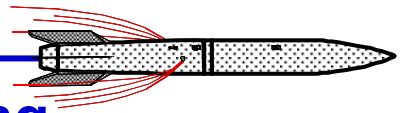
Test Before Flight:



Wind Tunnel Technology for Aerodynamic Testing

Steven J. Beresh
Engineering Sciences Center
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Albuquerque, NM

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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

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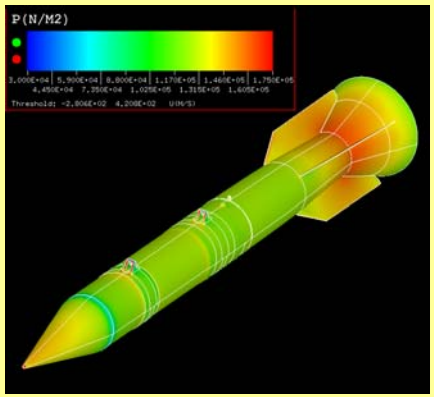
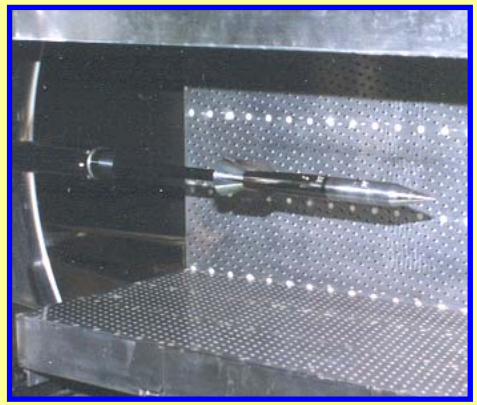
The Role of the Wind Tunnels





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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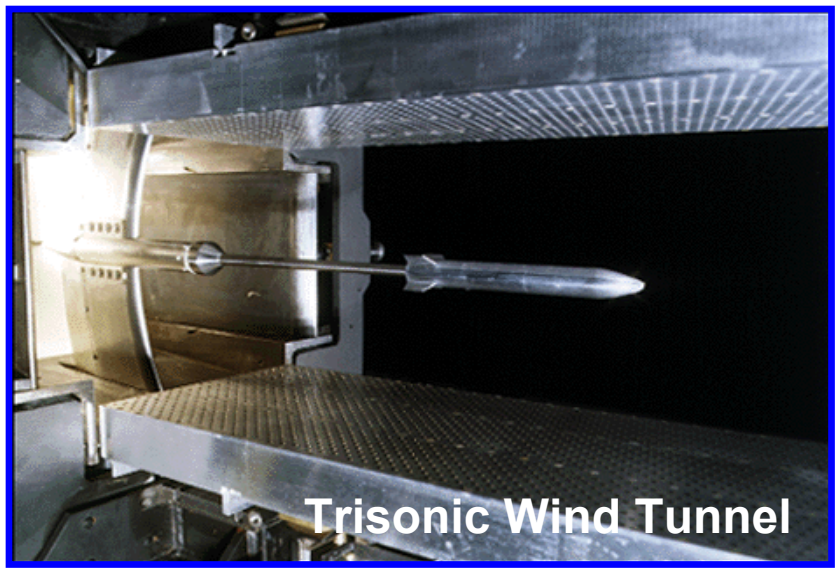
Experimental Aerosciences Facility


Trisonic Wind Tunnel

Hypersonic Wind Tunnel

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

High-Altitude Chamber

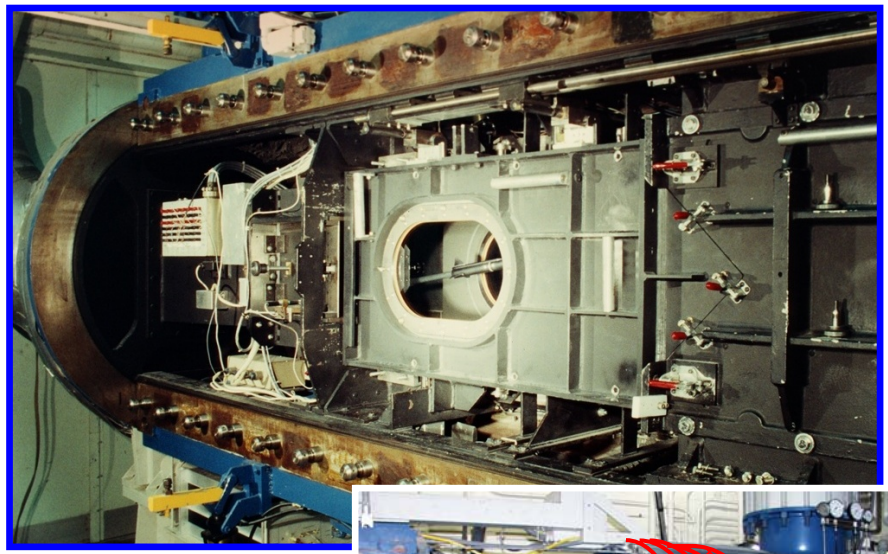
Trisonic Wind Tunnel (TWT)

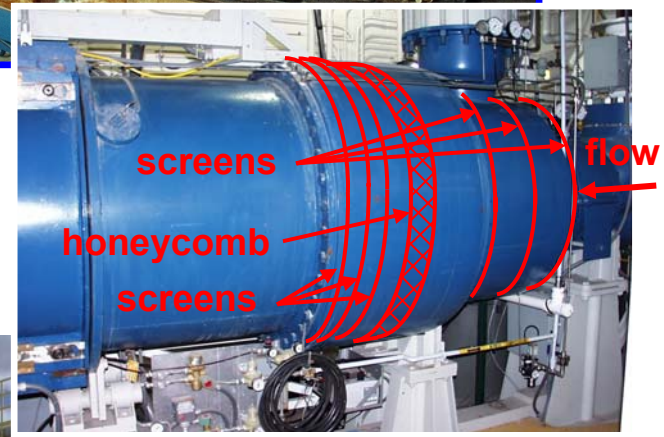
Blowdown Wind Tunnel

- Runs for 30-50 seconds at a time
- Turnaround of about 20-30 minutes
- Supplied by high-pressure air
- Exhausts to atmosphere
- 12" square test section

Flow Control

- A series of valves control the pressure and the flow rate
- Downstream of the valves are screens and honeycomb to “smooth” the flow
- The test section is where we do business





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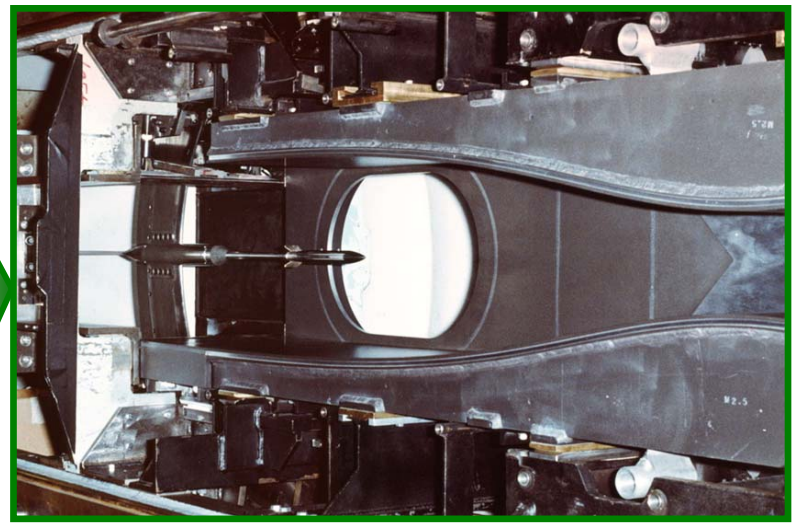
Trisonic Wind Tunnel (TWT)

Supersonic experiments are conducted in contoured nozzles

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



Transonic experiments are conducted in a porous-wall test section

- Any Mach number from 0.5 to 1.3
- Porous walls are needed to:
  - Prevent the reflection of shock waves back onto the model
  - Alleviate choking effects near Mach 1

- The typical wind tunnel test hangs a scale model of a flight vehicle off a sting
- Can pitch through a range of angles of attack during one run

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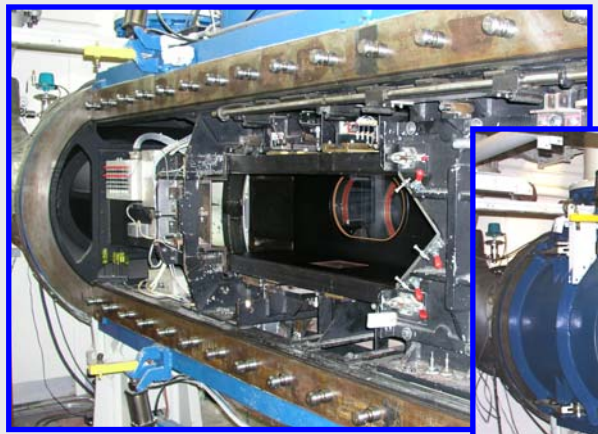
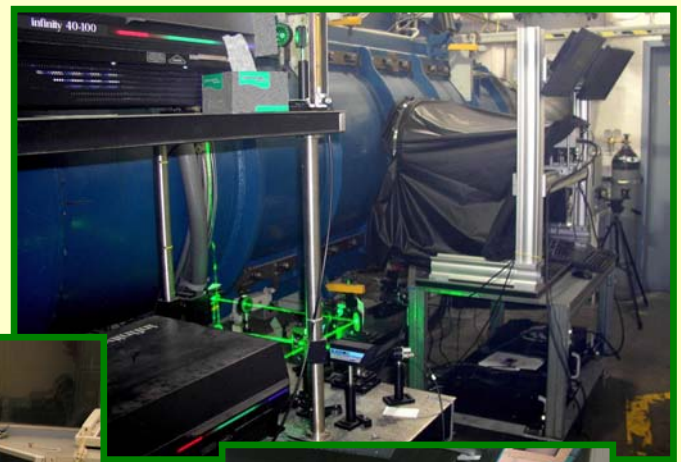
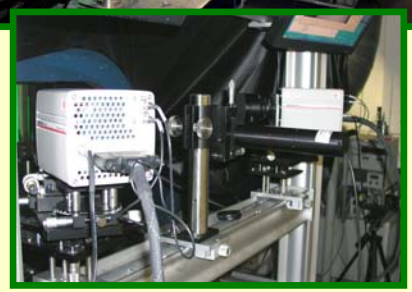
Trisonic Wind Tunnel (TWT)

The test section is enclosed in a pressurized plenum

- Contains the flow through the porous walls
- Makes optical access for measurements more difficult







The TWT is surrounded by additional systems needed for various experiments

- Secondary gas supply for simulating rocket motors
- Lasers and optics for advanced diagnostics
- The control console

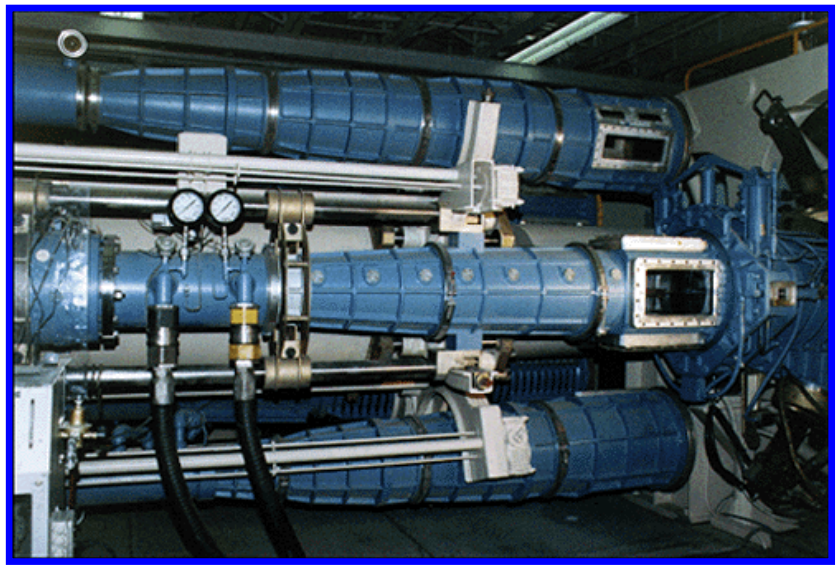
Hypersonic Wind Tunnel (HWT)

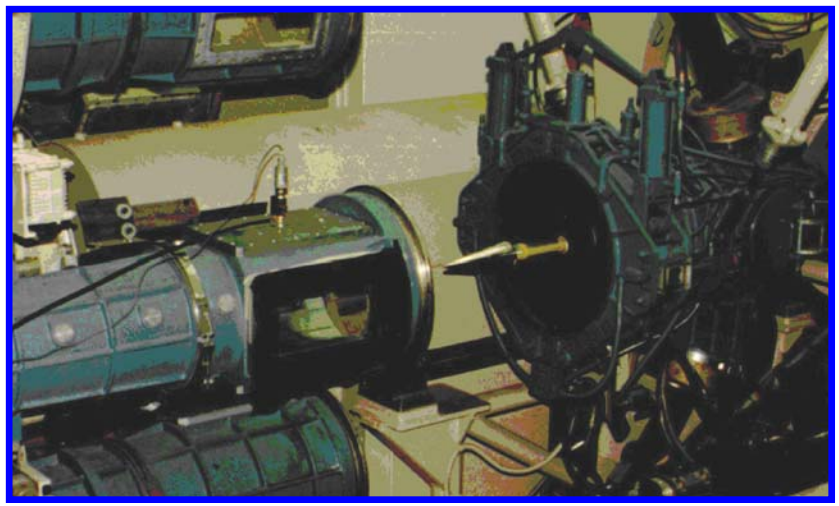
Also a blowdown wind tunnel

- Run times typically 45 seconds with 45 minute turnaround
- Blows down to vacuum
- Mach 5, 8, and 14 using different test sections
- 18" diameter test section
- Testing similar to TWT: pitch a model through a series of angles of attack

Gas source

- Mach 5 runs high-pressure air
- Mach 8 and 14 run nitrogen
  - High Mach numbers have a very low test section temperature
  - CO_2 and other trace gases in air will condense





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 nitrogen
- Use electric resistance heaters unique to each Mach number
  - Maximum of 3 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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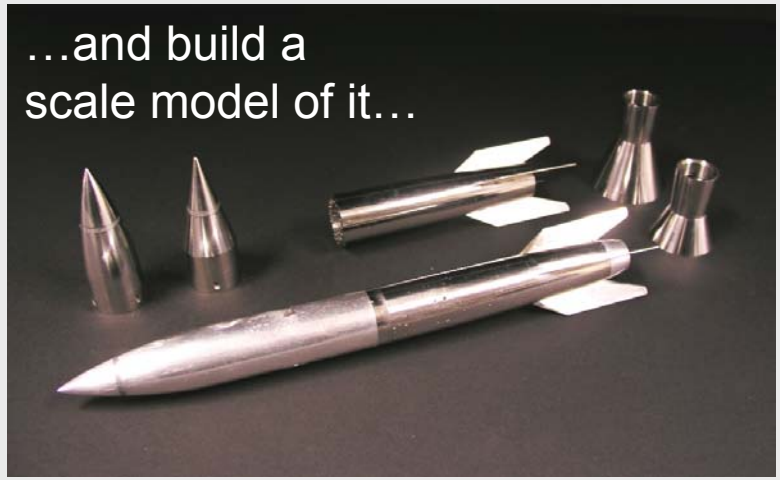
Wind Tunnel Models

Take an actual flight vehicle…

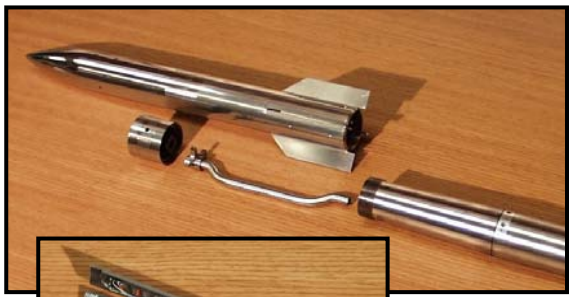
…and build a scale model of it…

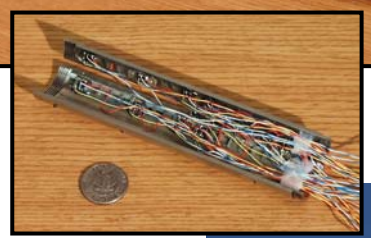


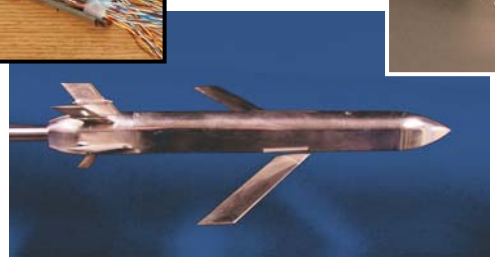
…which has features such as:

- Instrumentation
- Geometry changes
- Spin testing

Some other models tested at Sandia:







By necessity, a small model does not exactly replicate the full-scale version

Part of a wind tunnel engineer's job is to understand such scaling issues

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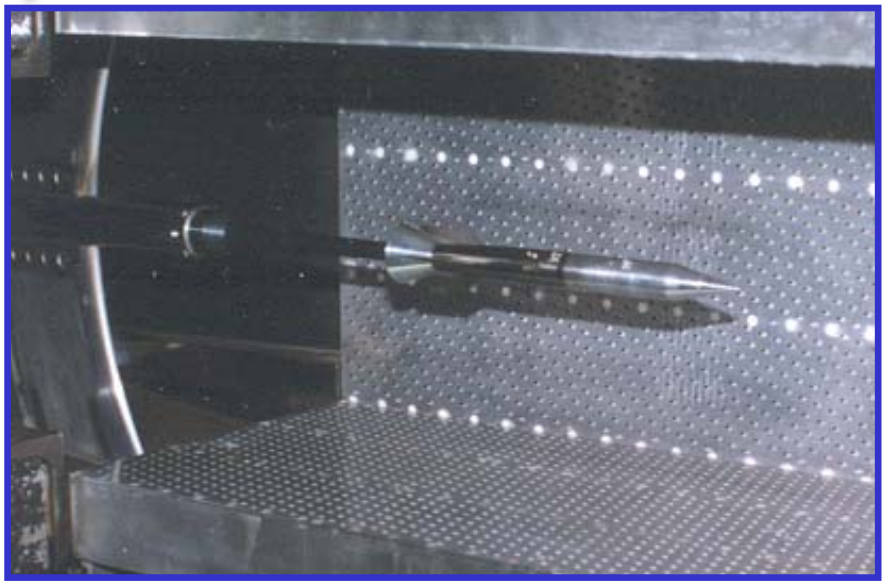
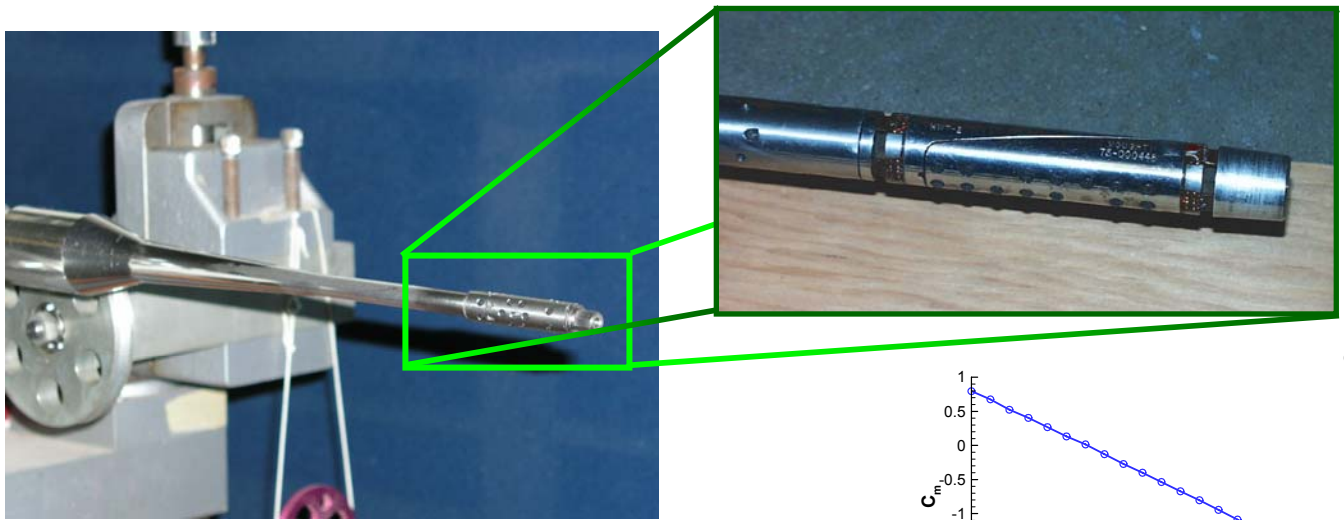
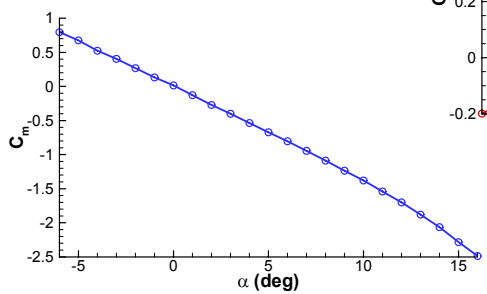
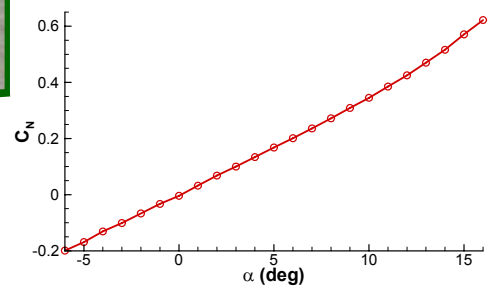
Aerodynamic Measurements



- Determine the aerodynamic forces and moments using an internal strain-gage balance placed inside the model
- Balance elements flex as they are loaded, producing a measurable signal
- Vary parameters such as tunnel Mach number, model angle-of-attack, model geometry, etc







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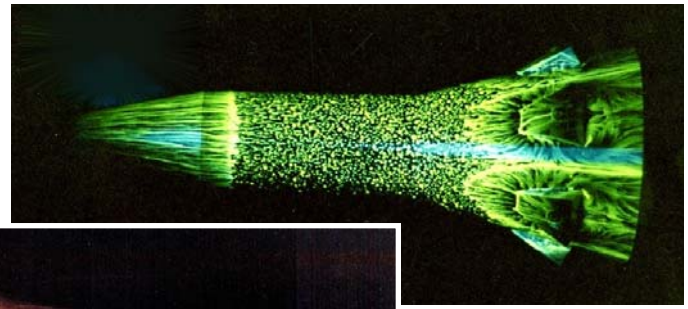
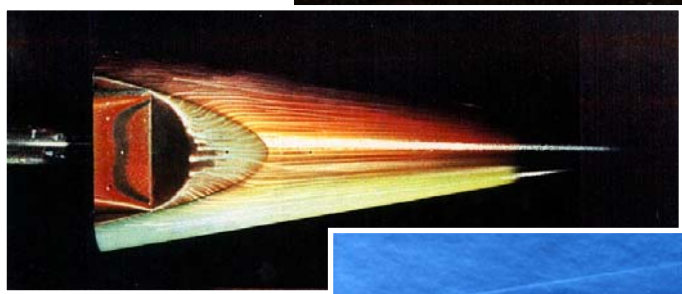
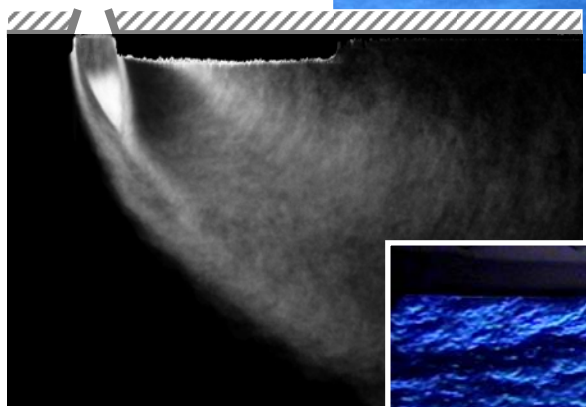
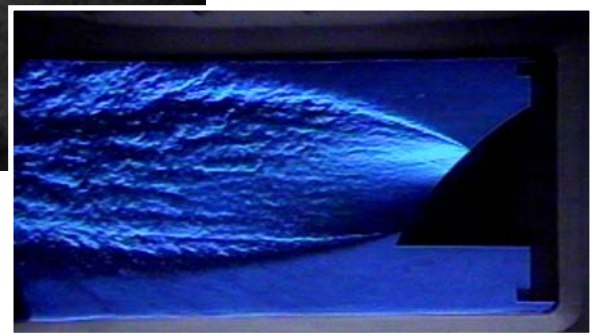
Flow Visualization

- Complement balance measurements with visualization of the gas flow over the model
- Helps to provide an understanding of the underlying fluid dynamics
- Can visualize:
  - Shock waves
  - Surface streamlines
  - Gas mixing









- 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

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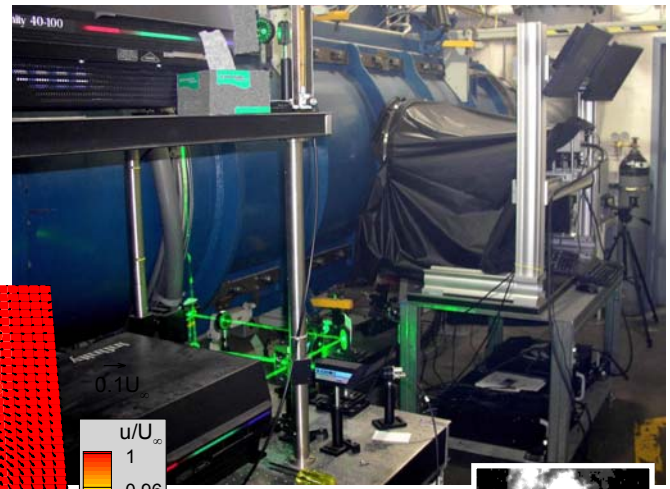
Advanced Measurements

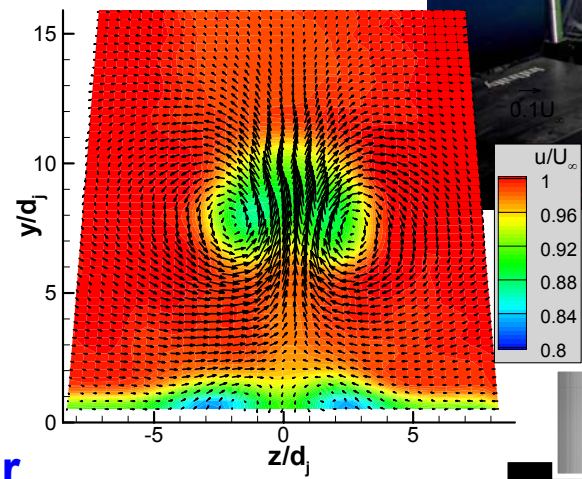
Why do we need laser diagnostics?

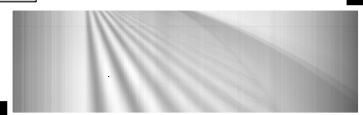
- Some wind tunnel tests need only provide aerodynamic forces…
- …but others must yield a better understanding of the underlying flowfield
- Development and validation of CFD requires high-fidelity measurements
- We can't let CFD have a monopoly on pretty vugrafs

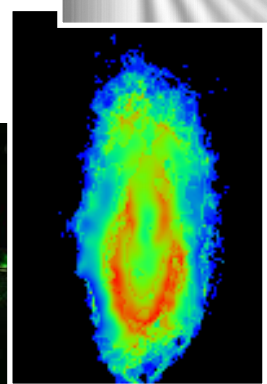
Sandia's wind tunnels are ideal for advanced measurements and research programs.

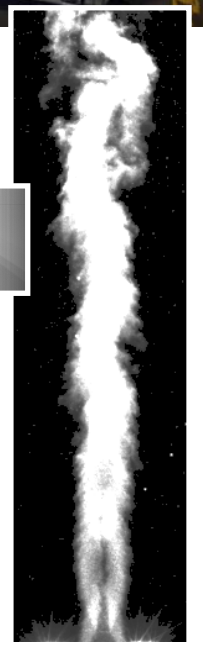
- Relatively inexpensive to operate
- Smaller scale is conducive to optical requirements

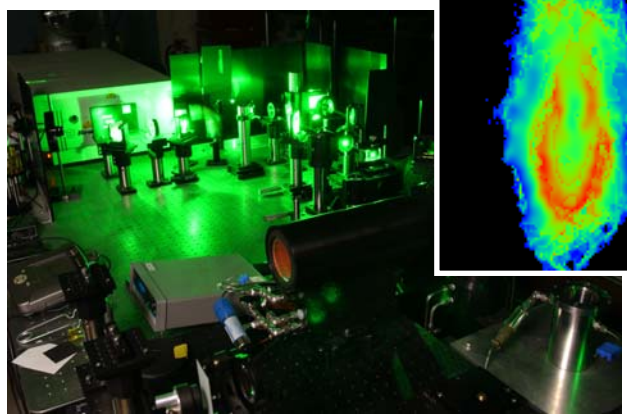












Advanced Measurements

Particle Image Velocimetry (PIV)

- A plane of 3-D velocity vectors
- Most effective at M_∞<3

Doppler Global Velocimetry (DGV)

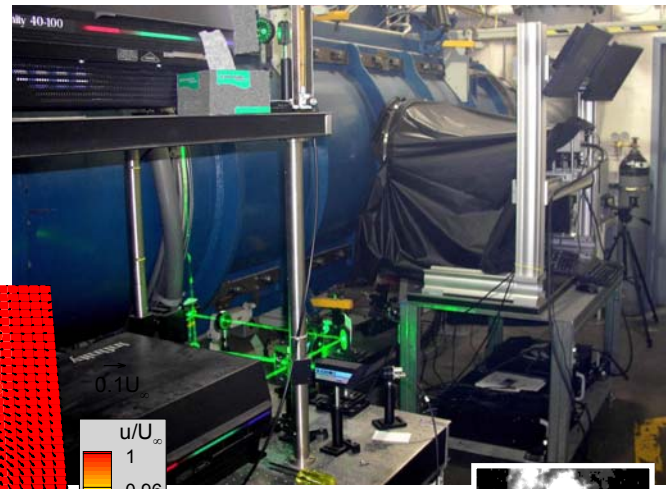
- A plane of velocity measurements
- Well-suited to hypersonics

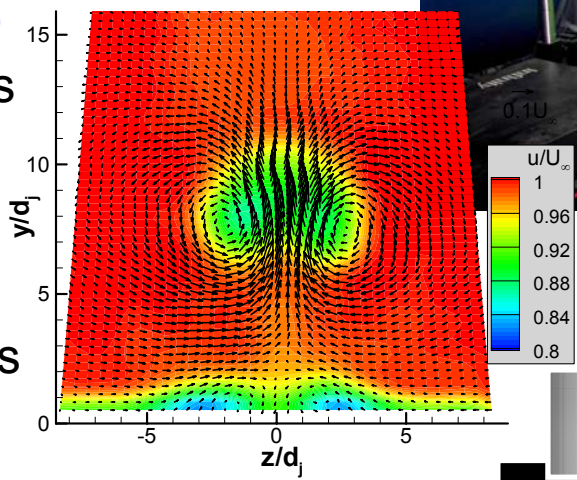
Pressure and Temperature Sensitive Paint (PSP and TSP)

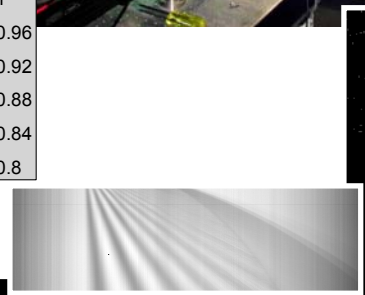
- Measure model surface pressures or temperatures
- Can cover the entire model body, including thin control surfaces

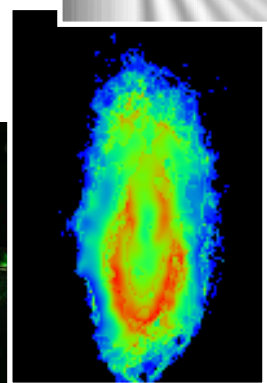
Oil-Film Interferometry (OFI)

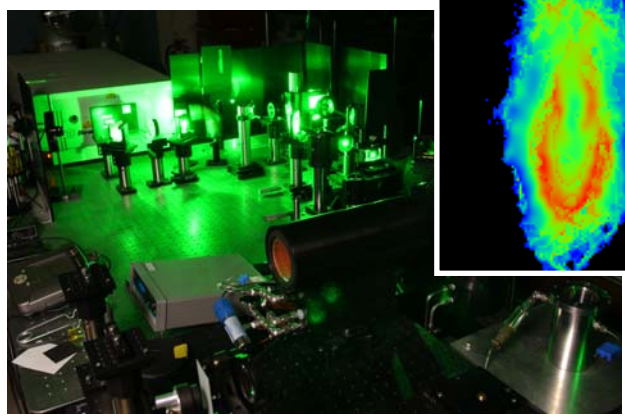
- Measures wall shear stress over a model surface
- Transition detection











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Jet-in-Crossflow Studies

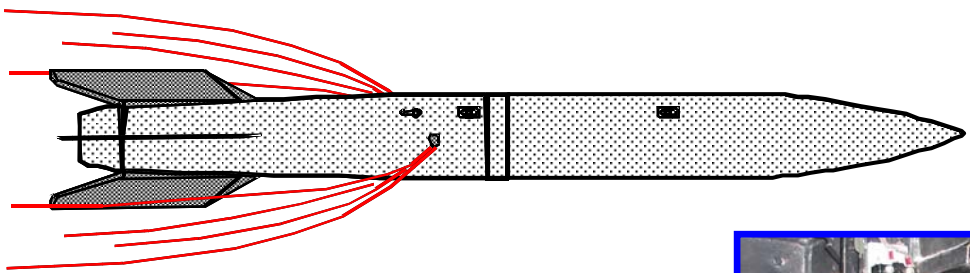
Examine a case study in which advanced diagnostics were used to resolve a flight vehicle concern

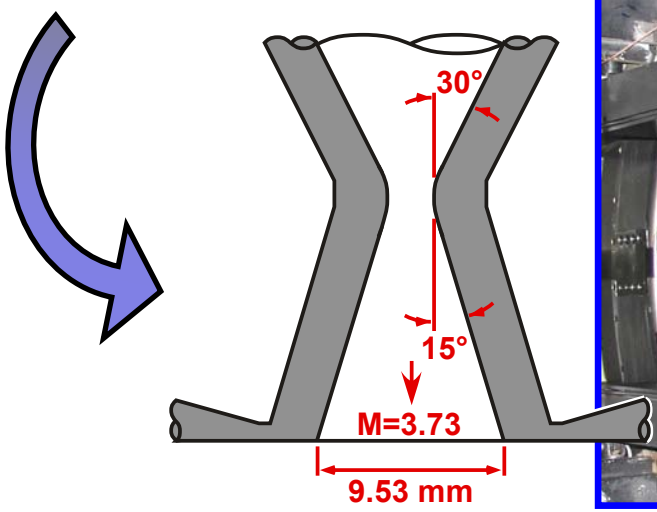
- **In this case, Particle Image Velocimetry (PIV)**

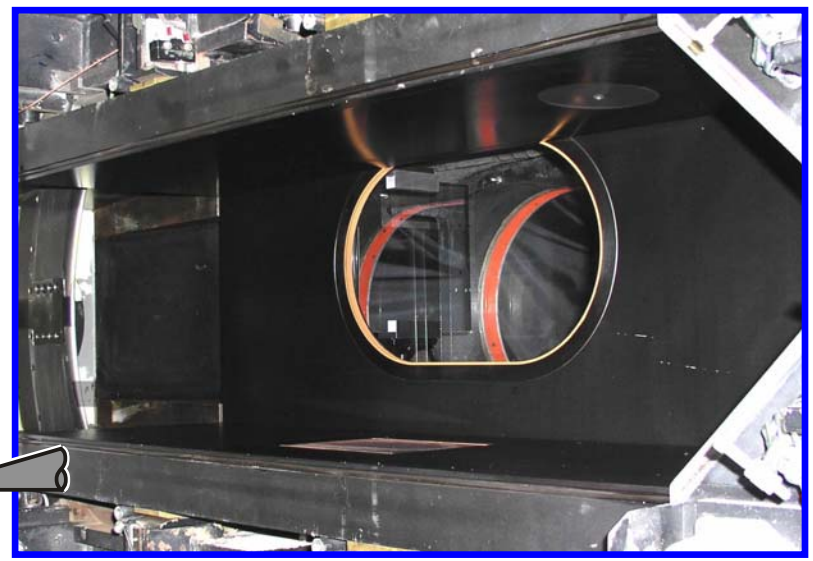
Flight vehicles with both fins and thruster rockets experience an interaction between them.

Our objectives are to:

- Directly detect the vortices responsible for the interaction
- Acquire data for developing and validating computational models







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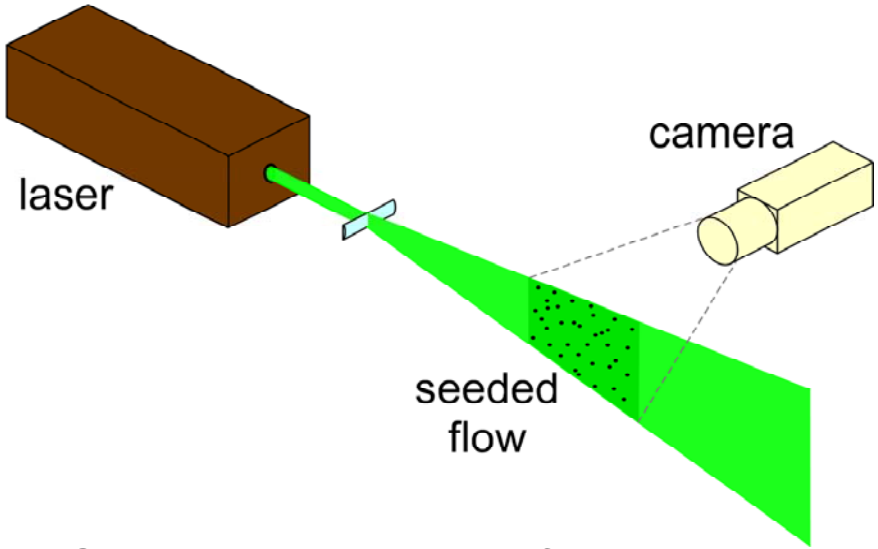
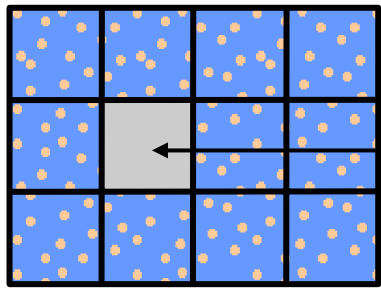
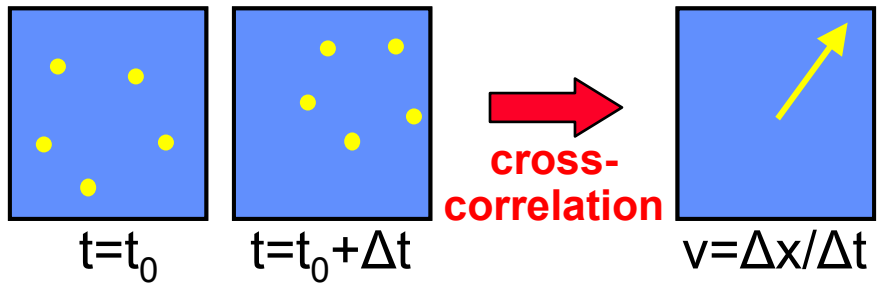
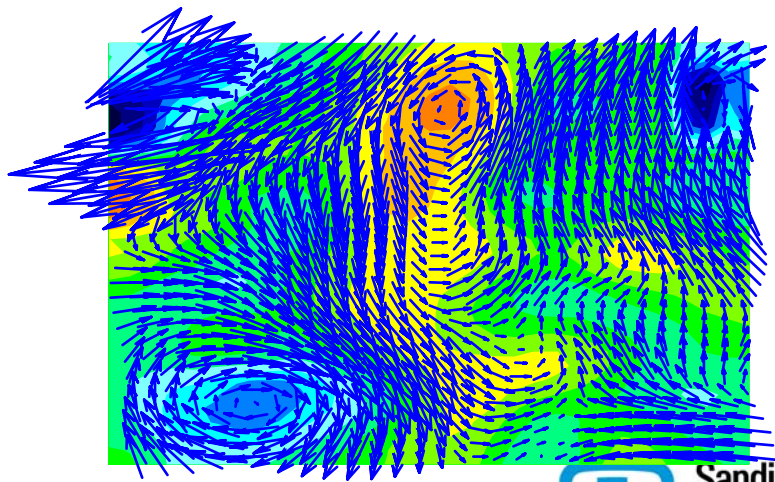
What is Particle Image Velocimetry (PIV)?







- 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



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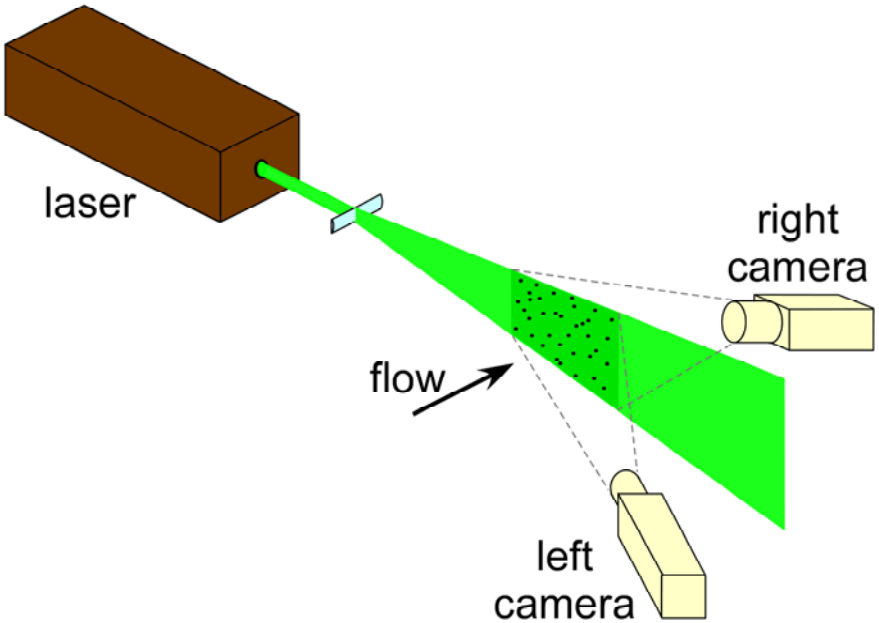
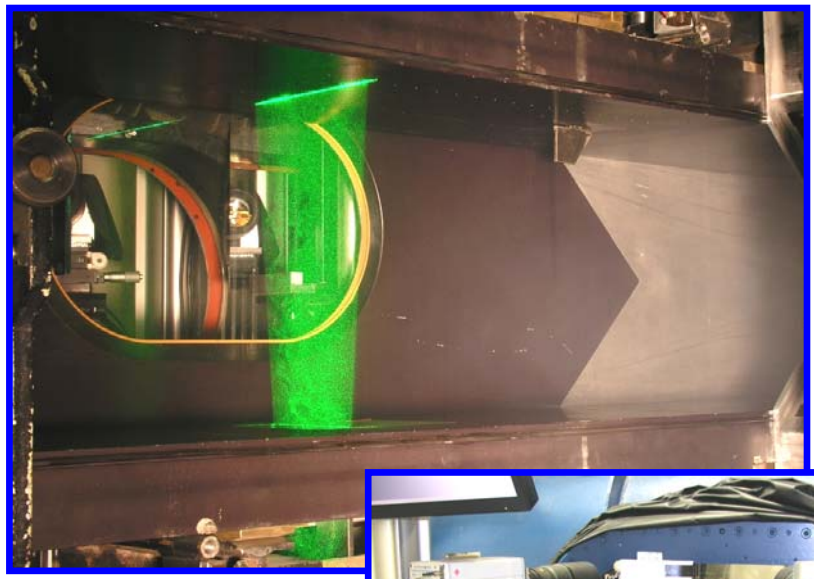
Stereoscopic PIV

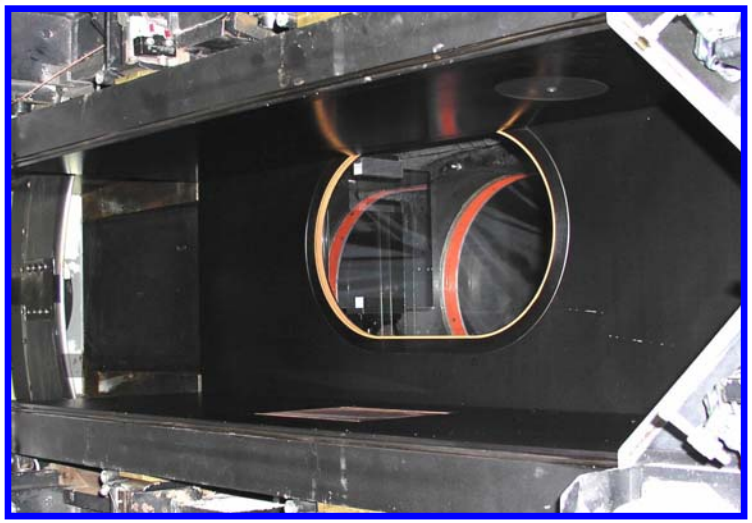




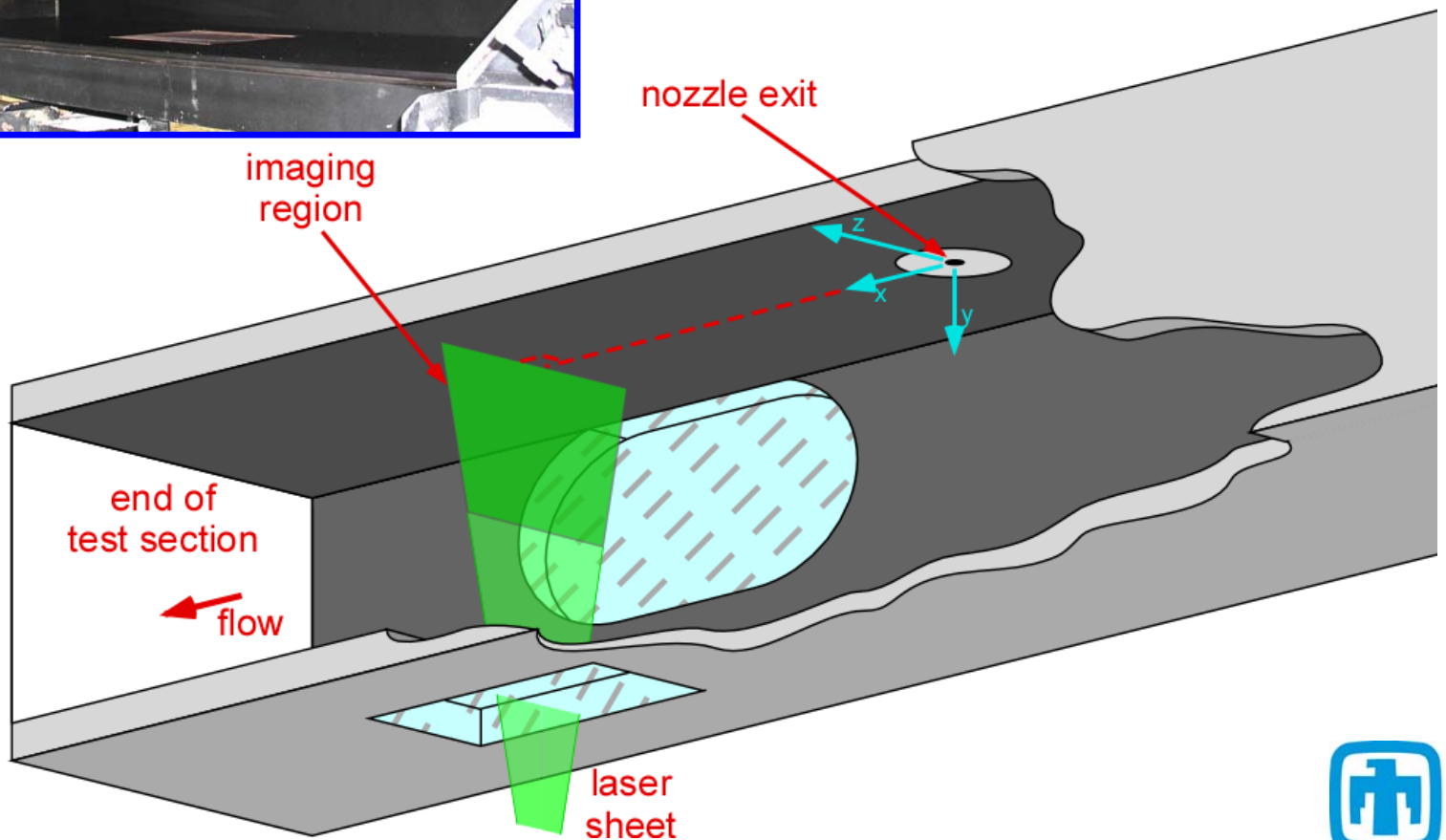
- Two cameras are used for a stereoscopic view, then the images are digitally reassembled for a three-dimensional perspective
  - Much like human vision
- It's a lot harder than 2D, but much more flexible

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

Laser Sheet Configuration

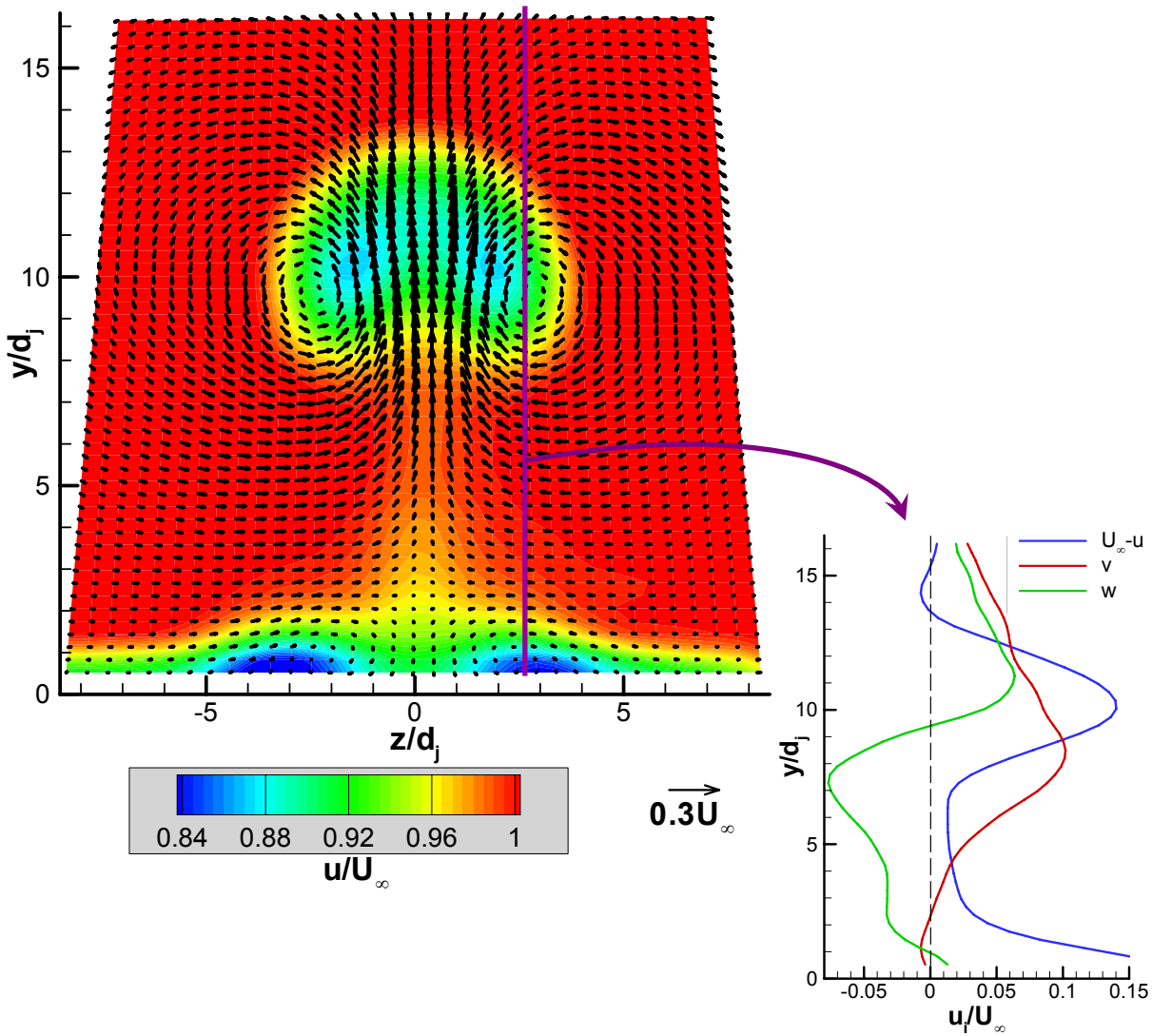


- View the interaction at a single downstream location where a fin would be located.
- Laser sheet aligned to the crossplane of the interaction to directly measure the induced vortices.



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



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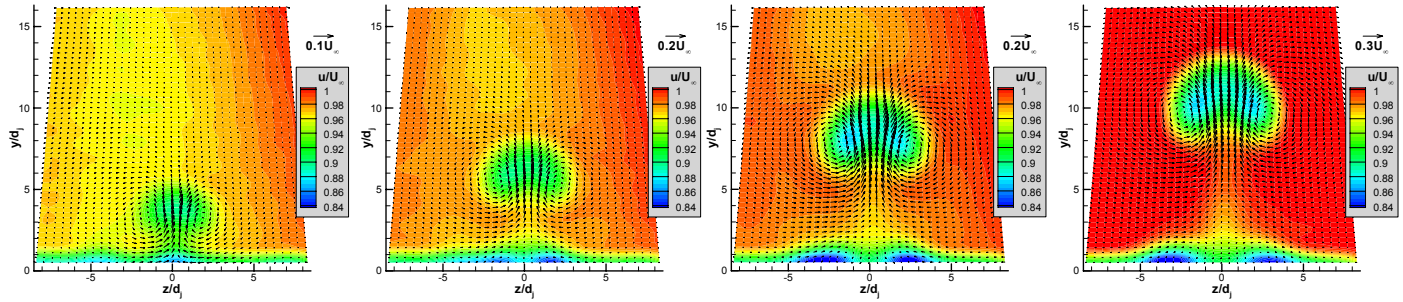
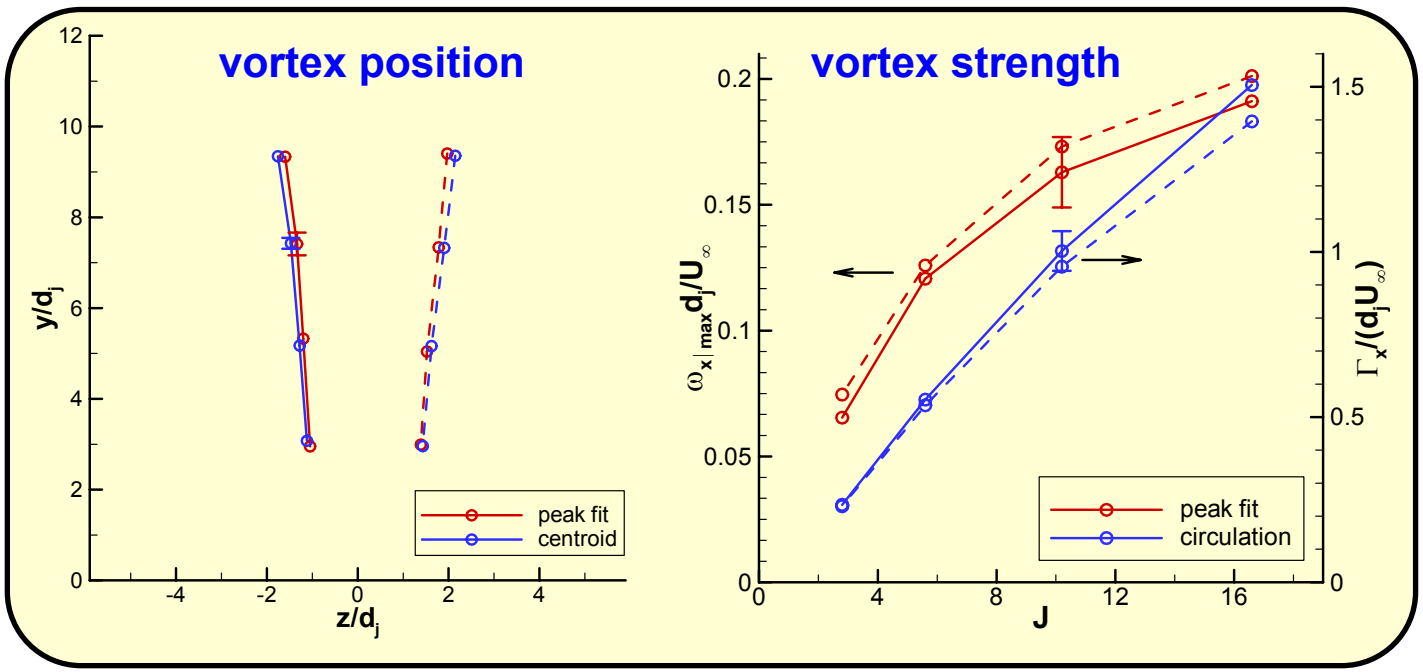
Data Analysis



M_∞=0.8 J=2.8 J=5.6 J=10.2 J=16.7

data reveal vortex characteristics

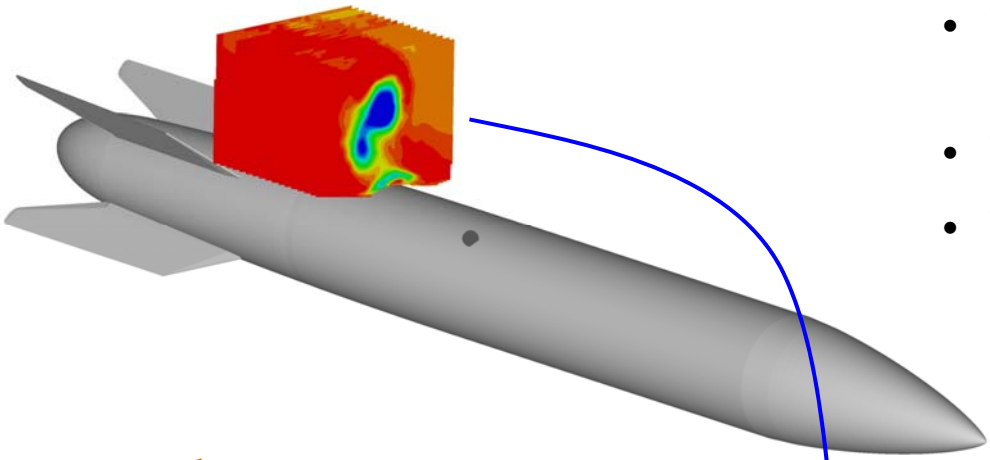


Data such as these are used to:

- **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



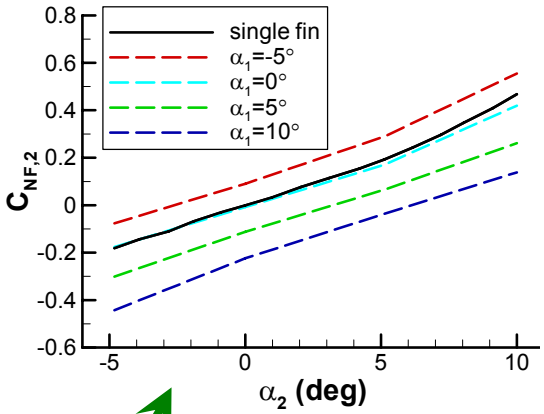
stretch x-axis for clarity

streamwise velocity component is shown

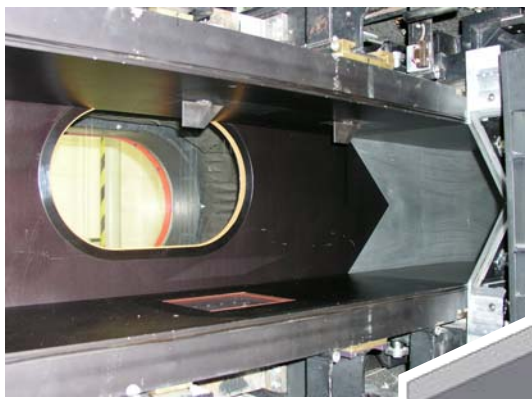
Fin Wake Interactions

We can apply similar technologies to solving other problems….

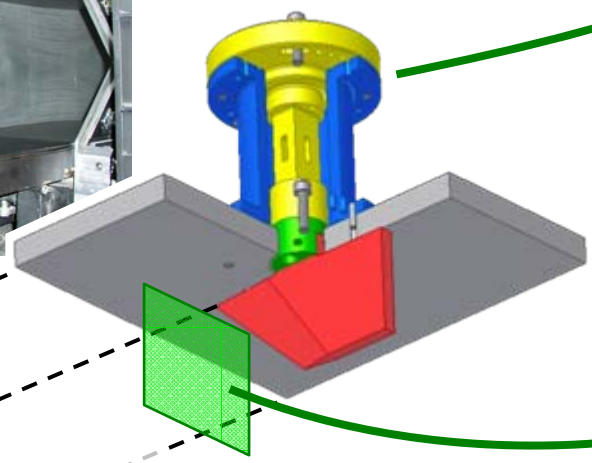
- Vehicles with two sets of fins experience an interaction that dramatically alters aerodynamic control.
- We have neither the knowledge base nor the modeling capability to accurately predict these effects.



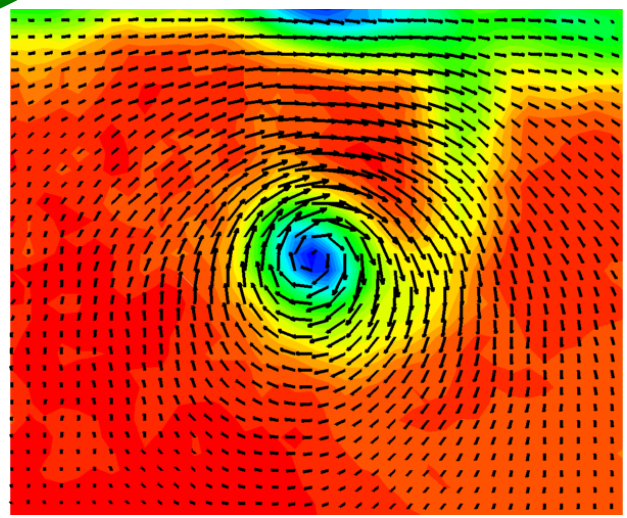
The balance measures the aerodynamics of the interaction...



A fin balance is behind one test section wall…



…and a second fin is mounted upstream.



…and PIV measures the fin tip vortex responsible for the altered aerodynamics.

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Hypersonics Research

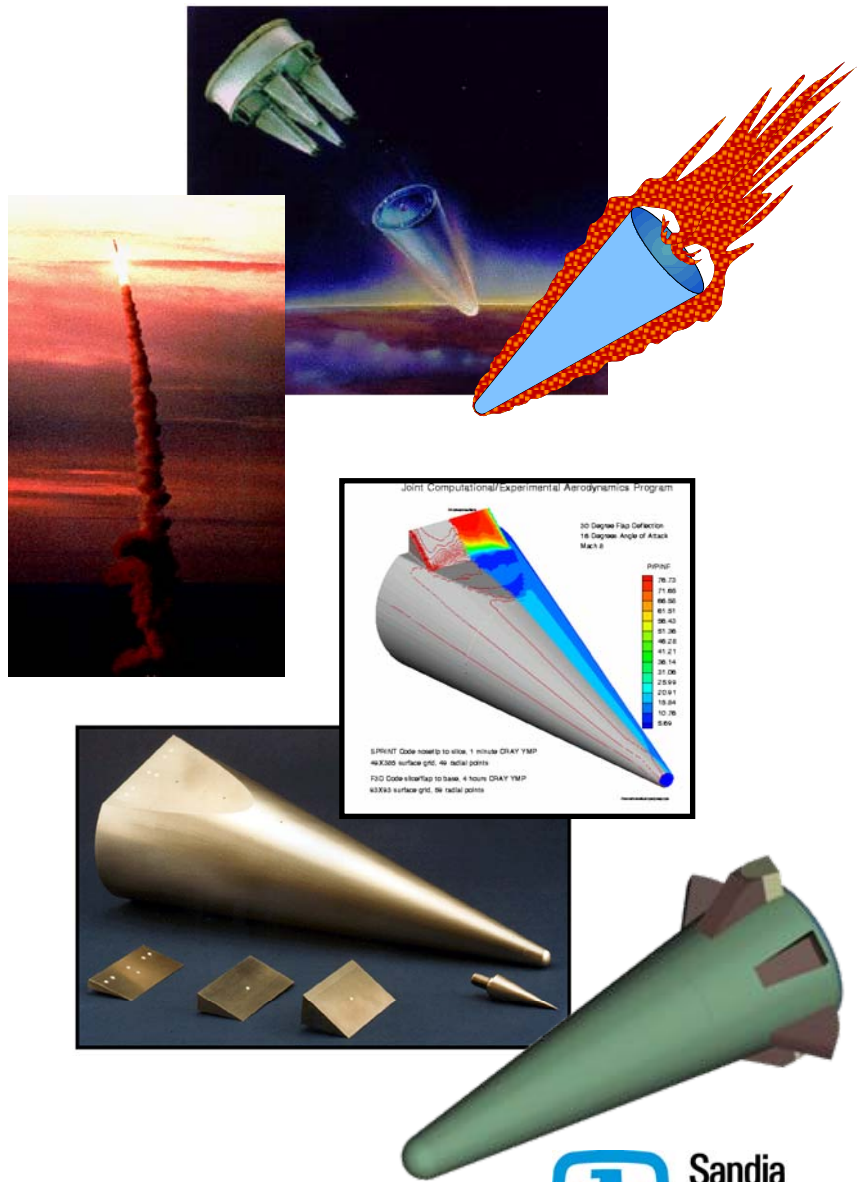
We also apply these technologies to hypersonics programs supporting Sandia re-entry vehicles.

Sandia has numerous hypersonic responsibilities:

- Ballistic re-entry vehicle dynamics
- Component performance due to aerothermodynamic environment
- Thermal protection systems

Current experimental hypersonic studies:

- Aerodynamic force and moment testing
- Unsteady pressure loading on RV's
- Control surfaces and maneuvering RV's
- Assessment of techniques for low-temperature ablation studies in the HWT



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Advanced Measurements for RV Physics

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

- At an earlier state of development for the HWT as compared to the TWT.
- Requires techniques applicable to the harsh environment of hypersonic flow.

Laser Rayleigh Scattering

- Flow visualization of shock waves, boundary layers, and wakes

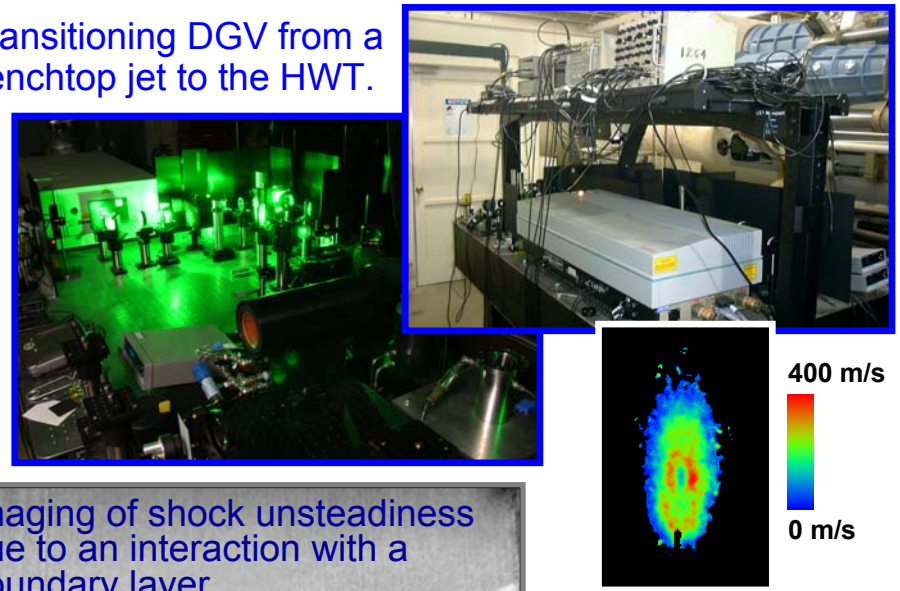
Doppler Global Velocimetry (DGV)

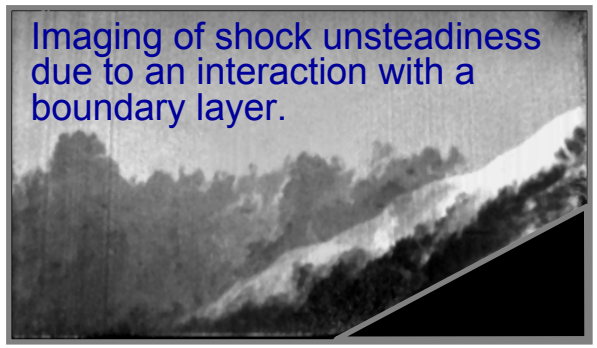
- Particle-based methods (PIV, LDV) are unsuitable for hypersonics

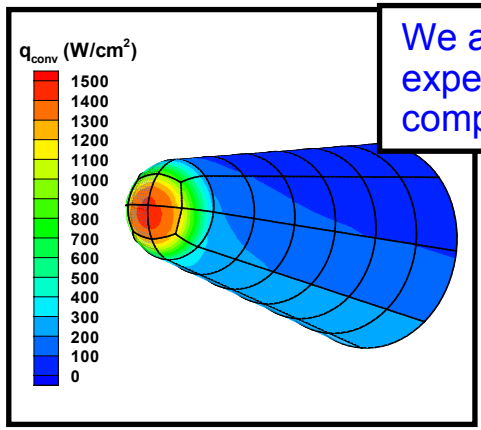
Pressure and Temperature Sensitive Paints (PSP & TSP)

- Measure loading and heating over re-entry bodies, including control surfaces.

Transitioning DGV from a benchtop jet to the HWT.







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

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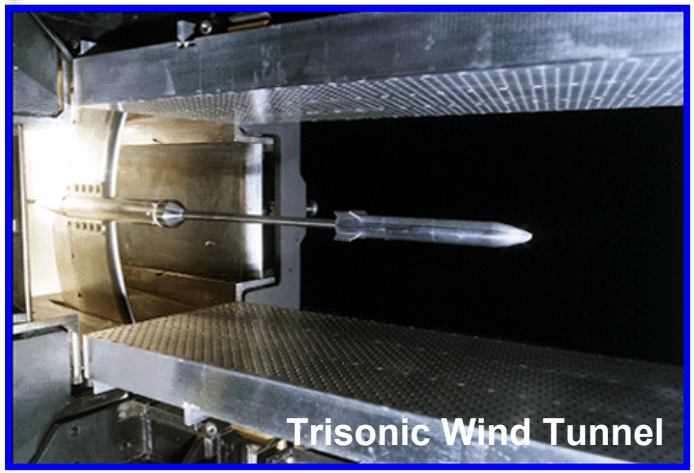
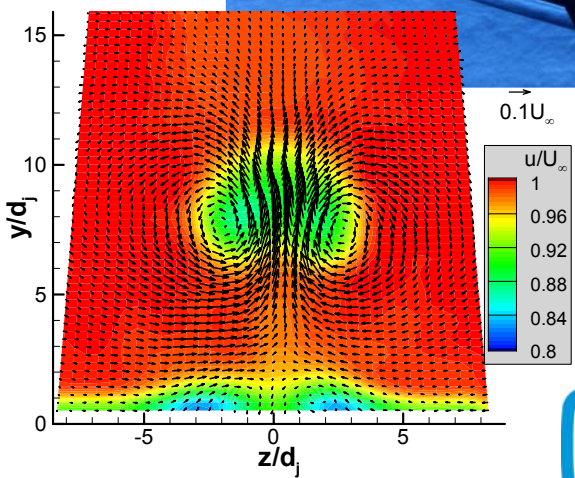
Summary





Sandia's wind tunnels:

- Cover the flight regime pertinent to DOE's defense responsibilities
- Provide aerodynamic characterization of flight vehicles
- Apply advanced diagnostics for measuring the underlying fluid dynamics
- Interact with facilities at NASA, DoD, and internationally to advance technologies

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