Empiricism-free Evaluation of Jet Noise Sources Based on the Generalized Acoustic Analogy and Second Order Statistics from LES Data

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Outline

- Motivation
- Goldstein generalized acoustic analogy (GGAA) and LES post-processing
- Cold and hot static single-stream jet problems
  - Aeroadynamic modelling
  - Aeroacoustic results
    - GGAA vs WFH vs experimental data
    - Investigation of cold and hot jet noise sources
    - Noise source information
- Conclusions

Motivation

CAA hybrid methods

Low-level models

RANS+acoustic analogy (statistic methods)

- **Noise sources information**
- **Fast turn-around calculations**
- **Correct physics?**

High-fidelity methods

LES + Goldstein generalized acoustic analogy

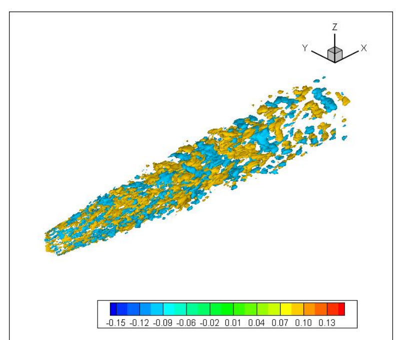
LES+FWH

- **Complete noise source information**
- **No noise source information**
- **Robust**
- **Sensitive to surface choice**

Any volume resolved sources?

Why not to compute noise source information from LES?

Calibrate low-level model



LES

Goldstein generalized acoustic analogy

- Frequency domain
- Laminar viscous terms are negligible
- Just the 90 degrees angle is considered (no meanflow effects in propagator)

$$iw\hat{u}_i + \frac{\partial}{\partial x_i}\hat{p} = \frac{\partial}{\partial x_j}\hat{e}''_{ij},$$
$$iw\hat{p} + \frac{\partial}{\partial x_j}\widetilde{c^2}\hat{u}_j = \frac{\partial}{\partial x_j}\hat{e}''_{4j} + (\gamma - 1)\,\hat{e}''_{ij}\frac{\partial \tilde{v}_i}{\partial x_j},$$

$\hat{e}''_{ij}, \hat{e}''_{4j}$ Fourier-transformed noise sources

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

$e''_{4j} = -\left(\rho v'_j h' - \overline{\rho v'_j h'}\right)$ Enthalpy fluctuations

$(\gamma - 1)e''_{ij}\frac{\partial \tilde{v}_i}{\partial x_j}$ Turbulent stresses multiplied by velocity gradient tensor

[Goldstein & Leib, 2008]

Current approach: compute the second order statistics

Complex far-field pressure value:

$$\hat{p}(w,x) = \int_{V_y} \left(\hat{e}''_{ij} \nabla_i \nabla_j \hat{\varphi} - \frac{iw}{\tilde{c}^2} \left(\hat{e}''_{4j} \nabla_j \hat{\varphi} - (\gamma - 1)\, \hat{e}''_{ij} \nabla_j \tilde{v}_j \right) \right) dy$$

$\hat{\varphi}(w,y)$ - complex Green's function

Pressure power in far-field:

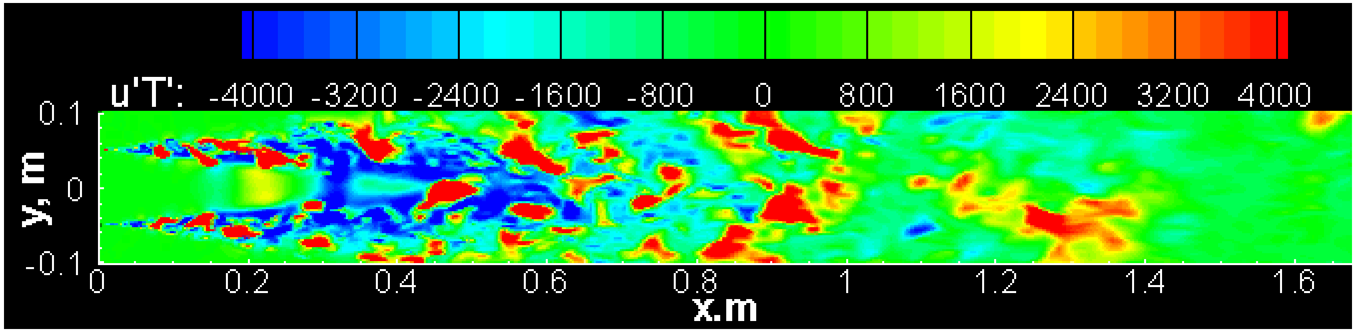
$$S(w,x) = \langle \hat{p}(w,x) \hat{p}^*(w,x) \rangle$$

where

$\hat{e}''_{ij}$, $\hat{e}''_{4j}$ Fourier-transformed noise sources

Enthalpy fluctuations

$$e''_{41}(x,y,t) \sim$$
$$\sim u'T' - \langle u'T' \rangle$$



Previous approach

Compute components of the 4th order auto covariance tensor for obtaining the acoustic power (6 dimensional space + time or frequency)

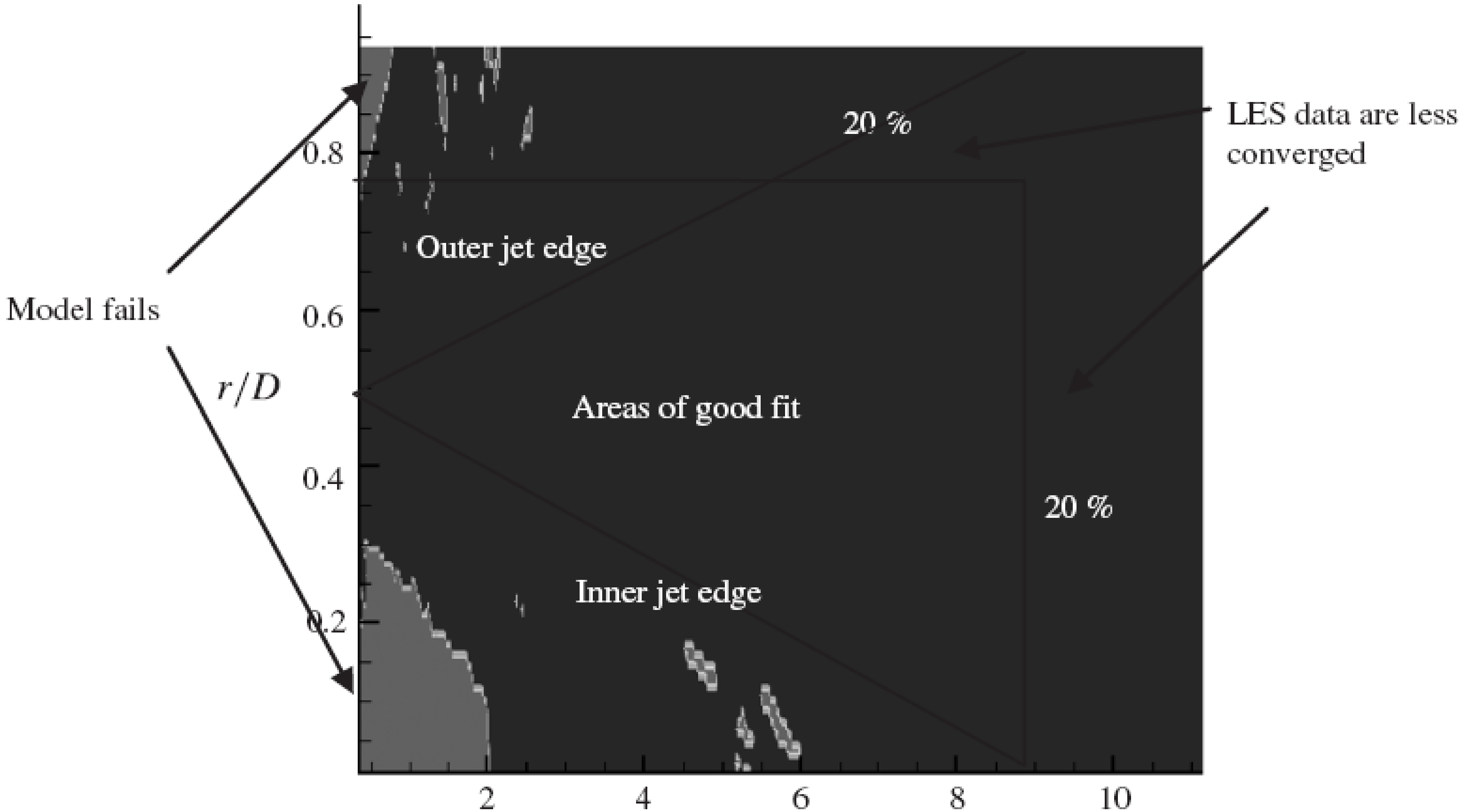
$$S(w,x) = \int_{V_y}\int_{V_\Delta} \hat{R}_{ijkl}(y,\Delta,w)\nabla_i\nabla_j\hat{\varphi}(y-x,w)\nabla_k\nabla_l\hat{\varphi}^*(y+\Delta-x,w)\,d\Delta\,dy$$

where

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

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

The 4th order statistics are typically very slow to converge outside of the jet shear layers



Karabasov et al 2013

Computer memory requirements

Example for problem size = 5 mln cells

	2nd order statistics	4th order statistics (10 components)	4th order statistics (all components)
data	260 Gb	160 Tb	480 Tb
# core with 2Gb RAM	~150 cores	~80,000 cores	~240,000 cores

Several orders of magnitude more efficient

The conditions of RR blind test: new QinetiQ experiment

D = 0.1016 m

1. **Cold static jet**
   V_j/c_0=0.875 **T_j/T_0=1** **V_0=0**

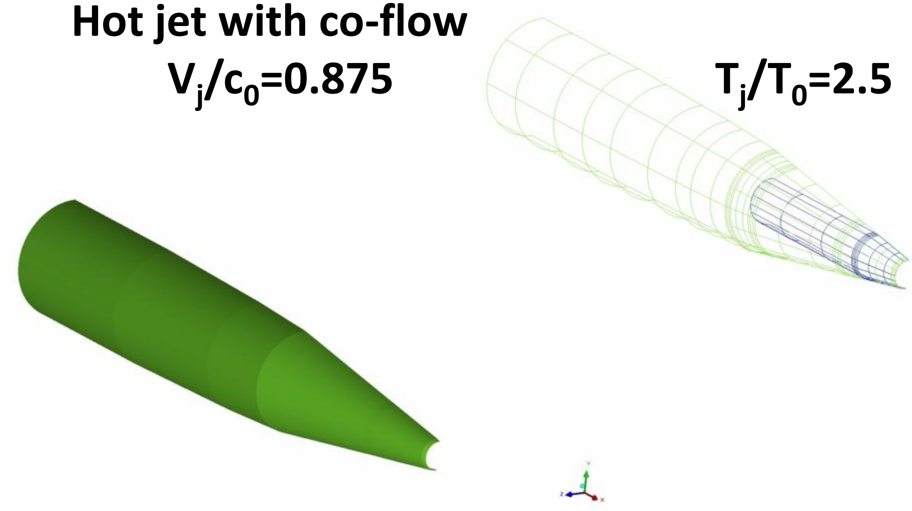
~SHJAR Sp7 jet

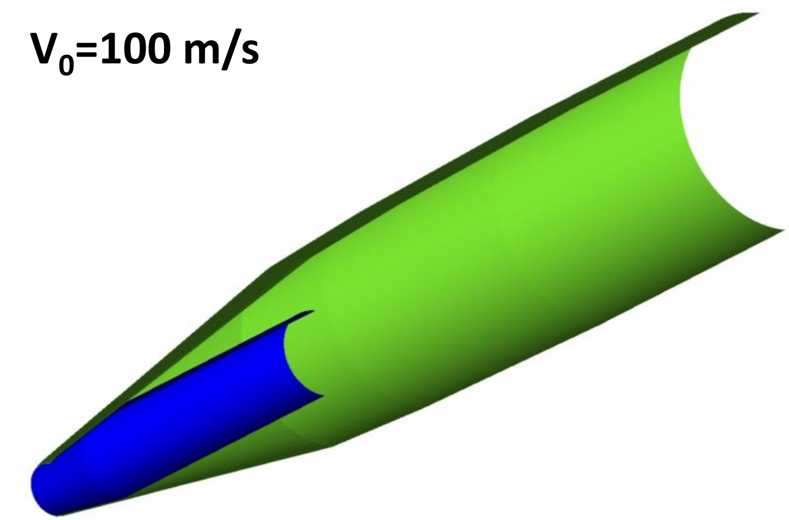
2. **Hot static jet**
   V_j/c_0=0.875 **T_j/T_0=2.5** **V_0=100 m/s**

Tanna, 1977
QinetiQ, 1983

3. **Cold jet with co-flow**
   V_j/c_0=0.875 **T_j/T_0=1** **V_0=0**

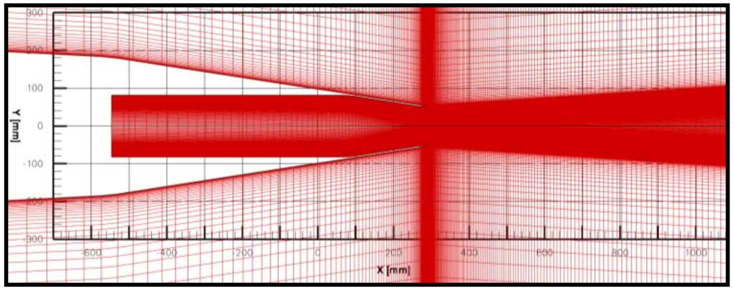
4. **Hot jet with co-flow**
   V_j/c_0=0.875 **T_j/T_0=2.5** **V_0=100 m/s**



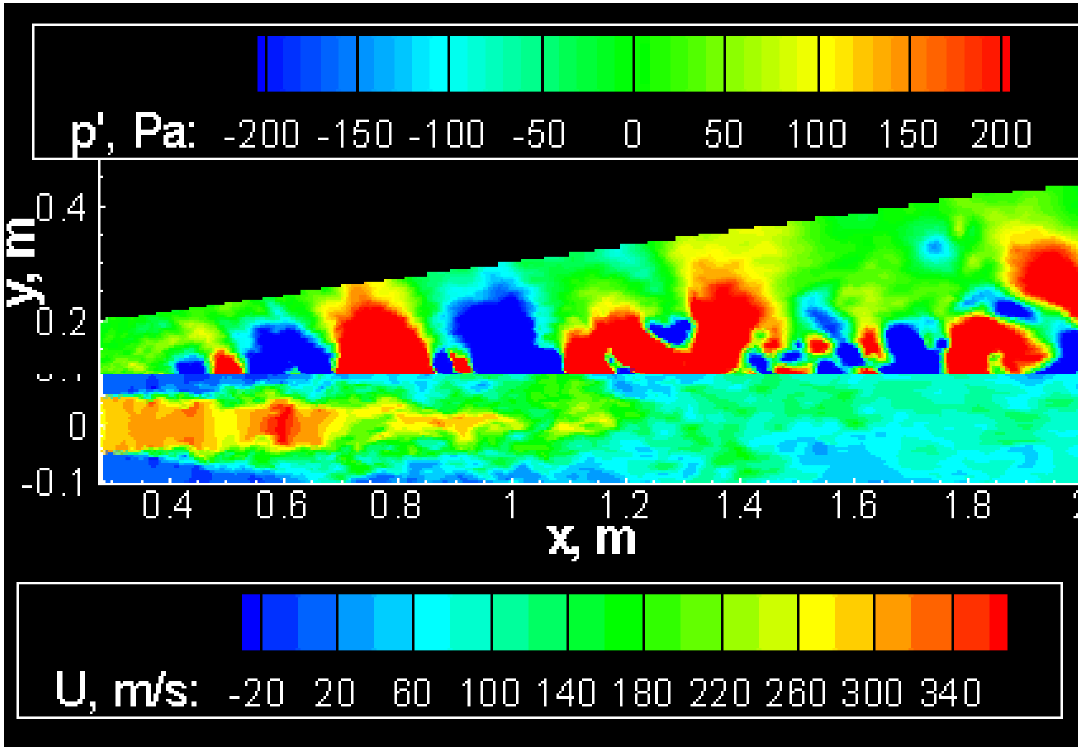


CABARET Monotonically Integrated LES Solver

21 mln grid cells
2048 MPI cores



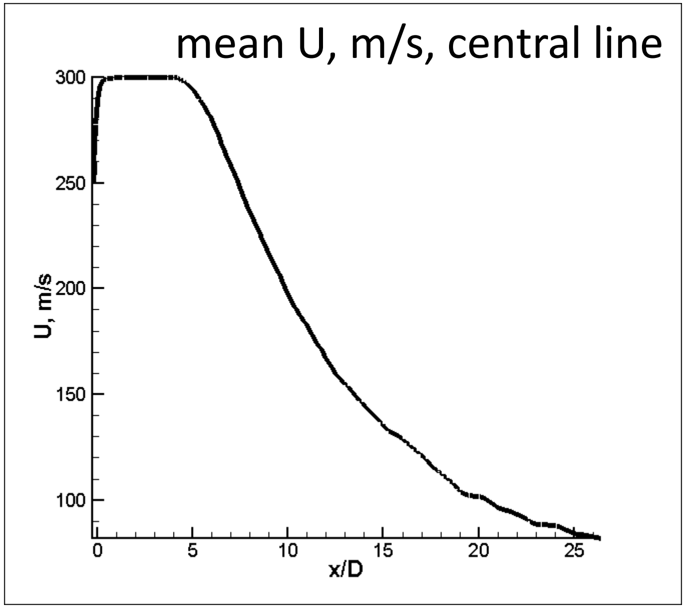
Statistic data	**260TU**
Computational time	**2 days per case**



ARCHER
(national resource)
UK flagship supercomputer
1k-4k MPI procs

https://www.archer.ac.uk/

Cold jet without co-flow, $V_j/c_0=0.875$, $T_j/T_0=1$



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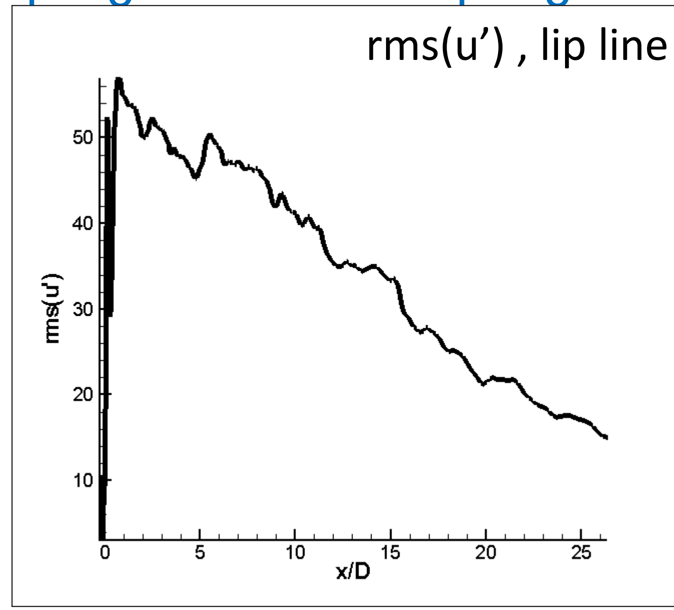
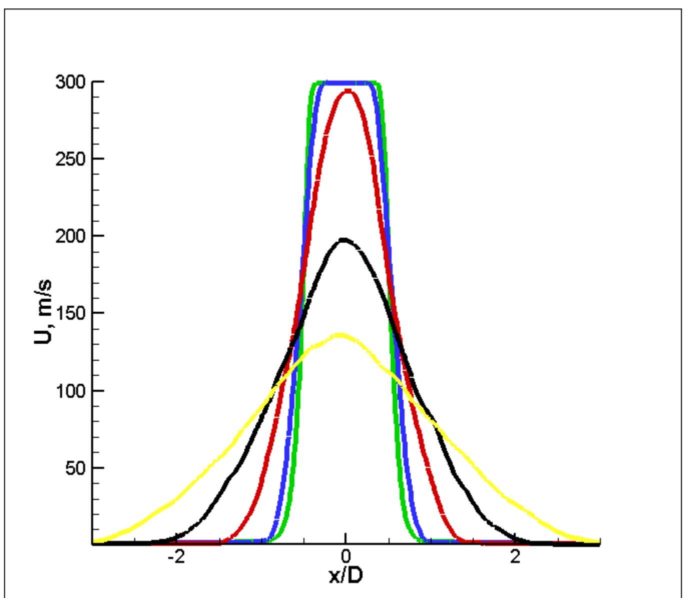
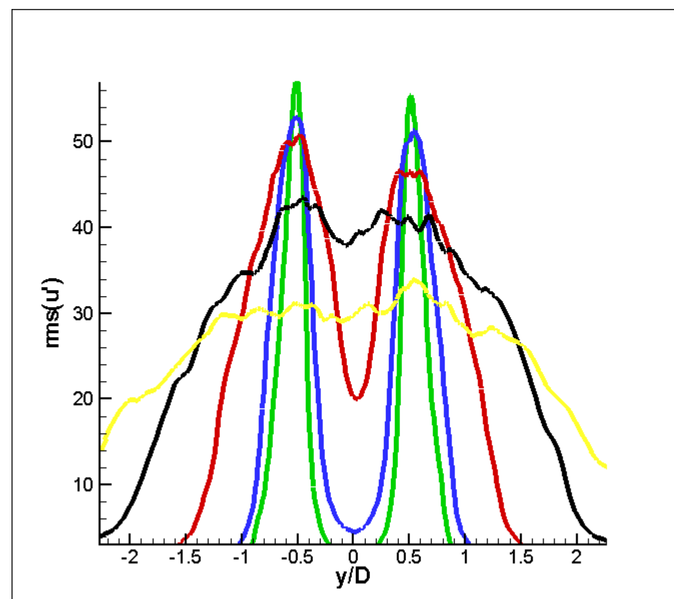
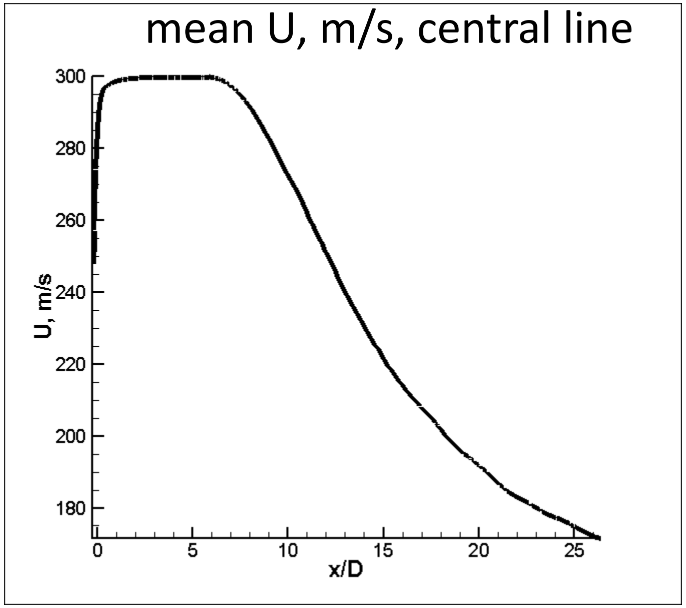


mean U and rms(u') at y/D=1,2,5,10,15





Cold jet with co-flow, V_j/c_0=0.875, T_j/T_0=1, M_c=0.3



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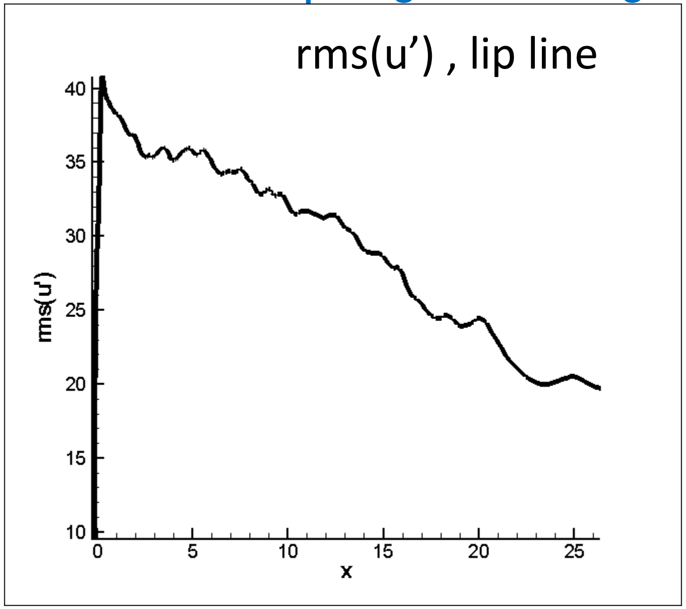
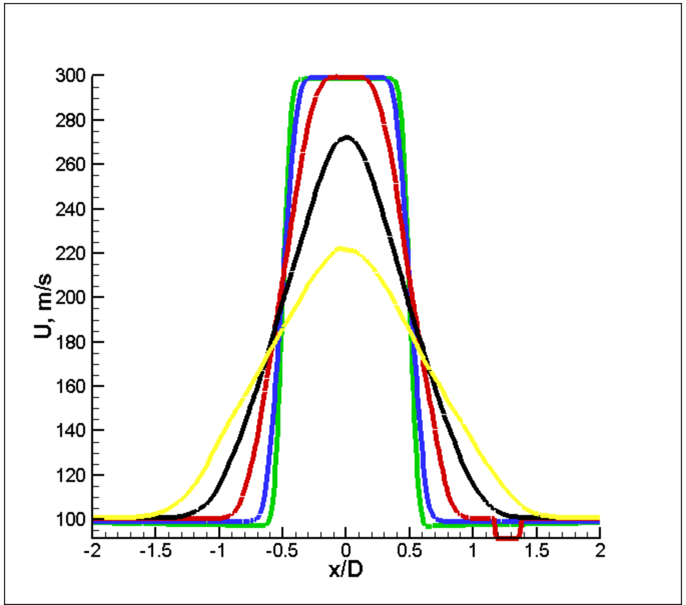
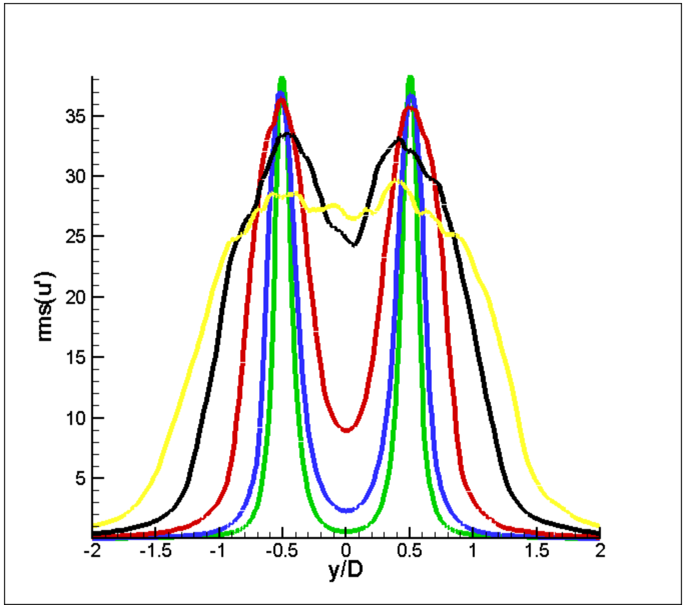
11% -
13%

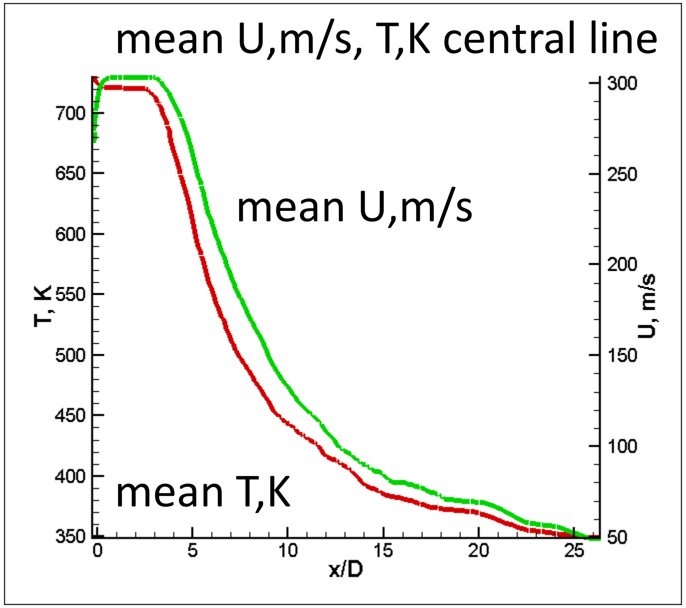


mean U and rms(u') at y/D=1,2,5,10,15





Hot jet without co-flow, $V_j/c_0=0.875$, $T_j/T_0=2.5$



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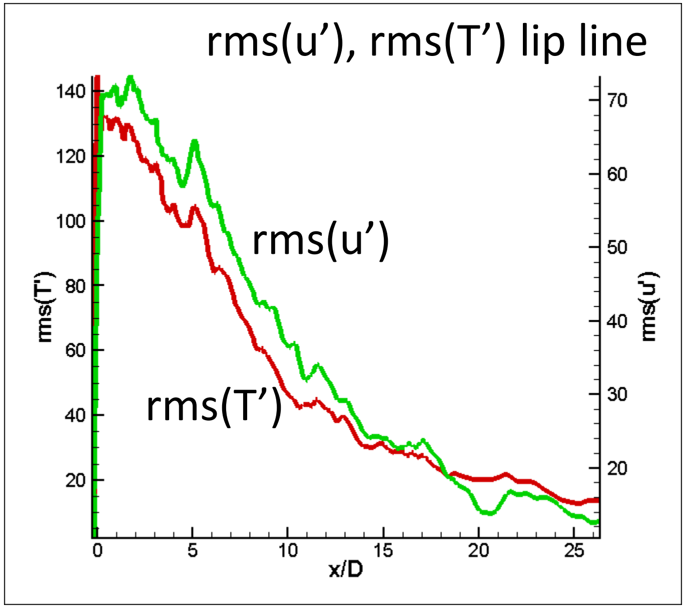
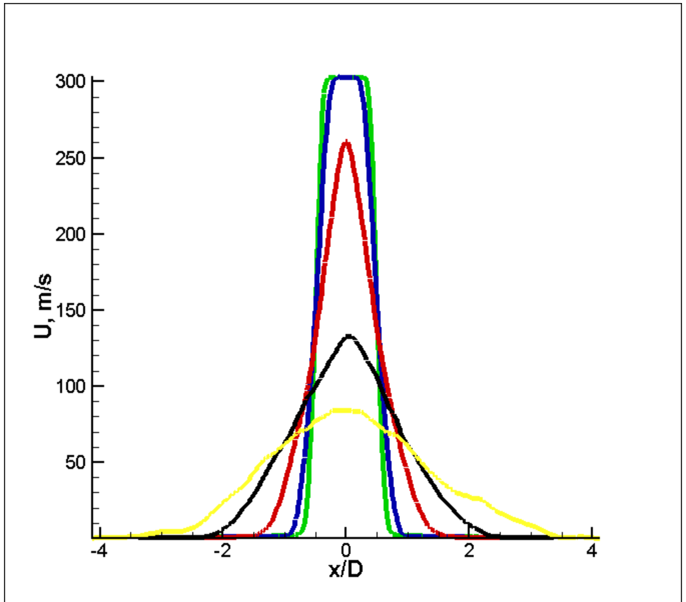
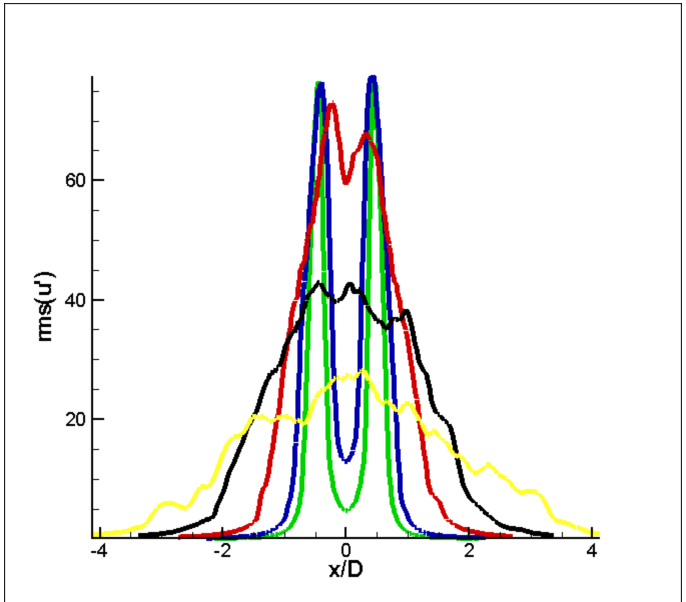
23%

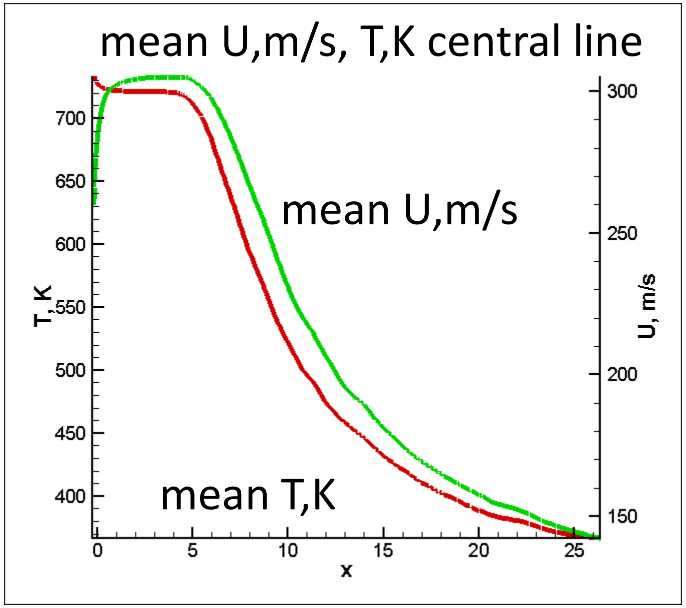


mean U and rms(u') at y/D=1,2,5,10,15





Hot jet with co-flow, $V_j/c_0=0.875$, $T_j/T_0=2.5$, $M_c=0.3$



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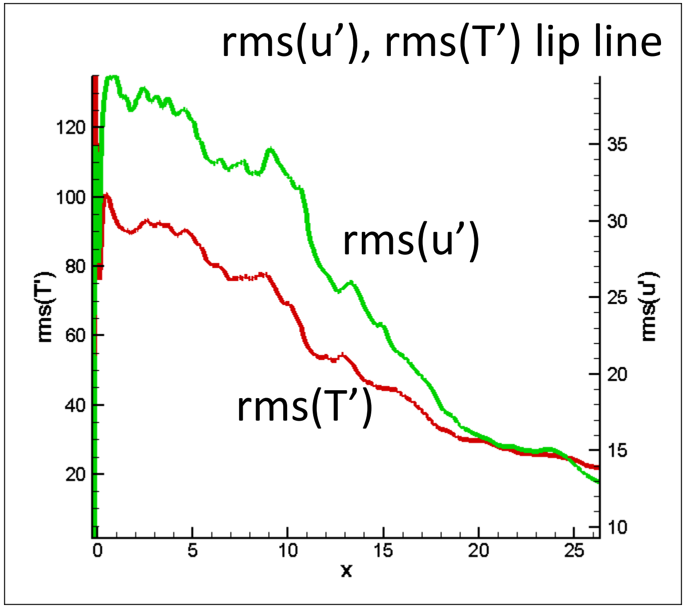
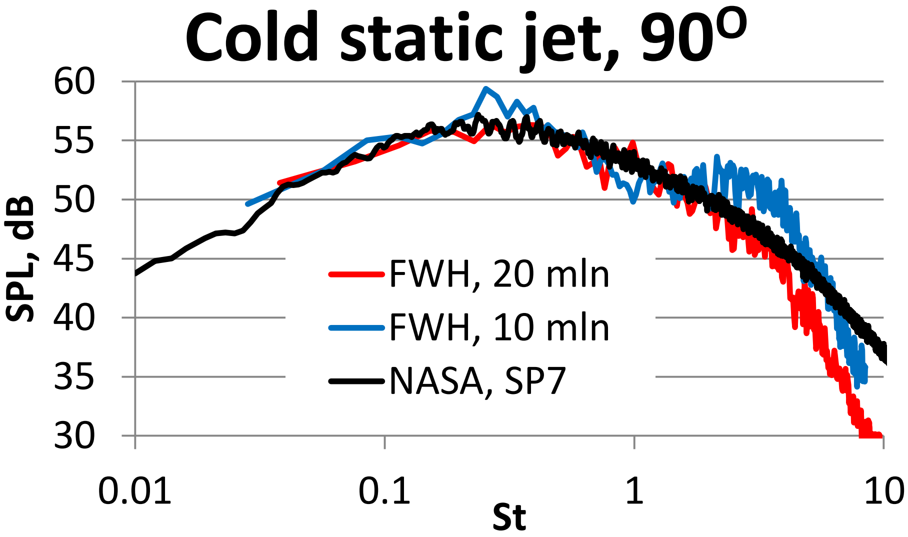
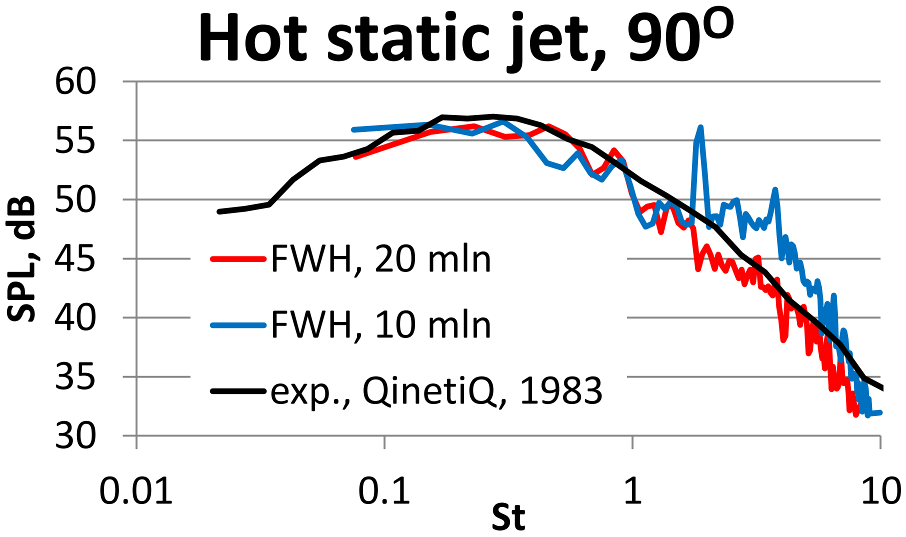
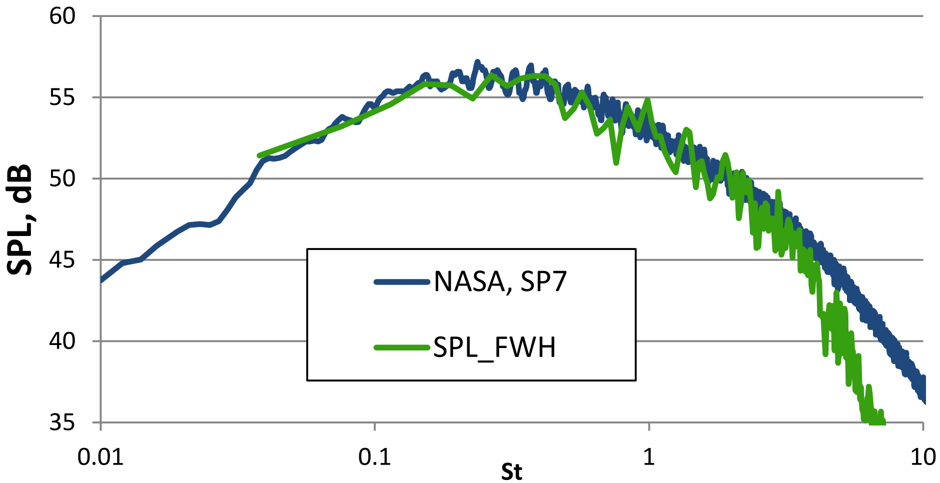


FWH, 10 and 21 mln meshes

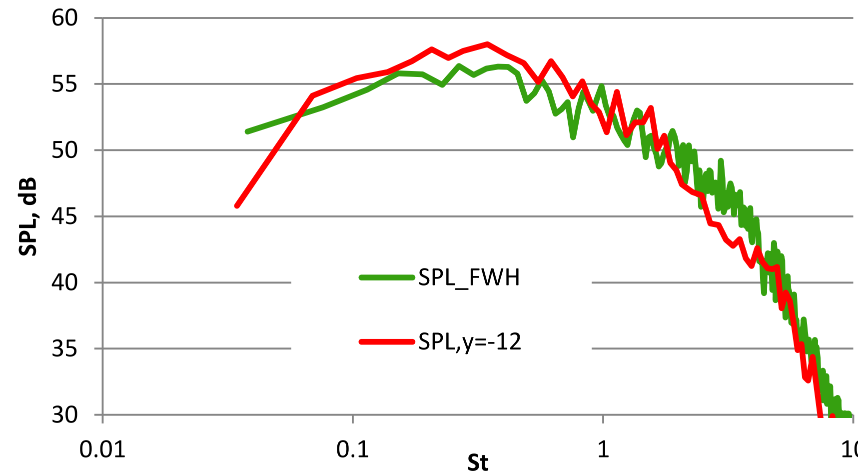




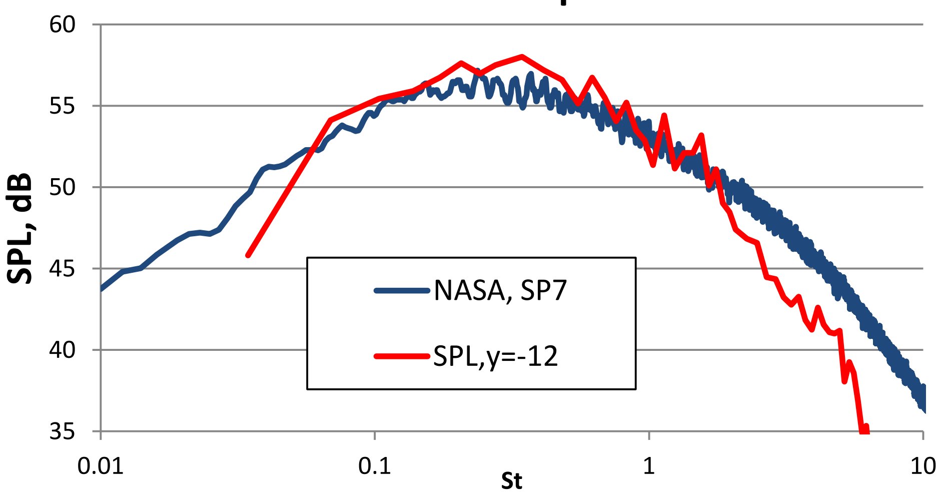
Cold static jet, $V_j/c_0=0.875$



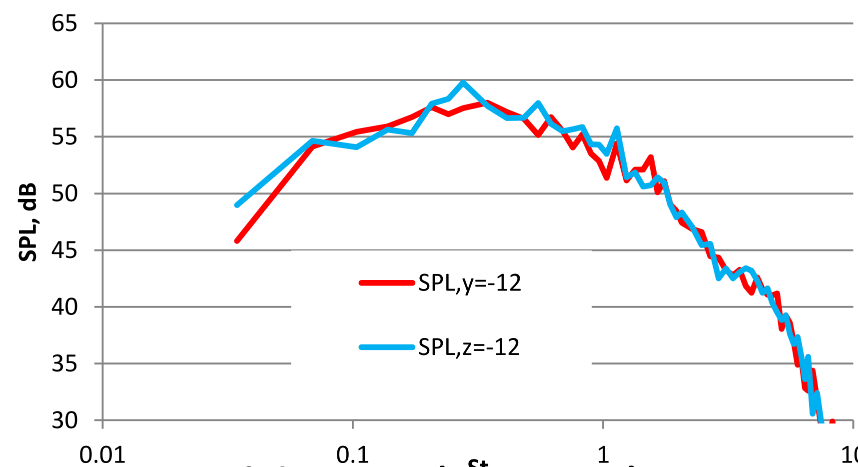
FWH vs exp.



Goldstein vs. FWH

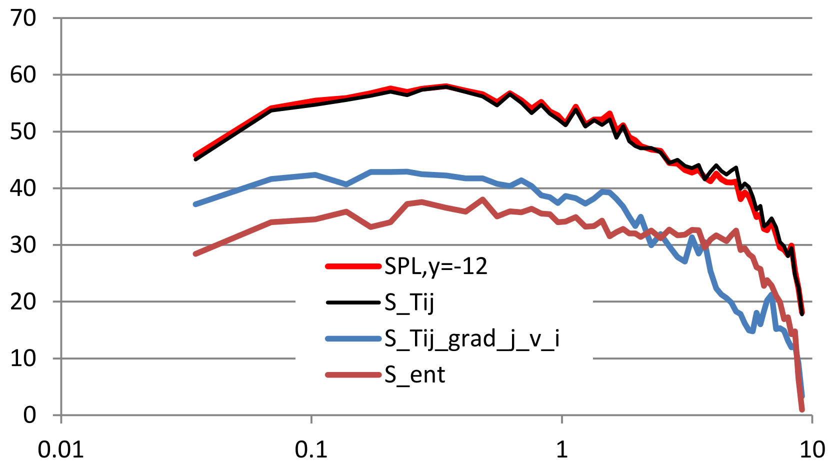


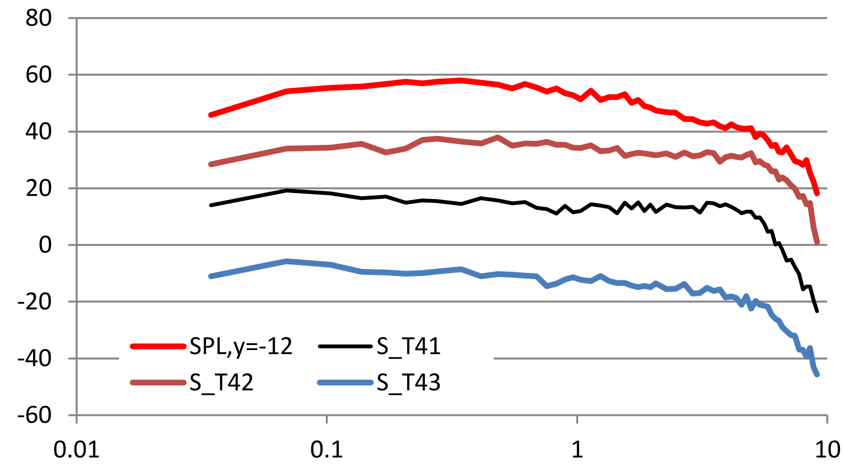
Goldstein vs exp.

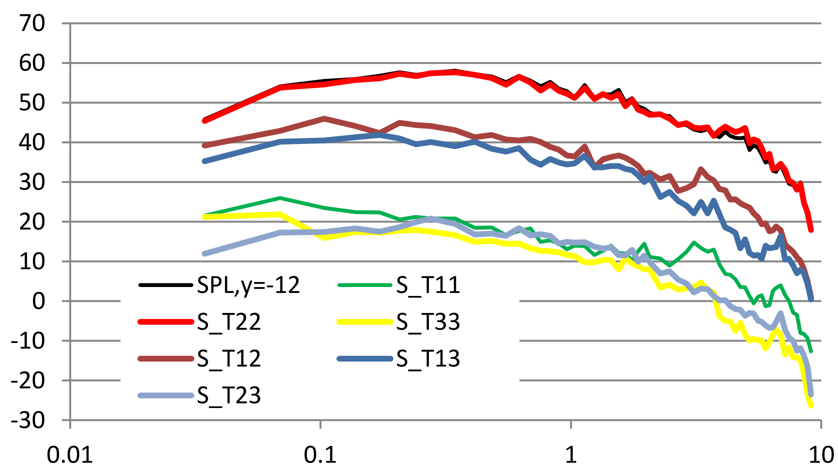


Goldstein (y=12m) vs
Goldstein (z=12m)

Component noise source analysis for observer (0,-12,0)

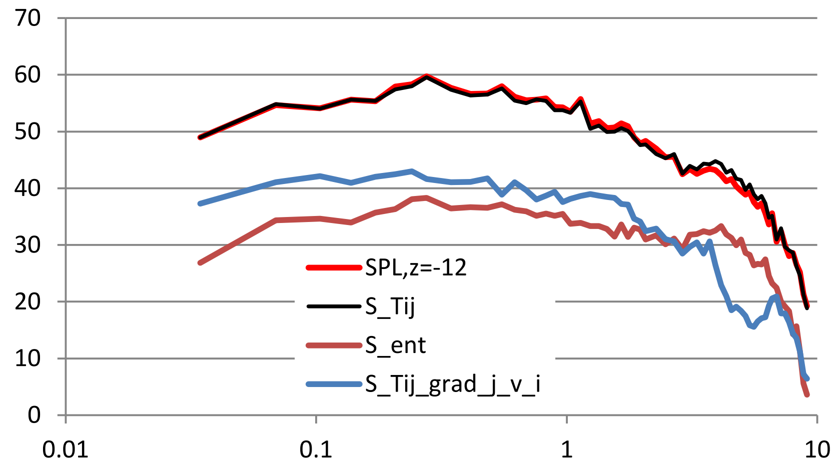


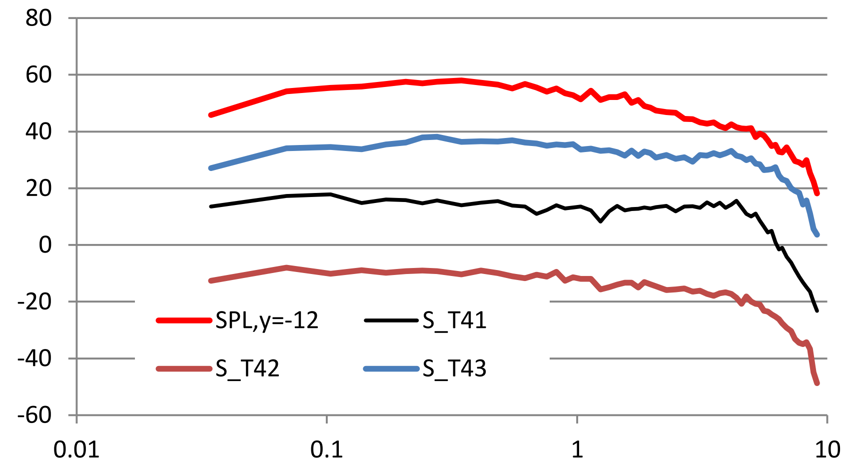


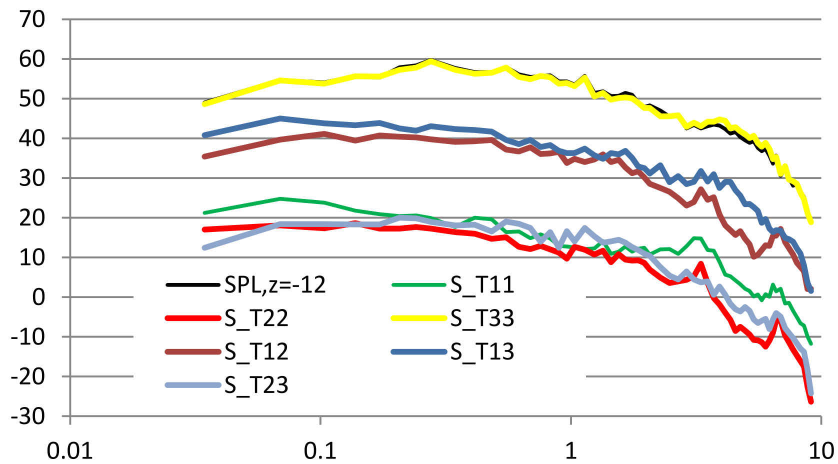


T_{22} is the main noise source

Component noise source analysis for observer (0,0,12)

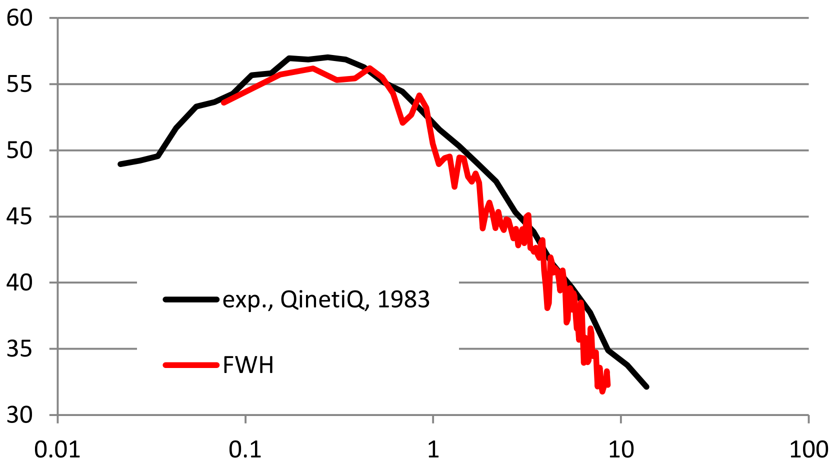




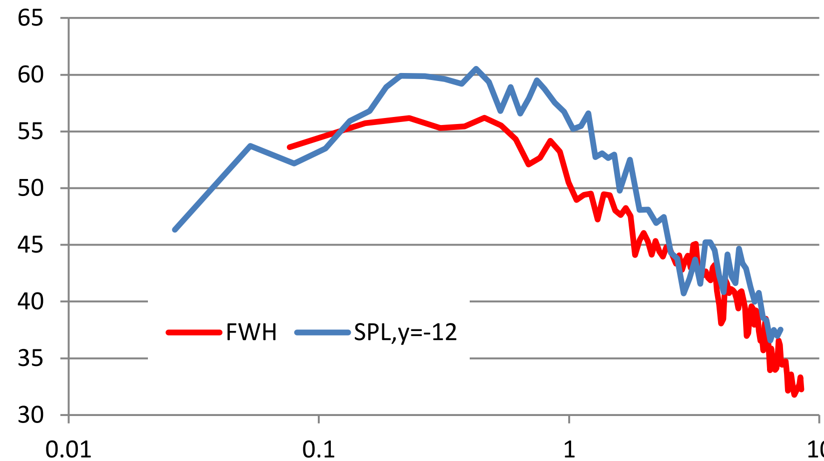


T_{33} is the main noise source

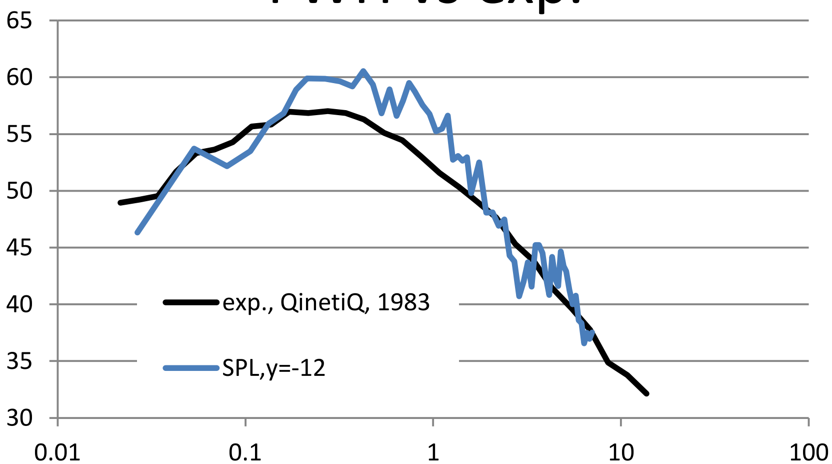
Hot static jet, $V_j/c_0=0.875$, $T_j/T_0=2.5$



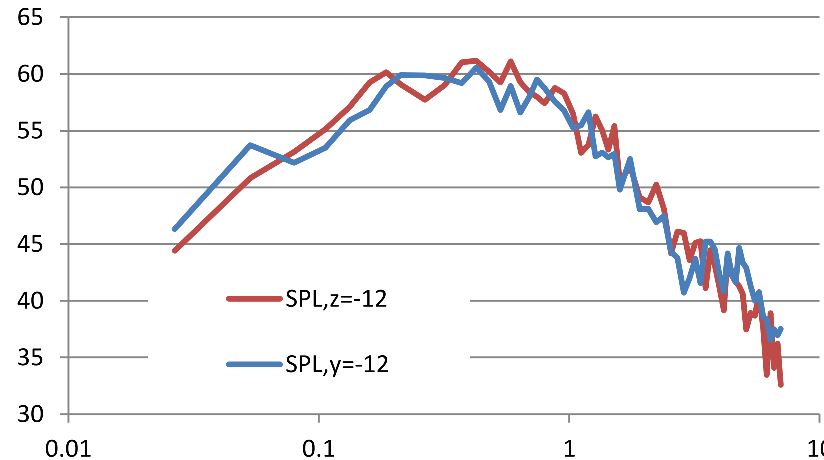
FWH vs exp.



Goldstein vs. FWH

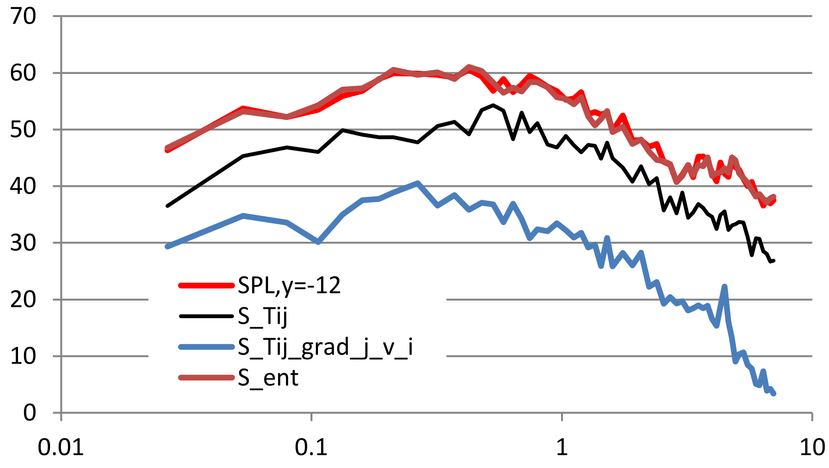


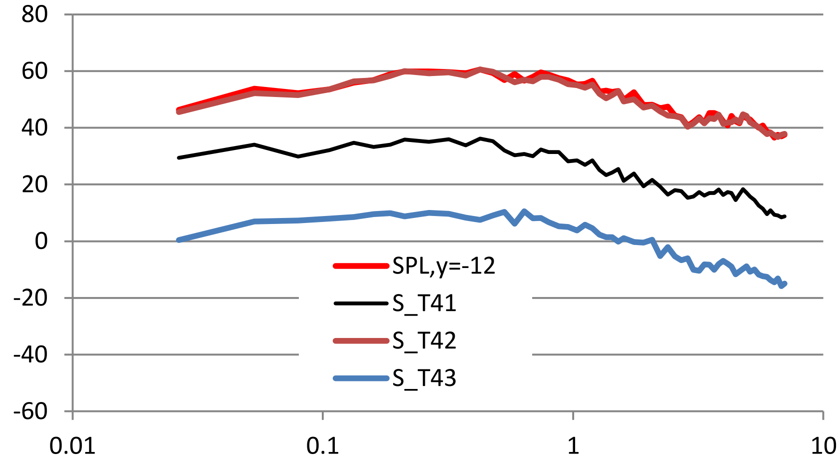
Goldstein vs exp.

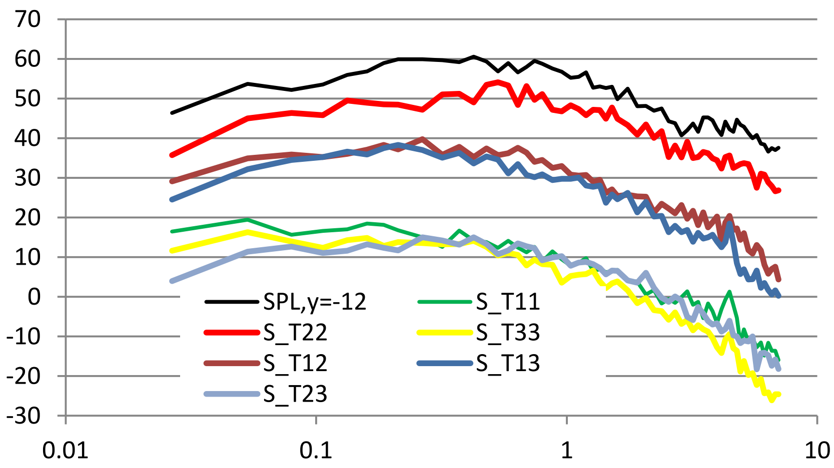


Goldstein (y=12m) vs
Goldstein (z=12m)

Component noise source analysis for observer (0,12,0)

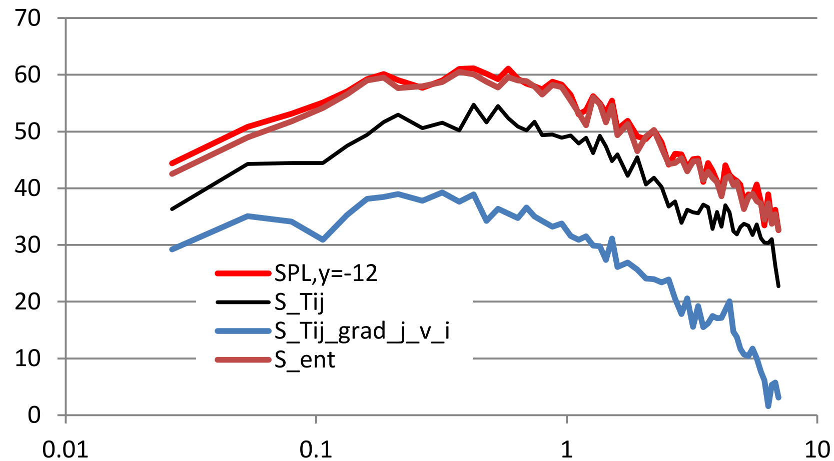


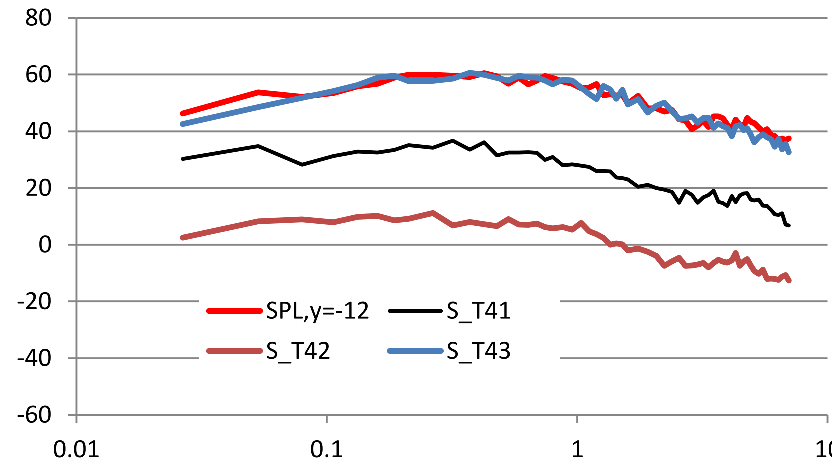


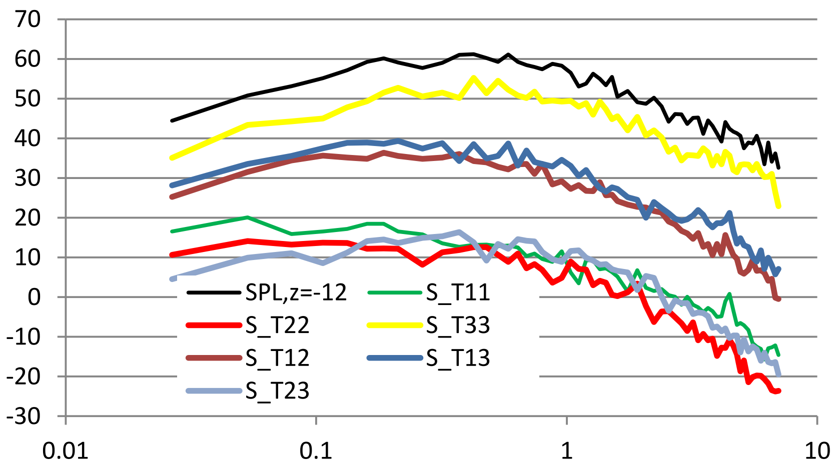


T_{42} is the main noise source

Component noise source analysis for observer (0,0,12)



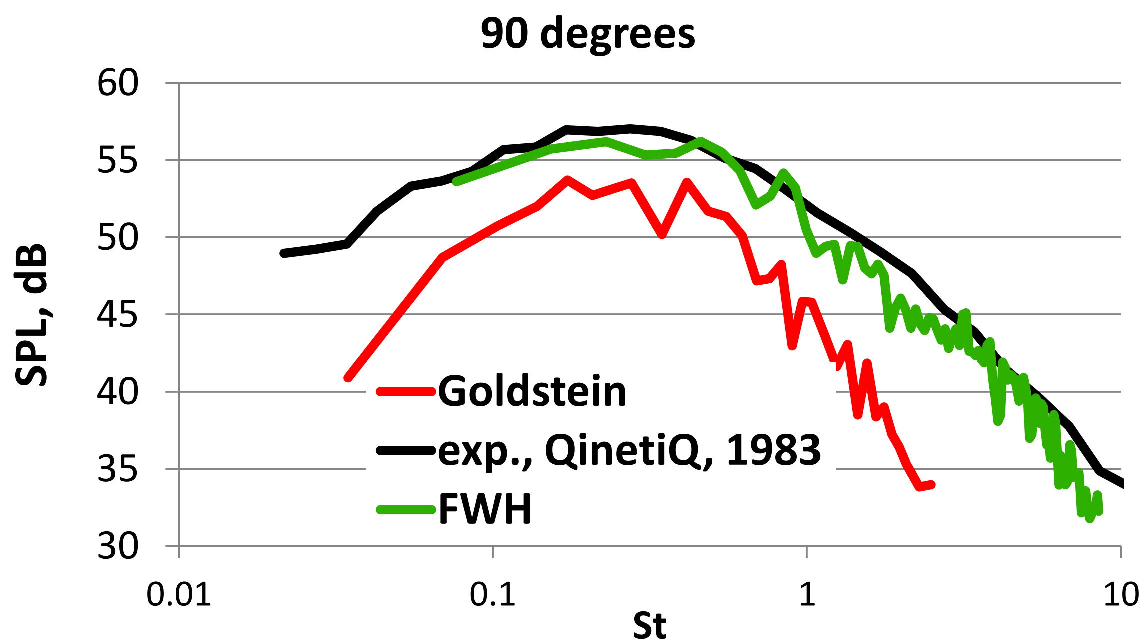




T_{43} is the main noise source

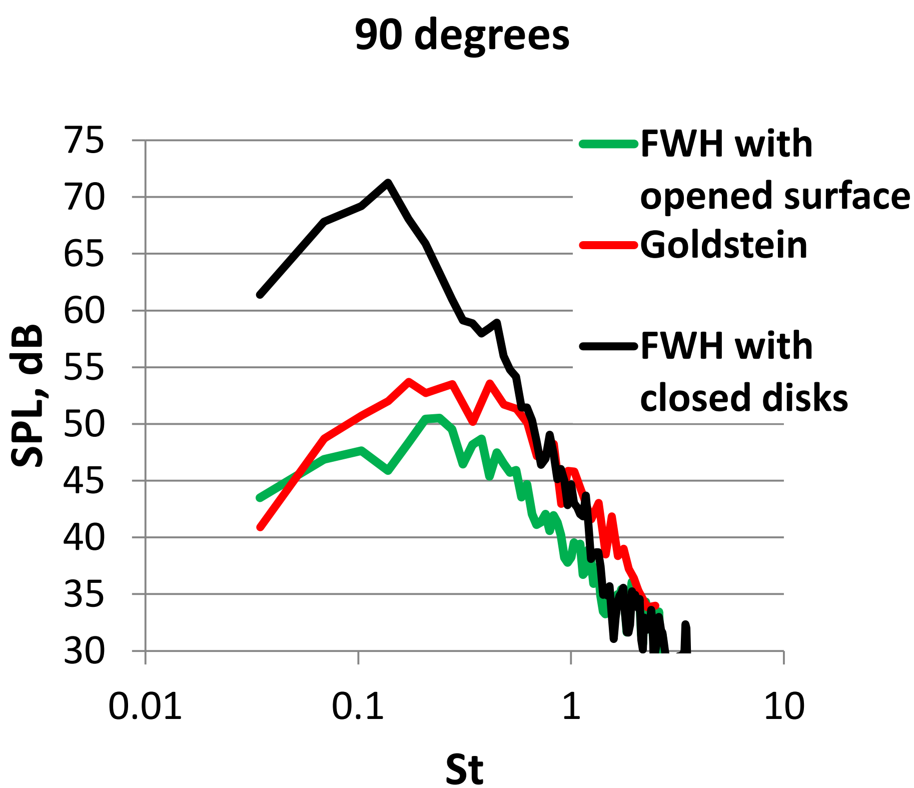
Acoustic predictions for the hot jet with the co-flow: Goldstein acoustic analogy

The noise predicted by the Goldstein analogy method for the jet with coflow M=0.3 is ~ 5 dB lower in comparison with the reference static jet;
This is consistent with the experimental observation that the jets with cofow are quieter by 2dB for each M_c=0.1



Black = hot jet without co-flow, exp. QinetiQ
Green = hot jet without co-flow, FW-H
Red =hot jet with co-flow, Goldstein analogy based on the free-space Green's function

FW-H with/without the closing disks (using same control surfaces as for the static jets) vs the Goldstein acoustic analogy



Red = hot jet with co-flow, FW-H, 4 closing disks, with free-stream convection
Black = hot jet with co-flow, FW-H, 4 closing disks, without free-stream convection
Blue = hot jet with co-flow, Goldstein analogy

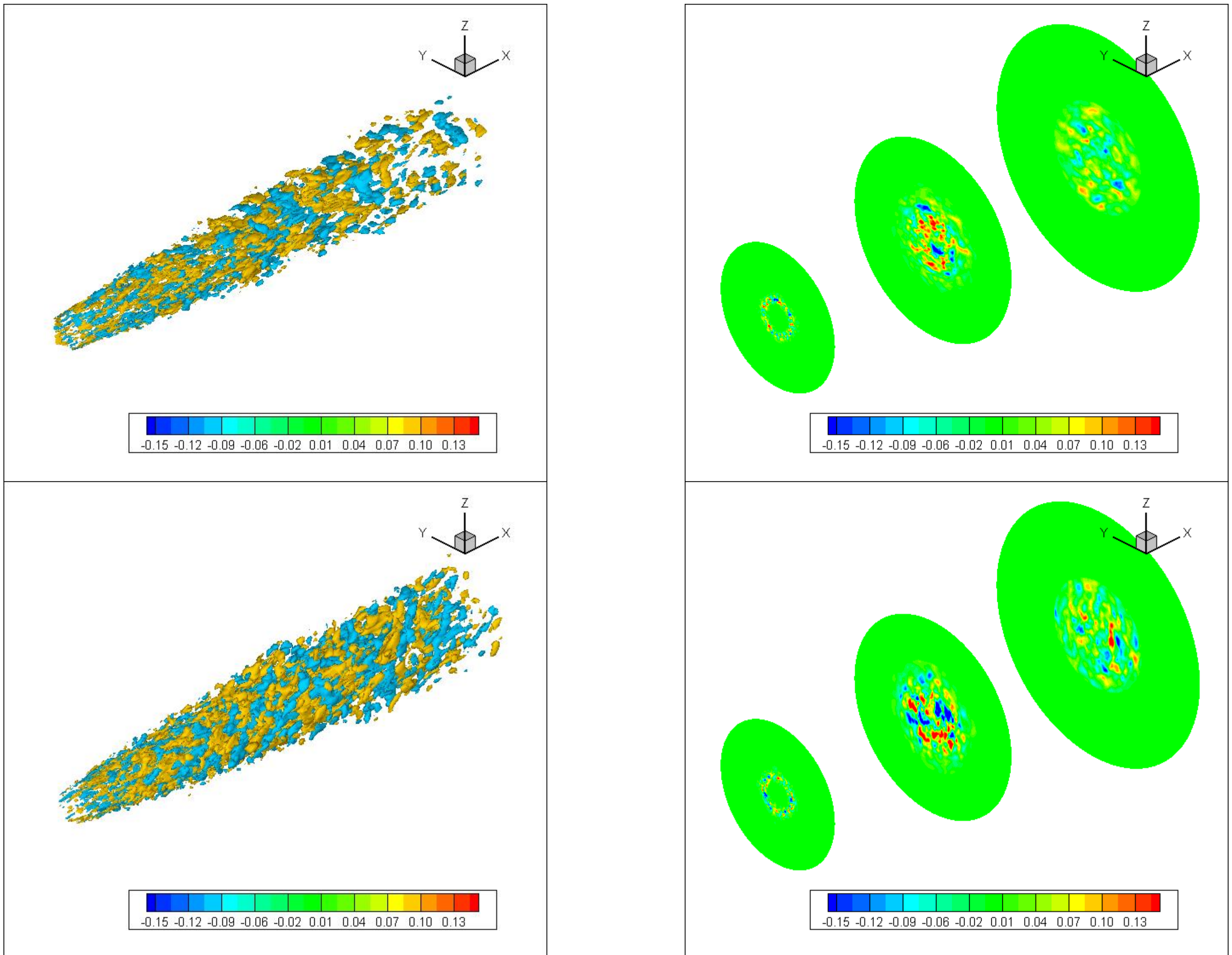
Pseudo sound: need a larger control surface for the jets with co-flow?

Noise Source Density at St=0.2 for cold jet and observer (0,12,0)

Full source

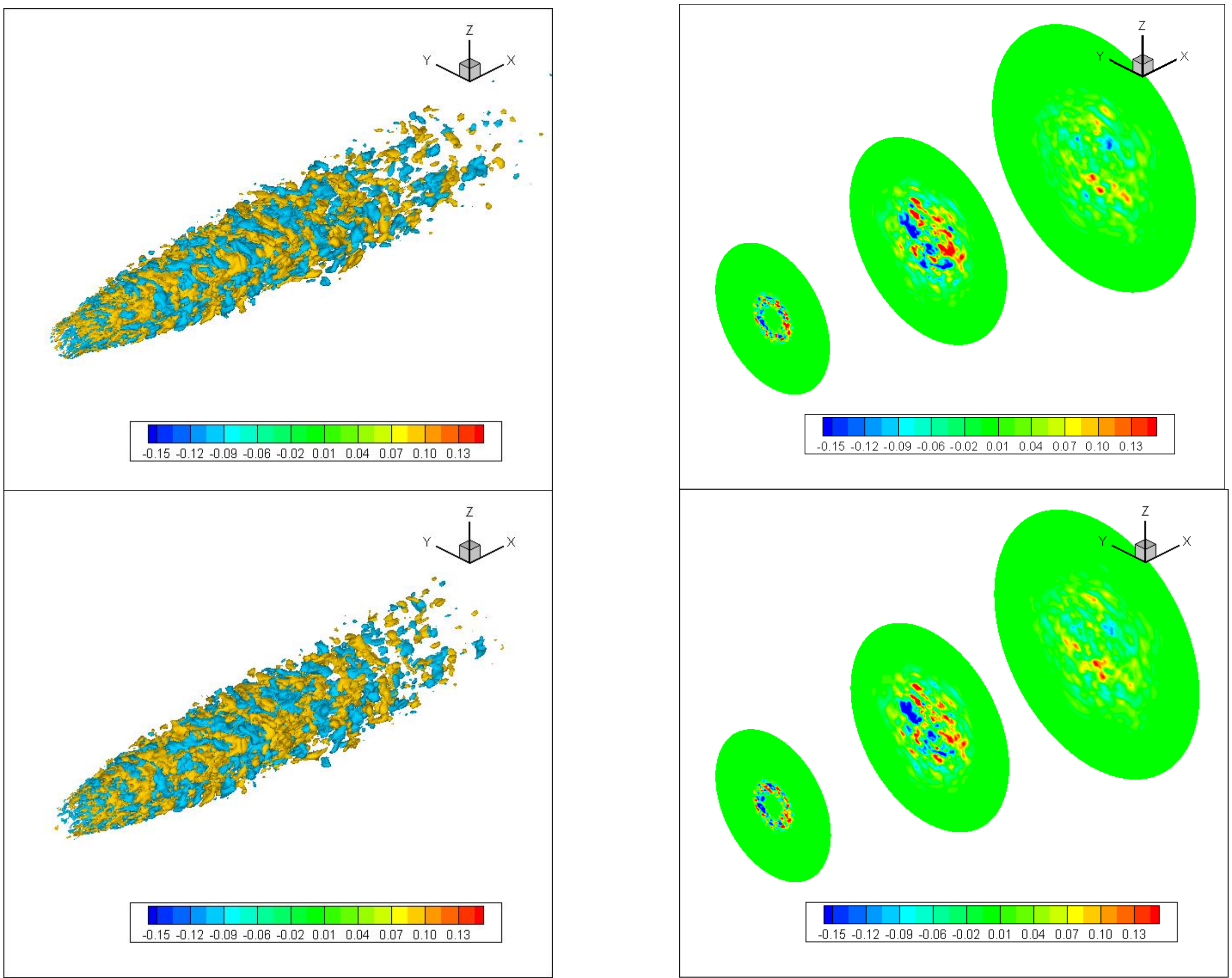
The dominant source is fluctuating Reynolds stresses ~*vvvv*

$\hat{e}''_{yy}$



Noise Source Density at St=0.2 for hot jet and observer (0,12,0)

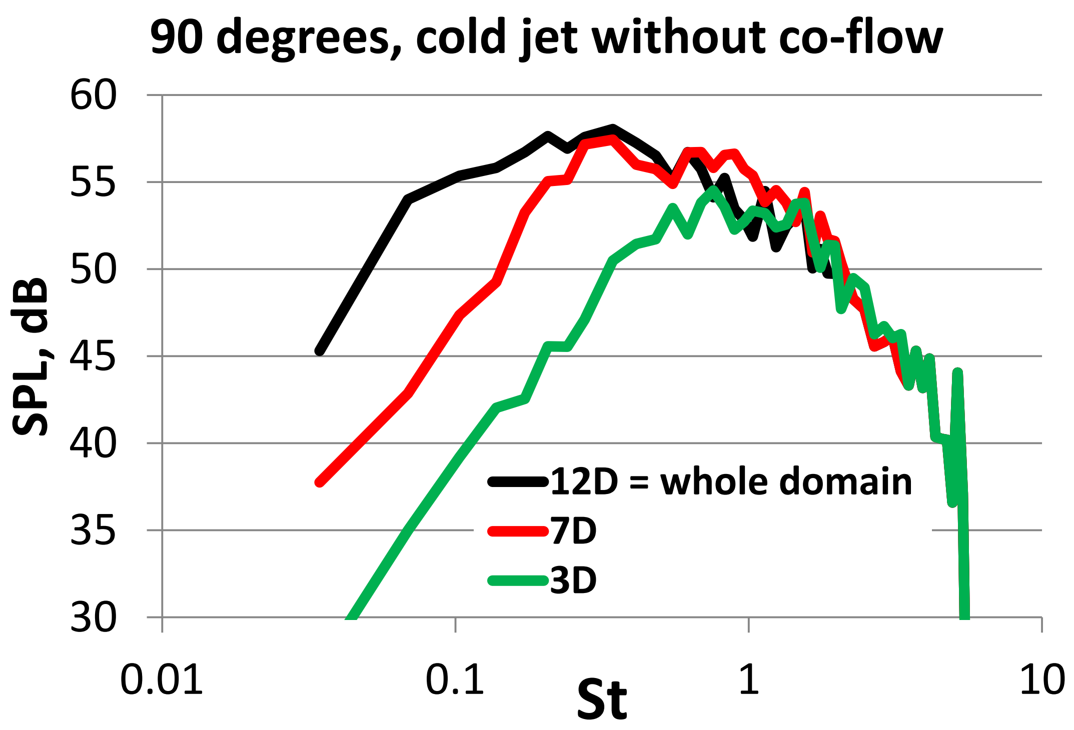
Full source



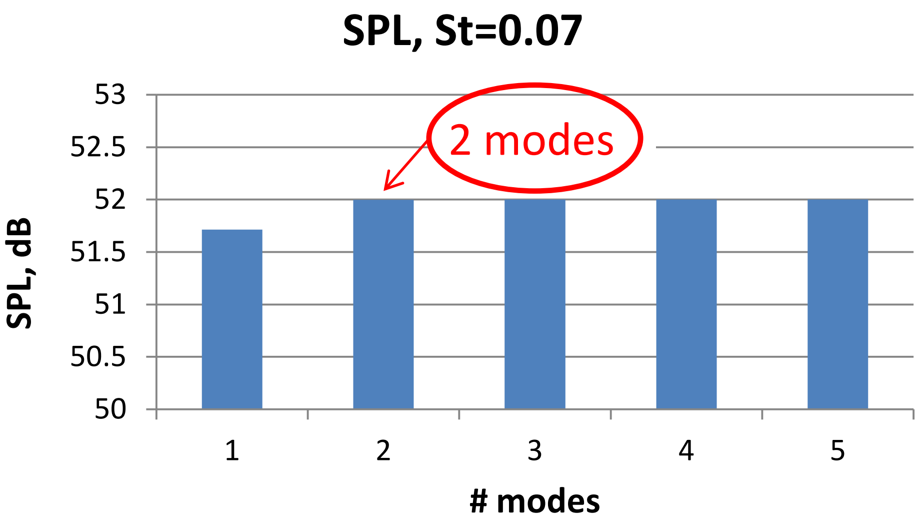
The dominant source is enthalpy fluctuations *~vh'vh'*

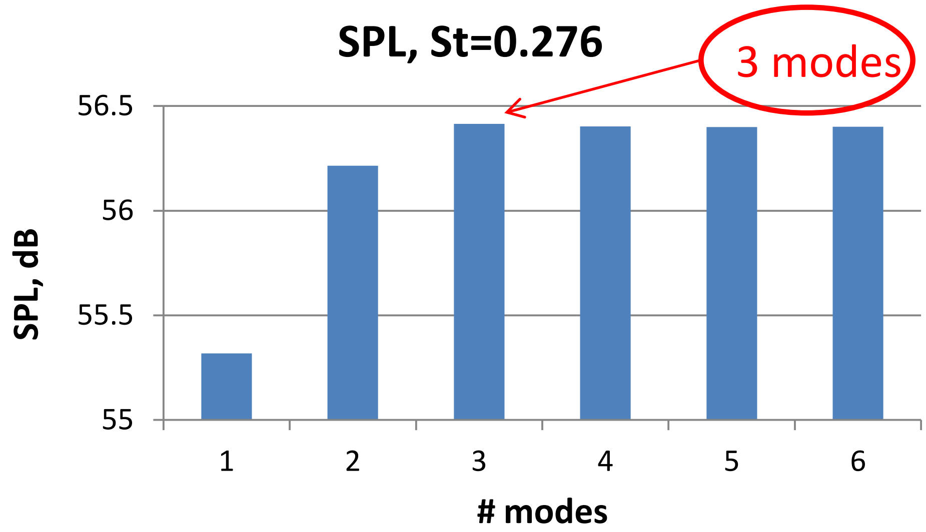
$\hat{e}''_{4y}$

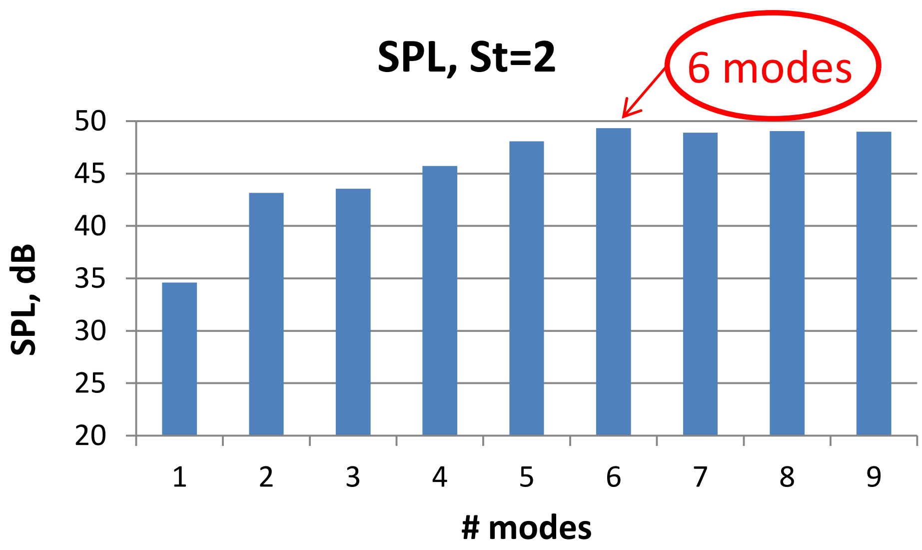
Sensitivity to length of the source volume



Distribution of SPL for different number of modes







Conclusions

- Post-processing LES data based on second order statistic data
  - In several orders of magnitude more efficient in comparison with previous approaches
  - More robust in comparison with FWH method
- Cold static jet
  - Turbulent stresses are the main source of far-field noise
  - Enthalpy fluctuations and turbulent stresses multiplied by velocity gradient tensor are negligible
  - Far-field noise in far field for 90 degrees in r-direction mainly produced by T_{rr}
- Hot static jet
  - Enthalpy fluctuations are the main source of far-field noise
  - Turbulent stresses and turbulent stresses multiplied by velocity gradient tensor are negligible
  - Main source of the far-field noise for 90 degrees is T_{4r} term