Computational Schlieren with Comparisons to Experiment

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Motivation and Previous Work

- Motivation
  - interest in additional means of comparing experiment and CFD results
  - specifically, we would like to compare RBOS results with the schlieren based on CFD solutions, *CFD schlieren*
  - working towards more precise comparisons, more than side-by-side
- Previous Work
  - Yates (1993), *Images Constructed from Computed Flowfields*
  - Svakhine *et al.* (2005), line-of-sight rays, shadowgraphs, schlieren
  - Brownlee *et al.* (2011), refracting rays, rendering at interactive rates, GPU
  - Settles & Hargather (survey of some relatively recent work, 2017)

Our CFD Schlieren Application: raycast

- Raycast produces images by casting rays through a CFD domain, integrating a user-defined scalar field along the ray
- Raycast uses straight, line-of-sight rays (*i.e.*, no refraction)
- Projection can be orthographic or perspective, arbitrary direction
- The user provides a scalar field equation, based on solver fields
  - the equation is parsed at runtime (*i.e.*, not hard coded)
  - operators such as grad, sqrt and mag are available
- We use the Embree library from Intel in order to build a spatial data structure that significantly accelerates ray queries

Ray-Integration Formulae

- Let the x and y coordinate axes correspond to the horizontal and vertical axes, respectively, relative to the viewer
- The incremental change in the angular deflection:

$$\delta\varepsilon_x = \frac{1}{n}\frac{\partial n}{\partial x} \qquad \delta\varepsilon_y = \frac{1}{n}\frac{\partial n}{\partial y} \tag{1}$$

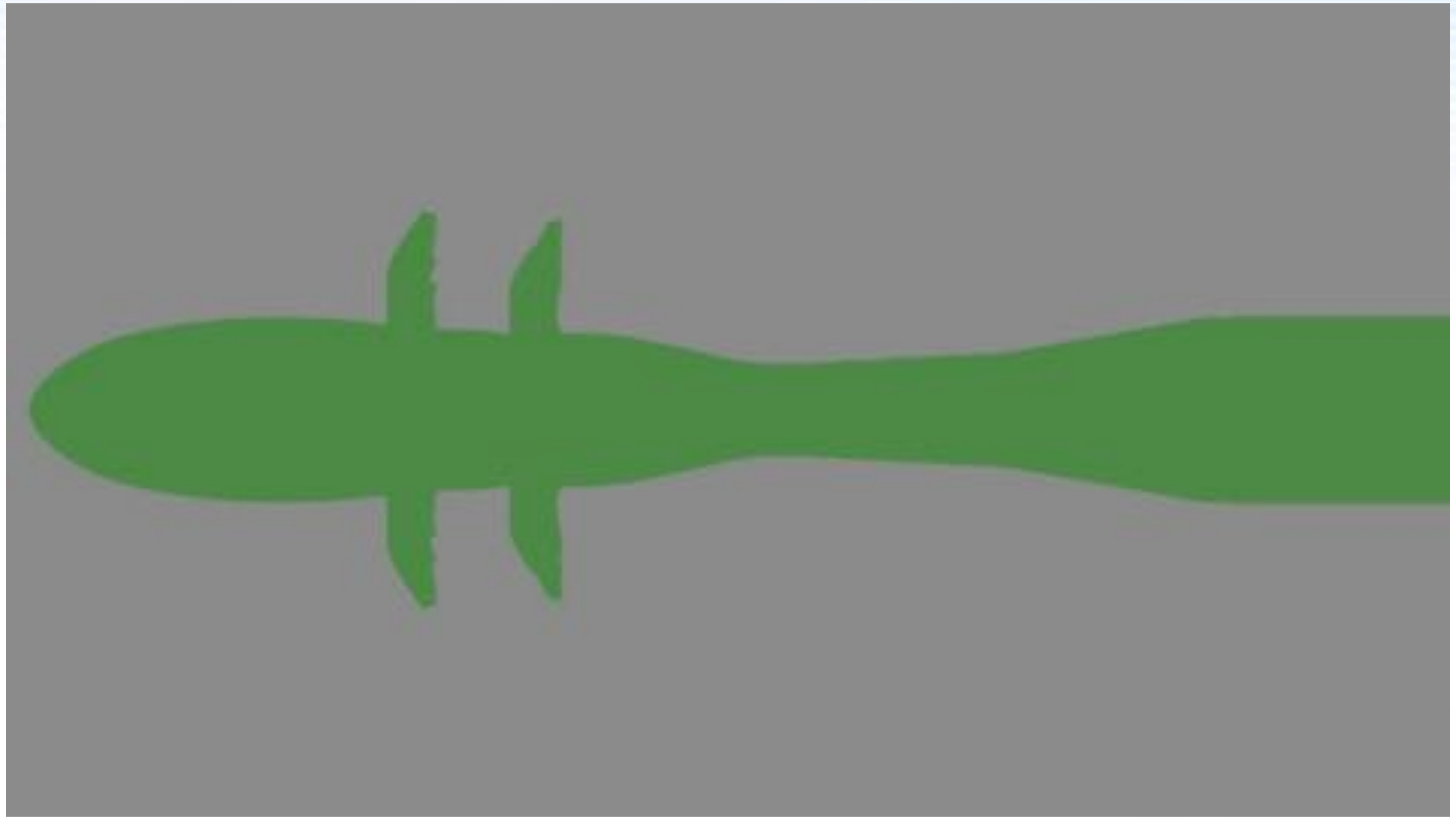
  - where *n* is the index of refraction
- The index of refraction, in terms of density (Gladstone-Dale):

$$n = \kappa\rho + 1 \tag{2}$$

- Rewriting the deflections in terms of the gradient of density:

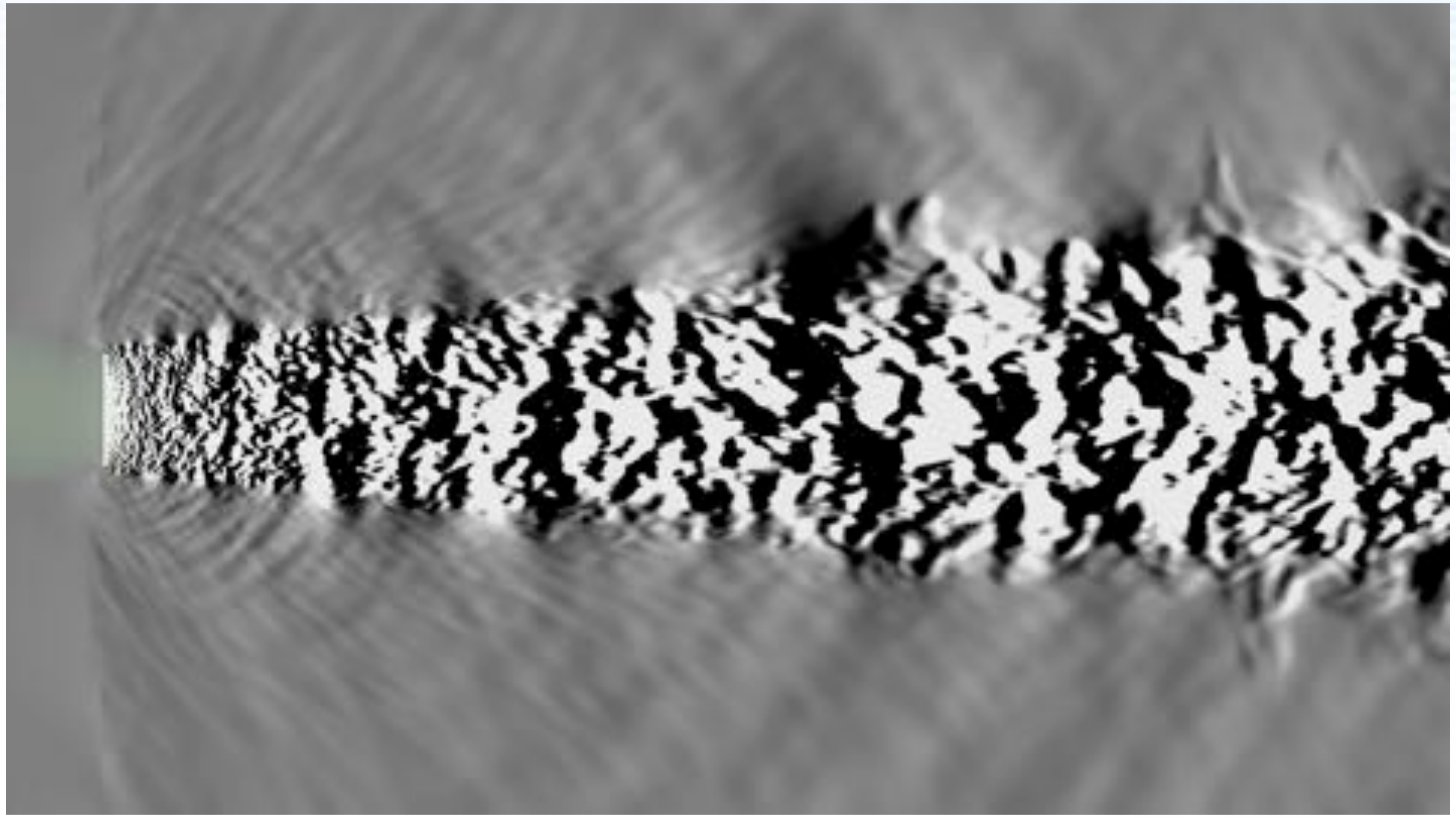
$$\delta\varepsilon_x = \frac{\kappa}{\kappa\rho + 1}\frac{\partial \rho}{\partial x} \qquad \delta\varepsilon_y = \frac{\kappa}{\kappa\rho + 1}\frac{\partial \rho}{\partial y} \tag{3}$$

LAVA / Structured-AMR Schlieren



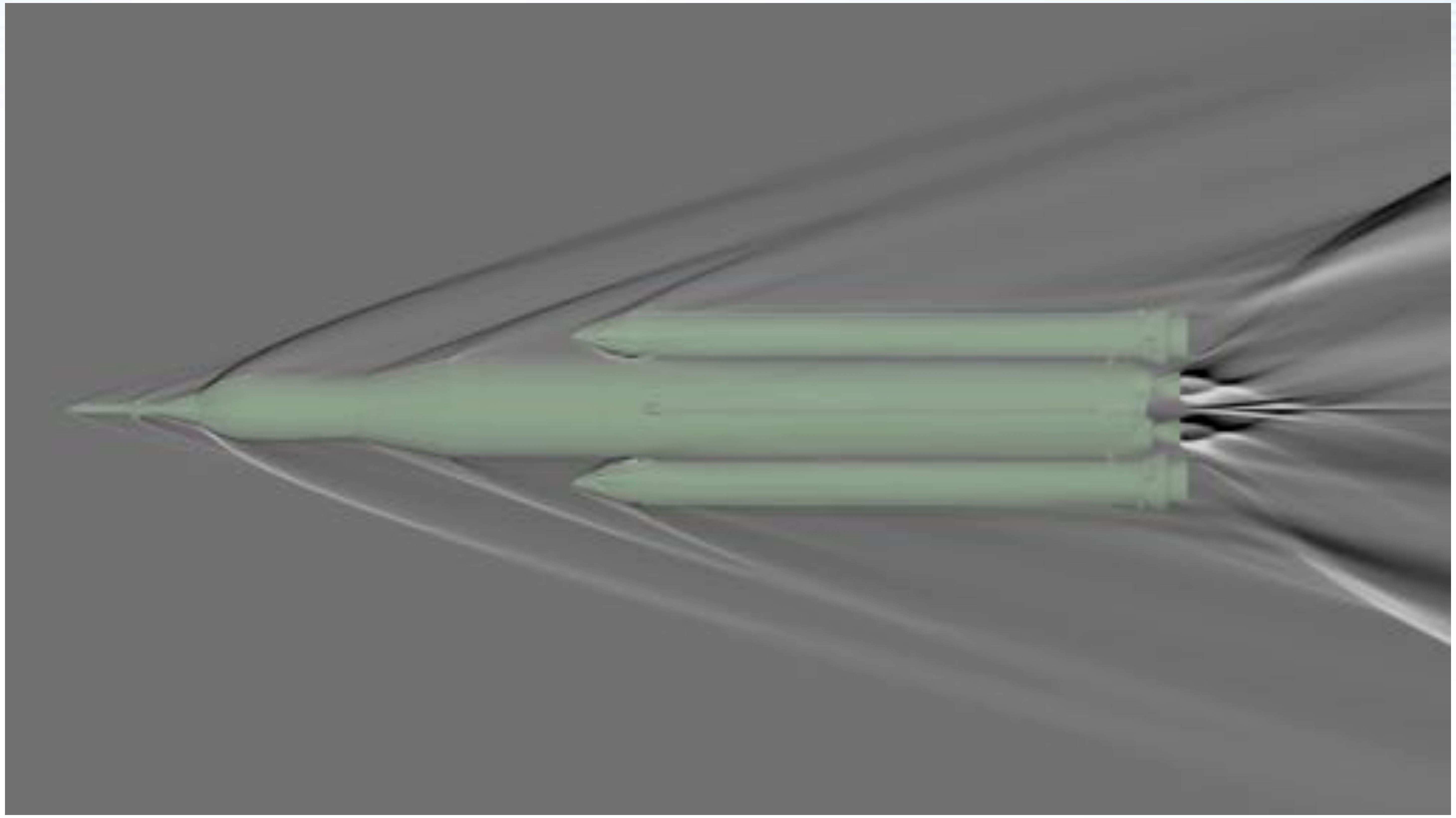
- Solver: Launch, Ascent and Vehicle Aerodynamics (LAVA) framework
- C. Brehm et al. *Open Rotor Computational Aeroacoustic Analysis with an Immersed Boundary Method*. AIAA 2016.

LAVA / Overset-Curvilinear Schlieren



- Solver: Launch, Ascent and Vehicle Aerodynamics (LAVA) framework
- J. Housman et al., *Jet Noise Prediction using Hybrid RANS/LES with Structured Overset Grids*. AIAA 2017.

Overflow Schlieren

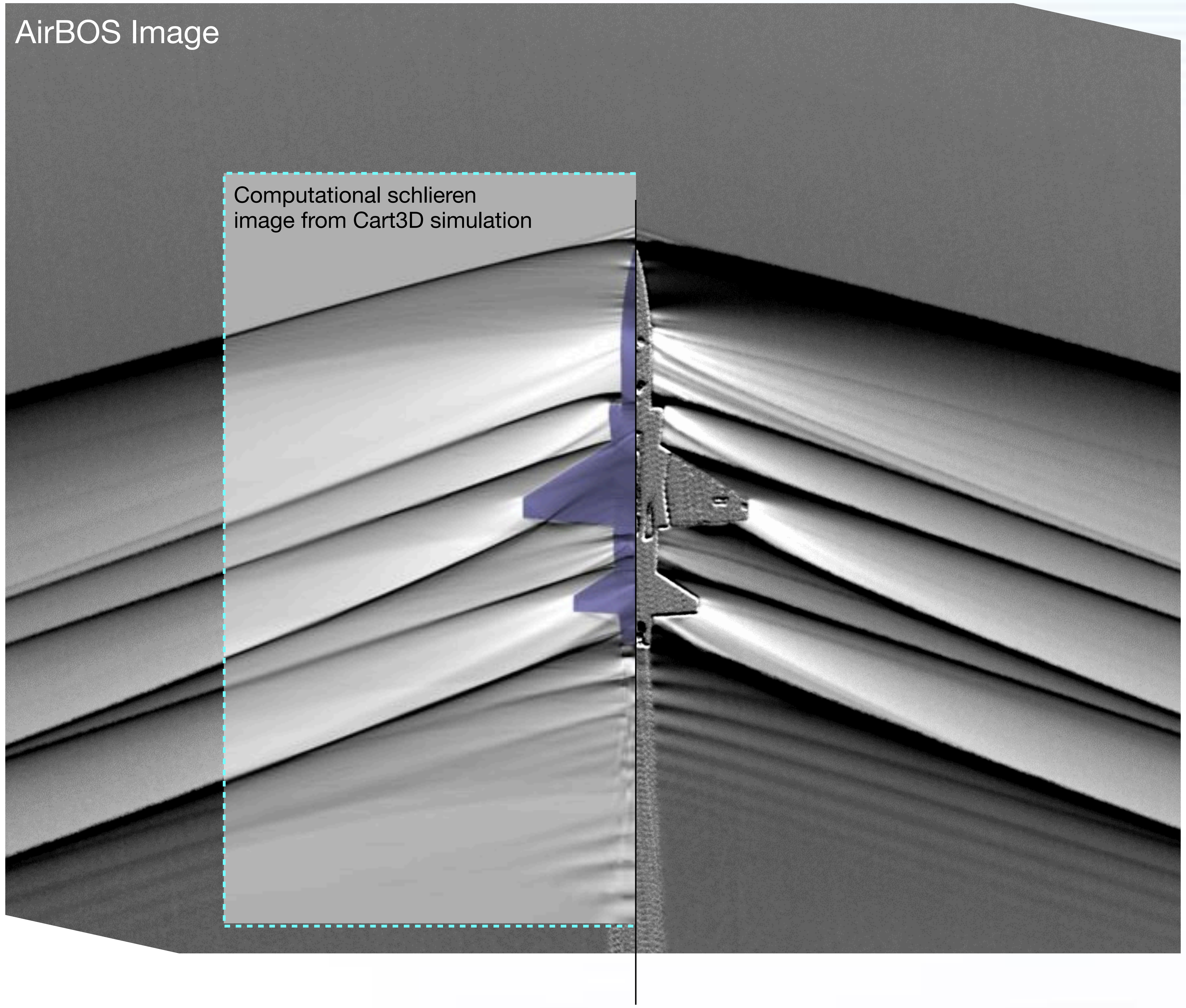


- Space Launch System (SLS) booster separation simulation
- Mesh: adaptive, overset curvilinear mesh, ~255M vertices

Overflow Schlieren, SLS Super-Sized

- NASA Ames hyperwall 2: (16 x 1600) x (8 x 1200) = 25600 x 9600
- Approximately 0.25B pixels

AirBOS vs. Cart3D Schlieren

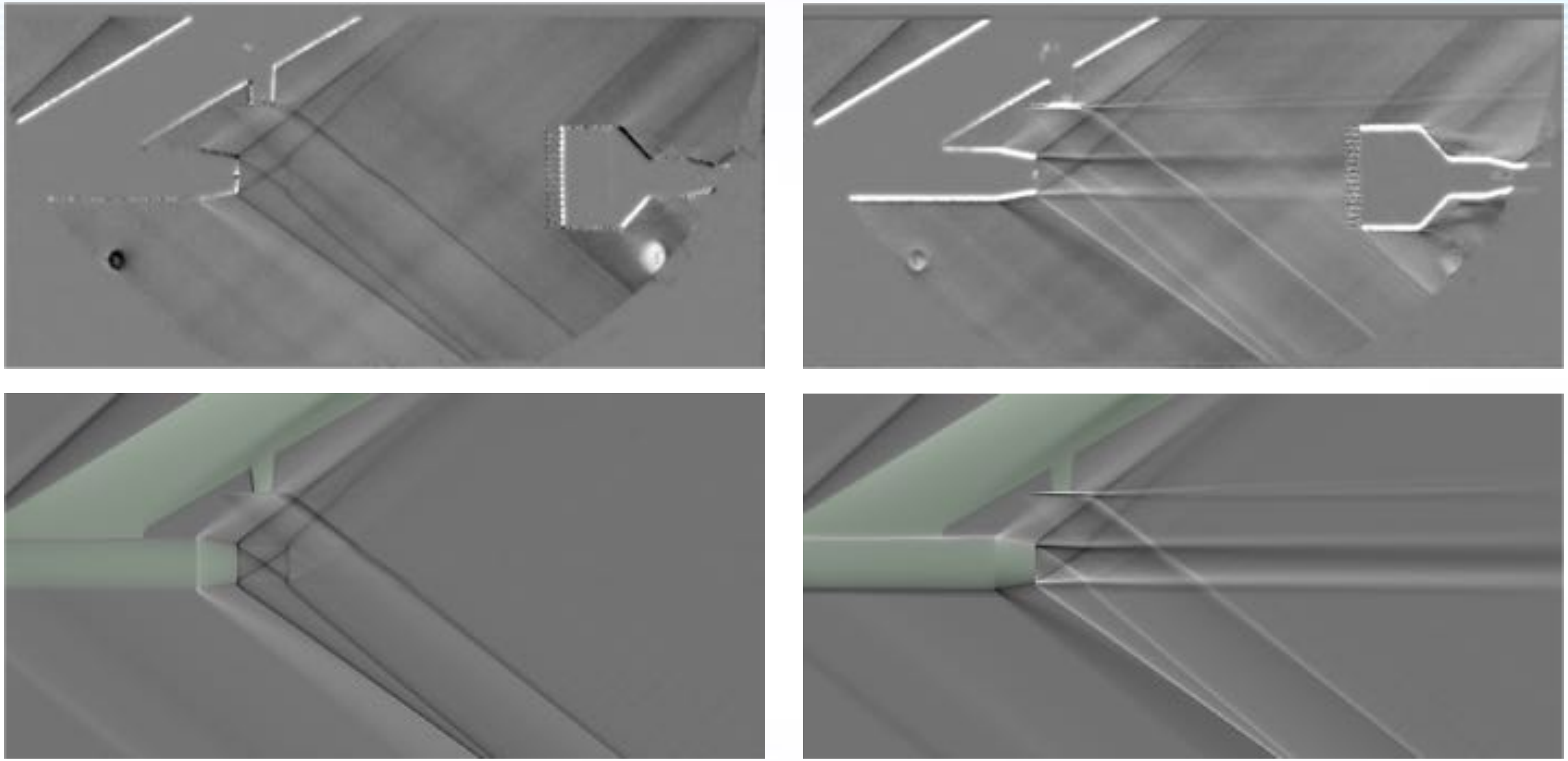


- *Image courtesy of M. Aftosmis.*

RBOS vs. LAVA / Polyhedral Schlieren

RBOS

CFDS

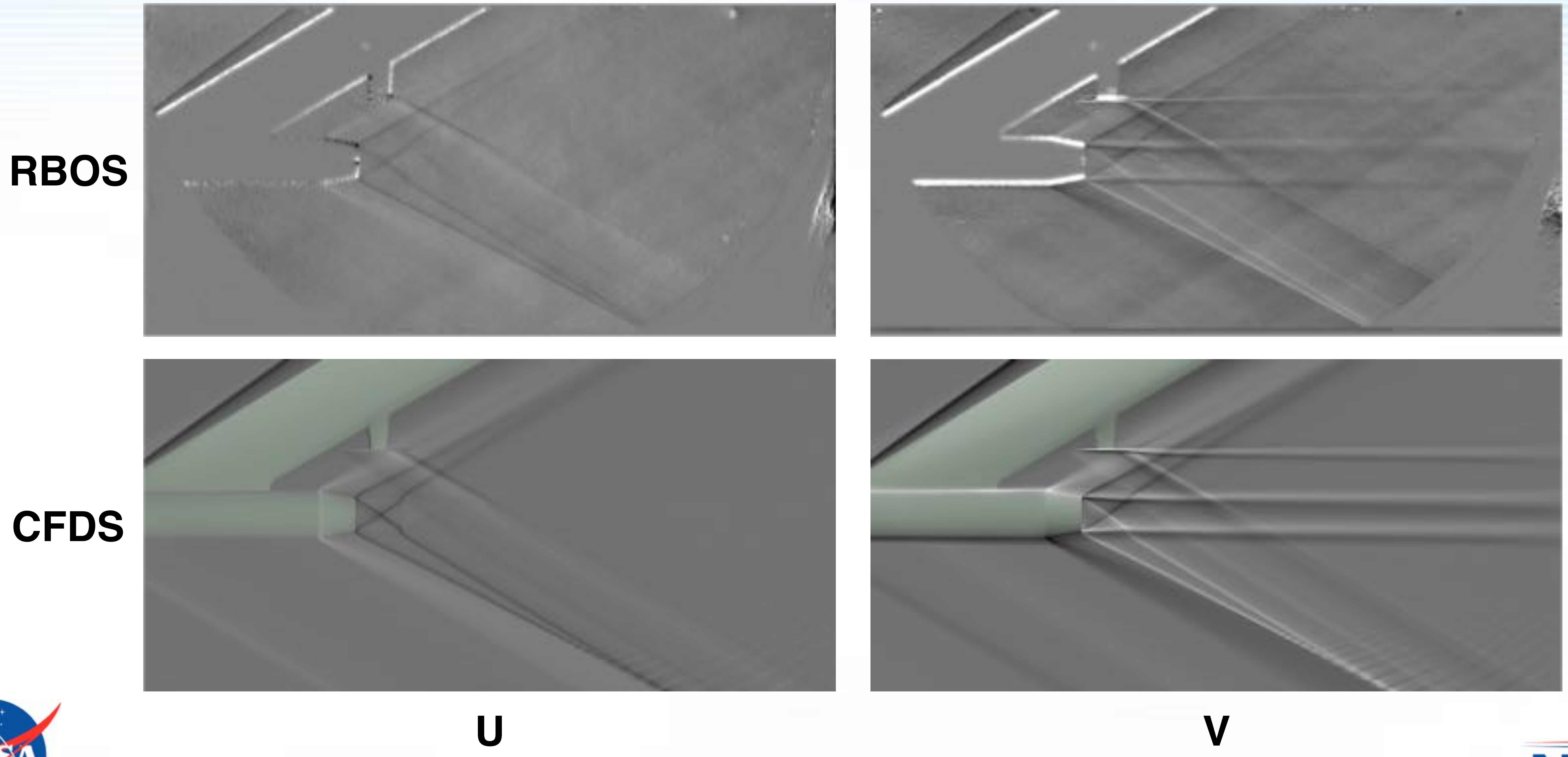


U

V

- Supersonic nozzle-plume study, Mach 1.6.

RBOS vs. LAVA / Polyhedral Schlieren



- Supersonic nozzle-plume study, Mach 2.0.

Alternate Views: e.g., Looking Up From Below

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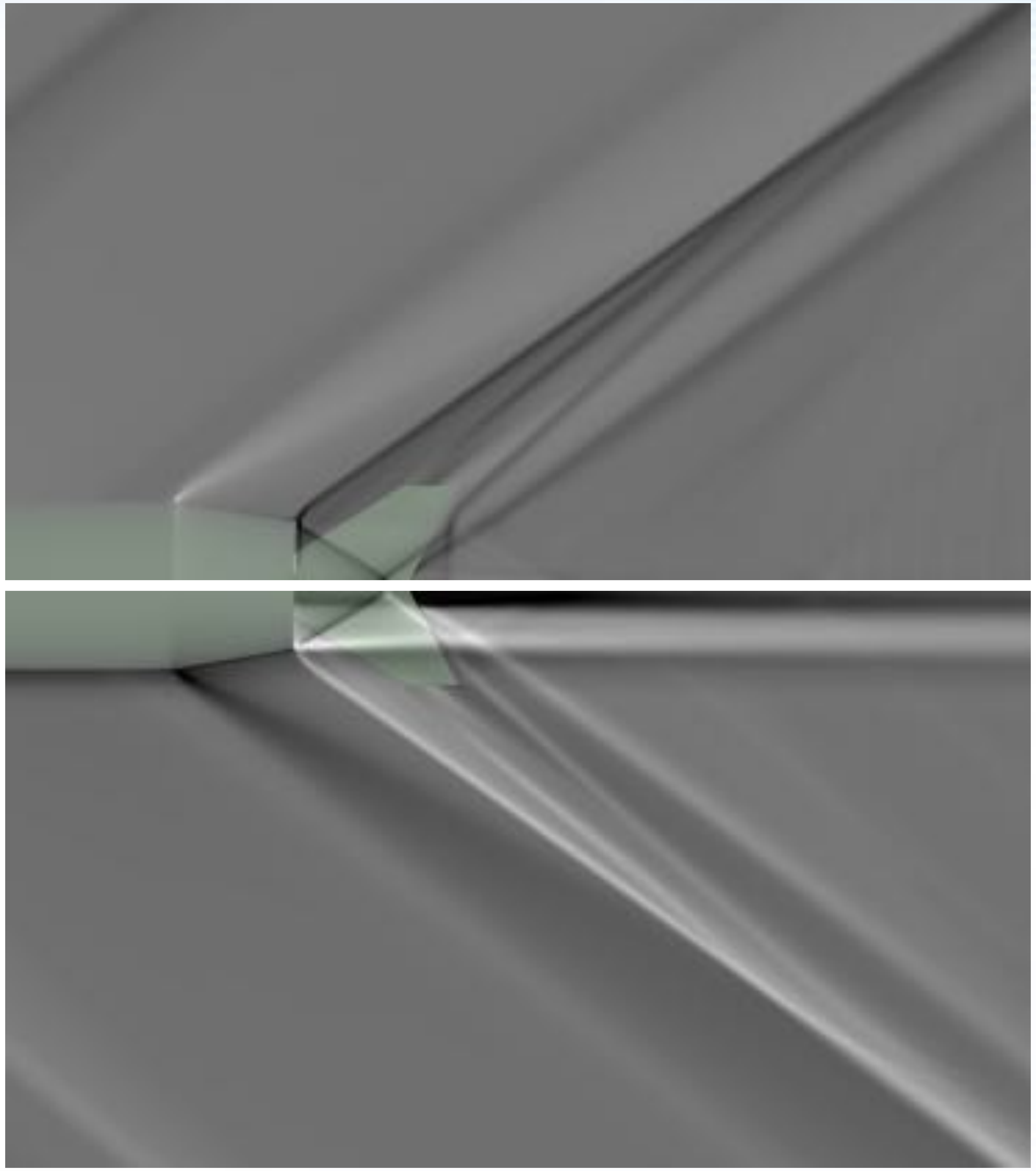
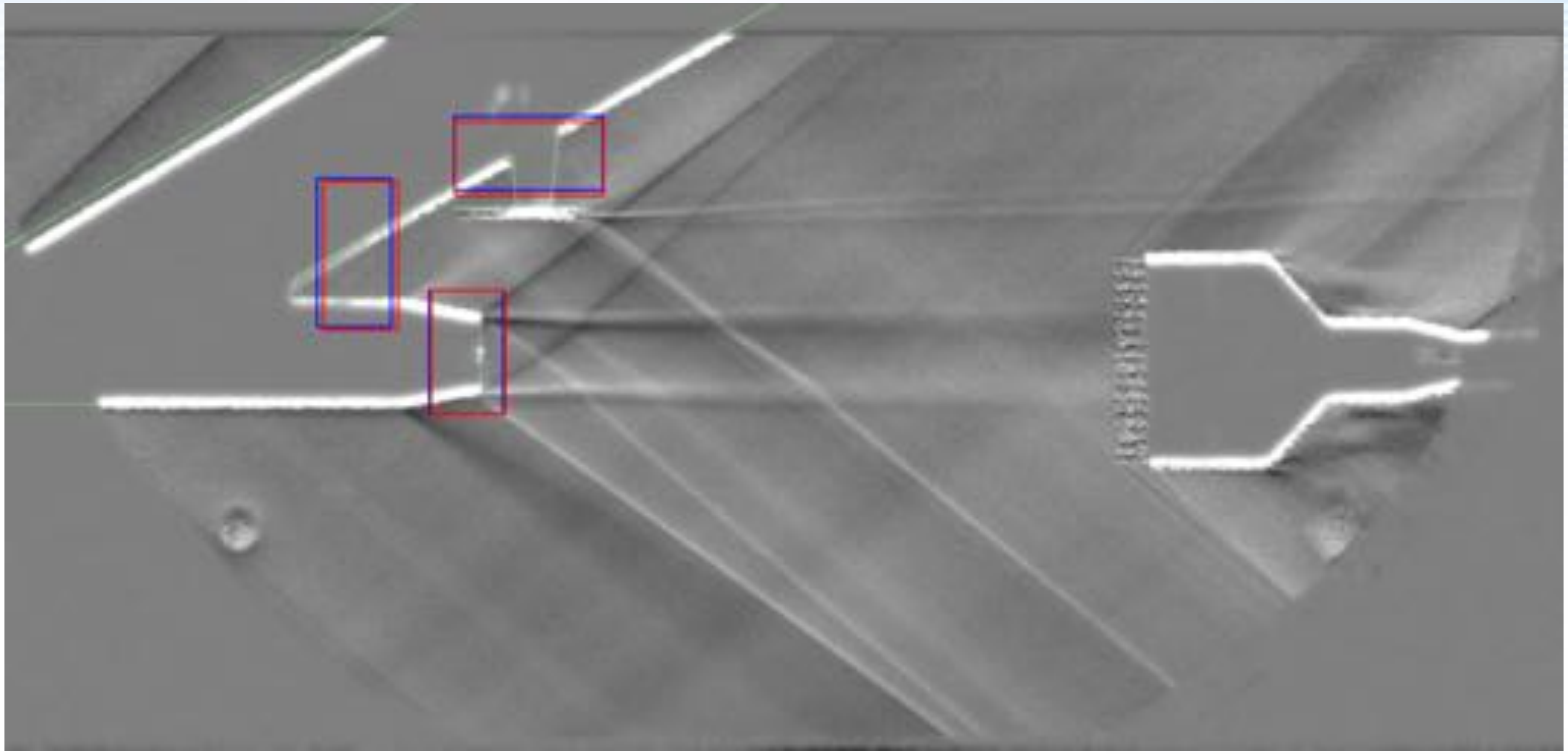


RBOS / CFD Schlieren Comparison by Overlay

- Rather than view side-by-side, we want to overlay the experiment and CFD results in order to create a more precise comparison
- Requires image registration
- The model is deflected slightly by wind conditions
  - we have photogrammetry data measuring the deflection
- The model vibrates slightly, RBOS images produced by averaging
- The camera used for RBOS may move slightly, but we do not have measurements of that
- We chose 3 corresponding regions in the RBOS and CFD schlieren, match by cross correlation, and solve for affine transform

Registering RBOS with CFD Schlieren

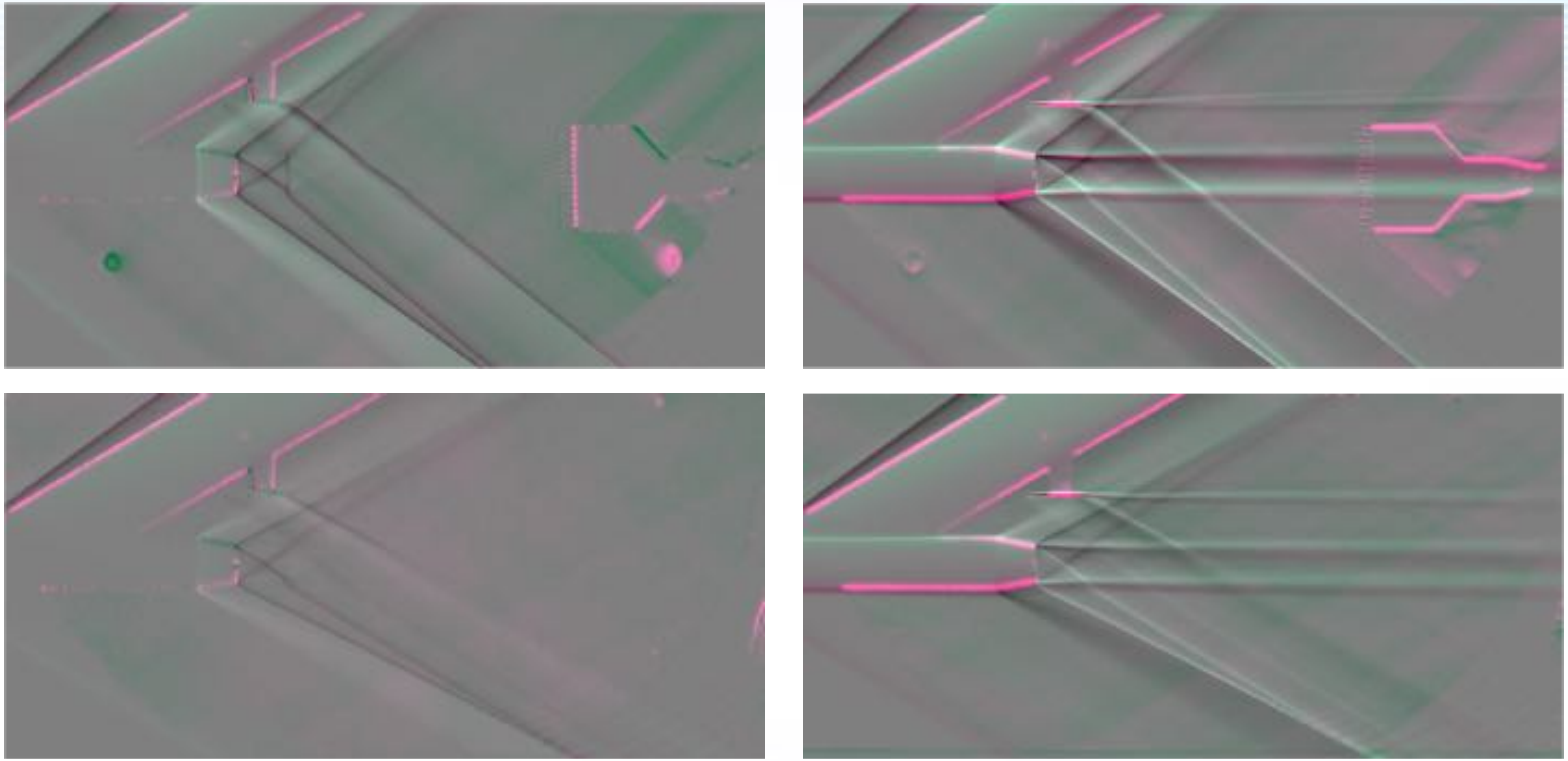


- Green: CFD model outline, blue: target regions, red: match in RBOS
- Registration implemented using OpenCV library.

Displaying Registered Results: Color Channels

- Where the RBOS and CFD schlieren differ, we want to see whether the RBOS intensity is greater than the CFD schlieren, or vice versa
- We use the red channel for RBOS
- We use the green channel for CFD schlieren
- We assign the average of the red and green channels to blue
  - also considered minimum, maximum
  - areas where RBOS and CFD schlieren match: gray scale
  - areas where CFD schlieren is higher intensity: green/cyan
  - areas where RBOS is higher intensity: red/magenta
- Primary interest is in seeing how well the shocks match

RBOS vs. CFD Schlieren by Color Channels



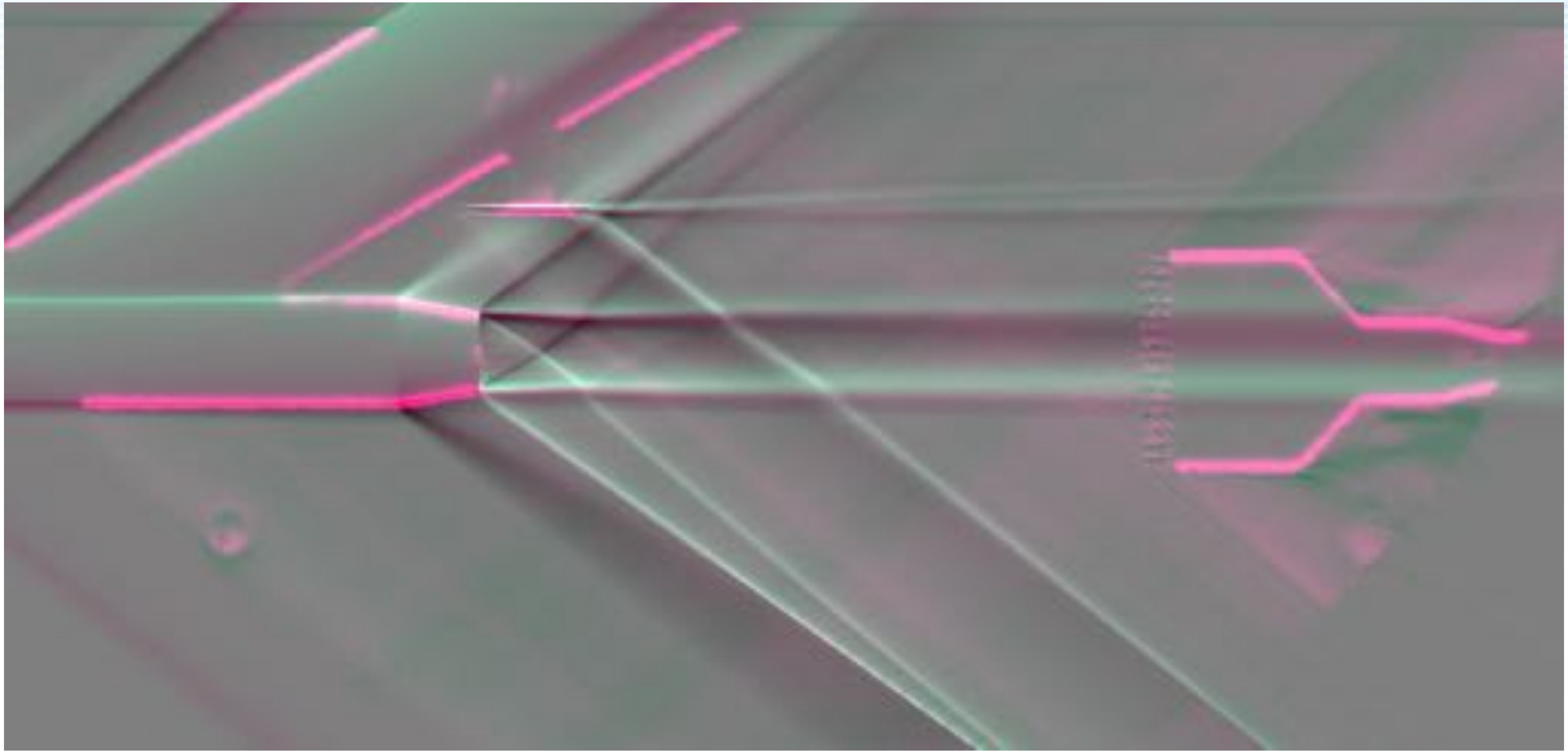
M1.6

M2.0

U

V

RBOS vs. CFD Schlieren: M1.6, V



Future Work

- Implement imaging based on refractive rays
  - would be slower, but much of the infrastructure would remain the same
- Further image comparison support, more automated registration
- More mesh types
  - FUN3D unstructured is the format most requested for us
- Work with native domain decomposition of solver
  - for high-resolution simulations, more efficient than re-composing into single large mesh object
  - preparing for very large runs on Summit, 1B+ vertices, unstructured

Conclusion

- We have implemented a new ray-caster renderer: raycast
  - capable of integrating through custom, user-defined fields
  - so far mostly used to produce schlieren based on density gradient magnitude
- Works with a variety of CFD solution types
  - overset curvilinear grids
  - polyhedral unstructured
  - structured adaptive mesh refinement (AMR), unstructured AMR
- Comparisons with RBOS look very good
- We are continuing to investigate more precise means of comparing BOS and CFD schlieren results

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