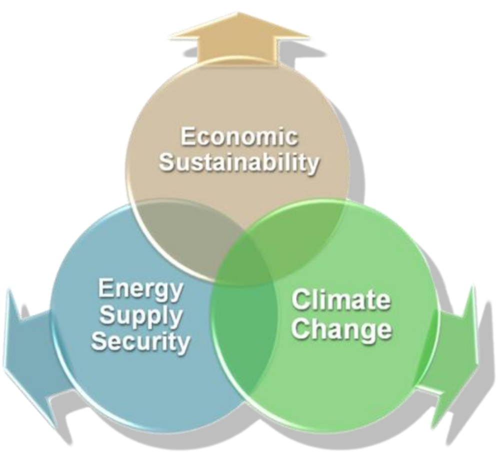
NATIONAL ENERGY TECHNOLOGY LABORATORY



Higher Order Analysis of High Speed PIV Data in CFB Risers

Balaji Gopalan & Frank Shaffer

Collaborators: PSRI

U.S. DEPARTMENT OF ENERGY

Motivation & Goals

Generating quality experimental data for validating CFD models to improved performance and reliability of fossil fuel conversion processes

- **Providing a database for validation of computational fluid dynamics simulations including MFIX, MP-PIC, DEM, etc.**
- **Understanding the dynamics of particulate flows by comparison of higher order statistics with computational models**
- **Measuring parameters and developing correlations that can be used within models**

Why look at higher order particle velocity statistics?

- **Lack of higher order particle velocity statistics for model validation** **(Bhuparasu et al., 2006)**

- **Ability of HS-PIV to measure large quantities of particle velocity statistics at much higher temporal and spatial resolution than before**

Initial results from HSPIV data in CFB risers:

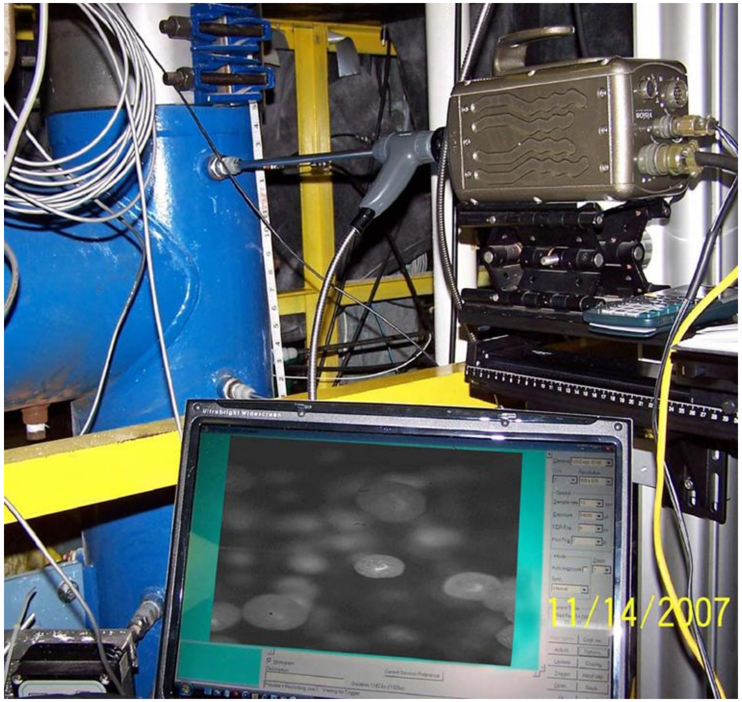
- **a non-Gaussian nature of local mean velocity**
- **standard deviation of local mean comparable to its overall mean**
- **observation of several modes of particulate flow**

Test Conditions and Particle Properties

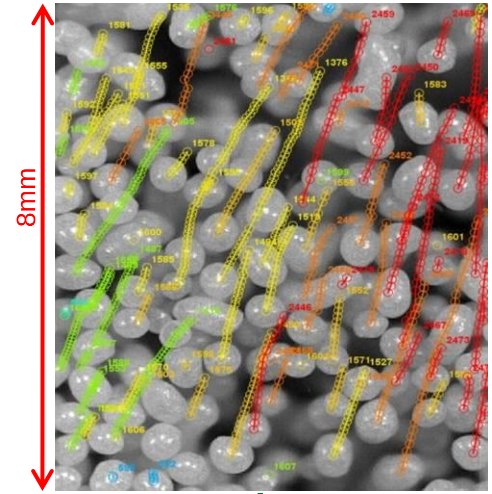
	Measurement Facility	Measurement Locations	Superficial Gas Velocity (U_g) (m/s)	Solids Flux (M_s) (kg/m^2/s)	Flow Regime
Condition 1	12 " NETL Riser	7 radial locations, ~35 riser diameters above inlet	7.58	96	Core-Annulus
Condition 2	8" PSRI Riser	6 radial locations, ~80 riser diameters above inlet	18.3	390	Dense Up-flow **(Grace et al. 1999)**

Facility	NETL	PSRI
Density (kg/m^3)	863.3	1490
Bulk Density (kg/m^3)	570.1	970
Minimum Fluidization Velocity (m/s)	0.2	0.003
Packed Bed Voidage	0.346	0.349
Diameter (μm)	802	81
	Group B (HDPE)	**Group A (FCC)**

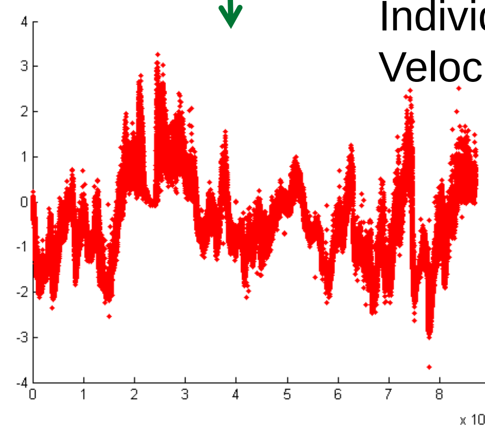
HSPIV Measurements



Tracked Particles

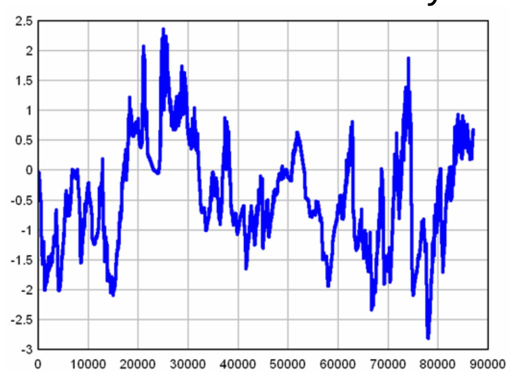


Individual Particle Velocities



Measurement Uncertainty of Individual Particle Velocity:
<1% at wall
~ 5% inside flow

Local Mean Velocity



Local Mean Velocity is comparable to Eulerian Particle Velocity in CFD Simulations and is equivalent to point measurement in LDV and Fiber optic probes

F. Shaffer (2010), B. Gopalan & F. Shaffer (2010, 2011)

Outline of Results

- Distribution of Local Mean Velocity

- Radial distribution of Local Mean Velocity RMS and GT

- Spatial gradient of Local Mean Velocity (i) Distribution
  (ii) Variation with GT
  (iii) Variation with Conc

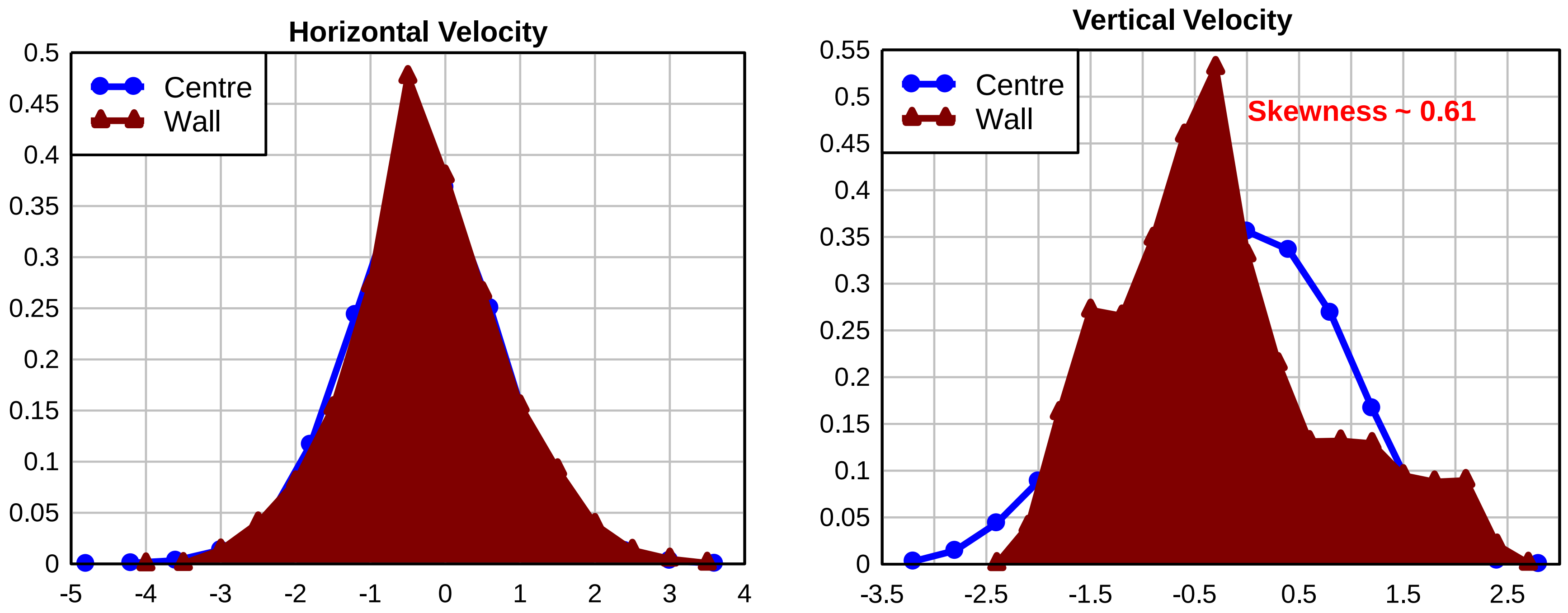
- Autocorrelation of Local Mean Velocity

- Temporal Gradient of Local Mean Velocity (i) Distribution

- Intermediate Scale FFT of Local Mean Velocity

Available but not discussed in this talk

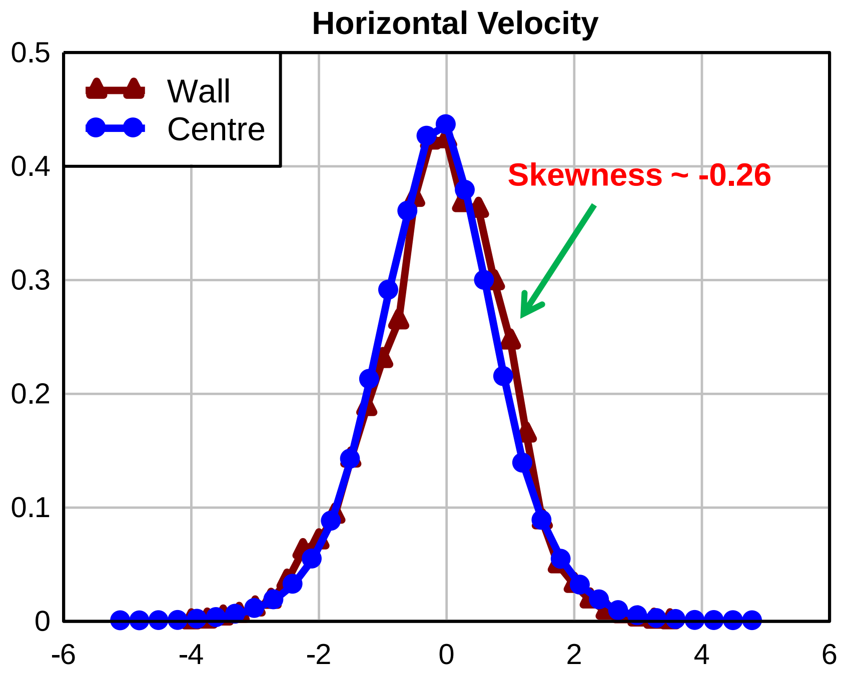
PDF of normalized local mean velocity at NETL riser

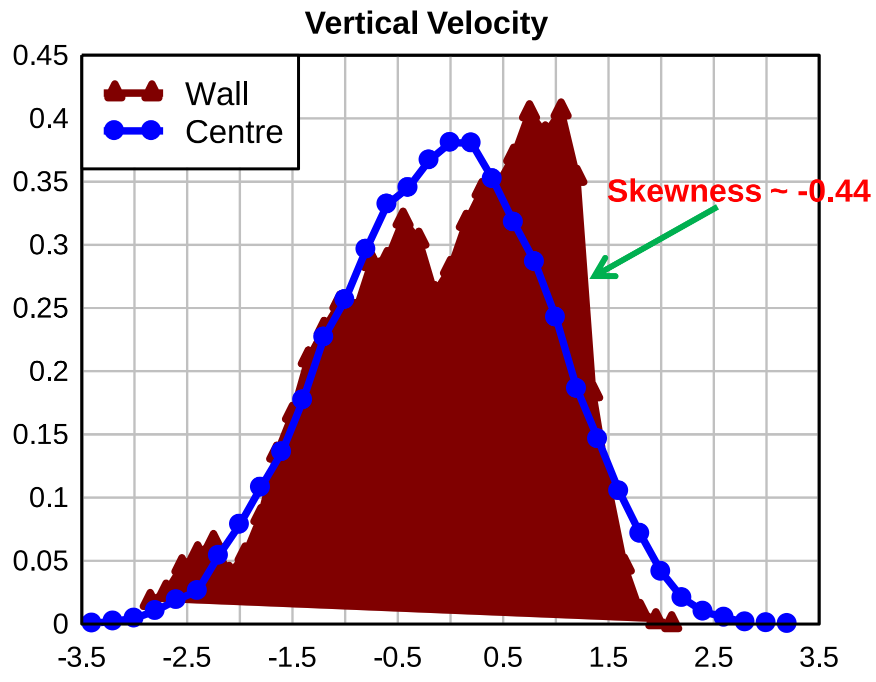


The PDF of the local mean velocity is close to Gaussian near the centre of the riser for the horizontal direction and has a small skewness in the vertical direction

The **presence of the wall introduces some skewness in the horizontal PDF while drastically altering the vertical velocity PDF**

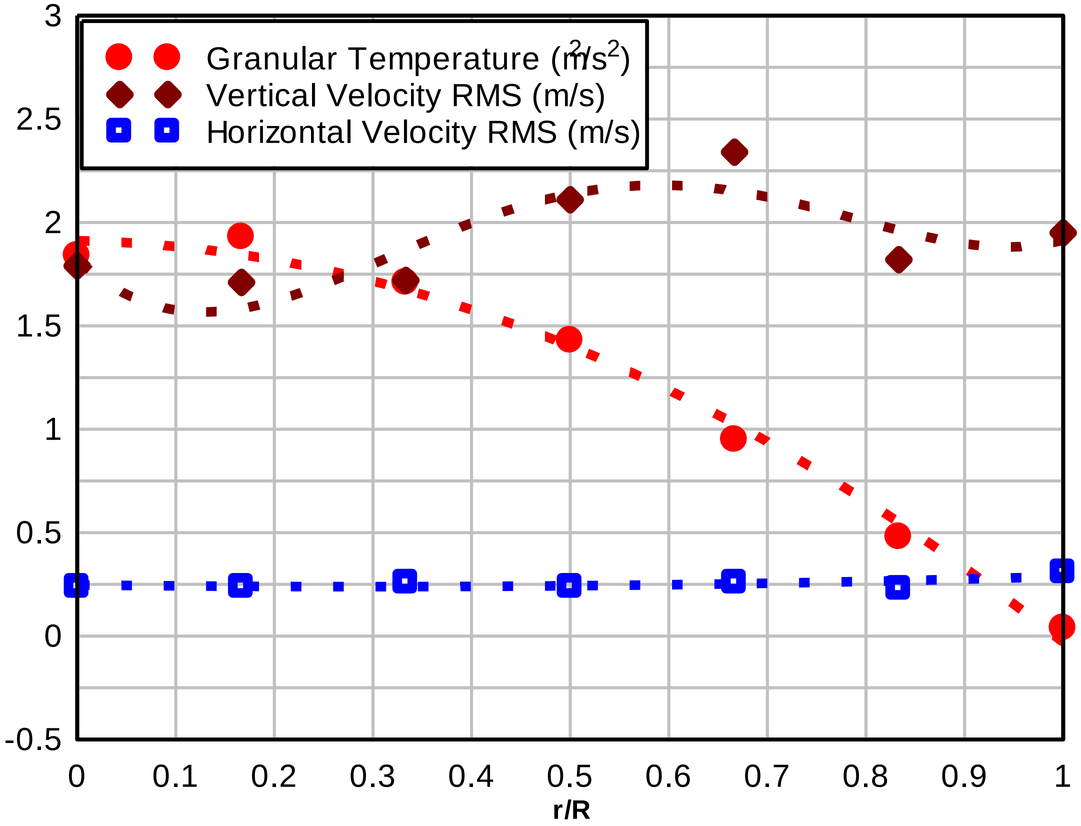
PDF of normalized local mean velocity at PSRI riser





Similar **multimodal distribution is observed for vertical velocity PDF in the both the riser data**

Radial distribution of RMS of Local Mean Velocity and GT (NETL Riser)



RMS of vertical component of local mean velocity is **much higher** than the horizontal one

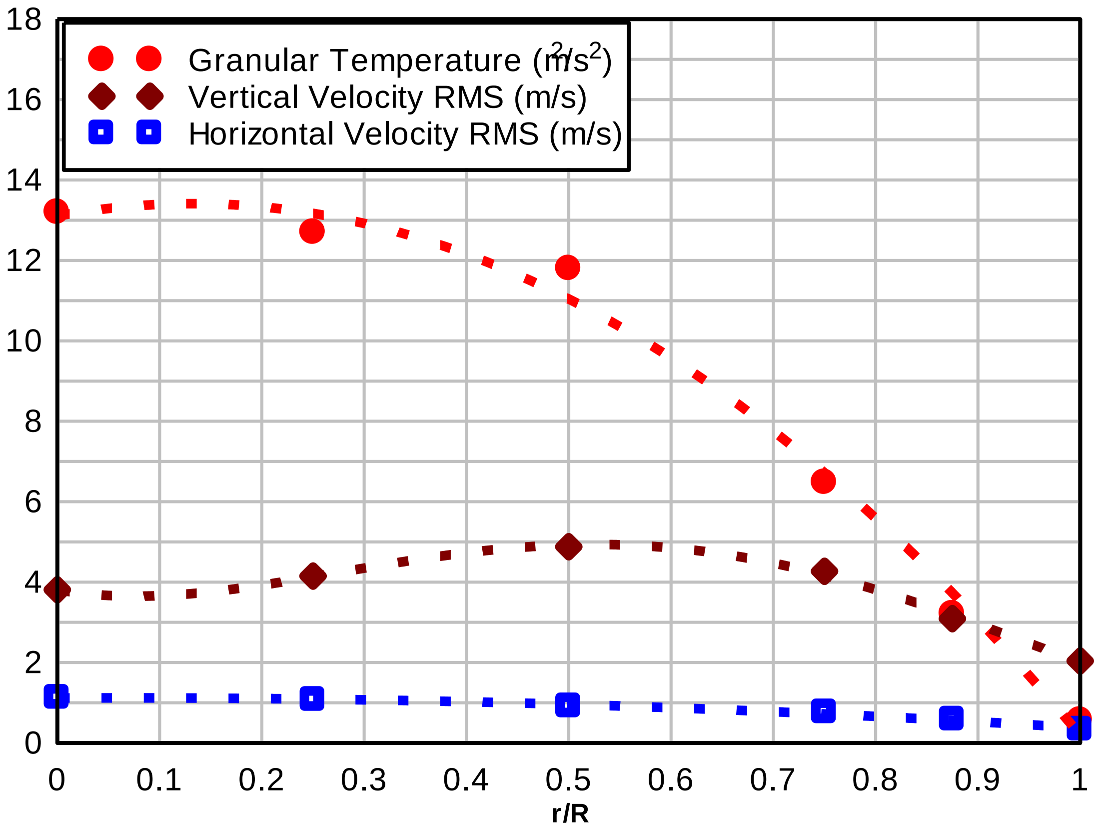
The variation of horizontal RMS with radial location is within experimental uncertainty

RMS of vertical component of local mean velocity **has its peak off centre**

GT is **maximum near the centre of the riser** and decreases as we approach the wall

Statistical Uncertainty (uncertainty due to finite velocity data) ~ 8%

Radial distribution of Local Mean Velocity RMS and GT (PSRI Riser)

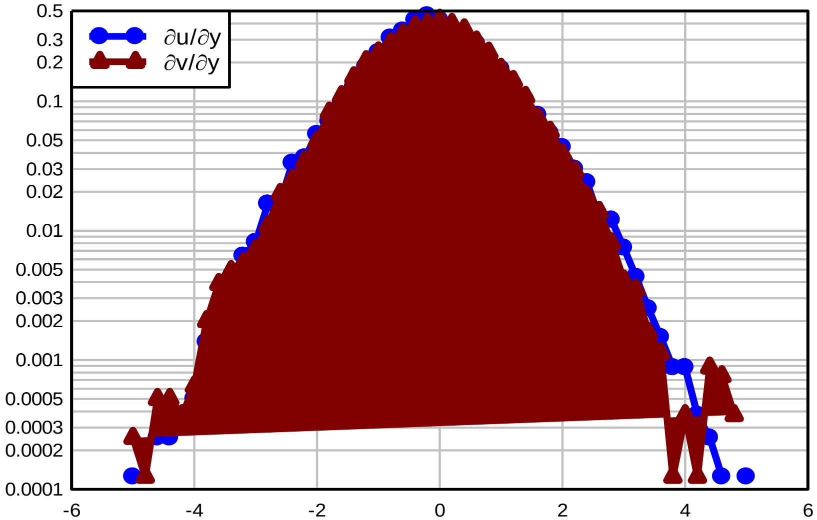


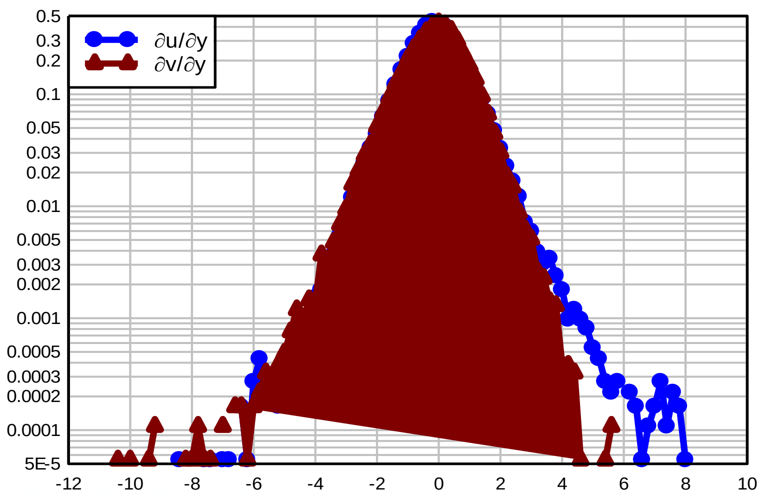
RMS of the horizontal component of local mean velocity decreases as we approach the wall

RMS of local mean velocity is higher than that of the NETL riser owing to higher superficial gas velocity

The **GT measured at PSRI riser is much higher than that of the NETL riser due to the combined effect of higher superficial gas velocity and smaller particle size and in spite of higher concentration**

PDF of Normalized Local Mean Velocity Strain Rate





The shape of the PDF is symmetric with a wide tail

$$\left\langle \left| \frac{\partial u}{\partial x} \right| \right\rangle > \left\langle \left| \frac{\partial u}{\partial y} \right| \right\rangle \ \& \ \left\langle \left| \frac{\partial v}{\partial x} \right| \right\rangle > \left\langle \left| \frac{\partial u}{\partial x} \right| \right\rangle \text{ for all data}$$

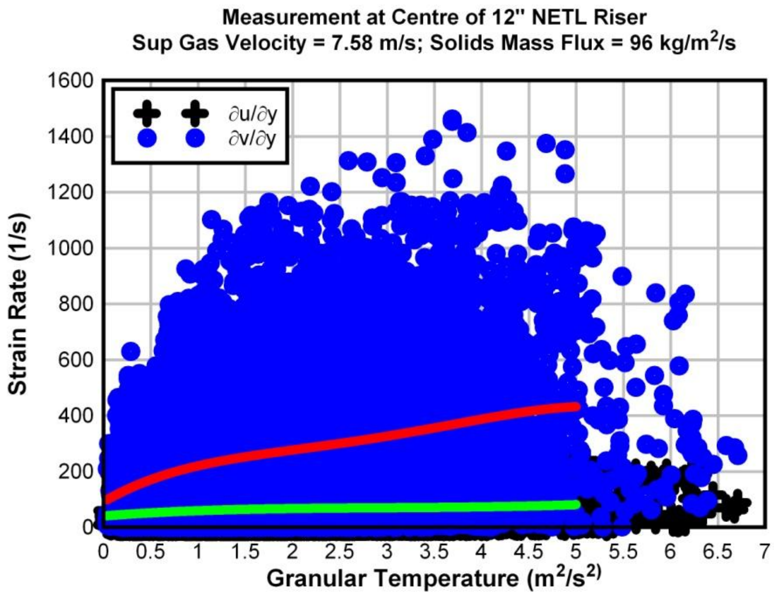
The magnitude of the strain rate at the centre of the riser is **~ 5-8 times** of that at the wall of the riser

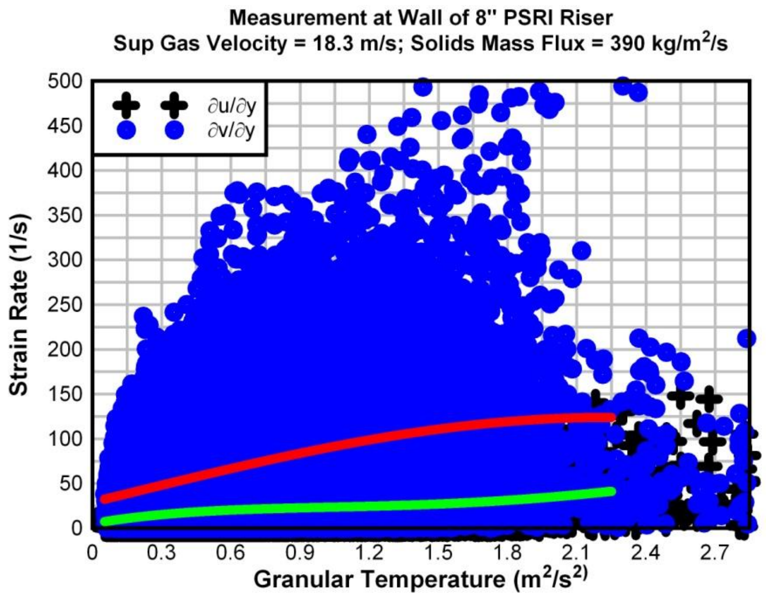
Horizontal gradient is ~**3-5 times** the vertical one

Vertical velocity gradient is ~ **2-4 times** the horizontal velocity gradient

The **magnitude of the strain rate for the PSRI riser is higher than that of the NETL riser** for all cases

Local Mean Velocity Strain Rate VS GT

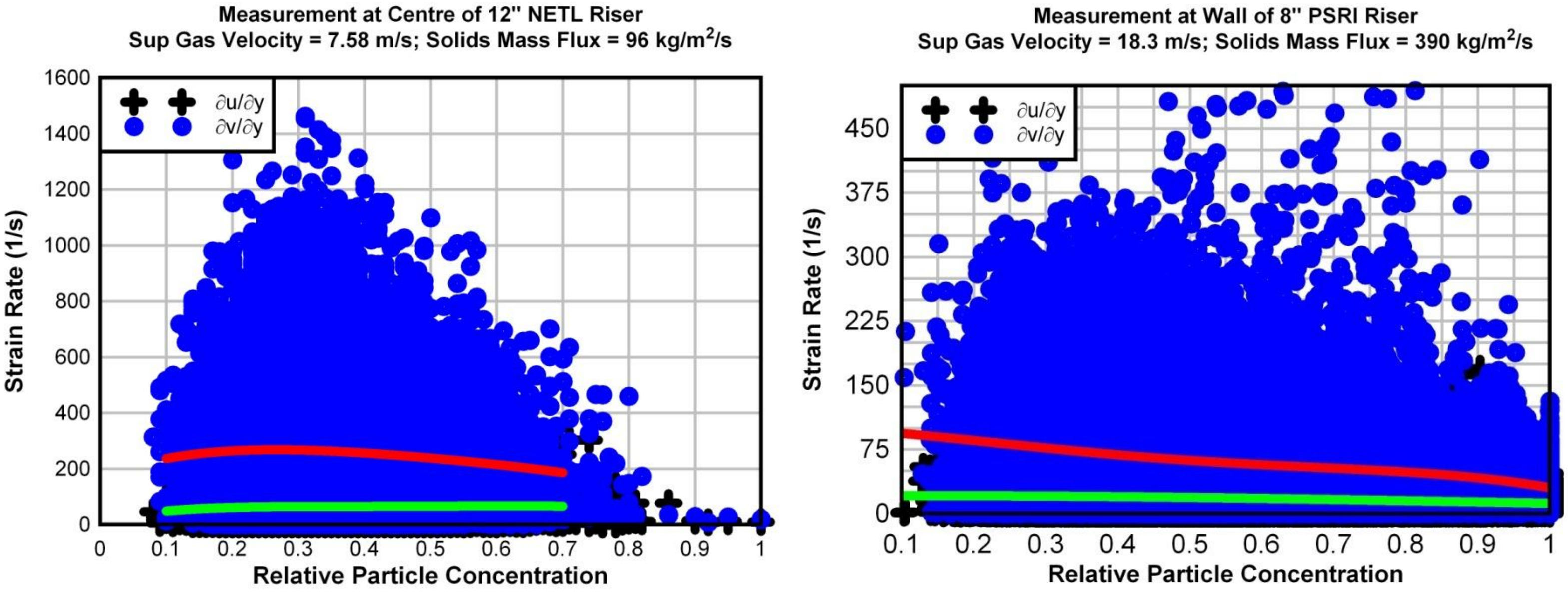




GT increases with increasing strain rate magnitude for all data conditions

There is a wide distribution of GT for a given strain rate, as GT depends on the velocity gradient in all directions

Local Mean Velocity Strain Rate vs Conc

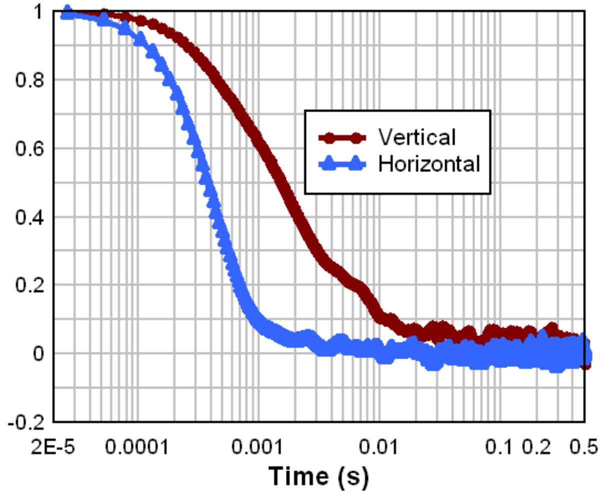


The **strain rate magnitude increases with decreasing concentration** agreeing with the trends of GT

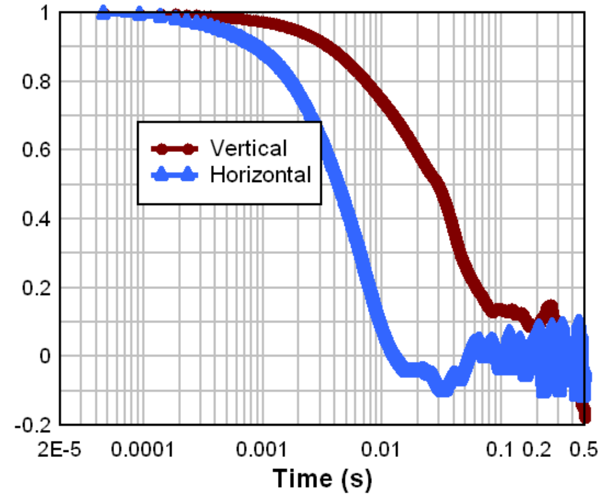
Autocorrelation of Velocity, Concentration and Granular Temperature

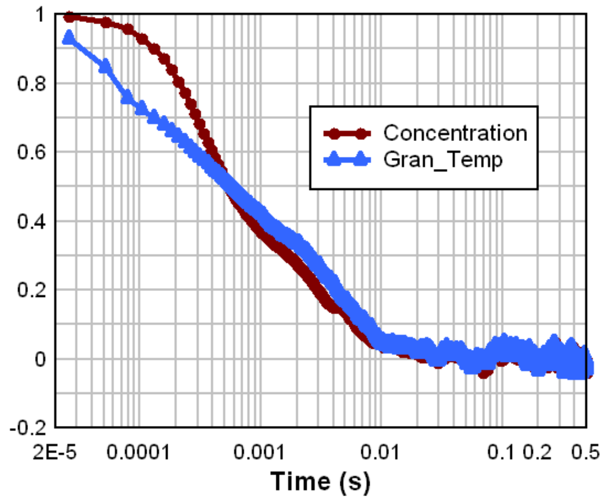
PSRI 8" Riser with 70 micron FCC; Flux = 390 kg/m²/s; Superficial Velocity = 18.3 m/s

Center of riser



Wall of riser





- The **vertical velocity autocorrelation** of the mean particle velocity is **higher than the horizontal one**
- As we approach the wall fluctuations in the particle velocity autocorrelation increases
- The granular temperature and concentration have a finite correlation (not random)

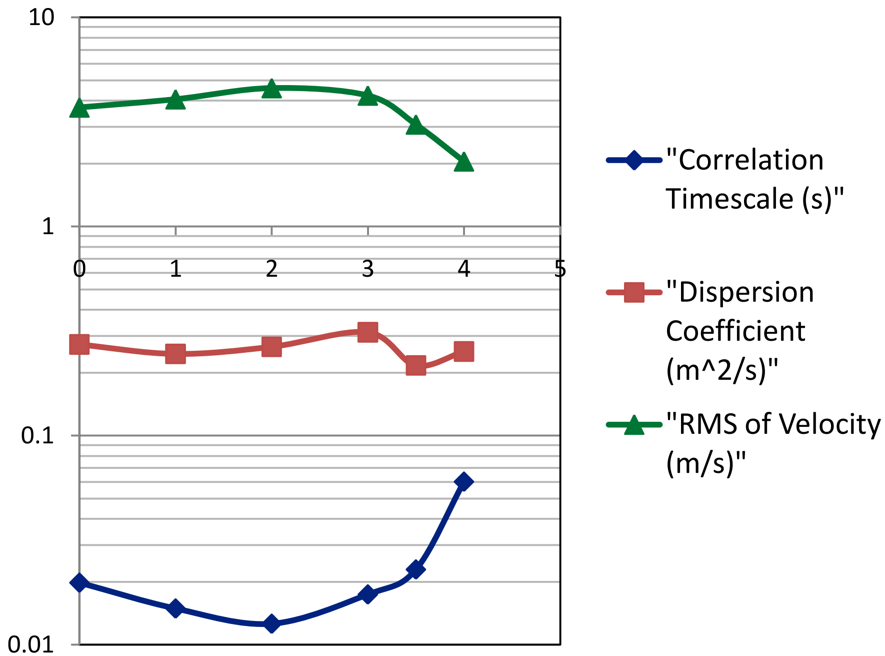
Estimation of Approximate Vertical Dispersion Coefficient

PSRI 8" Riser with 70 micron FCC; Flux = 390 kg/m²/s; Superficial Velocity = 18.3 m/s

$$D = U'^2 T_E$$

$$T_E = \int_0^\infty R_E(t)\,dt$$

Godfroy et al. (1999), Breault et al. (2008)

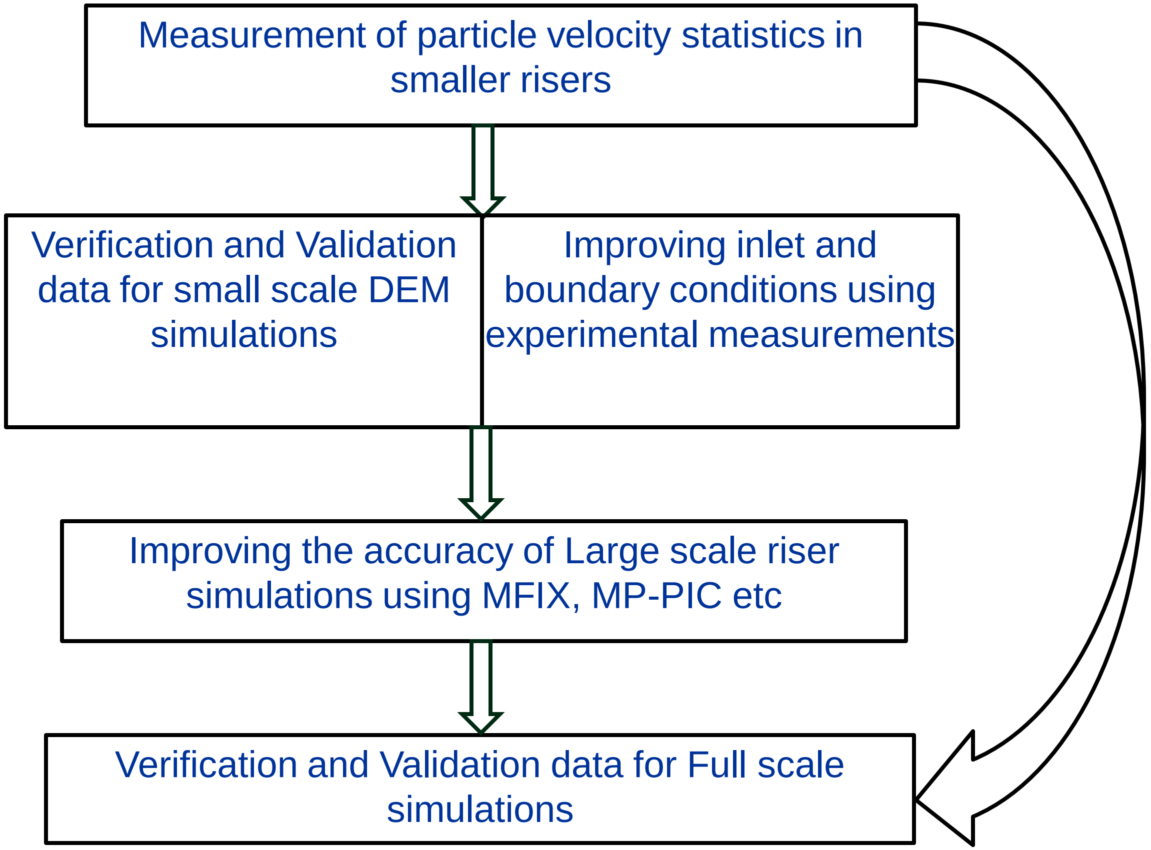


- The dispersion coefficient is ~ constant across the riser due to the opposing trends of the velocity rms and the correlation timescale

- The mean dispersion coefficient is ~0.26 m^2/s. Due to the approximations this is a lower estimate of the actual value

- A similar trend is observed for lateral dispersion but the coefficient is ~0.001 m^2/s

Future Work

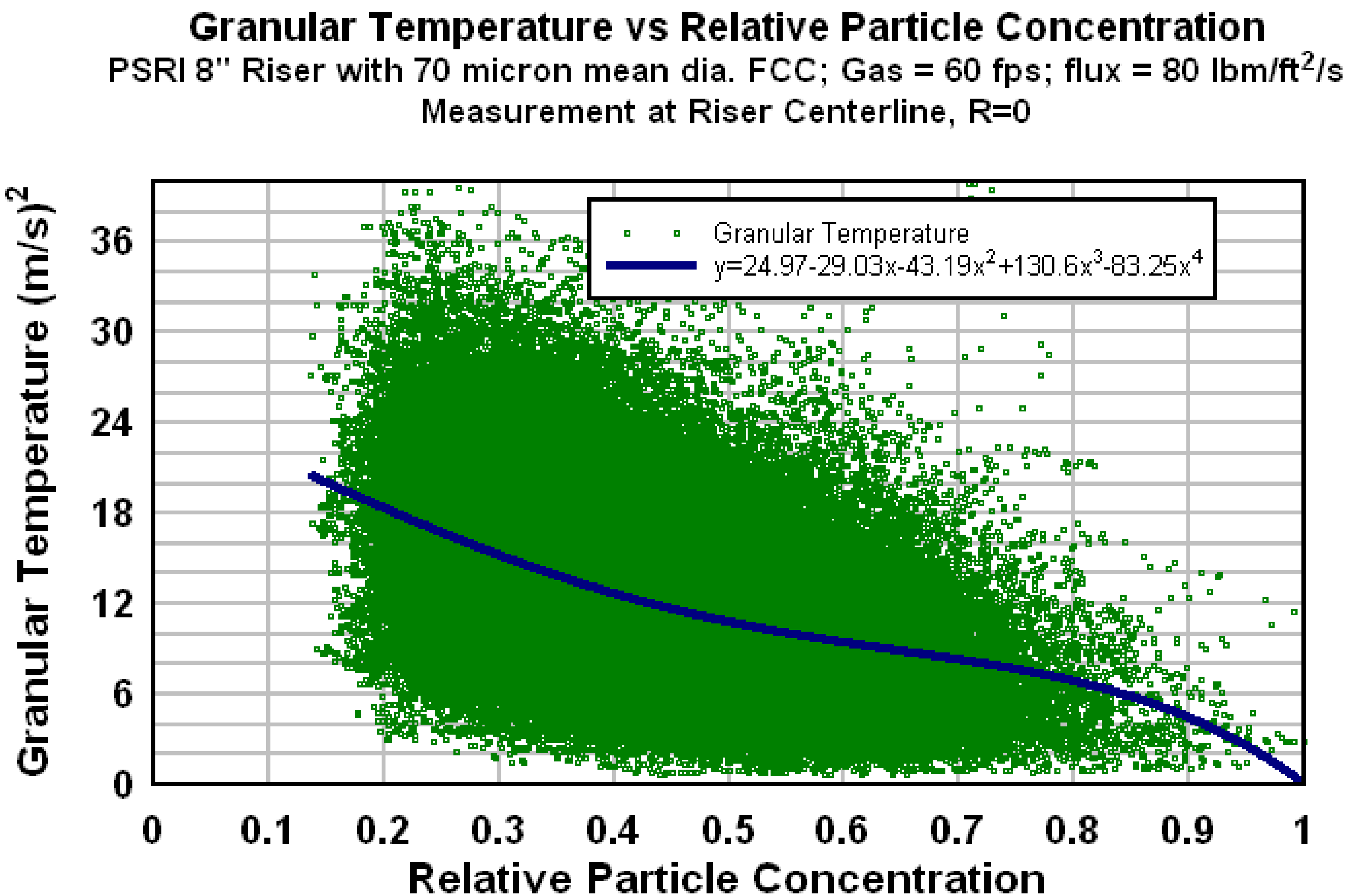

Measurement of particle velocity statistics in smaller risers
Verification and Validation data for small scale DEM simulations
Improving inlet and boundary conditions using experimental measurements
Improving the accuracy of Large scale riser simulations using MFIX, MP-PIC etc
Verification and Validation data for Full scale simulations

Summary

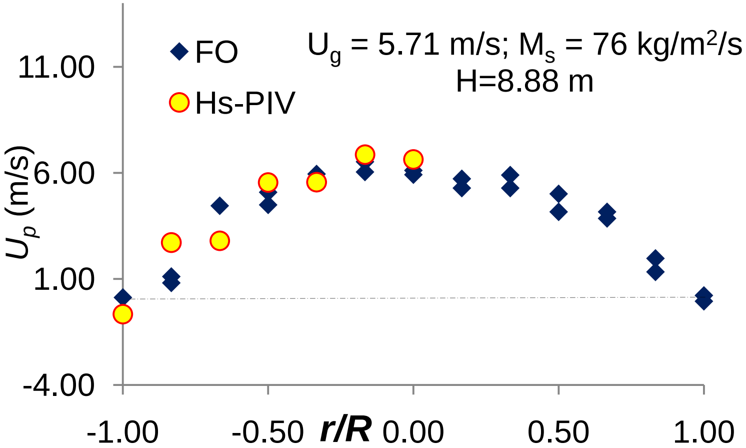
- **HSPIV measurements enable us to measure particle velocities in a riser at high spatial and temporal resolution**

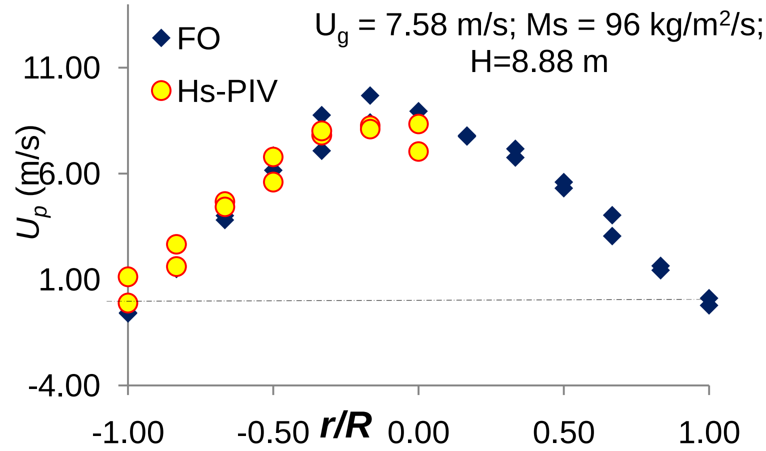
- **Higher order particle velocity statistics including RMS, skewness, velocity gradients and dispersion coefficients can be calculated from HSPIV data and are available for comparison with simulations**

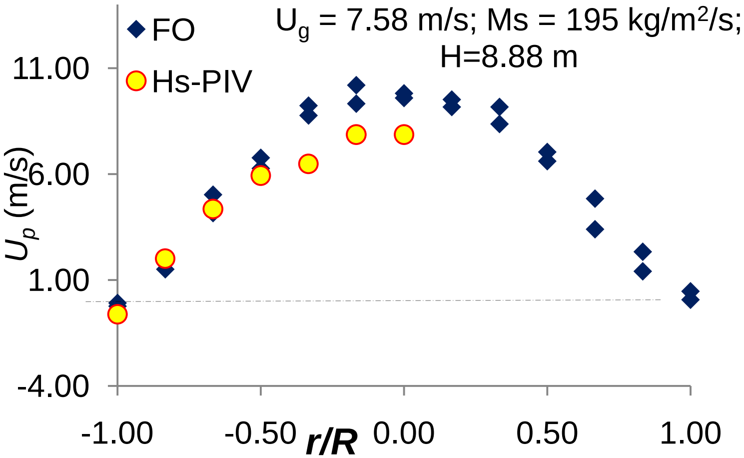
Granular Temperature Vs Relative Particle Concentration (2)



Application to PSRI/NETL Challenge Problem 2010



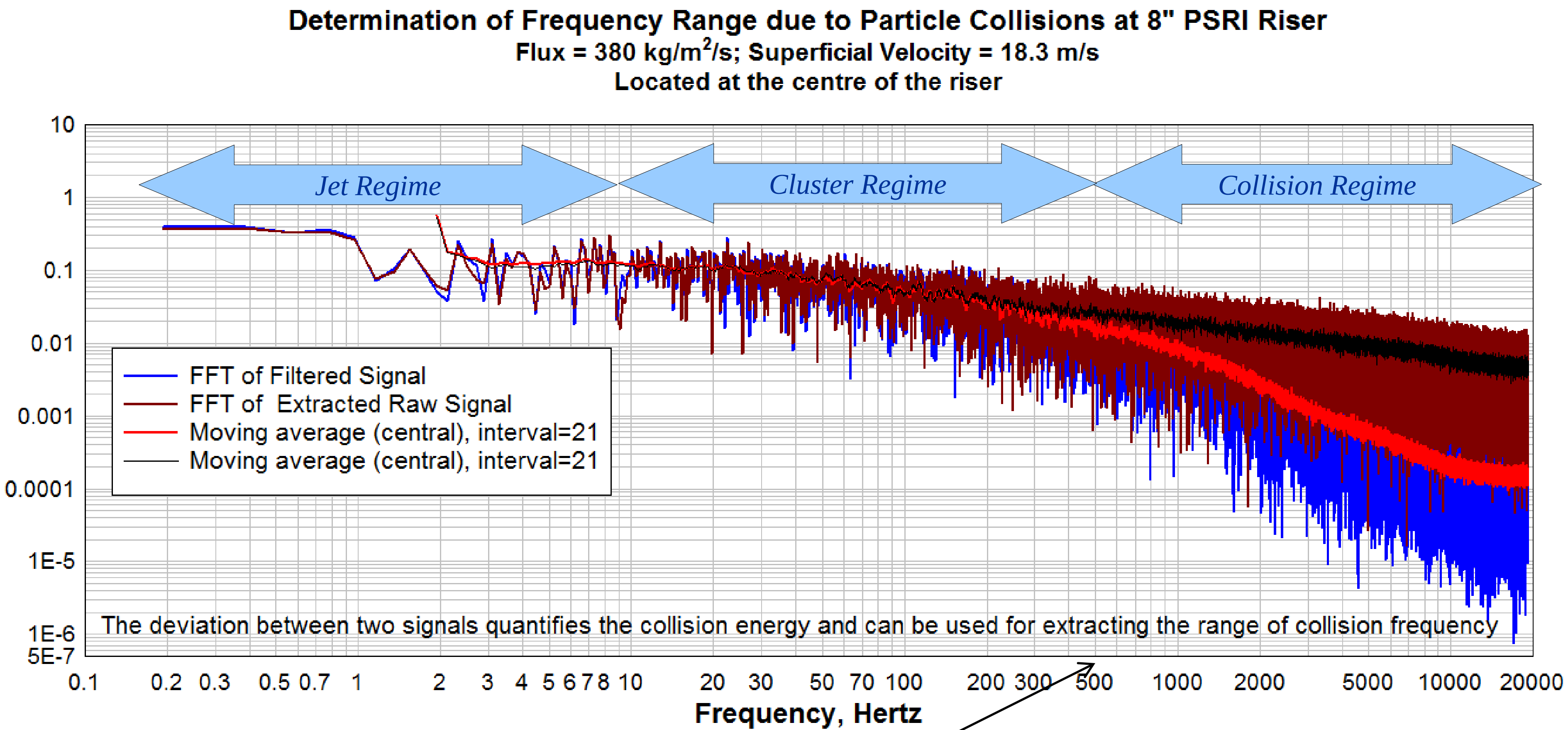




- HS-PIV has been used for measuring **mean particle velocity in NETL 12"** riser for several radial locations utilizing the borescope

- Similar data are available for particle rms velocity, granular temperature, particle velocity skewness and kurtosis to be compared with CFD modeling results.

How to obtain High Frequency Information using Eulerian Data (In Progress)



Collision Frequency $= 2\pi n d^2 v = 512\ Hz$

Prior Decomposition Methods

➢ **Standard Reynolds Decomposition: The overall mean or an ensemble mean is subtracted from the particle velocity at each instant of time.**

➢ **Decomposition using Frame Average Velocity: Particle velocities are averaged over a frame. The random component of velocity is calculated by subtracting individual particle velocities from the frame averaged value [Tartan & Gidaspow (2004)]**

$$\bar{v}_{frame} = \frac{\sum_{i=1}^{n_{vectors\_in\_frame}} v_i}{n_{vectors\_in\_frame}}$$

Random Component or Peculiar Velocity (v_r)

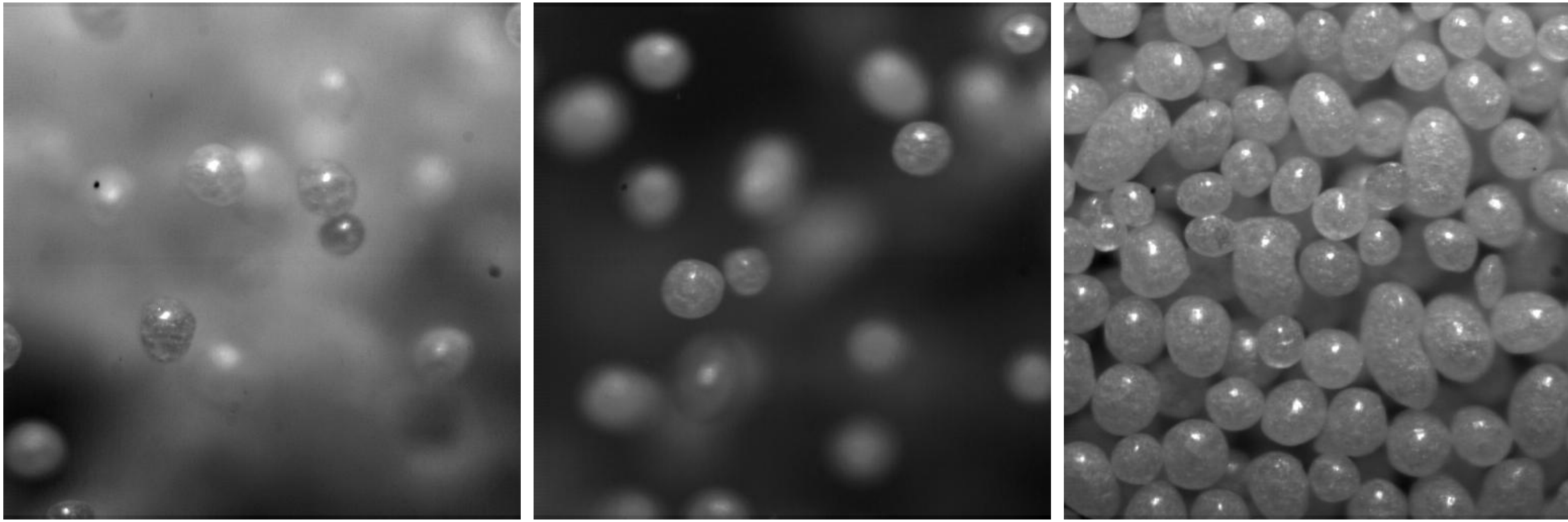
$$v = (v - \bar{v}_{frame}) + \bar{v}_{frame}$$

Hydrodynamic Velocity

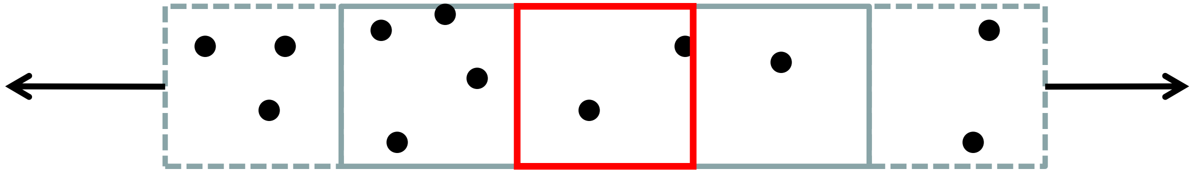
$$GT = \frac{1}{3}\sum_{i=1}^{3} v_{ri}^2$$

Local Averaging Window Method

HDPE particles on the wall of 12” NETL riser



Low Concentration **High Concentration**

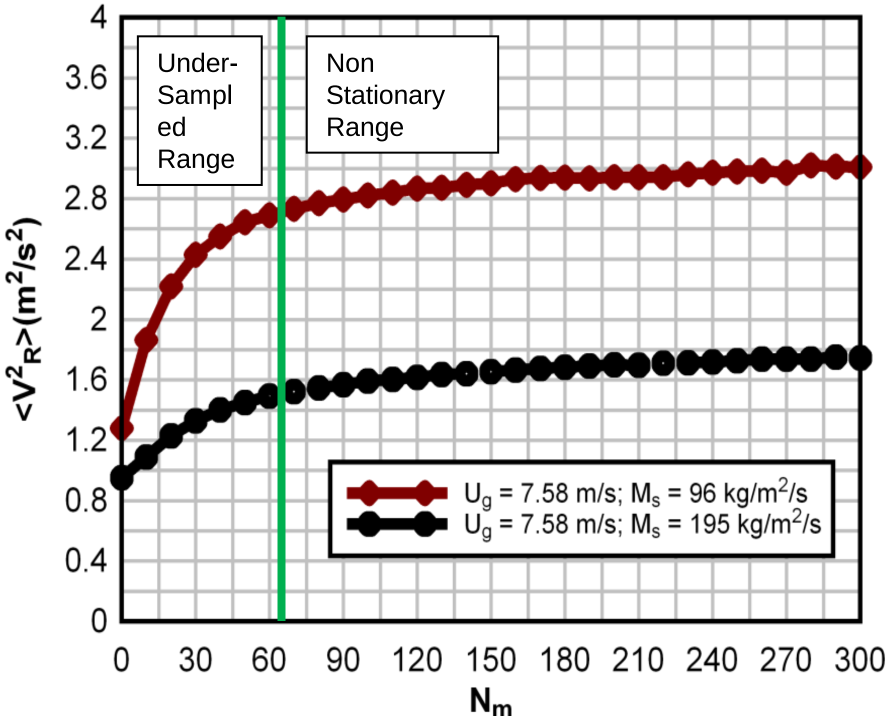


- The averaging frame size is **symmetrically expanded in either direction** to obtain enough velocity vectors

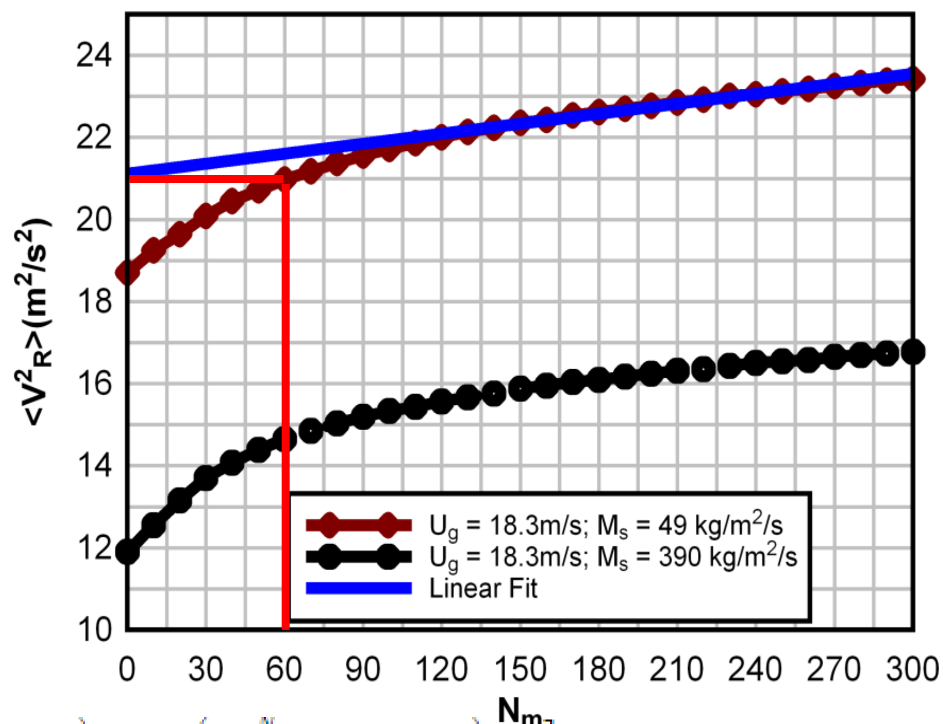
- The local mean velocity is averaged over the extended window

Selection of Optimum Size of Local Averaging Window

Centre of the NETL 12" riser



Centre of 8" PSRI riser



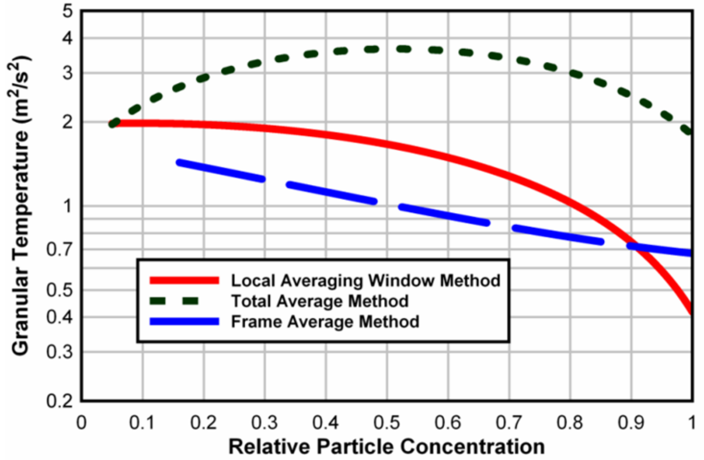
$$\langle v_R^2 \rangle = \frac{0.5}{N_{Tot}}\sum_{k=1}^{N_{Tot}}\left[\left(\frac{1}{N_p}\sum_{i=1}^{N_p}(v_i-\bar{v}_{LM})^2\right)_{Ver}+\left(\frac{1}{N_p}\sum_{i=1}^{N_p}(v_i-\bar{v}_{LM})^2\right)_{Hor}\right]$$

- The variation of v^2_R with the minimum number of particles (N_m) in extended window provides us the optimum local averaging window size

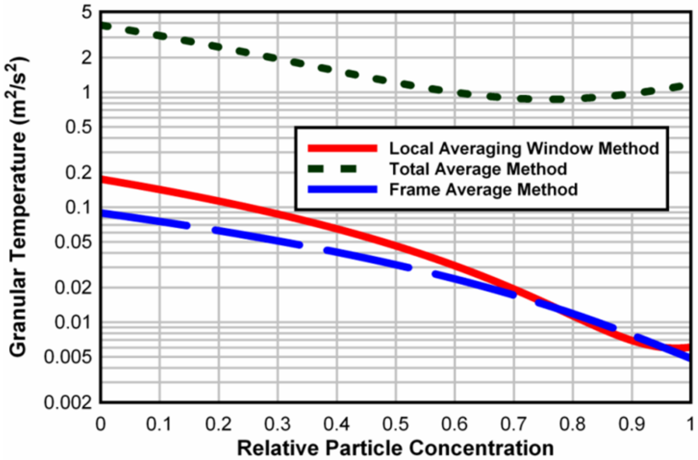
- We do see some evidence of **weak scale separation !!** (Goldhirsch , 2008)

Comparison of Granular Temperature for Different Decomposition Methods

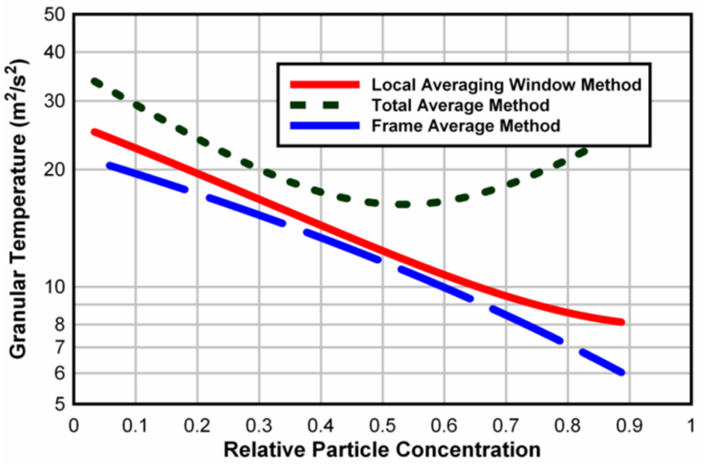
Center of riser

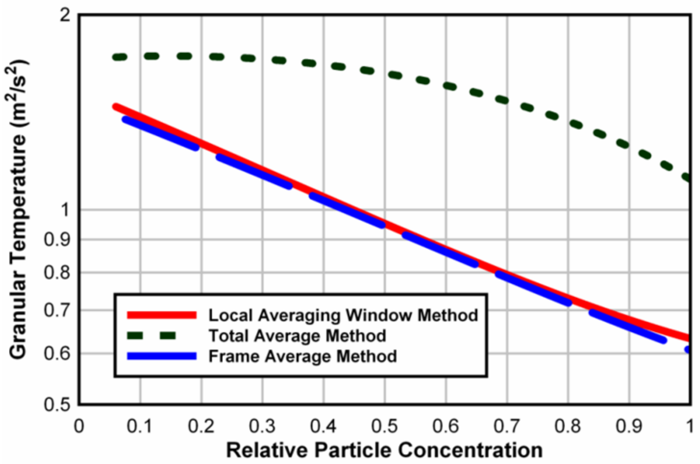


Wall of riser



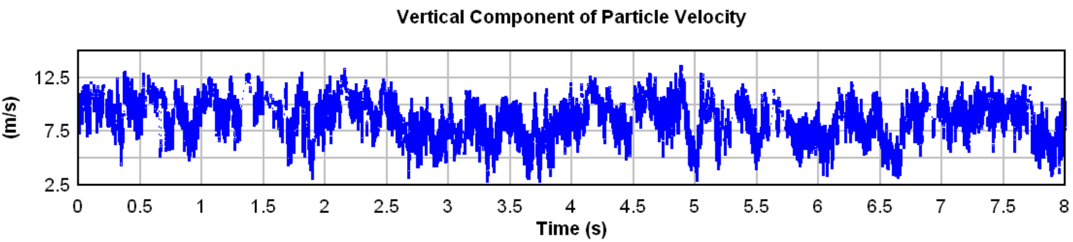
NETL 12" Riser with 800 micron HDPE; M_s = 96 kg/m²/s; U_g= 7.58 m/s

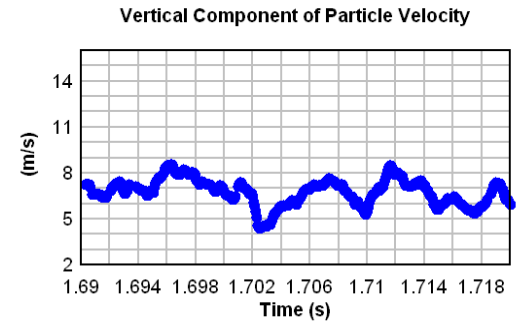




PSRI 8" Riser with 70 micron FCC; M_s = 49 kg/m²/s; U_g= 18.3 m/s

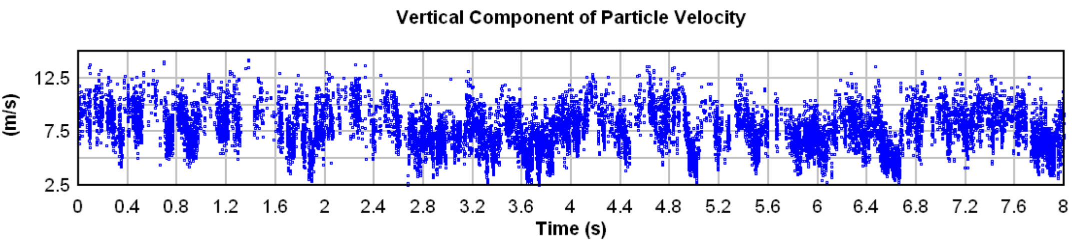
Local Average Window Method Vs Frame Average Method

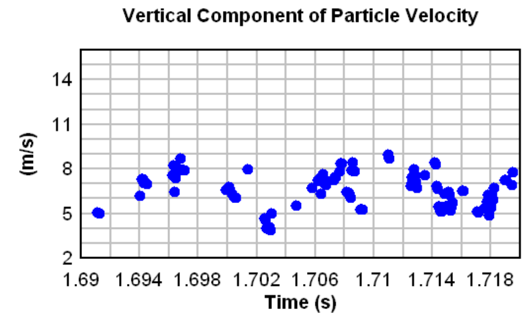




Local Average Window Method

Centre of NETL 12" Riser with 800 micron HDPE; M_s = 96 kg/m²/s; U_g= 7.58 m/s





Frame Average Method

Local average window method is superior as it provides:

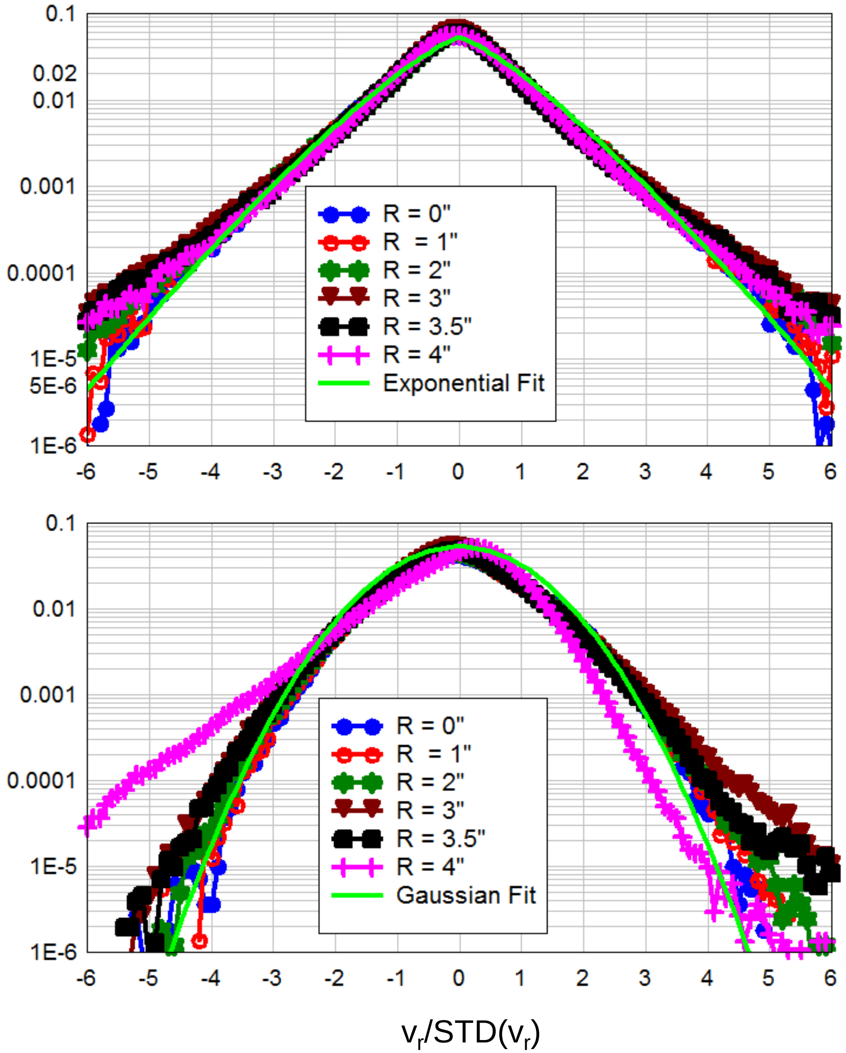
- High temporal resolution of mean particle velocity
- **Granular temperature independent of Field of View**

Centre of PSRI 8" Riser with 70 micron FCC; M_s = 49 kg/m²/s; U_g= 18.3 m/s

Field of View	GT with Local Averaging Window method (m^2/s^2)	GT with Frame Average method (m^2/s^2)
No Subdivision	17.25	15.17
2 Regions	16.93	13.33
3 Regions	17.06	12.24

Normalized PDF Random Fluctuating Particle Velocity

PSRI 8" Riser with 70 micron FCC; Flux = 380 kg/m²/s; Superficial Velocity = 18.3 m/s



Hor

Skew	Kurt
0.02	5.1
-0.01	5.4
0.03	6.1
-0.02	8.4
0.01	8.9
0.04	9.8

Ver

Skew	Kurt
0.24	3.3
0.27	3.5
0.18	3.6
0.27	4.5
0.11	4.0
-0.92	5.4

- **Exponential distribution** fits the horizontal random velocity data while vertical velocity distribution is close to **Gaussian**.
- **Is this an effect of drag ?**
- The tails get wider as we approach the wall