Goldstein Generalized Acoustic Analogy: Applications to Jet Noise Modelling

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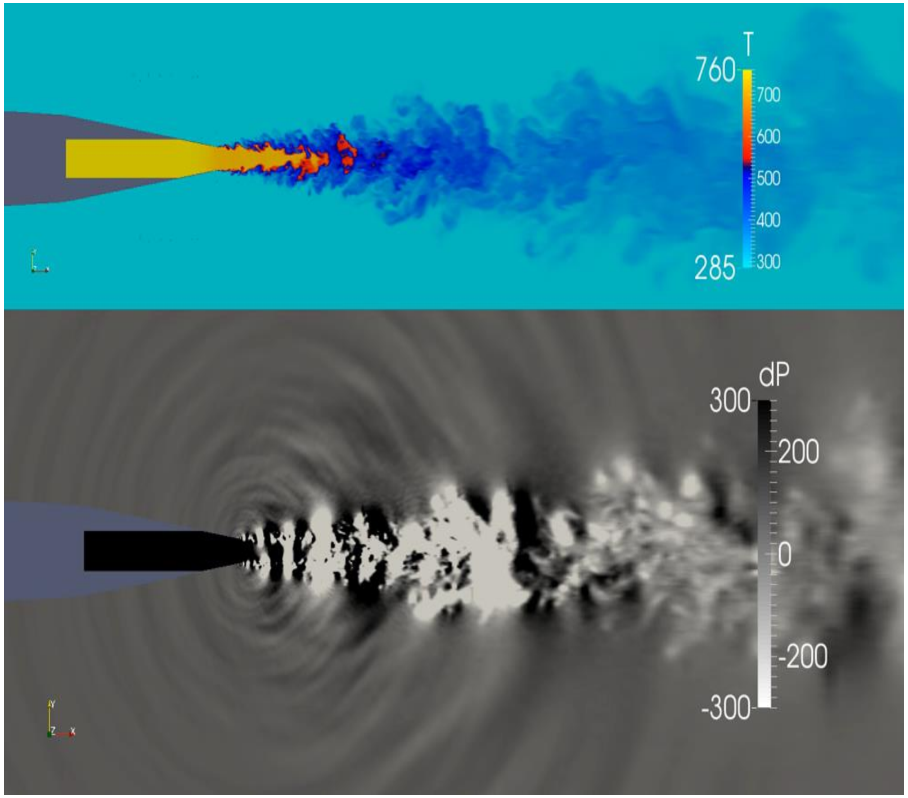
Outline

- Motivation
- Goldstein generalised acoustic analogy
- Single stream jet problem
  - Meanflow effects on jet noise directivity
  - Noise source azimuthal decomposition
  - Temperature effects on jet noise
- Conclusions

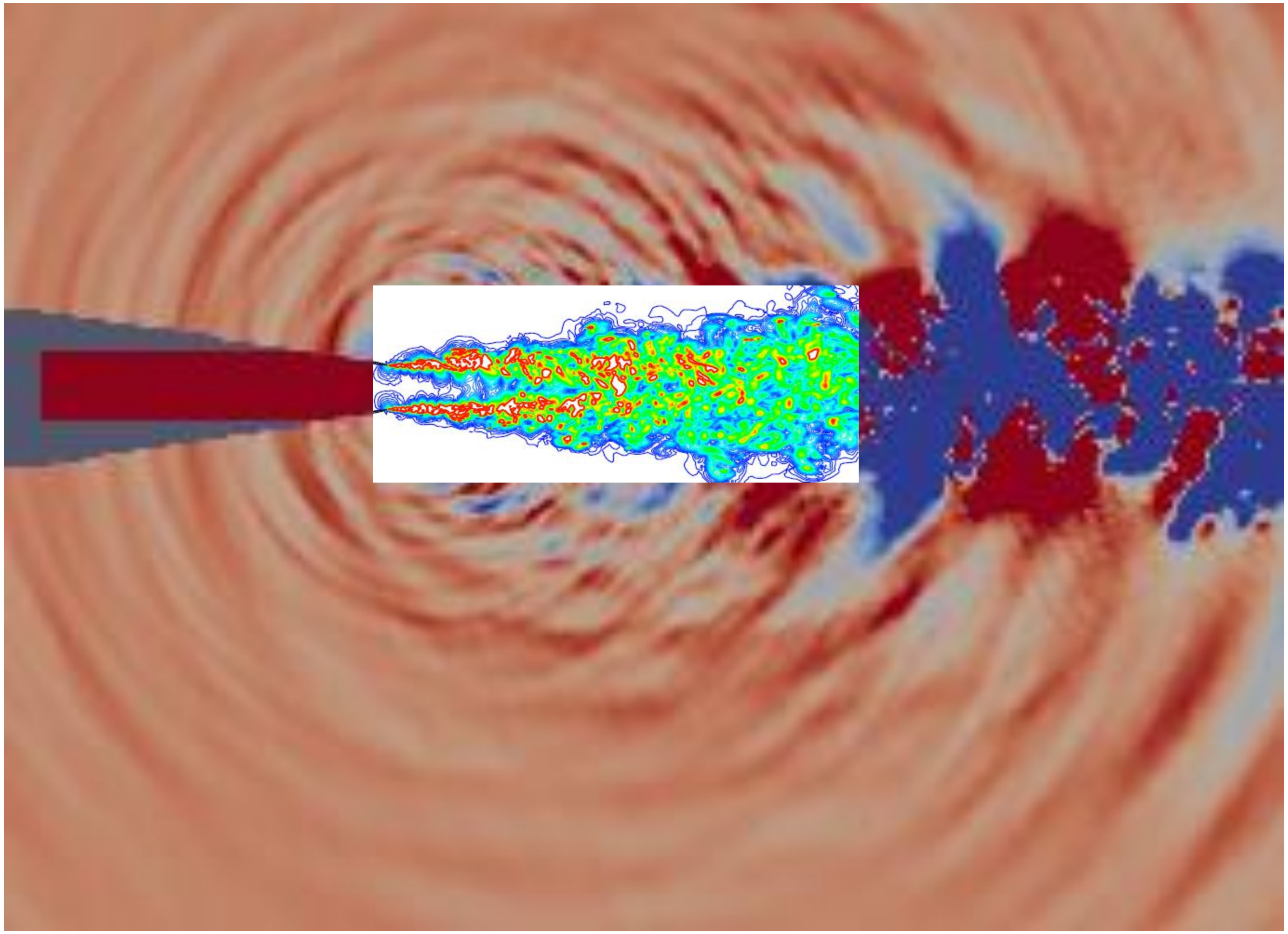
GPU CABARET CFD Code

"HiFi prediction for validation of designs is mandatory"

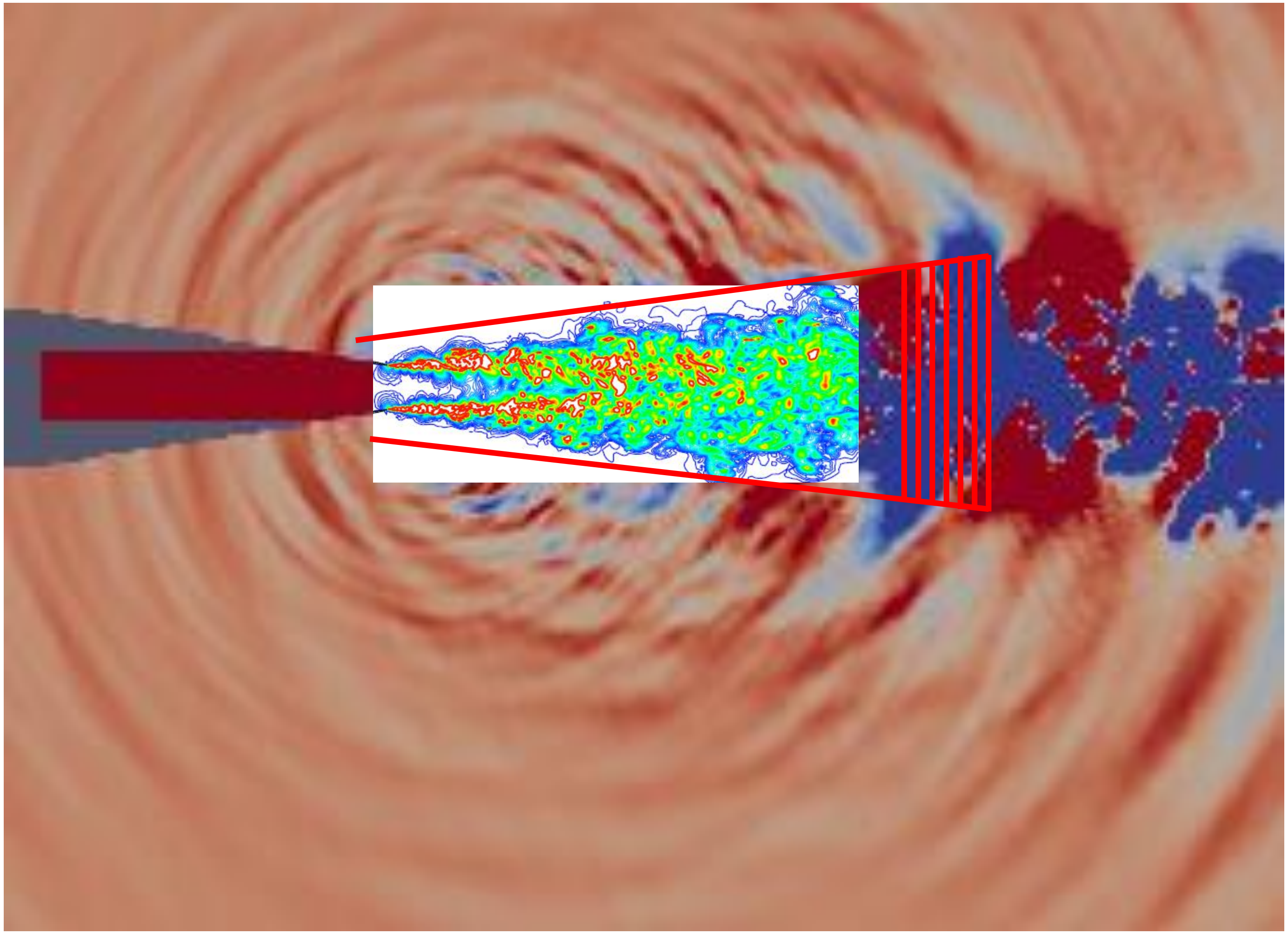
- Snappy-hex meshes (from OpenFOAM)
- CABARET scheme
- Memory-optimised:
  - 2.2 mln mesh per GB memory (6 GB~13mln)
- Asynchronous algorithm speeds-up computations
- FWH
- Goldstein acoustic analogy
- ParaView, OpenFOAM



Jet Noise Problem



Ffowcs Williams – Hawkings (FW-H)



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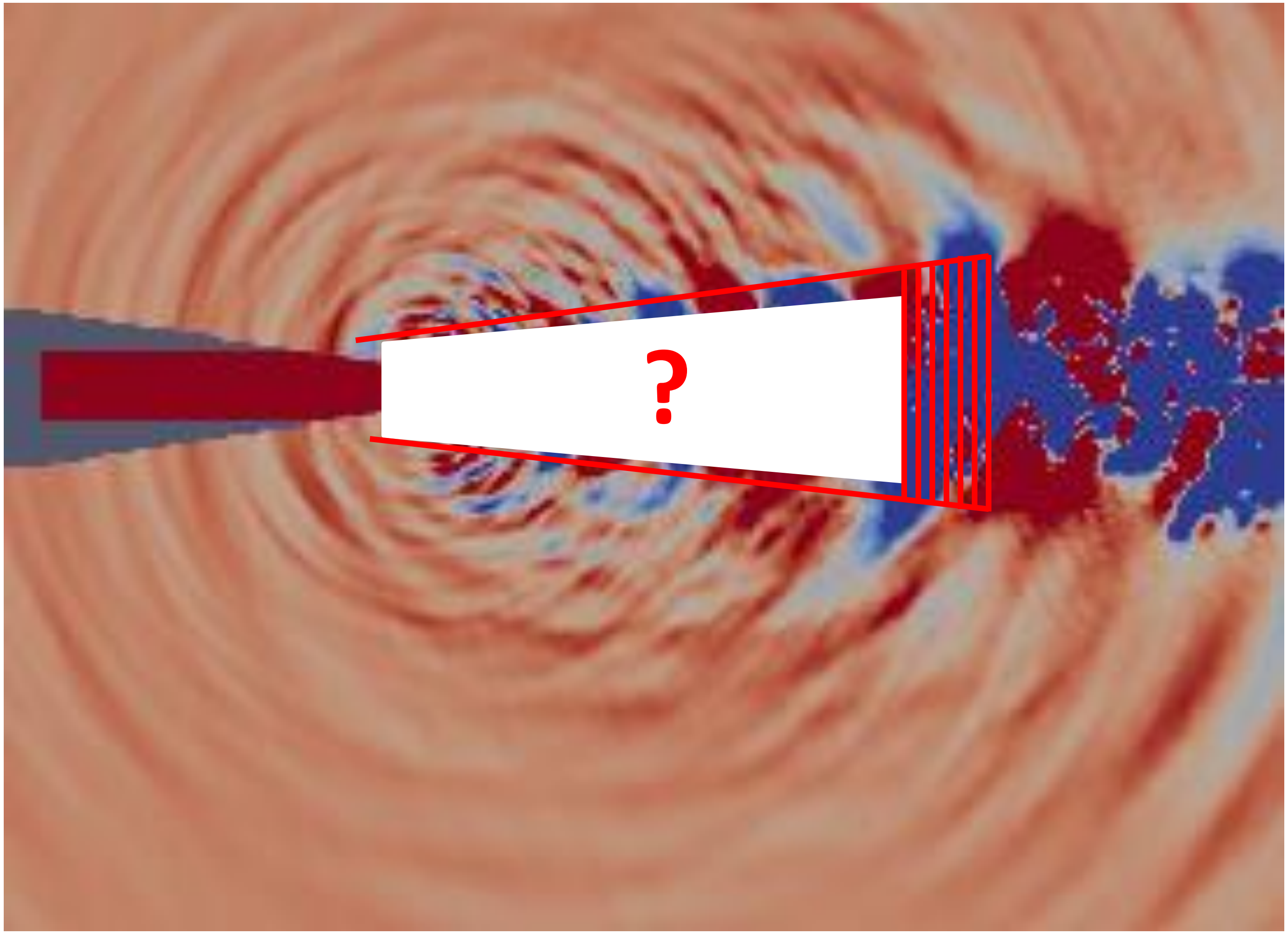
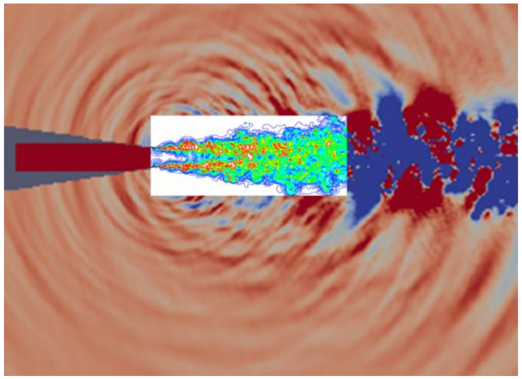


Goldstein Generalised Acoustic Analogy

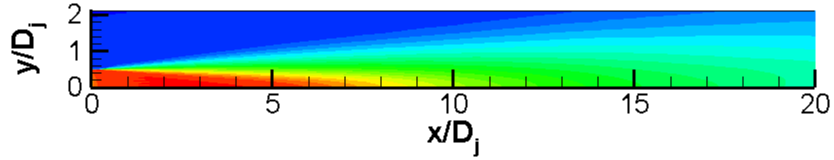
LES



Volume noise sources

$$e''_{ij} = -\left(\rho v'_i v'_j - \overline{\rho v'_i v'_j}\right)$$

Meanflow velocity

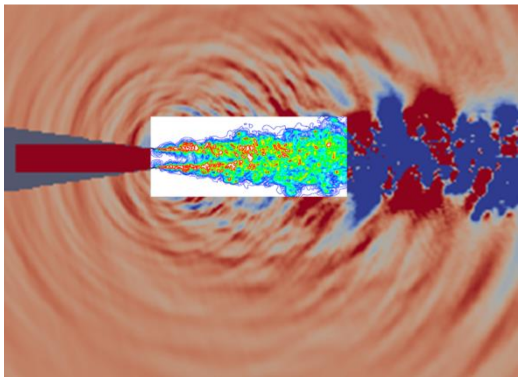


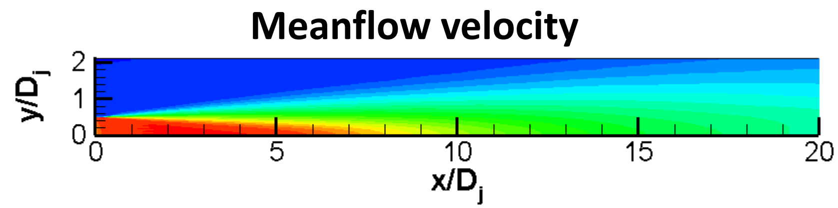
$\hat{\gamma}_{ij}\left(\boldsymbol{y}, \omega \middle| \boldsymbol{x}\right)$ - propagator

[Semiletov, Karabasov, AIAA, 2015]

Goldstein Generalised Acoustic Analogy

LES





$\hat{\gamma}_{ij}(\boldsymbol{y}, \omega | \boldsymbol{x})$ - propagator

Volume noise sources

$$e''_{ij} = -\left(\rho v'_i v'_j - \overline{\rho v'_i v'_j}\right)$$

Far-field pressure signal: $\hat{p}(w,\boldsymbol{x}) = \int_{V_y} \hat{e}''_{ij}(\boldsymbol{y}, w)\hat{\gamma}_{ij}(\boldsymbol{y} - \boldsymbol{x}, w)\,\mathrm{d}\boldsymbol{y}$

Power Spectral Density: $S(w,x) = \langle \hat{p}(w,x)\hat{p}^*(w,x)\rangle$

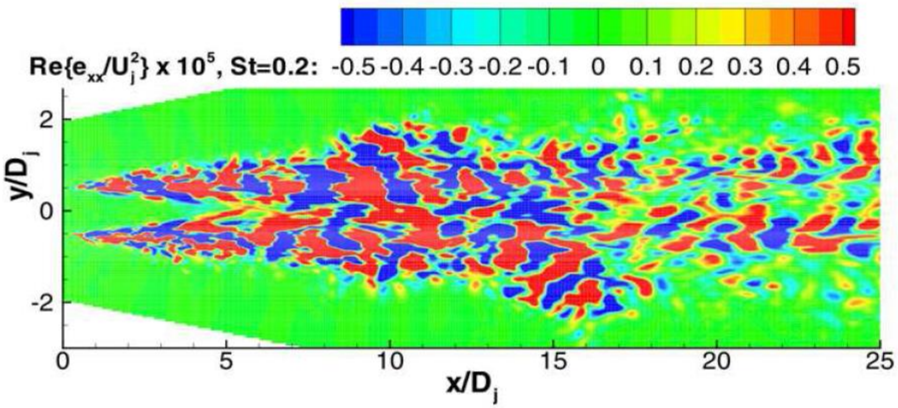
[Semiletov, Karabasov, AIAA, 2015]

Typical Noise Sources

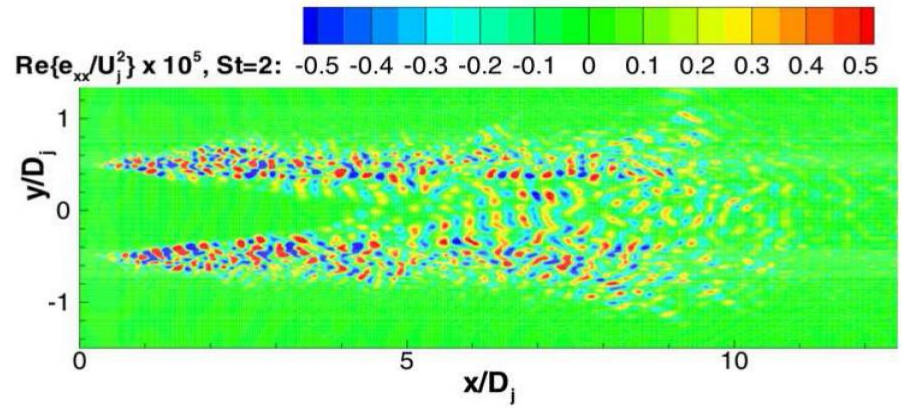
Cold Static Jet (M_a=0.9)

(fluctuating Reynolds stress)

St=0.2

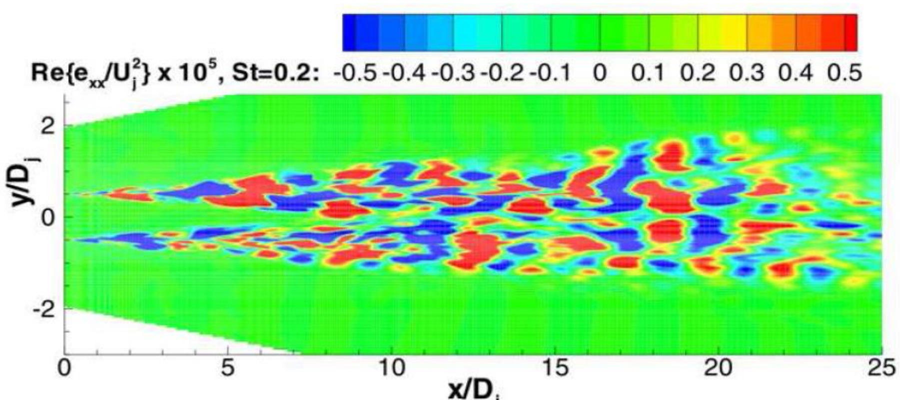


St=2



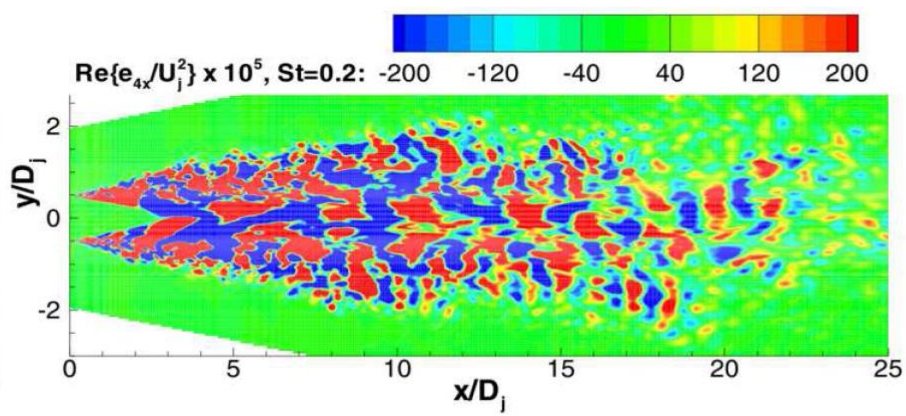
Cold jet (M_a=0.9, $M_{co\text{-}flow}$=0.3), St=0.2

(fluctuating Reynolds stress)



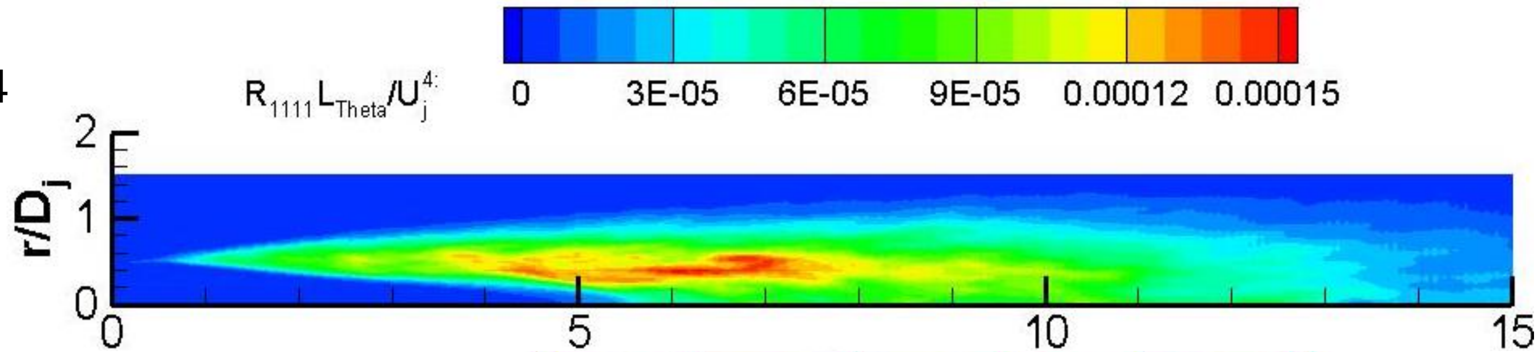
Hot static jet (M_a=0.9, T_j/T_a=0.3), St=0.2

(fluctuating enthalpy)

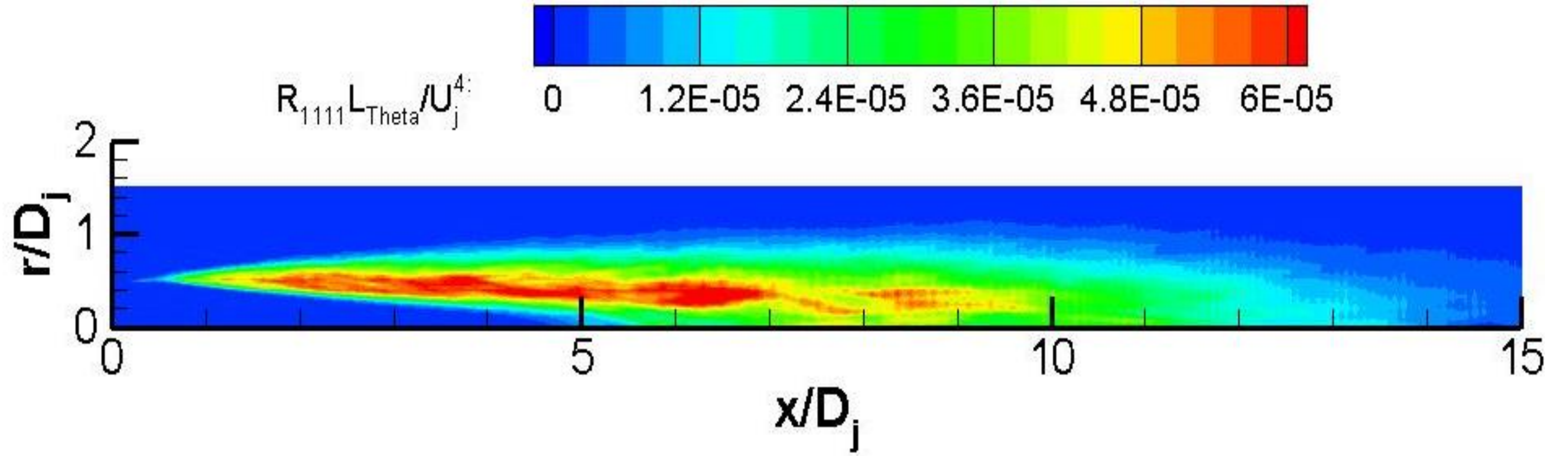


Noise Source Amplitudes (R_{1111})

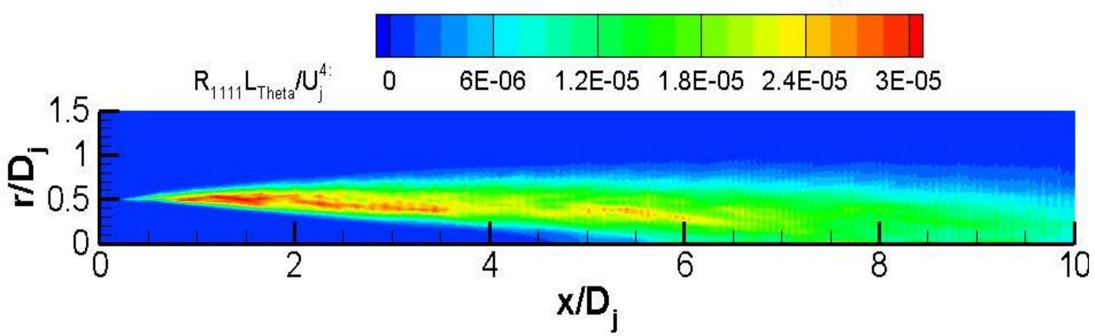
$St_D=0.4$



$St_D=0.8$



$St_D=1.4$



Noise sources

$$S(\boldsymbol{x},\omega)=\int_{V_y}\int_{V_\Delta}\hat{R}_{ijkl}(\boldsymbol{y},\boldsymbol{\Delta},\omega)\hat{\gamma}_{ij}(\boldsymbol{y},\omega|\boldsymbol{x})\hat{\gamma}^*_{kl}(\boldsymbol{y}+\boldsymbol{\Delta},\omega|\boldsymbol{x})\mathrm{d}\boldsymbol{\Delta}\mathrm{d}\boldsymbol{y}$$

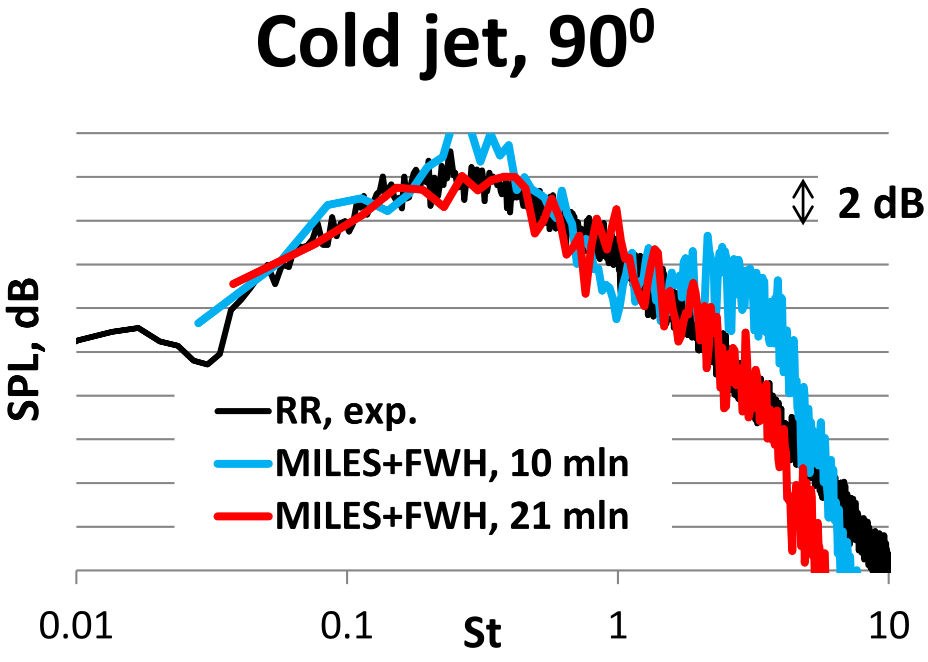
where

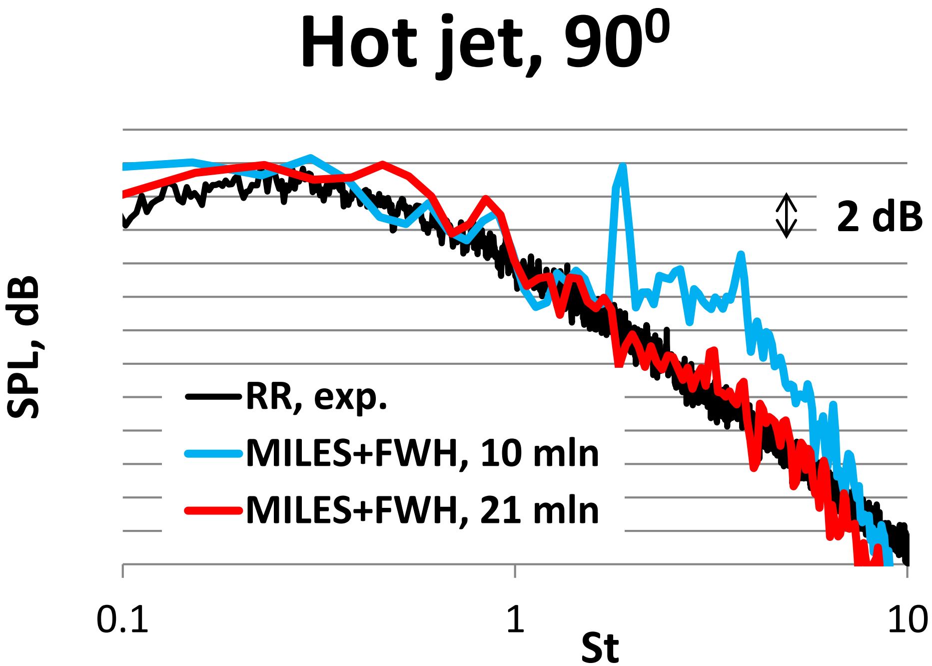
$$\hat{R}_{ijkl}(\boldsymbol{y},\boldsymbol{\Delta},\omega)=\int R_{ijkl}(\boldsymbol{y},\boldsymbol{\Delta},\tau)e^{-i\omega\tau}\mathrm{d}\tau=\overline{\hat{e}''_{ij}(\boldsymbol{y},\omega)\hat{e}''^*_{ij}(\boldsymbol{y}+\boldsymbol{\Delta},\omega)},$$

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

Needs modelling ...

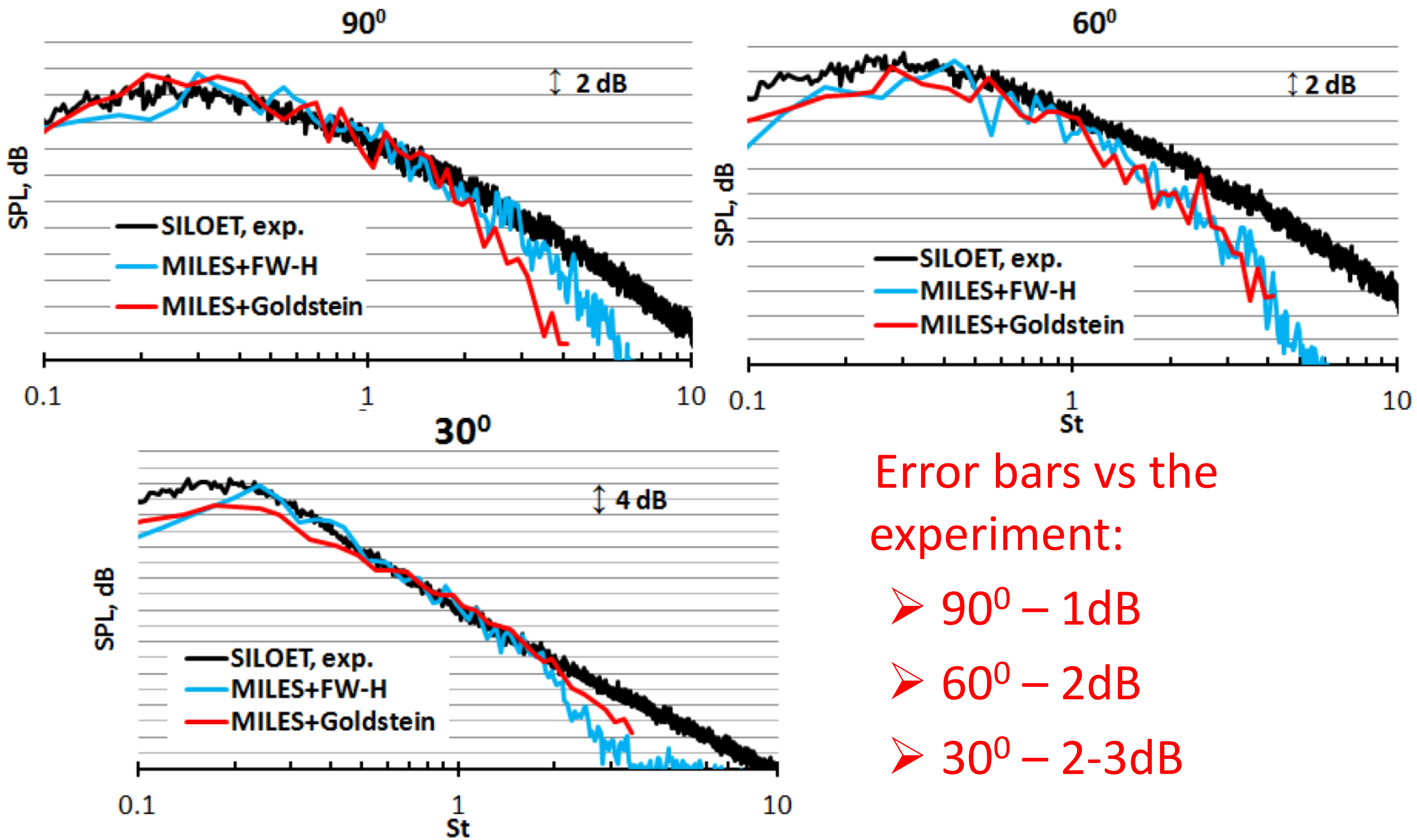
Convergence study:
FW-H solution for the 10 and 21 mln cell LES cases vs the QinetiQ experiment (SILOET)





Acoustic Analogy Informed by LES:

Cold static jet, V_j/c_0=0.875

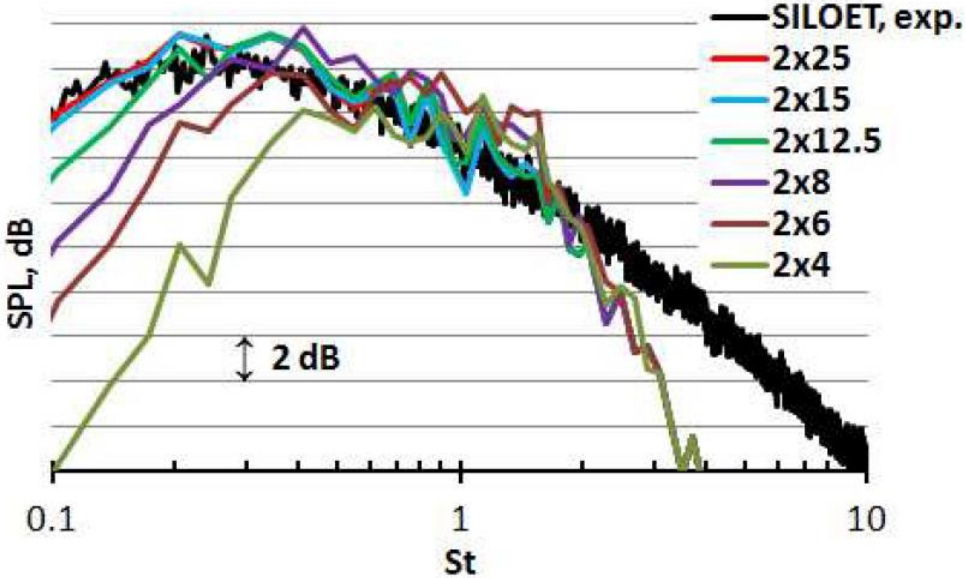


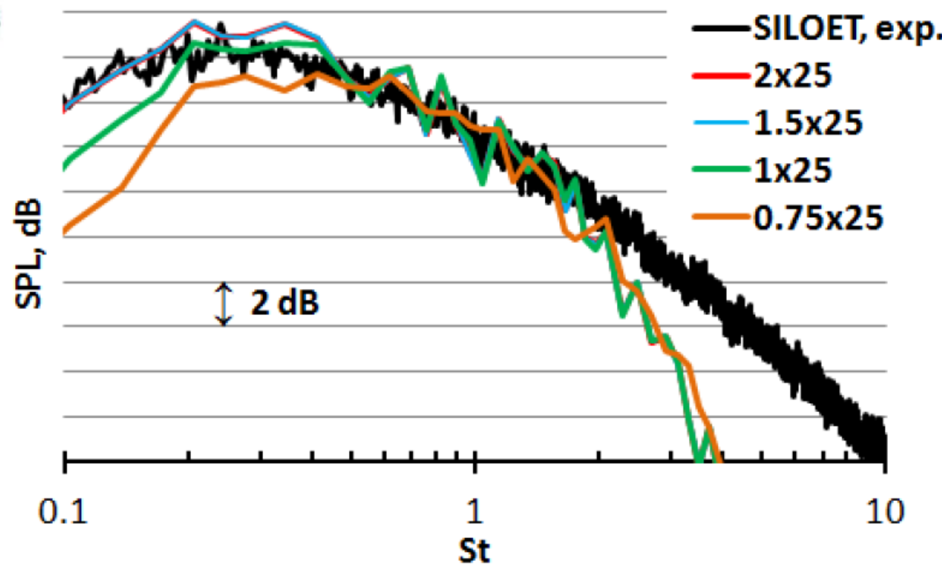
Error bars vs the experiment:

- 90^0 – 1dB
- 60^0 – 2dB
- 30^0 – 2-3dB

Acoustic Analogy Informed by LES:

Cold static jet, V_j/c_0=0.875

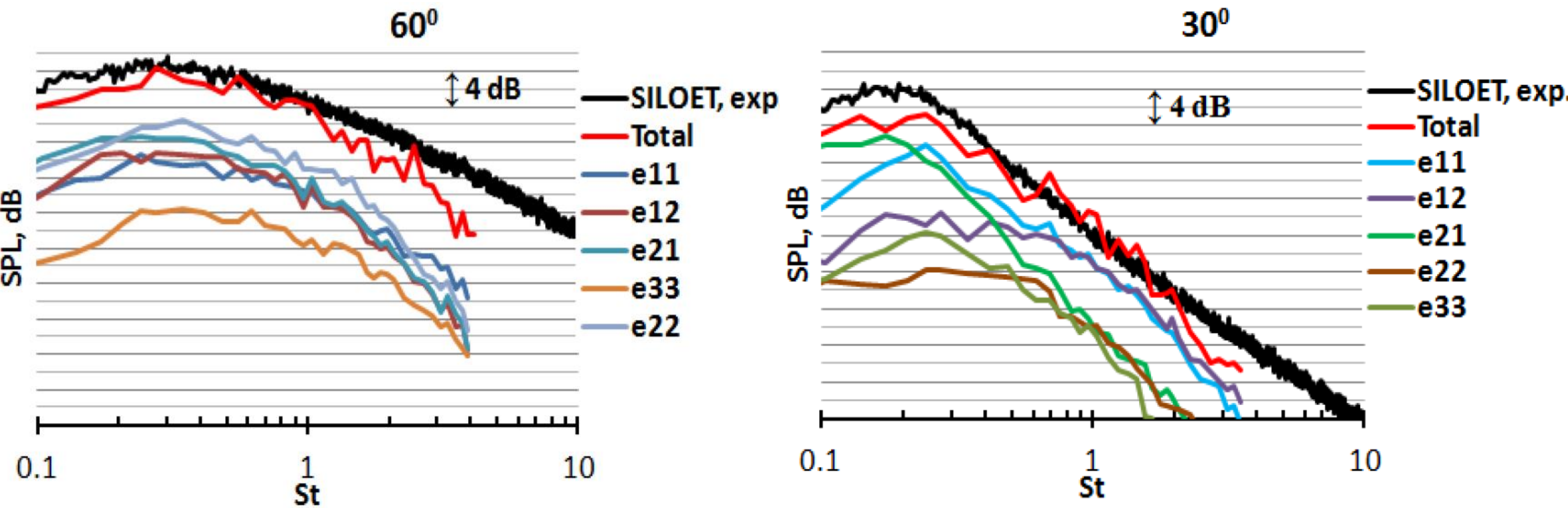




Goldstein Generalized acoustic analogy

is insensitive to the choice of integration volume

Cold jet: noise source components for other observer angles

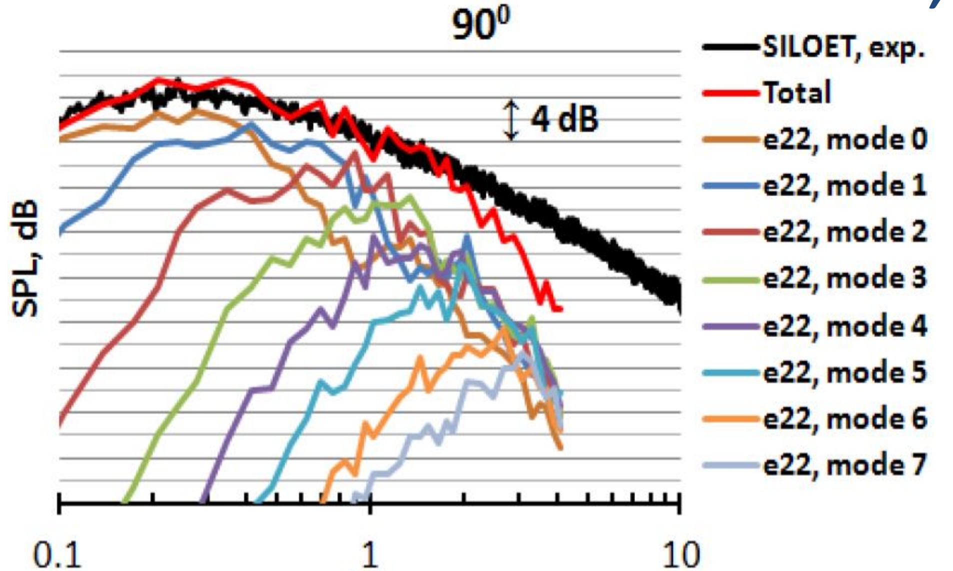


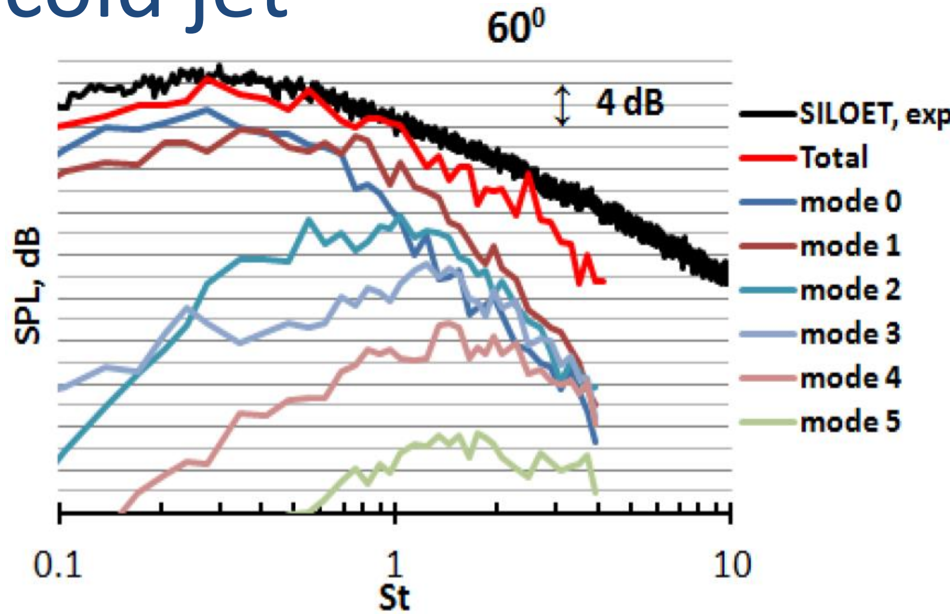
Dominant noise sources (by more than 5dB):

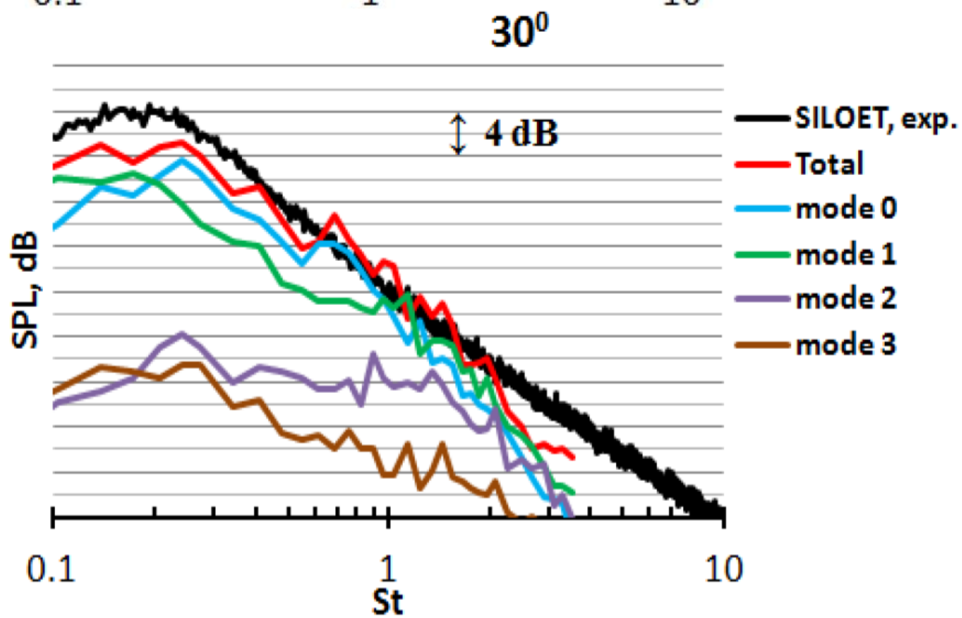
- **90^0 – T_{22}**
- **60^0 – T_{22}, T_{11}, T_{12}, and T_{21}**
- **30^0 – T_{11}, T_{12}, and T_{21}**

1-stream-wise-jet direction,
2-normal in-plane direction,
3-normal out-of-plane direction

Contribution from different azimuthal modes, cold jet

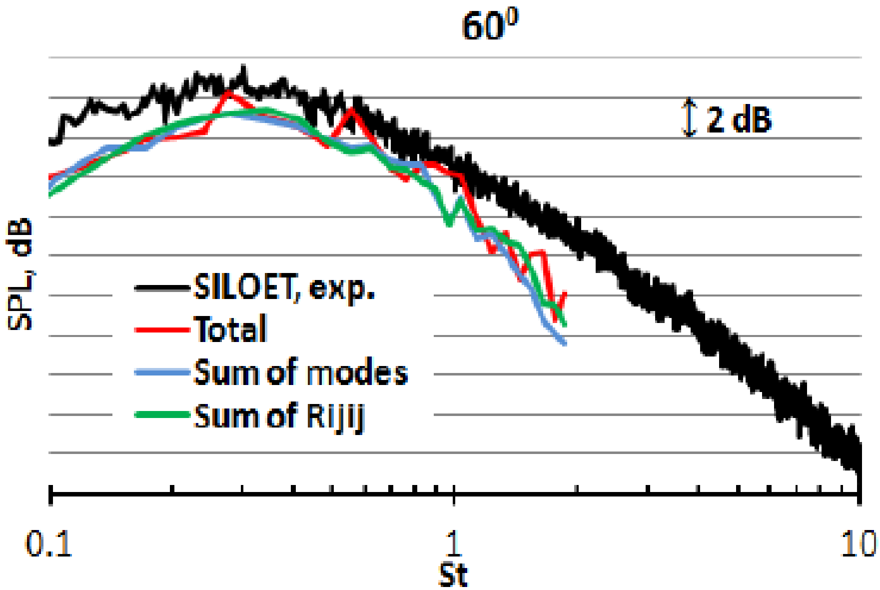


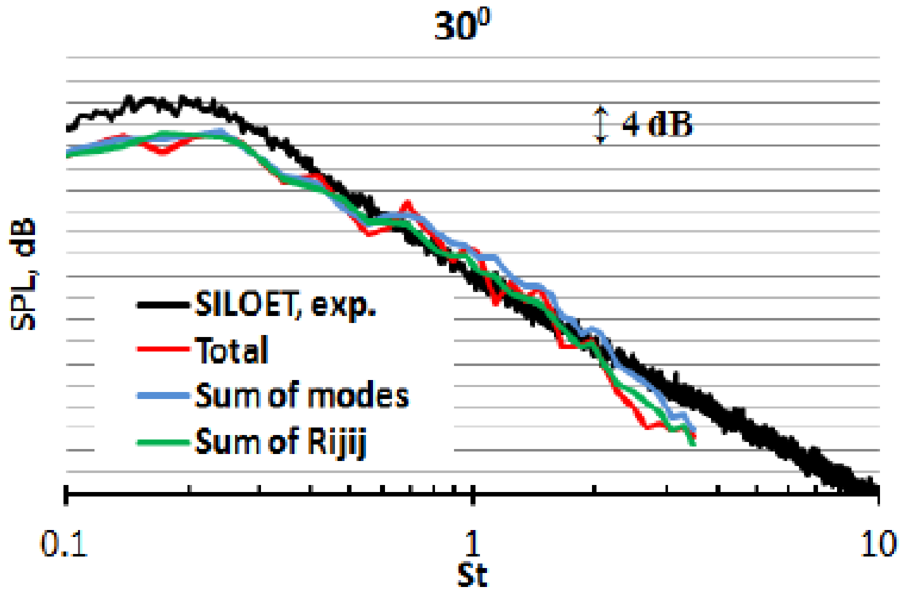




- All modes have the same asymptote at high frequencies for 90^0 observer angle: at least 5 modes are required for frequencies up to St=1-2
- Modes 0 and 1 are the only ones important for most frequencies at small observer angles

The previous result included all possible stress combinations, R_{1111},R_{1212},R_{2222} but also R_{1222} etc; Are they really small? How important are the correlations between different stress components?





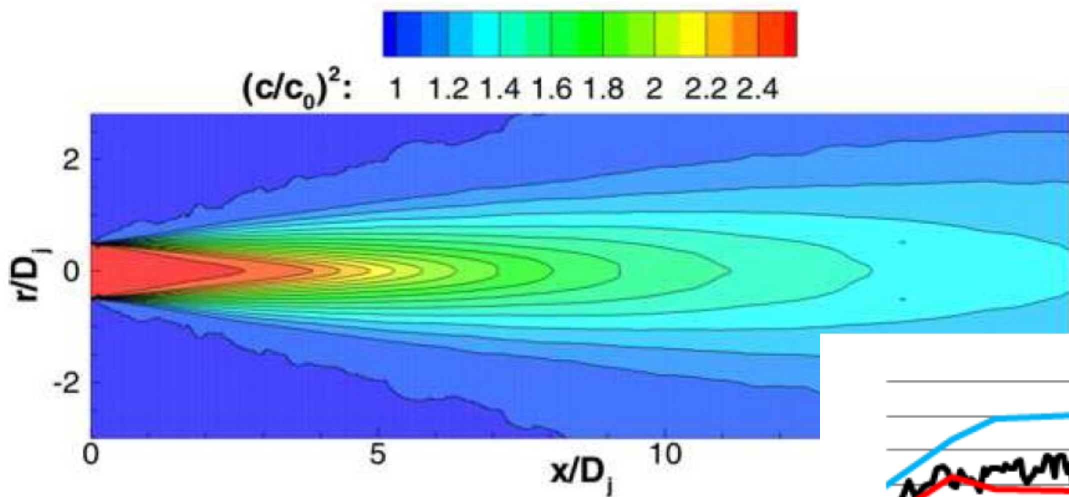
"Sum of all sources" includes only the diagonal terms $\overline{\hat{e}''_{ij}(\boldsymbol{y},\omega)\hat{e}''^{*}_{ij}(\boldsymbol{y}+\boldsymbol{\Delta},\omega)}$

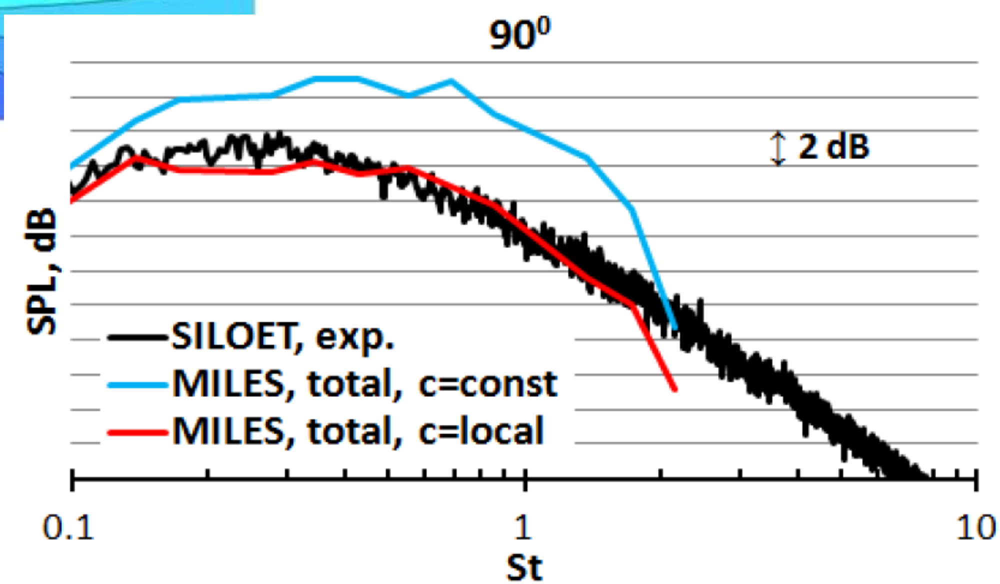
Yes, the off-diagonal terms which correspond to the correlations between different tensor components are small (expected for a round jet?). This leaves out only three major components of Reynolds stress to be modelled: R_{1111}, R_{1212} =R_{2121} and R_{2222}

[Semiletov, Karabasov, AIAA, 2015]

Hot static jet, V_j/c_0=0.875, T_j/T_0=2.5

Non-uniform sound speed



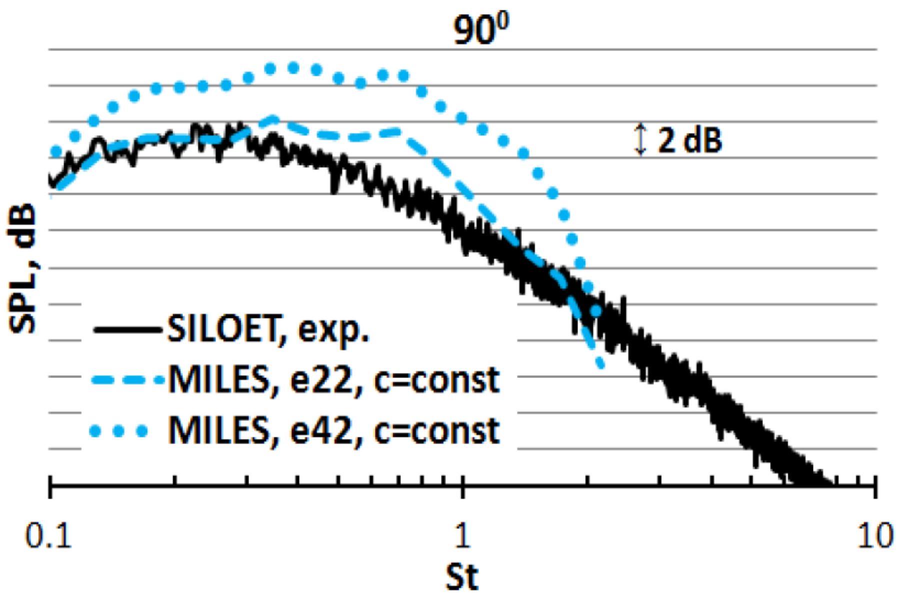


Error bars vs the experiment:

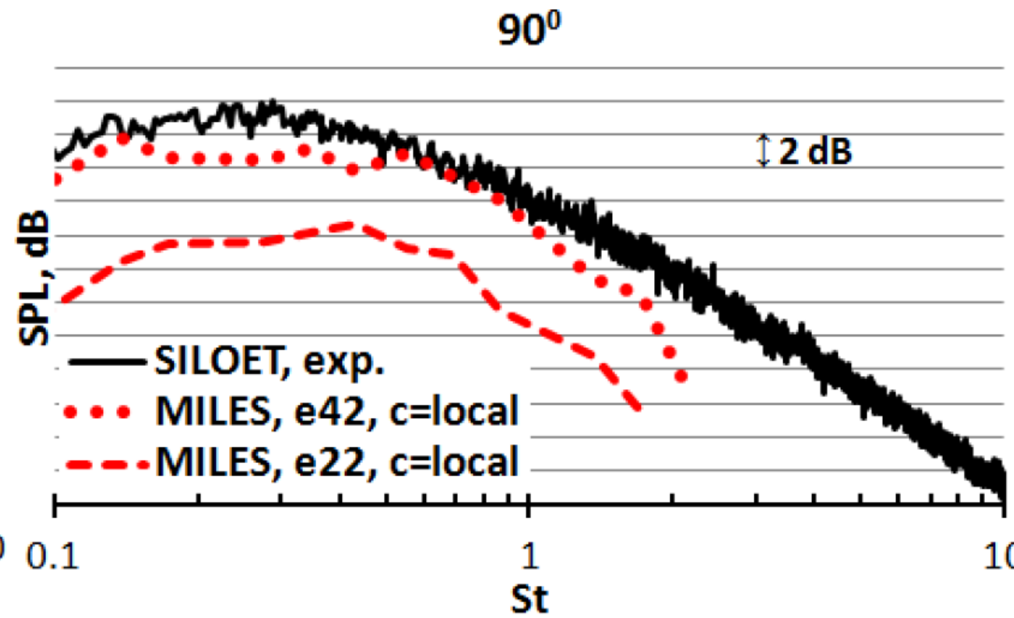
➢ 1-2dB for 90 degrees

Temperature Effect on Acoustic Propagation

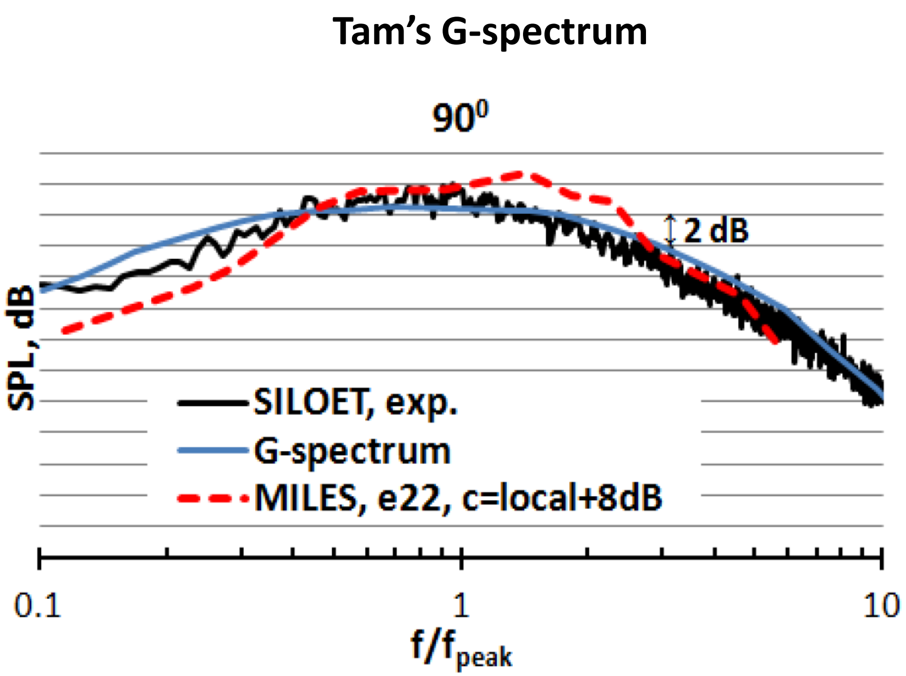
“Cold” propagator
(constant sound speed)

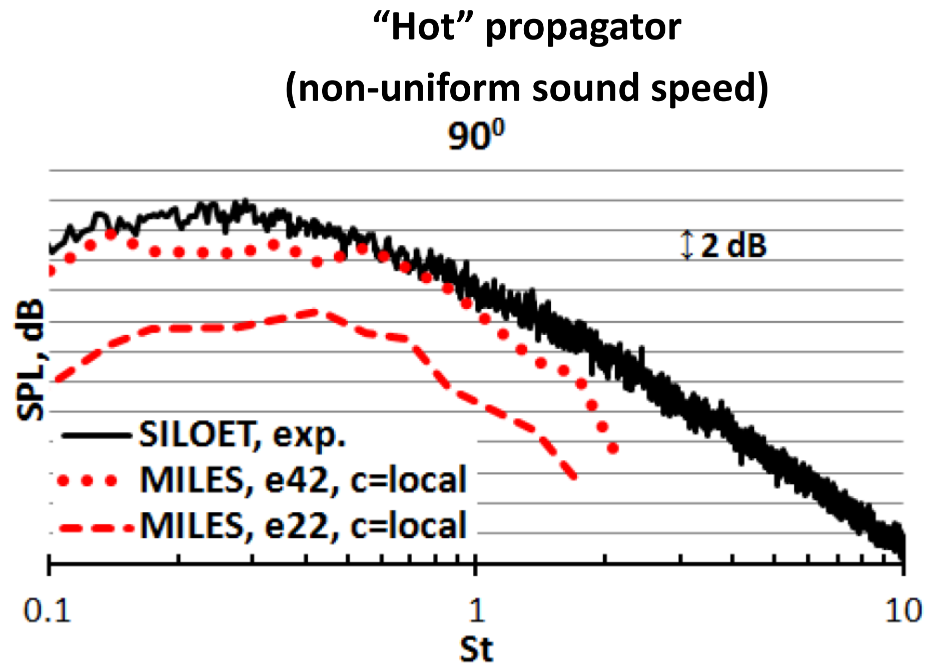


“Hot” propagator
(non-uniform sound speed)



Similar Far-field Spectrum





Conclusions

Calibration parameter free Goldstein acoustic analogy informed by LES:

- Agreement with the experimental data within 1-2 dB for most angles and frequencies
- Maximum 3 main source components are required for jet noise modelling: R_{2222} for 90^0 degrees, R_{1111}, R_{1212}, R_{2222} for 60^0 and R_{1111}, R_{1212} for 30^0
- Maximum 2 azimuthal modes (0 and 1) are required for jet noise modelling at 30^0 observer angle
- Enthalpy fluctuations are the dominant jet noise source in comparison with the fluctuating turbulent Reynolds stresses for cold jet