SAND2006-5181P

Wind Tunnel Technologies for Experimental Aerothermodynamics

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Albuquerque, NM

Sandia/NSWC Meeting
August 16, 2006

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Aerosciences at Sandia

Sandia's missions support national security

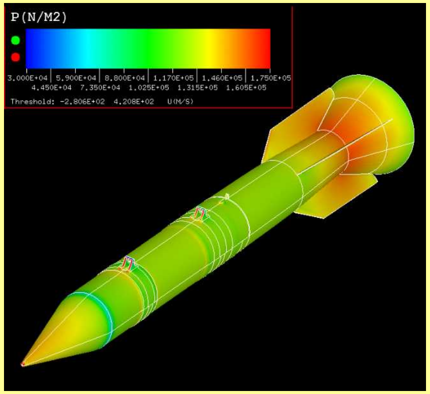
- Primary mission is stewardship of the nuclear stockpile
- Other missions are derived from our nuclear mission, including non-proliferation, surveillance, etc.
- We collaborate with DoD, NASA, and industry on other programs in the national interest

Many of these missions are centered upon flight hardware

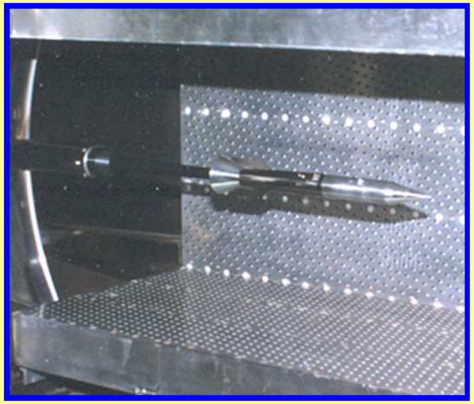
- Flight vehicles for nuclear weapons
- Precision weapons
- Missile defense
- Future prompt response systems
  - Rockets
  - Re-entry vehicles

The Role of the Wind Tunnels

Flight Test



Modeling & Simulation



Ground Test

We support Sandia's aero needs by:

- Aerodynamic characterization of vehicles
- Testing of flight components
- Investigating fundamental aerospace physics
- Providing data to develop and validate computational models

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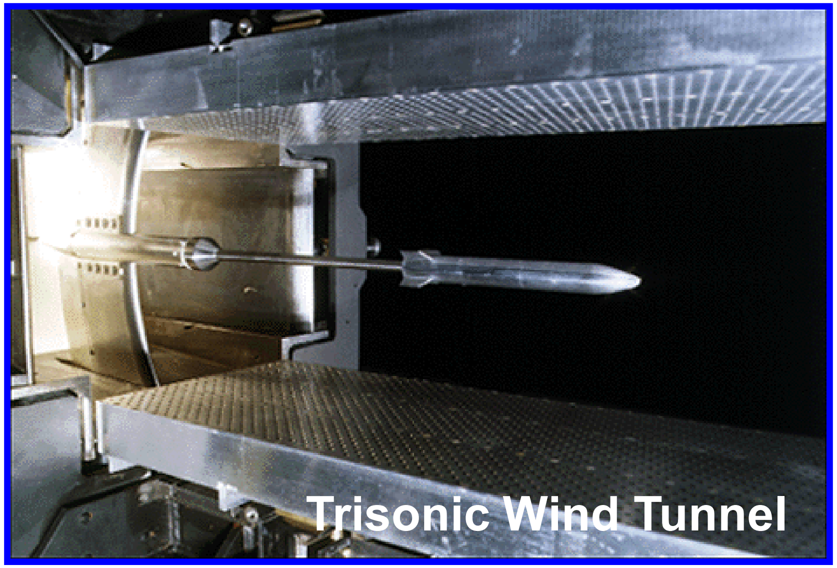
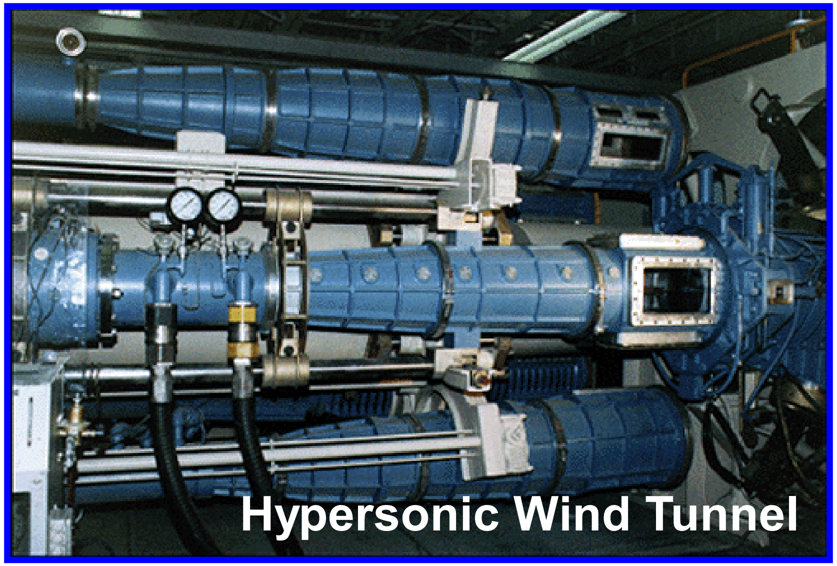
Experimental Aerosciences Facility





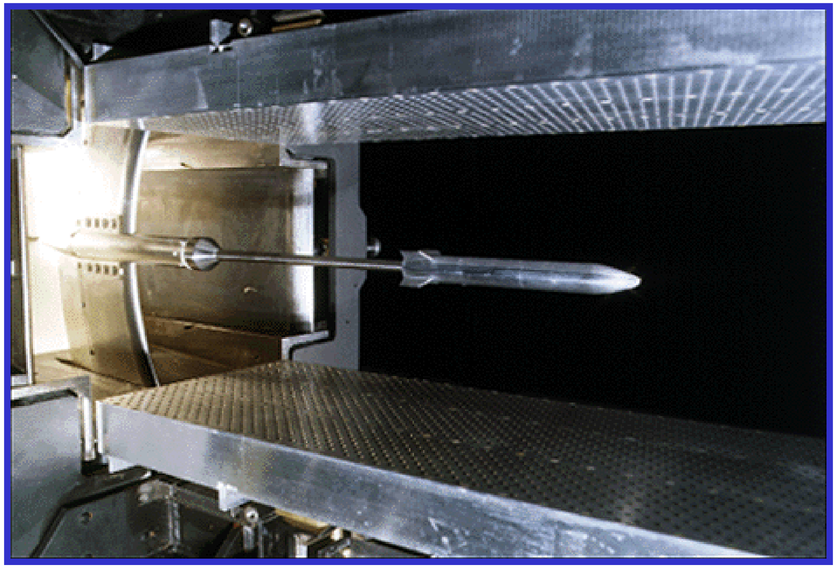
Trisonic Wind Tunnel (TWT)
- Mach 0.5 – 3
- Gravity bombs, missiles, commercial aerospace

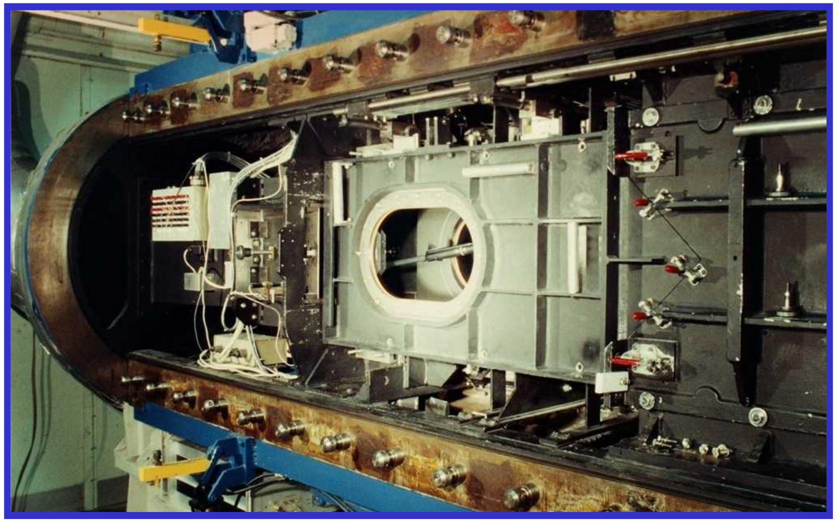
Hypersonic Wind Tunnel (HWT)
- Mach 5, 8, 14
- Re-entry vehicles, rockets

High-Altitude Chamber (HAC)
- Satellite components

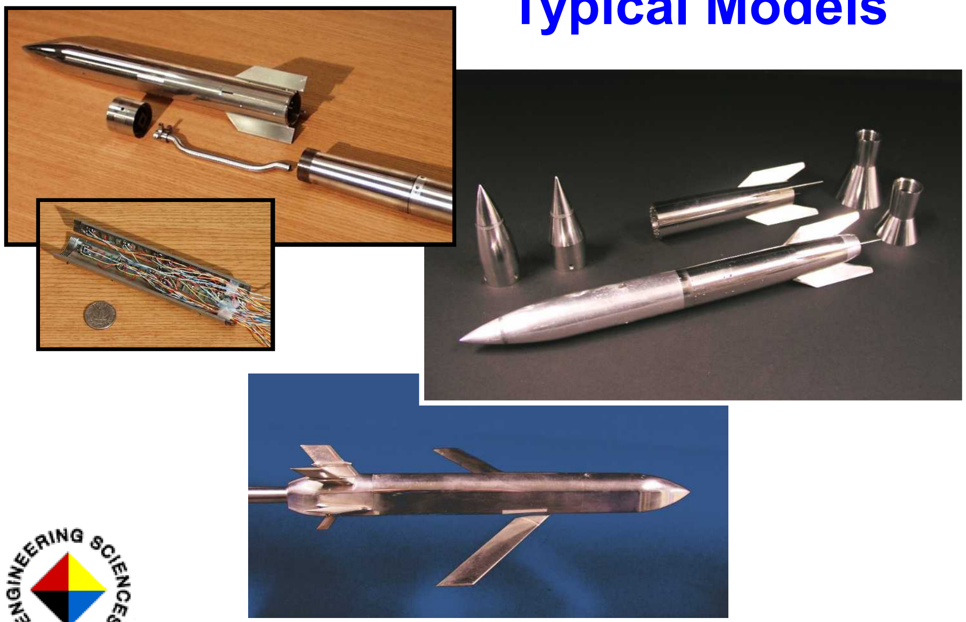
Trisonic Wind Tunnel (TWT)

- Blowdown to atmosphere
- M_∞ = 0.5 - 1.3, 1.5, 2.0, 2.5, 3.0
- Re = 3 - 20 × 10^6 /ft
- Run times: 20 - 120 seconds
  at 20 - 30 minute intervals
- 12" × 12" test section
- ~1" diameter model size





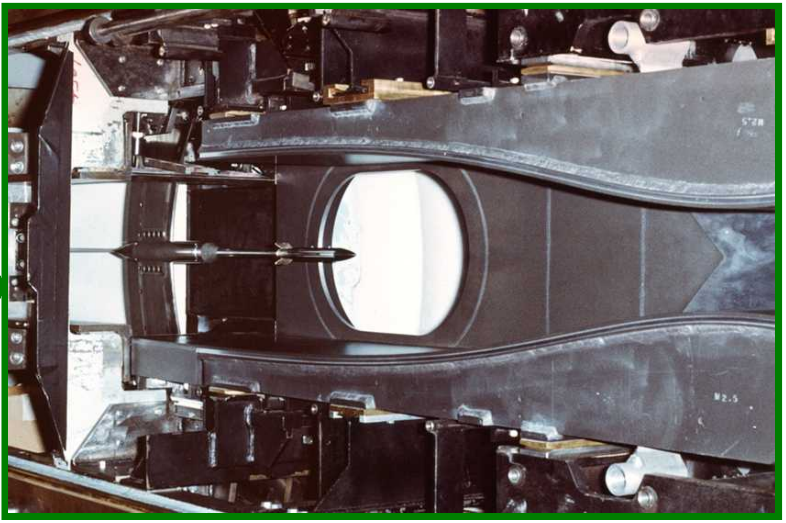
Typical Models



Trisonic Wind Tunnel (TWT)

Supersonic experiments are conducted in contoured nozzles

- Switch out walls to change Mach
- Mach 1.5, 2.0, 2.5, and 3.0



Transonic experiments typically are conducted in a porous-wall test section

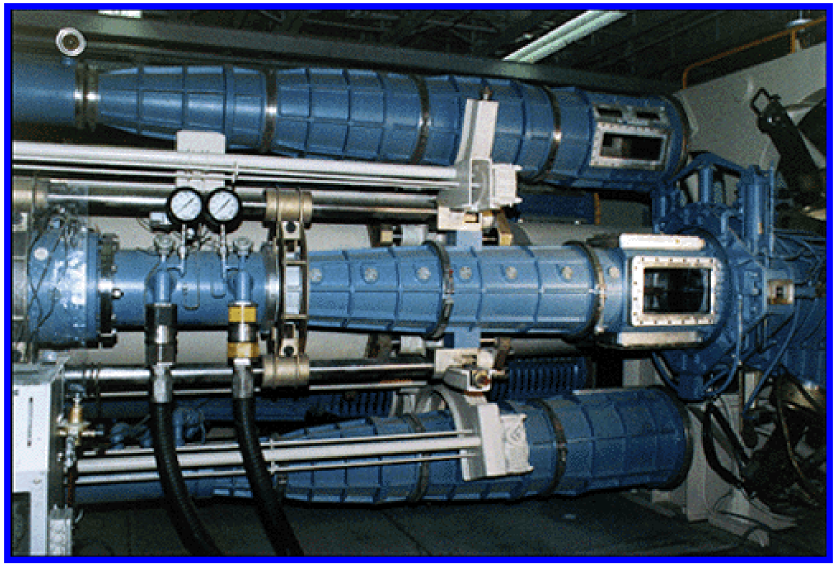
- Continuously variable Mach number from 0.5 to 1.3
- Porous walls are necessary for testing near Mach 1
- We also have a solid-wall test section for up to about Mach 0.85

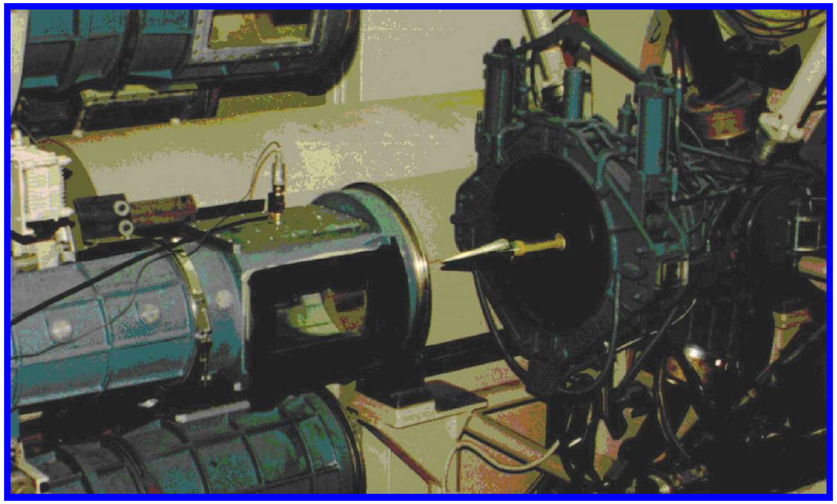
The test section is enclosed in a pressurized plenum

- Contains the flow through the porous walls

Hypersonic Wind Tunnel (HWT)

- Blowdown to vacuum
- M_∞ = 5, 8, 14
- Re = 0.2 - 10 x 10^6 /ft
- Run times: ~45 seconds at 45 minute intervals
- Gases: air at M_∞=5, N_2 at M_∞=8, 14
- 18" diameter test section
- 4" - 5" maximum diameter model size
- Stagnation temperature to 2500°R





Typical Models

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Hypersonic Wind Tunnel (HWT)

Hypersonics presents many more challenges than lower speeds

High Mach numbers require a much larger pressure ratio to operate

- Nitrogen pressures to 8600 psi
- Blowdown to vacuum

The wind tunnel gas must be heated

- Prevent condensation of air/nitrogen
- Use electric resistance heaters unique to each Mach number
  - Maximum of 2.5 megawatt
- Wind tunnel throat is jacketed by a high-pressure water line for cooling

Despite high pressure and temperature, the HWT cannot simulate the real gas effects associated with re-entry.

Mach 14 heater

Mach 5 heater

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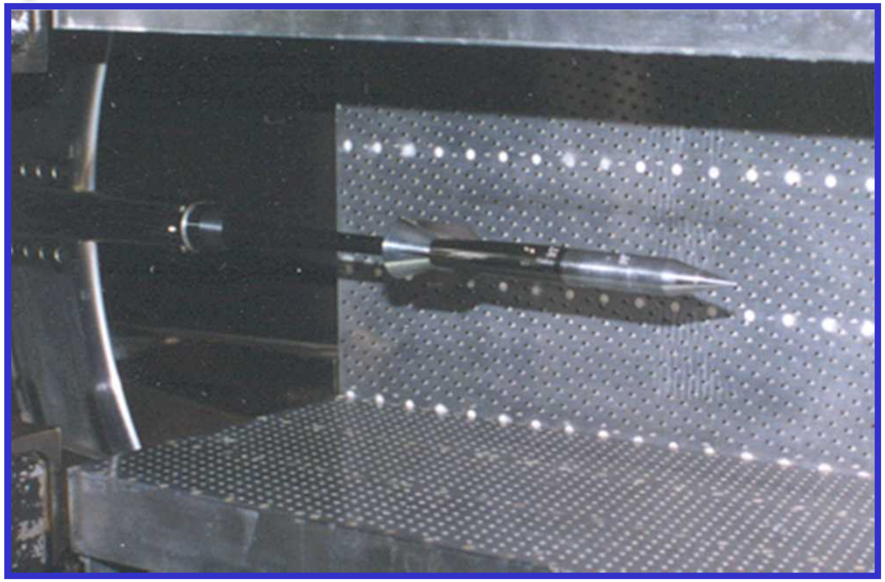
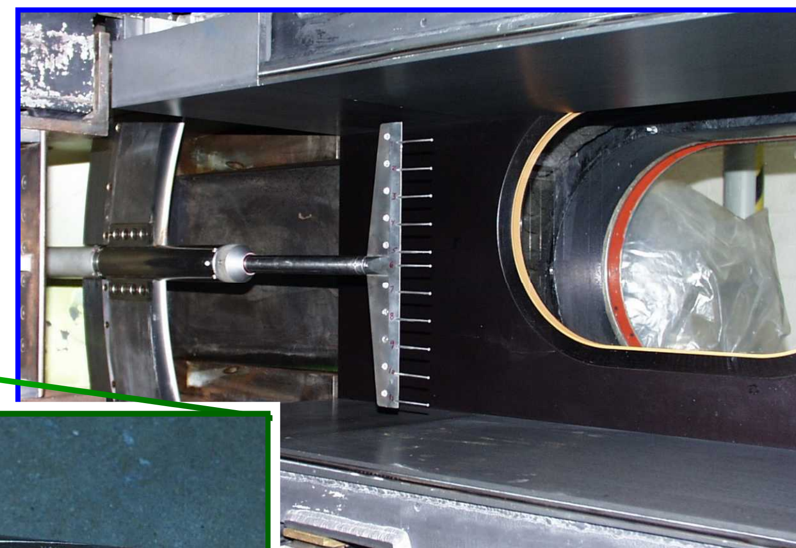
Aerodynamic Measurements



We employ traditional aerodynamic instrumentation such as:

- Internal strain-gage balances
- Surface pressure transducers
- Pitot probes and rakes
- Model spin testing
- Heat transfer gages



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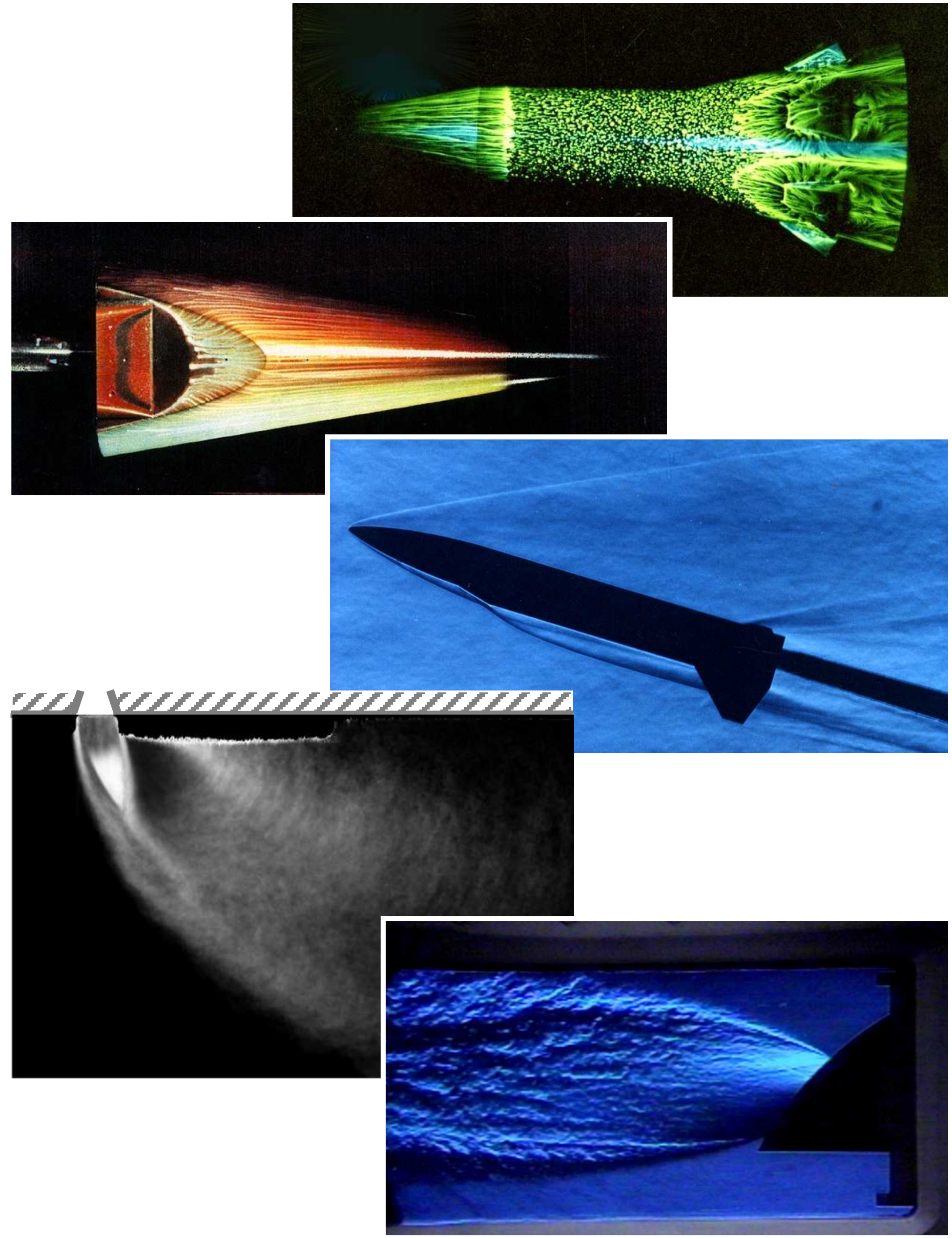
Flow Visualization

Complement balance measurements with flow visualization such as:

- Schlieren photography
- Surface flow tracers
- Laser vapor screen



- These images are nice, but we need quantitative flowfield measurements
- Improved technologies allow modern wind tunnel tests to accomplish much more than in the past

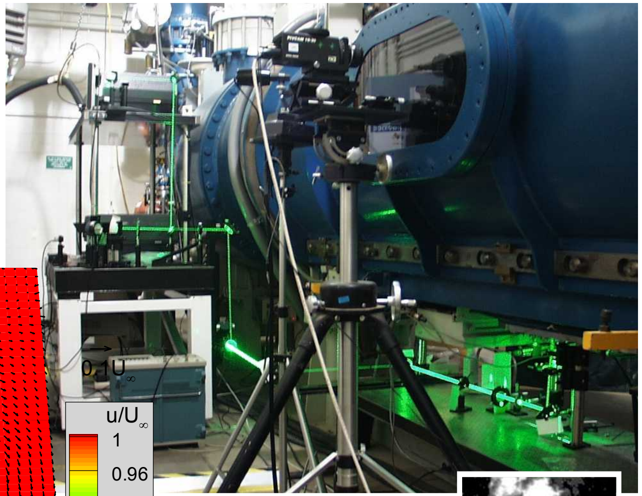
Advanced Measurements

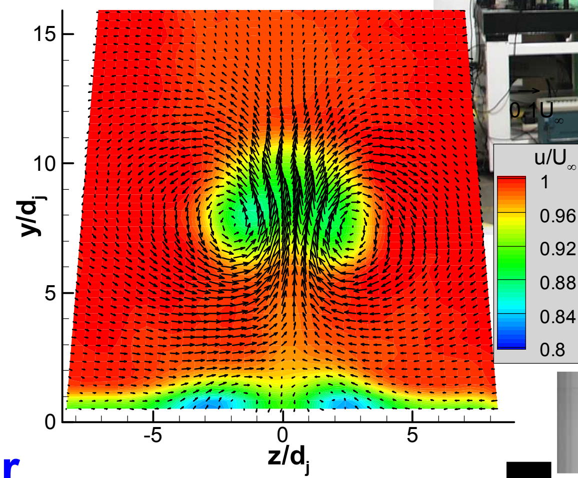
Why do we need laser diagnostics?

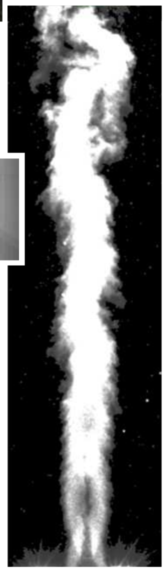
- Some wind tunnel tests need only provide aerodynamic forces…
- …but others must yield a better understanding of the underlying flowfield
- Development and validation of CFD requires high-fidelity measurements
- We can't let CFD have a monopoly on pretty vugrafs

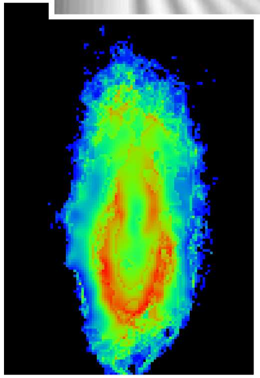
Sandia's wind tunnels are ideal for advanced measurements and research programs.

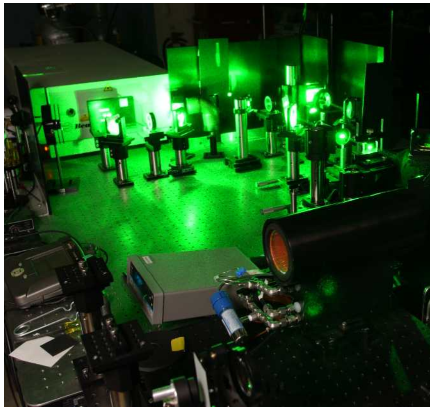
- Relatively inexpensive to operate
- Smaller scale is conducive to optical requirements











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Advanced Measurements

Particle Image Velocimetry (PIV)

- A particle tracking technique that measures a plane of 3-D velocity vectors
- Most effective at $M_\infty<3$
- Used in the TWT for several years

Doppler Global Velocimetry (DGV)

- Produces a plane of velocity measurements
- Complicated and noisy, but well-suited to hypersonics
- Being transitioned from the benchtop to the HWT

Pressure and Temperature Sensitive Paint (PSP and TSP)

- Measure the surface pressures or temperatures on a wind tunnel model
- Can cover the entire model body, including thin control surfaces
- Beginning implementation at Sandia

Oil-Film Interferometry (OFI)

- Measures wall shear stress over a model surface
- Transition detection

Examine a case study in which advanced diagnostics were used to resolve a flight vehicle concern

- **In this case, Particle Image Velocimetry (PIV)**

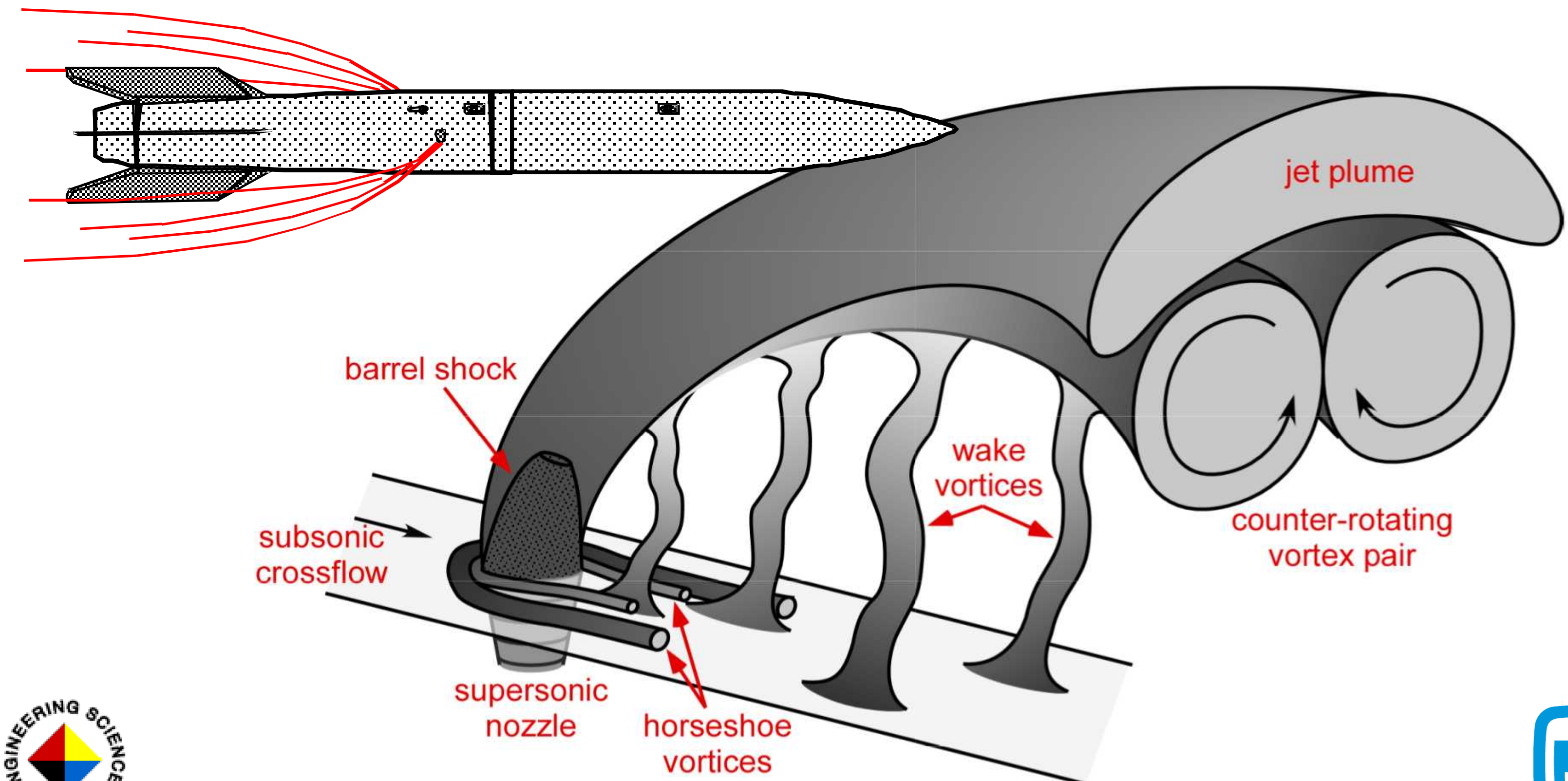
Jet-in-Crossflow Studies

Flight vehicles with both fins and thruster rockets experience an interaction between them

- Fundamentally the result of a jet in crossflow
- Ideally suited for application of PIV

Our objectives are to:

- Directly detect the counter-rotating vortex pair responsible for the interaction
- Acquire data to meet the needs of developing and validating computational models



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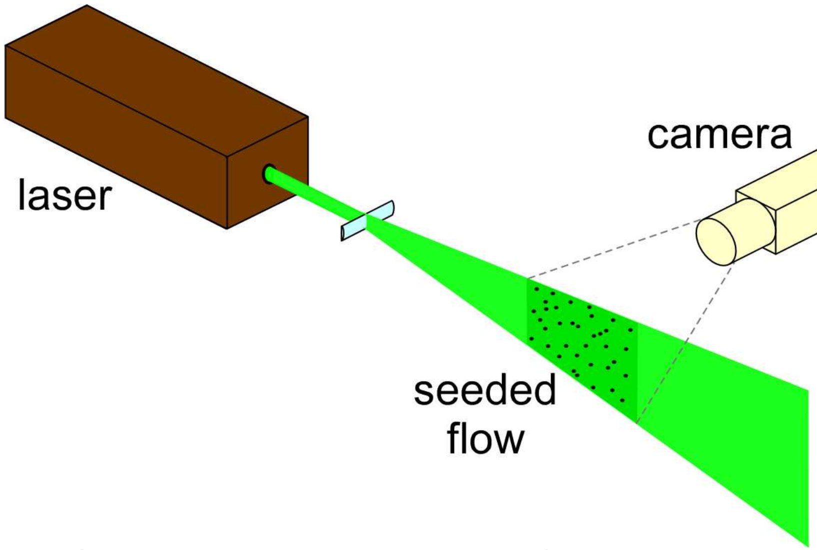
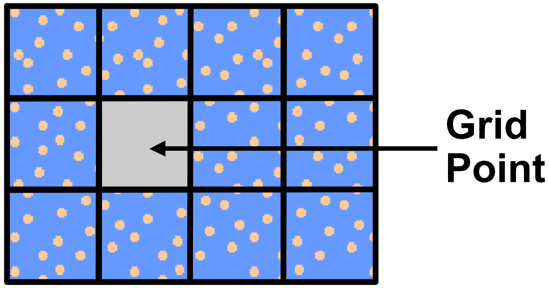
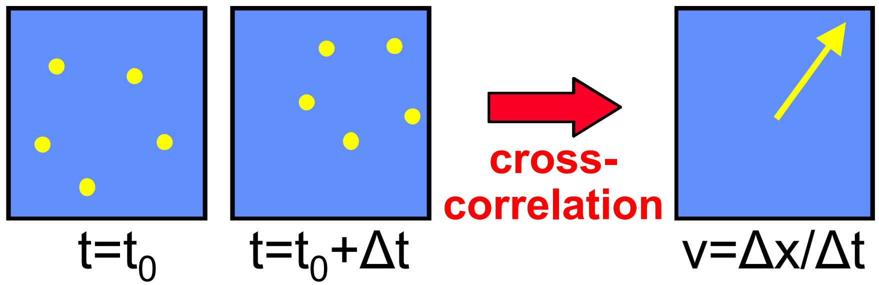
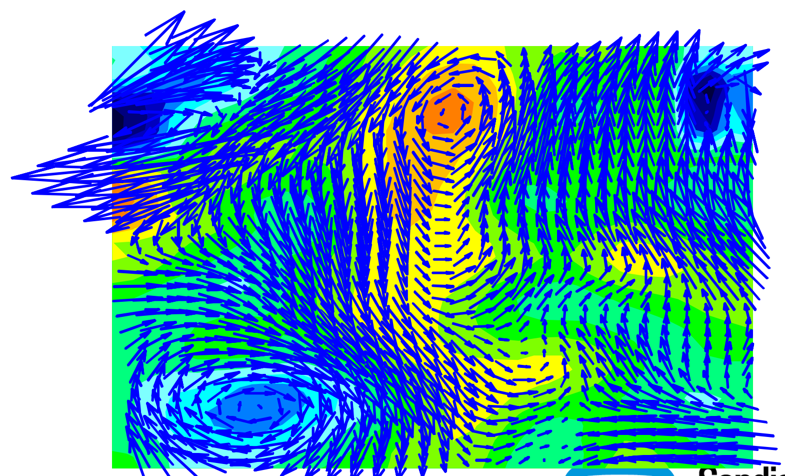
What is Particle Image Velocimetry (PIV)?



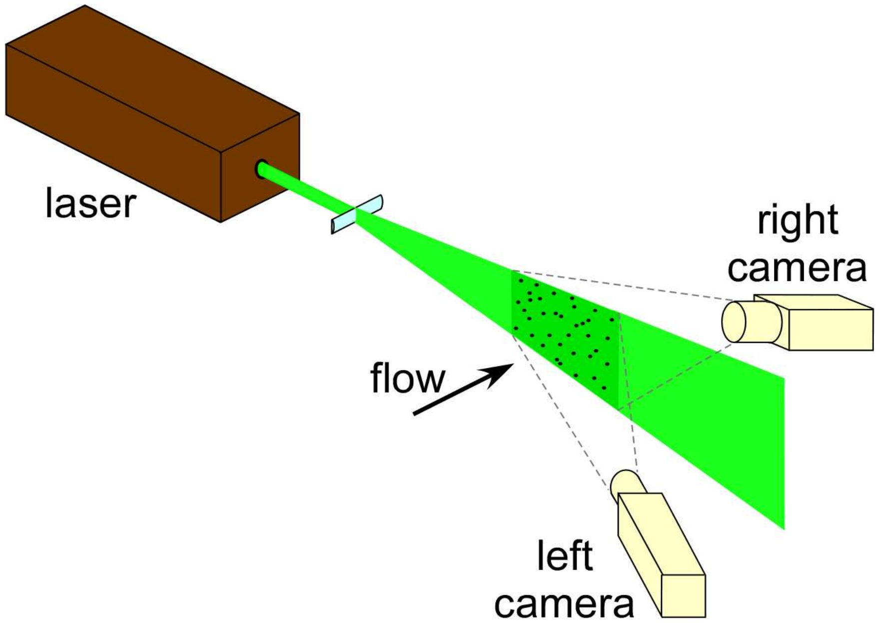


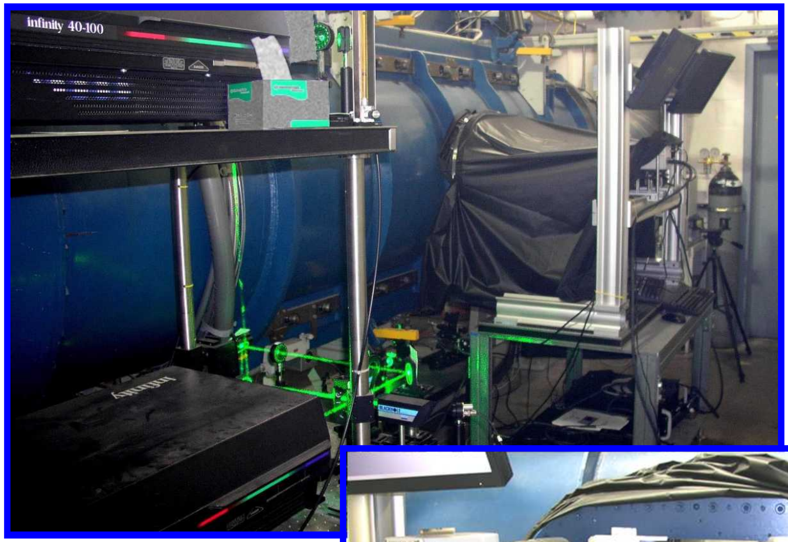


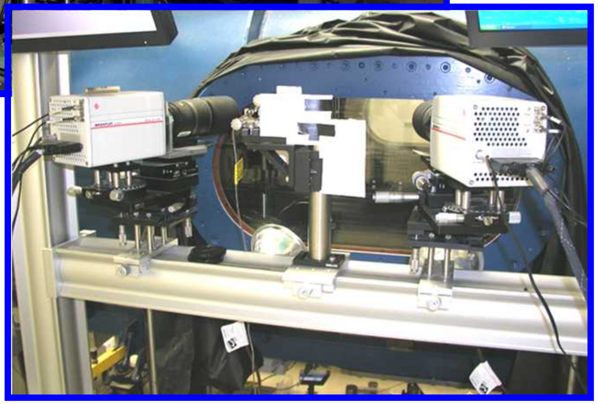
- **Seed a large quantity of small particles into the wind tunnel**
- **Illuminate with a double-pulsed laser sheet and image with a specialized digital camera**
- **Grid the images into smaller windows**
- **In each grid window, track a pattern of particles as they move from the first exposure to the second**
- **Compute a field of velocity vectors**



Stereoscopic PIV







- **Two cameras are used for a stereoscopic view, then the images are digitally reassembled for a three-dimensional perspective**
  - **Much like human vision**
- **It's a lot harder than 2D, but much more flexible**

This is what we need to see the vortices and measure their properties

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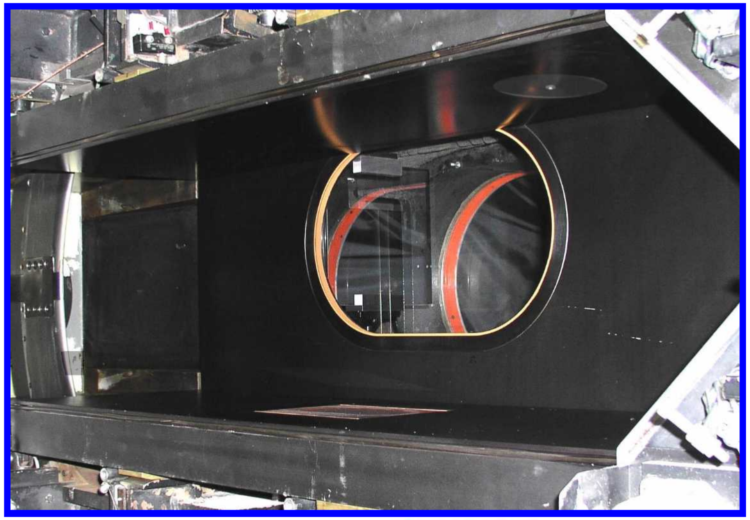
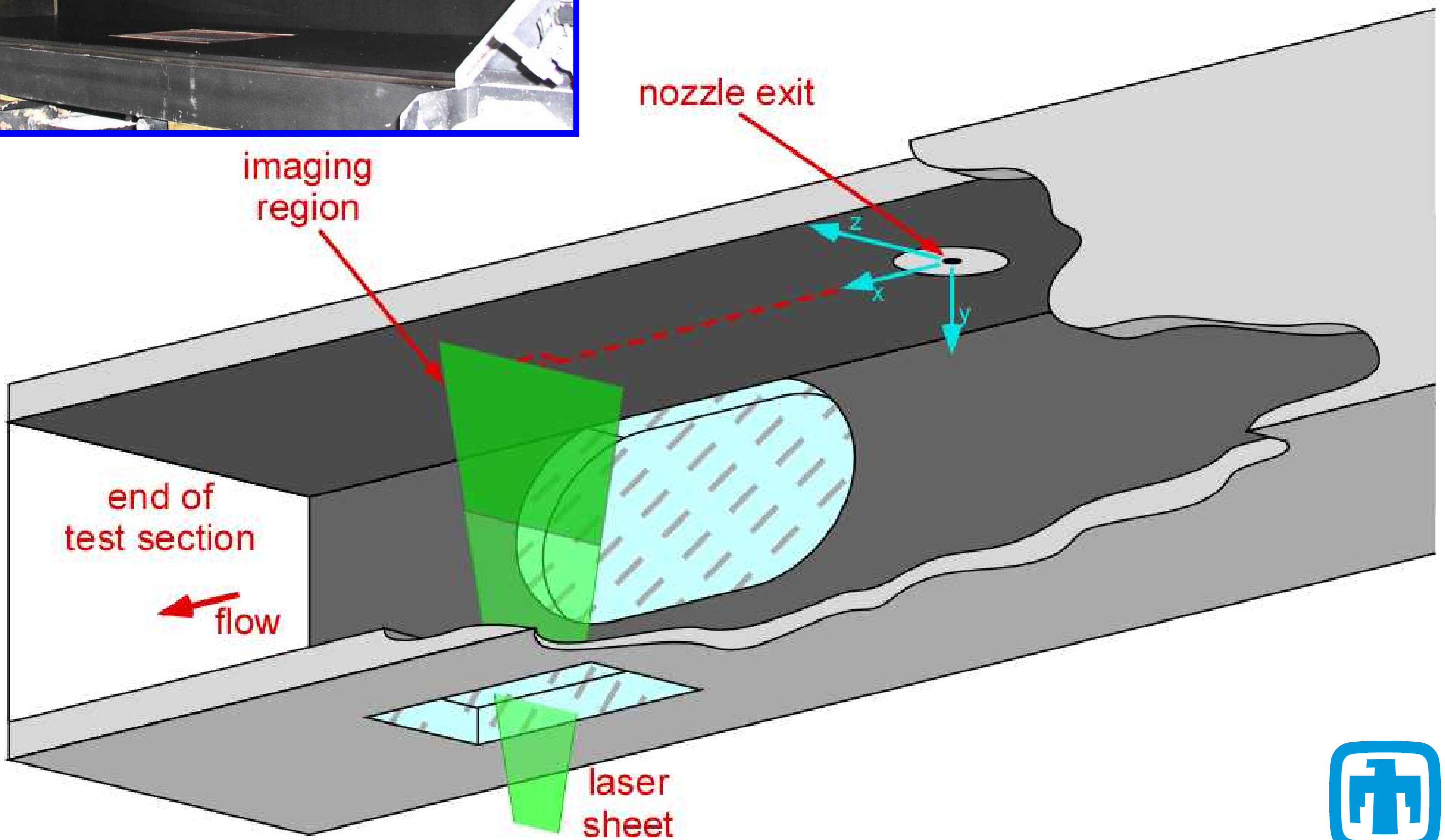
Laser Sheet Configuration

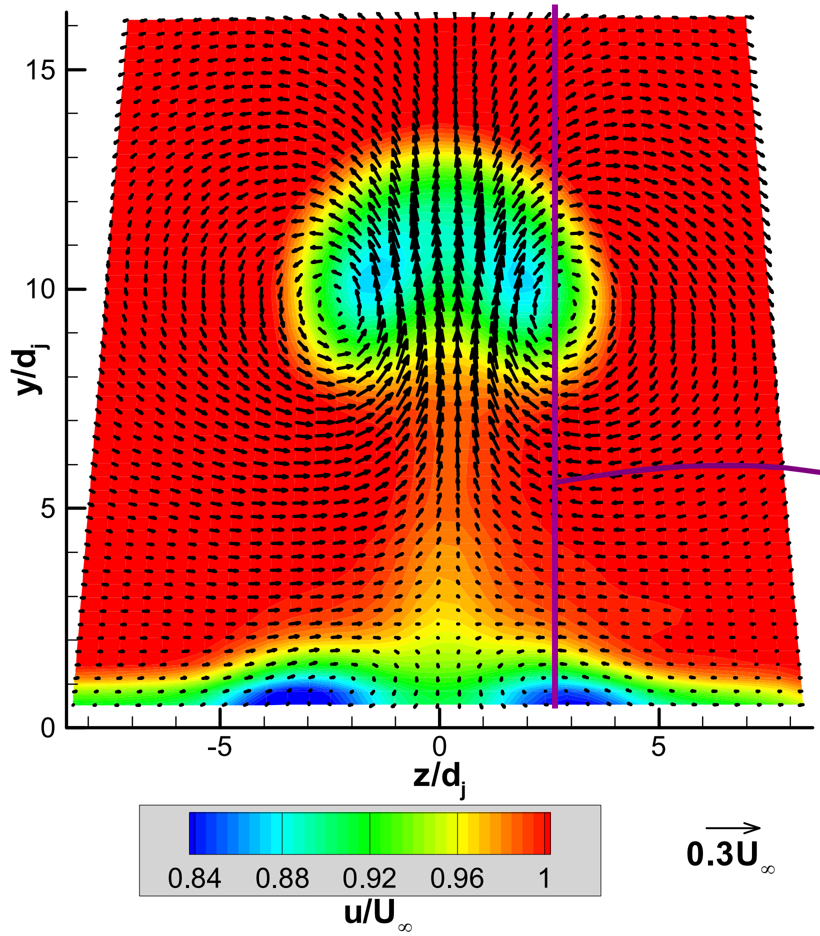


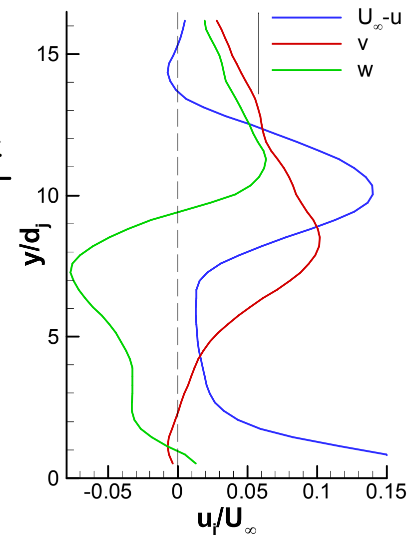
- View the interaction at a single downstream location where a fin would be located
- Laser sheet aligned to the crossplane of the interaction to directly measure the induced vortices



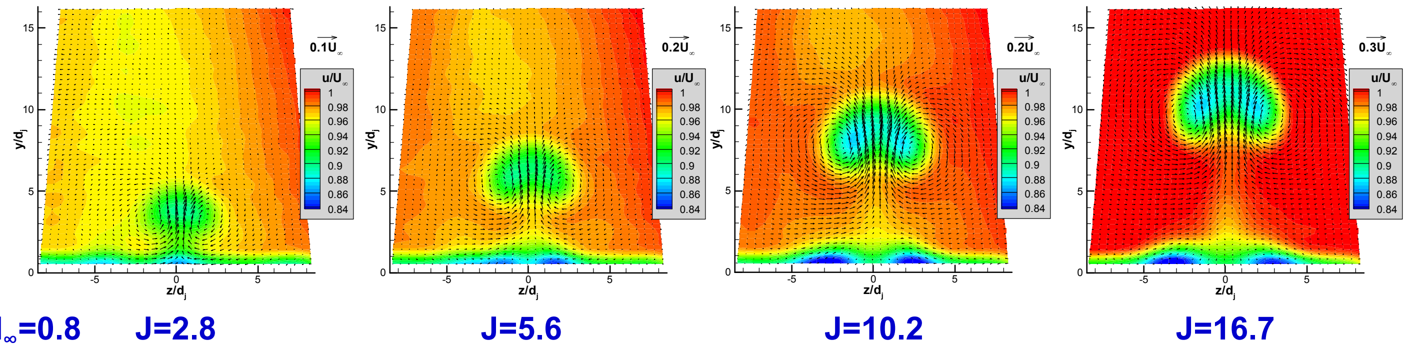
Crossplane Mean Velocity Fields

- In-plane velocities shown by vectors
- Out-of-plane velocities (streamwise component) shown by contour plot
- The counter-rotating vortex pair and the surface horseshoe vortex that are induced by the interaction are clearly visible
  - These vortices are responsible for jet/fin interaction

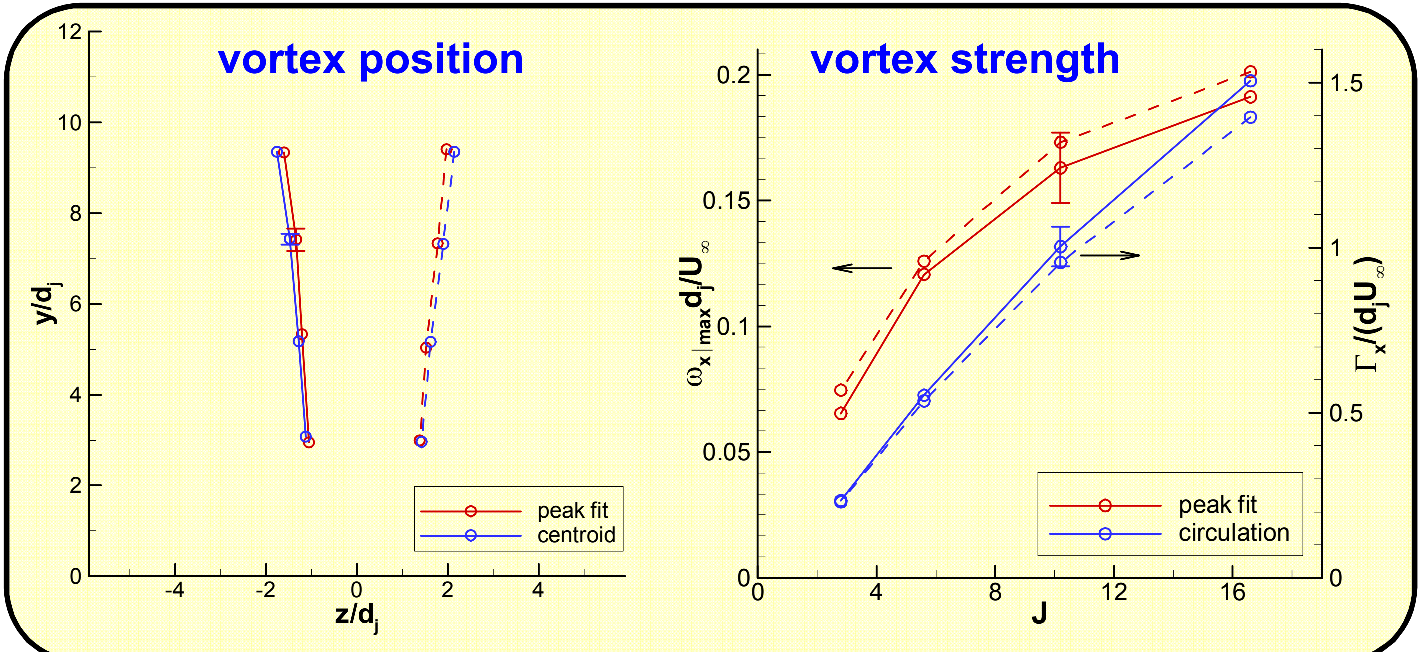




Data Analysis



data reveal vortex characteristics

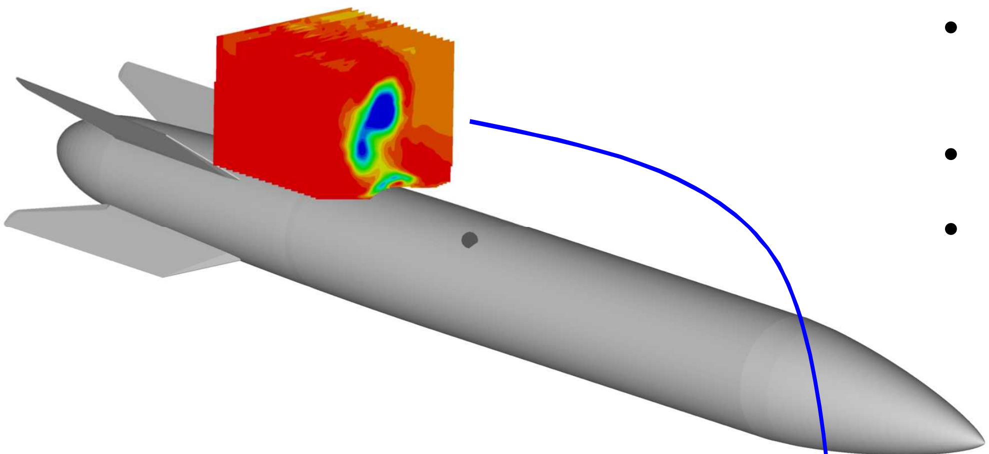


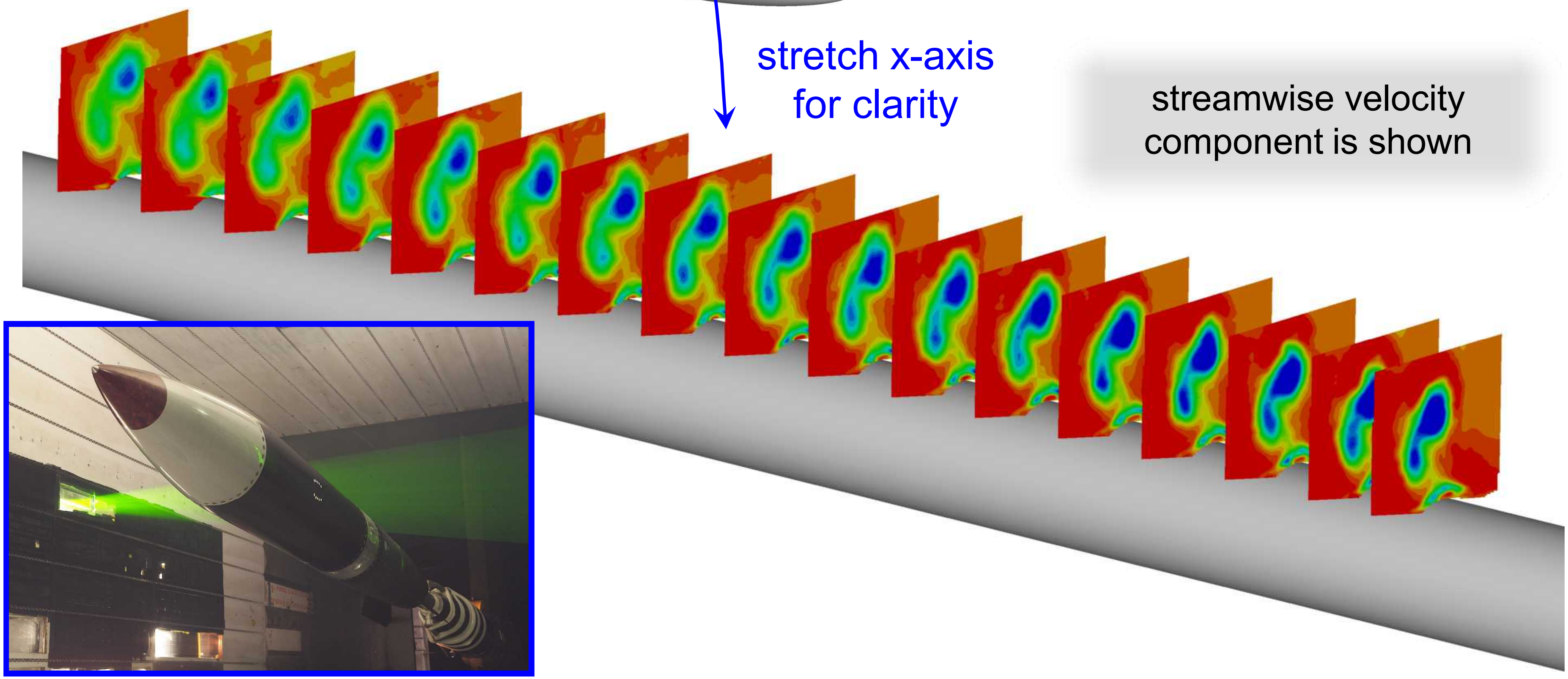
Data such as these are used to:

- Enhance physical understanding
- Provide guidance to vehicle design
- Validate computational models

Full-Scale Wind Tunnel Test

- Test conducted in the NASA Ames 11-Foot Transonic Wind Tunnel
- Transfer PIV to a large-scale facility
- The resulting data set is limited in comparison to the TWT, but important to connecting the study to the flight vehicle





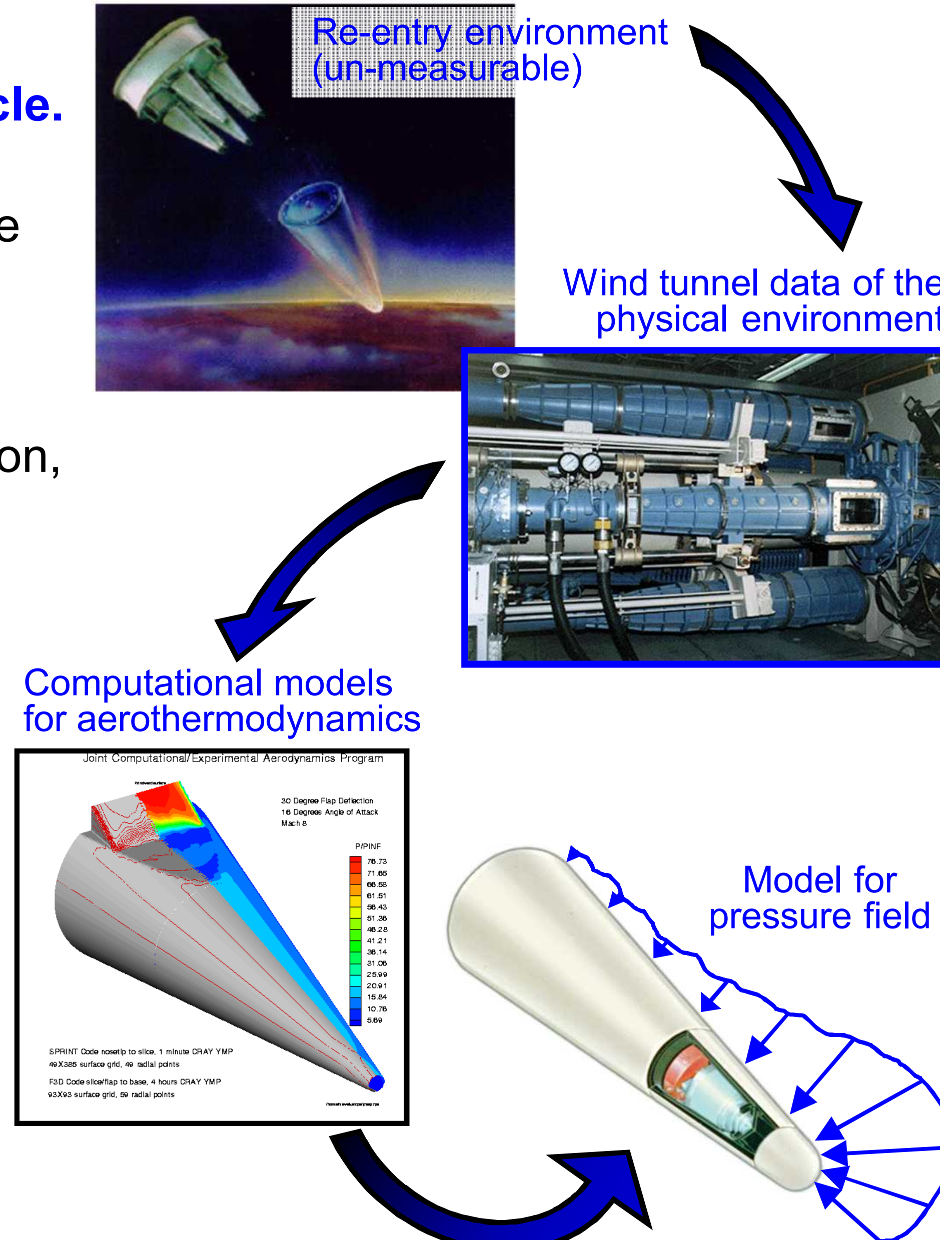
Planned Hypersonics Research

We are beginning a study of physical sources of vibration on a re-entry vehicle.

- To model the structural response to aerodynamically-induced vibrations, we must better understand the underlying physics.
- Significant real-world effects from ablation, deceleration, rotation, transition, unsteady shocks, etc.…

We begin with a study of pressure fluctuations due to a turbulent boundary layer.

- A fundamental place to start
- How does the turbulent velocity field yield pressure fluctuations?
- A robust model for predicting the pressure field requires knowledge of velocity field.



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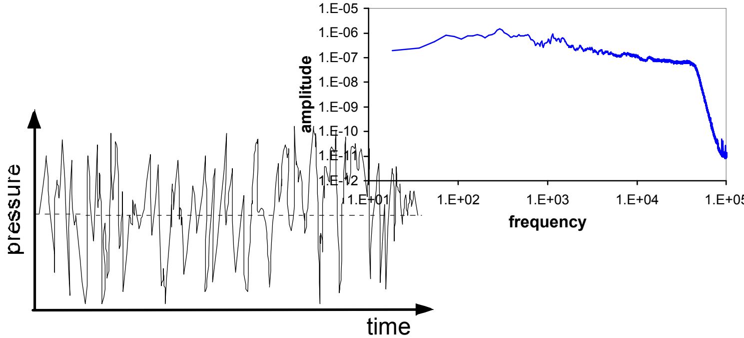
Supersonic Turbulent Boundary Layer

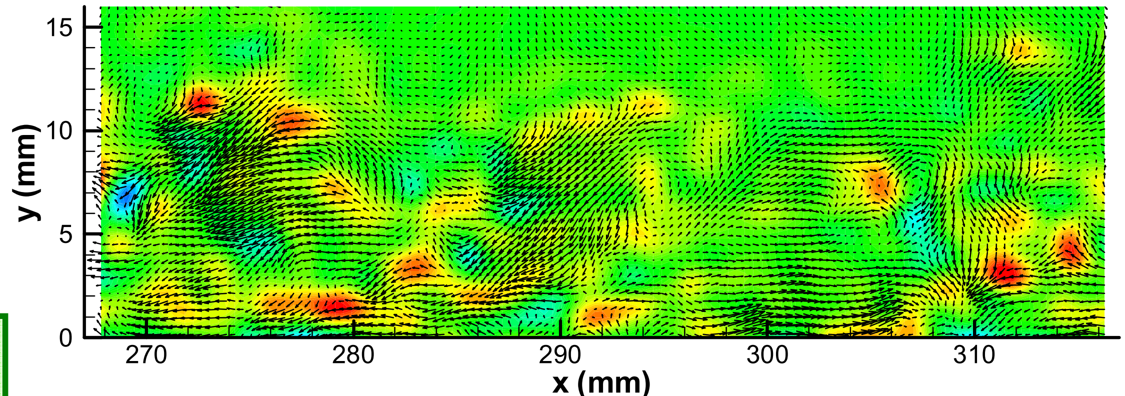
Arrays of high-frequency pressure transducers would measure the fluctuating wall pressure field

- Frequency spectrum
- Spatial and temporal correlations



Velocimetry of a M_∞=0.8 boundary layer in the TWT

- Uses stereoscopic particle image velocimetry



We would expand this technology to M_∞=1.5, 2.0, 2.5, and 3.0

- Covers part of the range of edge Mach numbers behind bow shock
- Significant additional challenges must be overcome
- *No such data set exists*

This experiment will help us understand the relationship between the velocity field and the pressure field it induces….

…which will improve our computational models.

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Advanced Measurements for RV Physics

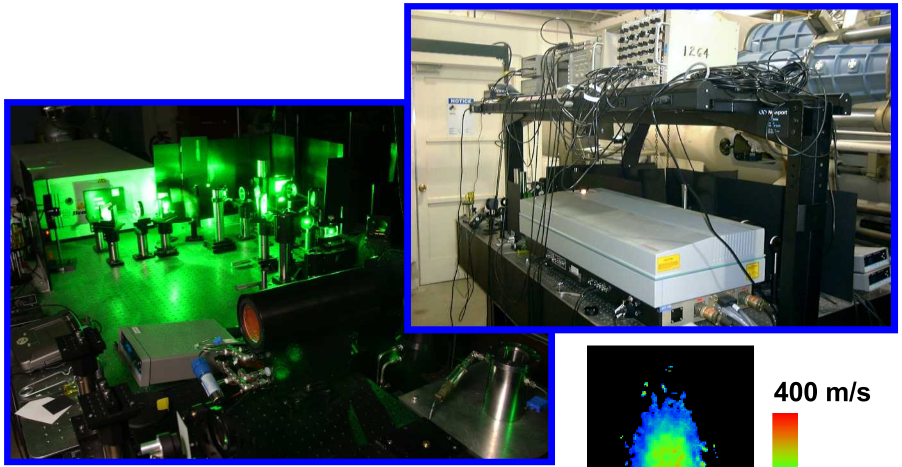
We wish to complement these fundamental boundary layer studies with experiments on RV models.

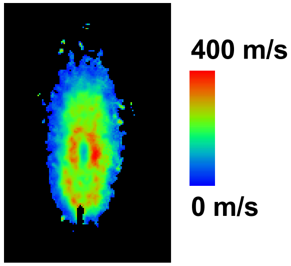
We are developing advanced laser diagnostics for hypersonic testing and code validation.

- Provide flow visualization and quantitative velocimetry capabilities
- Map the surface pressure and temperature fields

These experiments will be used to investigate other physical sources of vibration on an RV.

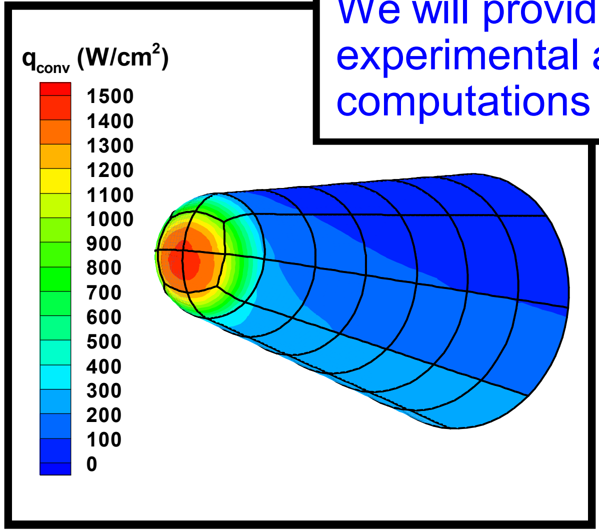
- Expand our models beyond boundary layer pressure fluctuations.





Transitioning Doppler Global Velocimetry from a benchtop jet to the HWT.

We will provide an experimental analogue to computations such as this.



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RV Physics of Interest

A plausible source of pressure fluctuations is unsteadiness of the bow shock.

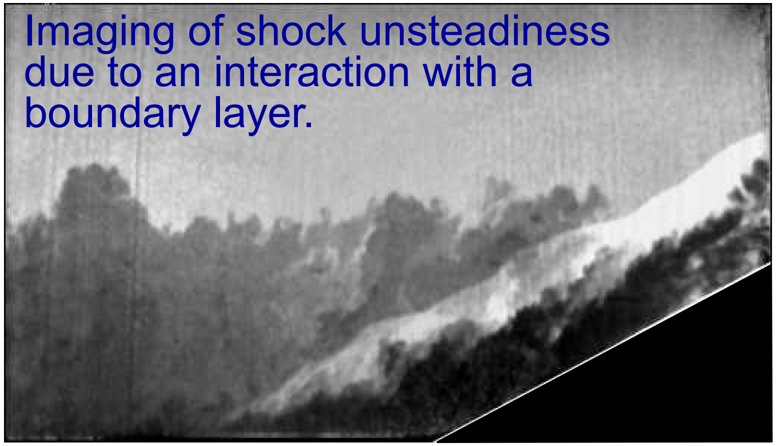
- We plan to examine this issue and the shock response to nosetip shape change as it ablates

Transition is a key concern, but one we cannot effectively address in the HWT.

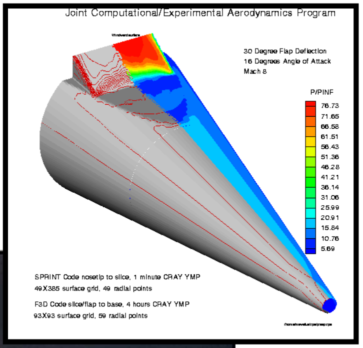
- We are helping fund university research

Other suggested future studies:

- We continue an interest in control surfaces and maneuvering RV's.
- We are examining techniques for low-temperature ablation studies in the HWT.
- We are considering means of simulating weather effects in our wind tunnels
    - Can our instrumentation still function?



Imaging of shock unsteadiness due to an interaction with a boundary layer.



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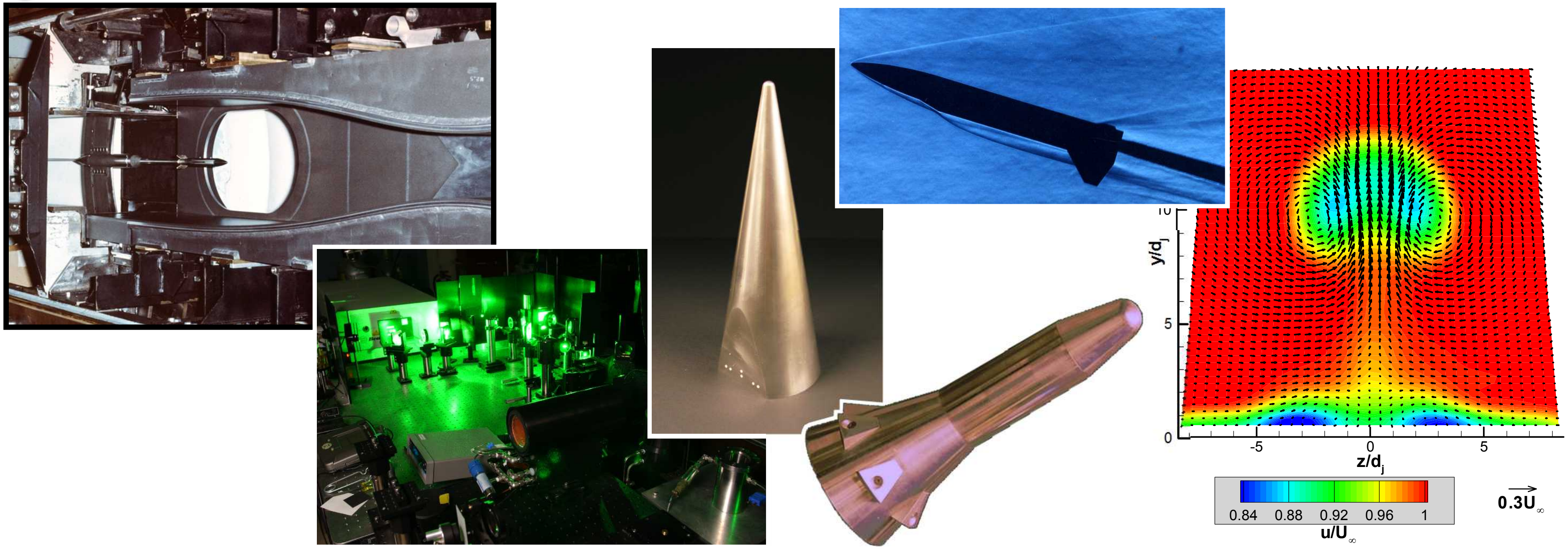
Summary



Sandia has successfully utilized its wind tunnels for applied research programs supporting flight vehicle concerns.

Advanced measurements have played a key role.

These capabilities are now being turned towards support of re-entry vehicle aerodynamics.

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