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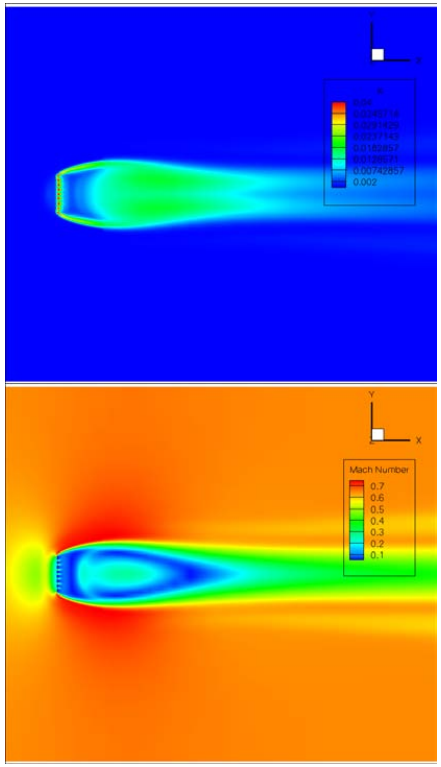
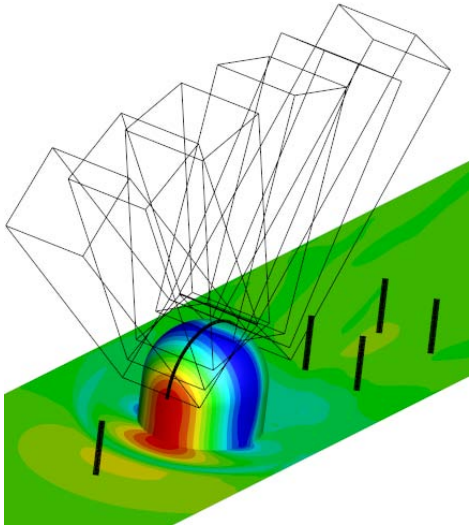
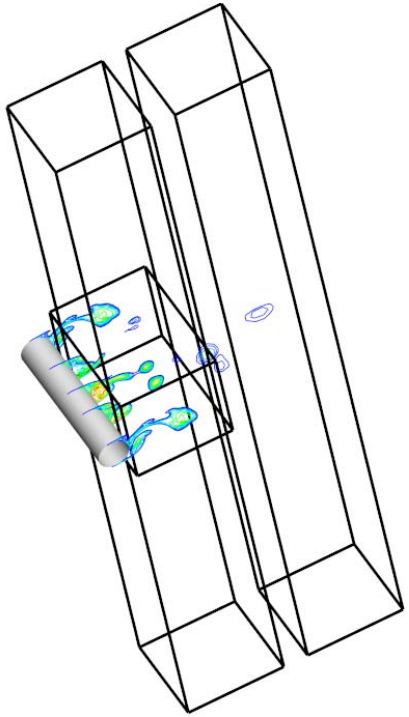
DEFENSE & SECURITY SOLUTIONS

Integration of Aero-Optics and Distributed Porosity Models within OVERFLOW







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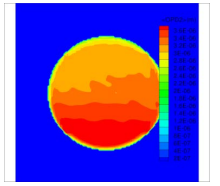
Advanced Technology Division

Presented at the

10th Symposium on Overset Composite Grids and Solution Technology
September 23, 2010



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Outline

- "Porous Media" Model
  - Identification of need and approach
  - Implementation in OVERFLOW
  - Comparisons/Demonstrations
- Aero-Optics Model Integration
  - Paraxial Beam Equations and Solver
  - Development and Integration into OVERFLOW: Approach #1
    - Validation and Demonstrations
  - Development and Integration into OVERFLOW (and others): Approach #2
    - Description of approach
    - Public API

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Porous Fence Model: Identification of Need

- Customer needs help mitigating effects of open cavities upon instruments located inside aircraft.
- An aerodynamic fence is presently being used on one cavity, while the other cavity might be improved with the addition of a fence there as well.
- Modeling either fence with an overset grid system is possible, but prohibitive:
    - "Fence #1" requires approximately 70 Million grid points for the fence alone for a total model size of about 105 Million grid points
- A simple body force model was applied earlier (Tramel), but needed some improvements:
    - Parallelization, body force same in all directions, flow realignment "fix"

Approach

- Develop a "Distributed Porosity Model" for incorporation into OVERFLOW
- Requirements:
    - Parallelizable
    - "Easy" to specify volumetric and areal porosities and regions

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Porous Fence Model

- Distributed Body Forces:
  - Simulate the effect of obstructions not resolved by mesh
  - Motivated by forest and urban canopy modeling used in numerical weather models and in urban CFD transport and dispersion models

$$S_x = \frac{A_x}{\beta}\frac{\rho}{2}u|U| = \Gamma_x \rho u|U| \qquad S_y = \frac{A_y}{\beta}\frac{\rho}{2}v|U| = \Gamma_y \rho v|U| \qquad S_z = \frac{A_z}{\beta}\frac{\rho}{2}w|U| = \Gamma_z \rho w|U| \qquad S_5 = uS_x + vS_y + wS_z$$

- Source terms added to the momentum and energy equations
  - There are terms that can be added to t.k.e. and dissipation rate equations, but these are neglected due to past experience
- Linearization of body force terms is included in two LHS operators:

$$J_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ -\Gamma_x u U & \Gamma_x \dfrac{\left(U^2 + u^2\right)}{U} & \Gamma_x \dfrac{uv}{U} & \Gamma_x \dfrac{uw}{U} & 0 \\ -\Gamma_y v U & \Gamma_y \dfrac{uv}{U} & \Gamma_y \dfrac{\left(U^2 + v^2\right)}{U} & \Gamma_y \dfrac{wv}{U} & 0 \\ -\Gamma_z w U & \Gamma_z \dfrac{uw}{U} & \Gamma_z \dfrac{vw}{U} & \Gamma_z \dfrac{\left(U^2 + w^2\right)}{U} & 0 \\ \dfrac{\partial S_5}{\partial q_1} & \dfrac{\partial S_5}{\partial q_2} & \dfrac{\partial S_5}{\partial q_3} & \dfrac{\partial S_5}{\partial q_4} & 0 \end{pmatrix}$$

Implementation Details

- Definition of porous regions and porosity values:
  - (j,k,l) range of regions and "type" of porosity definitions:
    - Ax, Ay, Az constant
    - Ax, Ay, Az define magnitude of areal porosity and are applied normal to the local coordinate surfaces using metrics (3 surfaces)
    - Ax, Ay, Az defined from a q-file
  - In practice, we use the q-file approach:
    - Given the fence geometry (hole pattern, hole diameters) and grid, each grid point is assigned the corresponding areal and volumetric porosity

$$n_i = \frac{\xi_i}{\sqrt{\xi_x^2 + \xi_y^2 + \xi_z^2}}$$

- Parallelization
  - After domain decomposition in OVERFLOW, on each processor each porous media "block" is intersected with the blocks/zones being solved on this processor resulting in a list of intersected porous media sub-blocks used for body force processing on this processor
- OVERFLOW entry points:
  - OVERRU, OVERST, STEP, RHSH, OVERGL, DISTGL, OVERDO
- Limitations:
  - Not set up for grid coarsening (FMG=.true.) or multi-grid or moving grids or …
  - Linearization only for 32 bit SSOR and BW (ILHS=0 or 5, in the j-factor split)

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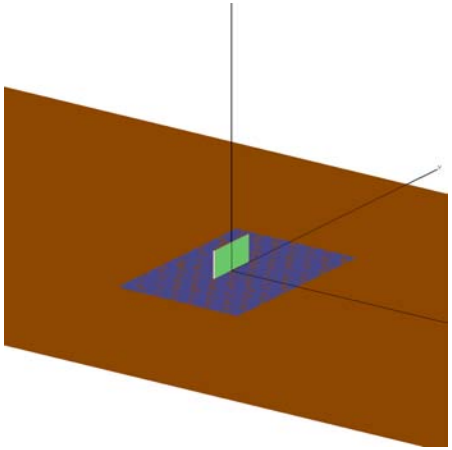
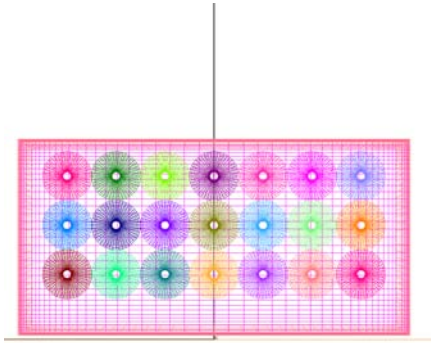
Porous Fence Model "Validation"

- We have been using the porous fence model to perform design trade studies for a particular aircraft in a particular program funded by a particular agency.
  - DES calculations of a complete aircraft with open instrument bays, simplistic models of instruments inside
  - Estimate improvements upon unsteady forces and moments imposed on instrument models with different fence designs
    - Fence height, inclination angle, location upstream, porosity
  - Flight tests have backed up our design trends and increments
  - Our recommendations are flying now

What we can show you:
- Spoiler on a plate
- Spoiler with 21 holes on a plate
- Compare overset results (resolving plate and holes) with porous media model results
- RANS (SST), HLLC, 2nd Order…





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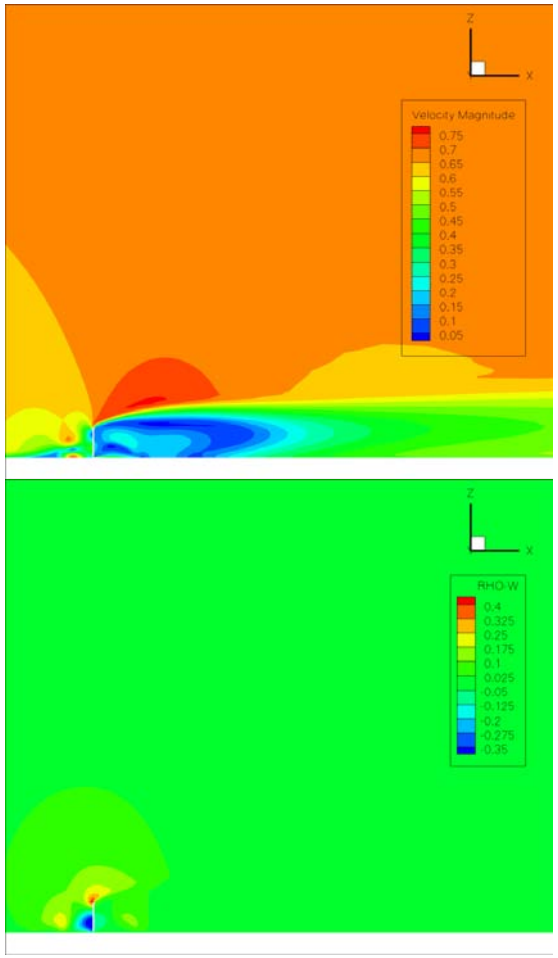
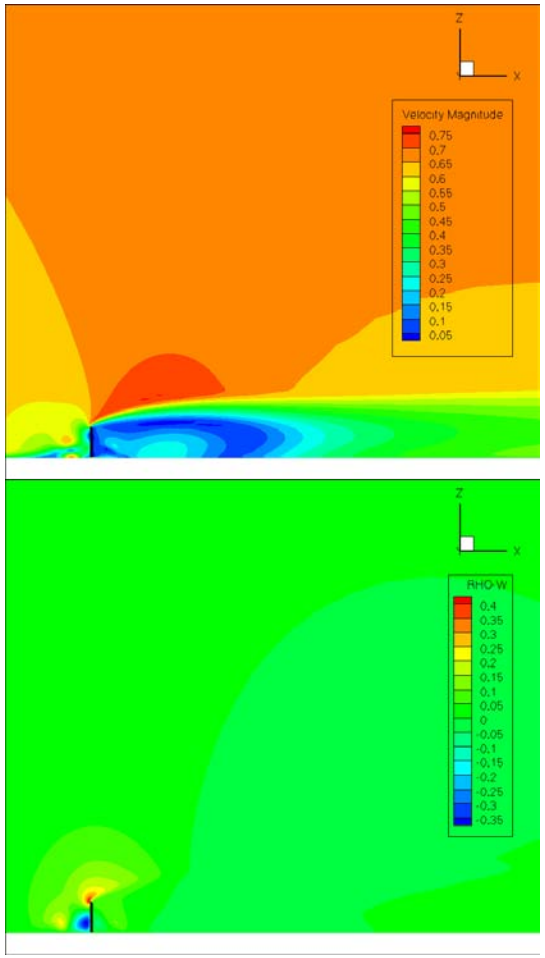
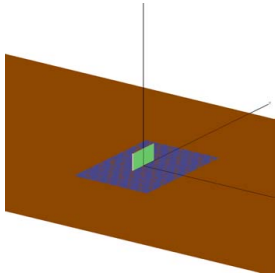
Porous Fence Model "Validation"

Gridded Spoiler



Porous Media Spoiler





Velocity Magnitude

Velocity Normal to Plate

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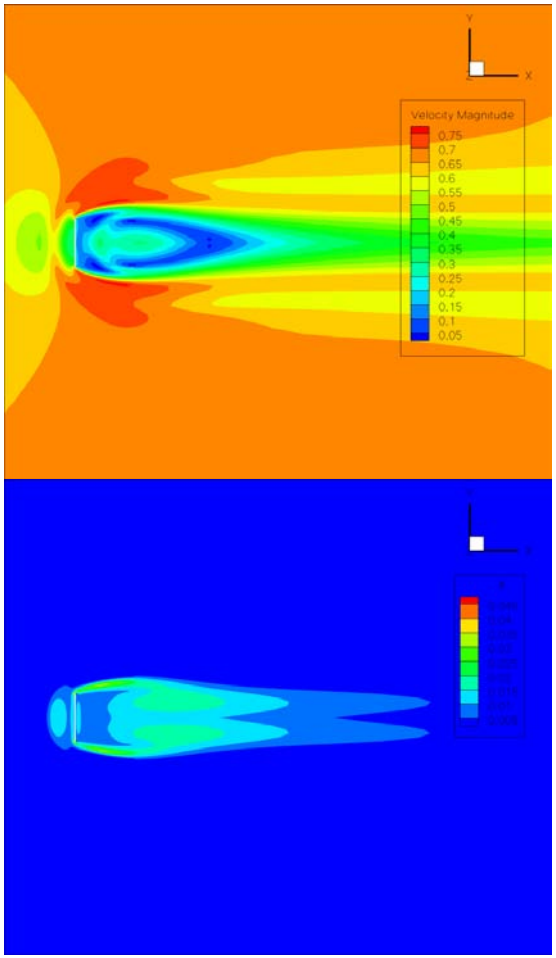
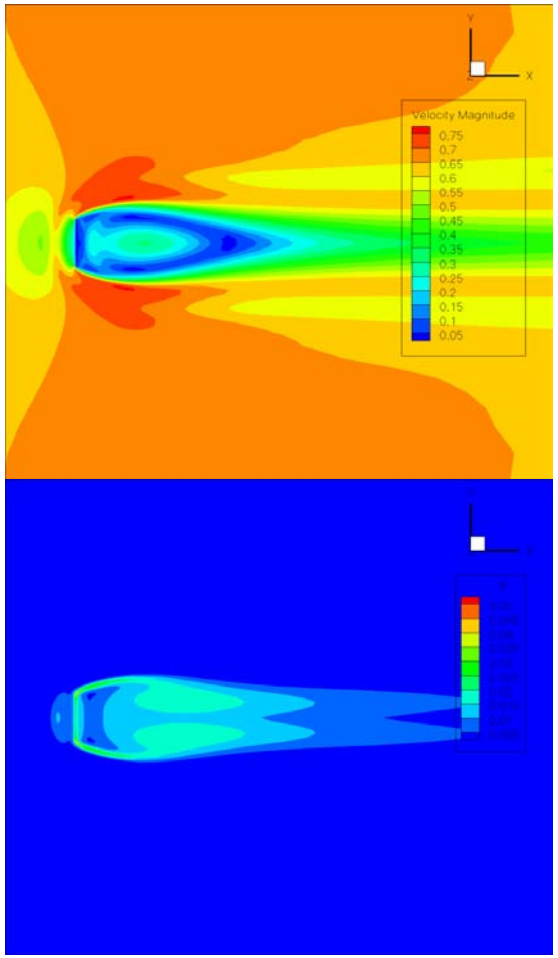
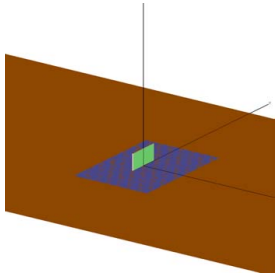
Porous Fence Model "Validation"

Gridded Spoiler



Porous Media Spoiler





Velocity Magnitude

Turbulence Kinetic Energy

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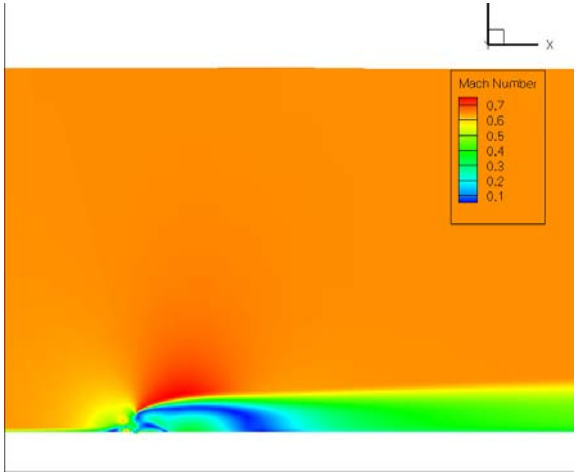
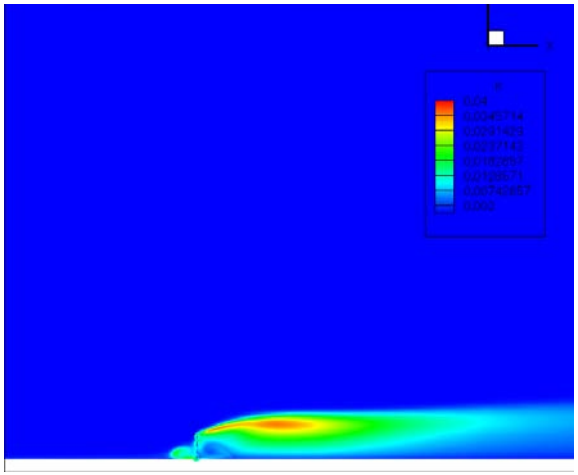
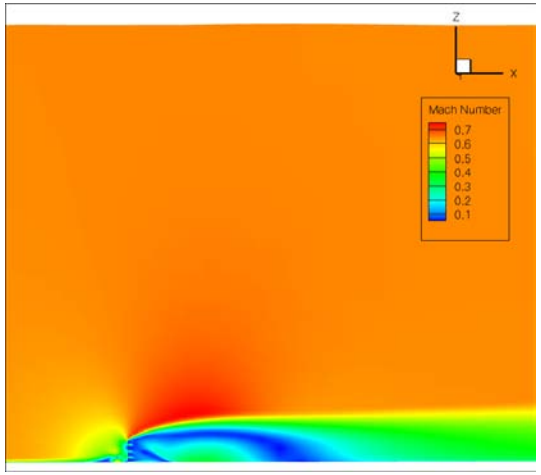
Porous Fence Model Improvements

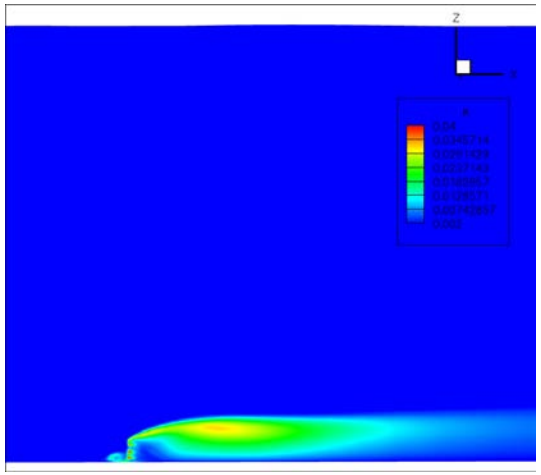
Gridded 21 hole Spoiler

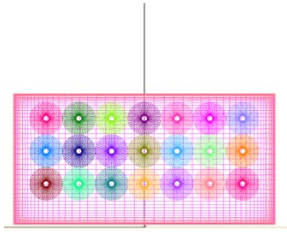




Porous Media “21 hole” Spoiler







Mach Number

Turbulence Kinetic Energy

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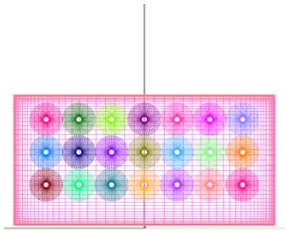
Porous Fence Model Improvements

Gridded 21 hole Spoiler

Porous Media “21 hole” Spoiler



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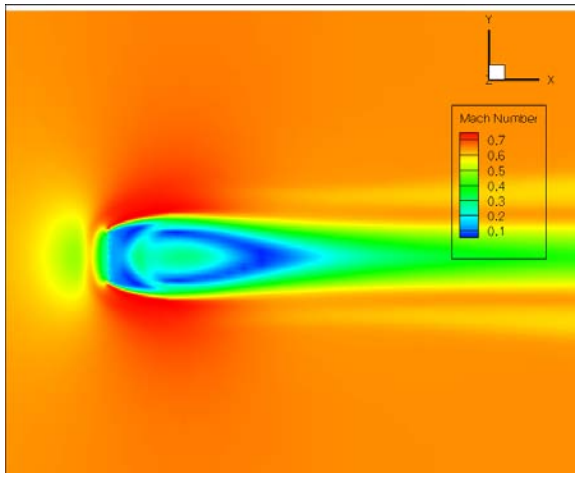

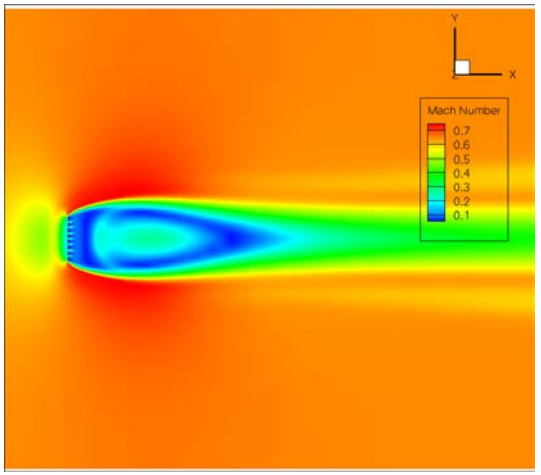

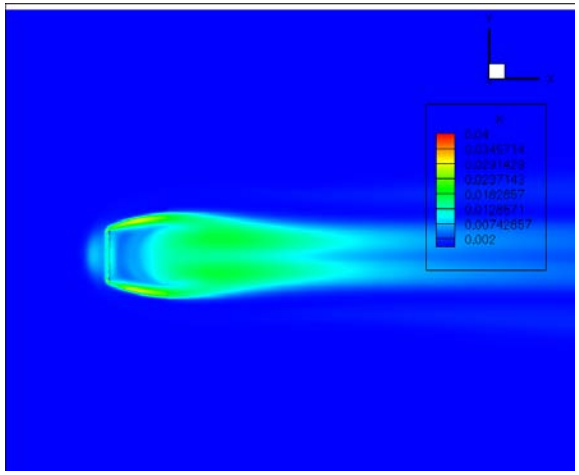

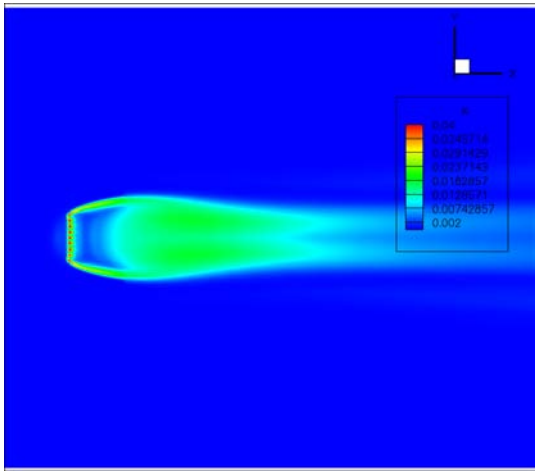

Turbulence Kinetic Energy

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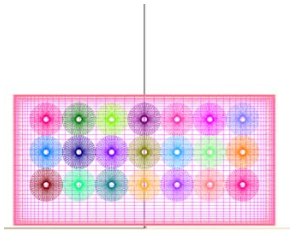

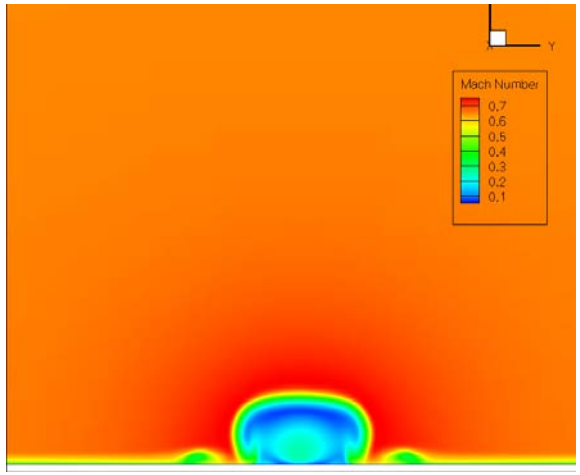

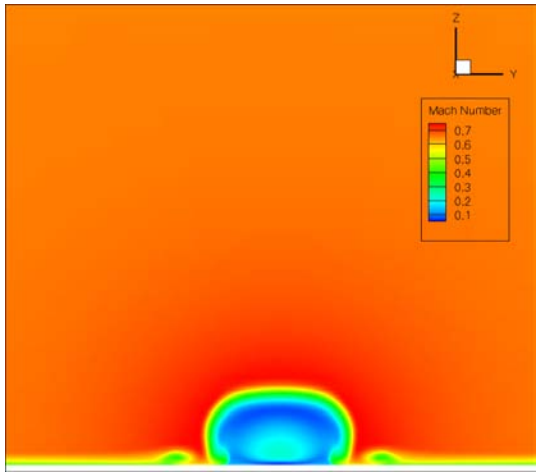

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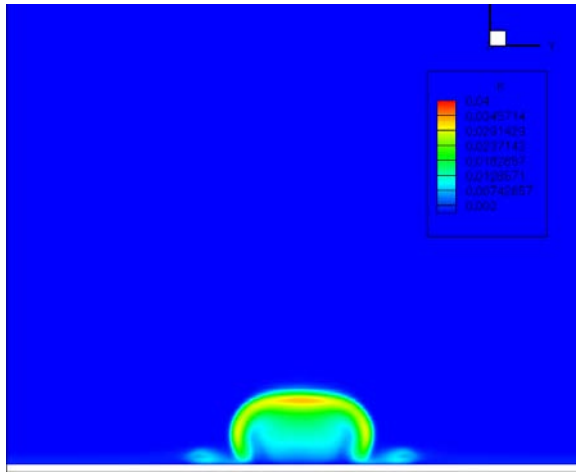

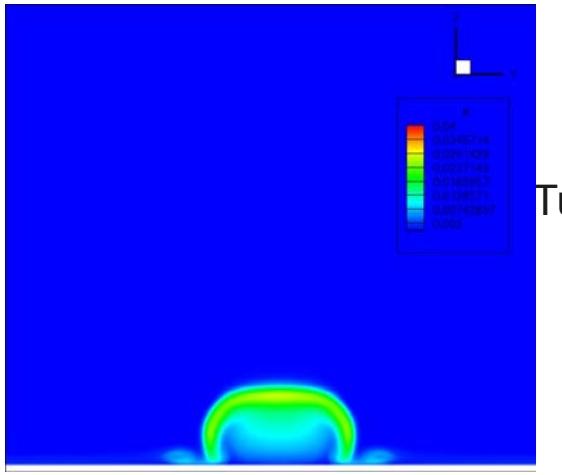

Turbulence Kinetic Energy

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Coupled CFD/Aero-Optics Modeling

"Then"

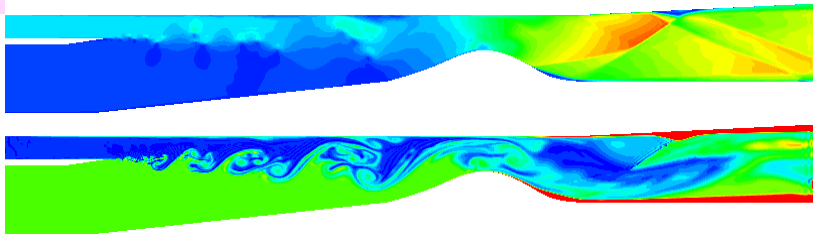
OVERFLOW 2.1x

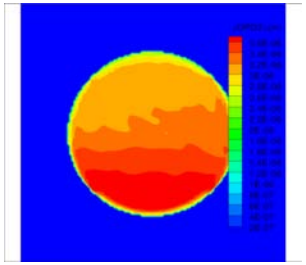
aeroOpticsModule

Beam Profiles

Post Processors

Aero-Optic Metrics





"Now"

Mesh Preprocessor

Paraxial Solver Class Library

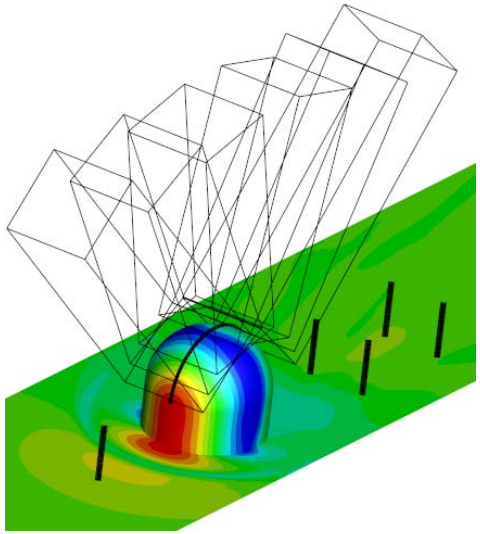
Overset or Unstructured CFD Solver

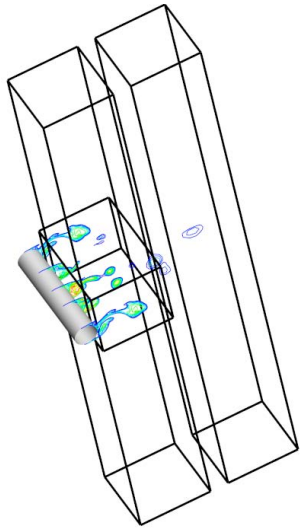
Paraxial Solver Class Library

Propagated Beam Data Files

Paraxial Solver Class Library

Aero Optical Quality Metrics





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Acknowledgements

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• Aerosciences and Engineering Analysis Group (Kratos/DFI):

• Bob Tramel (ex-DFI, now Kord Technologies)

    • Original PI, formulation of Paraxial Beam Solver

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General Description of Problem

- Characterize the near-field, aerodynamically-induced distortion of optical beams as they are propagated through the unsteady, compressible, turbulent flow fields in the vicinity of air vehicles.
    - "Aero-Optics" as opposed to "Atmospheric Propagation"
- Optical/Beam distortion caused by changes in index of refraction and beam spreading/attenuation:
    - Spatial variations in density (index of refraction) induce phase differences in planar waves
        - Beam phase and amplitude distribution related to beam spreading perpendicular to propagation direction
    - Temporal variations of density induce temporal variations in beam patterns
- Need to model:

Compressible flow field to capture the large-scale density variations.
Turbulent fluctuations to capture the small scale density variations.

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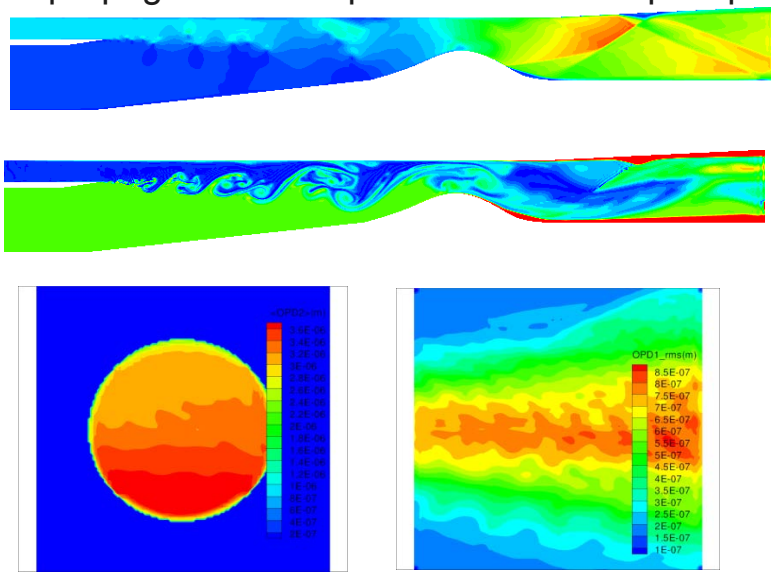
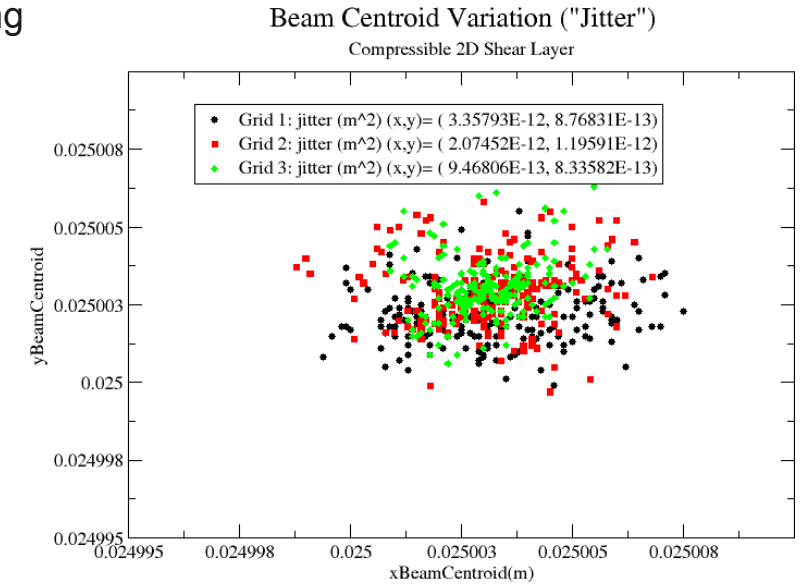
Original Approach

OVERFLOW 2.1x
aeroOpticsModule
→ Beam Profiles → Post Processors → Aero-Optic Metrics

- Integrate a Paraxial Beam Equation solver into OVERFLOW 2.1x
- Propagate Beams at specified time steps through “optical grids”
- Deposit propagated beam profiles to disk for post processing



- Post Processing utilities:
  - Produce visualization files (beam amplitude, OPD…)
  - Compute AO statistics/Metrics



FROM STRENGTH TO SUCCESS™

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Paraxial Beam Equation Solver Formulation

- Reduce Maxwell's equations to the Paraxial Beam equation by:
  - Non-conducting air, constant magnetic permeability, flow characteristic time >> emag propagation time, planar wave…
  - Paraxial Approximation

$$\nabla_{\perp}^{2} A + \frac{\partial^2 A}{\partial z^2} + 2jk\frac{\partial A}{\partial z} + \left(\frac{n^2\omega 2}{c_0^2} - k^2\right)A = 0$$

$$\frac{\partial^2 A}{\partial z^2} << k\frac{\partial A}{\partial z}$$

- Non-Dimensionalization by wavelength results in:

$$\frac{\partial^2 A}{\partial \xi^2} + \frac{\partial^2 A}{\partial \eta^2} + 4\pi j\frac{\partial A}{\partial \zeta} + 4\pi^2\left[\left(\frac{n}{n_r}\right)^2 - 1\right]A = 0$$

- Parabolic, Operator Splitting Approach:
  - Phase Shift:

$$j\frac{\partial A}{\partial \zeta} + \pi\left[\left(\frac{n}{n_r}\right)^2 - 1\right]A = 0$$

  - Wave Advance:

$$\frac{\partial^2 A}{\partial \xi^2} + \frac{\partial^2 A}{\partial \eta^2} + 4\pi j\frac{\partial A}{\partial \zeta} = 0$$

Phase Shift

$$A^*_{kl} = A_{kl}(\zeta)e^{j\pi\left[\left(\frac{n}{n_r}\right)^2 - 1\right]\Delta\zeta}$$

Wave Advance

$$\hat{A}_{kl}(\zeta + \Delta\zeta) = \hat{A}^*_{kl}e^{-j\left[\left(\frac{2\pi k}{N_x\Delta\xi}\right)^2 + \left(\frac{2\pi l}{N_y\Delta\eta}\right)^2\right]\frac{\Delta\zeta}{4\pi}}$$

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Integration with OVERFLOW 2.1x

- aeroOptics Solver is a Fortran90 Module with procedures called by the master process (IAM.eq.MNGR)
- "Optics" (CFD) grids donate density to "Spectral" (aeroOptics) grids
  - Spectral grid dimensions not tied to optics (CFD) grid dimensions
  - Identify which CFD grids are Optics grids, and associate aeroOptics data with them (such as spectral grid size, imposed beam type, …)
- Minimal changes to OVERFLOW:
  - OVERST: Initialization
  - OVERGL: read in "aeroOptics" namelist, distribute limited amount of namelist data to children processes
  - INEND: Parallel Gather of the density data onto the optics grid, Call the aeroOptics solver (from MNGR)
  - OVERDO: Finalization, freeing of memory
- Use the FFTW3 library for the Discrete Fourier Transforms

Aero-Optical Quality Metrics

- OVERFLOW-aeroOptics writes out (appends) beam data to a binary data file for each optics grid for every paraxial beam solve.
- Post process these files for visualization and Aero-Optics Quality Metrics:
  - Beam Centroids for each time slice
  - Average Beam Centroid
  - Jitter
  - Boresight Error
  - Contained Energy Diameters

$$I(f) = \iint_x \int_y AA^* f(x,y)\,dx\,dy$$

$$x_n = \frac{I(x)}{I(1)} \qquad y_n = \frac{I(y)}{I(1)}$$

$$\bar{x}_n = \frac{1}{N}\sum_{n=1}^{N} x_n \qquad \bar{y}_n = \frac{1}{N}\sum_{n=1}^{N} y_n$$

$$\sigma_x = \frac{1}{N}\sum_{n=1}^{N}\left(x_n - \bar{x}_n\right)^2 \qquad \sigma_y = \frac{1}{N}\sum_{n=1}^{N}\left(y_n - \bar{y}_n\right)^2$$

$$\varepsilon_x = \left|\bar{x}_n - x_0\right| \qquad \varepsilon_y = \left|\bar{y}_n - y_0\right|$$

Optical Path Differences:
- By Path Integral
- By Phase Differences between propagated and reference beam

$$OPD_1 = K_{gd}\lambda\int_0^{L_z} \rho\, d\zeta \qquad OPD_2 = \frac{\lambda}{2\pi}\left(\phi_L - \phi_r\right)$$

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Validation: Gaussian Beam Propagation

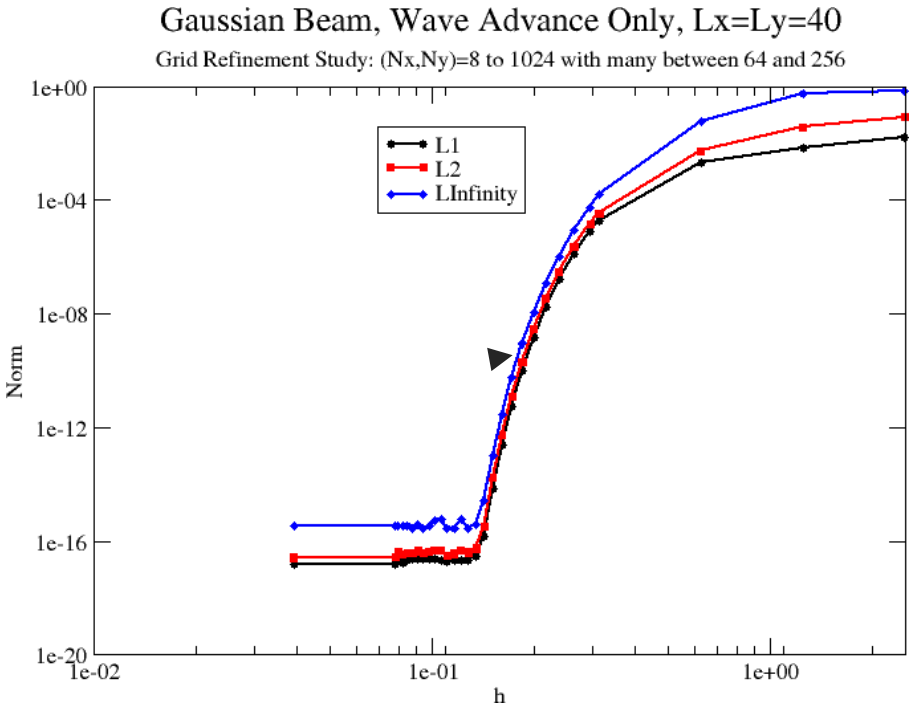
- Propagate a Gaussian Beam Profile through vacuum (no wave advance)
- Analytical Solution

$$A = \frac{A_0}{\left(1 + j\tilde{\alpha}\zeta\right)} e^{-\frac{\pi\tilde{\alpha}\tilde{r}^2}{\left(1+j\tilde{\alpha}\zeta\right)}} \qquad \tilde{\alpha} = \frac{1}{\pi\tilde{r}_0^2} + \frac{j}{\tilde{f}}$$

$$\tilde{r}_0 \equiv r_0/\lambda \qquad \tilde{f} = f/\lambda$$

- Evaluate Error by mesh refinement
- Exhibits “Spectral Convergence”

”Spectral” convergence:
Error decays faster than $\varepsilon \approx 1/N_x^k$
for any value of k



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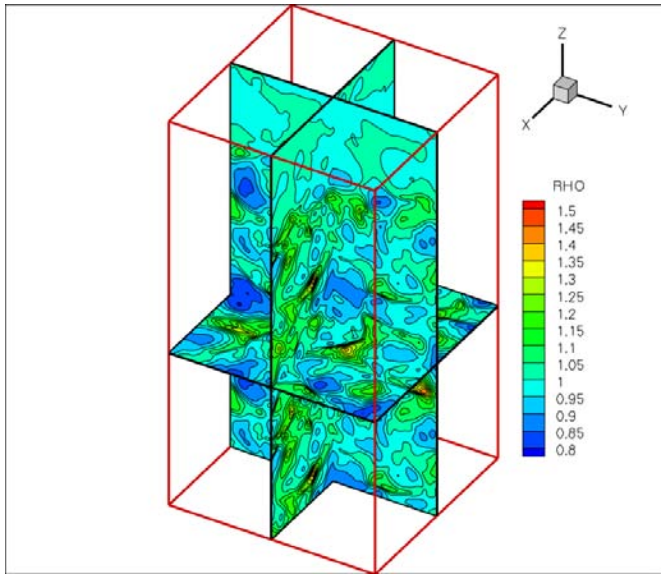
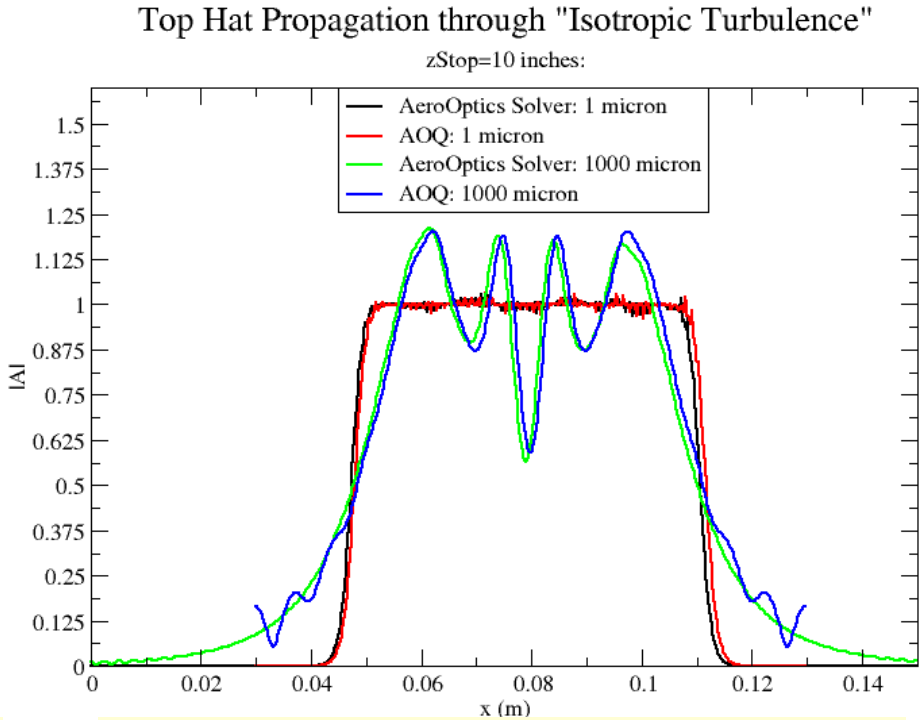
Propagation of a Top Hat Profile

- Compare aeroOptics solver to AOQ for propagation of Top Hat through isotropic turbulence field to Lz=10 inches
- Some differences between the aeroOptics grid and AOQ:
  - AOQ: 10x10 cm
  - aeroOptics: $(x, y) \in [-\pi, \pi]$ inches



Isotropic turbulence field computed via FDL3DI (supplied by AFRL/RBAC)



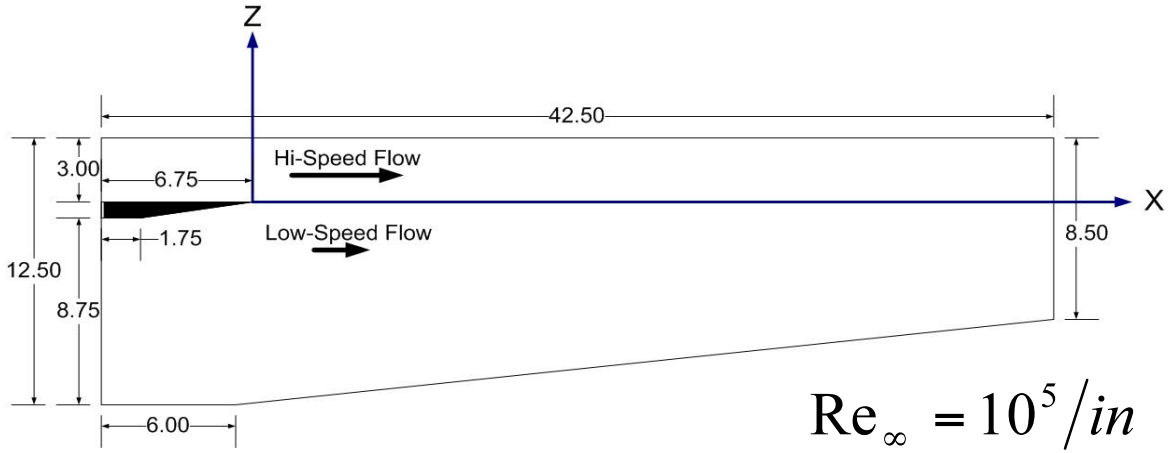
Compares well to AOQ: Note effect of smaller domain size upon AOQ solution

Two-dimensional Compressible Shear Layer

- Corresponds to a run in the Notre Dame Compressible Shear Layer Wind Tunnel (CSLWT)

$M_{high} = 0.65$

$M_{low} = 0.12$



$\mathrm{Re}_\infty = 10^5 / in$

- OVERFLOW 2.1x run:
  - Dual-time stepping, 2nd order in time, dtPhys=0.05, 5 sub-iterations per time step.
  - WENOM 5th-order spatial scheme
  - DDES using Menter's SST model with compressibility correction turned on
  - Two-dimensional problem (3 planes)
  - "FMG" run for 2 levels of mesh sequencing after initializing flow to a very crude initial condition
  - 2000 time steps to settle flow
  - Parallel on 56 processors on "bender" (Linux, DFI)
  - 3328 sec (flow) 110 sec (paraxial) (3.3%)

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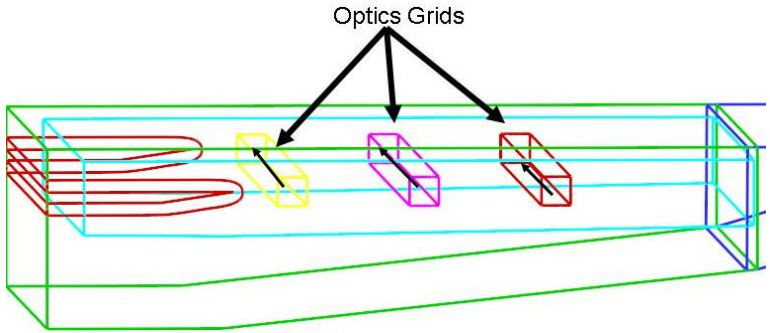
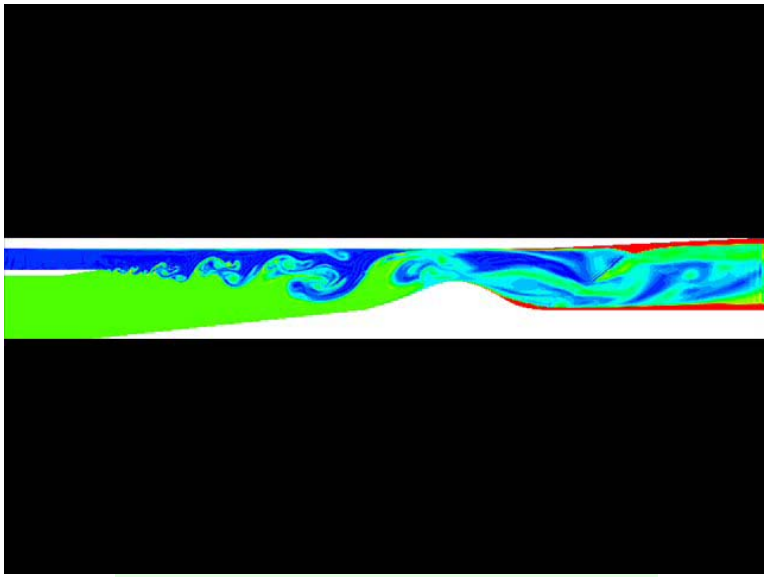
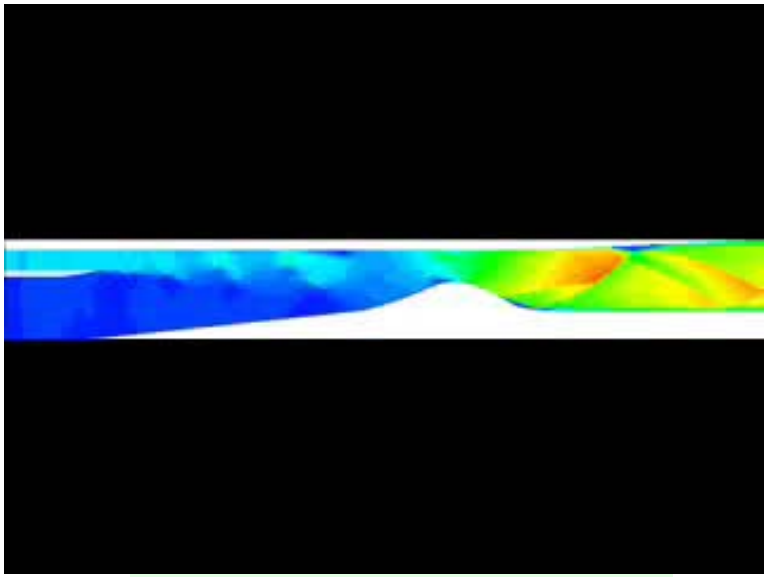
Two-dimensional Compressible Shear Layer

- "Optics" grids generated in the shear layer region
- LEVEL2 must be false in these grids, otherwise large portions of the optics grids can be blanked out.





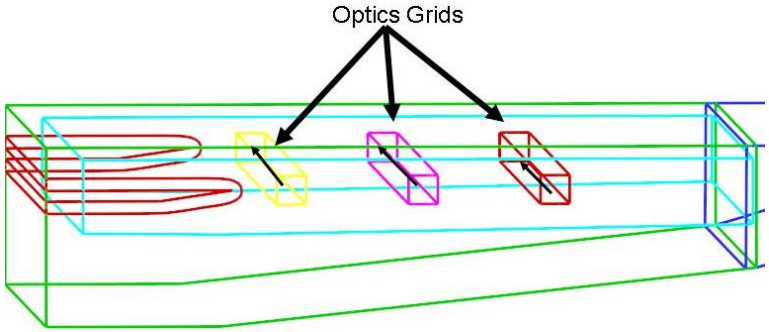
S1 entropy measure



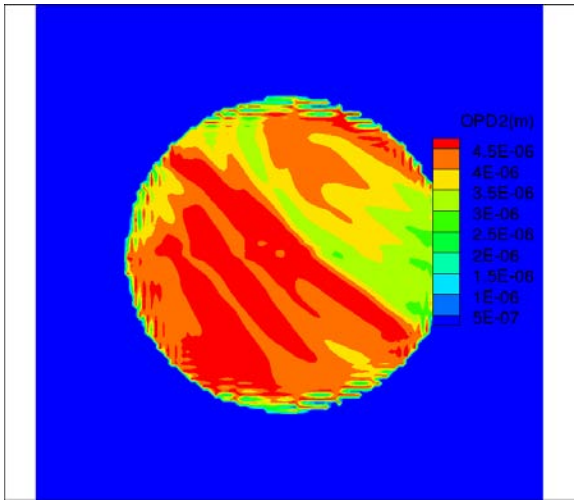
Mach Number

Two-dimensional Compressible Shear Layer

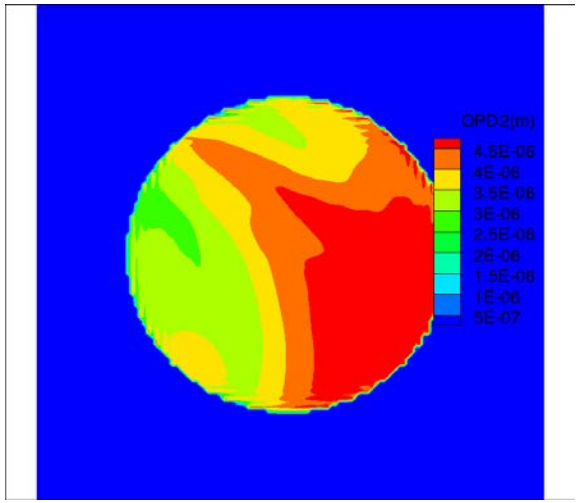
- OPD2 calculated via phase difference



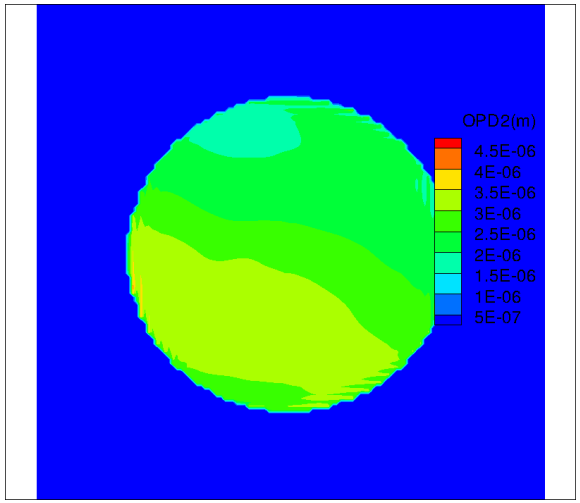
$$\lambda = 10^{-5}\,(meters)$$



Optics Grid 1



Optics Grid 2



Optics Grid 3

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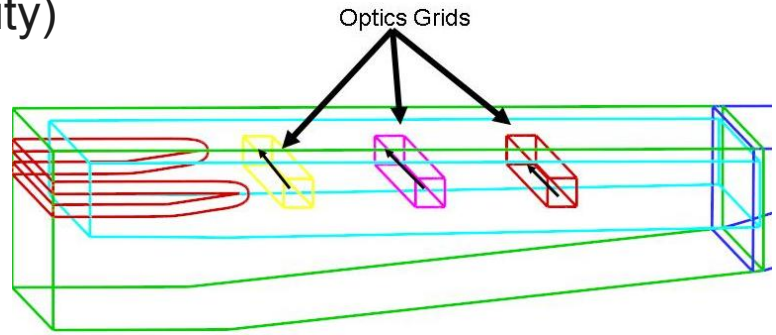
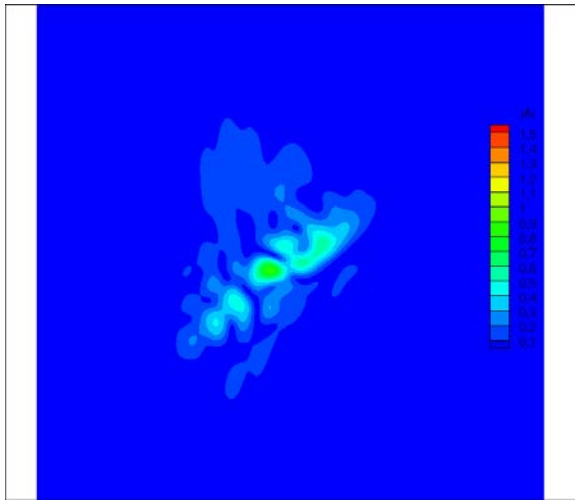
Two-dimensional Compressible Shear Layer

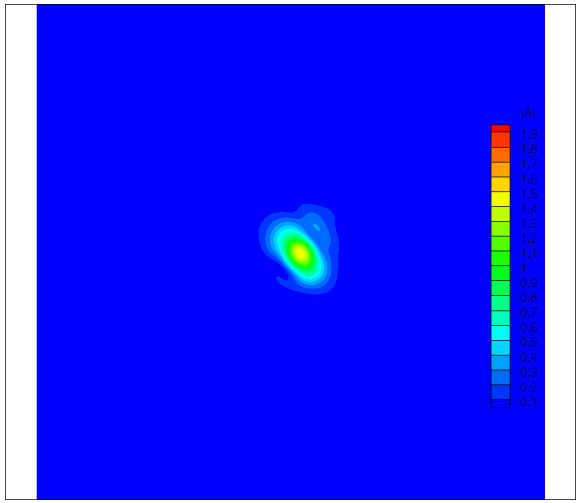
• Magnitude of beam propagated through tunnel then 10 meters more through air (constant density)



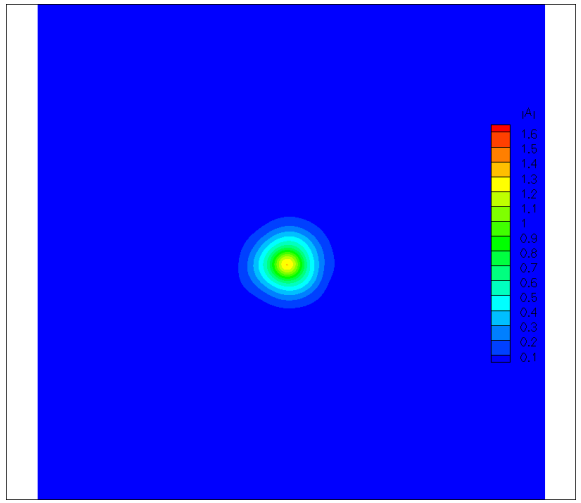
$$\lambda = 10^{-5}\,(meters)$$



Optics Grid 1



Optics Grid 2



Optics Grid 3

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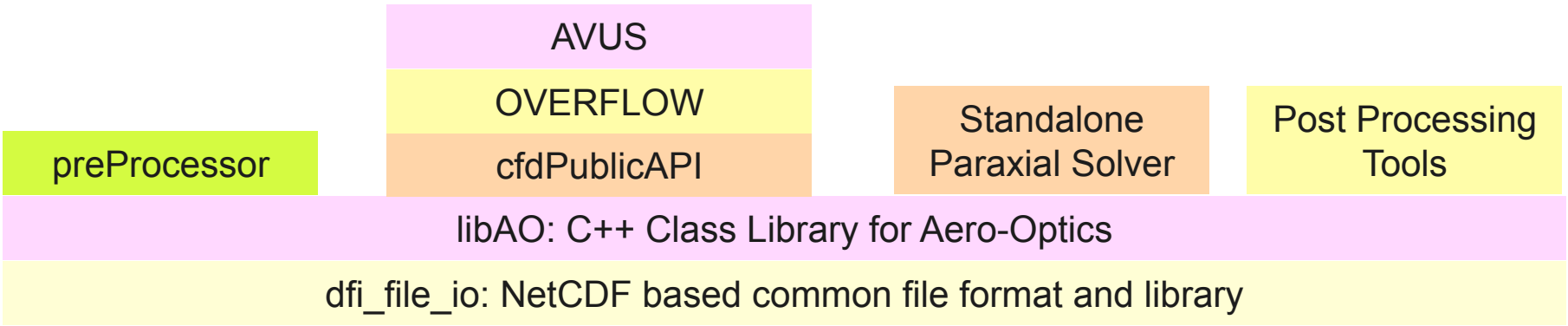
Lessons Learned and Recommendations

- Optics Grids tied too closely to CFD Grids: Must build optics grid into mesh system and they must win any blanking battles
- Solver too tightly integrated: Can't integrate with other codes easily, can't run standalone…

Recommendations

- Develop aero-optics solver library for integration into multiple CFD codes
- Modular approach to allow re-use of software (class libraries)
- Use 3rd party libraries and software wherever possible to reduce build time



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dfi_file_io: NetCDF-based File Format

- NetCDF: Network Common Data Format library and tools
  - C, C++, F77/F90 API to create and access data files for array-oriented scientific data
  - Open source, free, supported by Unidata (UCAR/NSF)
- dfi_file_io:
  - Library/namespace built upon NetCDF to read/write named std::vectors of basic data types (ints, floats, doubles, strings, complex)
  - Easy to write/read data to/from a commonly shared file

```
dfi_file_io::read(commonFileName,"X",X);
```

```
dfi_read_int(trim(preProcFileName)//CHAR(0),trim(varName)//CHAR
(0),donorCellList(p)%nDonorCells)
```

  - Built in error handling, resizes and fills in vectors on read
  - Not designed to be a full-fledged CFD common file format like CFD-DTF or CGNS
  - ncgen⇔ncdump: Used to process easy to read ASCII files for common parameter input

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libAO:: C++ Class Library for Aero-Optics

- Collection of classes, functions and executables related to aero-optics, paraxial beam solution, CFD pre-processing, CFD model integration and post-processing
- Example classes/functionality
  - paraxialSolverClass: encapsulates the paraxial solver
  - paraxialSolverExecutorClass: Used to marshall collections of paraxial solves
  - beamGridClass: defines beam grid extents
  - paraxInterpolatorClass: derived from beamGridClass, used to perform fast interpolation needed by paraxialSolver, is member data of paraxialSolverClass
  - cartSearchSpace<T>: templated spatial search class to find nearest neighbors
  - oversetPreProcessorClass: overset mesh pre-processor class
  - unstructuredFVMPreProcessorClass: unstructured FVM mesh pre-processor class
- Use third-party, open-source and standard libraries:
  - boost: Some useful classes
  - fftw3: Fastest Fourier Transform in the West (3)

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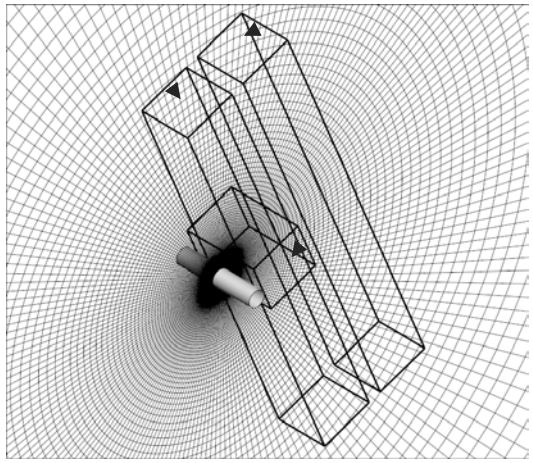
Mesh Pre-Processing Phase

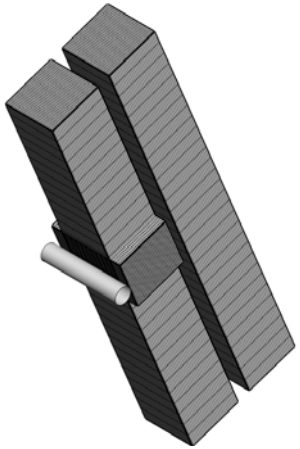
• Given a CFD mesh system (overset, unstructured) and a collection of beamGrids, pre-compute the CFD model donor nodes(cells) interpolants for a given interpolator grid size.

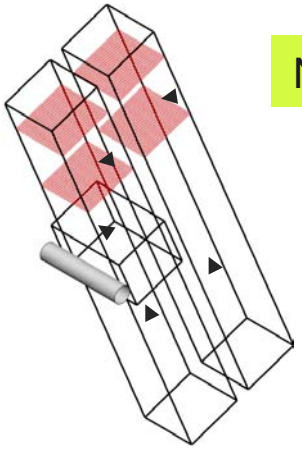
beamGrids: define extent and direction of beam propagation

interpolatorGrids: pre-compute CFD donor interpolants (nodes, weights) onto interpolator grids

Spectral Grids: Marching planes in propagation direction







N_x x N_y

• Pre-processing computes and stores CFD donor interpolants (nodes, cells, weights) to interpolate CFD solution onto interpolator grid

• Interpolator grid provides fast interpolation onto spectral grid

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Integration within OVERFLOW (and others)

- Provide a minimal set of API called by the flow solver

```
initializeParaxialBeamSolvers(commonFileName);
for each timestep
          . . .
          for each beam
                    setRhoDonor(beamNumber,RhoDonor,timeStamp);
                    runParaxialBeamSolver(beamNumber,timeStamp);
finalizeParaxialBeamSolvers
```

- initializeParaxialBeamSolvers:
  - Reads common file produced by pre-processor (donors, weights, …)
  - Initializes executor that runs paraxial solvers
- setRhoDonor:
  - CFD solver collects only the needed donor density data and supplies it to the executor
- runParaxialBeamSolver:
  - Solves paraxial equations, writes donor data, beam profiles,… to be used later
- finalizeParaxialBeamSolvers:
  - Frees up memory, closes files, finalizes things

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Integration within OVERFLOW (and others)

- Minimal hassle integrating within OVERFLOW:
  - OVERST:
    - initializeParaxialBeamSolvers
  - OVERGL:
    - Read an aeroOptics namelist, read common file, scatter data
  - INEND:
    - Gather donor density, setRhoDonor, runParaxialBeamSolver
  - OVERDO:
    - finalizeParaxialBeamSolvers
- Easily integrated into AVUS
- Master process does all the paraxLib invocations, density gather, i/o etc.

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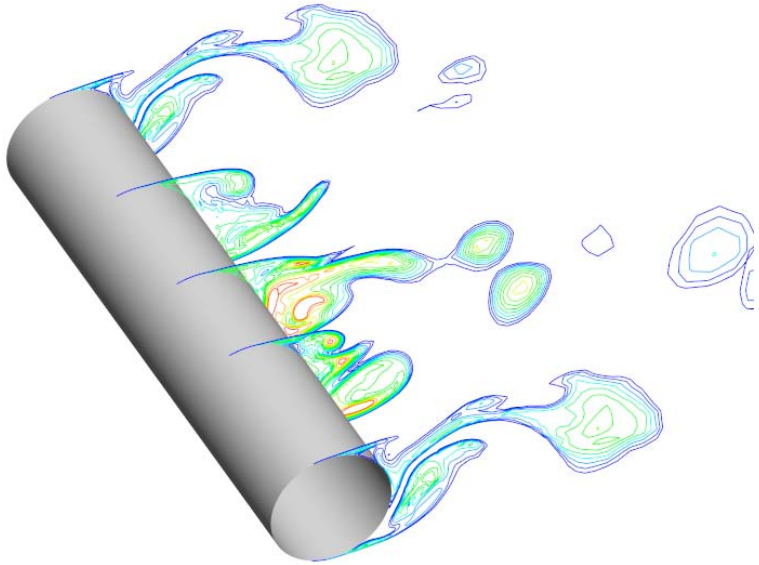
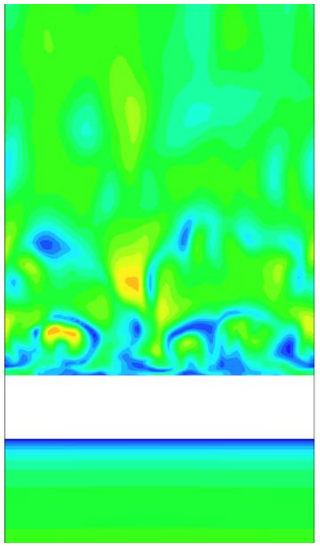
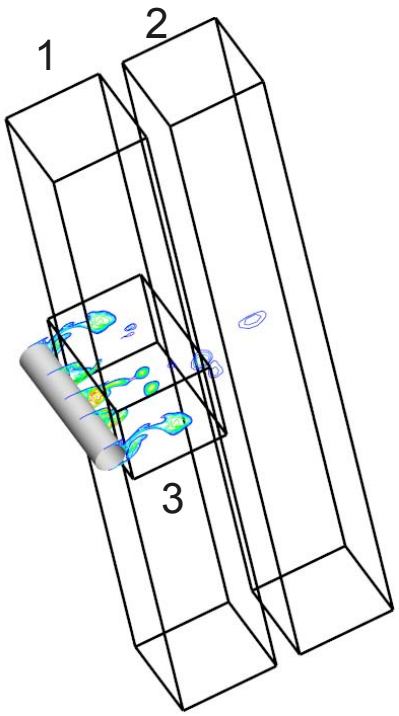
Example Problem: Shedding Cylinder

- Circular cylinder, diameter=1 inch
- M=0.2, Strouhal number used to get an estimate on time step:
  - 200 steps per shedding cycle
- Wall functions, SA-DES, third-order upwind, HLLC, 16000 time steps, dual time-stepping scheme







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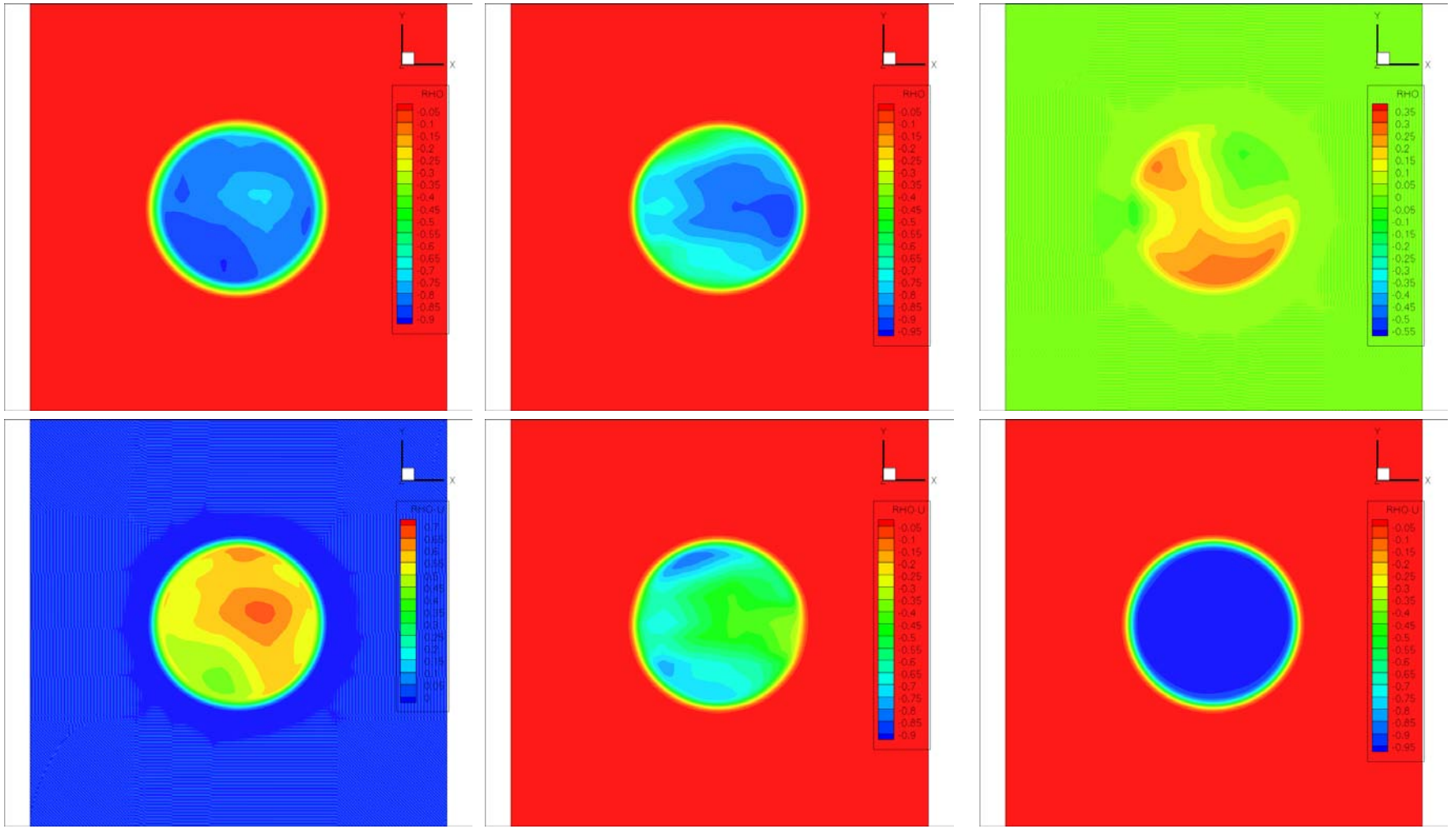
Example Problem: Shedding Cylinder

- Real (top) and Imaginary Components of beam propagated through 200 timesteps of flow



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Summary

- Integrated library into OVERFLOW 2.1z:
    - Will integrate into 2.2 soon…
- Integrated into AVUS
    - Demonstrated for the same shedding cylinder case
- Potential integration into FDL3DI
- Need to finish post-processing
- Validation cases:
    - Hemispherical turret
    - Flat windowed turret with pins
    - Other cases as needed
- Documentation, installation scripts, …