Chicago Workshop Summary

Below is a very brief summary, mainly in point form, of the main discussion points that were presented in the final "Summary and Discussion" session.

Lex Smits: Influences from earlier workshops:

- CICLoPE
- Focus on long, meandering structures
- Large scale array measurements in atmosphere and high Re facilities
- Major advances in channel flow computations, ongoing channel flow experiments
- Monty/Chong study of L/D effects in pipe, channel flow
- New focus on rough-wall flows
- New instrumentation, and instrumentation assessment
- Pitot/HW comparison in near-wall region
- Pipe flow computation?

Session 1: Pipe Flows, Roughness (Sreenivasan, Moser)

(see also copy of notes from Sreenivasan: Sreenivasan_Summarynotes_Session1.pdf)

Lex Smits (with James Allen and Gary Kunkel):

• Report on new superpipe experiments with roughness ($5.7\text{x}10^4 < \text{Re} < 3.5\text{x}10^7$)
• Measurements with honed surface with larger roughness
• Results indicate that "smooth" pipe data of superpipe were indeed smooth for approx. Re < $2\text{x}10^7$
• Monotonic C_f vs. Re of Colebrook fit not observed.
• Colebrook is "wrong" for a number of reasons.
• New "Moody"-diagram proposed for pipes with honed roughness
• Results may be specific to roughness type, planning experiments with industrial steel pipe.

Mike Schultz (with Karen Flack):

• Made connection with superpipe based on $k_s < 3k_{rms}$
• For large roughness, effects only extend to $< 3k_s$
• General support for Townsend's hypothesis
• Organized roughness elements (e.g. bars) may have effects in outer layer

Beverley McKeon:

• Consideration of inertial scaling and “mixing transition”
• No transport in *y* in log-region, have scale separation in part of log region
• “Mixing transition” for Re > 75,000
• Complete similarity for Re > 300,000

Jonathan Morrison:

• 2nd order structure functions and spectra used to deduce influence of outer scales on inner region.
• Suggests outer influence at large scale. In general the outer influence is weak.

Jason Monty (with Min Chong):

• Report on very recently obtained investigation of development length requirements for turbulent pipe flow up to L/D = 175
• Mean flow and turbulence statistics shown (including Reynolds stresses, skewness and flatness)
• Similarity observed for mean flow and second order statistics after 50D
• Not true for ducts/channels!

Casimir van Doorne:

• Time-resolved stereo-PIV measurements in transitional pipe-flow
• Relationship between puffs and unstable traveling waves investigated
• PIV measurements of puffs indicate similar structure to some features of traveling wave solutions.

Gary Kunkel:

• Issues of the “freestream” flow in the Princeton High Reynolds number facility have been re-examined. Work has been done to correct flow
• Report on fabrication of “nano-hotwire” (20nm x 20nm x 2μm)
• Have yet to make it work, with main remaining task being to lift the sensing element off the large substrate. However, progress has been steady.

Allesandro Talamelli:

• Progress on CICLoPE initiative: some funding secured, donation of tunnels (almost)
• Further funding required (< 4M euro)
• Renovation/initial construction on year time scale
• Ivan Marusic gave report on First Symposium on CICLoPE. Main sentiment from meeting was that the initial pipe facility be only the start of an international collaborative research center.

Talking points from Session 1:

• New superpipe experiments with roughness clearly show that the Colebrook formulation is not generally applicable. Speculation raised that the "monotonic"-Colebrook curve-fit may apply for roughness with a broad distribution of roughness elements, while an "inflectional" profile applies for sand-grain type roughness or roughness types that have a Gaussian distribution of roughness scales.
• Concern raised that we may need a new "Great book of roughness profiles".
• Monty/Chong experiments seen as good news for CICLoPE.
• Issue of spatial resolution discussed. Some uncertainty remains as to what the required resolution needs to be in l^+ and/or l/η units.
• λ_s and η scale differently in wall, intermediate and outer regions and issues of "adequate resolution" require possible further study.
• DNS of long turbulent pipe flow complicated and expensive, and not worthwhile unless compelling questions can be identified.

Session 2: Structure and Organized Motions (Narasimha; Chong)

Ron Adrian:

• Contributions from LSM vs VLSM considered by partitioning spectra. Approx. 50-50 contribution found – cf. earlier distinctions between weak large eddies versus energy-bearing eddies/scales.
• k^{-1} apparent from "bridge" between VLSM/inertial subrange

Javier Jimenez:

• DNS of large channel carried out up to $Re_\tau = 2k$
• Vortex clusters identified with associated long 'conical wake'
• Clear evidence of near-wall influence of outer-scaled motions

Kaoru Iwamoto:

• DNS of channel at $Re_\tau = 2.3k$
• Hierarchical large structures
• p-ε changes sign several times in y: 2 maxima and 3 minima
• Complex transport?

Ivan Marusic and Nick Hutchins:

• 'Superstuctures' another term for VLSM, but what causes these large structures is not clear. Characterized by large streamwise extent up to 20δ with notable meandering in spanwise direction.

• Increasing "strength" with increasing Reynolds number, and clear influence down in viscous buffer region – supports mixed scaling for streamwise and spanwise intensities.
• Experiments compared across 3 orders of magnitude of Re_τ – R_{uu} scales on δ.

Ken Christensen:

• Relative to vortices having the same sense of rotation as Ω_z, a significant number of opposing sign vortices exist channels and boundary layers
• The distributions and Reynolds number dependencies of the population statistics of these vortices in boundary layers and channels are different
• There is a strong tendency for the appearance of counter-rotating pairs of vortices.

Takahiro Tsukahara

• Low Re puffs in channel flow propagating at bulk velocity

Talking points from Session 2:

• Structures: Terminology is still an issue with differing interpretations of causal relationships (cf. Roshko's cartoon of elephant and blind men?)
• Relation between LSM, VSLM, superstructure, vortex/cluster wake, hierarchical structures, packets, spots/puffs: Synthesis/conflict?
• Sreenivasan raised possibility that "very long streamwise motions" could be statistical artifact with no underlying physical mechanism causing them.
• Significant energy resides at very low wavenumbers – different to Townsend description.
• Need for experimental 2-D spectra
• Narasimha described experiments in early 1970's in Thar India also showing large scales motions with significant influence on near-wall events – cf. Marusic *et al* Utah results using array of sonic anemometers.

Session 3: Scaling I (Smits; McKeon)

Peter Davidson:

• Model study, based on artificial turbulence made up of Gaussian eddies with the same K.E. scale (so that k^{-1} scaling enforced in 3D spectrum) appears to model boundary layer results well.
• Emphasizes usefulness of structure functions (2nd and 3rd order) as diagnostics for scaling.
• 1-D spectra are not a good diagnostic due to aliasing.
• $<(\Delta u)^2>$ does better, although it is still a leaky filter (allows contributions from enstrophy above scale r).

Carlo Casciola (with Renzo Piva):

• Investigation of small-scale isotropy by expansion of 2^{nd} order structure function in terms of spherical harmonics (j=1 is isotropic part).
• For linear shear flow $R_\lambda \sim 160$ (numerically and experimentally).
• Shear has significant effects on anisotropy of small scales and dissipation tensor.
• Isotropy recovered for wall-bounded flows far from the wall in the log layer, but as shear increases near wall ($S^*/h = S_c$ decreases), flow becomes more anisotropic.

Joe Klewicki:

• Examined scale selection in contribution to momentum transfer in terms of cospectra of v and ω_z, starting with decomposition of -<uv> gradient in terms of velocity/vorticity plus small streamwise gradient of K.E.
• Spectra of v and w_z separate in k-space with Reynolds number (depending on the velocity/vorticity components involved, scale separation occurs at significantly different rates with increasing Reynolds number).
• In contrast to expectation that cospectrum will peak in the overlap region, peaks of opposite sign appear near peaks in v and w_z, demonstrating scale selection.

Meredith Metzger:

• Plug for SLTEST: review of past experiments, open for future business (she is the contact).
• Examined scaling of the near-wall peak in streamwise intensity using inner and mixed scaling.
• Consequence of $u^+_{max} \sim \log Re_q$ with $u^{mixed}_{max} \sim$ const is $U^+_{inf} = a \log Re_q + b$
• Extended region of (not self-similar) k^{-1} scaling where mixed scaling works, with implications for scaling u^+_{max} .

Katepalli Sreenivasan:

• Power of logarithmic expansion as a tool for finite Reynolds number correction
• Works well for -<uv>, S_3
• Physically: thickness of vortex filaments (ubiquitous feature of turbulence) is $O(\lambda)$ and instability considerations give $\ln R_\lambda$, # of cascade steps ~ ln Re, etc.
• U^+ as a perturbation of laminar solution

Bob Moser:

• Small separation two-point correlations in the log layer (to construct optimal LES models)
• Where is small-scale local isotropy valid in wall-bounded flow? Expect we're OK for r/h <<1 far from the wall.
• Indeed ΔR_{ij} approximately self-similar for r<<h (can account for viscous scales) and almost isotropic, approaching Kolmogorov 2/3rds law near centerline.
Looking for k^{-2} scaling in 2-D spectrum avoids confusion due to integration over non self-similar parts in 1-D spectrum.

Peter Monkewitz (with Kapil Chauhan, Hassan Nagib):

• Consistency of constants in log and friction laws sets constraints
• Clauser-Rotta D a superior scale to L although this introduces both d and scale of the streamwise variation
• Is $B(R^+)$ (i.e., effect of outer flow on the log layer) unexpected?
• Determination of these issues requires very high measurement accuracy (<0.1% in U^+) and unrealistically large Reynolds numbers

Talking points from Session 3:

• Are we talking about two-layer or multi-layer structure?
• How do we define the overlap region (eddies scaling on y, constant stress, scale separation, inertial sublayer…) and its limits? Where does roughness, pg come in?
• Mean velocity is a poor indicator function for scaling
• 1-D spectrum is poor indicator function for scaling – structure functions "better"
• BUT: should explore scaling on turbulence which can lead (by integration) to lower order scaling. Example: spectral scaling u_iu_j (Perry, Marusic, Chong etc)
• Need for a diagnostic that is not so critically dependent on measurement accuracy
• What can we measure on earth? Terrestrial Re gives U^+ = 20-40
• Framework for finite Reynolds number corrections – intermediate asymptotics?
• Pipe vs b/l: long structures have different geometrical constraints
• Pipe/channel vs. b/l: interaction from opposing wall

<u>Session 4: Scaling II (Adrian; Klewicki)</u>

Tim Nickels:

• The k^{-1} region in the axial velocity spectrum appears in for a region close, but not too close to the wall.
• To attain one decade in this region one must reach a δ^+ of about 50,000
• Spatial resolution is a significant confounding factor

Hassan Nagib (with Kapil Chauhan and Peter Monkewitz):

• Karman "constant" (coefficient) is constant for zero-pressure-gradient for $R_\theta > 8k/12k$ but function of pressure gradient.
• Otherwise largely confirmatory of classical picture, using Rotta Δ.
• Power laws do not seem to apply.

Ron Panton:

• Used a composite expansion model of the mean profile to explore the approach to asymptotic behavior.
• Provided estimates of how high Re must be to determine κ to within a certain accuracy.
• The question of two slopes in the mean profile (and the possible Re dependence in their location) ensued.

Noor Afzal:

• Used an inner/outer matching framework.
• Employed a roughness function and a roughness velocity.
• Determined a transformation that allows the normalization of rough wall data such that mean profile equation has the same form as it does for the smooth wall.

Gunnar Johansson:

• Wall shear stress is determined from measurements of all terms in the integrated momentum equation.

• The pressure gradient contribution to the integral momentum equation is significant even in "nominally" zero pressure gradient flows.

Jens Fransson:

• Presented high Re pressure fluctuation data from the KTH tunnel
• Pressure variance scales best on outer variables
• Wall pressure appears to scale best on mixed scaling
• Was able to closely reproduce the v rms profile from pressure

Talking points from Session 4:

• k^{-1} behaviour is noted in different parts of boundary layer for different reasons.
• See issues raised in session 3.