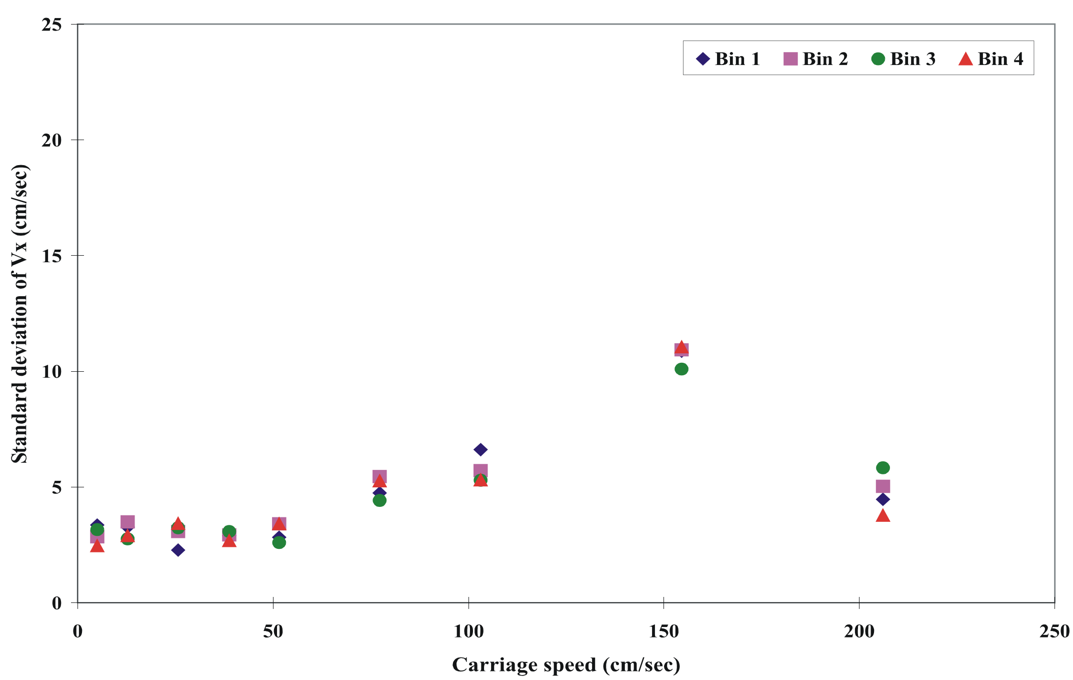

Fig. A31 Standard deviation of velocity component for ADP s4032/1500 KHz unit (4/16/98)

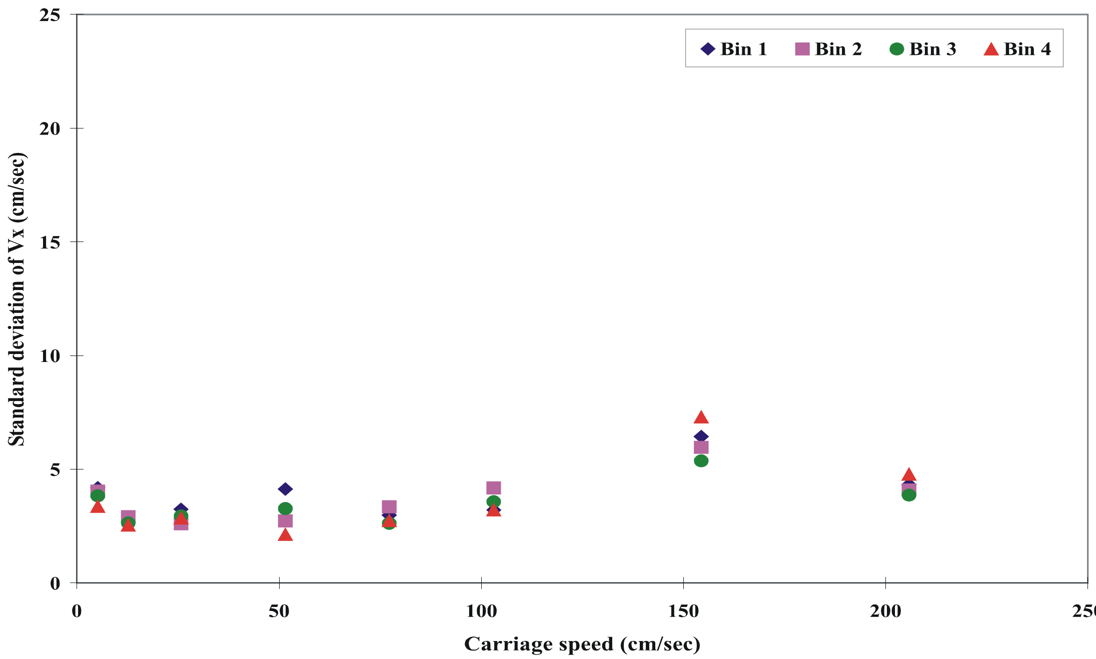

Fig. A32 Standard deviation of velocity component forADP s4033/1500 KHz unit (2/24/98)