Benchmark Session on the Estimation of Power Spectra from LDA Signals: An Overview for Participants

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1 List of Nomenclature

English Symbols

$C(\tau)$	autocovariance function (ACF) , $C_{uu}(\tau) = \overline{u(t)u(t+\tau)} = \int_0^\infty G_{uu}(f)\cos(2\pi f\tau)df$
f	frequency in Hz
f_p	frequency at which a peak occurs in PSD
$G(f)$	one-sided autospectral density (ASDF), $G_{uu}(f) = \frac{2}{T}\left\lvert \int_{-\infty}^{\infty} u(t)\exp(i2\pi ft)dt \right\rvert^2$ or $G_{uu}(f) = 4\int_0^\infty C_{uu}(\tau)\cos(2\pi f\tau)d\tau$
$n(t)$	zero-mean, random noise with Gaussian amplitude distribution
N	number of samples
$\dot{N}$	data validation rate, DVR
$\dot{N}_D$	mean data density, $\dot{N}T_u$ or alternatively T_u/τ_m
T_u	integral time scale, $\int_0^\infty \rho_{uu}(\tau)d\tau = \frac{1}{\overline{u^2}}\int_0^\infty C_{uu}(\tau)d\tau = \frac{G_{uu}(0)}{4\overline{u^2}}$
$u(t)$	fluctuating velocity, $u(t) = U(t) - \overline{U}$

Greek Symbols

λ	Taylor time scale, $\frac{1}{\lambda_u^2} = \frac{2\pi^2}{\overline{u'^2}}\int_0^\infty f^2 G_{uu}(f)df$
$\rho(\tau)$	autocorrelation coefficient function (ACCF), $\rho_{uu}(\tau) = \frac{C_{uu}(\tau)}{C_{uu}(0)} = \frac{\overline{u(t)u(t+\tau)}}{\overline{u^2}}$
τ	lag-time
τ_m	mean time between validated bursts (mean interarrival time), 1/DVR

Superscripts

–	denotes time average

Acronyms

ASDF	autospectral density function(one-sided)
ACF	autocovariance function
ACCF	autocorrelation coefficient function
DVR	data validation rate
LDA	laser Doppler anemometer, laser Doppler anemometry
SNR	signal to noise ratio, defined as $\overline{u^2}/\overline{n^2}$

2 Rules of the Game

2.1 Overview

Participants will be provided with a variety of simulated and real LDA data sets (described in §3). The goal for the participants will be to estimate, as accurately as possible, the *one-sided autospectral density function* (ASDF) defined as

$$G_{uu}(f) = 4\int_0^\infty C_{uu}(\tau)\cos(2\pi f\tau)d\tau \qquad \text{or} \qquad G_{uu}(f) = \frac{2}{T}\left|\int_{-\infty}^{\infty} u(t)\exp(i2\pi ft)dt\right|^2 \tag{1}$$

using any estimator available in the literature or any which they have developed themselves. Window functions for the improvement of ASDF estimates are encouraged, but each participant must mathematically specify the type of window used in the description of his estimator.

In the case of the simulated data, each data set has been developed to provide a particular challenge to the participants' ASDF estimators, e.g. low data density, presence of band-limited Gaussian white noise, or presence of velocity bias. For each simulated data set, the theoretical ASDF is known exactly to the organizers, but not to the participants (although quite a good general description is given in §3). The participants are simply asked to do the best they can and to return their results to the organizers.

In the case of the LDA data, these are also being developed with certain challenges in mind. Hot-wire data collected under exactly the same conditions will serve as reference for the LDA data, but, like the theoretical ASDFs for the simulated data, will not be made available to the participants. All results returned by the participants will be analyzed by the organizers according to various figures of merit (described in §4).

2.2 General Comments on Simulated Data

Simulated data are described by number of samples, *N*, and data density, $\dot{N}_D$. They are divided into *groups* (of which there are 3) and *cases* (34 in all). For each case, there are 10 data sets. The reason for having 10 data sets for each case is to try to get a handle on the statistical variance of each participant's ASDF estimator. This is explained further in §2.5

These data (with random arrival times) have been interpolated from evenly-spaced, discrete time series with extremely high sample rate. The Nyquist frequency for these primary series determines the maximum frequency any participant could hope to resolve with his spectrum estimator. Round-off errors in the double precision velocity estimates, on the other hand, ultimately limit the number of decades in amplitude which can be calculated. This limit may also be influenced by *N* and $\dot{N}_D$, however. Thus these limits will be checked directly from the primary time series by the organizers to make sure that the limits will not interfere with the evaluation of the performance of the various ASDF estimators.

2.3 General Comments on Real Data

Real LDA data sets will be described in terms of *N*, $\dot{N}_D$, and the flow in which the data sets were collected. They will be collected in conjunction with hot-wire data acquired in the same flow under the same conditions; however, the hot-wire data will not be provided to the participants.

2.4 Distribution of Data

The simulated data sets are provided by means of a "data generation" program available via Internet at http://www-nt.e-technik.uni-rostock.de/~nobach/bm.exe. This method of distributing data seems most practical as each data set is roughly 12 MB. Once the program has been downloaded, the user simply types the program name followed by the desired data set name given in §3. For example, the command **bm s2-14-1** produces the first of 10 data sets belonging to Case s2-14.

Real data sets will also be distributed via Internet. Participants will be notified shortly as to their availability.

2.5 Results from the Participants

A prerequisite for participation of a participant is a summary of the method used to obtain the ASDF estimates – including mathematical specification of any window function used to improve results. This summary should be detailed enough for someone to repeat the work of the participant if so desired. (Allowances will be made for the withholding of company proprietary material if agreed to beforehand by the organizers.)

For each case, participants will be provided with 10 data sets. The one-sided ASDF estimates (Eq. 4) for EACH DATA SET and the average of these ten should be returned to the organizers INCLUDING NEGATIVE VALUES. The ten power spectra for each case will be used by the organizers to calculate the statistical variance of the spectral estimators. The average of the ten ASDF estimates for each case will be used to determine the bias error for each case. It is hoped that in this way, the bias and variance errors can be separated from one another and evaluated individually. Although we do not require that each participant attempt every case, we do expect that for any case attempted, an ASDF for all 10 data sets will be estimated such that the bias and variance errors can be calculated.

Additionally, it is asked that for each case, the participants provide the *autocorrelation coefficient function* (ACCF) for the averaged ASDF estimates. These can be obtained by Fourier transform of the ASDF estimates if they are not available as an intermediate step in the ASDF estimation (see Eq. (2) below).

$$\rho_{uu}(\tau) = \frac{1}{\overline{u^2}}\int_0^\infty G_{uu}(f)\cos(2\pi f\tau)\,df \qquad \text{or}$$

$$\rho_{uu}(\tau) = \frac{C_{uu}(\tau)}{C_{uu}(0)} = \frac{\overline{u(t)u(t+\tau)}}{\overline{u^2}} \qquad (2)$$

All results should be returned via e-mail to the following address: **benedict@lstm.uni-erlangen.de**

2.6 Results Returned to the Participants

All analysis performed by the organizers will be sent to each participant at least a month before the conference in order that each participant can compare his method to those of the other participants. Each participant will then be given a brief time period at the conference to give his assessment of the overall results. We assume that the practitioner/inventor of each method will be best able to highlight the deficiencies/merits of his method and, furthermore, that his assessment will be relatively free of bias towards his own method due to the comparative analysis.

3 Description of Data Sets

3.1 Simulated Data

General Characteristics: $\overline{U} = 0$, $\overline{u^2} = 1\,\mathrm{m}^2/\mathrm{s}^2$, $N = 250000$

<u>Group S-1</u> (one case)
Band-limited random noise with Gaussian amplitude distribution (and very steep roll-off at very high frequency)
General Purpose: Flat spectrum (up to a high cut-off frequency) will make filtering effects immediately obvious

<u>Group S-2</u> (24 cases in all)
Variations on Pao's Spectrum, a realistic simulation of turbulence with no peak at a particular frequency
General Purpose: Test estimators' ability to retrieve a realistic turbulence spectrum in the presence of noise and velocity bias at high and low data densities

<u>Cases S-2-1 to S-2-6</u>
T_{u1}, T_{u2}, T_{u3} at $\dot{N}_D = 0.5$ and $\dot{N}_D = 10.0$, no noise or velocity bias
Purpose: 3 different integral time scales at 2 different data densities. These will used as a standard for comparison with other cases including the effects of noise and velocity bias.

<u>Cases S-2-7 to S-2-12</u>
with Gaussian white noise
Purpose: By maintaining a constant $\overline{u^2}$ but changing the integral scale, the signal to noise ratio (SNR) is varied and therefore tests an estimator's ability to resolve multiple decades in the presence of noise

<u>Cases S-2-13 to S-2-18</u>
with one-dimensional velocity bias (i.e. correlation between instantaneous velocity and particle rate)
Purpose: To test an estimator's ability to counter velocity bias effects at different data densities

<u>Cases S-2-19 to S-2-24</u>
with noise and velocity bias
Purpose: To test an estimator's ability to counter the combined effects of noise and velocity bias at different data densities

<u>Group S-3</u> (9 cases in all)
Simulation of turbulence with a power peak at frequency f_p
General Purpose: To test an estimator's ability to resolve a power peak in a realistic turbulence spectrum at different data rates (relative to f_p) and at different noise levels (relative to the amplitude at f_p)

<u>Cases S-3-1 to S-3-3</u>
$\dot{N} > 2\pi f_p$, $\dot{N} \approx f_p$, $\dot{N} \approx f_p/5$ without noise

<u>Cases S-3-1 to S-3-3</u>
$\dot{N} > 2\pi f_p$, $\dot{N} \approx f_p$, $\dot{N} \approx f_p/5$ with noise level below power at peak

<u>Cases S-3-1 to S-3-3</u>
$\dot{N} > 2\pi f_p$, $\dot{N} \approx f_p$, $\dot{N} \approx f_p/5$ with noise level above power at peak

3.2 Real LDA Data (yet to be determined)

General Characteristics: Data density will be varied through particle concentration. Noise level will be varied through optical alignment, amplification factors, and number of signal periods (counter processor).

4 Figures of Merit

The following characteristics will be used to evaluate the performance of each estimator:

1. Plot of estimator variance versus frequency. (Estimator variance will be computed as described under §2.5.)
2. Plot of estimator bias error versus frequency. (Bias error determined as described in §2.5.)
3. Filtering behavior of the estimator. In so far as it can be shown that, above a certain frequency, an estimator creates a filtering effect with slope not related to the energy content of the measured (or simulated) turbulence , the results above this frequency will simply be declared invalid, and no error analysis will be attempted.
4. Number of decades in amplitude for which the bias and variance errors remain below a standard value.
5. Maximum frequency for which the bias and variance errors remain below a standard value, normalized by the mean data rate.
6. For Group S-2, the error in the integral time scale, T_u, and Taylor time scale, λ_u, as determined from the ASDF estimates according the following formulas:

$$T_u = \frac{G_{uu}(0)}{4\overline{u^2}} \qquad\qquad \frac{1}{\lambda_u^2} = \frac{2\pi^2}{\overline{u^2}} \int_0^{\infty} f^2 G_{uu}(f)\, df$$

No evaluation will be made based on computing time; however, each participant will be asked to give a ballpark estimate of the amount of computing time required on a PC for one of the data sets (yet to be determined).

5 Time-Plan

	S	O	N	D	J	F	M	A	M	J	J
Invitations and outline of program sent to participants	■										
Simulated and real LDA data sets made available	■	■	■								
Results of participants returned to organizers							■				
Data analysis returned to participants									■		
Lisbon conference											■

.6 Outline of Special Session

I Introductory paper delivered by the organizers addressing the following items:

1. Scope of the session
2. General approaches to estimating power spectra from LDA data
3. General problems in estimating power spectra from LDA data
4. Description of simulations
   a) Types
   b) Reason for choosing
5. Description of experiments
   a) Flows
      i) Integral time scales
   b) LDA system
      i) Sampling parameters
   c) Hot-wire system
6. Basis for comparison of results, i.e. explanation of figures of merit

II Second paper from the organizers presenting results of computations by participants and comparison of these results

III Short responses from each participant who is present

IV Open panel discussion

7 List of Potential Participants

Recipients are encouraged to pass this information on to other colleagues who may wish to take part.

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