The spatial resolution of velocity and velocity gradient turbulence statistics measured with multi-sensor hot-wire probes

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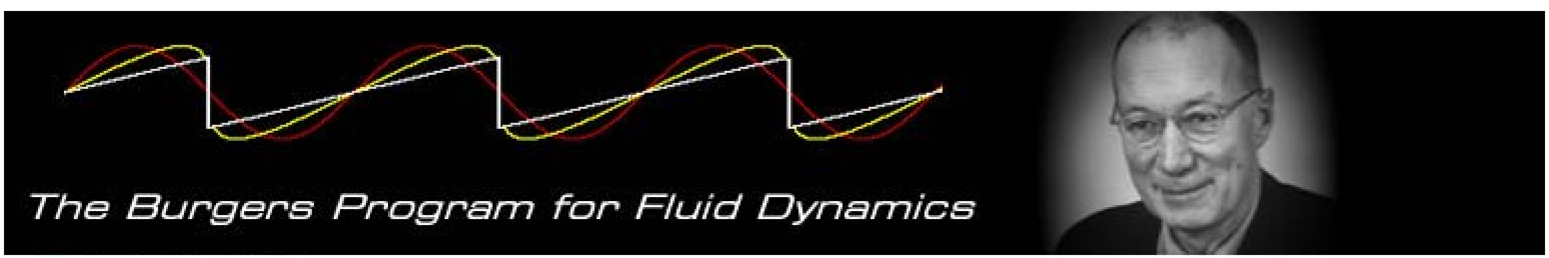

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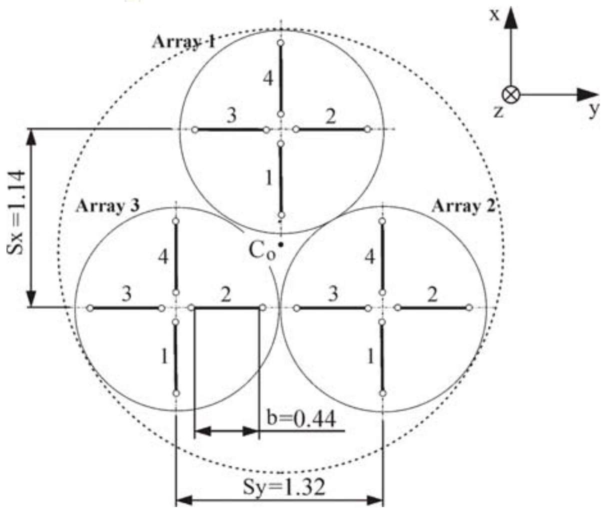
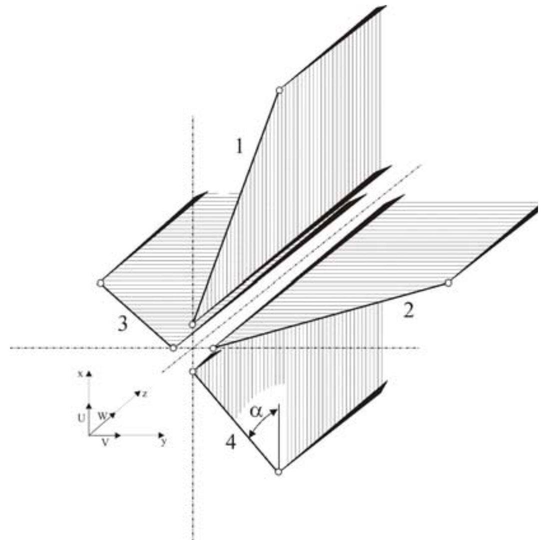
Overview

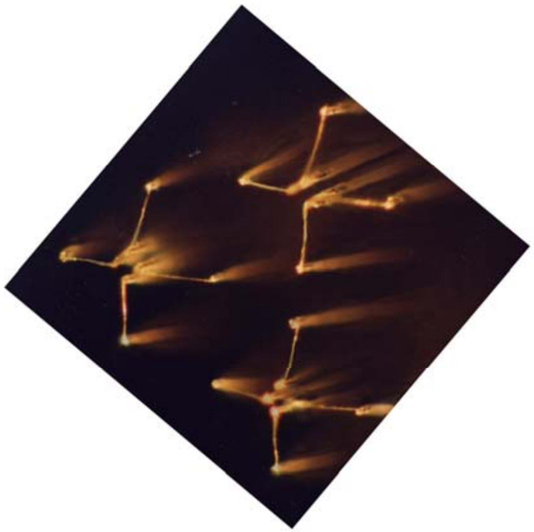
- Background
- Operational principles of 12-sensor hot-wire probes
- **Resolution** of a 12-sensor Hot-wire probe
- Highly resolved **DNS** of a **Narrow Channel Turbulent Flow** at $R_\tau = 200$
- Resolution effects on **velocity** component statistics
- Resolution effects on **vorticity** component statistics
- Summary and Conclusions

12-sensor Hot-wire Probe



Dimensions in mm





12- sensor probe used to measure velocity and velocity gradient properties of turbulent flows

P. Vukoslavčević, J.M. Wallace & J.-L. Balint (1991) J. Fluid Mech. 228
A. Tsinober, E. Kit & T. Dracos (1992) J. Fluid Mech. 242
B. Marasli, P. Nguyen , J.M. Wallace (1993) Exp. Fluids. 15
P. Vukoslavčević & J.M. Wallace (1996) Meas. Sci. Technol. 7
A. Honkan & Y. Andreopoulos (1997) J. Fluid Mech. 350
L. Ong & J.M. Wallace (1998) J. Fluid Mech. 367
R. Loucks (1998) Ph.D. Dissertation, University of Maryland

Operational principles of hot-wire probe

The effective cooling velocity is usually defined by Jorgensen's expression

$$U_e^2 = U_n^2 + k^2 U_t^2 + h^2 U_b^2 .$$

Using this expression, the effective velocities cooling each sensor can be expressed as a function of the three velocity components at the sensor center,

$$U_{eij}^2 = U_{ij}^2 + a_{ij1} V_{ij}^2 + a_{ij2} W_{ij}^2 + a_{ij3} V_{ij} U_{ij} + a_{ij4} W_{ij} U_{ij} + a_{ij5} W_{ij} V_{ij} .$$

The necessary assumption that the velocity variation is linear over probe spacing area leads to a set of 12 equations of the following form,

$$U_{eij}^2 = F_{ij}\left\{ \boxed{a_{ijk}}, U_0, V_0, W_0, \partial(U,V,W)/\partial y, \partial(U,V,W)/\partial z \right\},$$

In terms of the velocity components at the probe centers U_0, V_0, W_0 and the six velocity gradients as unknowns.

Ideal probe: k=0, h=1, α=45 deg.

$$\boxed{a_{1jk}} = \begin{vmatrix} 1 & 2 & -2 & 0 & 0 \\ 2 & 1 & 0 & -2 & 0 \\ 1 & 2 & 2 & 0 & 0 \\ 2 & 1 & 0 & 2 & 0 \end{vmatrix}$$

Real probe: calibration proc.

$$\boxed{a_{1jk}} = \begin{vmatrix} 1.0 & 2.8 & -1.70 & -0.15 & -0.15 \\ 2.8 & 1.0 & 0.15 & -1.70 & -0.15 \\ 1.0 & 2.8 & 1.70 & -0.15 & -0.15 \\ 2.8 & 1.0 & 0.15 & 1.70 & -0.15 \end{vmatrix}$$

Physical experiment

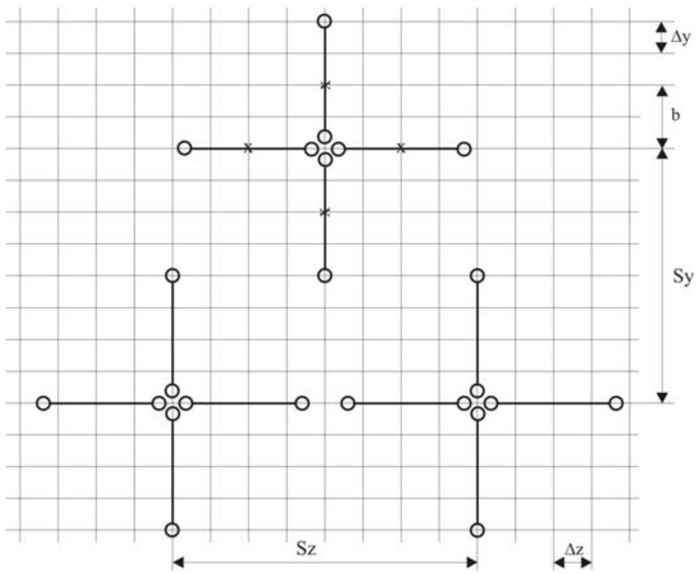
The effective cooling velocity for each sensor, $U_{ij,}$ can be found from King's Law or from a polynomial fit

$$E^2 = A + BU_e^n, \qquad \sum_{p=1}^{5} b_p E^{p-1} = U_e^2.$$

Virtual experiment

Database: DNS of a minimal channel flow at $Re_\tau = 200$

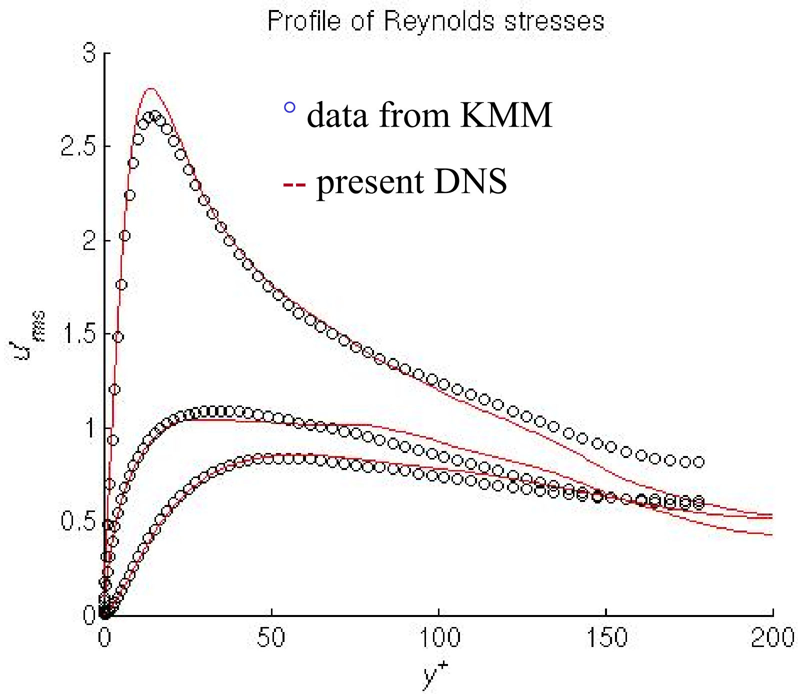
Grid resolution: $\Delta x^+ = \Delta y^+ = \Delta z^+ = 1$ $(400 \times 192 \times 400)$

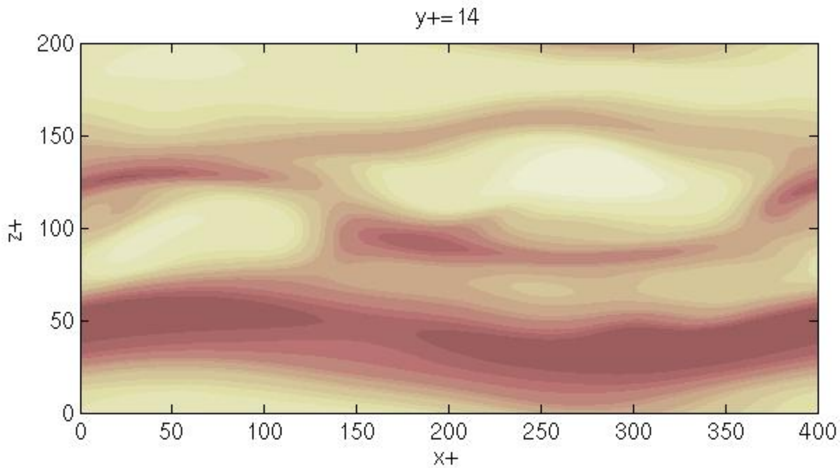


Virtual probe with S_y = 8 Δy over the numerical grid where Δy is 1 viscous length

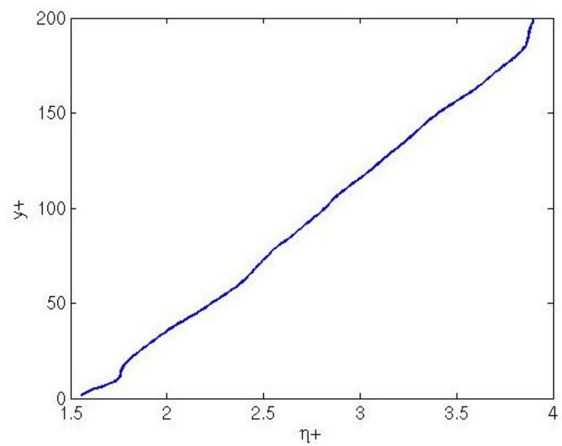
$$S_y^+ = 2,\ 4,\ 8,\ 12$$

DNS data base



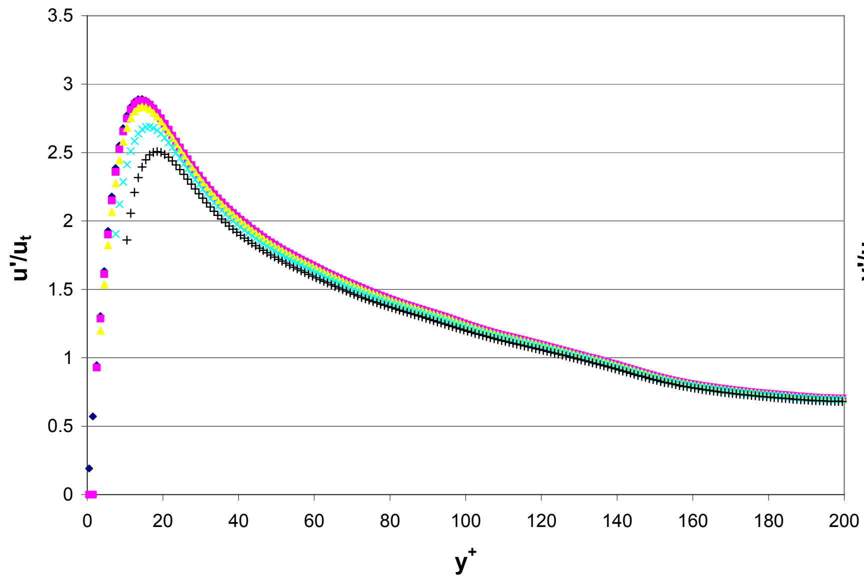


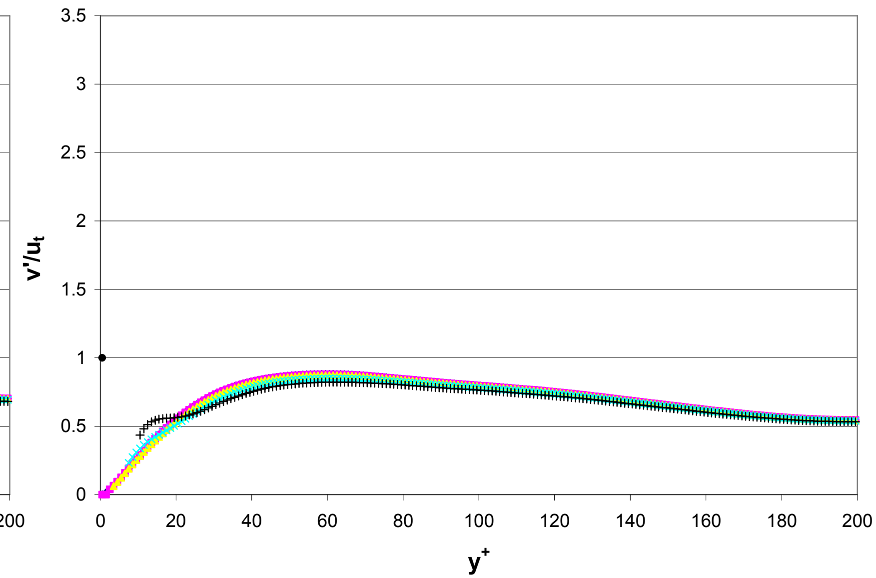
High and low speed streaks at an instant in time, in a plane parallel to the wall at y+=14

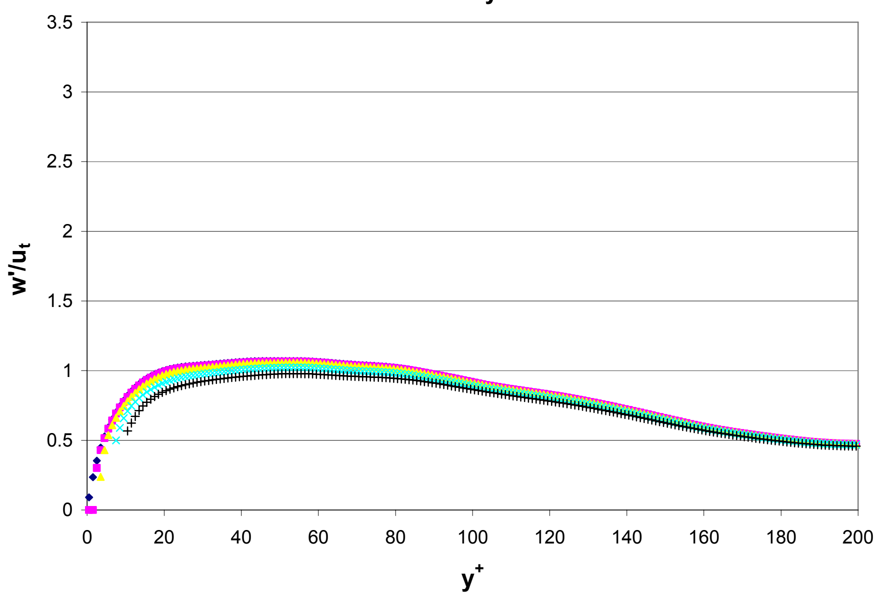


Ratio of Kolmogorov to viscous length scale

Velocity Statistics - RMS

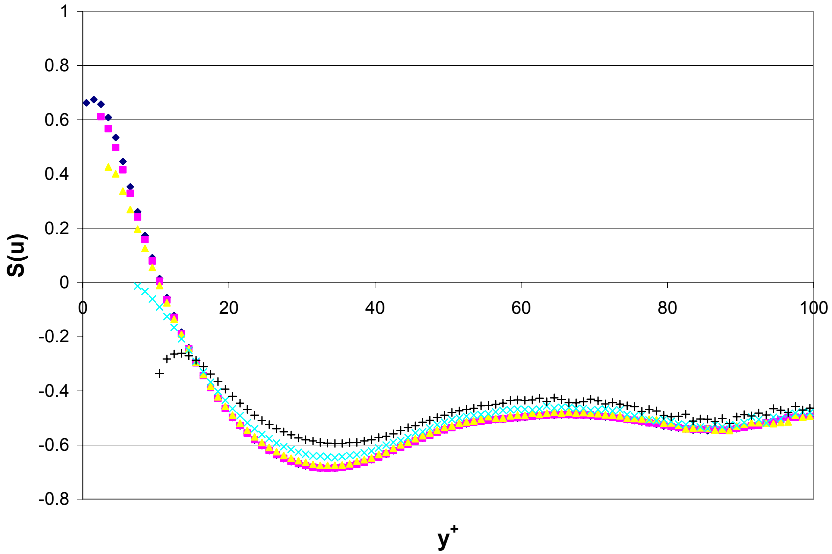


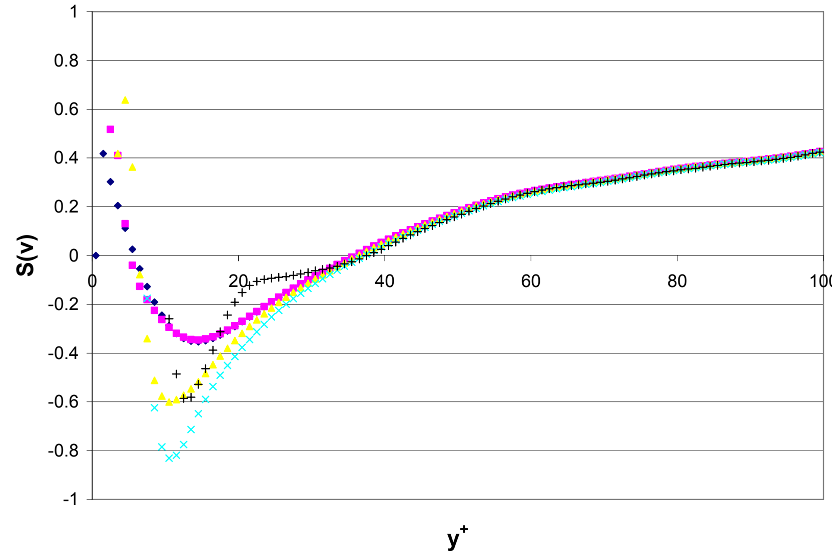


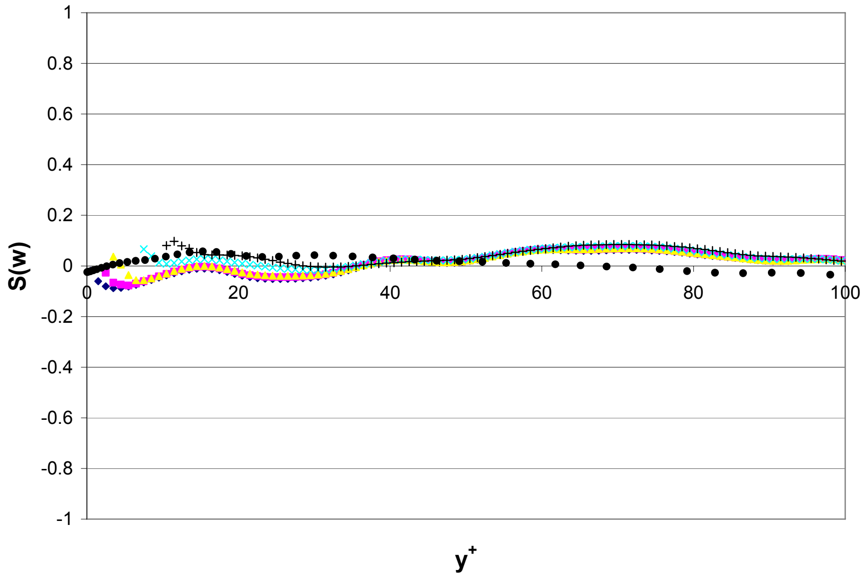


♦ DNS					
		y+ = 15		= 150	
■ S+=2	→	1.2 η	→	0.6 η	
▲ S+=4	→	2.4 η	→	1.2 η	
x S+=8	→	4.8 η	→	2.4 η	
+ S+=12	→	7.2 η	→	3.6 η	

Velocity Skewness







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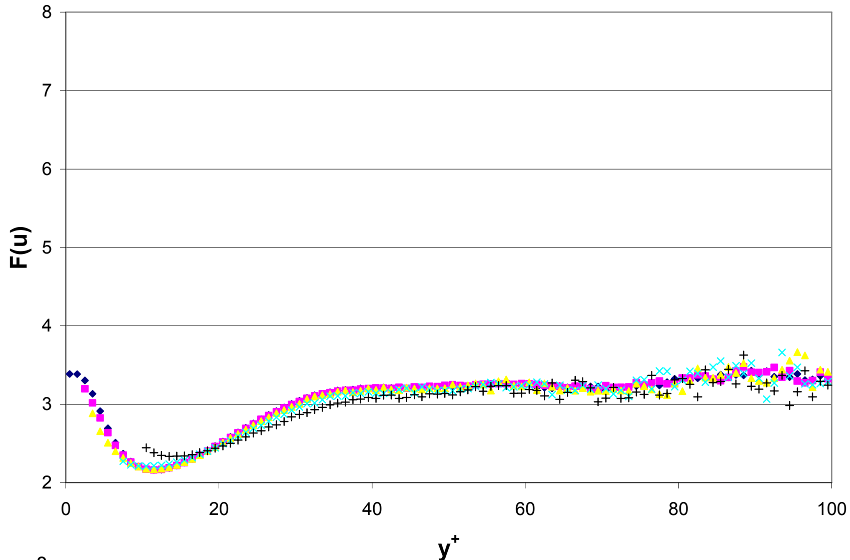
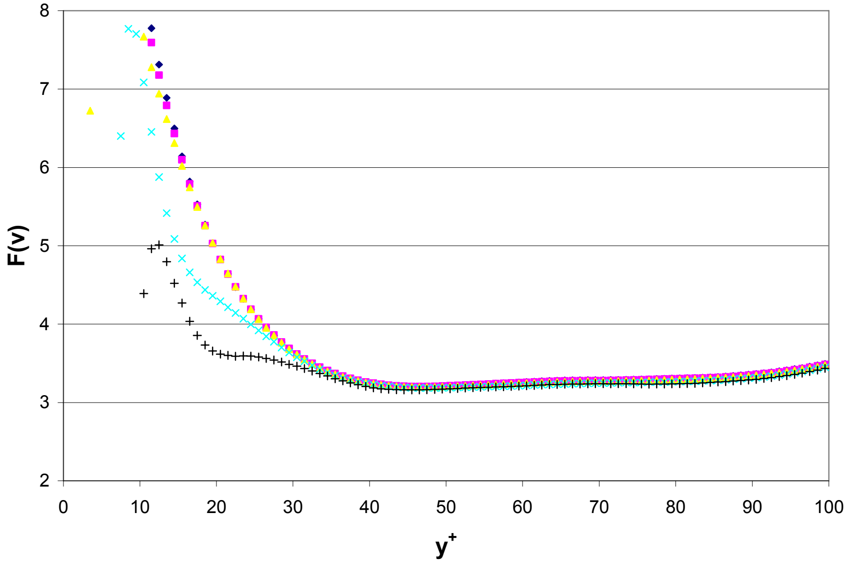
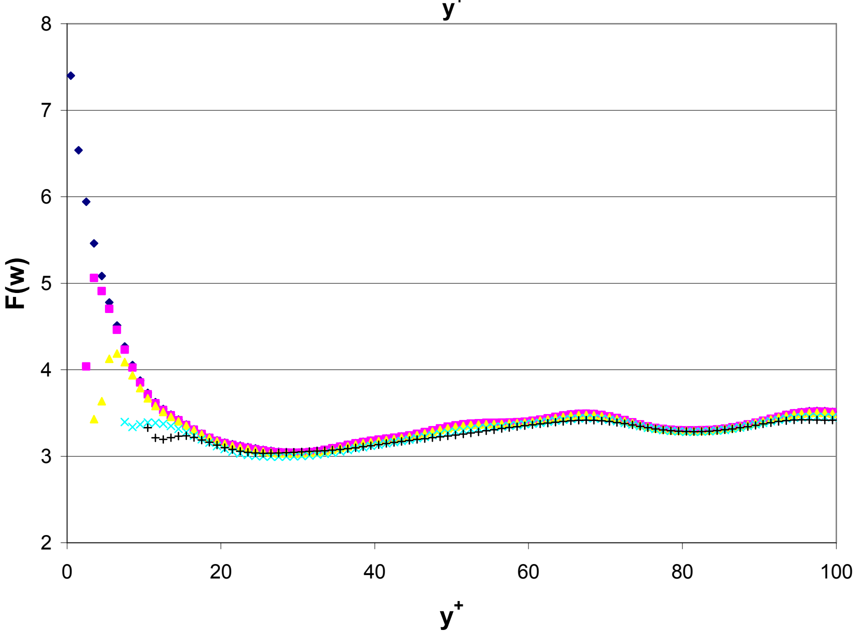
Velocity Flatness







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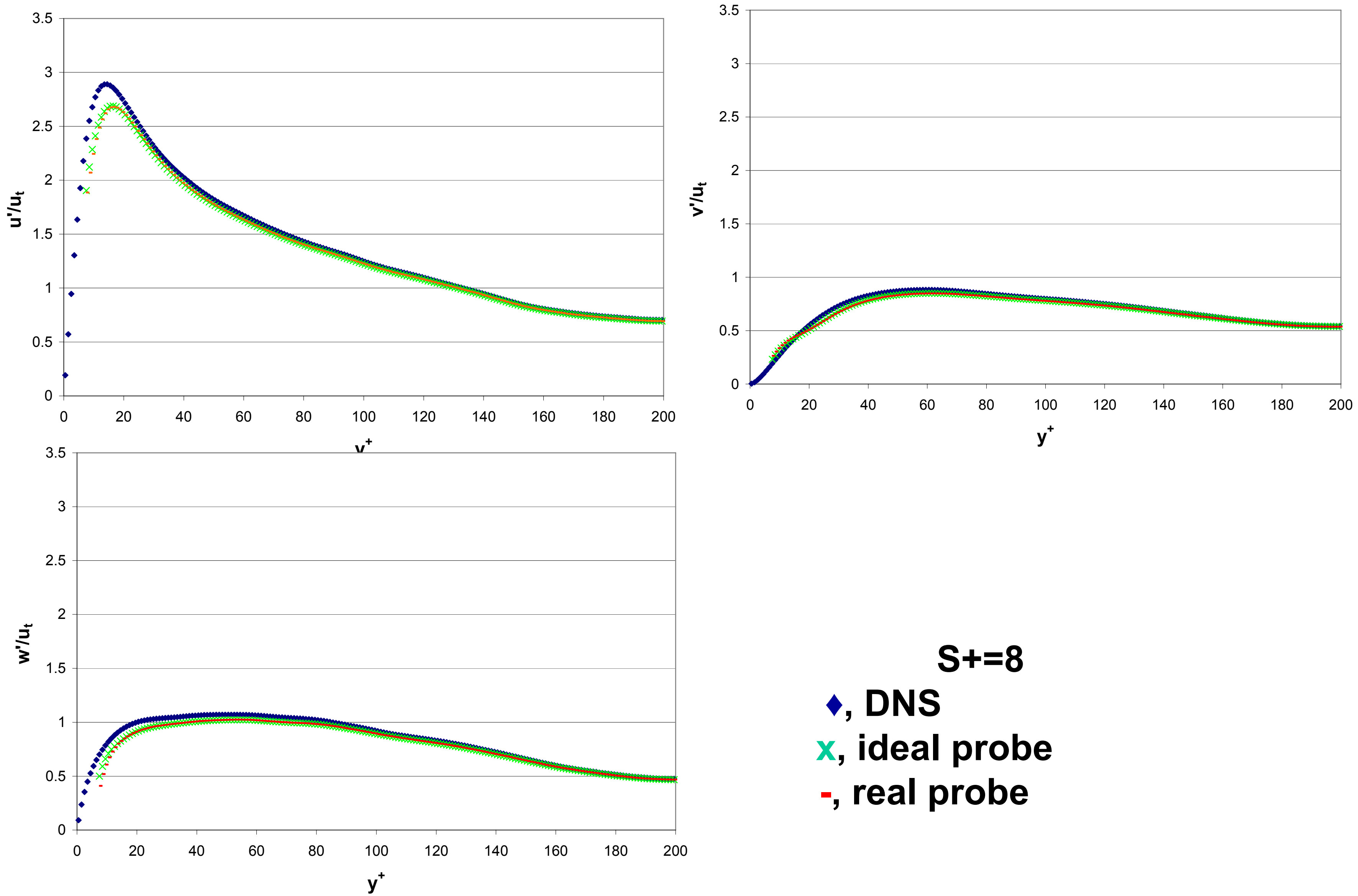
Comparison of ideal and real probe response



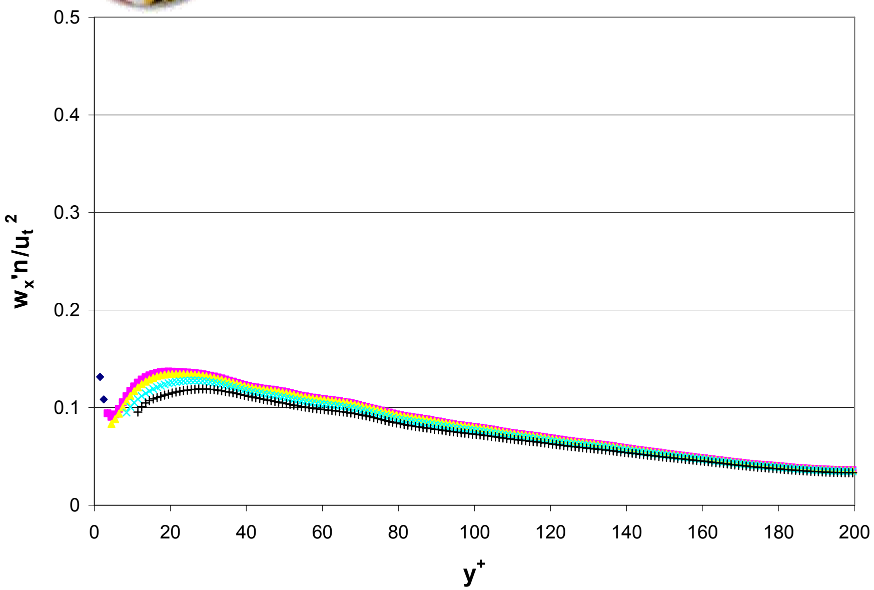
S+=8

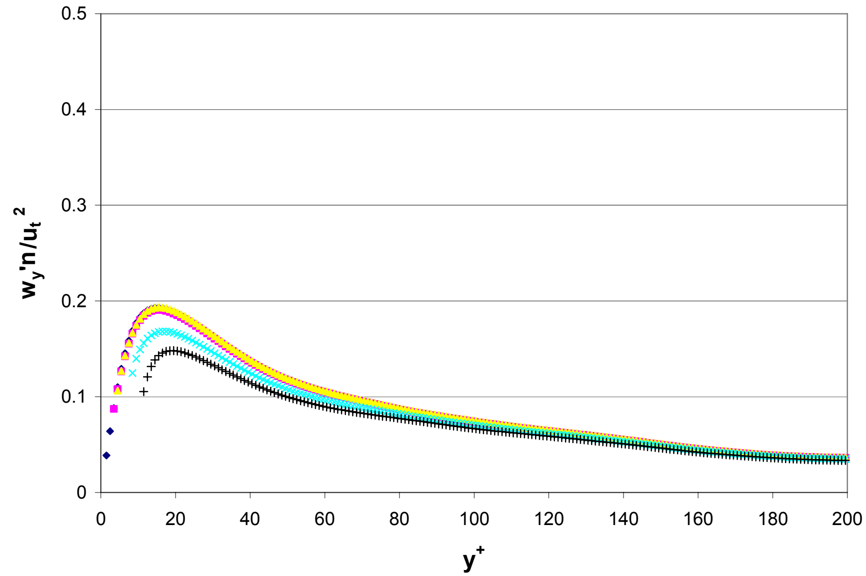
♦, DNS

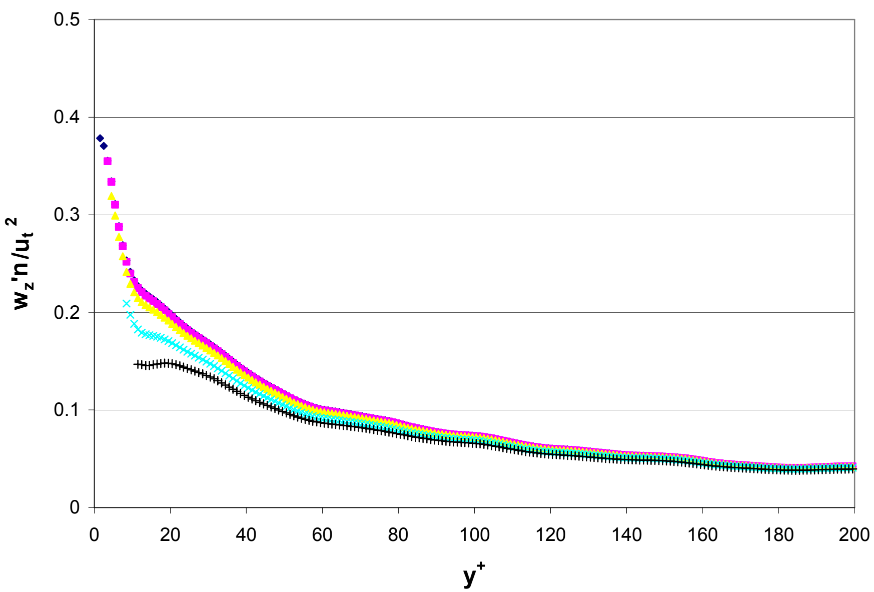
x, ideal probe

-, real probe

Vorticity Statistics - RMS







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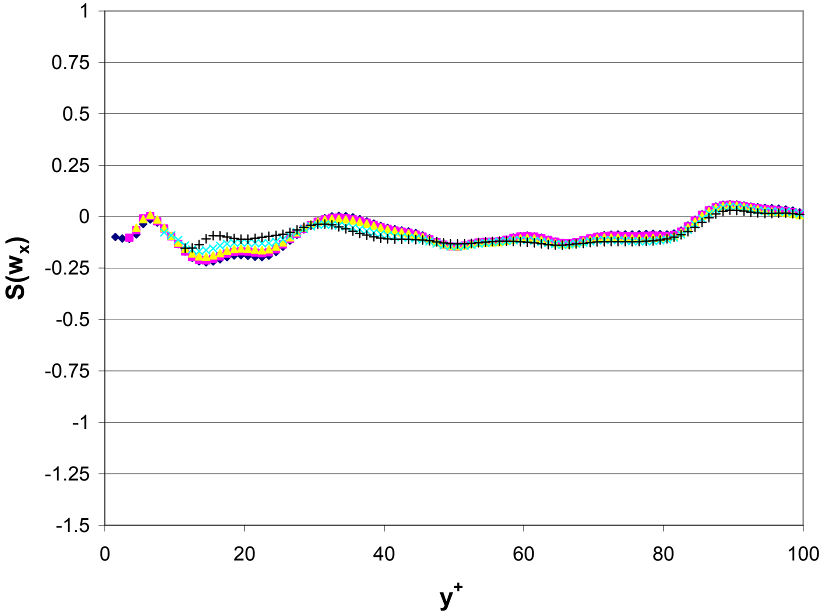
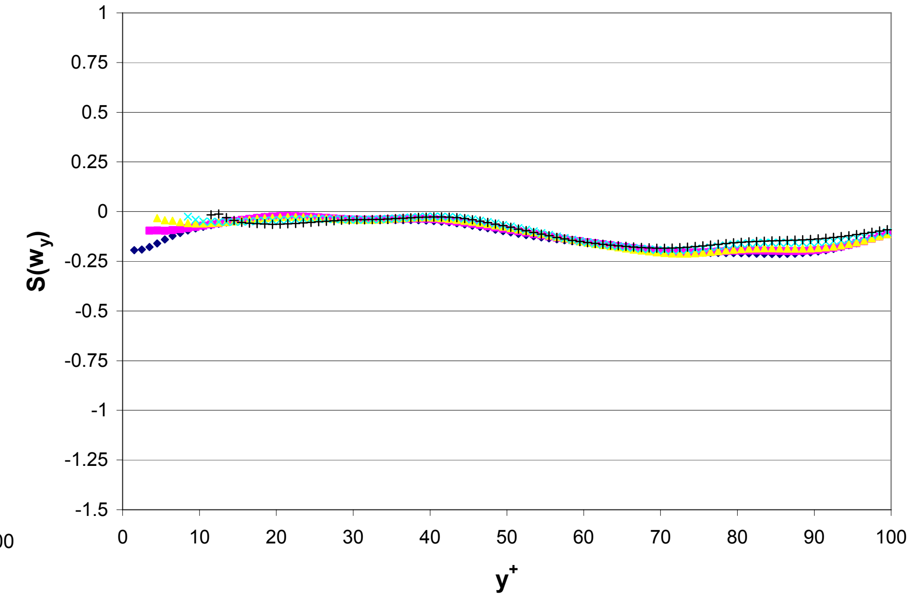
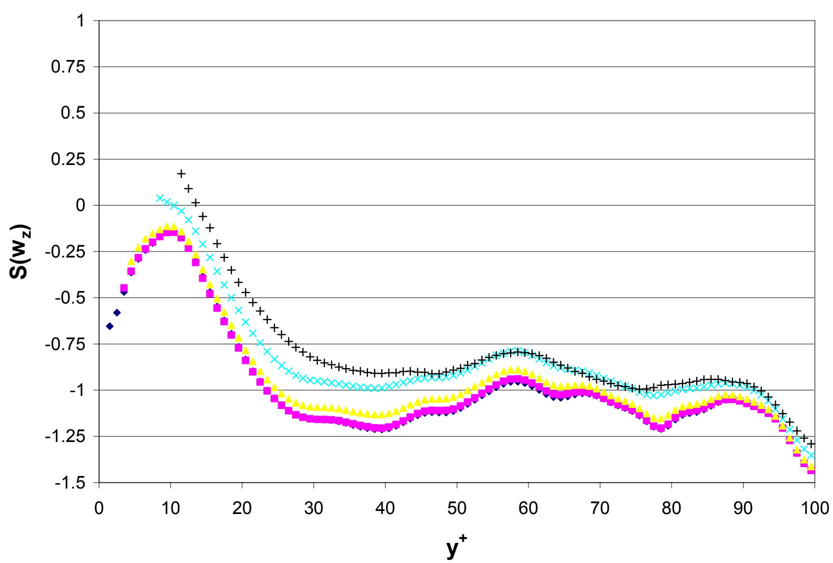
Vorticity Skewness







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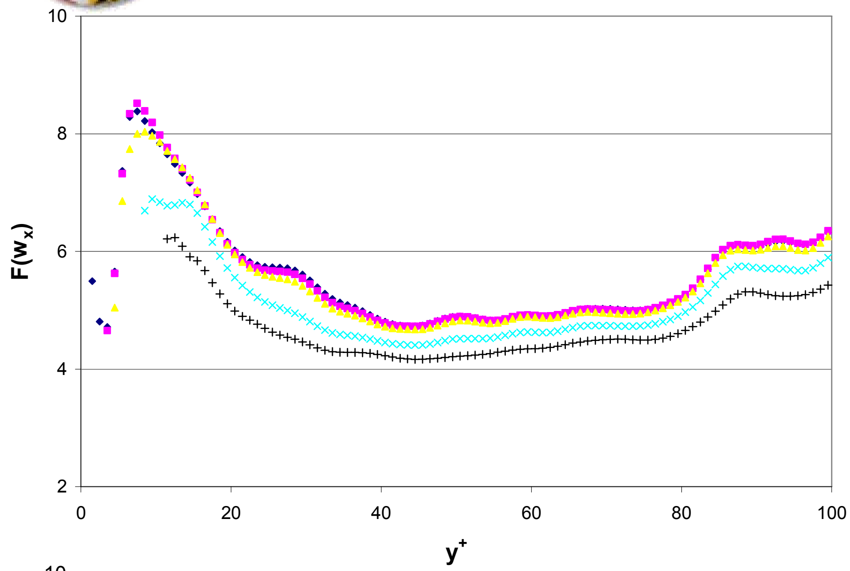

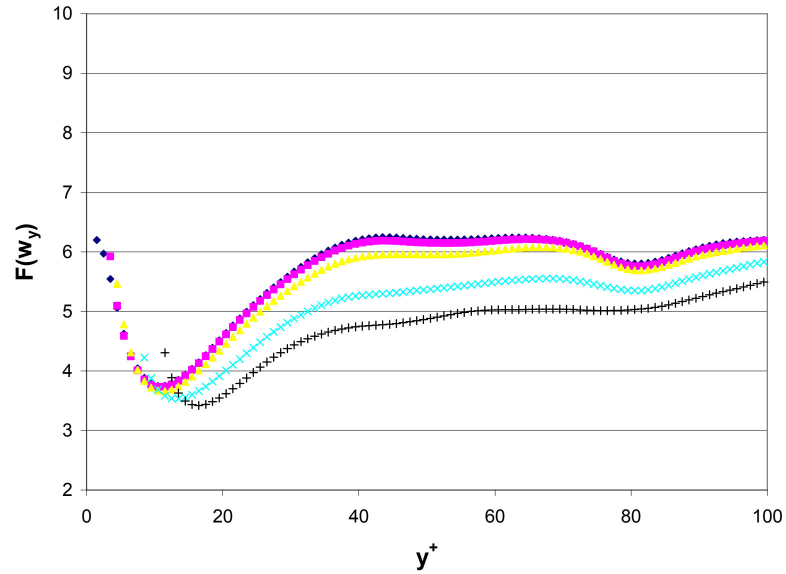

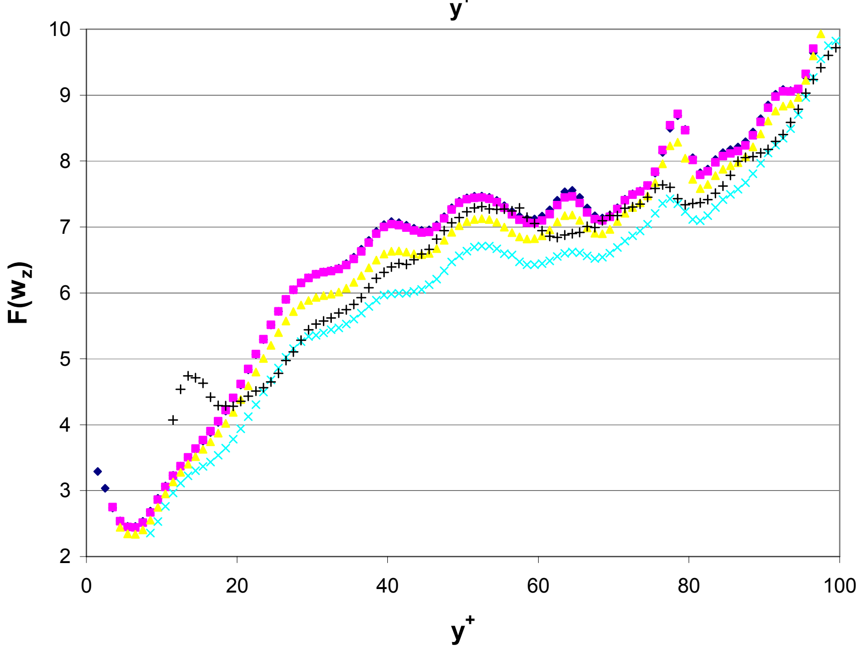

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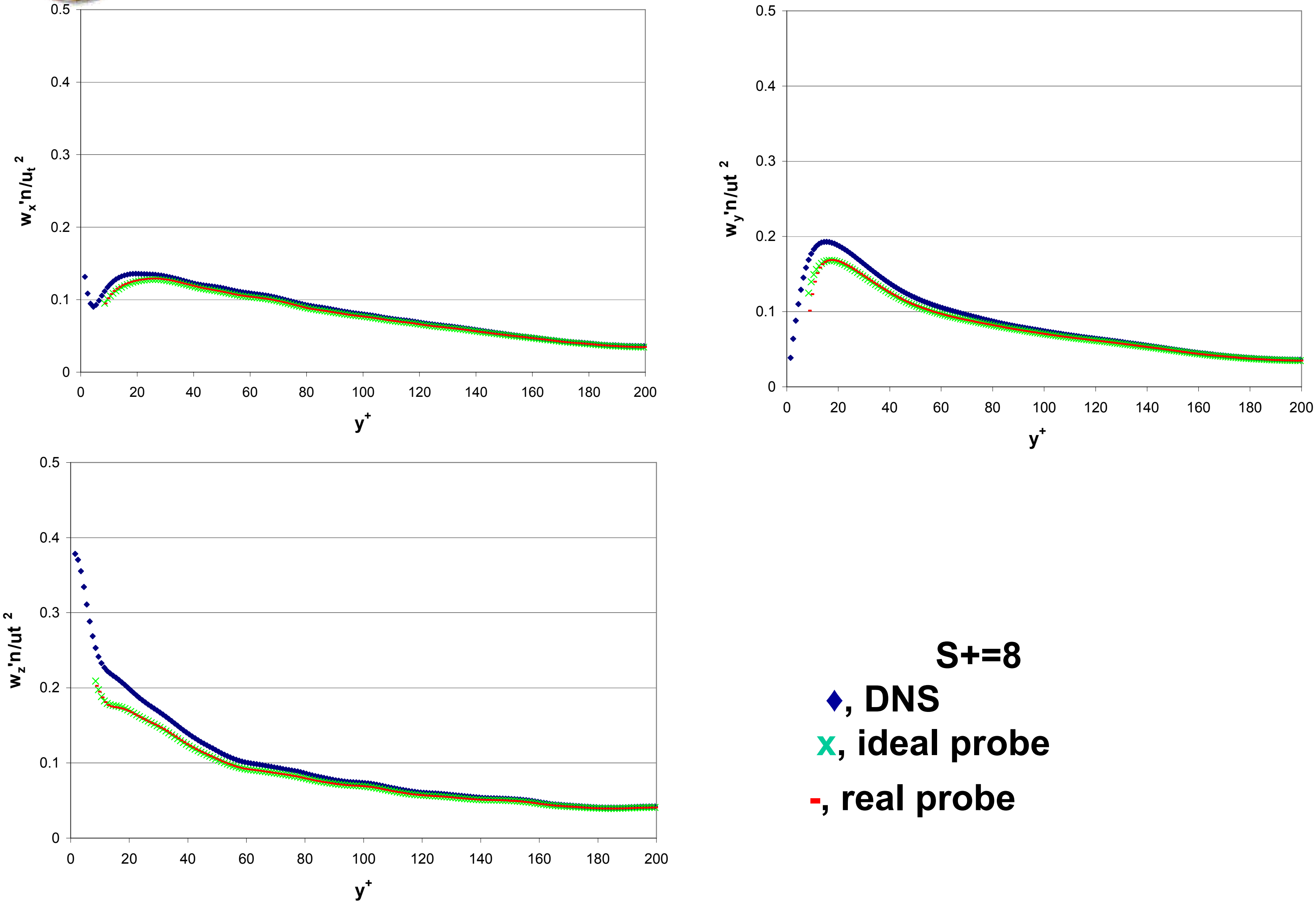
Comparison of ideal and real probe response



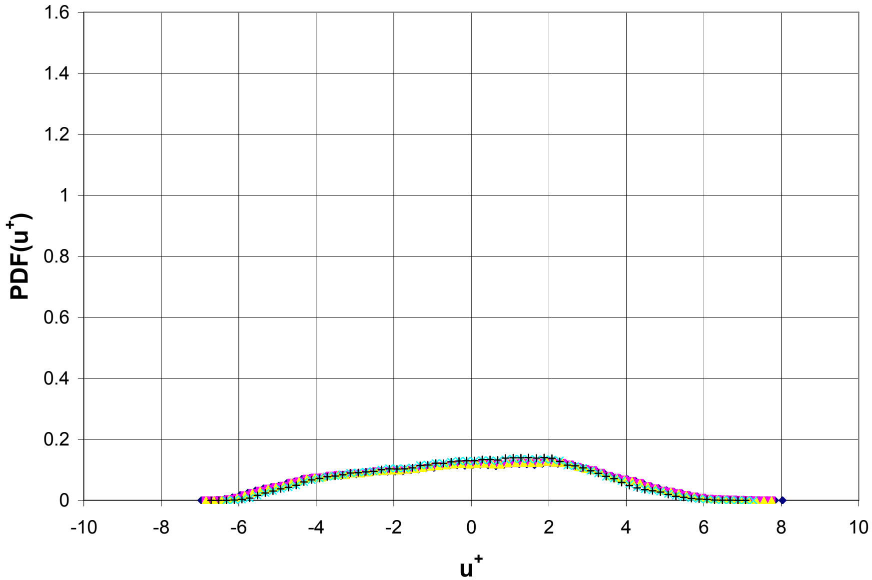
S+=8

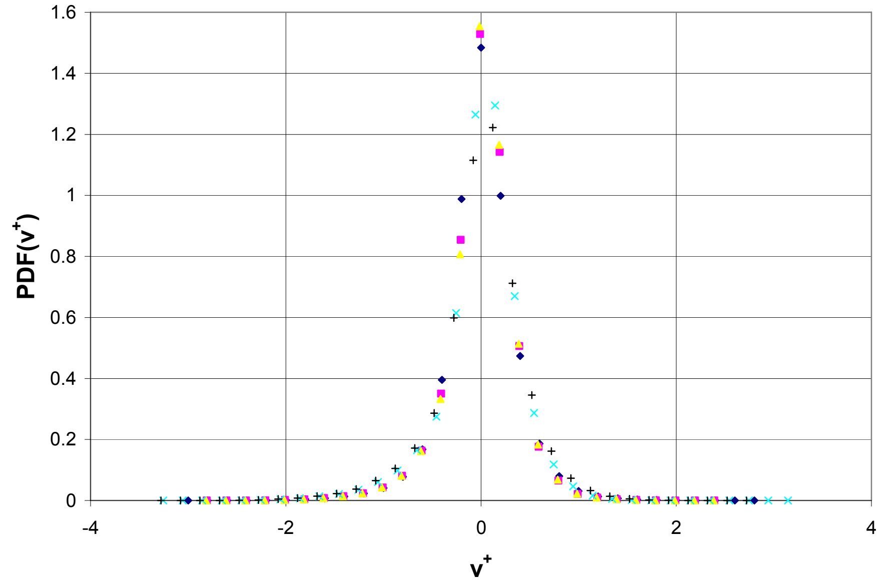
♦, DNS

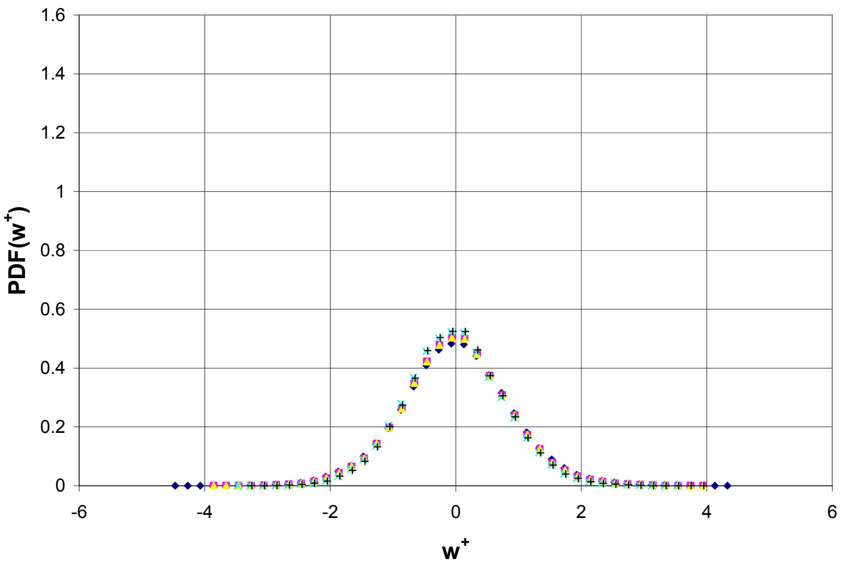
x, ideal probe

-, real probe

Velocity PDFs of real and ideal probe response at y+=12.5







♦, DNS

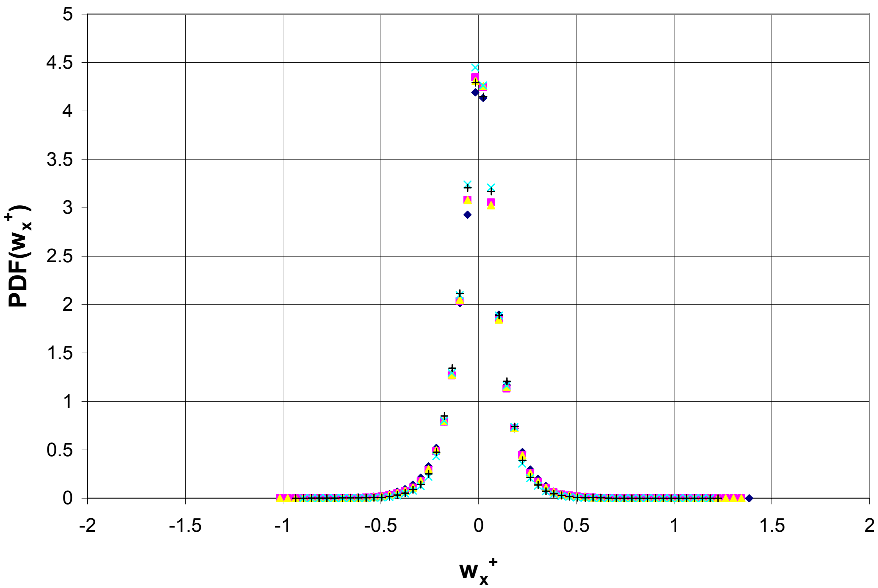
■, s+=4, ideal probe response

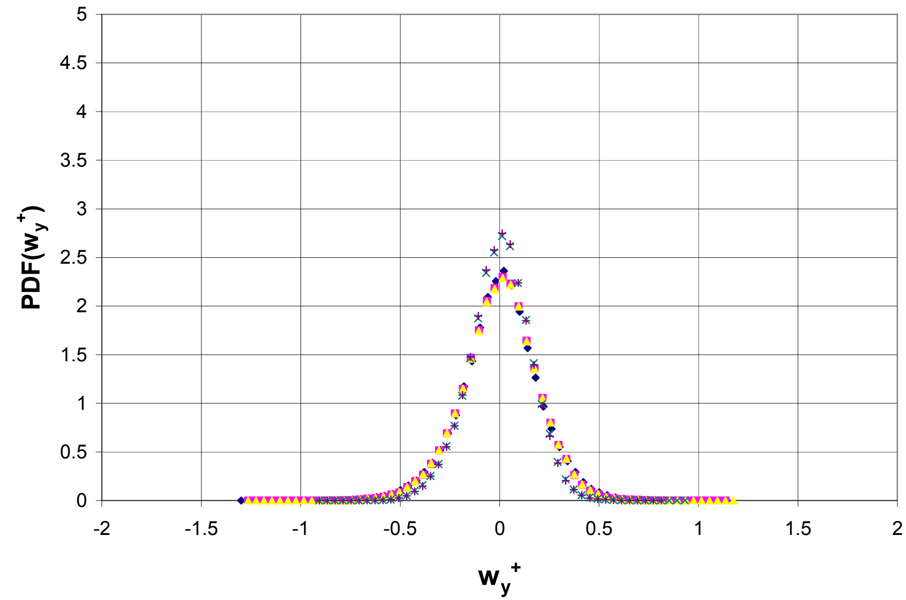
▲, s+=4, real probe response

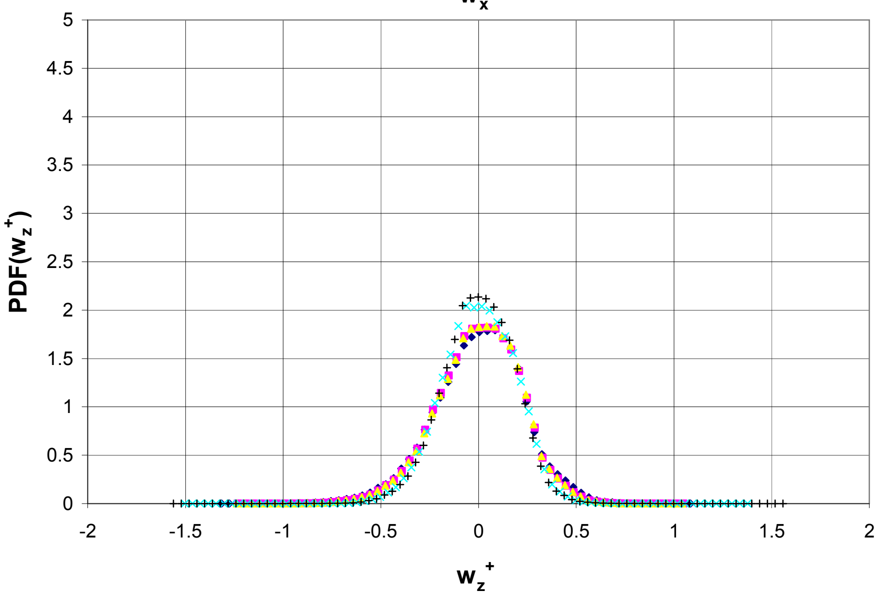
x, s+=8, ideal probe response

+, s+=8, real probe response

Vorticity PDFs of real and ideal probe response at y+=12.5







♦, DNS

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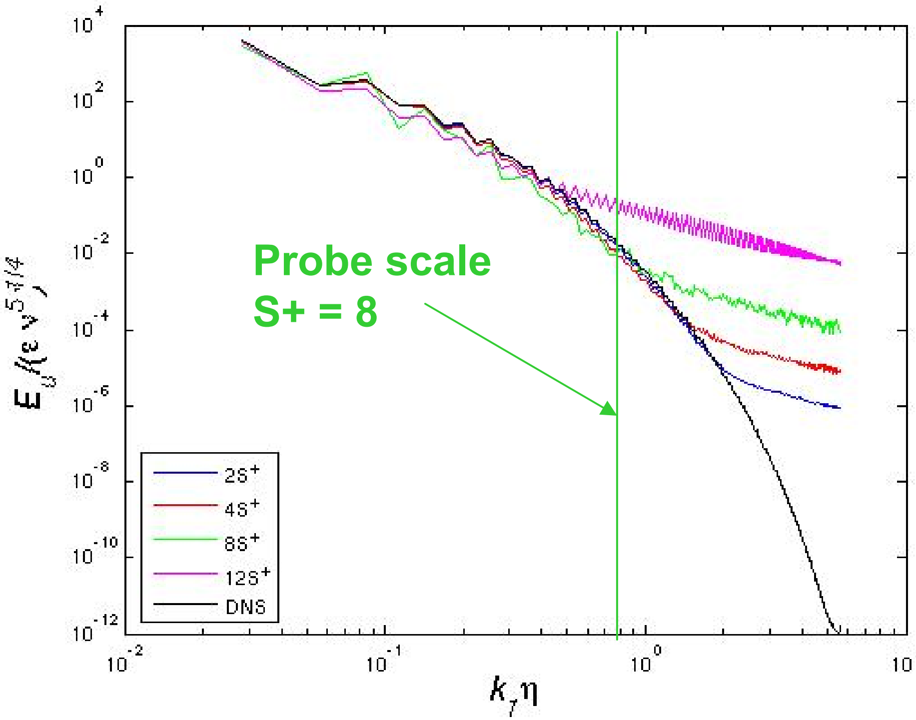
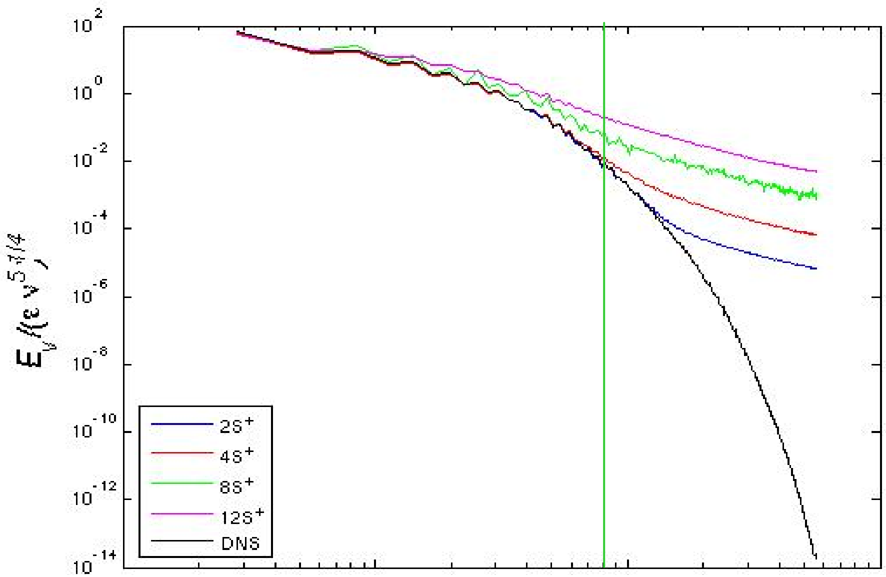
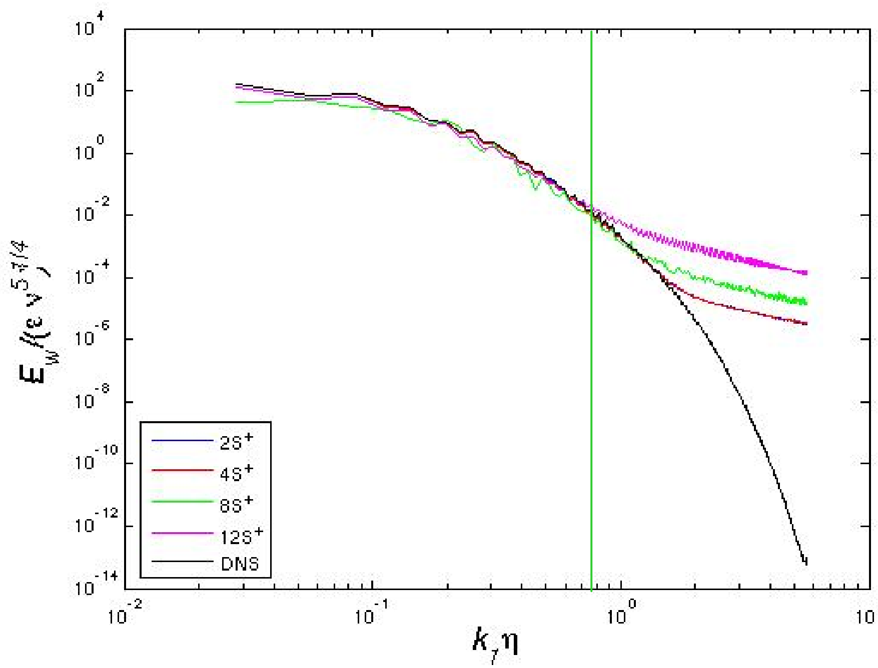
Velocity Spectra

@ y+ = 20





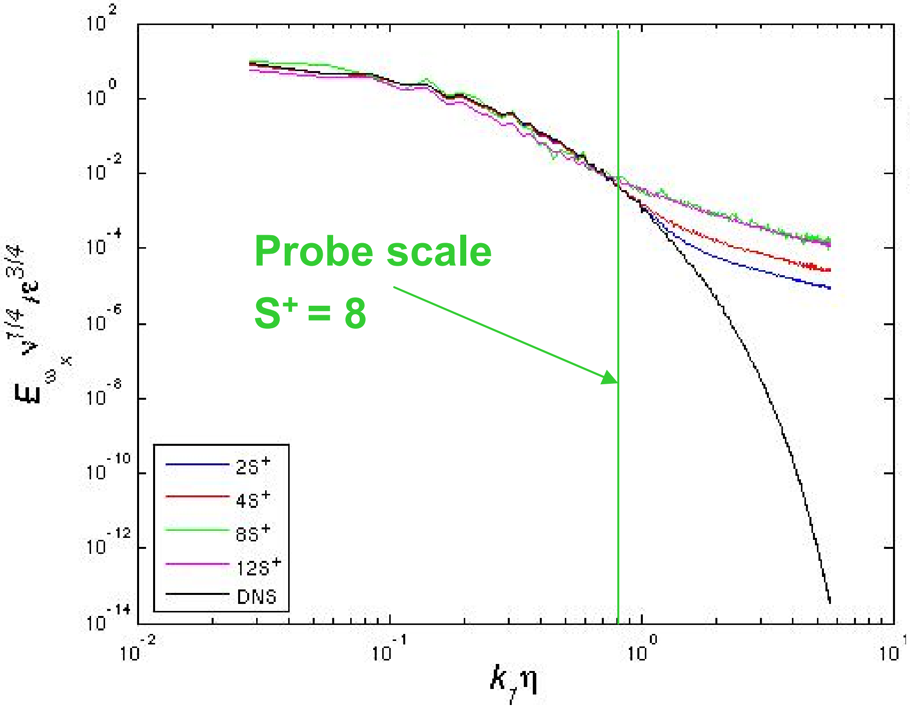


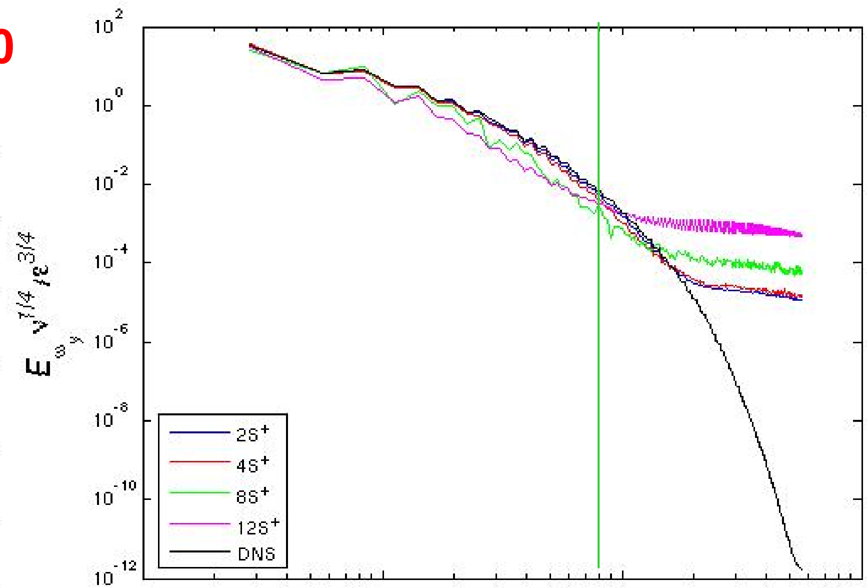
— **DNS**

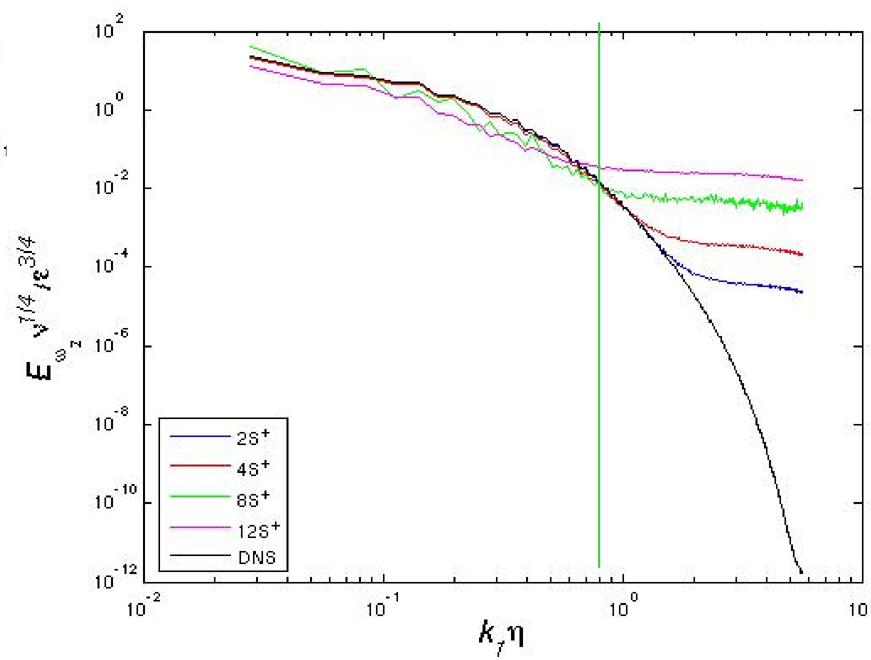
	y+ = 15		= 150
$S^+ = 2$ →	1.2 η	→	0.6 η
$S^+ = 4$ →	2.4 η	→	1.2 η
$S^+ = 8$ →	4.8 η	→	2.4 η
$S^+ = 12$ →	7.2 η	→	3.6 η

Vorticity Spectra

@ $y^+ = 20$







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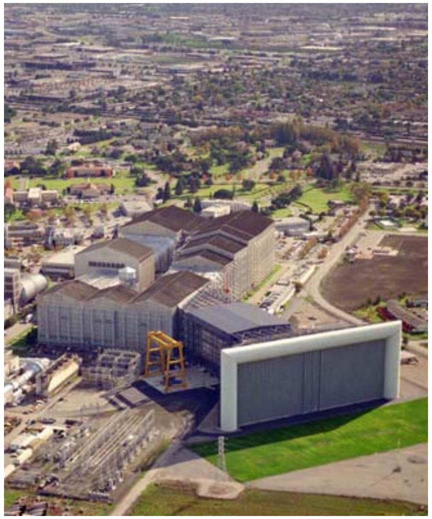
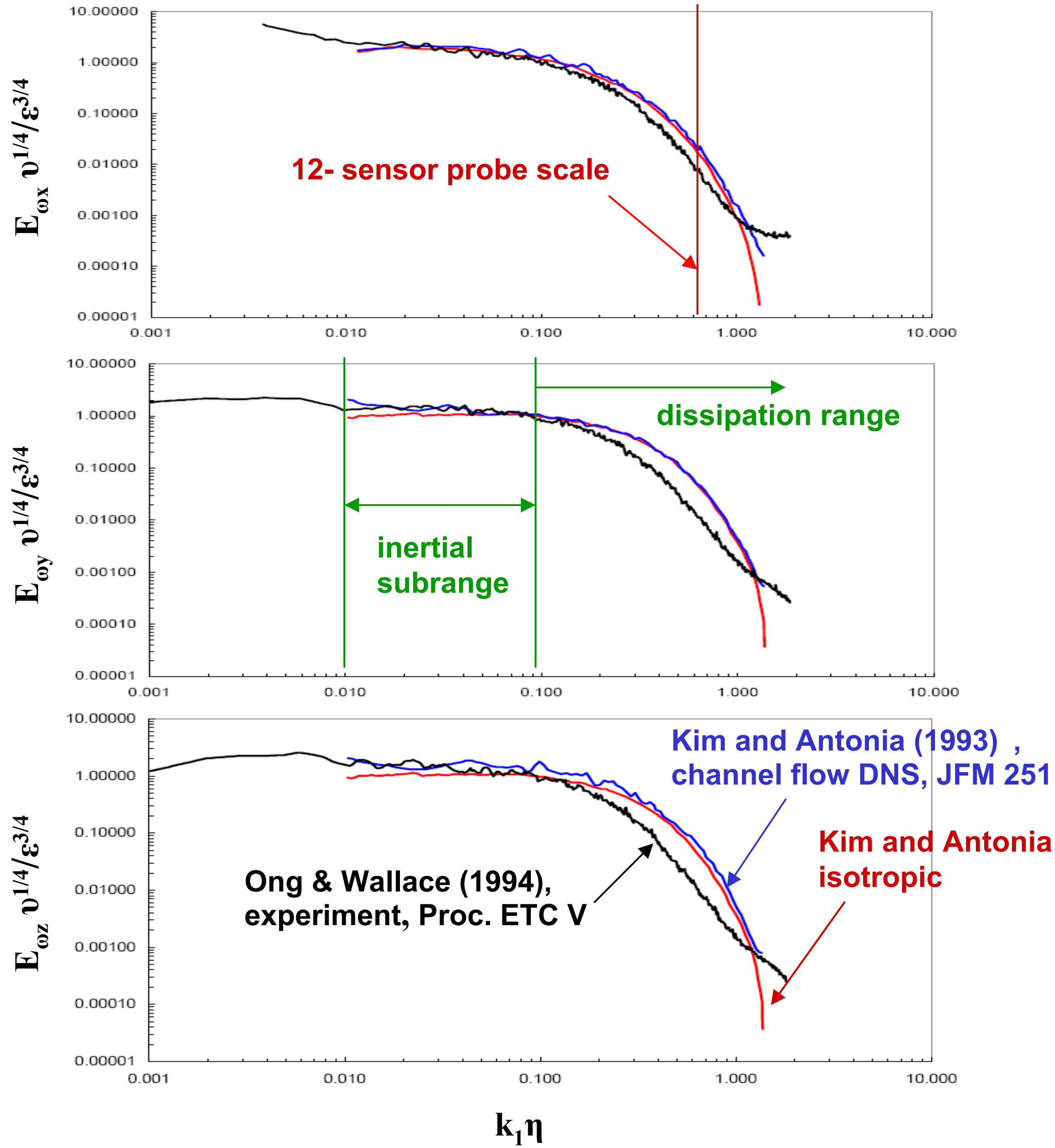
Local Isotropy of the Vorticity Field in a High Reynolds Number Turbulent Boundary Layer



NASA Ames 80´ x 120´ Wind Tunnel

probe location



Summary & Conclusions

Spatial resolution of 12-sensor hot-wire probe investigated using highly resolved minimal channel flow DNS.

Virtual probe with 12 point sensors varied so that spacing between arrays is 2, 4, 8 and 12 viscous lengths.

The velocity component rms values are attenuated les then 10% everywhere in the flow for $s^{+}<8$.

The skewness factor of the wall normal velocity fluctuations, S(v), display stronger dependence on spatial resolution.

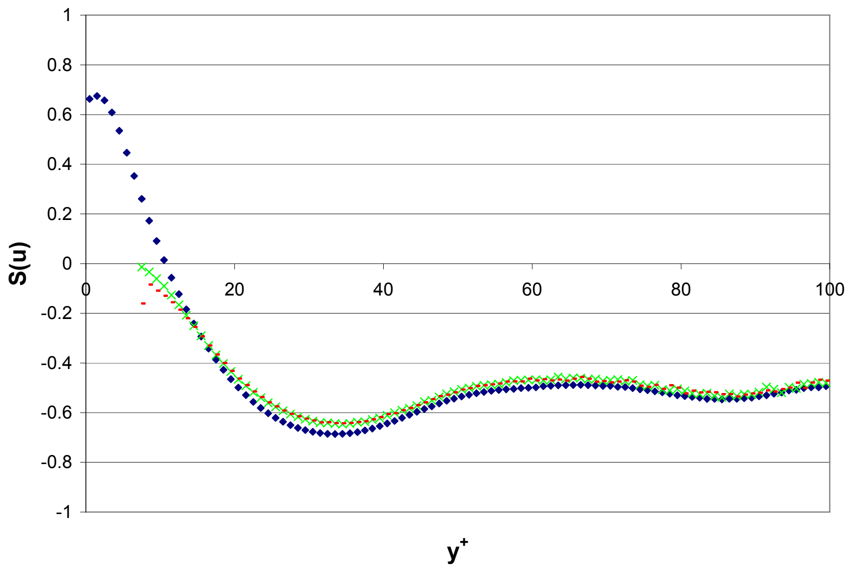
In the wall layer all the vorticity component rms values are strongly influenced by spatial resolution for $S^{+} = 8$ and 12.

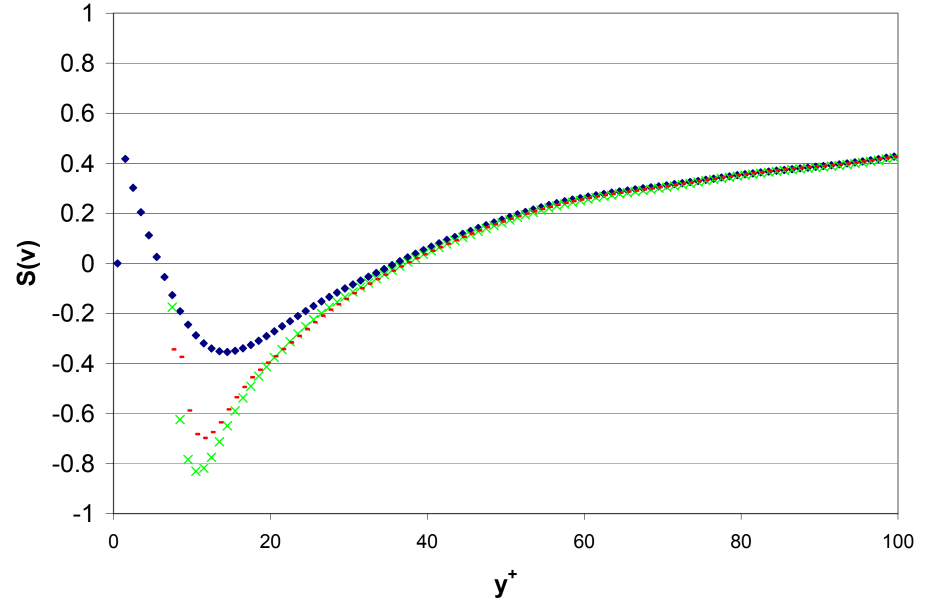
The statistics from the ideal and real probe responses are nearly identical.

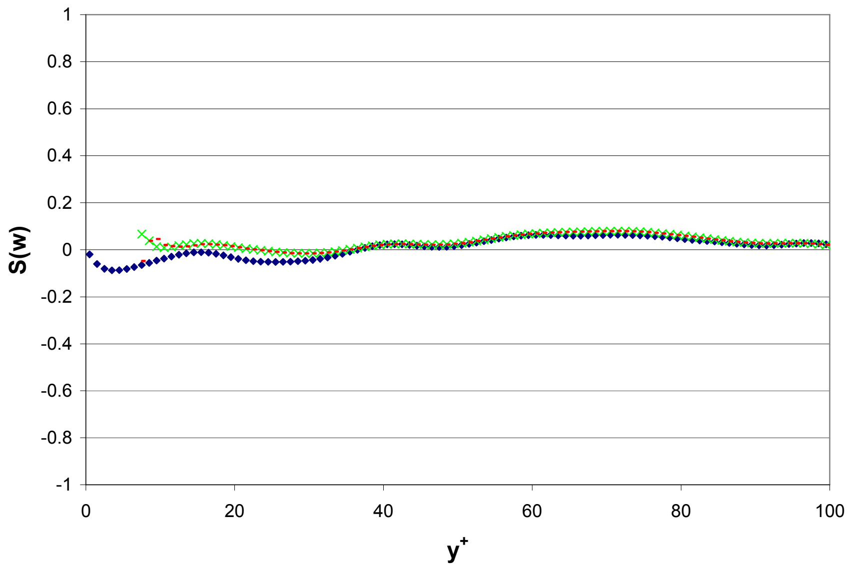
The shapes of the velocity and vorticity pdfs reflect the resolution effects.

Spectra demonstrate the attenuation due to spatial resolution

Comparison of ideal and real probe response







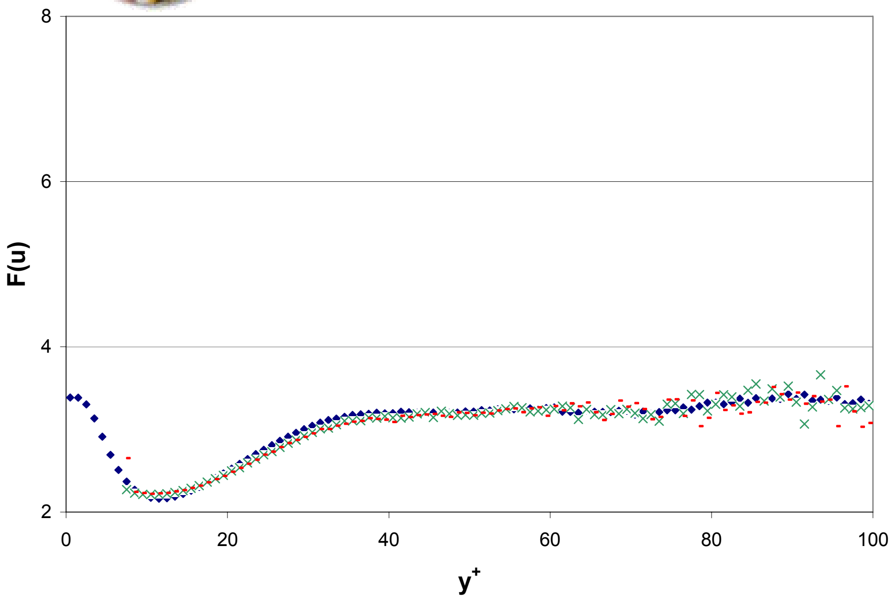
S+=8

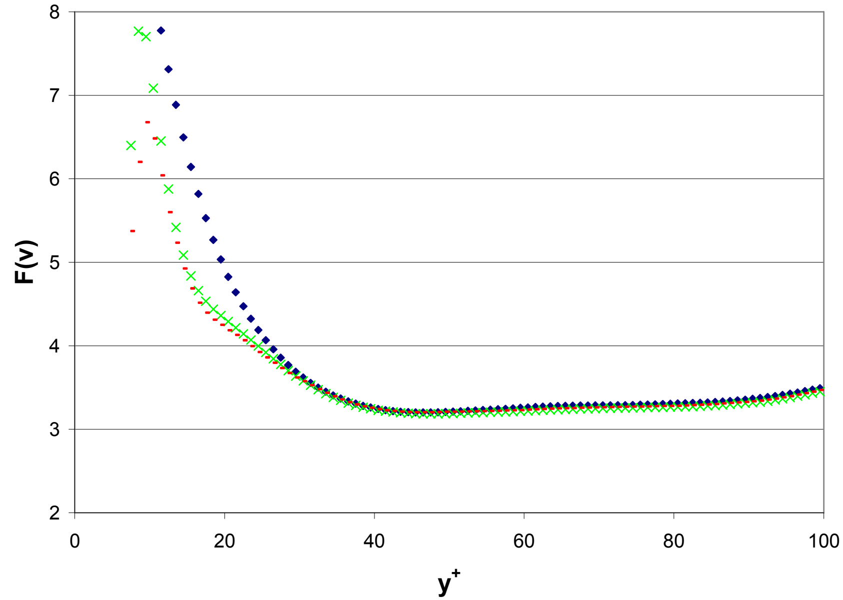
♦, DNS

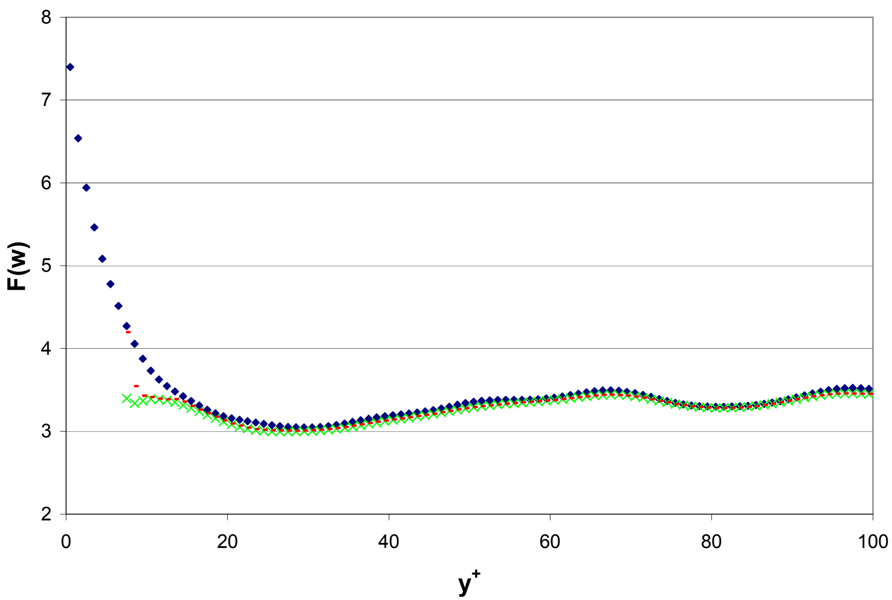
x, ideal probe

-, real probe

Comparison of ideal and real probe response







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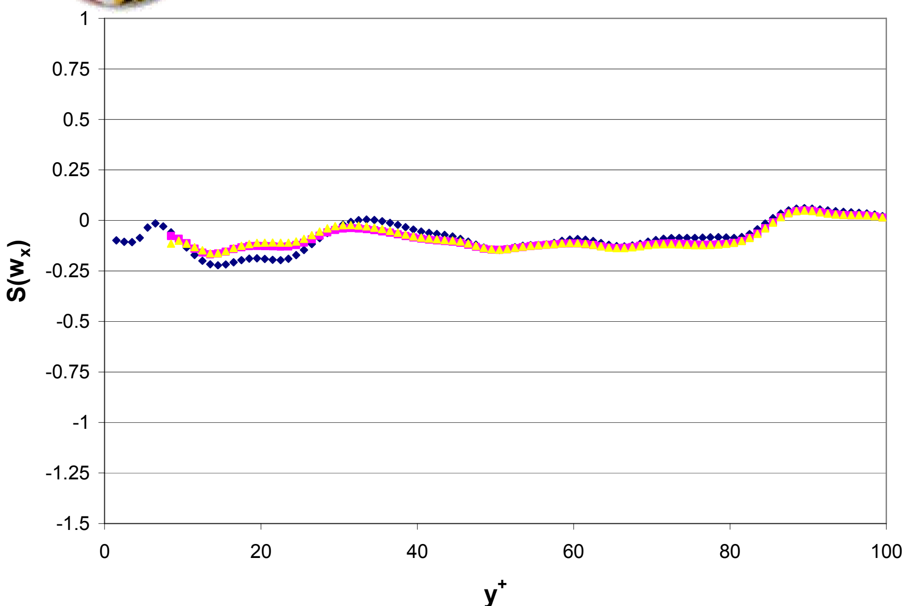

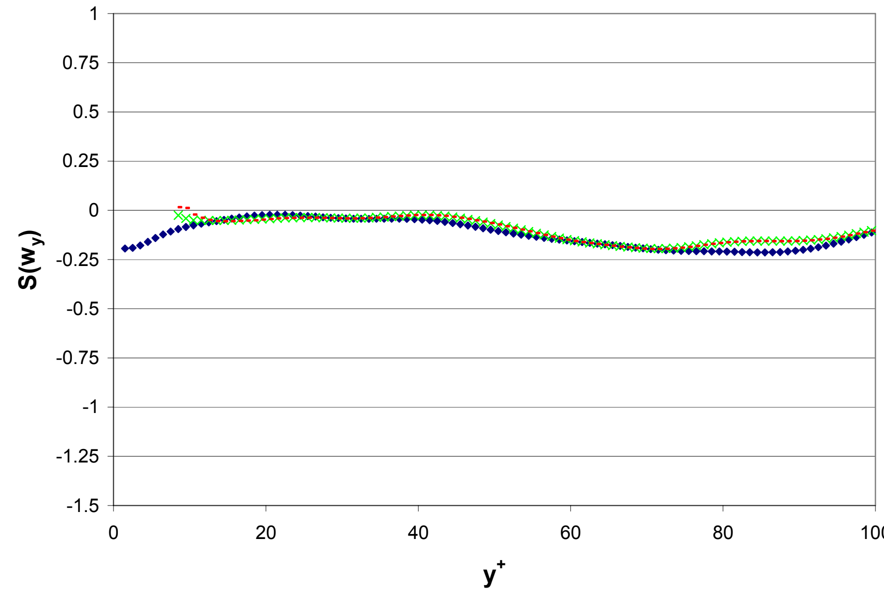

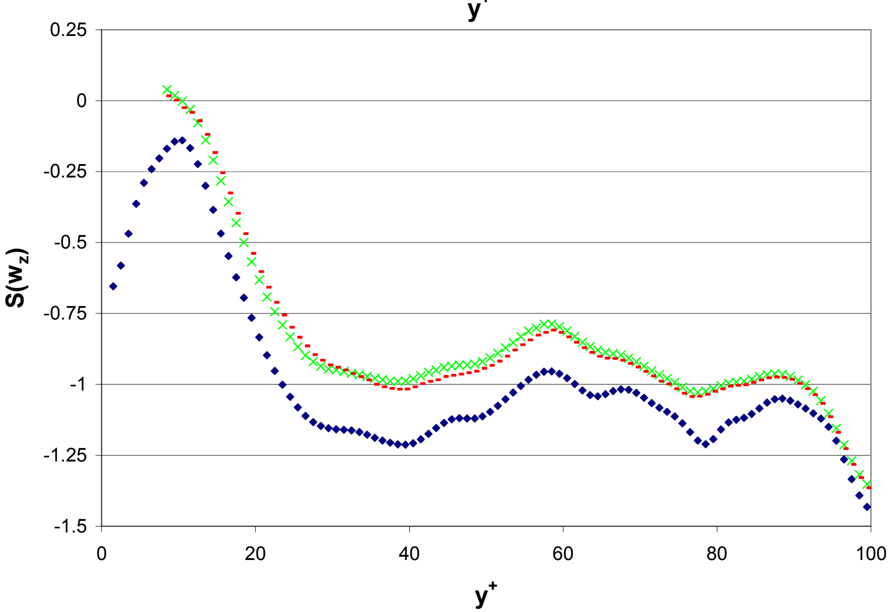

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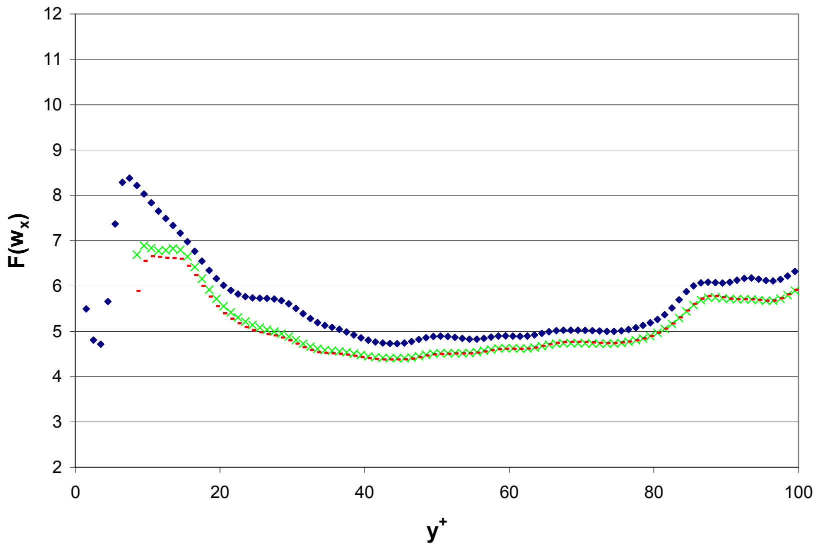

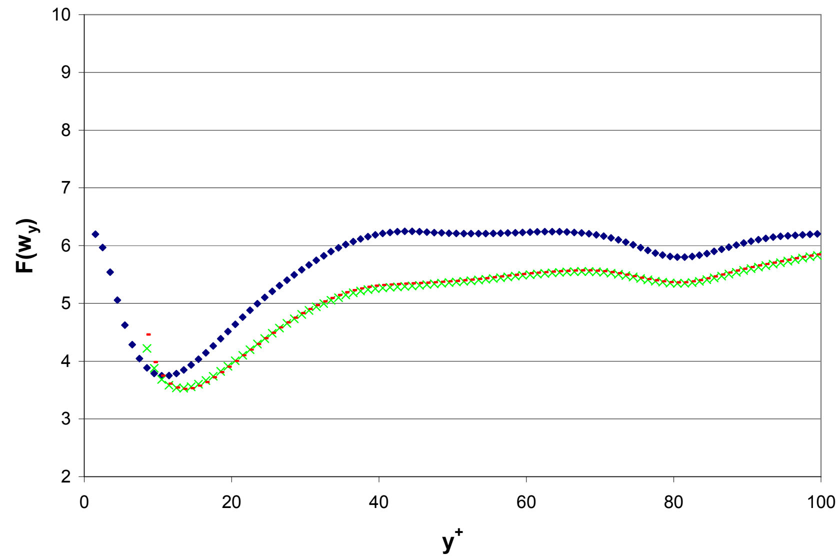

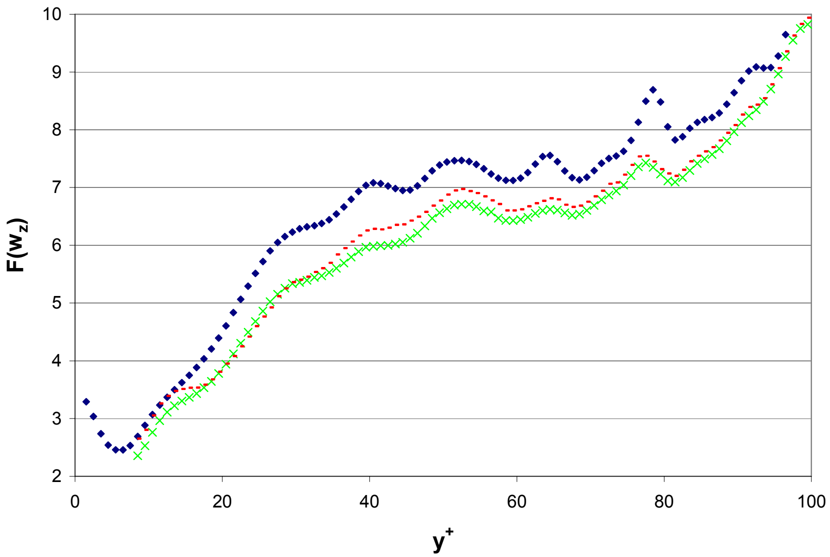

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