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CORRECTING FOR PARTICLE COUNTING BIAS ERROR IN TURBULENT FLOW

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RATIONALE

Even if the result of this meeting is an ideal seeding device that generates particles that exactly follow the flow and are of sufficient major source of error, I refer to particle counting bias wherein the probability of measuring velocity <u>if it occurs</u> is a function of velocity. The error in the measured mean can be as much as 25% (ref. 1).

Many schemes have been put forward to correct for this error, but there is not universal agreement as to the acceptability of anyone method. In particular it is sometimes difficult to know if the assumptions required in the analysis are fulfilled by any particular flow measurement system.

In an effort to check various correction mechanisms in an ideal way and to gain some insight into how to correct with the fewest initial assumptions, a computer simulation was constructed to simulate laser anemometer measurements in a turbulent flow. That simulator and the results of its use are the topic of this paper.

INTRODUCTION

All measurements of mean quantities in a sparsely seeded turbulent flow using a laser anemometer generate a <u>measured velocity probability function</u> $P_m(v)$ that differs from the true Eulerian probability of interest $P(v)$. The relation between the two is given by

$$P_m(v) = \frac{r_m(v)}{\langle r_m \rangle} P(v) ,$$

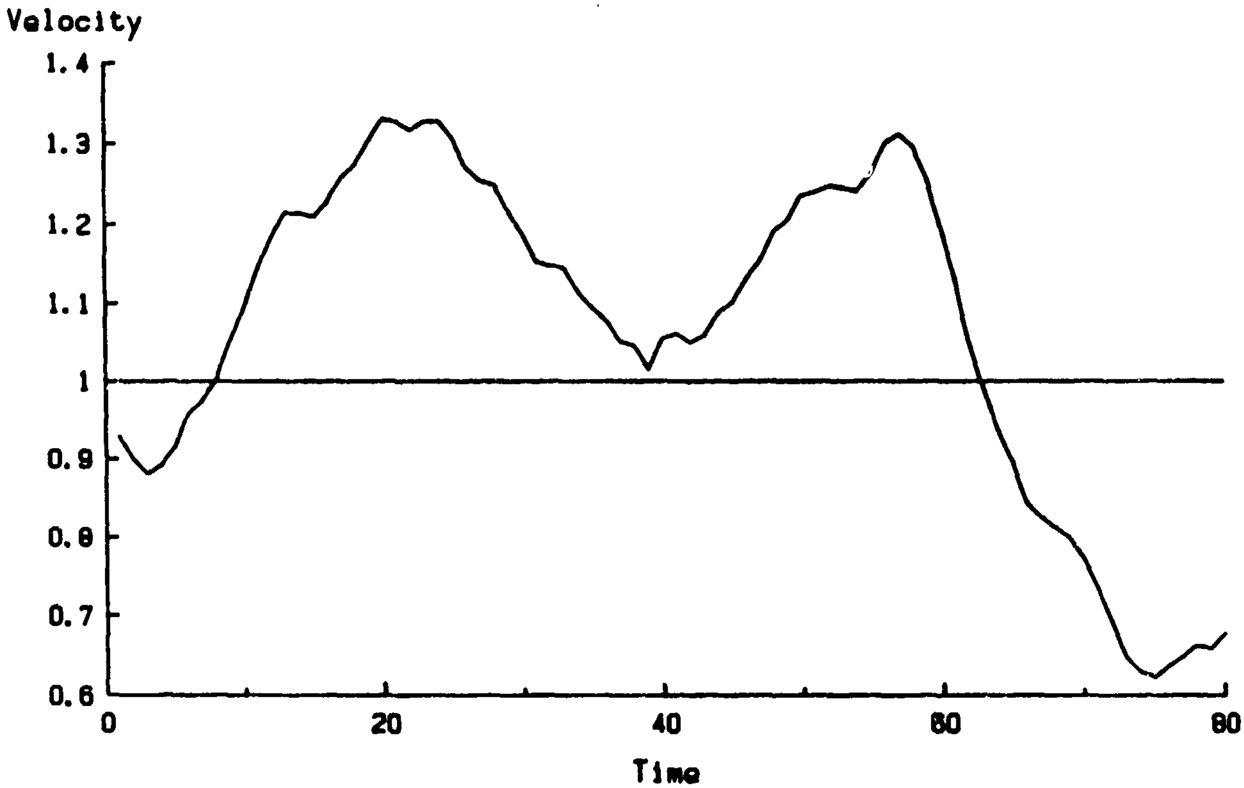
where $r_m(v)$ is the measurement rate <u>if</u> the velocity is v. < > denotes average value.

Any correction scheme's function is to eliminate the effect of $r_m(v)$.

SIMULATOR

First a pseudo-continuous signal, the "hot wire" signal, is generated by passing a digital white noise signal through a digital filter. Shown here is a typical segment of the "hot wire" signal.

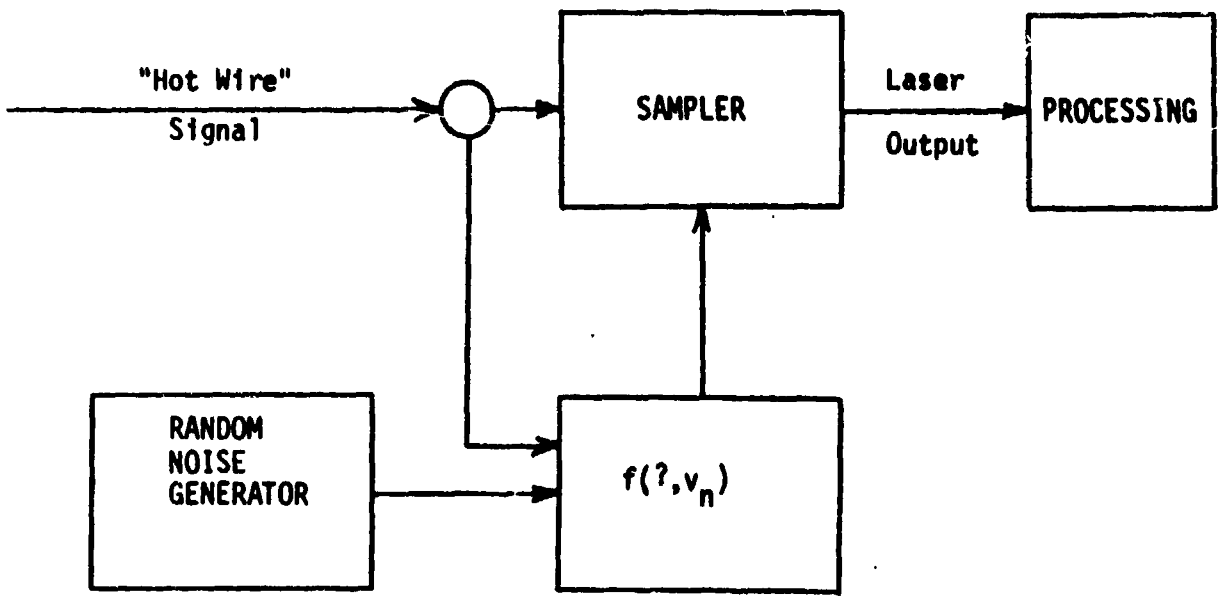
Sample Hot Wire Velocity Signal



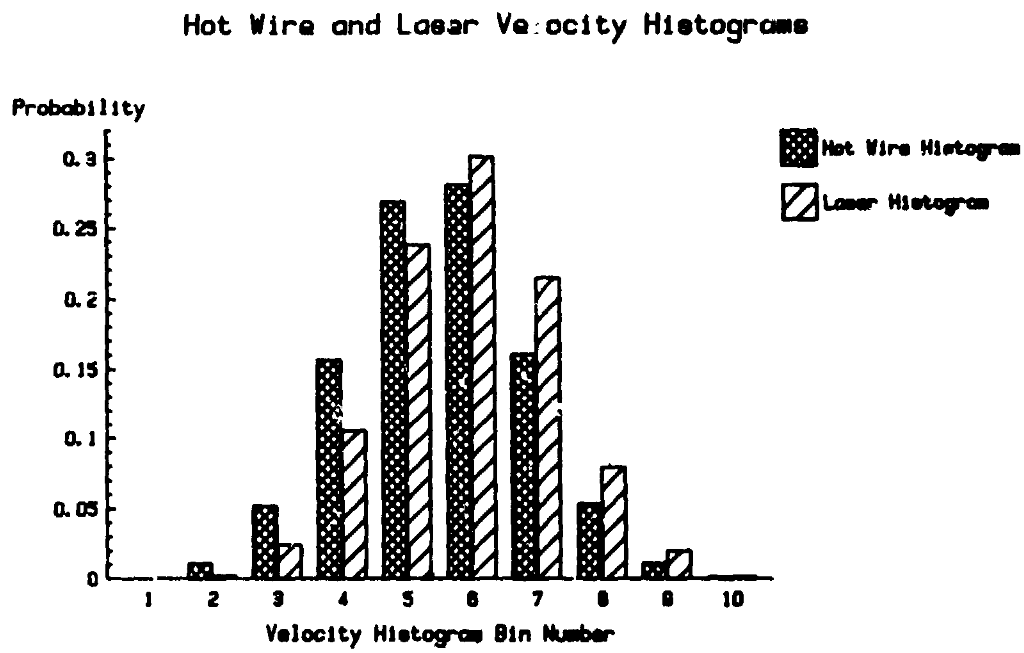
Vbar = 1.0, TI = 0.30

The "laser anemometer" signal is generated by a random sampling of the hot wire signal. The simulator is constructed so that the average measurement rate as a function of velocity can be set to be any desired function of the velocity. In this study the measurement probability, $r_m(v)$, was set to be either a linear or quadratic function of the velocity magnitude. Shown here is a block diagram of the particle sampling section.

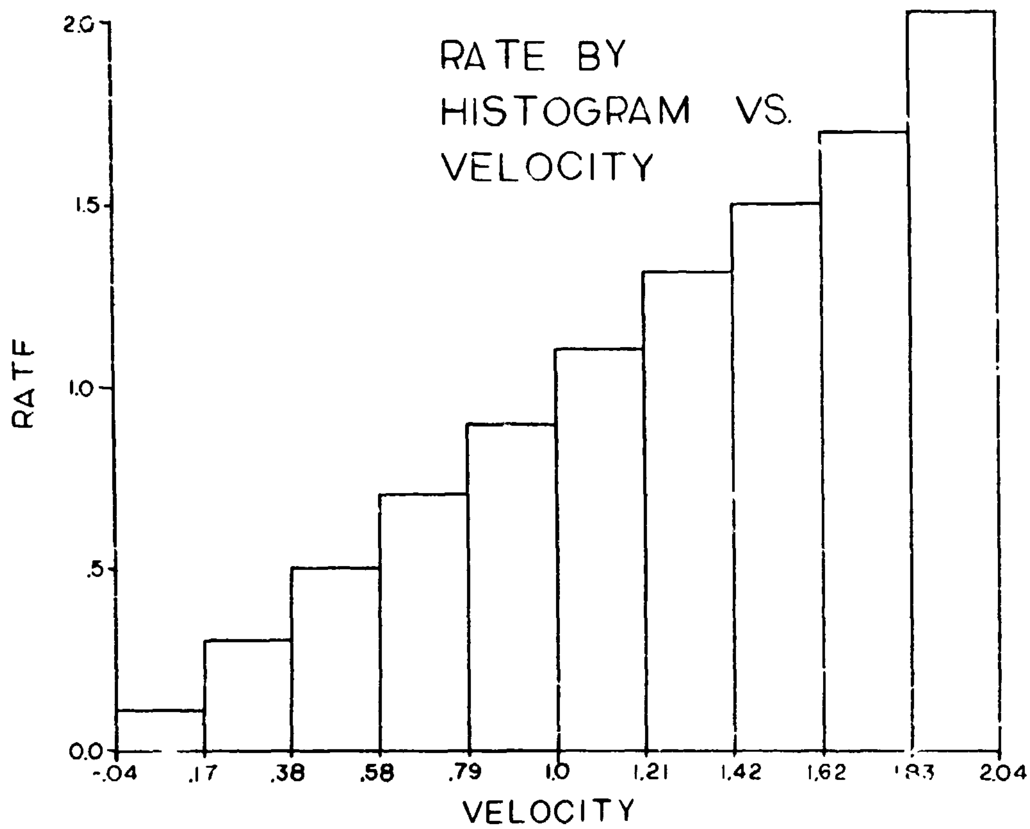
Flow Diagram of Particle Arrival Simulation



Shown here is a histogram of the hot wire signal and laser anemometer signal for a typical simulation. They are close in shape, but there are differences.



If one takes the ratio of the laser anemometer histogram to the hot wire histogram, the result should be the normalized rate corresponding to the velocity (see the first figure). That ratio is shown here. Note the linear dependence of the rate on velocity.



CORRECTION SCHEMES

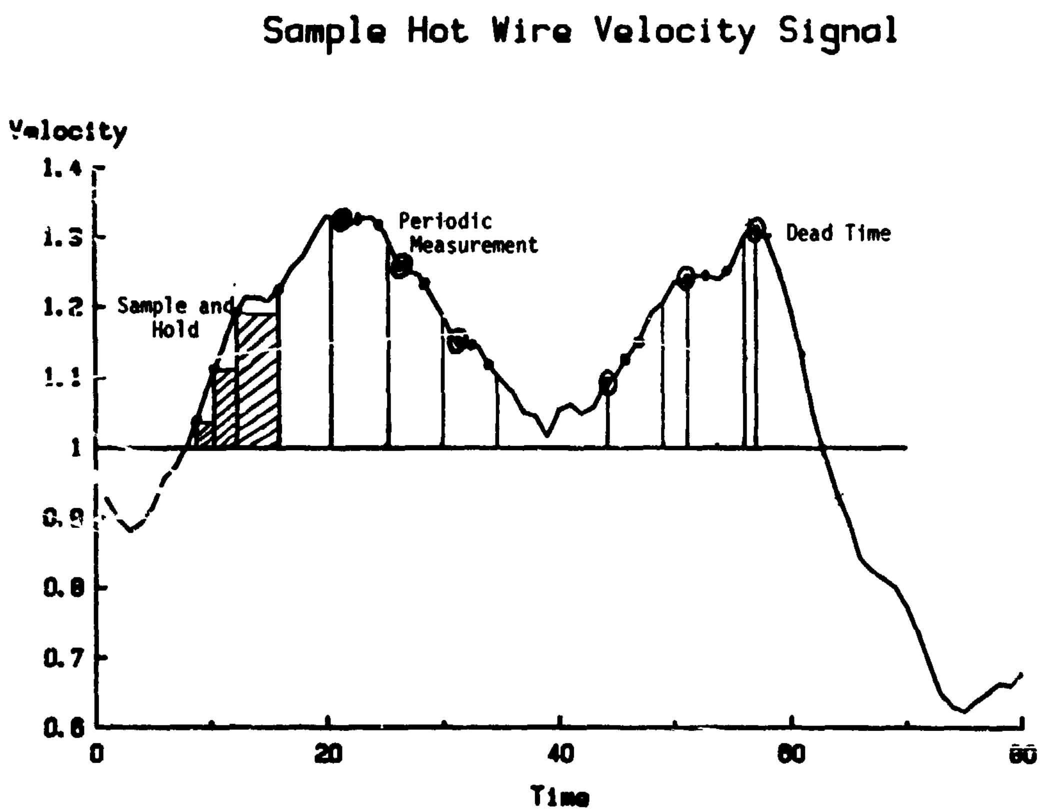
Three correction schemes from the literature were checked using the simulator.

1) Sample and Hold. A continuous signal is generated by holding the last measured velocity until a new measurement arrives. That new one is the held... It has been predicted that in the limit of many measurements per flow correlation time, the continuous signal generates unbiased statistics.

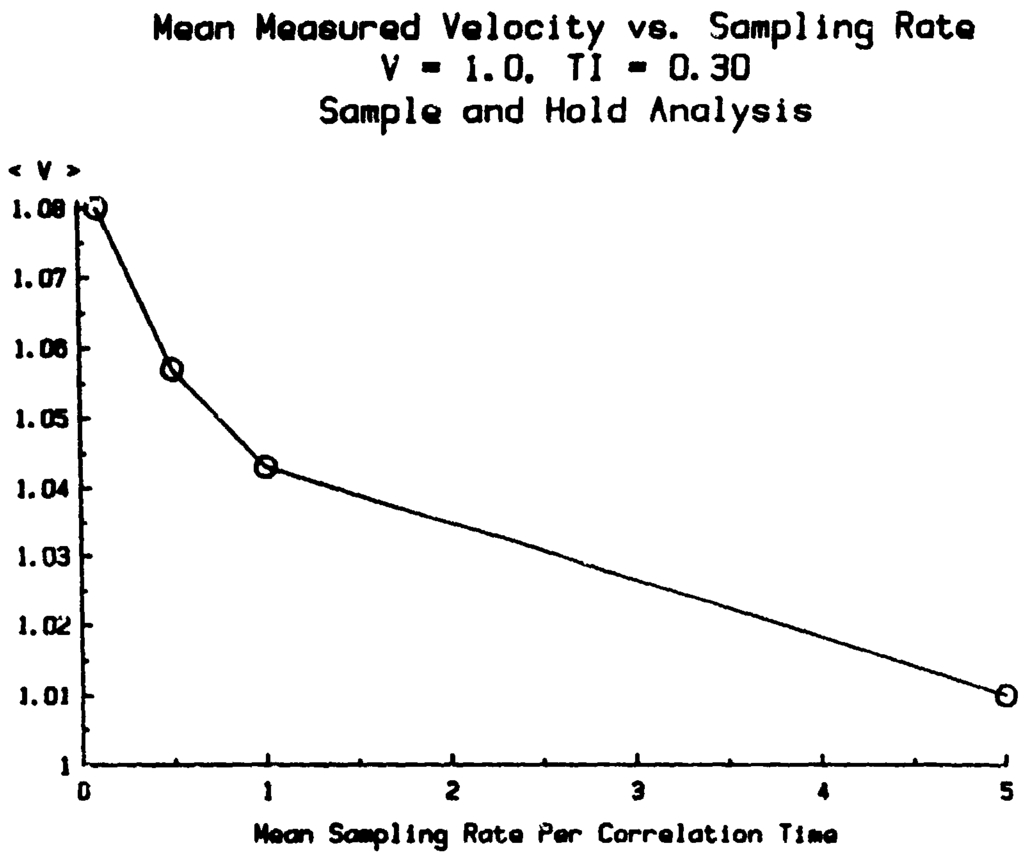
2) Periodic Measurement. Time is divided into intervals of constant length. If only the first measure in each interval is recorded, a periodically sampled signal is generated. It has been predicted that all bias vanishes when it is highly probable that there is a measurement in each interval.

3) Dead Time. Any data recording device has a reset time during which no new measurement is recorded. If the dead time is small compared to the flow correlation time and if the particle rate is high enough, the bias should vanish.

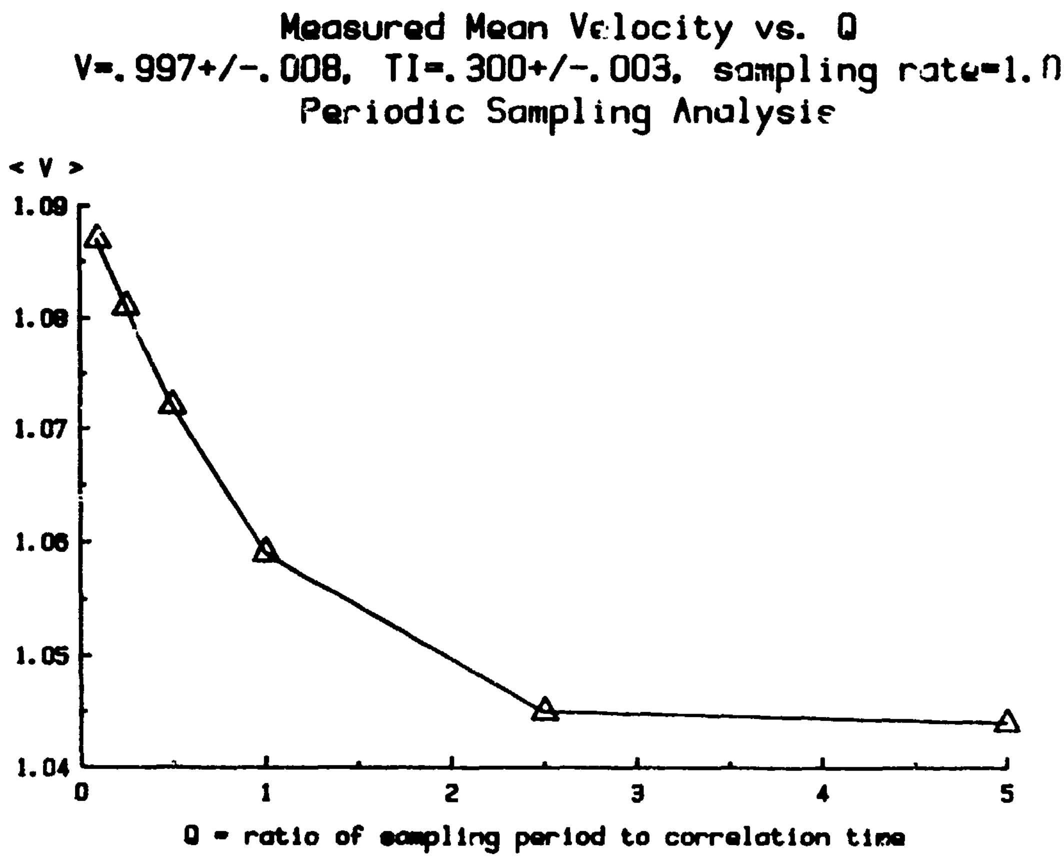
This figure shows each scheme graphically.



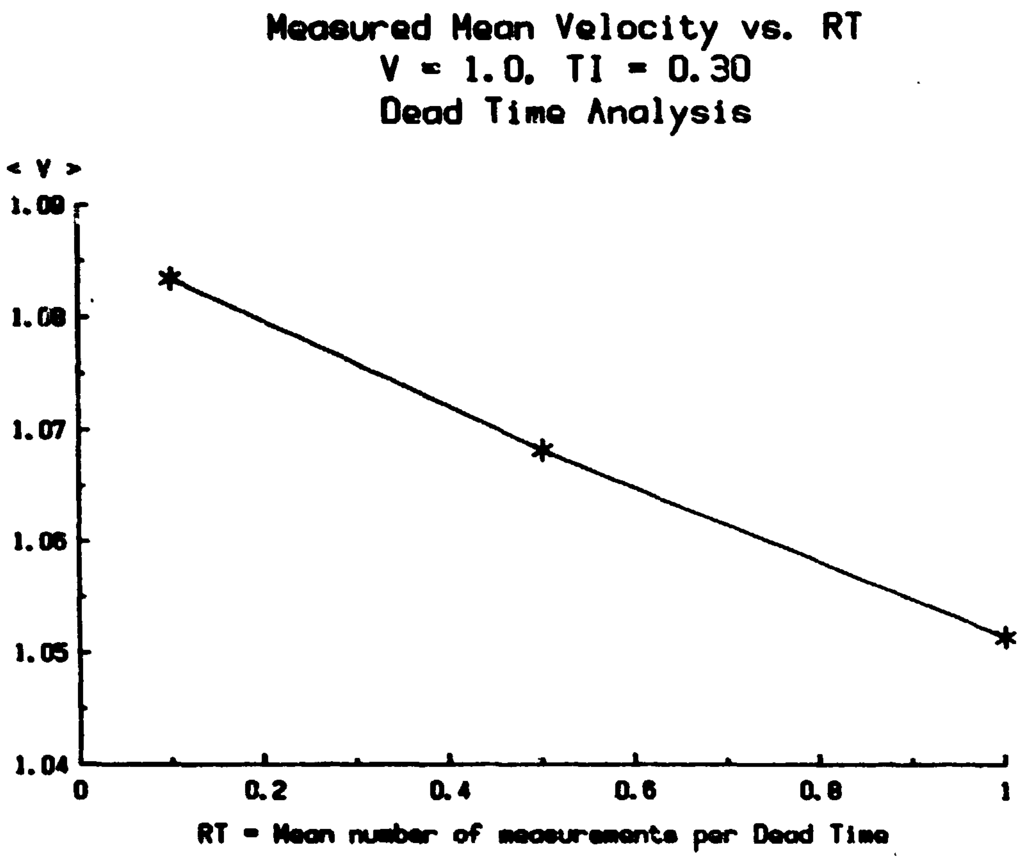
The bias in the mean definitely does decrease as the mean rate per flow correlation time increases. This is shown in the next figure.



If the mean particle arrival rate is held constant and if the periodic sampling rate is varied, the bias in the measured mean does decrease but not to zero. See below.

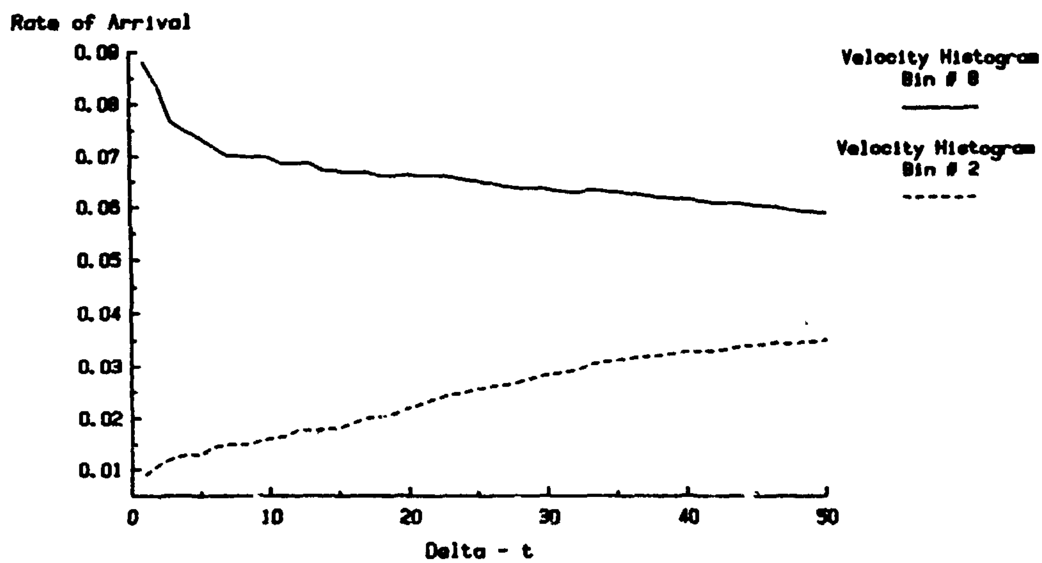


If the dead time is kept smaller than the flow correlation time, the bias is supposed to decrease to zero as the particle arrival rate increases. This is borne out by the following figure. Although the figure doesn't show the bias going to zero, the measurements closely fit the theory that does go to zero. We haven't had enough computer time to check the high particle rate limit.

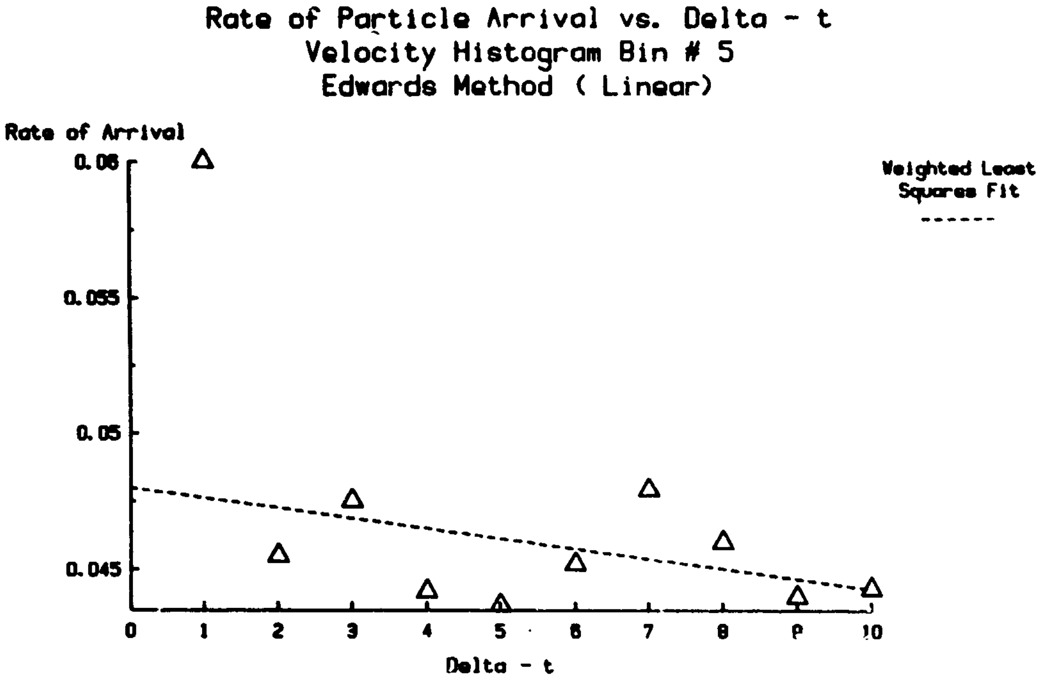


Recently Edwards and Meyers put forth a correction scheme that involved direct measurement of $r_m(v)$ (ref. 2). Simply, one measured that rate for each interval in the velocity histogram by counting the average number of measurements occurring in a small interval Δt after the appearance of a velocity in a given interval. It can be shown that the procedure's averaging result is exact in the limit of Δt going to zero. Unfortunately, it can also be shown that the relative measurement error goes to infinity as Δt goes to zero. The figure below shows the measured rate as a function of Δt. Note that as Δt increases, the measured rate tends toward the mean value, independent of which interval one starts in.

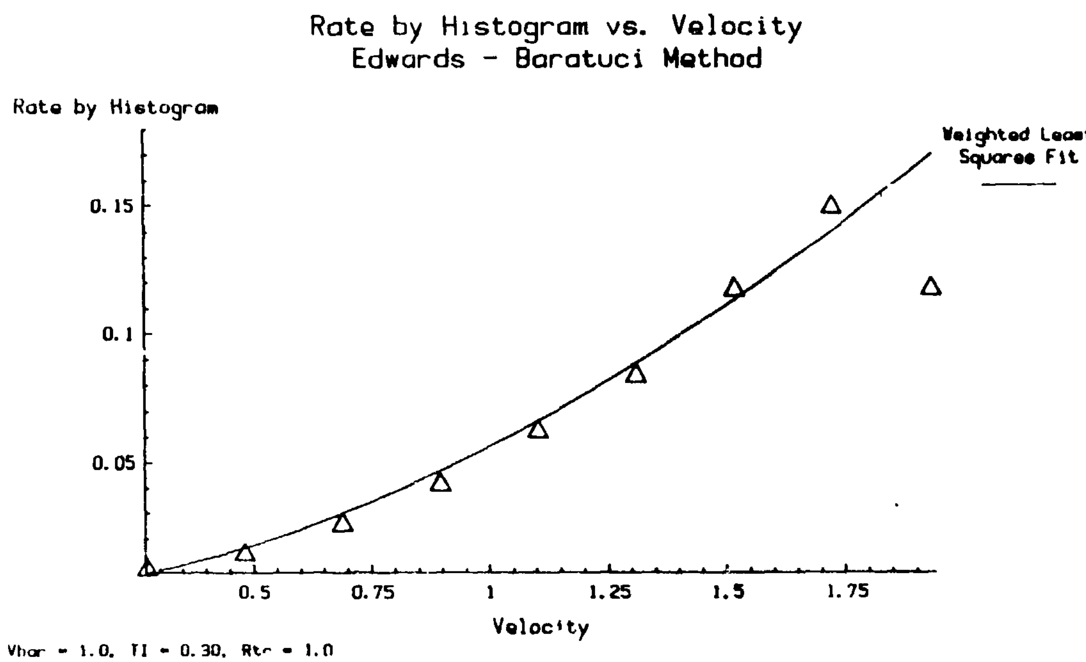
Rate by Time of Arrival vs. Delta - t
Edwards Linear Method



Edwards and Baratuci have invented a scheme that computes the limit as Δt goes to zero starting with relatively large values of Δt (ref. 3). A line is fit to the results for various Δt and the intercept is taken as the "ccrrect" value.



The following figure shows the measured rate versus velocity for a typical simulation with a quadratic dependence on velocity magnitude. The measured rates are very close to the values set by the simulation.



The following figure from reference 3 gives a summary of the results of our correction schemes for a set of simulations. McLaughlin and Tiederman (ref. 1) and the histogram corrections are included only as a self consistency check of the simulator. The two Edwards correction schemes are here because in general one does not know the functional form of $r_m(v)$. Edwards (quadratic) is a general quadratic fit to $r_m(v)$.

Edwards - Baratuci Correction Method.

Rate dependence on velocity is linear.

	Mean Velocity	Turbulence Intensity
Eulerian	0.998 ± .008	0.302 ± .004
Measured	1.092 ± .009	0.289 ± .004
McLaughlin & Tiederman	1.000 ± .012	0.302 ± .017
Histogram (linear)	1.002 ± .010	0.302 ± .006
Histogram (quadratic)	1.003 ± .012	0.300 ± .009
Edwards (linear)	1.000 ± .027	0.304 ± .014
Edwards (quadratic)	1.010 ± .023	0.290 ± .018

Note : Vbar = 1.0, TI = 0.30, $R\tau_c$ = 1.0.

Note : Edwards (linear) means a linear fit was done on $r_m(\Delta t, v_\kappa)$ and Edwards (quadratic) means a fit was done to a second order polynomial. The same explanation applies to the Histogram Methods.

Note : Error bars are the standard deviation of the mean of the mean velocity obtained from twenty data sets of 2700 points each.

This table (from ref. 3) is the same as the previous except that $r_m(v)$ is generated as a quadratic function of v.

Edwards - Baratuci Correction Method.
Rate dependence on velocity is quadratic.

	Mean Velocity	Turbulence Intensity
Eulerian	1.000 ± .010	0.301 ± .004
Measured	1.169 ± .013	0.281 ± .004
McLaughlin & Tiederman	1.093 ± .013	0.429 ± .019
Histogram (linear)	1.047 ± .029	0.296 ± .030
Histogram (quadratic)	1.010 ± .019	0.297 ± .011
Edwards (linear)	0.968 ± .097	0.289 ± .053
Edwards (quadratic)	1.016 ± .045	0.274 ± .028

Note : Vbar = 1.0, TI = 0.30, $R\tau_c$ = 1.0, N = 2700.

Note : Edwards (linear) means a linear fit was done on $r_m(\Delta t, v_k)$ and Edwards (quadratic) means a fit was done to a second order polynomial. The same explanation applies to the Histogram Methods.

Note : Error bars are the standard deviation of the mean of the mean velocity obtained from twenty data sets of 2700 points each.

CONCLUSIONS

Sample and Hold eliminates bias for high particle densities.

Dead Time reduces bias for sampling rates tested [Prediction not checked due to large run time]

Periodic Sampling with long periods reduces but does not eliminate velocity bias

New correction is excellent when the form of rate as a function of velocity is known

Further work using "unknown" functional forms is in process

REFERENCES

1. McLaughlin, D.K. and Tiederman, W.G.: Biasing Corrections for Individual Realization of Laser Anemometer Measurements in Turbulent Flow. Phys. Fluids 16, 2082, 1973.

2. Edwards, R.V. and Meyers, J.: An Overview of Particle Sampling Bias. Presented at the Second International Symposium on Applications of Laser Anemometry to Fluid Mechanics, July 2-4, 1984, Lisbon, Portugal.

3. Baratuci, W.: Particle Arrival Statistics in Laser Anemometry. M.S. Thesis, Case Western Reserve University, 1985.