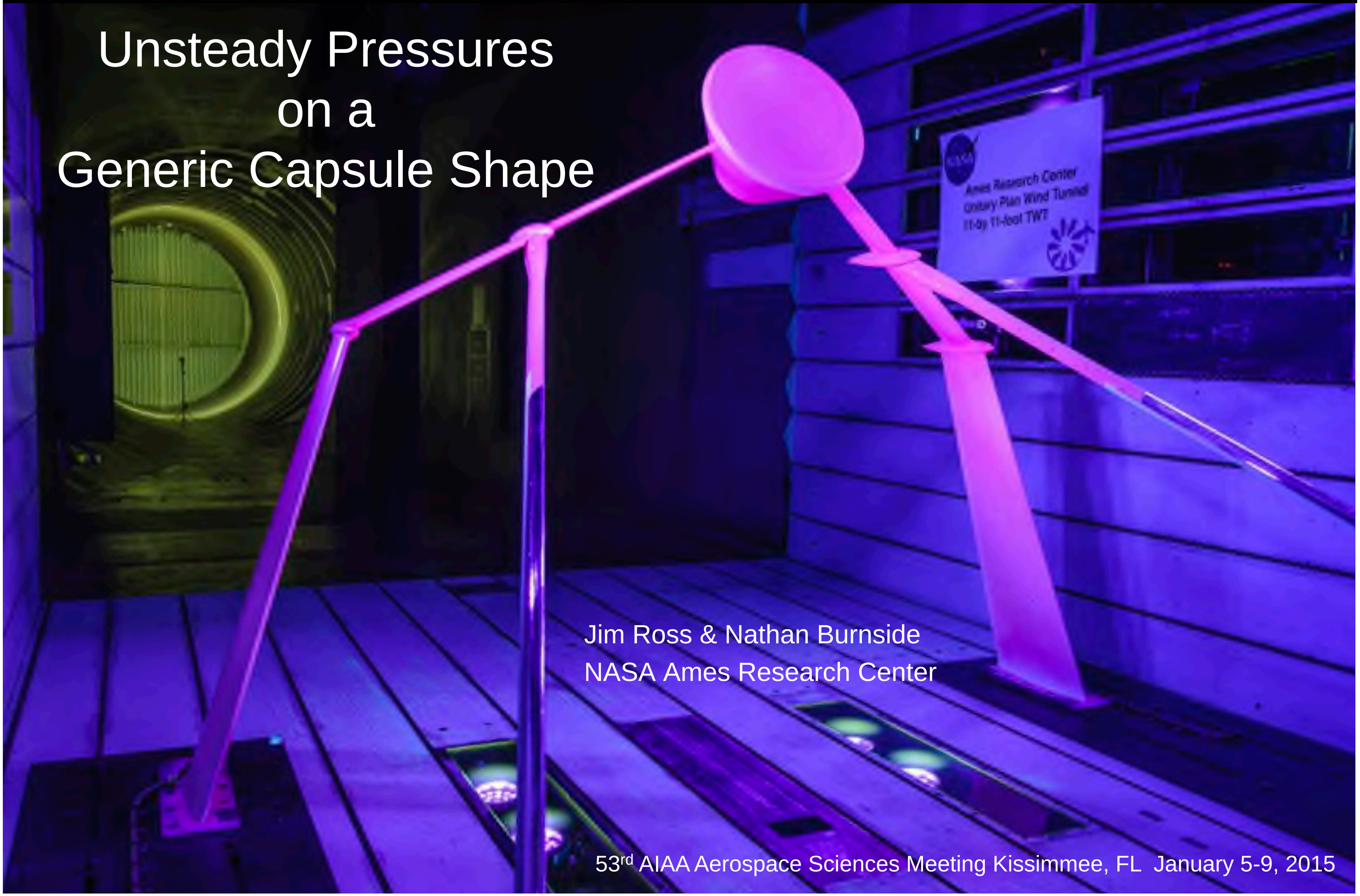
# Unsteady Pressures on a Generic Capsule Shape

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53rd AIAA Aerospace Sciences Meeting Kissimmee, FL January 5-9, 2015

# Outline

- Background
- Test Objectives
- Test Description
  - Model design
  - Instrumentation
  - Flow conditions tested
- Unsteady Pressure Processing
- Selected Results
- Concluding Remarks

# Background

- Agreement between CFD and experiments for Orion CM was poor below Mach 0.7
  - Uncertainty in the CFD-determined capsule flow
  - Wind-tunnel and CFD did not match low-M results from pad-abort flight test
- Wind-tunnel testing of Orion showed boundary-layer state on heat shield significantly affected CM aerodynamics
  - Reynolds number sensitive for Mach numbers below about 0.7
  - Method of tripping flow also had an effect on the aerodynamics
- NASA Engineering and Safety Center funded study to make measurements on and around an idealized Orion Crew Module shape
- General test overview and preliminary results
  - Ross, J. C., et al., “Comprehensive Study of the Flow Around a Simplified Orion Capsule Model,” AIAA paper 2013-2815, 31st AIAA Applied Aerodynamics Conference, San Diego, CA, June 24-27, 2013.

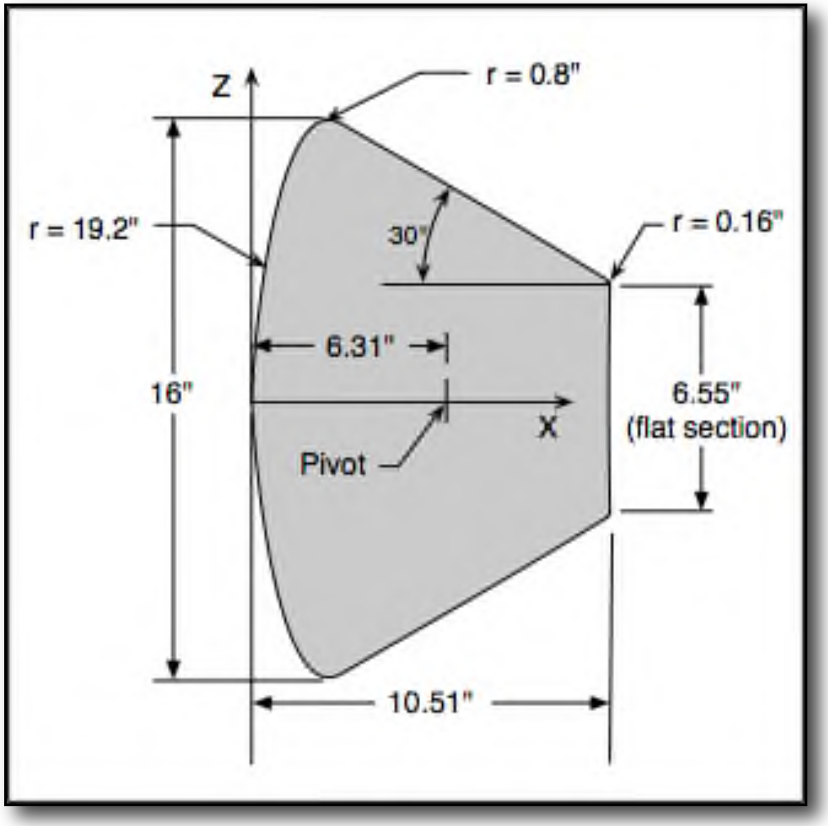
# Objectives

- Detailed characterization of the flow around a capsule shape for subsonic/transonic flight
- Document effect of heat-shield roughness
  - Post-entry Avcoat is very rough
- Comprehensive measurement suite
  - **44 Unsteady pressures around heat-shield shoulder and on back shell**
  - Wake velocity from near the capsule to ~5.5 capsule diameters downstream - Particle Image Velocimetry (PIV)
  - Detailed pressure over entire model surface - Pressure Sensitive Paint (PSP)
  - Boundary-layer transition and separation locations - IR Thermography
  - Boundary-layer profiles at one location on the heat shield
  - High-speed shadowgraph videos (6,000 frames per second)

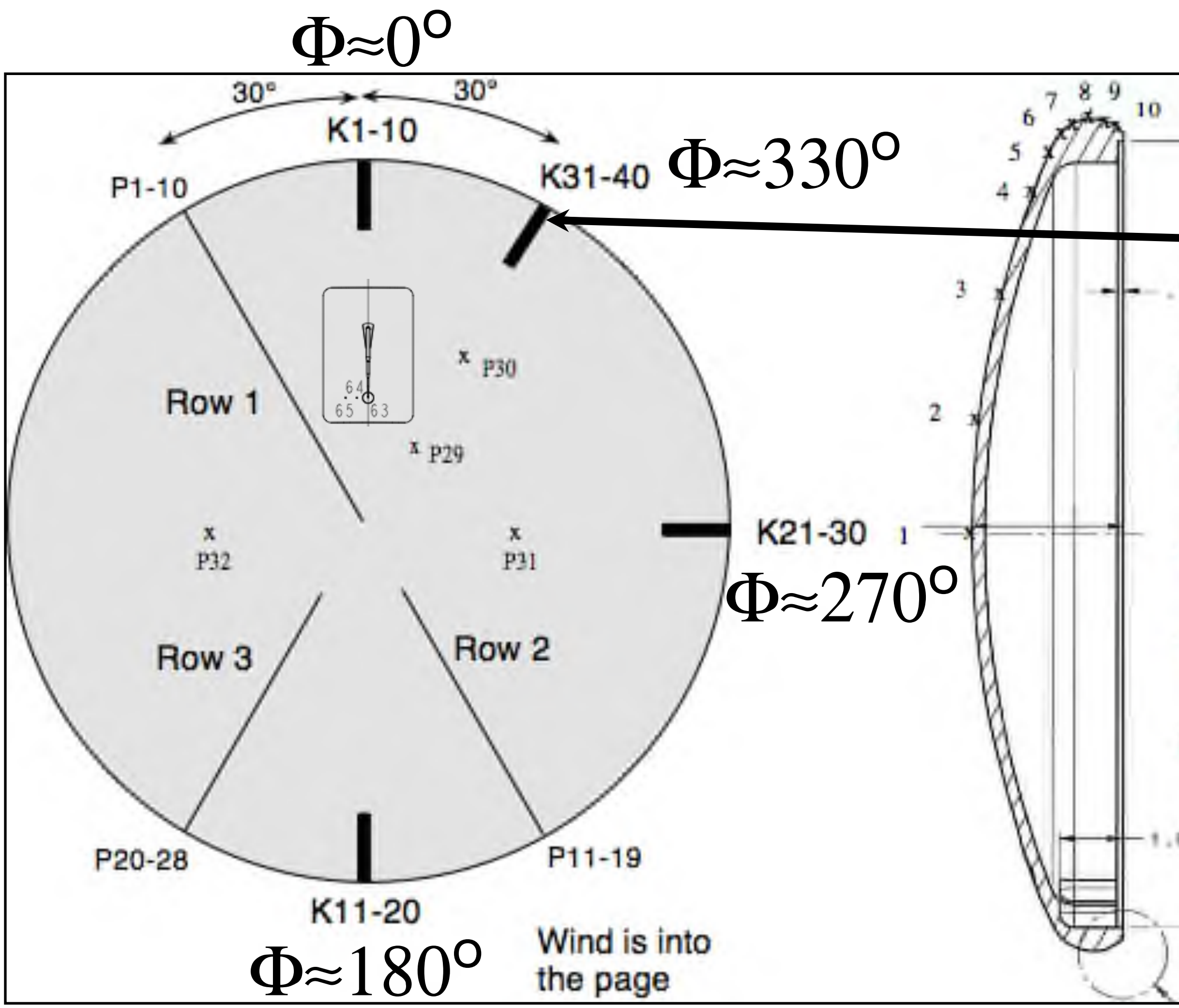
# Model Description

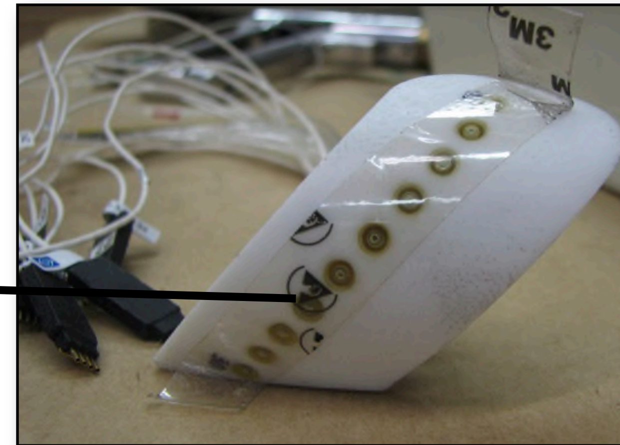
- Model is axi-symmetric based on the analytic description of the Orion CM
  - Smooth heat shield
  - Rough heat shield to represent post-entry Avcoat roughness pattern
- Struts used for support
  - Side entry to keep the strut wakes out of measurement plane
  - Stiff support to minimize model deflections and motion
  - Provide optical access for all of the cameras

Model Definition



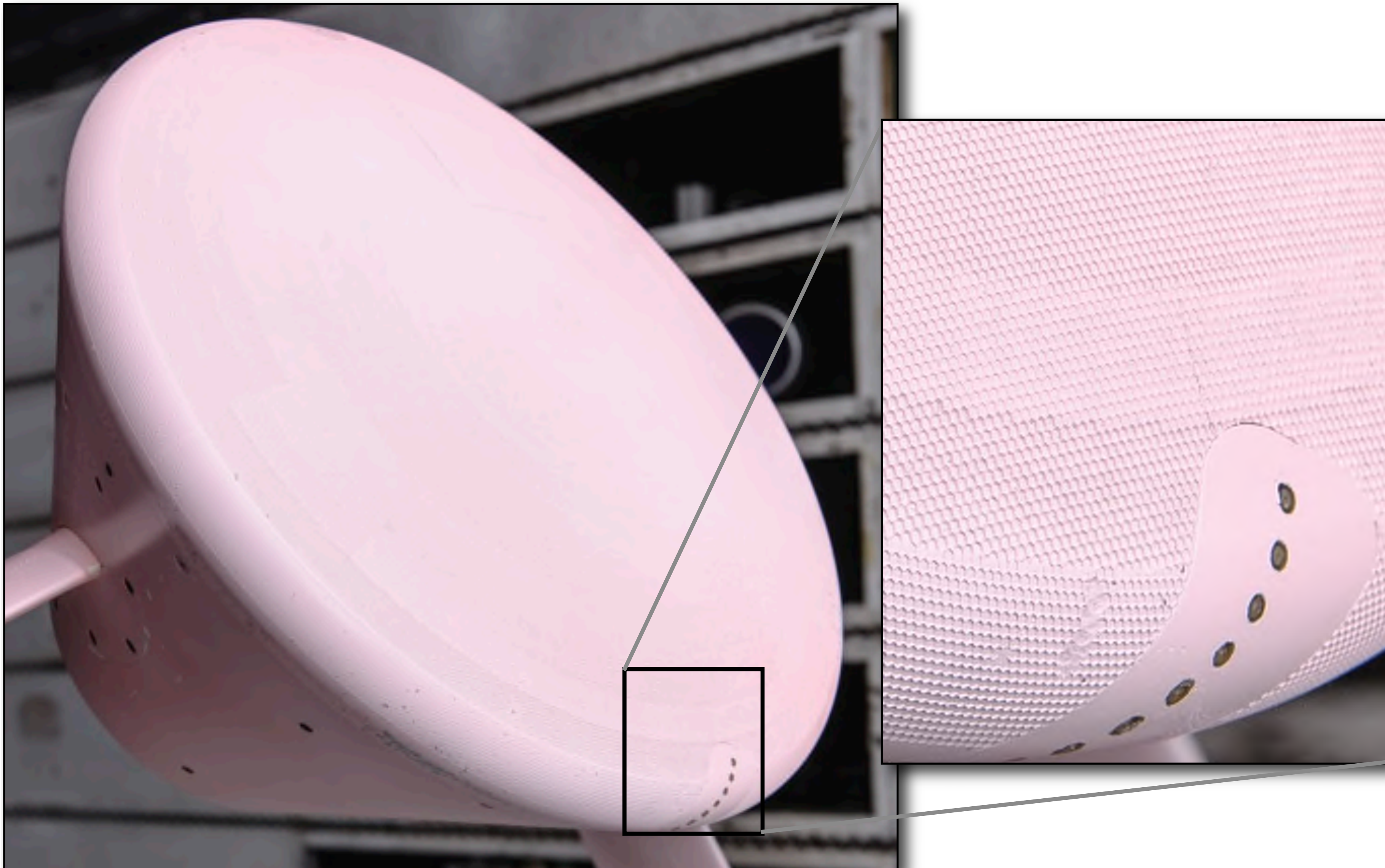
# Heat Shield Details



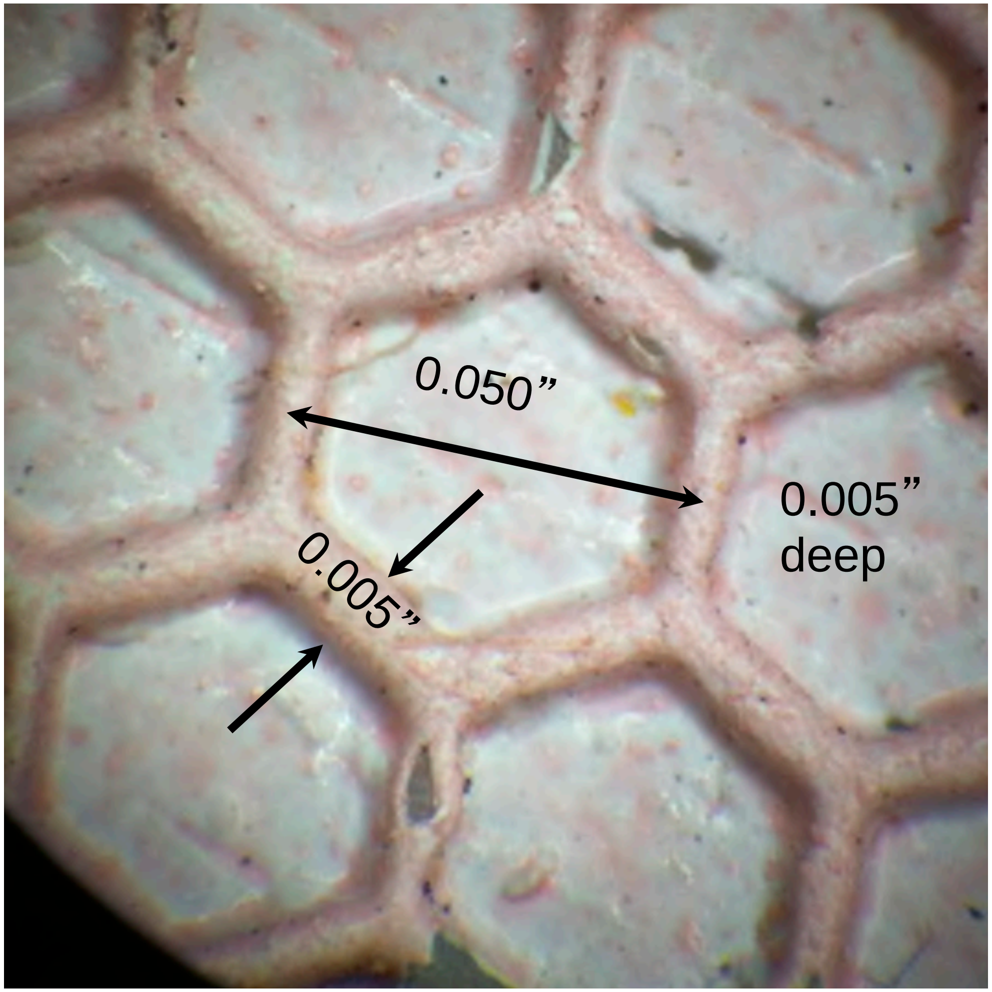
- Two-layer heat shield fabrication
  - ! ” aluminum structural layer
  - ! ” polycarbonate outer surface
- Provides enhanced IR signatures for transition/separation visualization

# Rough Heat Shield

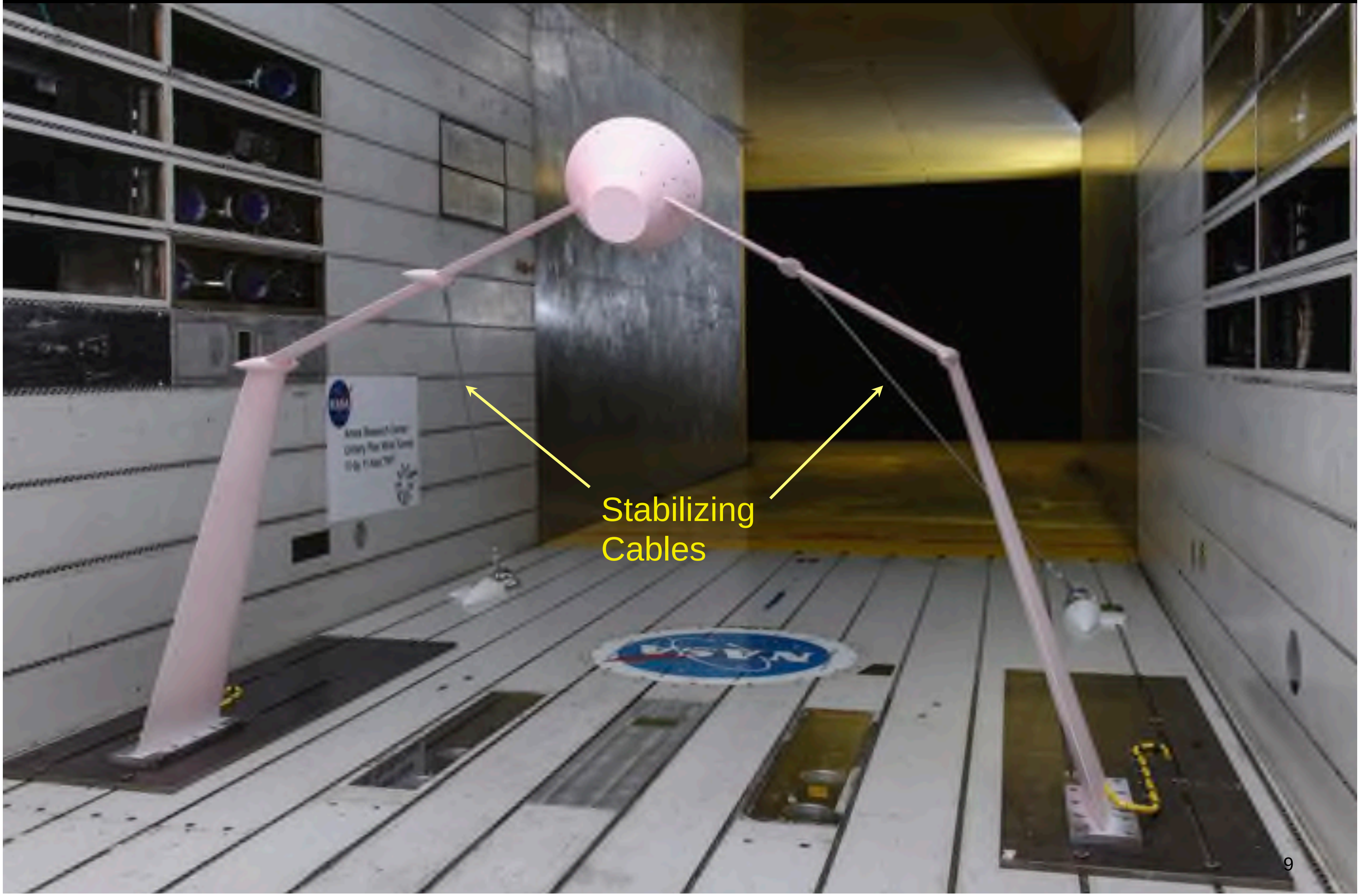


# Micrograph of Dimpling

- Hex pattern scaled from post-entry Avcoat honeycomb roughness (Orion and Apollo)
- ~75,000 dimples machined into plastic outer layer
- PSP coating ~0.002” thick



# Tunnel Installation



# Test Conditions for Various Measurements

### PSP, IR Thermography, Unsteady Pressures, Shadowgraph

| Heat Shield | Angle of Attack | Mach 0.3 | Mach 0.5 | Mach 0.7 | Mach 0.9 | Mach 1.05 |
|---|---|---|---|---|---|---|
| Smooth | 30° | | | 1.3x10$^{6}$ | | 1.3x10$^{6}$ |
| Smooth | 30° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | 10x10$^{6}$ | 6.6x10$^{6}$ |
| Rough | 15° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | 10x10$^{6}$ | 6.6x10$^{6}$ |
| Rough | 30° | | | 1.3x10$^{6}$ | | 1.3x10$^{6}$ |
| Rough | 30° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | 10x10$^{6}$ | 6.6x10$^{6}$ |

### Boundary-Layer Surveys, Skin Friction, IR Thermography

| Heat Shield | Angle of Attack | Mach 0.3 | Mach 0.5 | Mach 0.7 | Mach 0.9 | Mach 1.05 |
|---|---|---|---|---|---|---|
| Rough | 0° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | | |
| Rough | 15° | 5.3x10$^{6}$ | | 10x10$^{6}$ | | 6.6x10$^{6}$ |
| Rough | 30° | 5.3x10$^{6}$ | | 10x10$^{6}$ | | 6.6x10$^{6}$ |

### PIV, Unsteady Pressures, Shadowgraph - Rough heat shield

| Model Position | Angle of Attack | Mach 0.3 | Mach 0.5 | Mach 0.7 | Mach 0.9 | Mach 1.05 |
|---|---|---|---|---|---|---|
| Downstream | 15° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | | |
| Upstream | 15° | 5.3x10$^{6}$ | 8.7x10$^{6}$ | 10x10$^{6}$ | | |

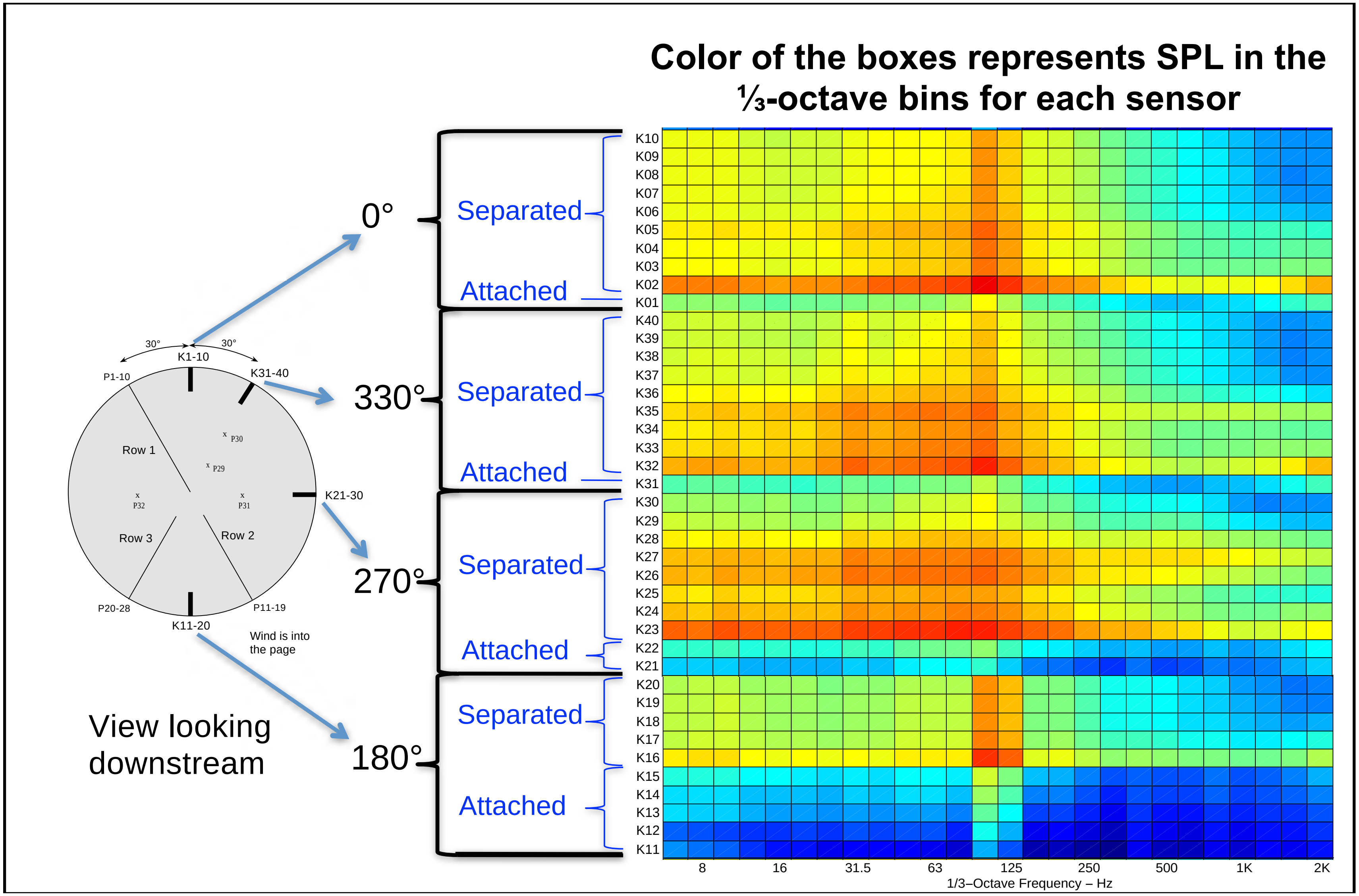
Numbers in green boxes indicate Reynolds number tested

Black boxes indicate conditions not tested

# Unsteady Processing Parameters

- Sample rate of 6400 samples / sec
  - 2.5 kHz bandwidth
- 4096 point FFT
- 25% overlap
- Energy corrected Hanning window
- 30 to 50 averages
- Cp’ spectra
  - dB = 20 $\log_{10}$(Cp’)

# Separation
# Rough Heat Shield, M 0.7, "  = 30°, $Re_D = 10x10^6$



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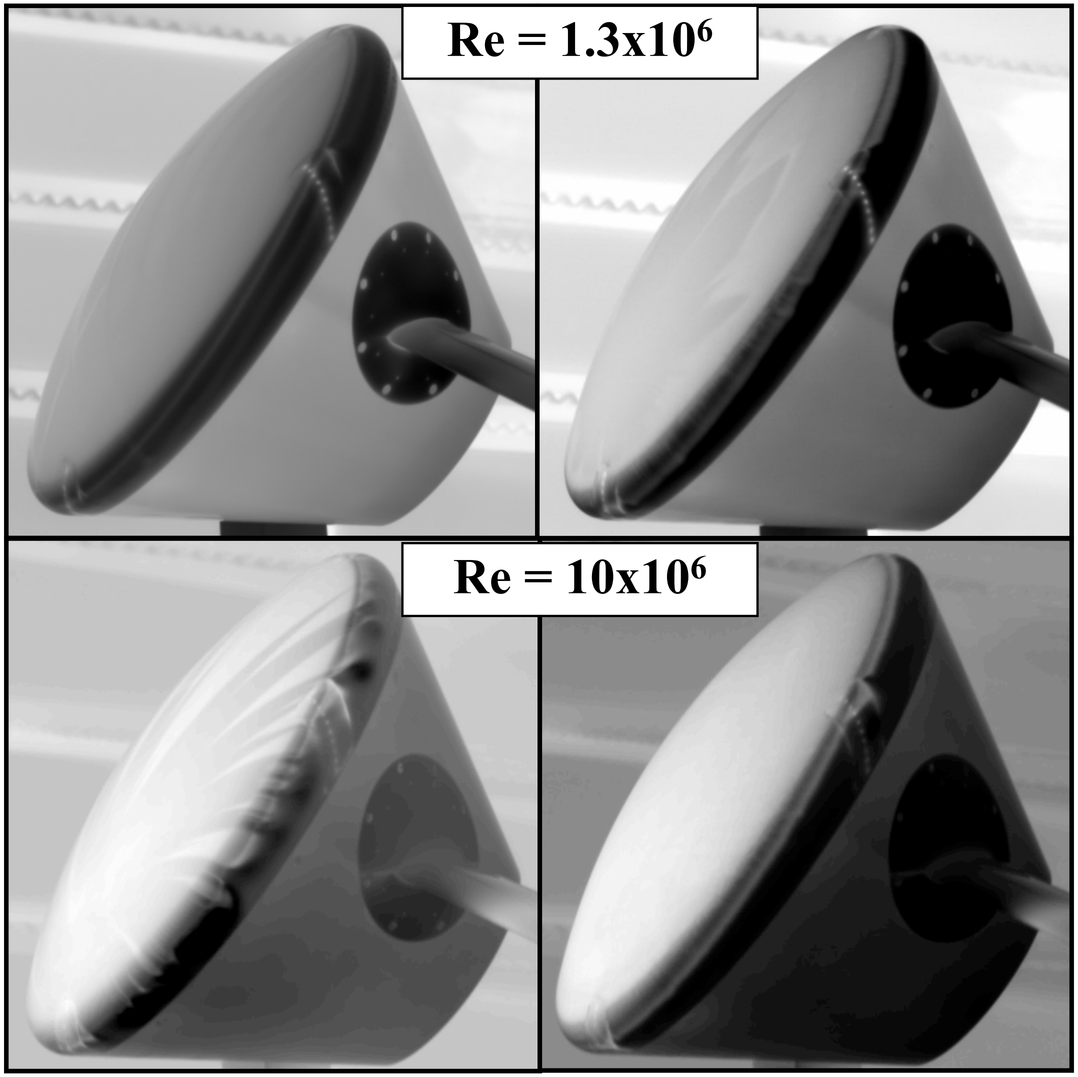
# Effect of Heat Shield Roughness on Capsule Flow
## M = 0.7, " = 30°, $Re_D = 10x10^6$

Laminar

Transitional



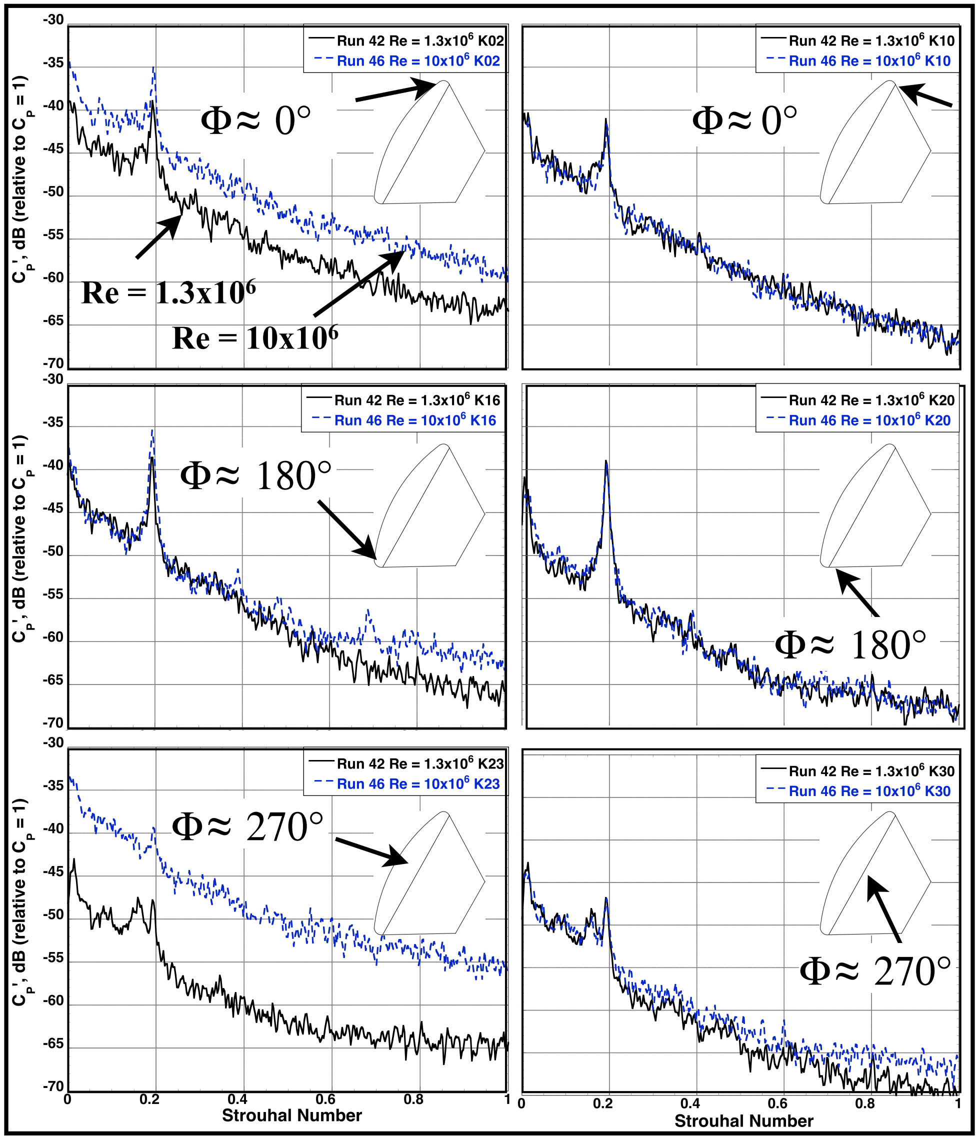

Transitional

Turbulent

**Smooth heat shield** **Rough heat shield**

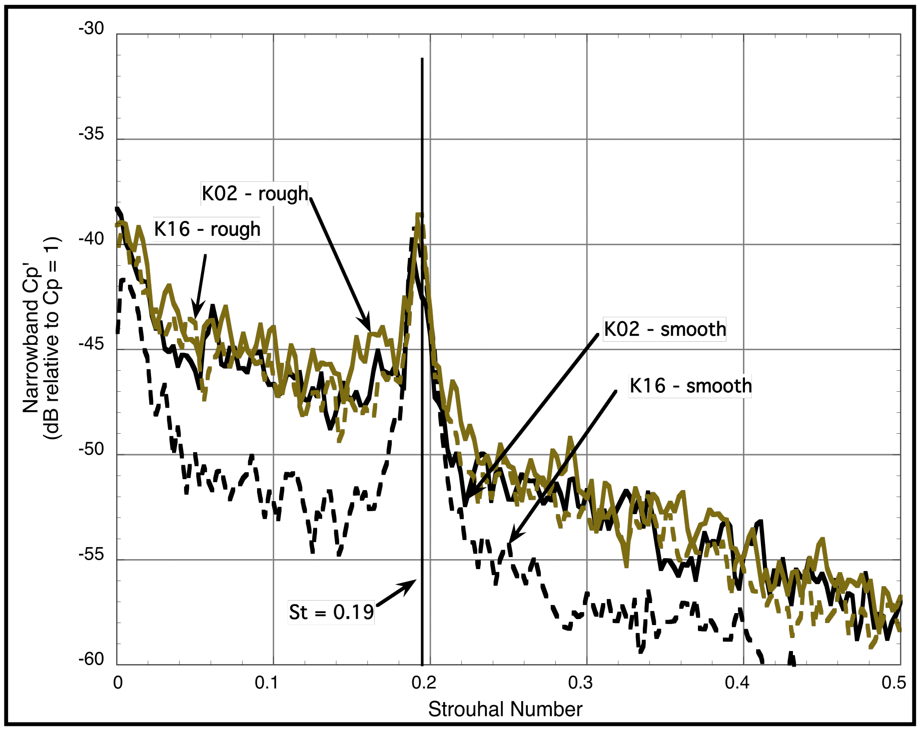
# Effect of Reynolds Number on Spectral Amplitude
# M = 0.7, " = 30°

Before Separation | After Separation

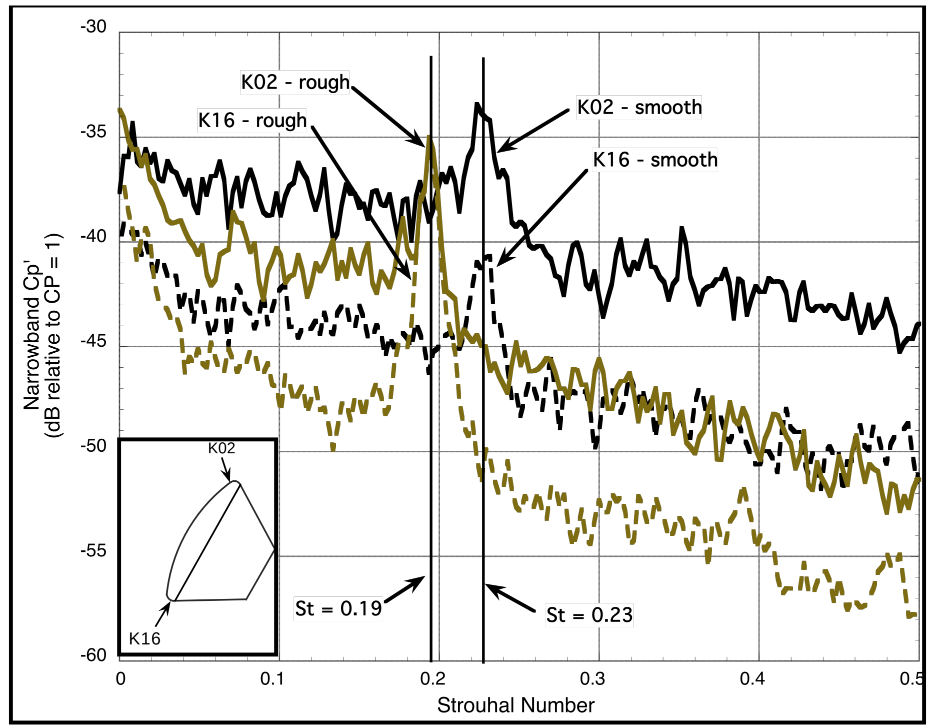


# Effect of Reynolds Number on Shedding Frequency
## M = 0.7, " = 30°

$Re_D = 1.3 \times 10^6$



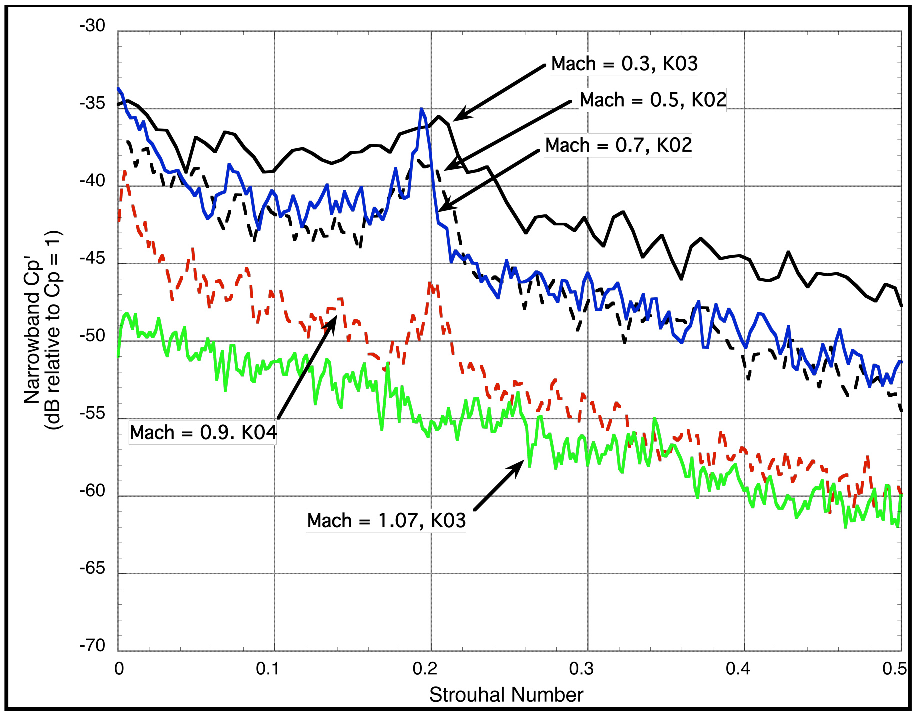

$Re_D = 10 \times 10^6$



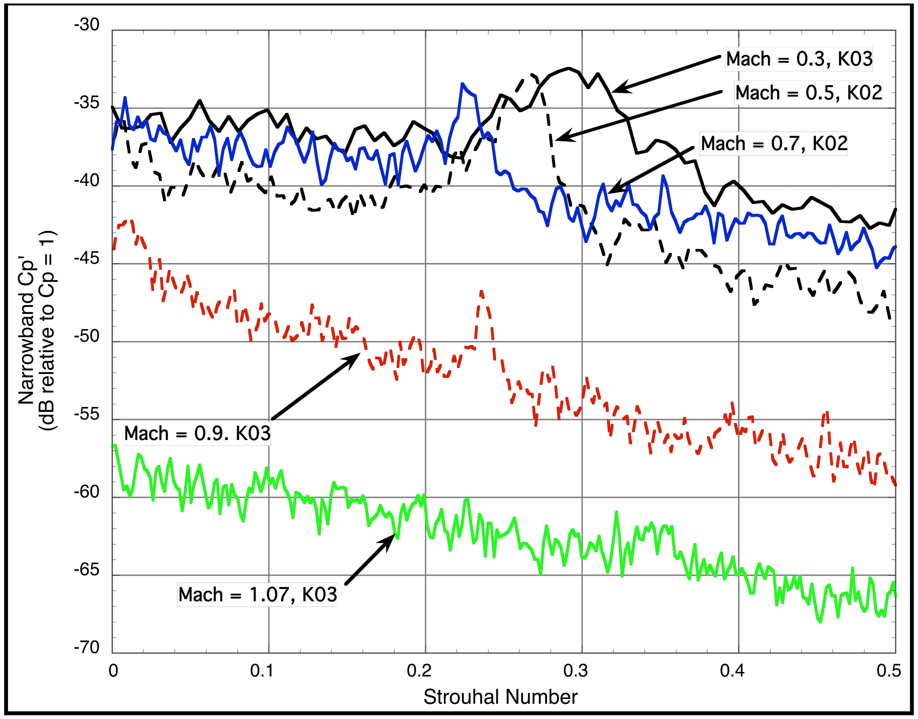

Shih, W.C.L., Wang, C., Coles, D., and Roshko, A., "Experiments on Flow Past Rough Circular Cylinders at Large Reynolds Numbers," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 49, pp. 351-368, 1993.

# Effect of Mach Number on Shedding Spectra
" = 30°, # = 0, High Re

## Rough

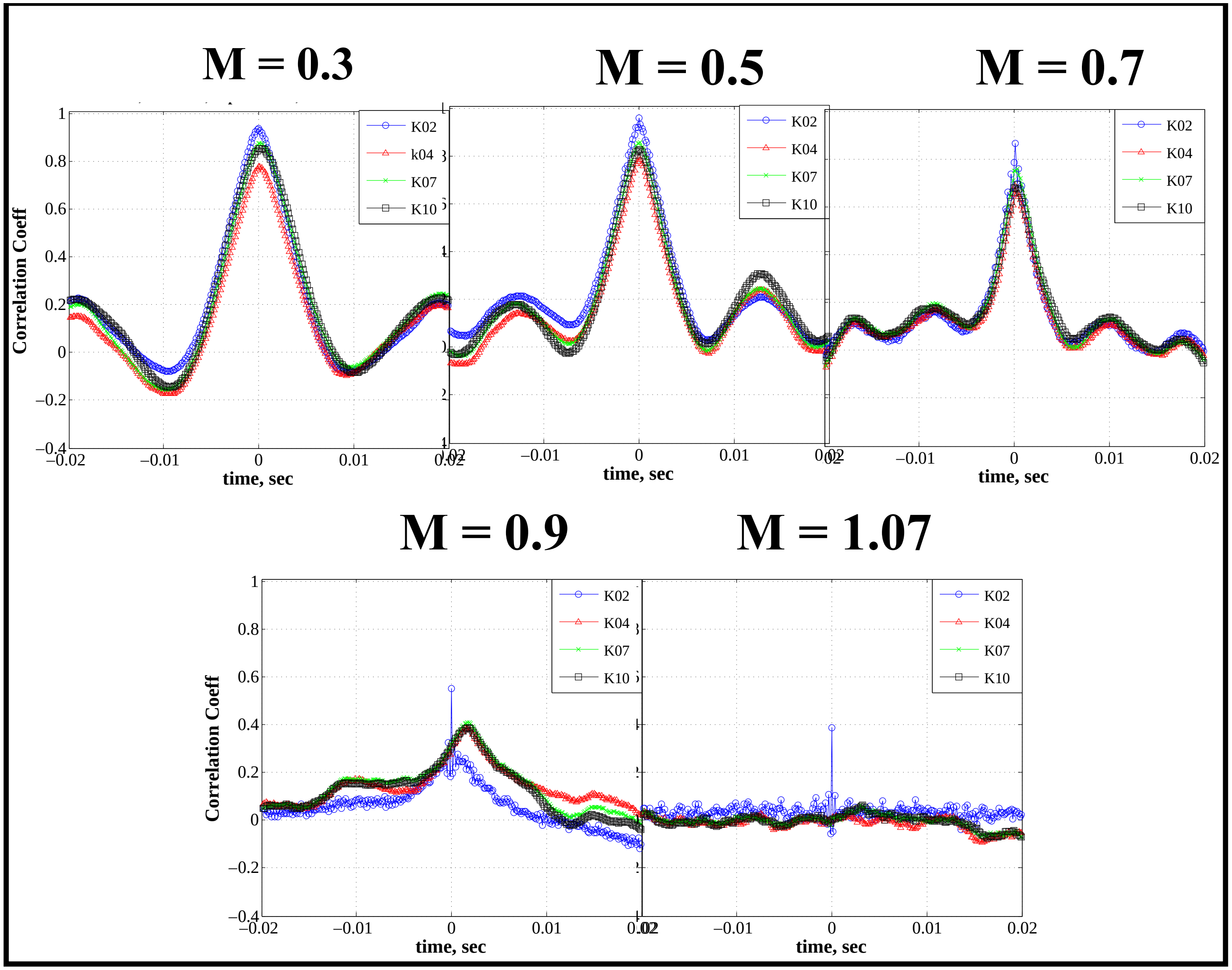



## Smooth

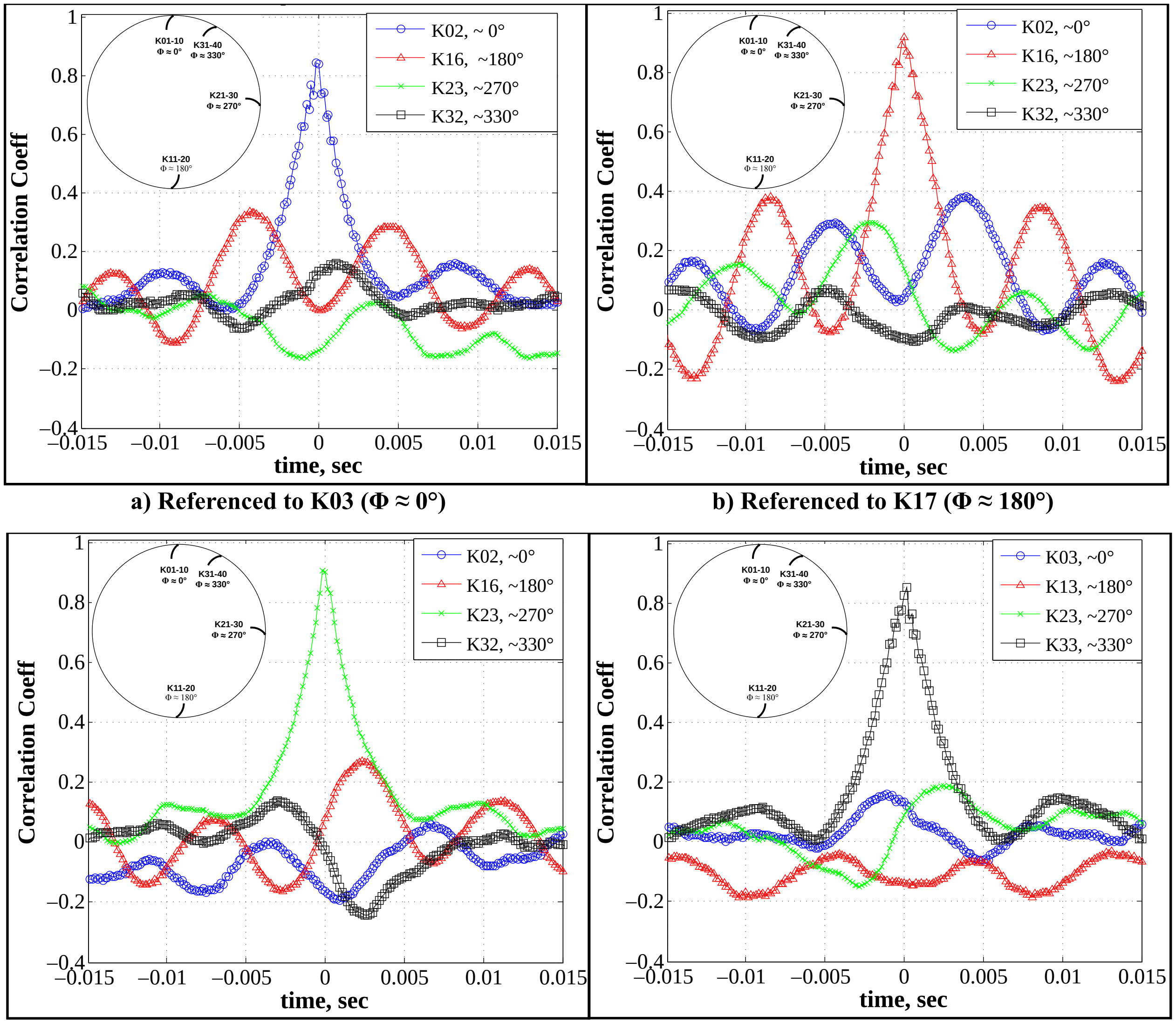


# Effect of Mach Number on Azimuthal Correlation
# " = 30°, High Re, Rough Heat Shield

## Referenced to K01



# Helical Shedding Mode
# M = 0.7, "  = 30°, $Re_D = 10x10^6$, Rough Heat Shield




a) Referenced to K03 (Φ ≈ 0°)

b) Referenced to K17 (Φ ≈ 180°)

c) Referenced to K24 (Φ ≈ 270°)

d) Referenced to K33 (Φ ≈ 330°)

# Summary

- Comprehensive data set now available of flow around generic capsule at variety of subsonic/transonic conditions
- Unsteady pressure results
  - Spectra is a good indicator of separation
  - Spectra is Reynolds dependent
  - Shedding frequency shifts for rough heat shield at high Re
  - Capsule is more stable at higher Mach
  - Helical shedding is similar to CFD results