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**DIRECT MEASUREMENT OF TURBULENT DISSIPATION
RATE USING DUAL LASER DOPPLER VELOCIMETERS**

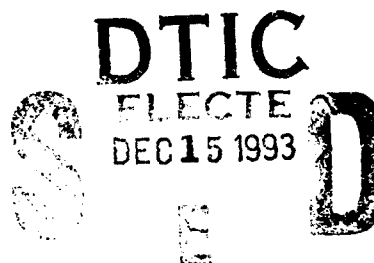


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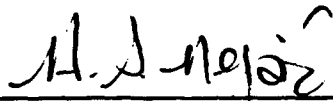
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13. ABSTRACT (Maximum 200 words) The analysis of two-point velocity correlation measurement, made in the antisymmetric flowfield of axisymmetric sudden expansion using two-single component LDV systems, has been performed. Estimations of the Taylor microscale were made and the one-dimensional energy spectrum was determined using the spatial and auto-correlation functions from these measurements. Difficulties in estimating the Taylor microscale from spatial and auto-correlations are discussed and methods to overcome these difficulties are suggested. Calculations of the one-dimensional energy spectrum from curve fits to the correlation functions are explored and some hazards of the process are highlighted.				
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DIRECT MEASUREMENTS OF TURBULENT DISSIPATION RATE USING DUAL LASER DOPPLER VELOCIMETERS

INTRODUCTION

The research program had two major thrusts, both of which have been completed. The first was to perform a detailed analysis of two-point and single point velocity measurements, obtained using laser Doppler velocimetry (LDV), in an effort to give accurate turbulent length scales and the turbulent dissipation rate. Four publications reporting our findings regarding the calculation of turbulence scales from LDV measurements have resulted in the past.

Benedict, L. H. and Gould, R. D. (1993) "Calculation of One-Dimensional Energy Spectra from Spatial Correlation Measurements using LDV," Accepted ASME 1993 Forum on Turbulent Flows, Washington, DC, June 20-24.

Gould, R. D., Nejad, A. S. and Ahmed, S. A., (1992a), "Turbulent Length Scale Measurements in an Axisymmetric Sudden Expansion Using LDV, The Fourth International Conference for Fluid Mechanics, Alexandria, Egypt, April 28-30.

Gould, R. D., Benedict, L. H., Nejad, A.S., and Ahmed, S.A., (1992b), "Two-Point Velocity Correlation Measurements in an Axisymmetric Sudden Expansion Using LDV," Proc of 6th Intl Sym on Appl of Laser Anemometry to Fluid Mech., Lisbon, Port.

Gould, R. D., Benedict, L. H., (1992c) "A Comparison of Spatial Correlation and Autocorrelation Measurements in an Axisymmetric Sudden Expansion Using LDV," 13th Symposium on Turbulence, Univ. of Rolla-Missouri, Rolla, Mo., September 21-23.

A summary of the important findings from this analysis is given below. The second task involved fabricating a dual LDV capable of making two-point and single-point velocity correlation measurements at the Applied Energy Research Laboratory (AERL) at North Carolina State University (NCSU). Details of this system are also given below.

EXPERIMENTAL APPARATUS

Two-point velocity correlation measurements using two single component LDV's and single-point velocity correlation measurements using one single component LDV were made in an axisymmetric sudden expansion air flow¹. The geometry was produced by joining a 101.6-mm (4-in.) inside diameter entry pipe to a 152.4-mm (6-in) inside diameter clear acrylic test section. The entry pipe was 3.5-m long so that a fully developed pipe flow velocity profile existed at the entrance to the sudden expansion. The step height for this geometry was 25.4-mm (1-in.). Flat quartz windows 50-mm x 152-mm x 3.2-mm (2 x 6 x 0.125-in) were mounted in flanges on both sides of the 152.4-mm-diameter test section such that the inner flat surfaces were flush with the inside diameter of the test section.

Flow velocities for the spatial correlations were measured using two TSI single component dual-beam LDV systems, both operating in backscatter mode. Both systems were oriented to measure the axial velocity component on the diameter of the test section as shown in Figure 1. One LDV system was adjusted so that the probe volume was located at the required axial, x , and radial, r , measurement location. Once this position was found, the LDV system was locked in place. The 514.5- μm laser line from a Model 2025 Spectra Physics argon ion laser was used in this system. A Bragg cell shifted the frequency of one beam by 40 MHz causing the fringes to move in the downstream direction. A second LDV system (TSI Model 9277 190-mm fiber optic probe), mounted on a precision xyz positioning table with resolution of $\pm 2.5\mu\text{m}$ in each axis, was located on the opposite side of the test section (see Figure 1). The 488- μm laser line from a Model 165 Spectra Physics argon ion laser was used in this system. A frequency shift of 40 MHz was used causing the fringes of this system to move in the upstream direction. Both LDV systems employed 3.75x beam expansion optics and gave probe volumes approximately 60- μm in diameter and 450- μm in length.

A 20- μm -diameter pinhole mounted on a fixture supported on a spare test section window was used to find the position where both laser beam probe volumes initially overlapped. This fixture was used prior to each test sequence, thus ensuring that both probe volumes overlapped at the zero separation distance point. Specially designed beam blocks were fabricated to block reflections from the LDV focusing lens (they faced one another) and from test section windows. Narrow bandpass filters were placed in front of each photomultiplier tube to eliminate cross-talk between the two channels.

Two TSI Model 1990C counter processors interfaced to a custom built coincidence timing unit were used in the data collection and processing system. High and low pass filters were set to 10 MHz and 50 MHz, respectively, for the stationary LDV system, and 20 MHz and 100 MHz, respectively, for the fiber optic LDV system. Both processors were set to sample continuously (multiple measurements per burst) count 16 fringes and use a 1% comparator. A hardware coincident window was set at 20- μs for all of the tests. Data (two velocities and the running time for each realization) were transferred through two DMA ports to a MicroVax minicomputer and later uploaded to a VAX 8650 for analysis.

The flow field was seeded using titanium dioxide (TiO_2) particles generated by reacting dry titanium tetra-chloride (TiCl_4) with the moist shop air. Craig et al.² measured the particle sizes generated by this device and found that they were fairly uniform and in the 0.2 - 1- μm -diameter range. Data validation rates varied between 5000 and 500 per second on each counter processor and depended mainly on how well the chemical reaction proceeded. This seemed to be very sensitive to shop air temperature and relative humidity. Coincident data validation rates ranged from 1000 to 50 measurements per second.

EXPERIMENTAL PROCEDURE

All flow conditions were maintained at near constant values throughout the testing procedure. The inlet centerline velocity, U_{cl} , was maintained at 18.0-m/s $\pm$ 0.1-m/s (59-ft/s $\pm$ 0.3-ft/s) giving $\text{Re}_D = 114,000$ based on centerline velocity and inlet diameter. Spatial correlation statistics and histograms were formed by using 5000 individual realizations for each velocity channel at each measurement point. Autocorrelations were formed by using 50,000 individual realizations from the stationary LDV system with data validation rates between 25,000 and 1000 per second. In computing statistical parameters, a two step process suggested by Meyers³ was used to eliminate noise from the data. All velocity measurements deviating more than 3 standard deviations from the mean are thus eliminated. For a properly operating LDV system less than 1% of the data should be discarded. In addition, Srikantaiah and Coleman⁴ have found that as long as the total number of removed points

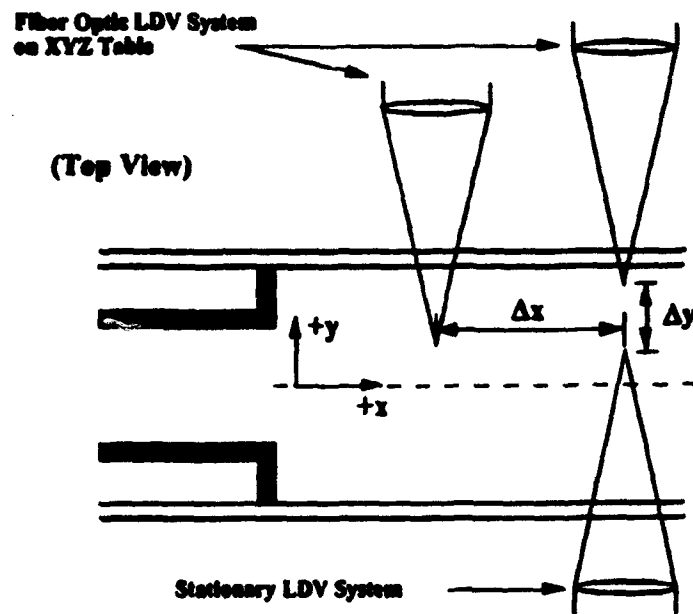


Figure 1. Dual LDV's in an axisymmetric sudden expansion.

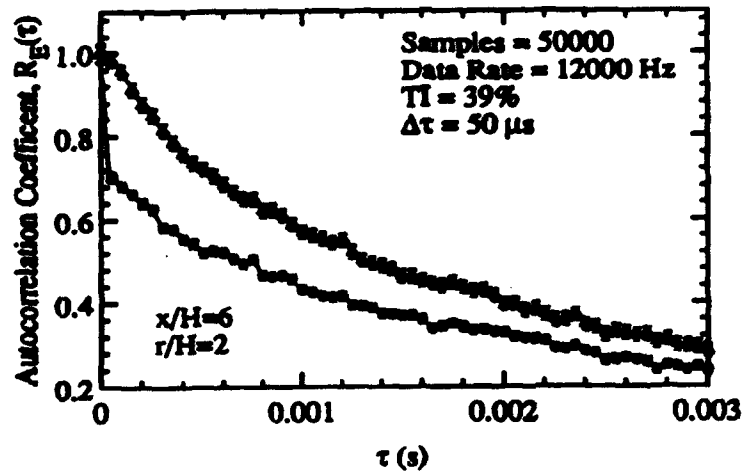


Figure 2. Autocorrelation measurements.

is within 1% of the total sample size, the effect of the removal of noise on the autocorrelation function is negligible.

EXPERIMENTAL RESULTS

Autocorrelations and Microscales

Two-point (spatial) velocity correlation measurements and single point (auto) velocity correlation measurements were made at three locations in the axisymmetric sudden expansion flowfield. These results, including the calculation of integral length scales and Taylor microscales, were presented by Gould and Benedict¹. In this earlier paper mention was made of the difficulty in accurately determining the Taylor microscale from either the discrete spatial or autocorrelation functions. This difficulty is addressed in more detail here. Additionally, the problem of calculating one-dimensional energy spectra from spatial and autocorrelation functions is discussed.

In Figure 2, typical autocorrelation functions measured at 6 step heights downstream ($x/H = 6$) and 2 step heights ($r/H = 2$) from the axis are presented. The autocorrelation can be transformed to the spatial domain by use of Taylor's hypothesis (i.e., $x = Ut$) which was shown to be an accurate transformation for this flow field¹. Discrete autocorrelation measurements were made using the slotting technique described by Jones⁵ and Mayo, et al.⁶ The time lag axis was divided into bins of equal width and the exact lag products of all points up to a specified maximum lag time were accumulated in appropriate bins. The average of all the auto-products falling in each bin was assumed to be the value of the discrete autocorrelation function, i.e:

$$R_E(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2(t)}}$$

at the midpoint of the bin. The data was filtered first using the previously described method to eliminate velocity measurements more than 3 standard deviations from the mean. The zero-lag products were not included to avoid the spiking effect at the origin ($\tau = 0$) due to squaring of uncorrelated noise⁷. The discrete autocorrelations, shown in Figure 2, were obtained using a slot width of 50- μ s with a maximum lag time of 3-ms. Note that there is still some scatter in the data even though 50,000 samples were used to build the autocorrelation functions. A mean data validation rate of approximately 12,000 per second was used here. This scatter is statistical in nature and is due to too few lag products in each slot which causes some variance in the data (each bin contained approximately 30,000 lag products). The error bars shown in this figure indicate the variances of the calculated mean values of the autocorrelation function. These statistical uncertainties in the mean of the quantity $\overline{u'u'}$ are estimated using the sample size and standard deviation of the sample in each slot⁸. Interestingly, although zero-lag products were not included in the first slot of the discrete autocorrelation function, a severe spike results at the origin (bottom curve). This spike is an unnatural characteristic of the autocorrelation function and prohibits the estimation of the Taylor micro-scale (dissipation scale).

One popular, but perhaps questionable, way around this problem is simply to ignore the first slot value and normalize the autocorrelation with respect to the second slot. Another approach was considered, however, based on the belief that the spiking effect was caused by the continuous sampling of the LDV system. Continuous sampling allows for multiple measurements to be made on a single Doppler burst. In such a situation, a slow moving particle can be sampled more than once as it passes through the probe volume. Such measurements are inherently highly correlated with one another as they come from the same particle at close proximity in time. A simple

computer algorithm was employed to remove multiple velocity measurements resulting from passage of single scattering source through the probe volume from the data set. Basically, the data set was searched for successive measurements which had velocity-time between data products less than the probe volume diameter. If this occurred, these measurements were assumed to have come from the same particle. After eliminating these redundant measurements, a new autocorrelation function was calculated and is also shown in Figure 2 (top curve). One may observe that this new autocorrelation function displays the expected parabolic behavior near the origin without any spiking.

From such an autocorrelation function the Taylor microscale may be easily estimated by fitting an osculating parabola to the spatial correlation function between the first measured two points. The discrete spatial correlation function is obtained by transforming the discrete autocorrelation function via Taylor's hypothesis (i.e., $\lambda_f = U \tau_E$). Thus the longitudinal microscale is obtained from:

$$R(x) = 1 - \frac{x^2}{\lambda_f^2}$$

where x represents the separation distance between the first two measurements. For the autocorrelation function shown as the top curve in Figure 2, where $U = 8.5$ m/s, λ_f was found to equal 3.3-mm. In previous work¹ this estimate had been considered to be on the order of 6-mm, however, an earlier experimental investigation¹ estimated the dissipation at this location in the flow field to be approximately 1340-m²/s³ by using turbulent kinetic energy balance. Using an isotropic turbulence assumption, the microscale can be estimated from:

$$\epsilon = 30 \nu \frac{\overline{u'^2}}{\lambda_f^2}$$

The microscale estimate based on a turbulent kinetic energy balance and the assumption of isotropy is then calculated as approximately 2.3-mm. As the dissipation rates obtained from the turbulent kinetic energy balance are believed to be more accurate than the first microscale estimates from the autocorrelation functions presented by Gould and Benedict¹, the newer estimate of the microscale from these functions is considered to be an improvement over the old one.

As will be shown later, two-point spatial correlations seem to suffer from probe volume integration effects such that near the origin ($\Delta x = 0$) no parabolic region can be found and any estimation of the microscale must be considered a crude approximation. Until these probe volume integration effects can be reduced, the transformed autocorrelation function (using Taylor's hypothesis) should be considered as the method of choice for estimating the micro-scale from LDV measurements.

Some guidelines are thus in order as to how to best pursue this goal. First, one should always be aware that Taylor's hypothesis is limited by turbulence intensity. It should not be applied in flows with turbulence intensities greater than about 20%. Work by Gould and Benedict¹ and Cenedese¹⁰ suggests, however, that oftentimes Taylor's hypothesis is approximately valid for much higher turbulence intensities. Another point to make is that a very high mean data validation rate is often necessary to resolve the small scales. Previous work such as that of Cenedese¹⁰, Morton and Clark¹¹, Absil⁷, and Fraser et al.¹² make use of relatively low Reynolds number flows to simplify the measuring process. In the current work, a Reynolds number based on inlet diameter of approximately 114,000 was achieved in the axisymmetric sudden expansion flow. For this flow condition additional studies, not reported here, suggest that approximately 100,000 samples need to be recorded at data rates approaching 20,000 Hz in order to accurately resolve the small scales.

Oftentimes, however, such high data rates are not achievable. Additionally, single measurement per burst mode is preferred over continuous sampling in order to prevent biasing of the autocorrelation function as described above. As was done in this work, zero-lag products should not be included in the first slot of the discrete autocorrelation function.

Spatial Correlations and 1-D Energy Spectra

As mentioned above, spatial correlations suffer from a probe volume integration effect at small separation distance. This effect tends to obscure correlation information pertaining to the microscale as even when the two probe volumes overlap (i.e., $\Delta x = 0$), their lengths allow for a finite separation distance¹. If the probe volume length is of the same size as the parabolic region of the correlation function, then this parabolic section can quite possibly be obscured. As flow Reynolds number increases, such a situation is more likely to happen, and thus the determination of a microscale through a two-point spatial correlation function becomes an approximate analysis.

Figure 3 shows the longitudinal spatial correlation coefficients at $x/H = 10$ and $r/H = 2$ in the axisymmetric sudden expansion flow obtained using two-point correlation measurements and also shows an exponential fit to the data. The lack of a parabolic region in the data near zero spatial separation should be pointed out. Also, it can be seen that the spatial correlation function does not reach unity at zero spatial separation. Both of these characteristics may be attributed to the probe volume integration effect mentioned above. Obviously, there is little basis for fitting a parabola to such a correlation function near zero separation, which, in turn, increases the difficulty in making an estimation of the microscale.

It is also possible to make an estimation of the microscale from the one-dimensional energy spectrum defined as the Fourier transform of the spatial correlation function:

$$E_1(k) = \frac{\overline{4u_1'^2}}{U} \int_0^{\infty} dx_1 R_{11}(x_1) \cos(kx_1)$$

where $\overline{u_1'^2}$ is the variance of the velocity, U is the mean velocity, x is the separation distance and k is the wavenumber. The subscript "1" denotes that quantities are measured in the axial direction only. The microscale can be obtained by integration of the one-dimensional energy spectrum

$$\frac{1}{\lambda_f^2} = \int_0^{\infty} \frac{k^2}{2U} \Lambda_f E_1(k) dk$$

where Λ_f denotes the integral length scale in the axial direction.

From the correlation function shown in Figure 3, the 1-D energy spectrum may be arrived at by a discrete numerical integration process involving the cosine transform of the correlation function as stated mathematically above. This process may be carried out on the discrete correlation data points themselves if care is exercised. If the discrete cosine transform is applied to the discrete correlation data shown in Figure 3, an unrealistic energy spectrum as shown in Figure 4 results. The solid line in Figure 4 shows the theoretical energy spectrum corresponding to the exponential fit to the spatial correlation data.

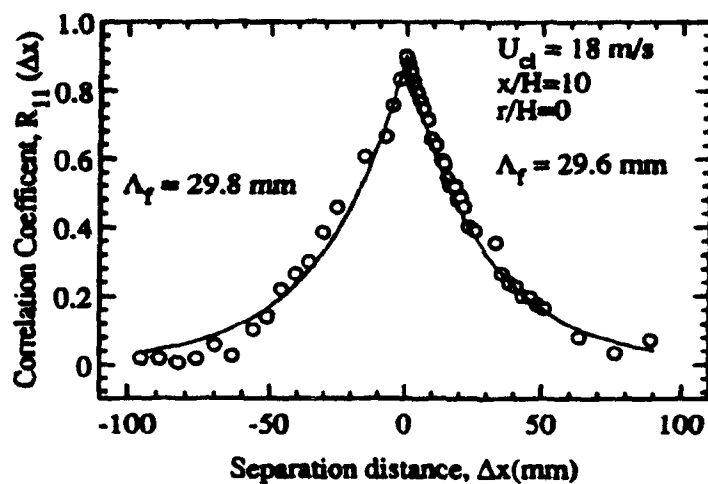


Figure 3. Longitudinal spatial correlation measurements.

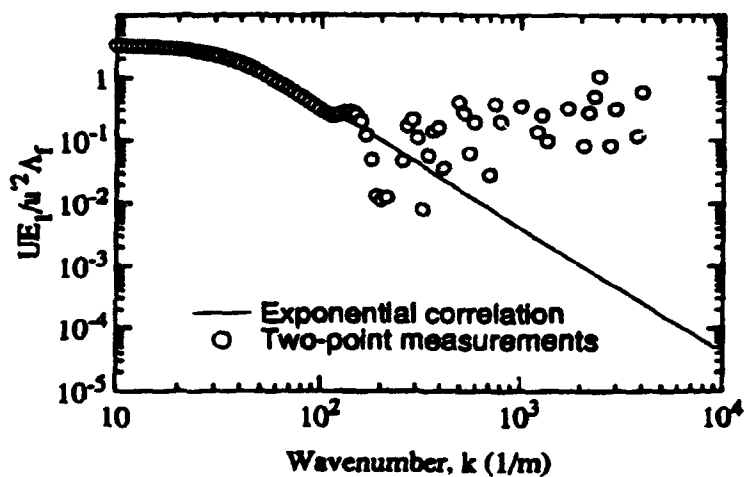


Figure 4. 1-D energy spectrum.

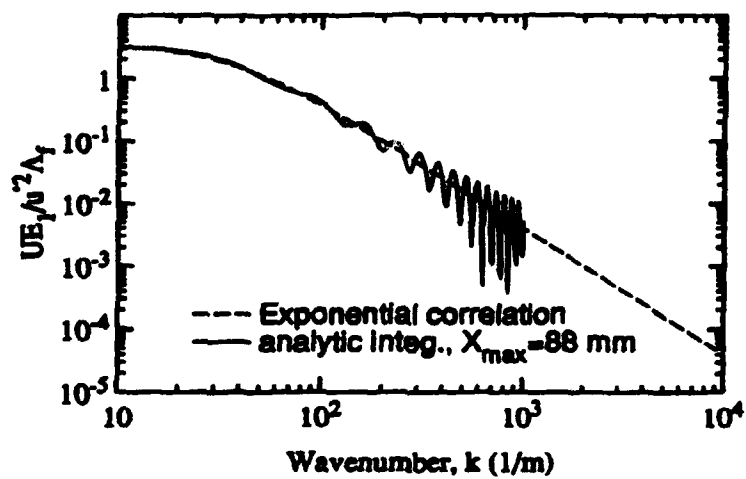


Figure 5. 1-D energy spectrum.

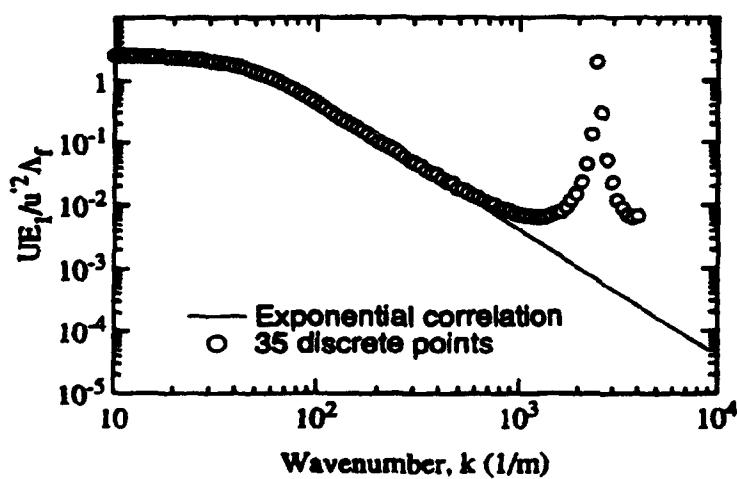


Figure 6. Lateral spatial correlation measurements.

This misrepresentation of the 1-D energy spectrum can be traced to two problems: (1) a non-zero value for the correlation coefficient at maximum separation distance (i.e., the correlation function does not approach zero closely enough) and, (2) insufficient spatial resolution of the cosine function within the transform at high wavenumbers (i.e., discrete correlation coefficients not spaced closely enough). The first problem is usually solved by applying a window function to the correlation coefficient such that the correlation coefficient is forced to zero when Δx becomes larger than a prescribed value.

To study the problem of nonzero correlation coefficient at maximum separation distance, the exponential fit to the data was integrated analytically using various maximum separation distances. Analytic integration allowed the truncation problem to be isolated from the spatial resolution inaccuracies. Figure 5 shows the effect produced by integration over a distance equivalent to the maximum separation present in the data set shown in Figure 3 (i.e., $\Delta x_{max} = 88\text{-mm}$). Since the correlation function did not reach zero at this maximum separation distance (the LDVs could not be separated further), a truncation effect in the Fourier transform produced the oscillatory behavior in the energy spectrum as seen in Figure 5. This problem can be eliminated through the use of a smoothing window which effectively drives the correlation coefficient to zero at maximum separation.

To study the resolution problem, the correlation function was modeled with an exponential fit with various discrete separation distances in the data. The Hanning window was used to eliminate the problem of truncation of the correlation curve. Figure 6 shows the discrete cosine transform results for an exponential correlation coefficient when 35 evenly spaced points, out to a separation distance of 88-mm, were used. Notice the large spike in the one-dimensional energy spectrum at high wavenumber. This corresponds to the wavenumber at which the cosine function in the Fourier transform is no longer properly resolved. Proper resolution of the cosine function requires the spacing of the correlation data, Δx , to be less than $\pi/2k$.

The above examples indicate that fairly simple operations, such as the Fourier transform of a correlation function, can give highly erratic results if used improperly. In order to properly represent the one-dimensional energy spectrum from spatial correlation functions, the correlation function must be driven to zero by a window function if it does not go to zero naturally at the maximum separation distance. Note that there will always be a practical maximum separation distance limited by the experimental equipment. Moreover, the spacing of the discrete data points must be less than $\pi/2k$, where k is the maximum wavenumber of interest.

The maximum wavenumber for which the energy spectrum may be calculated can be increased by curve fitting experimental data and interpolating intermediate values of the correlation coefficient -- while remaining conscious of the $\pi/2k$ guideline. It is well known that the exponential fit shown in Figure 3 has a Fourier cosine transform which may be integrated analytically¹³. This transform is represented as either a solid or dashed curve in Figures 4-6. It should be noted that the exponential representation of the spatial correlation function produces a 1-D energy spectrum with a slope of -2 on a log-log axis plot. Such a function has a non-finite integral. The Taylor microscale, therefore, cannot be estimated by integration of the 1-D energy spectrum which is calculated using a pure exponential representation of the spatial correlation function.

In order to more properly represent the 1-D energy spectrum a multi-piece fit to either the spatial or autocorrelation function is necessary. Since the high frequency portion of the spectrum is dominated by behavior near zero separation in the correlation functions and typical correlation functions possess a parabolic region near zero separation (not characterized by the exponential fit shown in Figure 3), an attempt was made to mate a parabolic curve near zero separation to an exponential

curve (which represents the measurements well at large separation distances). Some results appear in Figure 7, which show the effects on the 1-D energy spectrum of mating parabolic regions representing differing microscales to the exponential curve. As expected, the parabolic region is responsible for driving the energy spectrum to zero at high frequency and that the larger the microscale, the lower the wavenumber where this happens. This makes sense from the standpoint that a larger microscale implies more correlation which, in turn, implies less turbulence intensity (in the limit laminar flows are perfectly correlated) and hence less energy. Interestingly, the steep descent of the 1-D energy spectrum at high frequency mimics the (-7) slope predicted by Kolmogoroff for homogeneous turbulence.

These energy spectra, which result when representing the spatial correlation coefficient with two-piece fits, may indeed be integrated using Eq. (5). The microscales returned by the integration process, however, are 30 to 40 percent higher than the original values assumed to determine the exact shape of the parabolic fit. Obviously, an actual correlation function cannot usually be represented exactly by mating a parabolic and an exponential curve; so one would not expect such a fit to return the exact value of the microscale when determined by numerical integration of the 1-D energy spectrum. Microscales calculated by numerical integration of the 1-D energy spectrum would be reasonably close, however, to the actual values and would provide valuable insight into turbulent structure.

Figure 9 is a similar plot of the 1-D energy spectrum. In this case, the 1-D energy spectrum using the parabolic fit near zero-separation is compared to that using a third order polynomial fit. In both cases, these curves are mated to the same exponential curve. Note that the third order fit drives the 1-D energy spectrum to zero at a lower wavenumber when compared to a parabolic fit. Both fits were derived from an assumed microscale of 10-mm. Numerical integration of the 1-D energy spectrum (using Eq. 5) returned a microscale value of 12.6-mm for the third order fit as opposed to 14.2-mm for the parabolic fit. Once again this trend makes sense as the third order fit rolls off more slowly than a parabolic fit giving higher correlation values near zero separation and thereby less turbulent intensity and less energy. Evidently a fourth or fifth order fit would return through numerical integration of the 1-D energy spectrum almost the exact value of the microscale that had been used to create the fit. It is recommended then that when using LDV, microscales be determined by the following procedure: (1) measure the autocorrelation function, (2) fit this function with a higher order polynomial near zero-separation and an exponential function at larger separation distances, (3) calculate the 1-D energy spectrum from the curve fit to the correlation function, and (4) numerically integrate the resulting 1-D energy spectrum to determine the microscale. When making the curve fit to the experimental data and interpolating between data points, spacing requirements and window function requirements should be observed as mentioned above.

One last point to mention concerning the curve fitting of correlation functions is that when merging two different curve fits, continuity of slope is of utmost importance. Any discontinuity in slope will produce ringing at high wavenumber in the calculated 1-D energy spectrum. This is because the Fourier cosine transform of the correlation function is the integral of the correlation function multiplied by a cosine function which in effect is a weakly damped cosine function. As wavenumber increases such a function has an integral which rapidly approaches zero, which is profoundly obvious when the energy spectrum is plotted on normal (not log) axes. A small discontinuity in the slope of the correlation function thus changes the way the integral approaches zero. But for each new wavenumber this happens in a different way since the discontinuity occurs each time at a different location on the damped cosine function. Ringing in the 1-D energy spectrum is a direct and inevitable consequence of slope discontinuity.

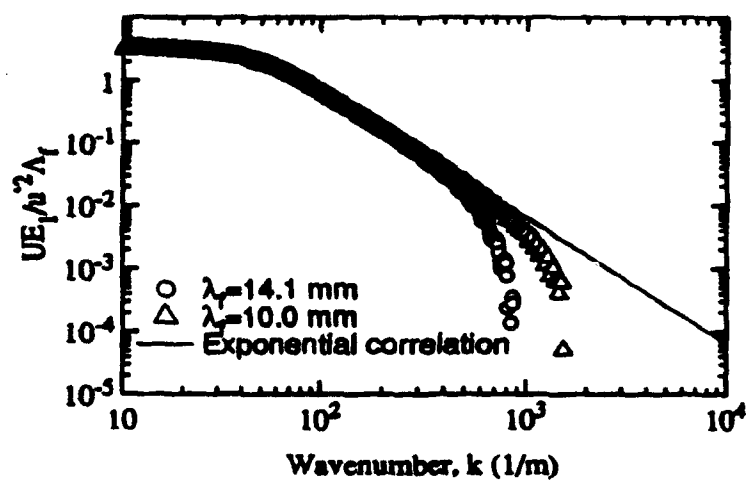


Figure 7. 1-D energy spectrum(fits to correlation function).

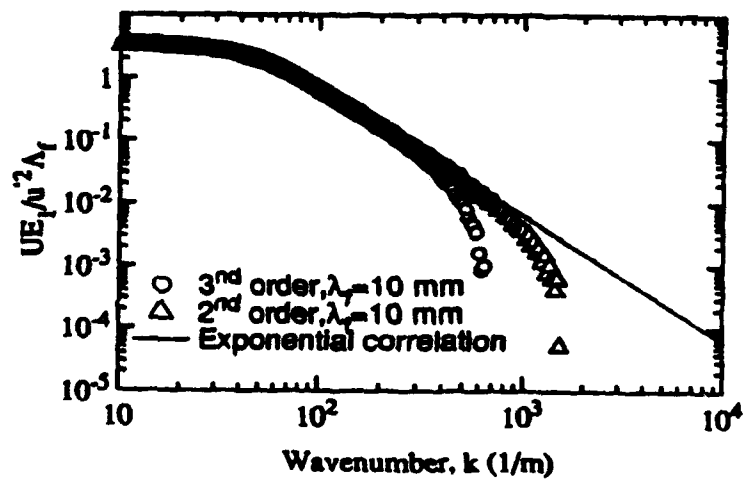


Figure 8. 1-D energy spectrum(fits to correlation function).

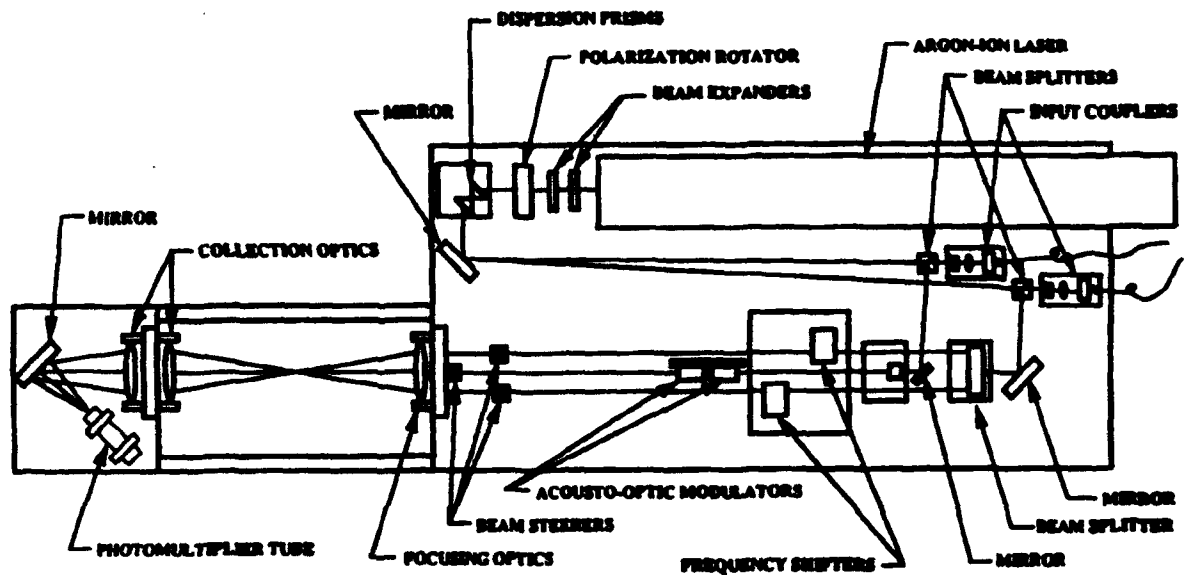


Figure 9. Two-color, two-component LDV system.

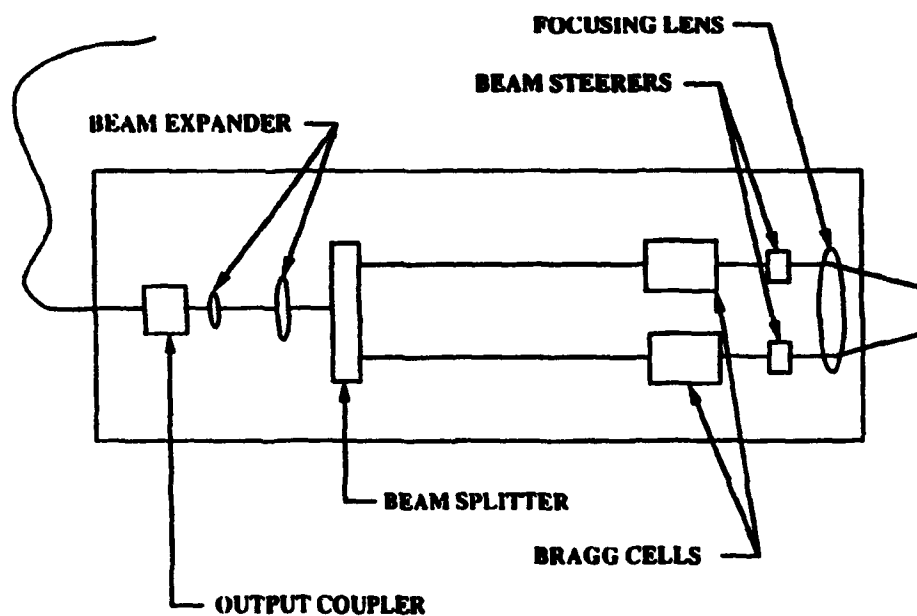


Figure 10. Single-component fiber optically coupled LDV system.

DEVELOPMENT OF DUAL LDV AT NCSU

Optical components including, fiber optic input and output couplers, polarization preserving optical fiber, bandpass laser line filters, and an acoustic optic modulator (Bragg cell) were purchased to modify an existing LDV system so that two-point velocity correlation measurements can be made at NCSU. A schematic diagram of the completed dual LDV system is shown in Figures 9 and 10. The LDV system shown in Figure 9 is a two-color, two-component. It has been modified, by adding beam splitting prisms and fiber optic input couplers, to provide laser light for the second LDV system which is required to make two-point velocity measurements. This second system is a single-color single-component LDV system. Note that two fiber optic input couplers have been added to the two-color system. This allows the flexibility to choose either color (blue or green) for the single component system. Both systems are mounted on three-axis tables so that the probe volumes can be placed at user selected locations. Presently, both systems operate in forward scatter collection mode; however, modifications are being made to the systems so that either forward scatter or 90 degree collection angle can be used. In addition to the optical components, the LDV data acquisition interface has been upgraded so that up to three channels of velocity data can be acquired simultaneously. It is envisioned that this apparatus will be used to make many state-of-the-art turbulence measurements in the future. Measurements in combustion environments are of particular interest.

SUMMARY

It has been shown that spiking in autocorrelation measurements obtained using LDV is a prevalent phenomena that may be caused by biases induced by continuous sampling. This spiking should be distinguished from that attributed to inclusion of zero-lag terms in the slotting technique. The spiking caused by a continuous sampling bias may be overcome by filtering the data to remove the multiple sampled velocity realizations. Spatial correlation measurements have been shown on the other hand to suffer from probe volume integration effects which cannot be remedied once the measurements have been made. These probe volume integration effects may obscure the classic parabolic region near zero-separation in spatial correlation functions, which degrade micro-scale estimations.

Calculation of 1-D energy spectra from correlation functions for purposes of calculating the Taylor microscale is a viable alternative to fitting a parabola to either spatial or autocorrelation functions. It has been shown, however, that even a fairly simple operation such as the Fourier transform of a correlation function can give highly erratic results if used improperly. In order to properly represent energy spectra from correlation measurements or curve fits to those measurements, the correlation function must be driven to zero by a window function and the spacing of the discrete data points must be less than $\pi/2k$, where k is the maximum wavenumber of interest. For piece-wise curve fits, continuity of slope must be maintained when merging the different pieces of a given curve fit. Lastly, an in-house dual LDV system capable of making general two-point velocity measurements has been fabricated and will be used to further our understanding of turbulence and the combustion process.

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