Jet noise modelling within a generalized acoustic analogy approach

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Outline

- Motivation
- Goldstein generalized acoustic analogy (GGAA)
- Jet noise modelling
  - Single-stream jet modelling results
  - Non-uniqueness of calibration parameters
  - Dual-stream jet modelling results
- 4th-order correlation function similarities (LES post-processing)
- Conclusions

Motivation for Goldstein Generalised Acoustic Analogy

Goal: development a robust suite of CAA tools at different levels of fidelity – from low-level model based on RANS to high-fidelity LES post-processing

with including more physics:

- **Preserving the same dispersion relation as of the original NS equations, e.g., capturing full sound meanflow propagation effects**
- **Fluctuating Reynolds stress and enthalpy effects are generically included in the same formulation (same goes to co-flow effects, solid surfaces, etc)**
- **In comparison with the integral surface methods, a complete source information is provided (various possibilities for low-order modelling)**

Generalized Goldstein acoustic analogy

$$\rho' \equiv \rho - \overline{\rho}, \quad p' \equiv p - \overline{p}, \quad h' \equiv h - \tilde{h}, \quad v_i' \equiv v_i - \tilde{v}_i,$$

$$\mathrm{D}_0 \rho' + \frac{\partial}{\partial x_j} u_j = 0,$$

$$\mathrm{D}_0 u_i + u_j \frac{\partial \tilde{v}_i}{\partial x_j} + \frac{\partial}{\partial x_i} p_e' - \frac{\rho'}{\overline{\rho}} \frac{\partial}{\partial x_j} \tilde{\theta}_{ij} = \frac{\partial}{\partial x_j} e_{ij}'',$$

$$\mathrm{D}_0 p_e' + \frac{\partial}{\partial x_j} \widetilde{c^2} u_j + (\gamma - 1)\left(p_e' \frac{\partial \tilde{v}_j}{\partial x_j} - \frac{u_i}{\overline{\rho}} \frac{\partial \tilde{\theta}_{ij}}{\partial x_j} \right) = \frac{\partial}{\partial x_j} e_{4j}'' + (\gamma - 1) e_{ij}'' \frac{\partial \tilde{v}_i}{\partial x_j},$$

$$p_e' \equiv p' + \frac{\gamma - 1}{2}\left(\rho v'^2 - \overline{\rho} \widetilde{v'^2}\right) \qquad u_i \equiv \rho v_i'$$

$$e_{\mu j}'' \equiv e_{\mu j}' - \overline{e_{\mu j}'}, \qquad \tilde{\theta}_{ij} \equiv \delta_{ij} \bar{p}_e - \overline{e_{ij}'}$$

$$e_{\nu i}' \equiv -\rho v_\nu' v_i' + \delta_{\nu i} \frac{(\gamma - 1)}{2} \rho v'^2 + [\sigma_{\nu i} + (\gamma - 1) \delta_{\nu 4} \sigma_{ik} v_k']$$

$$v_4' \equiv (\gamma - 1)\left(h' + \tfrac{1}{2} v'^2\right) = (c^2)' + \frac{(\gamma - 1)}{2} v'^2,$$

[Goldstein & Leib, 2008]

Acoustic analogy model for cold jets reduces to a volume integral of the statistical source and the Green's function

Pressure power

$$S(w,x) = \int_{V_y}\int_{V_\Delta} \hat{R}_{ijkl}(y,\Delta,w)\hat{\gamma}_{ij}(y-x,w)\hat{\gamma}^*_{kl}(y+\Delta-x,w)\,d\Delta\, dy$$

where

$\hat{\gamma}_{ij}(y-x,w)$ - complex Green's functions

$$\hat{R}_{ijkl}(y,\Delta,w) = \int R_{ijkl}(y,\Delta,\tau)e^{-iw\tau}d\tau = \int \overline{e''_{ij}(y,t)e''_{ij}(y+\Delta,t+\tau)}e^{-iw\tau}d\tau$$

$$e''_{ij}(y,t) = -\left(\rho v'_i v'_j - \overline{\rho v'_i v'_j}\right)$$

Needs modelling

Fluctuating Reynolds stresses

Current low-order 7-parameter acoustic source model

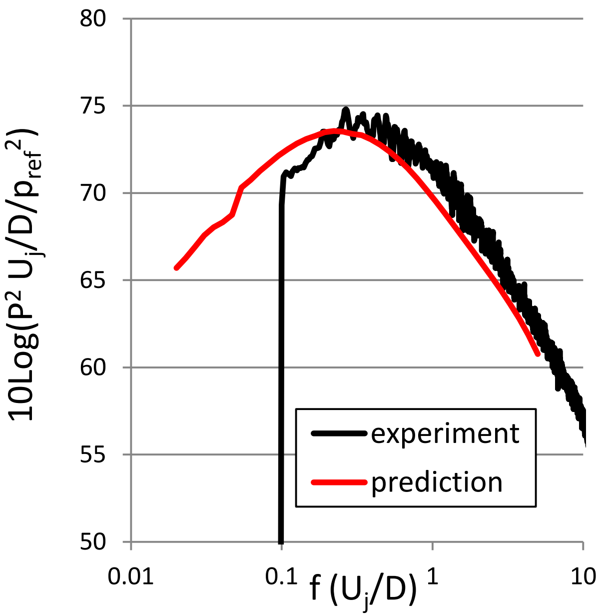
- Gaussian space-time domain model for 2-point 2-time Reynolds Stress covariance function (different to the non-Gaussian domain model of L&G2011)
- Main Reynolds stress components are: R_{1111}, R_{2222} ,R_{3333} , R_{1212} , R_{1313} , R_{1122},R_{1133} (1-axial, 2-azimuthal, 3-radial)
- Amplitude R_{1111} scaled on T.K.E. =1 shape function parameter and 6 relative amplitudes: R_{ijkl}/ R_{1111} are prescribed from L&G2011
- Stream-wise and tangential length scale, time scale: 2 groups = (i)1111, 2222,3333, 1122,1133 and (ii) 1212,1313; scaling based on T.K.E. and ε (lesser number than in L&G2011) -> +6 model parameters
- Eddy convection speed is defined based on the local jet velocity (different to L&G2011)
- Compact eddy scale approximation: (i) variation of the Green's function in the radial direction is much slower than that of the turbulent source, (ii) variation of the Green's function in the stream-wise direction can be represented by a phase change (similar to WKBJ approximation):

L&G2011 model implementation is in progress

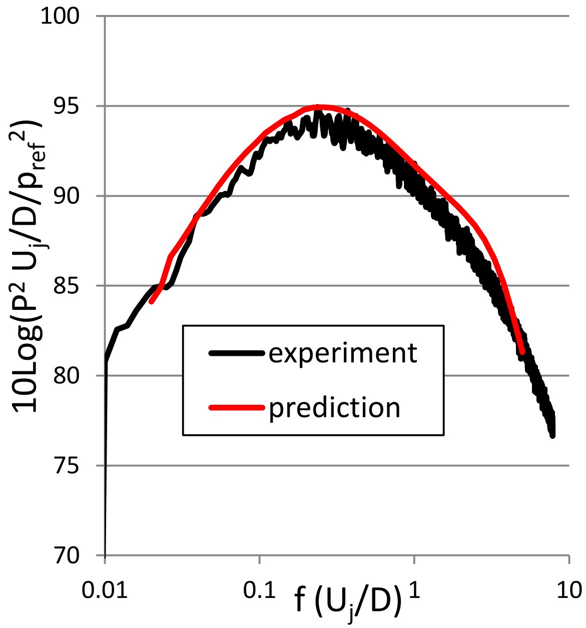
Single-stream SHJAR cases: 90^0

Low order model based on RANS + model parameter set #1

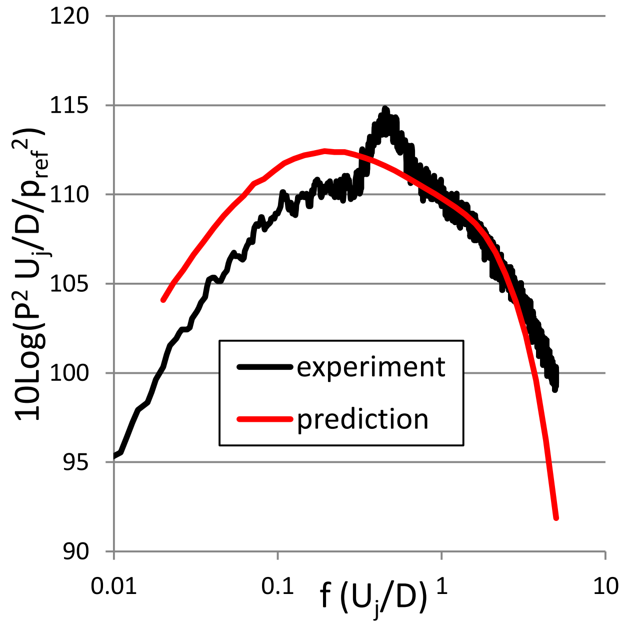
M=0.5, 90^0



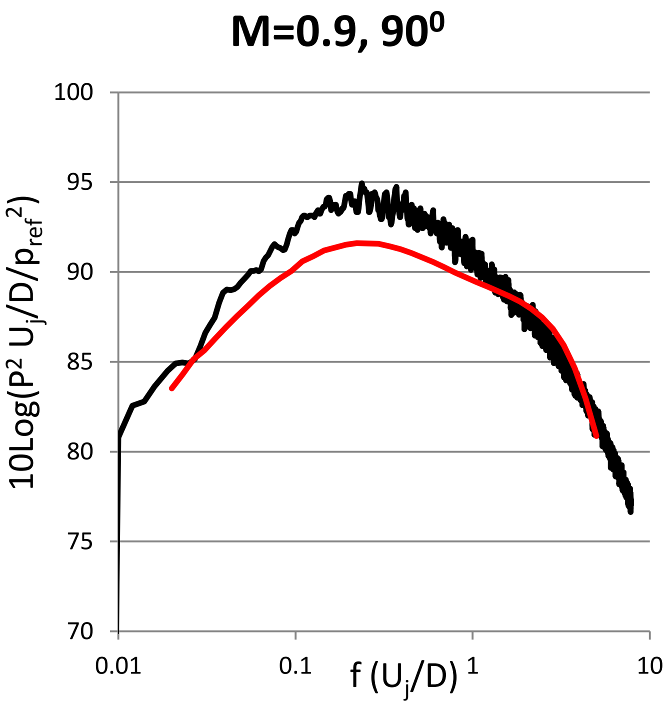
M=0.9, 90^0

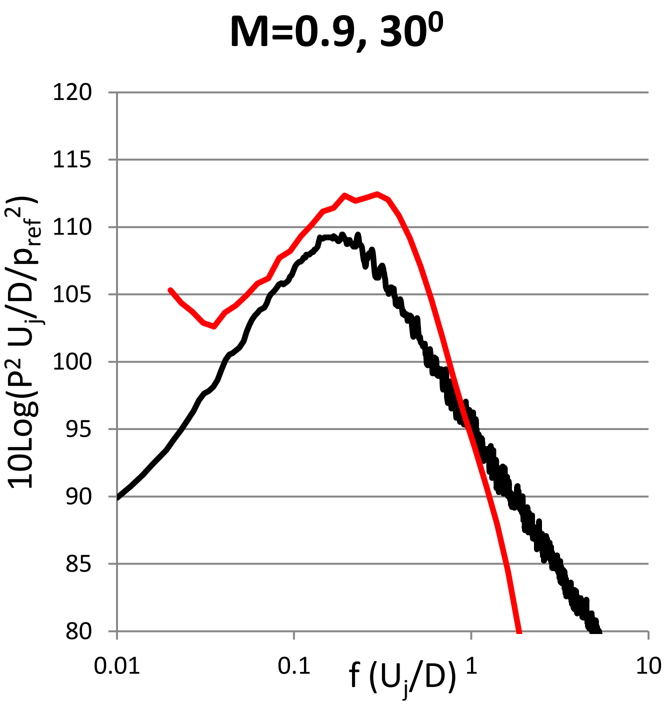


M=1.4, 90^0



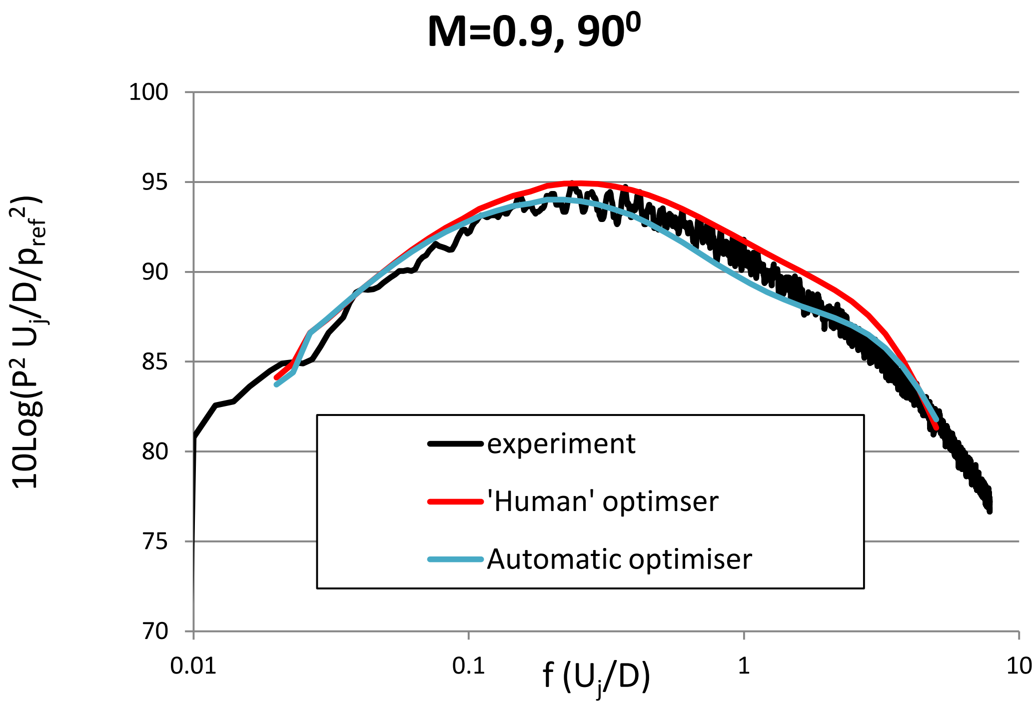
Single-stream SHJAR case M=0.9
Low order model based on RANS
+ model parameter set #2





Propagation: linearised Euler equations in the frequency domain

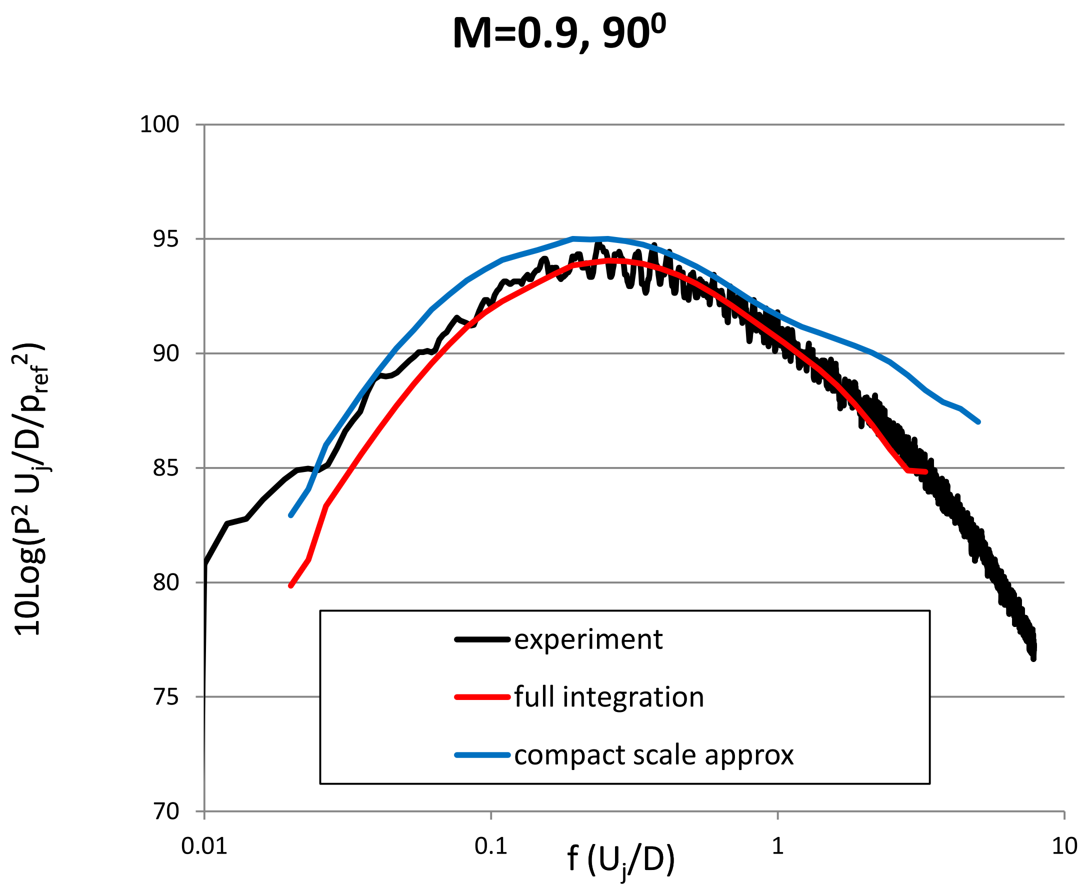
Automatic calibration of the acoustic model?



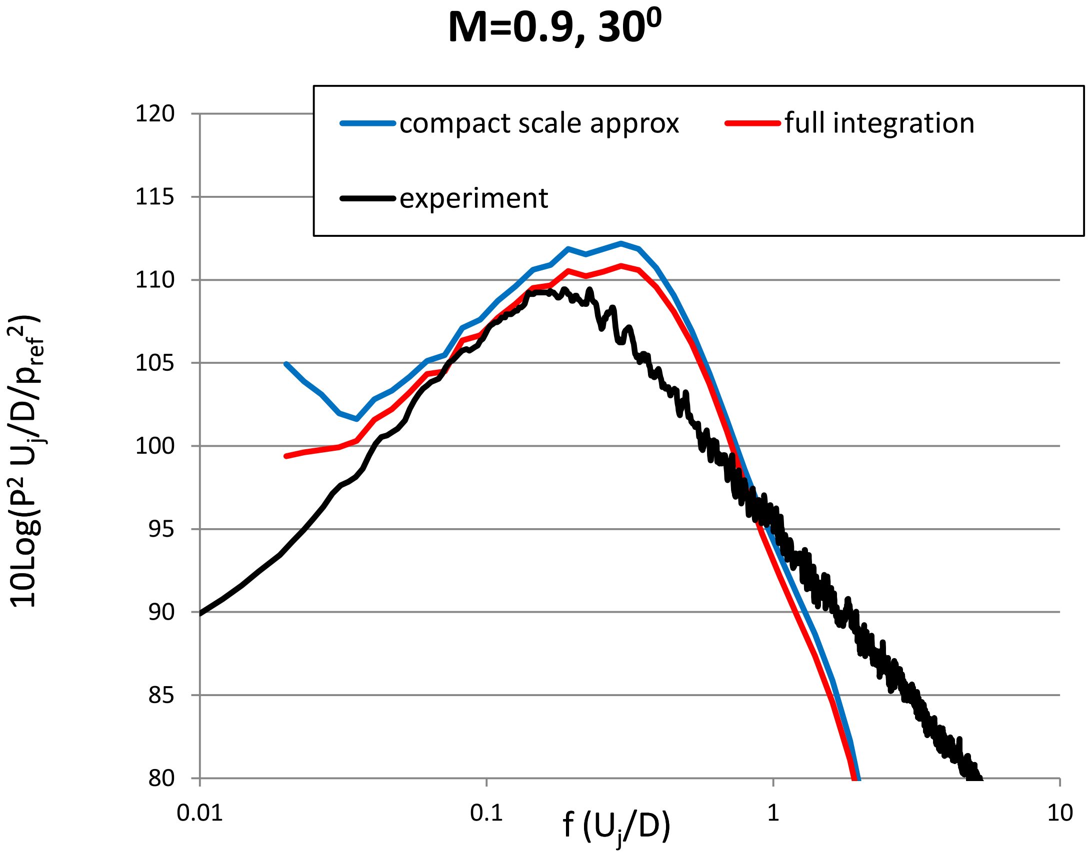
The work based on optimisation algorithms for other jet cases is in progress in collaboration with the group of Prof Toropov in QMUL

NB: Calibration constants leading to the same far-field noise prediction from the 'human' optimiser and the automatic optimiser are different!

Effect of the compact eddy scale approximation: 90 deg, M=0.9 case



Effect of the compact scale approximation: 30 deg, M=0.9 case

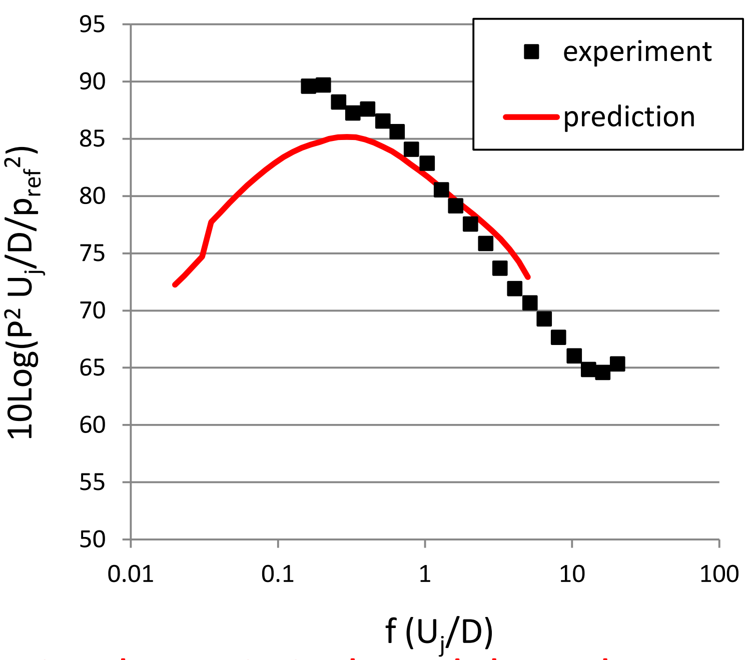


Within the accuracy of the current low-order Gaussian source model, the compact eddy scale approximation is reasonable

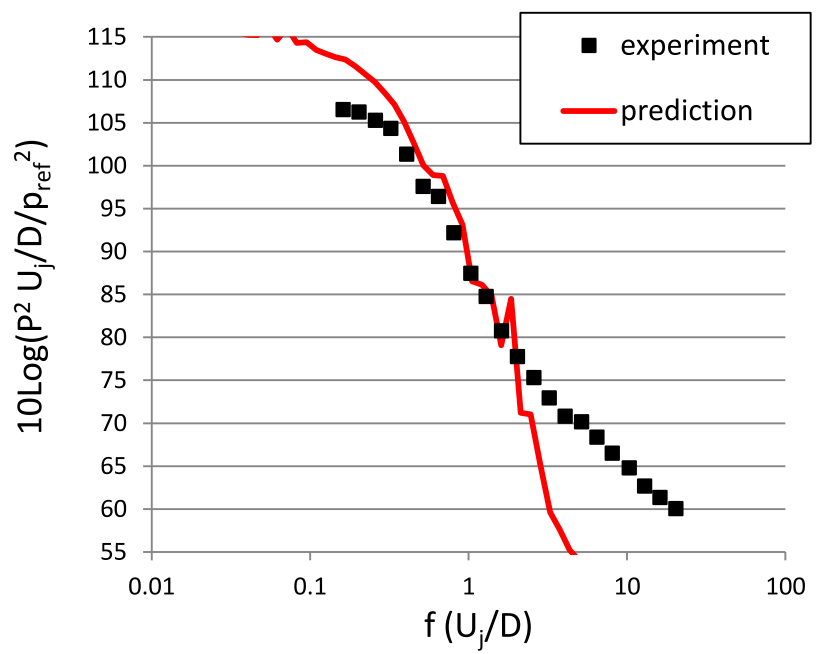
Extension to dual-stream jets co-axial, BPR=8, static

Low-order model based on RANS
+ source model parameters#1

90^0



30^0

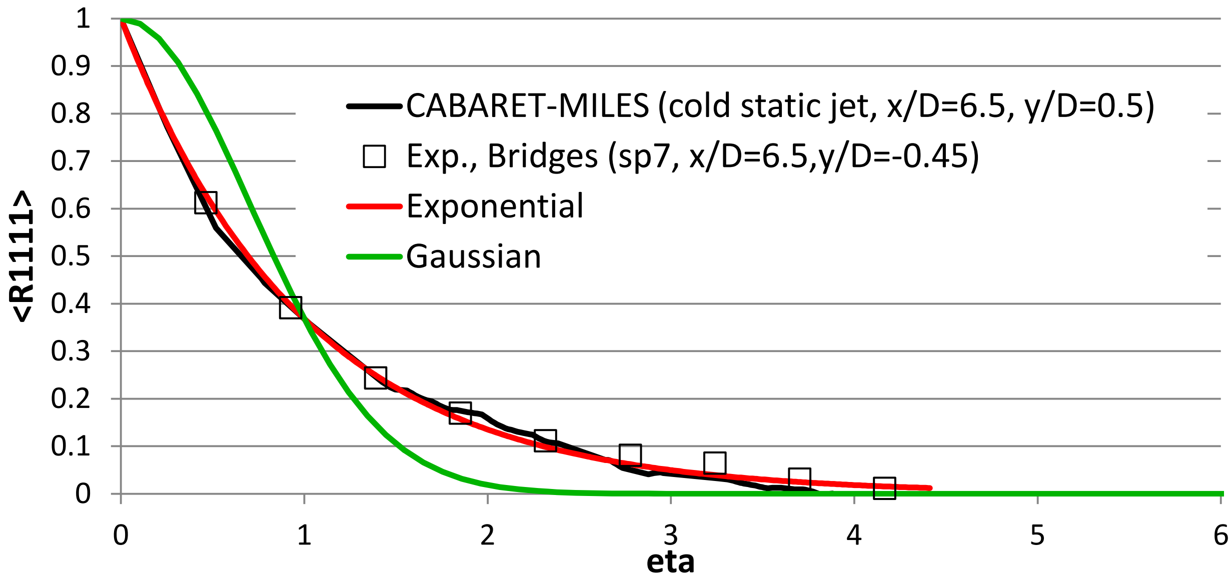


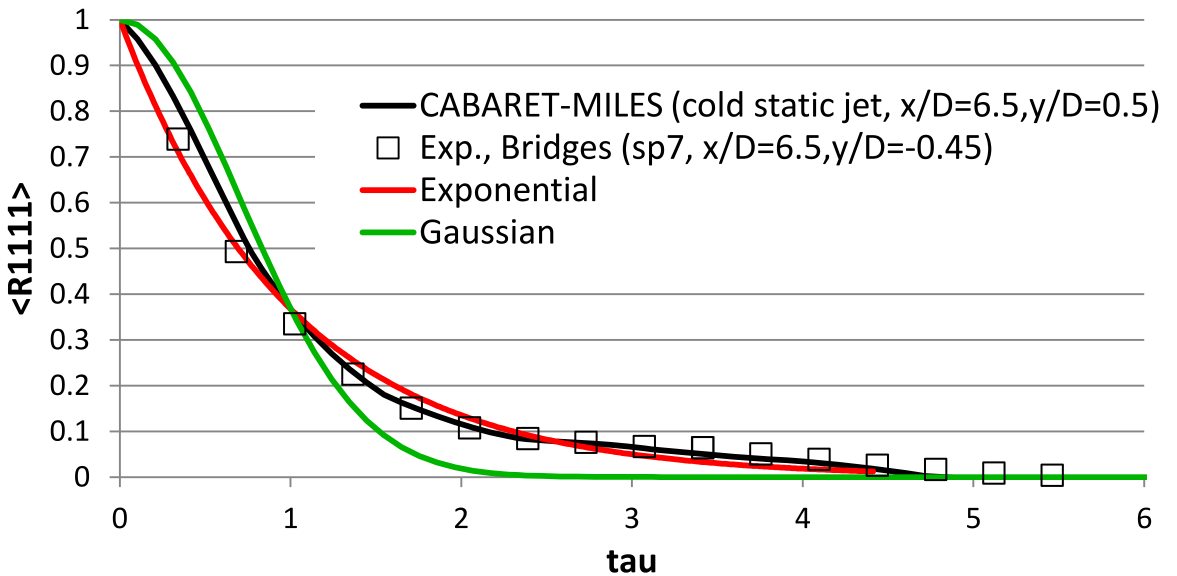
Simple statistical models such as Tam & Auriault 1999 or Morris &Farassat 2002 are applicable for 90^0 and lead to significant (~10dB+) noise underprediction for small angles

Sensitivity to the model parameters needs to be evaluated (not always available from the experiment):

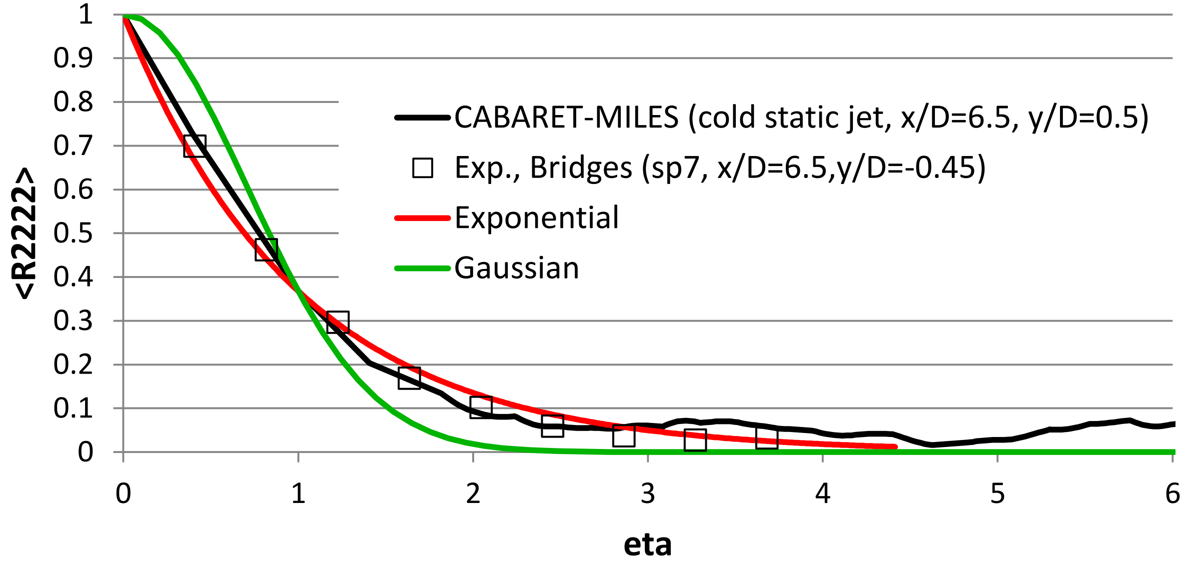
- **Use of LES as a post-processing tool?**
- **Length scales, source function shapes?**

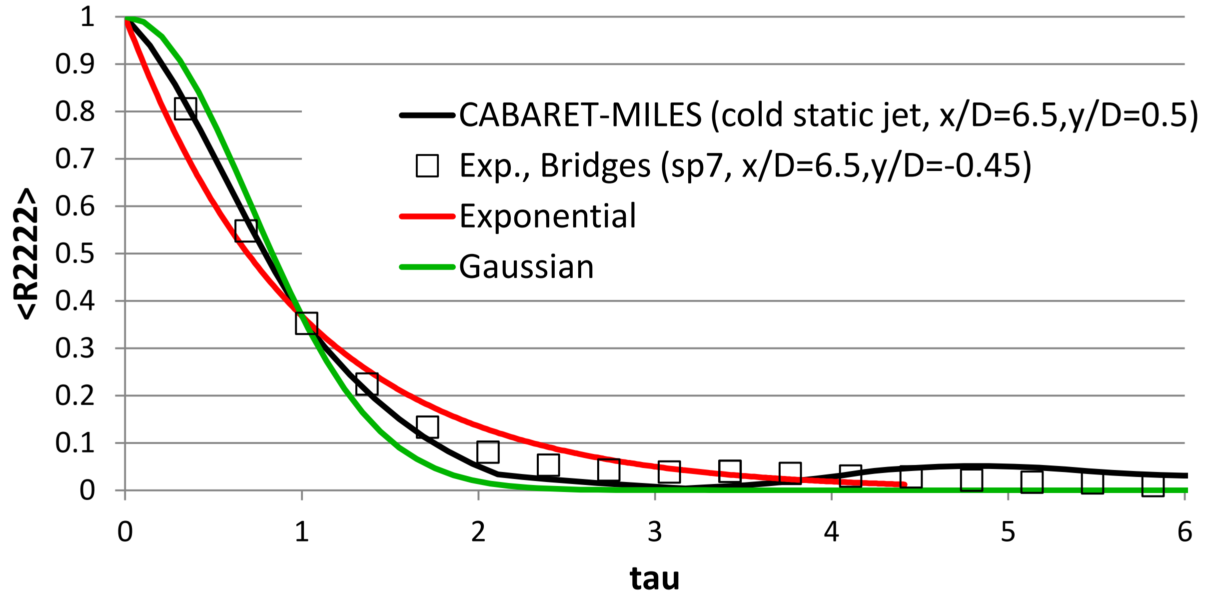
Reynolds stress covariance vs the Bridges experiment, axial scales, time domain: R_{1111}





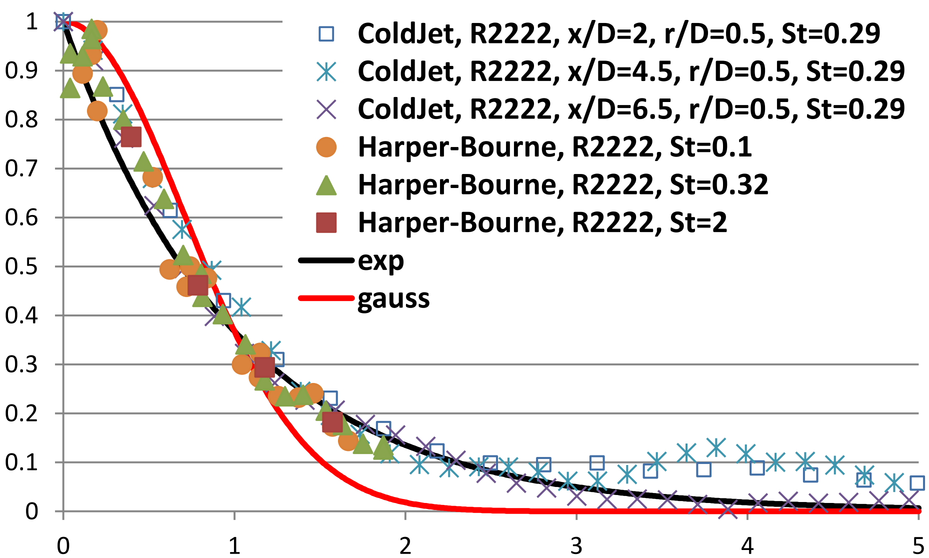
Reynolds stress covariance vs the Bridges experiment, axial scales, time domain: R_{2222}



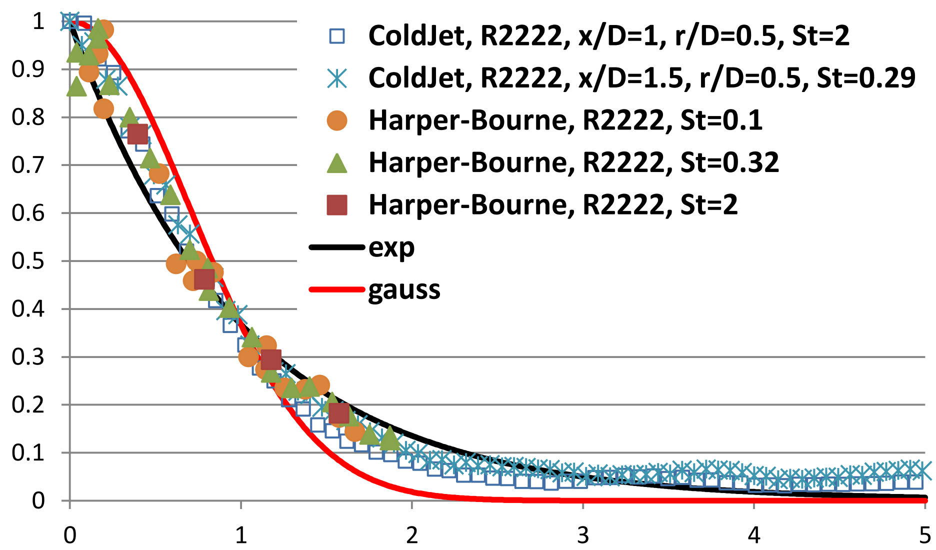


Frequency domain Reynolds stress covariance vs the Harper-Bourne experiment, axial scales

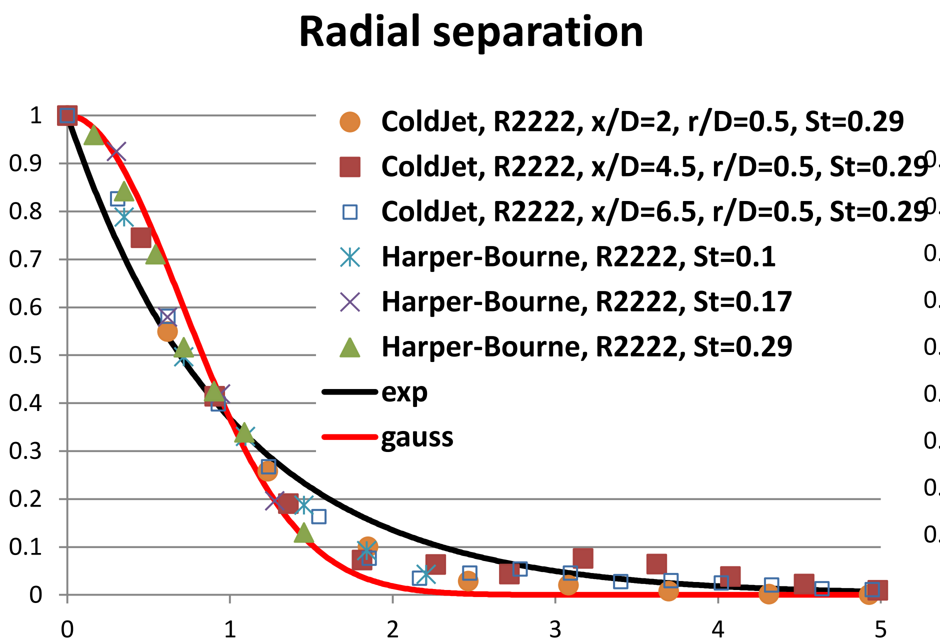
Axial Separation

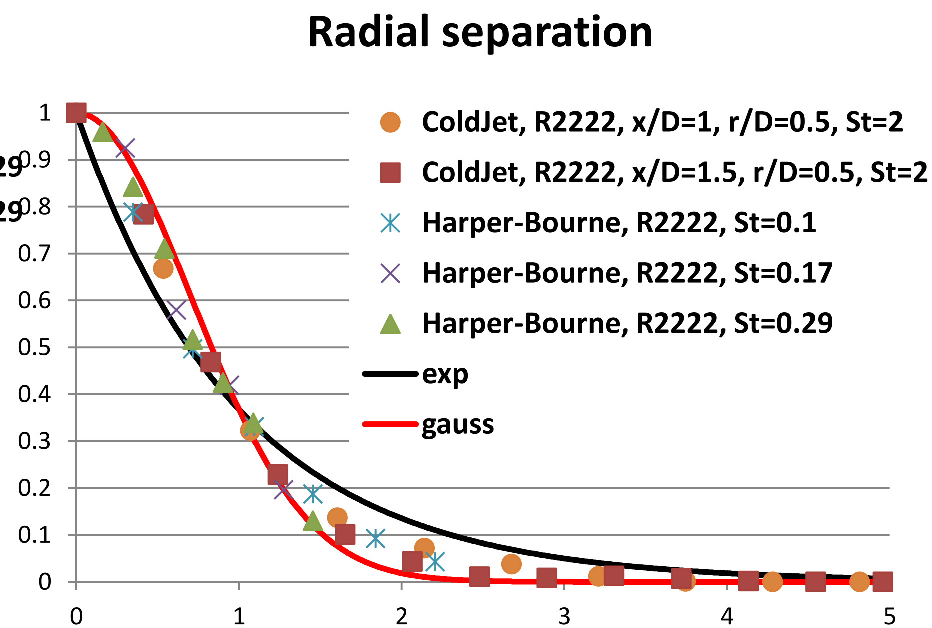


Axial Separation

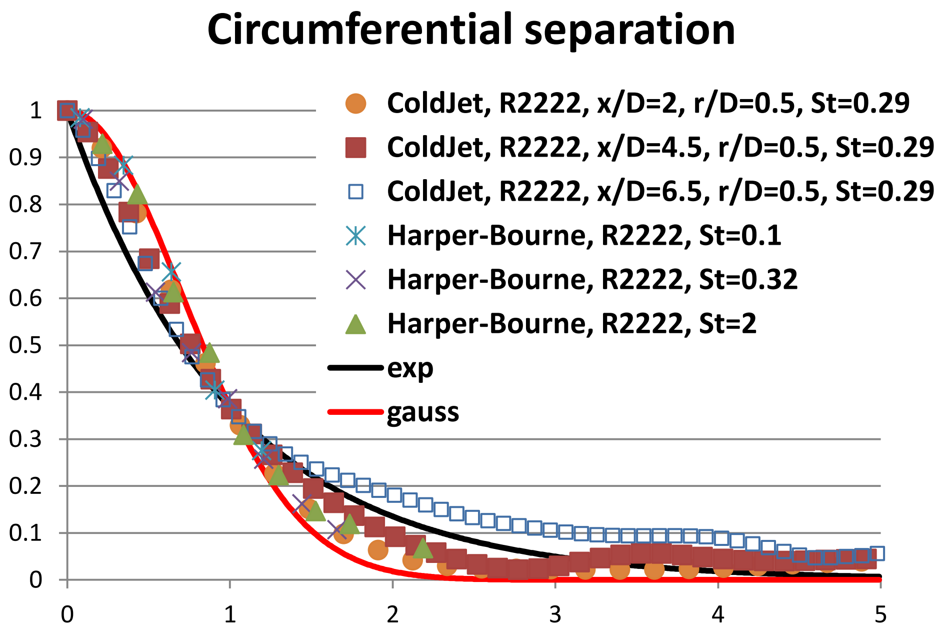


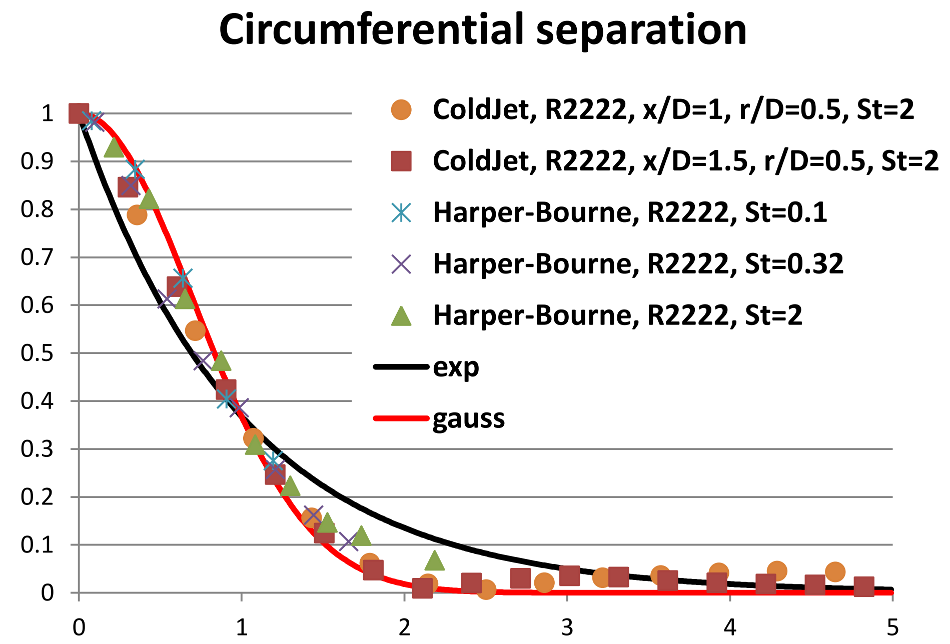
Frequency domain Reynolds stress covariance vs the Harper-Bourne experiment, radial scales





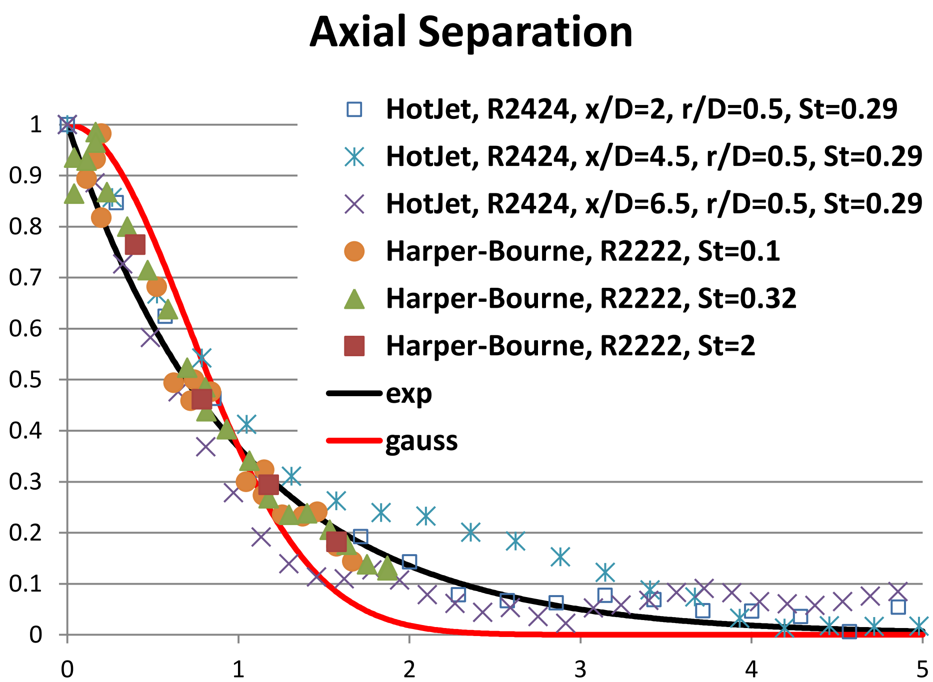
Frequency domain Reynolds stress covariance vs the Harper-Bourne experiment, circumferential scales

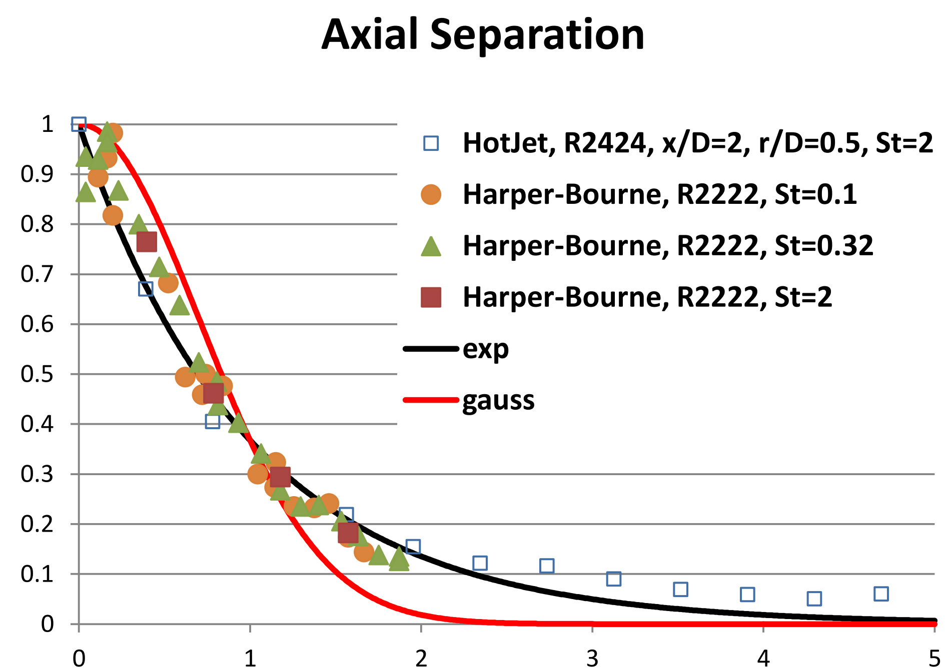




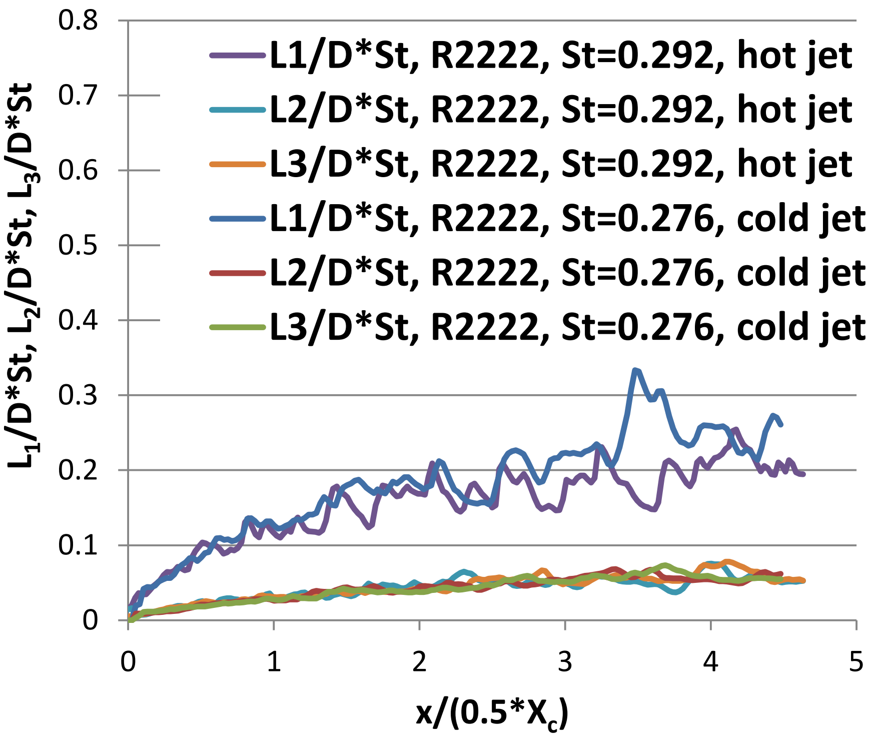
Reynolds stress covariance curves collapse for various frequencies and scales; scaling of the hot jet?

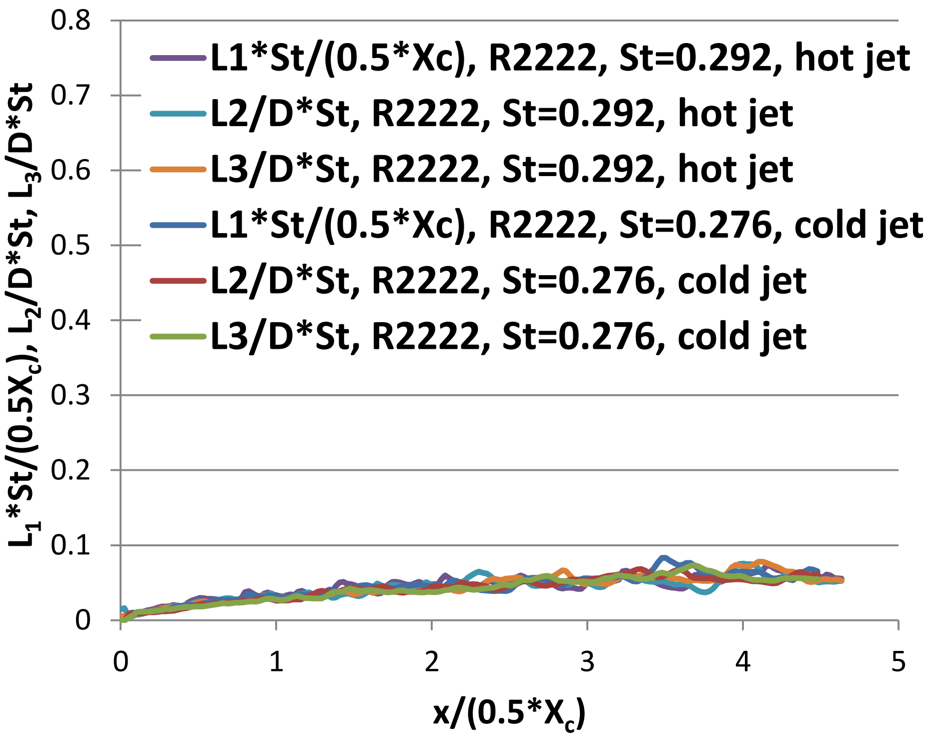
Frequency domain Fluctuating enthalpy source vs Reynolds stress covariance from the Harper-Bourne experiment, axial scales





Scaling of the Reynolds stress covariance (R_{2222}): L_1,L_2,L_3 for cold and hot jet

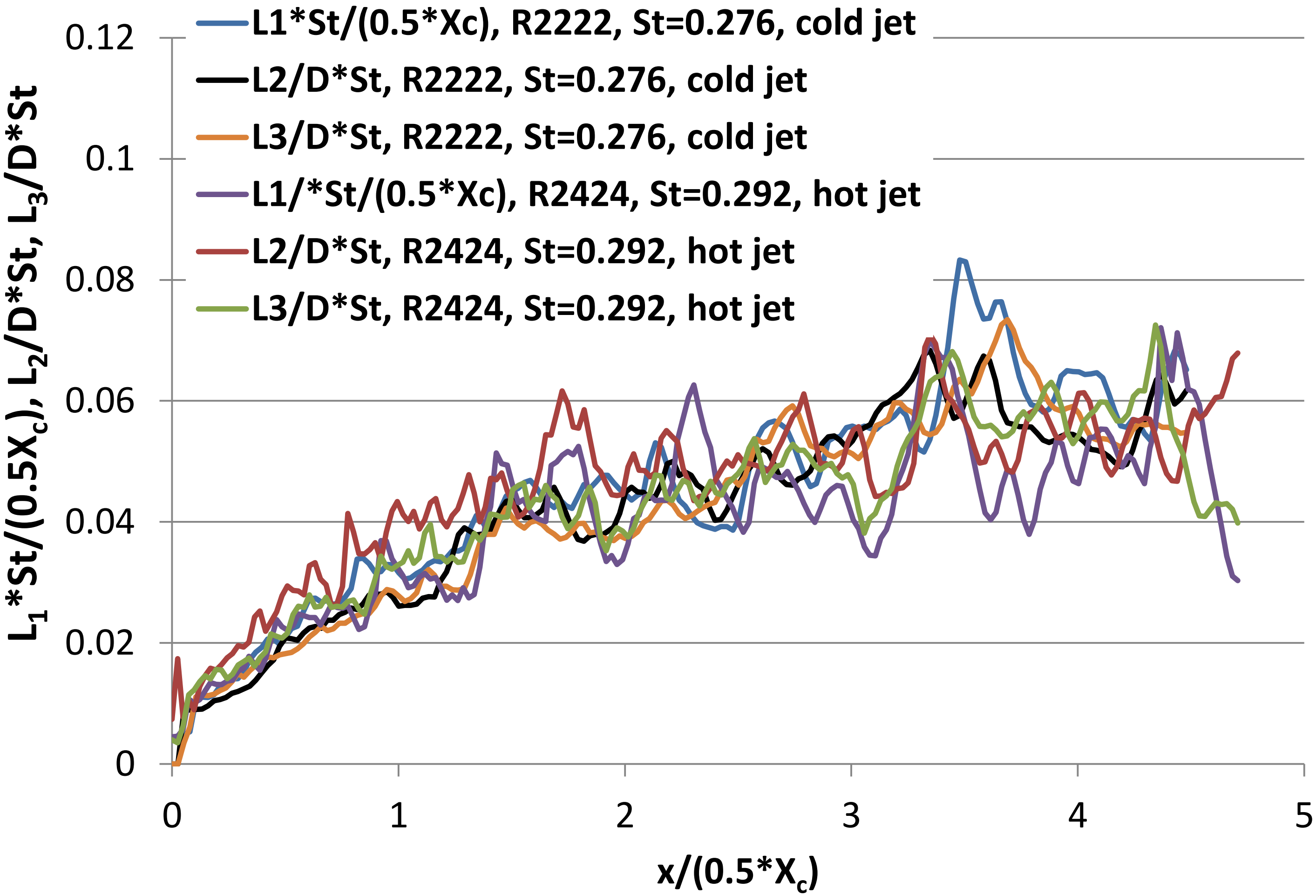




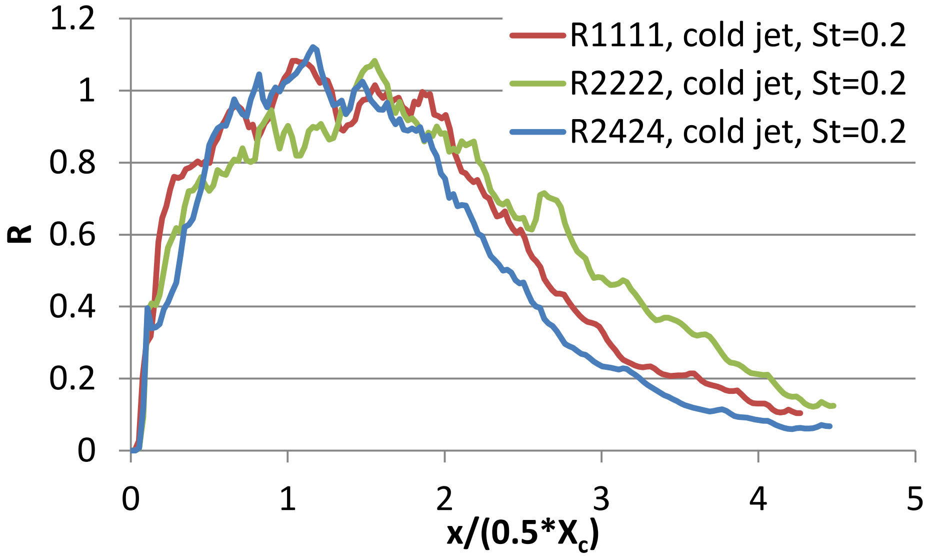
$L_1/(0.5*X_c)$ coincides with L_2,L_3

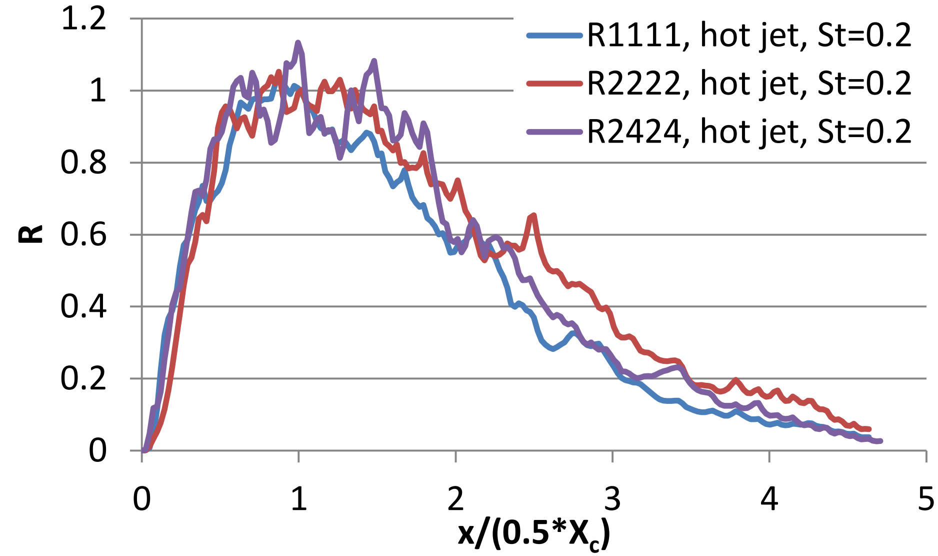
X_c = core length (maximum rms(u') on central line)

Scaling of the Reynolds stress covariance for cold jet with the fluctuating enthalpy for hot jet: all 3 scales

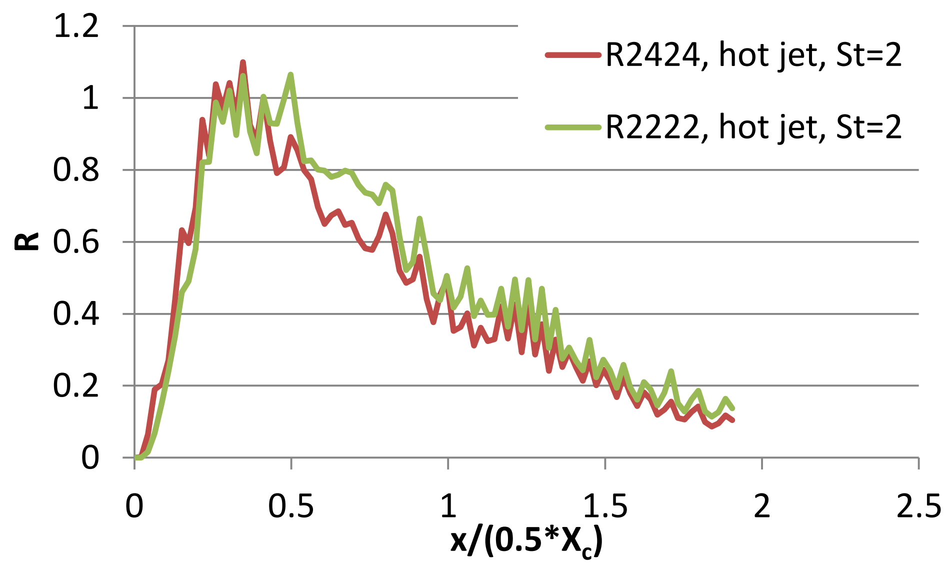


Correlation amplitudes in frequency domain

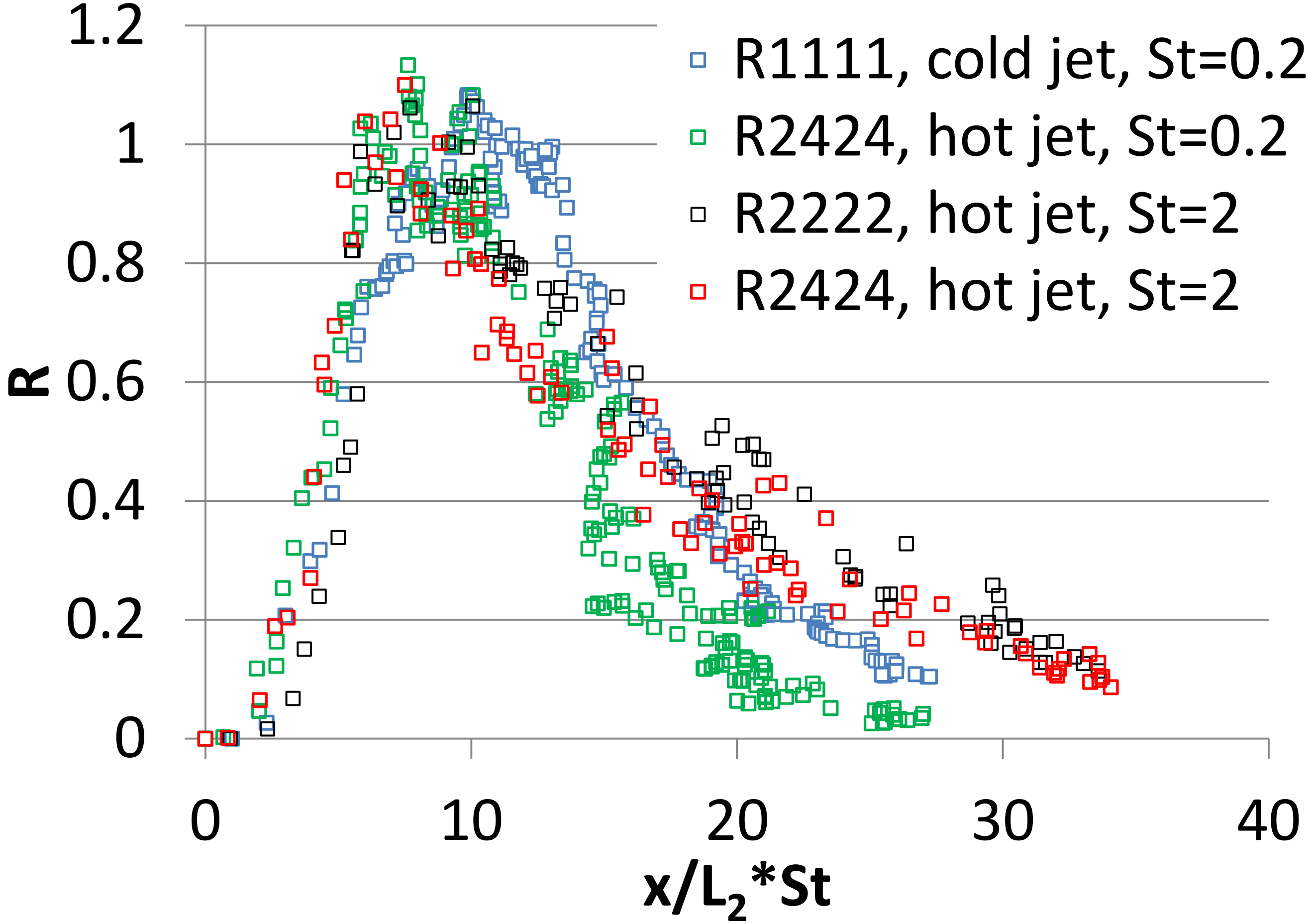




Cold and hot jet: lipline distribution of different source components scaled by a peak amplitude



Cold and hot jet: lipline distribution of different source components and frequencies scaled by a peak amplitude



Conclusions (I)

- The same set of empirical source coefficients, as used for the single-stream jets, works for the static dual-stream jet at the sideline observer position, accuracy ~ 3dB for a range of angles and frequencies;

- **Sensitivity to the model parameters needs to be evaluated (not always available from the experiment):**
  - **Use of LES as a post-processing tool?**
  - **Length scales, source function shapes?**

Conclusions (II)

Correlation function similarities are found:

- Shapes of the Reynolds stress covariance components collapse both in time and in frequency domain; in the frequency domain enthalpy fluctuation source collapse in a similar way

- Correlation length scales of cold and hot jets collapse when properly non-dimensionalised on jet diameter (radial and circumferential) and potential core length

- Correlation amplitudes normalised by a peak along lipline collapse for different components and different frequencies with a proper spatial scaling