Baseball Aerodynamics and Unsteady, High-Fidelity CFD

Brent Pomeroy

NASA Langley Research Center

Configuration Aerodynamics Branch

brent.w.pomeroy@nasa.gov

Boeing CFD Community of Excellence Lecture Series
May 5, 2023

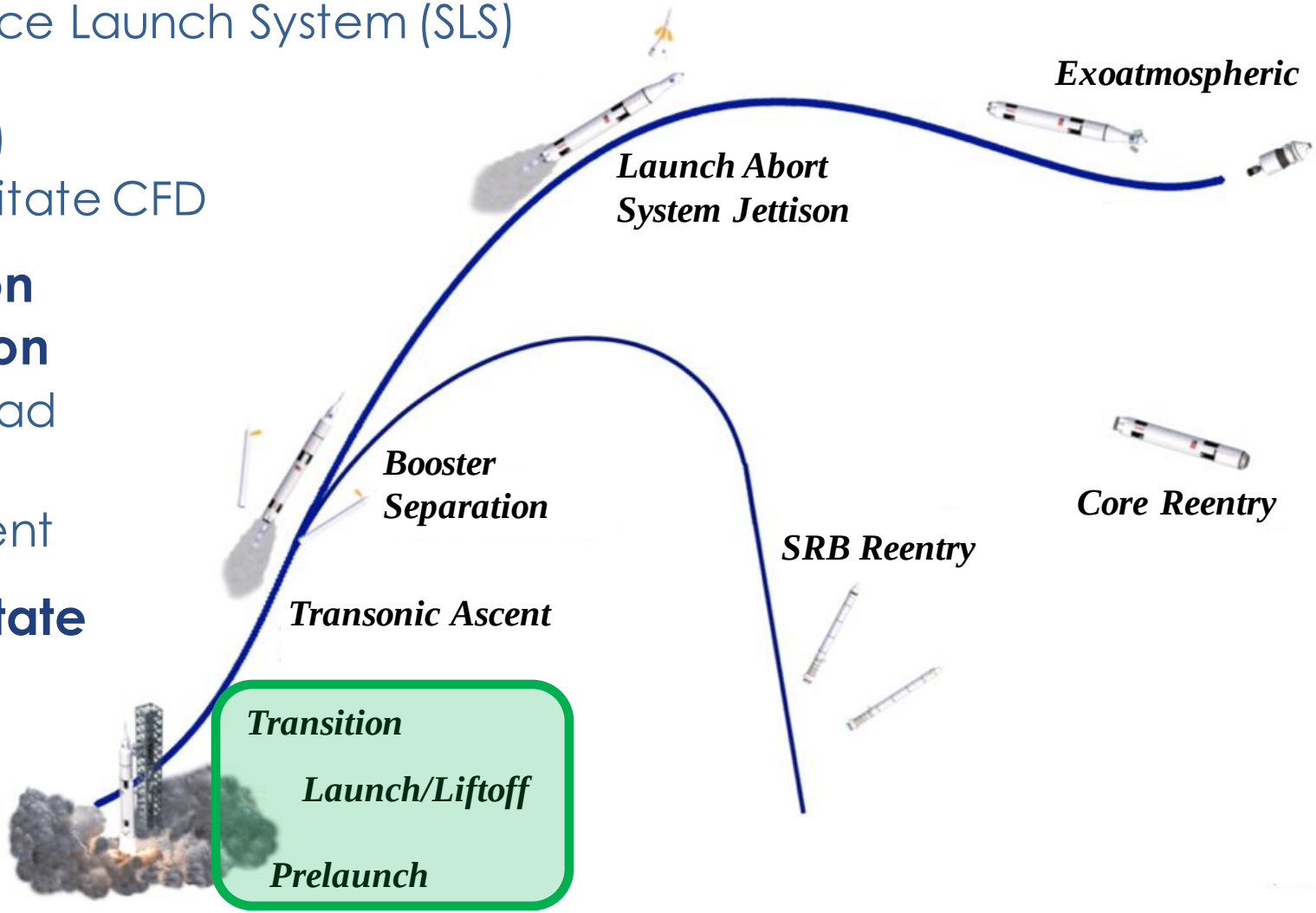
Outline



- **Motivation and Application to the Space Launch System**
- **Baseball Geometry and Grid**
- **Computational Methods**
- **Flight Characteristics of Baseball**
  - Knuckleball
  - Prescribed rotation
  - Six Degree of Freedom (6-DOF)
- **Conclusions**

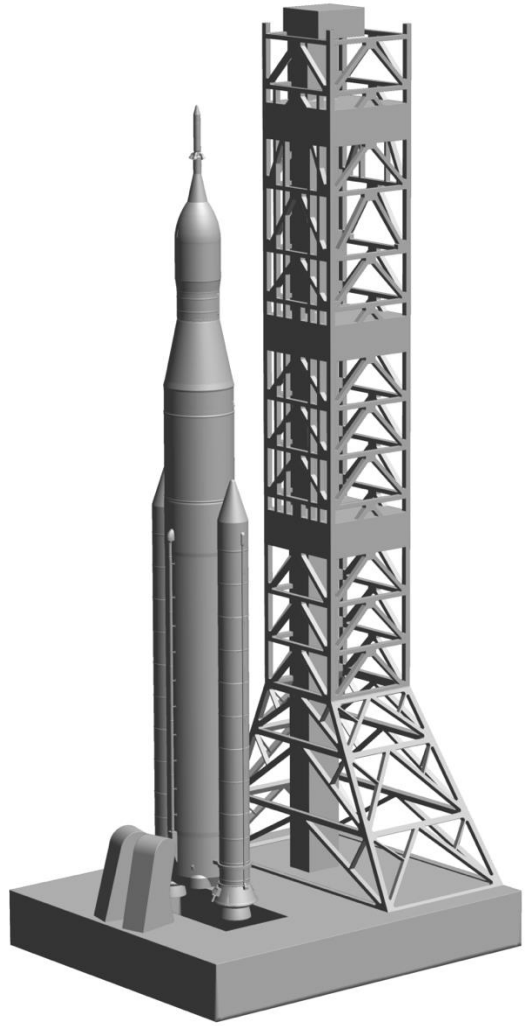
Motivation

- **High-fidelity computations are actively performed at NASA Langley**
  - Low-speed portion of the Space Launch System (SLS) mission profile
  - Massive separation (> 90 deg)
  - Program requirements necessitate CFD
- **Langley CFD efforts focused on the early portions of the mission**
  - Rocket static on the launch pad
  - In proximity of the tower
  - Above the tower, before ascent
- **Challenging computational state**



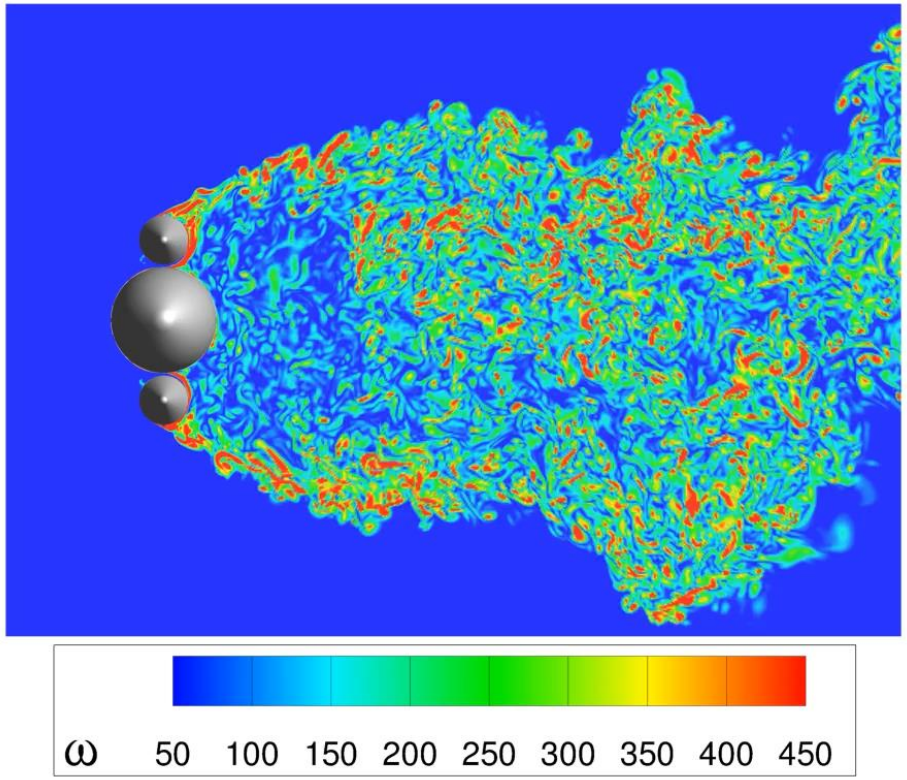
SLS Low-Speed Flight Regime

- **Prelaunch**
  - Begins when vehicle exits the Vehicle Assembly Building
  - Can last for numerous weeks



SLS Low-Speed Flight Regime

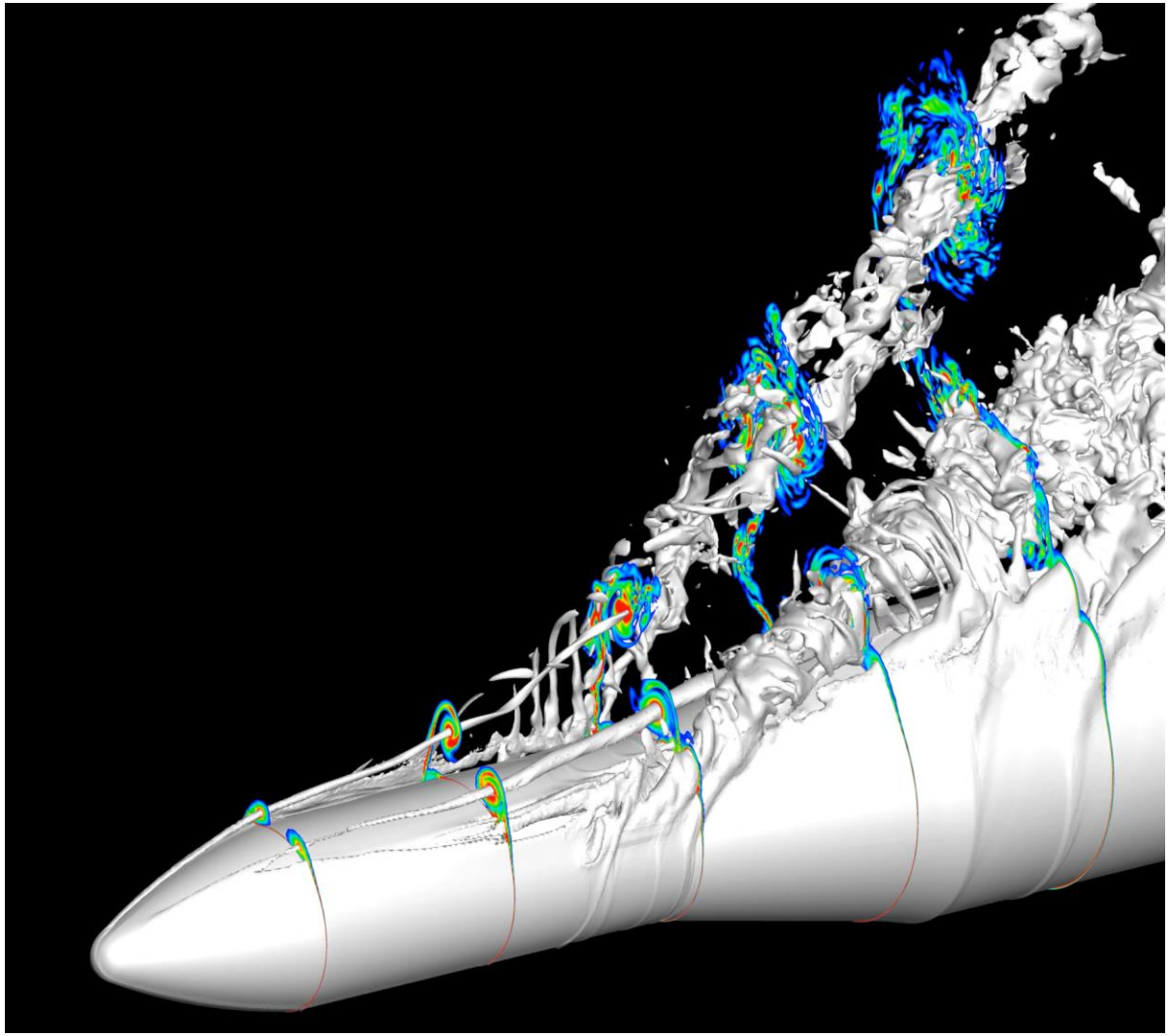
- **Prelaunch**
  - Begins when vehicle exits the Vehicle Assembly Building
  - Can last for numerous weeks
- **Liftoff and Transition Near Tower**
  - Vehicle stationed on launch pad
  - Freestream alpha from 0 to 90 deg
  - Roll angle from 0 to 360 deg



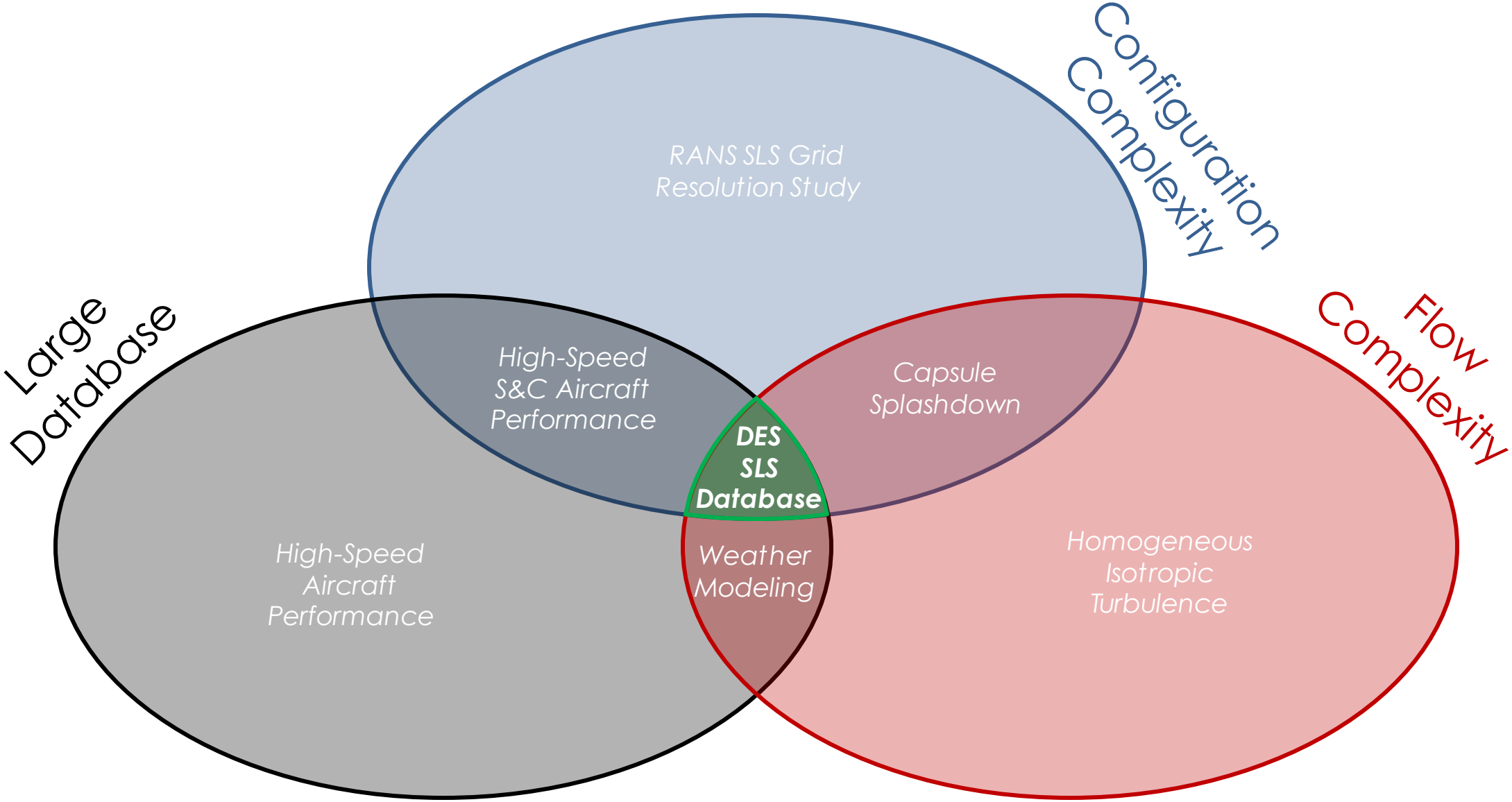
Representative SLS-type launch vehicle at liftoff conditions

SLS Low-Speed Flight Regime

- **Prelaunch**
  - Begins when vehicle exits the Vehicle Assembly Building
  - Can last for numerous weeks
- **Liftoff and Transition Near Tower**
  - Vehicle stationed on launch pad
  - Freestream alpha from 0 to 90 deg
  - Roll angle from 0 to 360 deg
- **Liftoff and Transition in Isolation**
  - Begins after rocket clears the tower
  - Ends at Mach 0.3
  - Centered on the isolated vehicle
  - Angle of attack 0 to 80 deg
  - Roll angle 0 to 360 deg

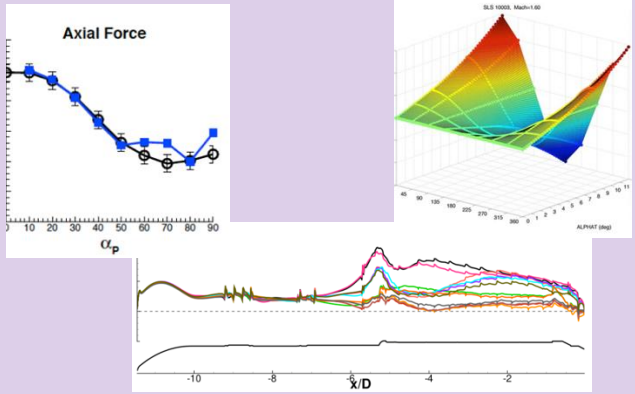


SLS Computational Complexities

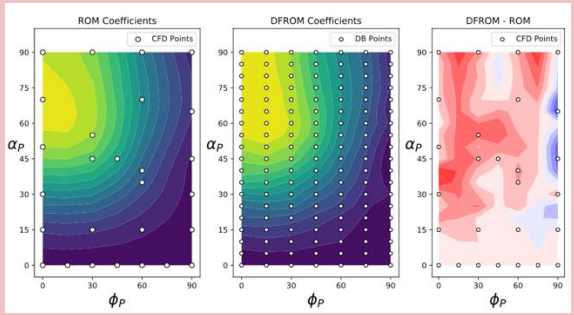


Artemis Support

Databases

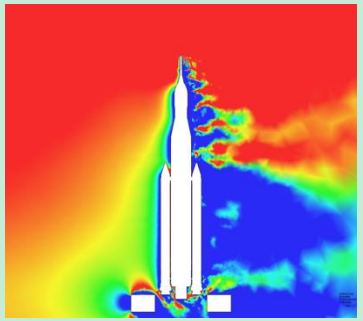


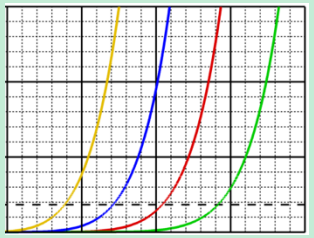
Reduced Order Modeling



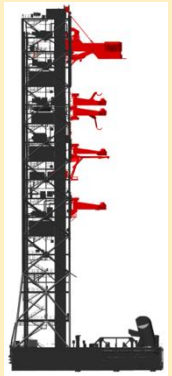
$$\frac{\partial L}{\partial \lambda_j} = \lambda_j \sum_{i=1}^{npc} \sum_{l=1}^{nvar} \hat{a}_i^l \Delta c_{i,j}^l - C_{F_j}$$

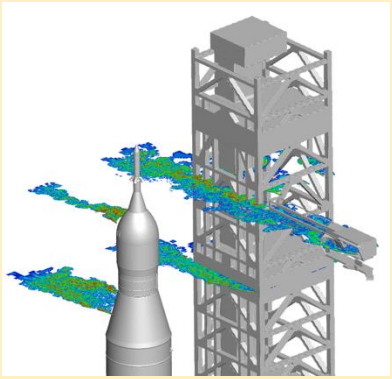
Launch Environment Effects



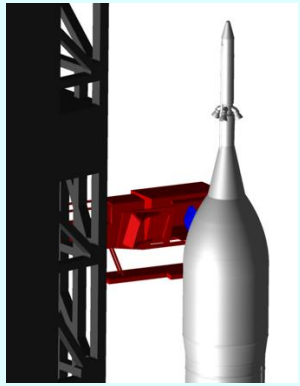


Launch Pad and Tower

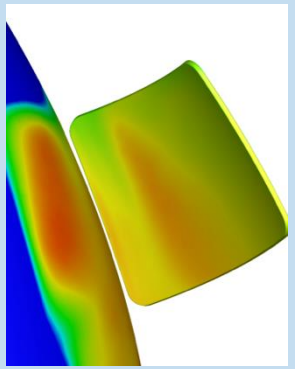


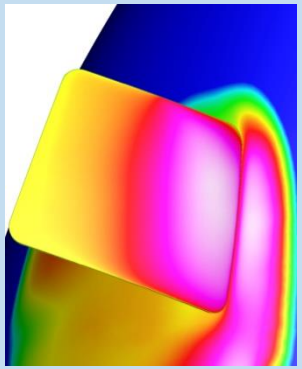


Crew Access Arm



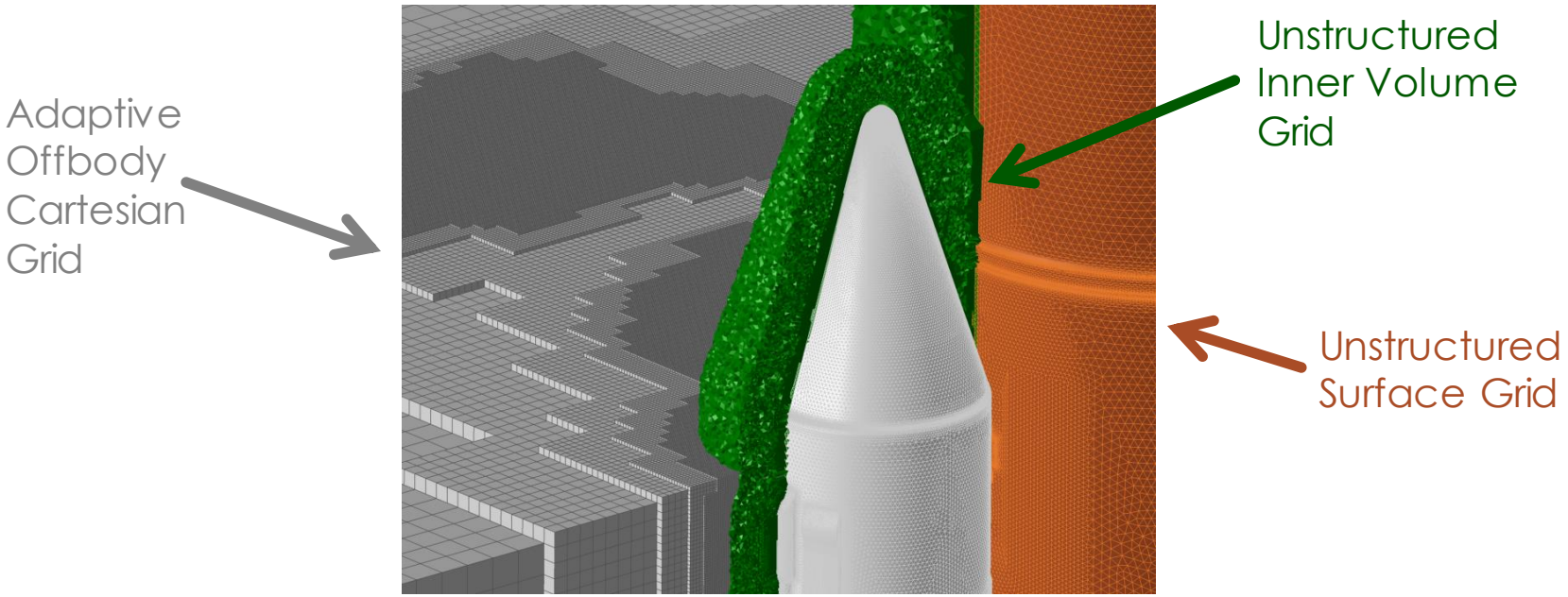
Launch Abort System Hatch





Kestrel CFD Solver

- **Computational code from Department of Defense CREATE-AV**
- **Satisfies requirements for database-level low-speed SLS CFD analysis**
  - Advanced IDDES model contributes to a high-fidelity solver
  - Inner unstructured grid and adaptive offbody Cartesian grid yields reduced cost
  - Offbody Cartesian solver is extremely fast and efficient
  - Integrates well with HeldenMesh unstructured mesh generator



Kestrel Technology Advancement

- **Kestrel contains many models**
  - Aerodynamic, propulsion, stability and control, multi species, fluid-structure interaction, and more
  - Key to DOD contract bidding process
- **Team leverages Kestrel methods in regular work**
  - IDDES (Improved Delayed Detached Eddy Simulation)
  - Adaptive mesh refinement
  - Computational efficiency
- **Desired methods development to advance computational capabilities**
  - Free transition
  - Surface roughness
  - Prescribed motion
  - Responding-body motion





Kestrel logo source: US Navy
Used with permission

Selection of Baseball

- **Not ITAR protected (good for interns)**
- **Why a baseball?**
  - Topologically simple yet yields complex aerodynamics
  - Testing of new automated geometry preparation tool
  - Availability of flight data and surface roughness measurements
- **Provides vehicle to investigate applicability of new technology to other programs**



Source: NASA

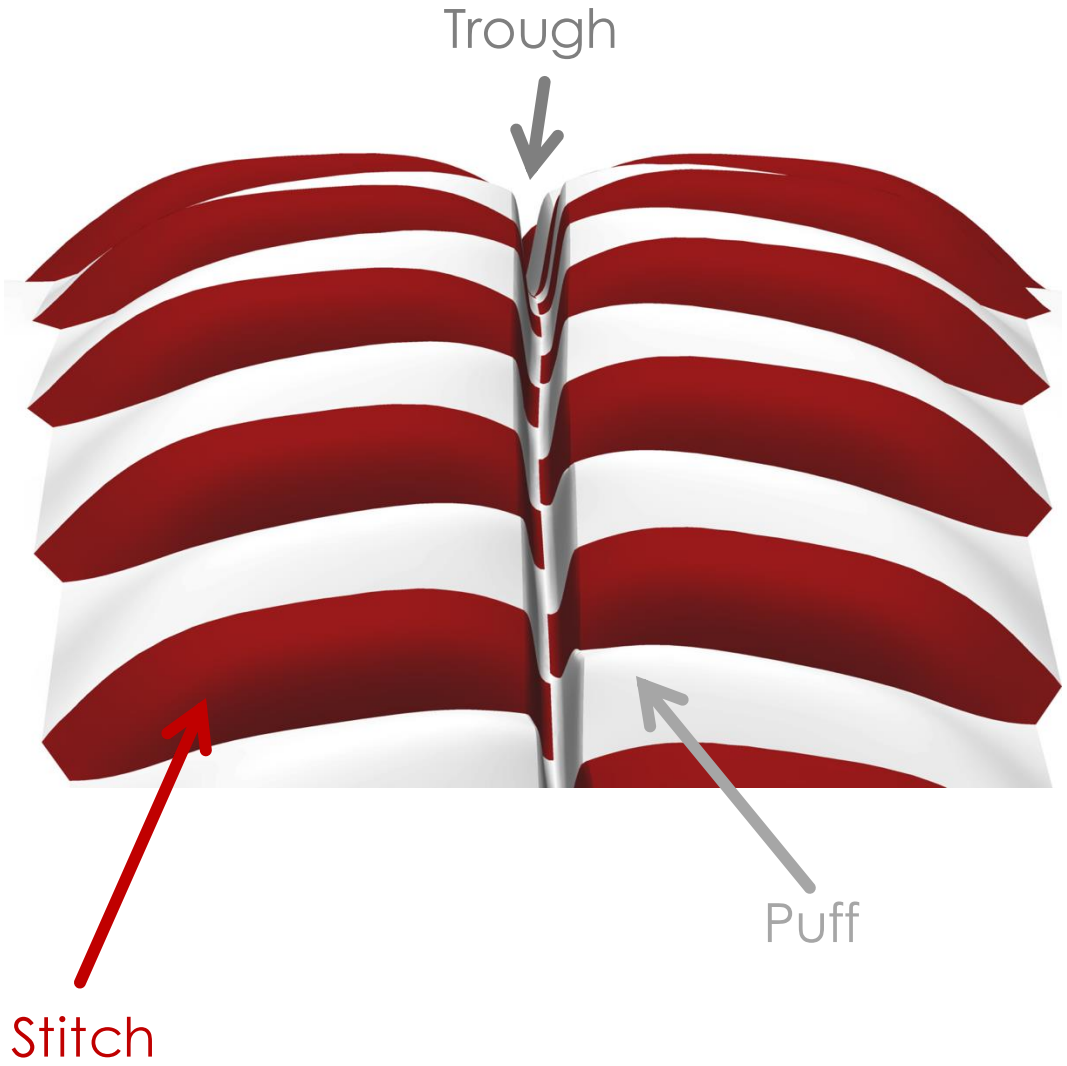
History of Baseball Geometry



- **Varying geometry over original era**
  - Differing weight, moment of inertia, materials, and other considerations
  - Efforts to reduce variability in mid 1800s
  - National League defined rules in 1876
  - Live ball era entered in 1920s
- **Standardization in 1934 largely reflects current ball**
- **Unknown inventor of stitch pattern**

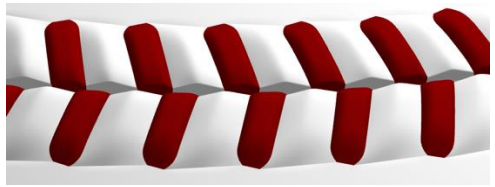
Baseball Topology

- **Made by hand by Rawlings in Costa Rica**
- **Geometry consists of a variety of features**
  - Stitches, puffs, troughs, holes, and panels
  - 108 stitches
  - Puffs previously unnamed
  - Spanwise and chordwise thickness distributions



Baseball Topology

- **Made by hand by Rawlings in Costa Rica**
- **Geometry consists of a variety of features**
  - Stitches, puffs, troughs, holes, and panels
  - 108 stitches
  - Puffs previously unnamed
  - Spanwise and chordwise thickness distributions
- **CFD geometry includes simplifications**



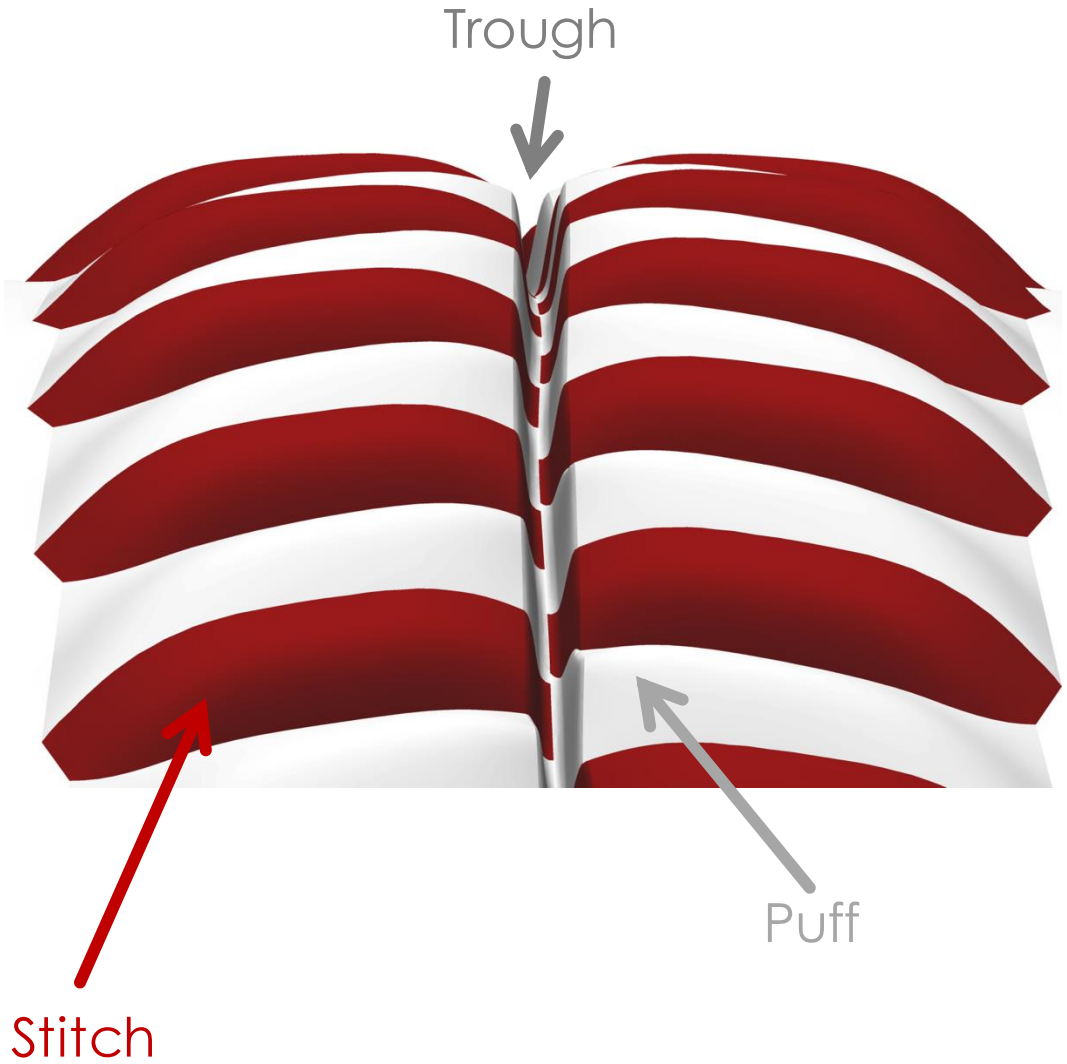


Stitches do not extend across trough





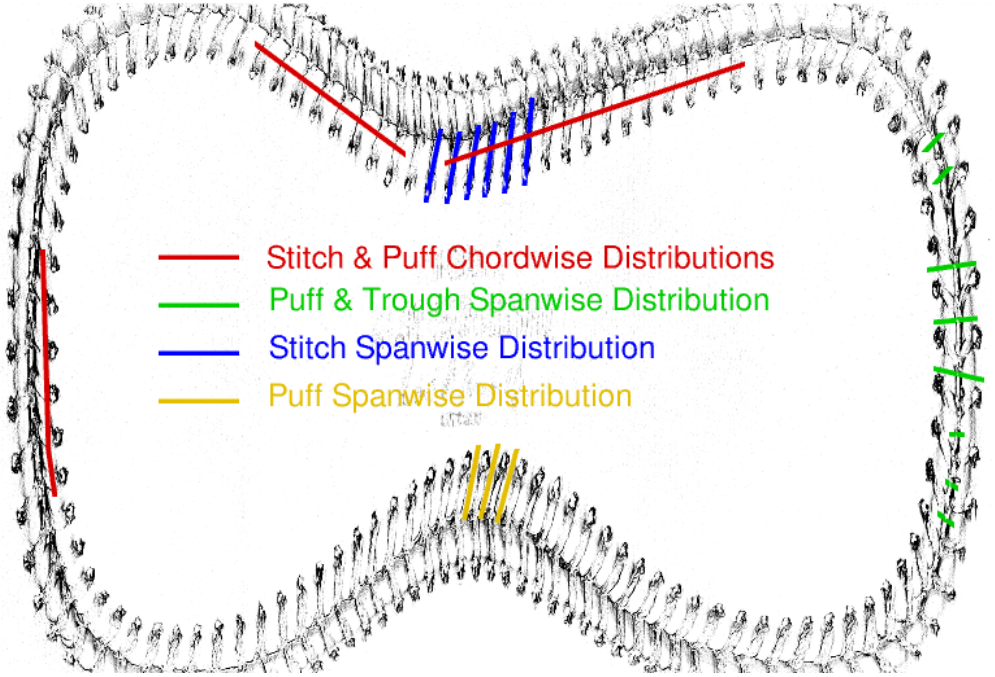
No stitch holes

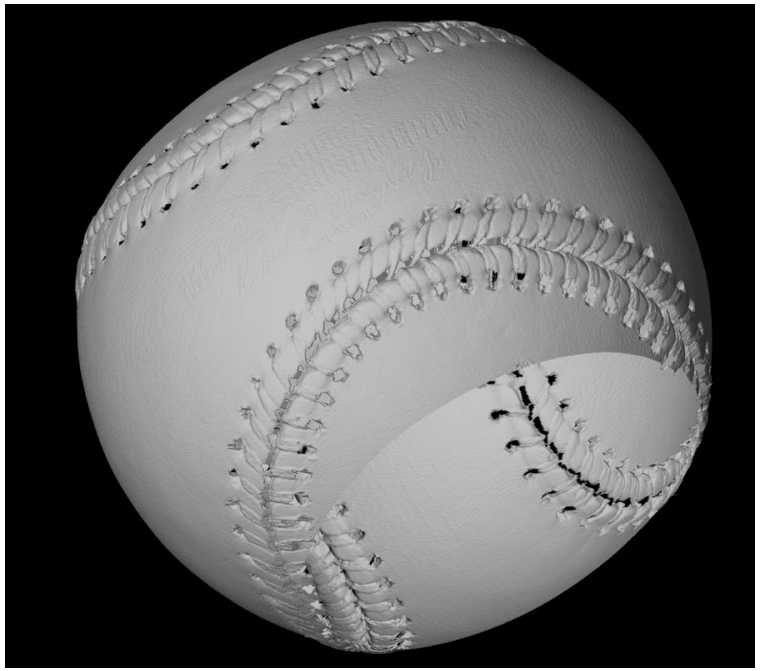


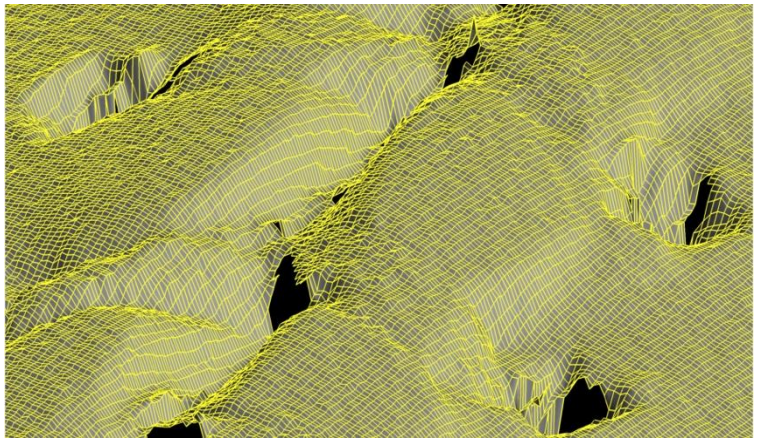
Source (all): NASA

Major League Baseball (MLB) Geometry Digitization

- **Point-scanned rubbed, unused regulation MLB ball**
  - 2.56 million point measurements
  - Measured at Washington State University (WSU) Sports Science Lab
  - Interrogated data for thickness distributions
- **WSU data augmented with LaRC measurements**

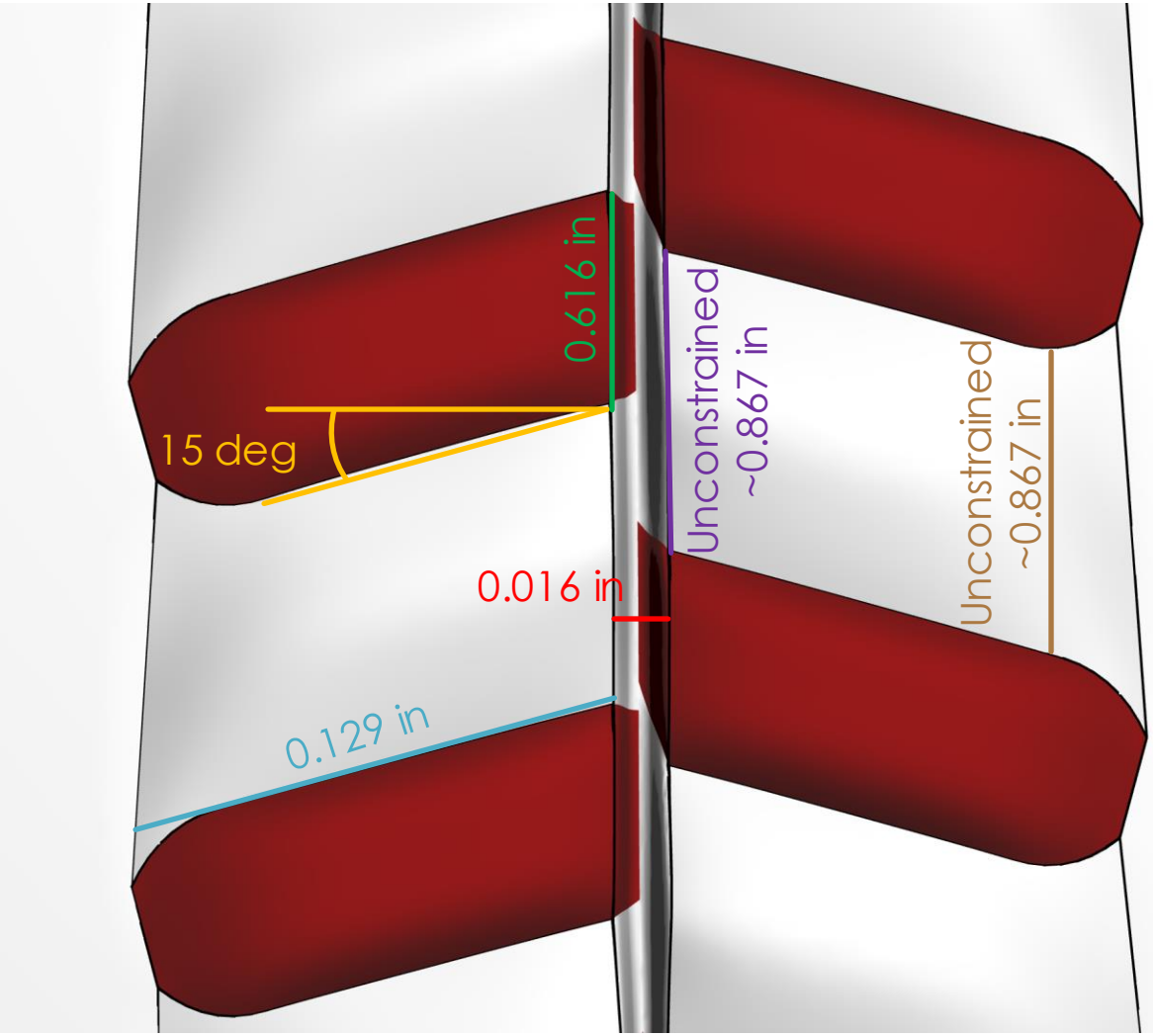






Physical Geometry

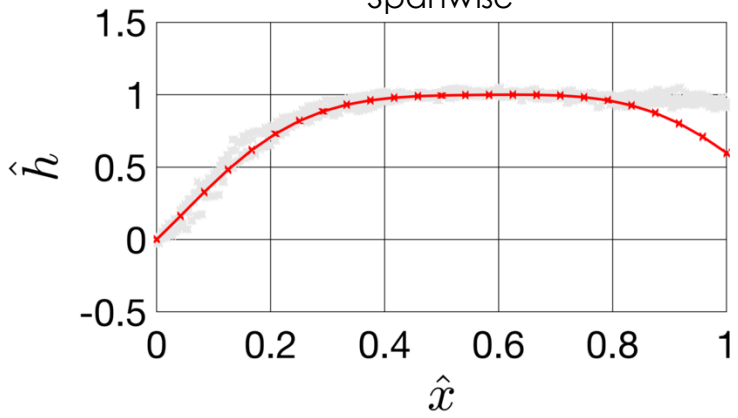
- **Geometry defined by league rules**
- **Digitized height and depth**
  - Stitch height = 0.031 in
  - Puff height = 0.018 in
  - Trough depth = 0.011 in
- **Idealized ball**
  - Weight = 5.125 ounces
  - Moment of inertia = 4.01 ounce-in^2
  - Centered center of mass
  - Identical stitch geometry
  - Identical puff thickness distributions



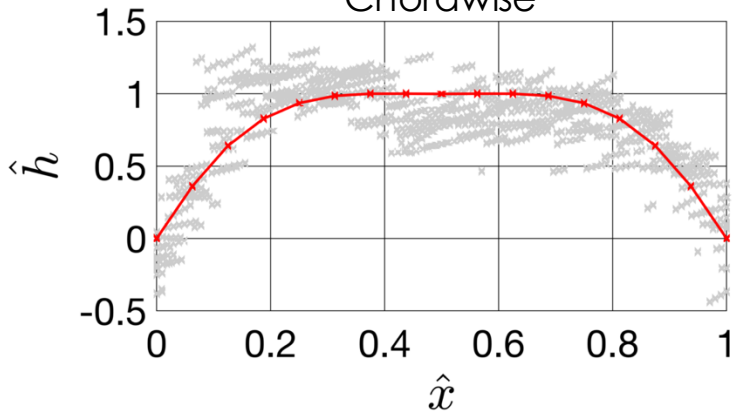
Nondimensional Thickness Distributions

Stitch

Spanwise

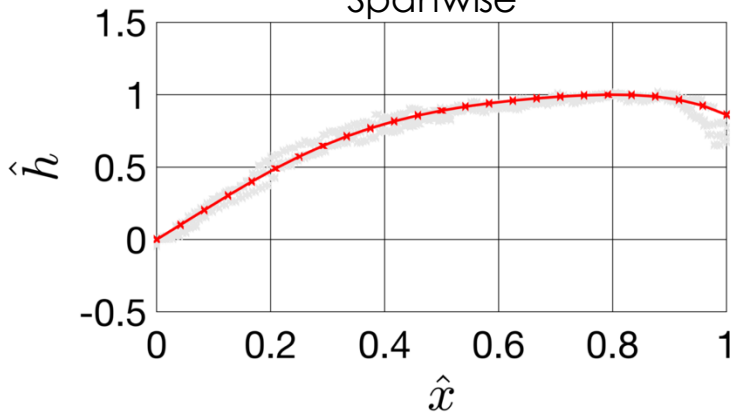


Chordwise

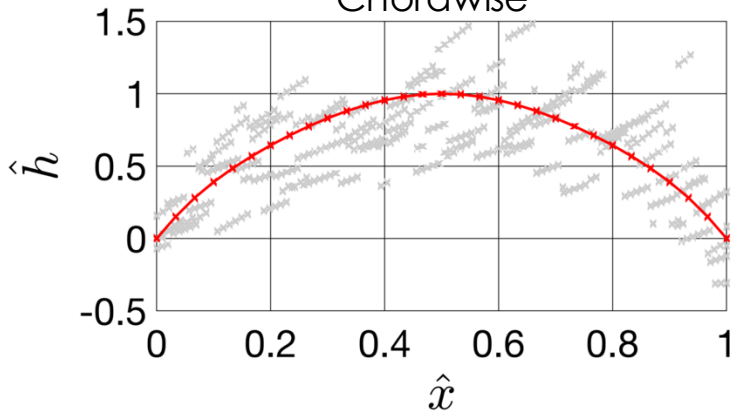


Puff

Spanwise

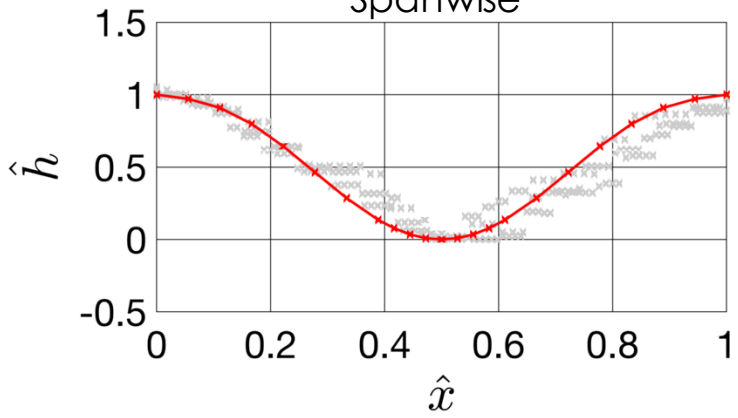


Chordwise



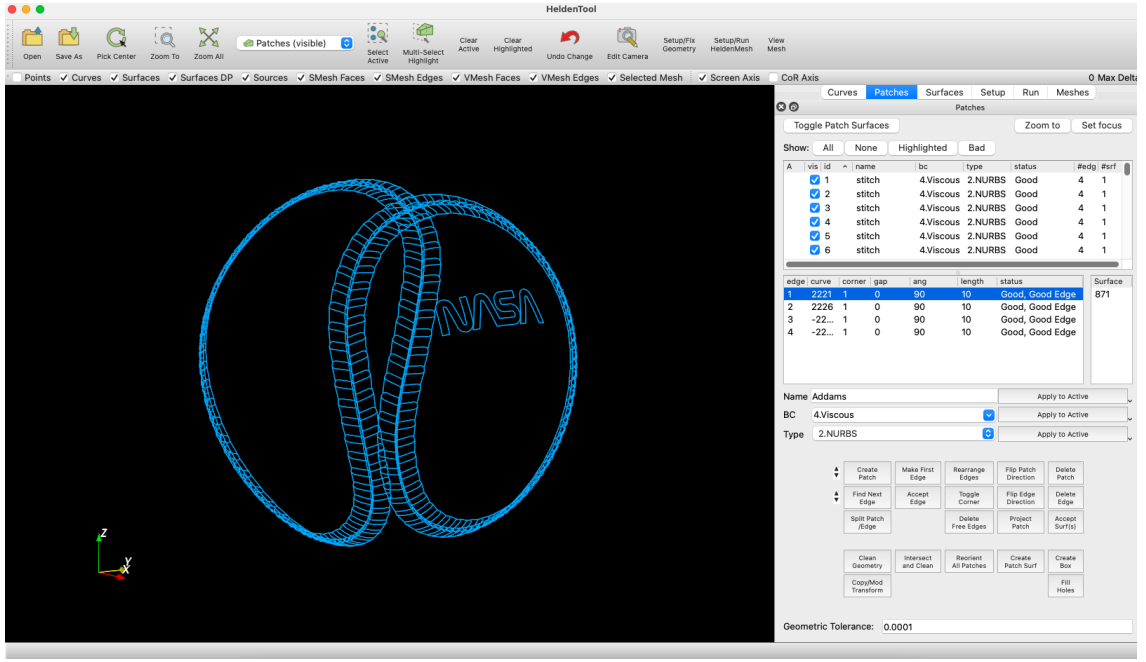
Trough

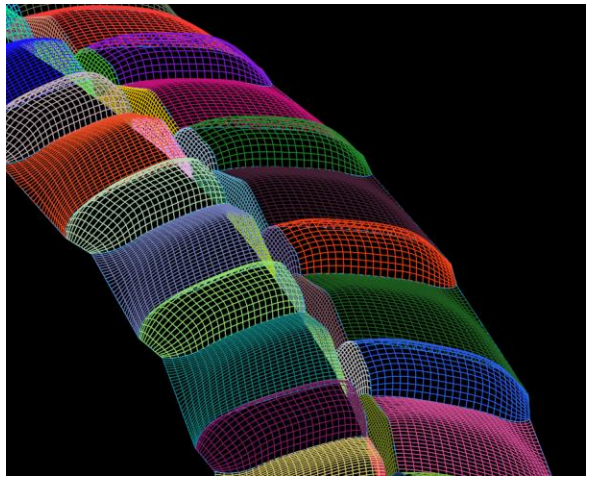
Spanwise

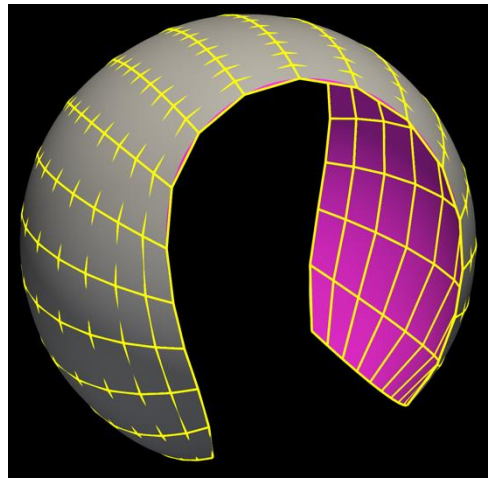


Geometry Preparation

- **HeldenTool**
  - Developed by Helden Aerospace
  - Interactive and graphical suite of programs
- **HeldenPatch**
  - Automatically generated 869 patches and associated NURBS surfaces
  - Required hand work for ~20 patches
  - Reduced engineering time by multiple orders of magnitude







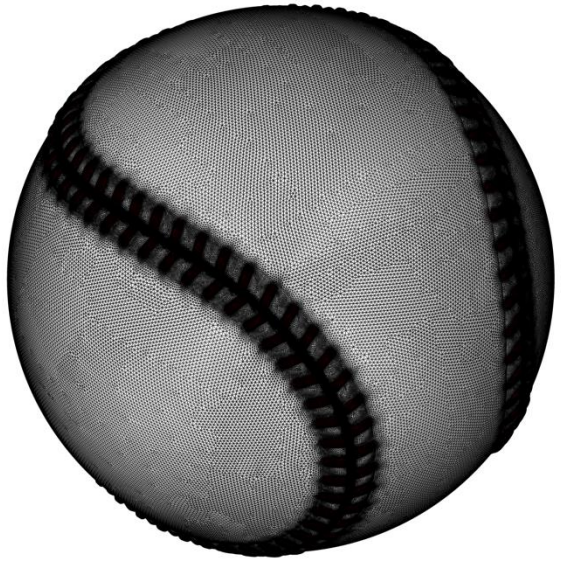
HeldenMesh

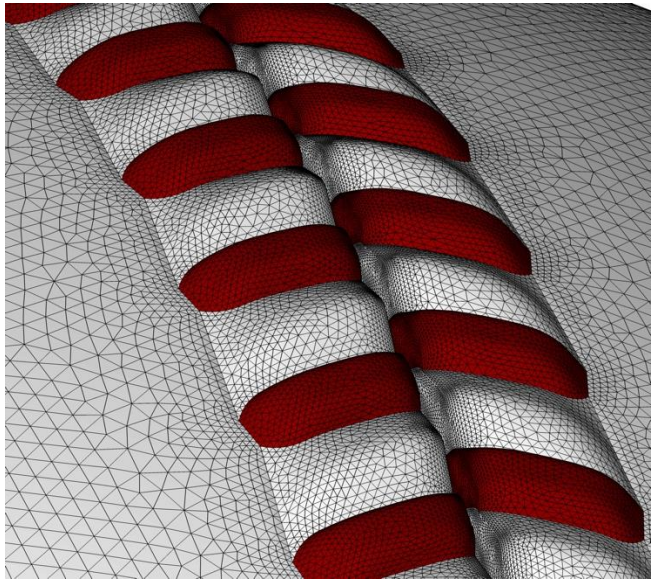
- **Unstructured grid generator from Helden Aerospace**
  - Input-file driven command-line utility
  - Advancing layer/advancing front method
  - Triangular surface elements
  - Single element surface cells (triangles)
  - Mixed element volume cells (prisms and tetrahedra)
  - Utilizes similar technology to Vgrid (ViGYAN)
- **User has significant control of density**
  - Cell size can be specified by patch name or family name
  - Volume sourcing can also be specified
- **Target number of layers and surface y^+ control viscous grid growth**

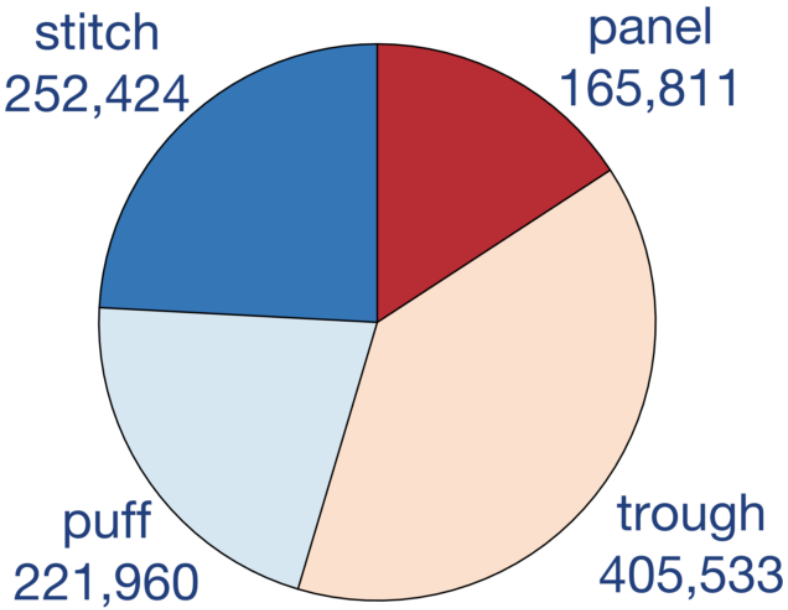
Helden Aerospace logo used with permission

Surface Grid

- **Triangular surface grid**
  - About 843k cells
  - Similar cell size on stitches and puffs
  - Coarser cells on panels
  - Geometry necessitates finely-resolved trough
- **Target surface $y^+ < 0.7$**

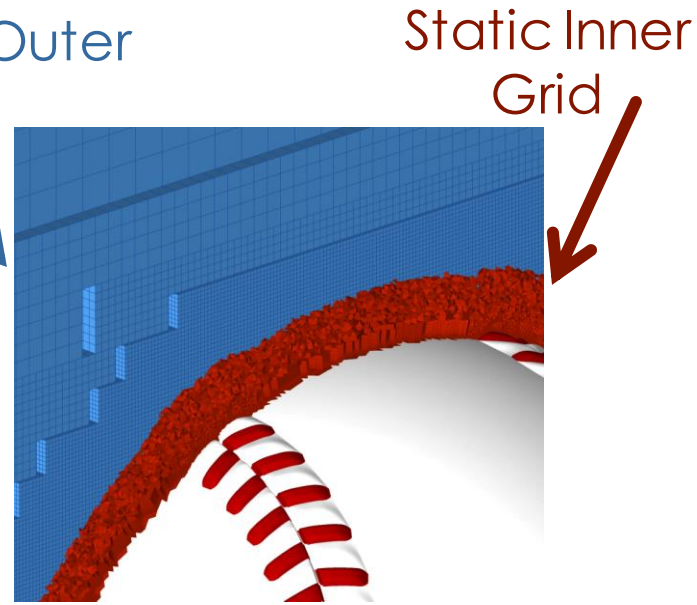


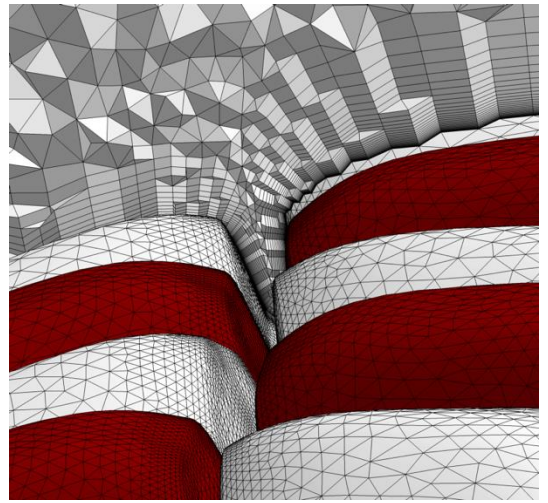




Volume Grid

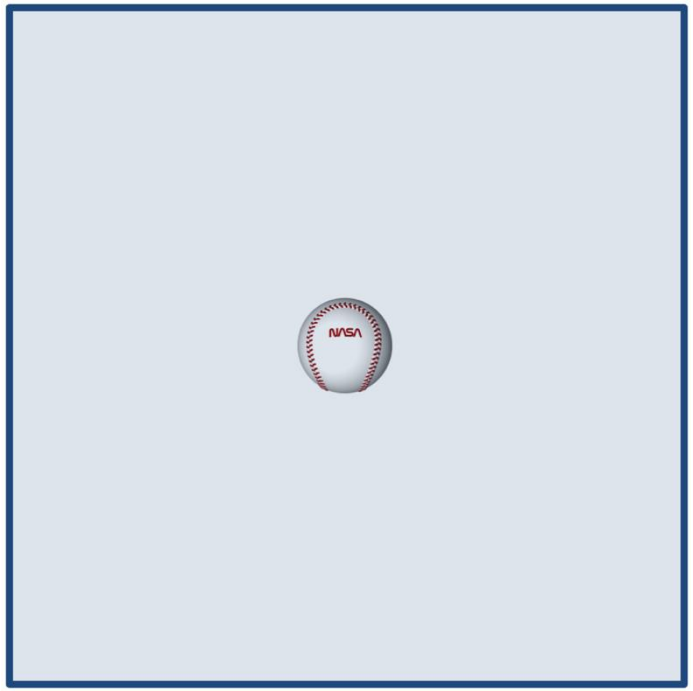
- **Dual mesh inner/outer grid formulation**
  - Inner unstructured grid and adaptive offbody Cartesian grid
  - Inner grid trimmed at constant offset distance
  - Cartesian solver is extremely efficient
- **Inner grid details**
  - Prisms in viscous layer, tetrahedra in volume
  - Trimmed at 0.20 inches (0.07 diameter)
- **Outer grid details**
  - Inner-most Cartesian cell automatically determined to be similar characteristic length
  - Domain extended 75 reference diameters in all directions
- **Domain extends 100 diameters**

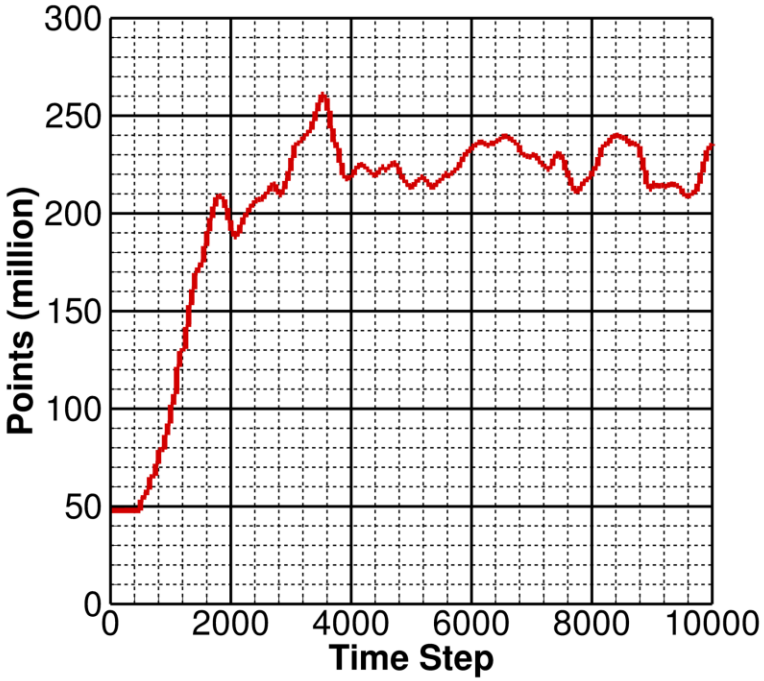




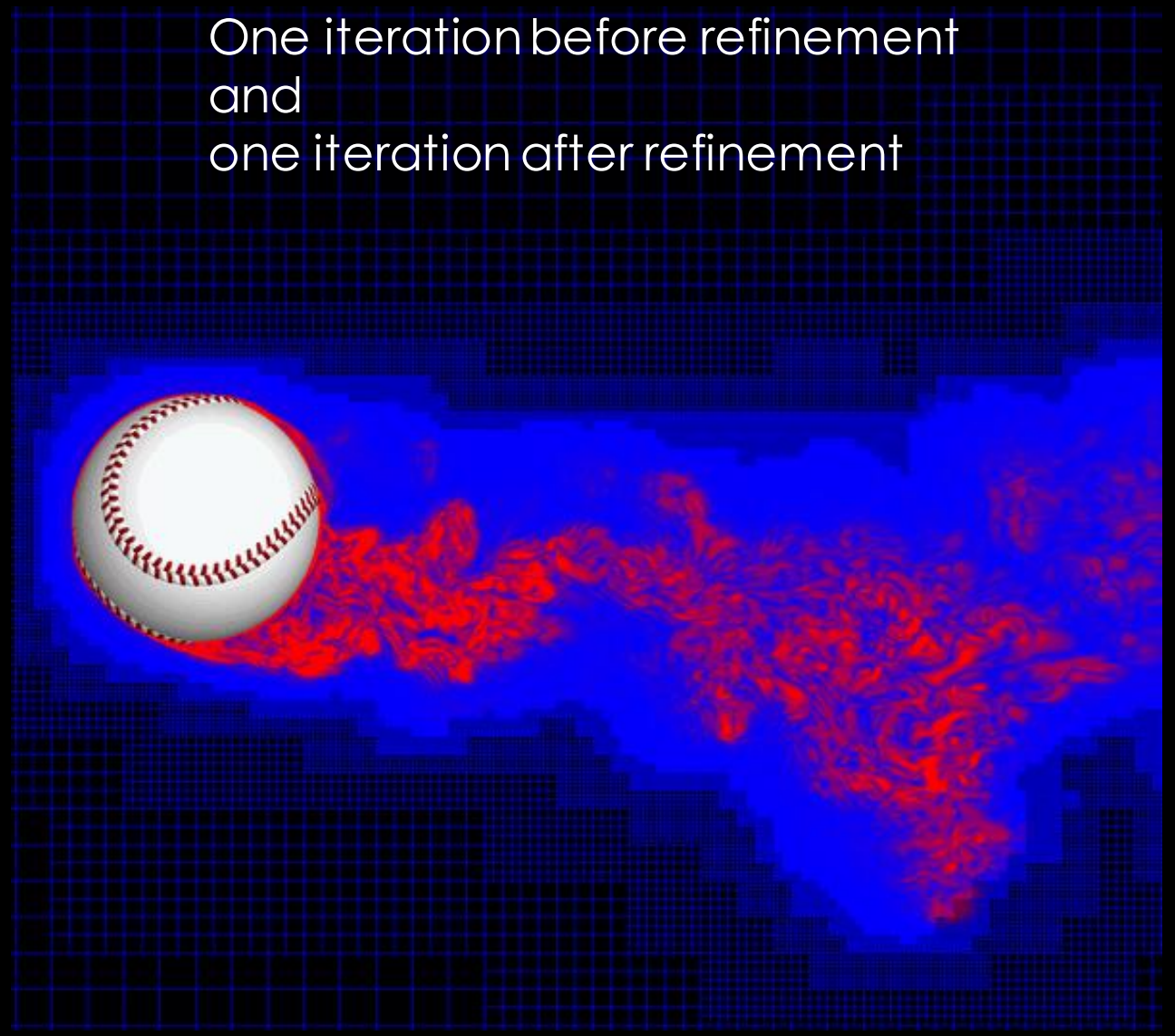
Offbody Grid Adaptation

- **Refinement domain 3 diameters from ball**
- **Grid refinement applied during solution**
  - Refined on vorticity every 50 iterations
  - Baseline grids ~220 million points





Offbody Grid Adaptation



Supercomputing Environment

- **Executed on NASA Advanced Supercomputing (NAS) facility**
  - Supported by NASA Ames
  - Comprised of four different supercomputers
  - More than 11,000 nodes and 241,000 compute cores
  - Contains both Intel and AMD chips
  - TOSS3 (Linux 3) operating system
- **Resource usage**
  - Intel Skylake nodes on Skylake (Electra) and Cascade Lake (Aitken)
  - Run with ~2,000 processors
  - Walltime from 18 hours to a few days



Source: NASA

Solution Setup



- **KCFD (inner solver) and SAMAir (outer solver)**
- **Computational Approach**
  - SARC-QCR (QCR 2000)
  - HLLE++ inviscid flux and LDD+ viscous flux
  - Second-order spatial and temporal accuracy
  - Temporal damping applied to inner and outer grids
- **Executed with Kestrel 12.4.1 SDK**

Freestream Conditions

- **Set for Seattle Mariners at T-Mobile Park**
- **Representative fall start-of-game temperature of 60 deg (during a playoff run)**
- **Elevation 20 ft**
  - Elevation at second base
  - Field variation from ~18 to ~30 ft, depending on tides
- **Conditions set based on velocity and elevation**



Source: NASA

Time Step

- **Example fastball (95.0 mph and 2250 RPM)**
  - Goal of $dt^* < 0.01$ or rotation<0.5 deg/time step
  - Selected time step of 0.00001 is smaller than both dt^* (0.0000346 sec) and revolution (0.0000370) goals

$$dt^* = \frac{V_\infty \, dt}{D}$$

$$0.01 = \frac{\left(\frac{1672 \text{ in}}{\text{sec}}\right) dt}{2.9 \text{ in}}$$

$$0.0000346 \text{ sec} = dt$$

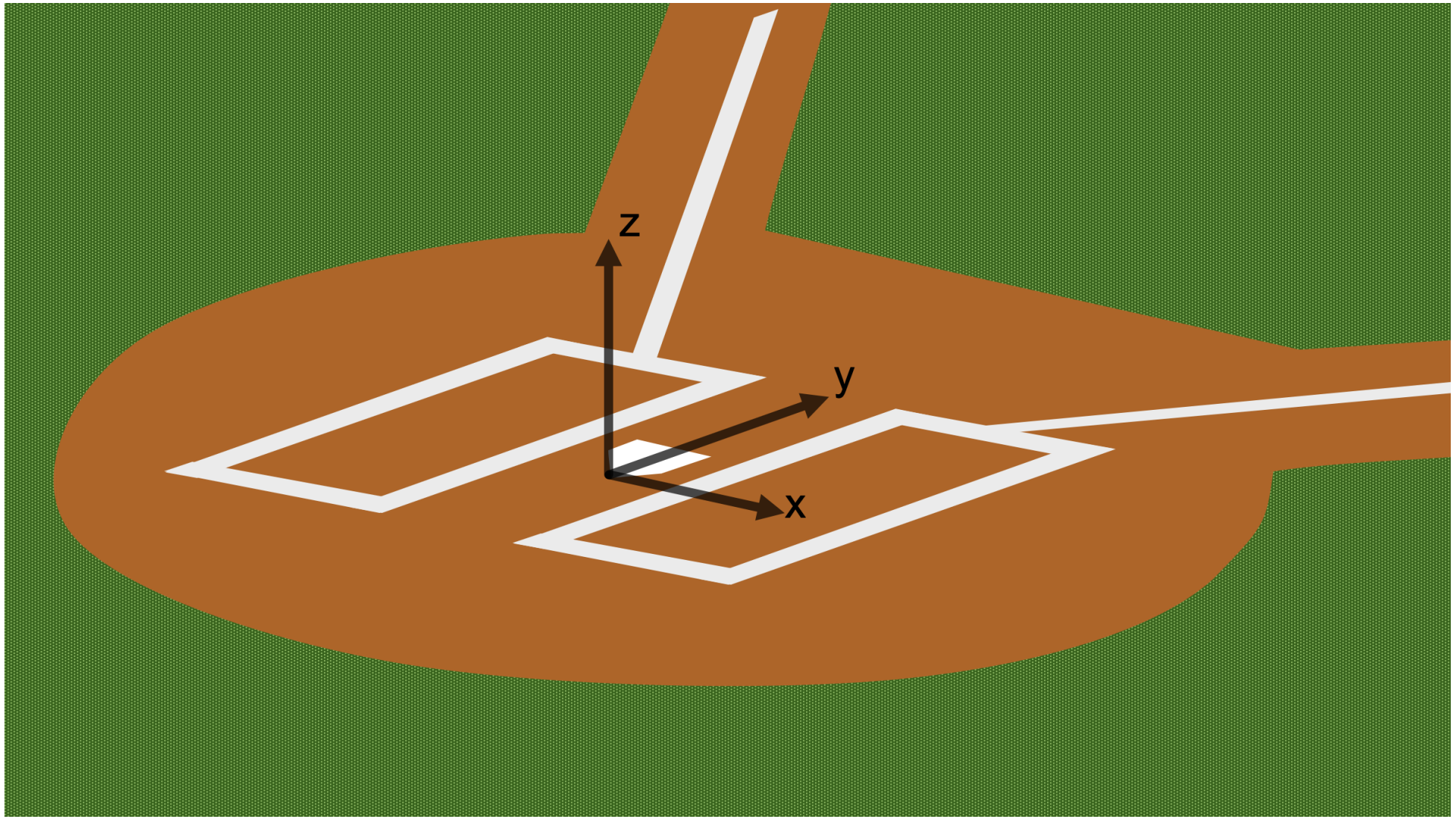
$$2250 \left(\frac{\cancel{\text{rev}}}{\cancel{\text{min}}}\right)\left(\frac{1 \cancel{\text{min}}}{60 \text{ sec}}\right)\left(\frac{360 \cancel{\text{deg}}}{1 \cancel{\text{rev}}}\right)\left(\frac{1 \text{ it}}{0.5 \cancel{\text{deg}}}\right) = \frac{27{,}000 \text{ it}}{\text{sec}}$$

$$dt = \frac{1 \text{ sec}}{27{,}000 \text{ it}}$$

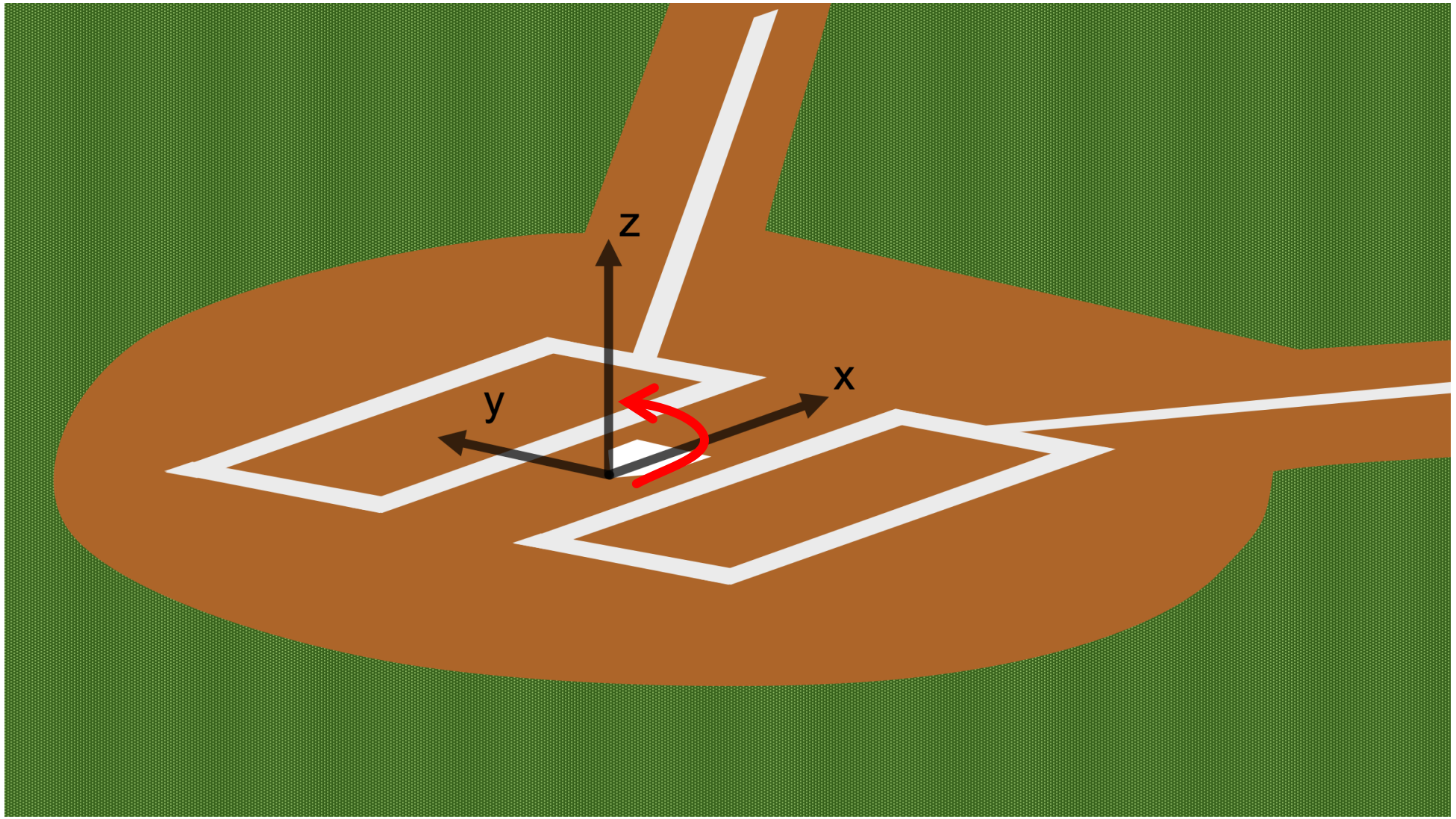
$$= 0.0000370 \text{ sec}$$

- **Representative fastball rates (95 mph and 2250 RPM)**
  - About 175 iterations/diameter
  - Approximately 2600 iterations/rotation

Standard Baseball Coordinate System

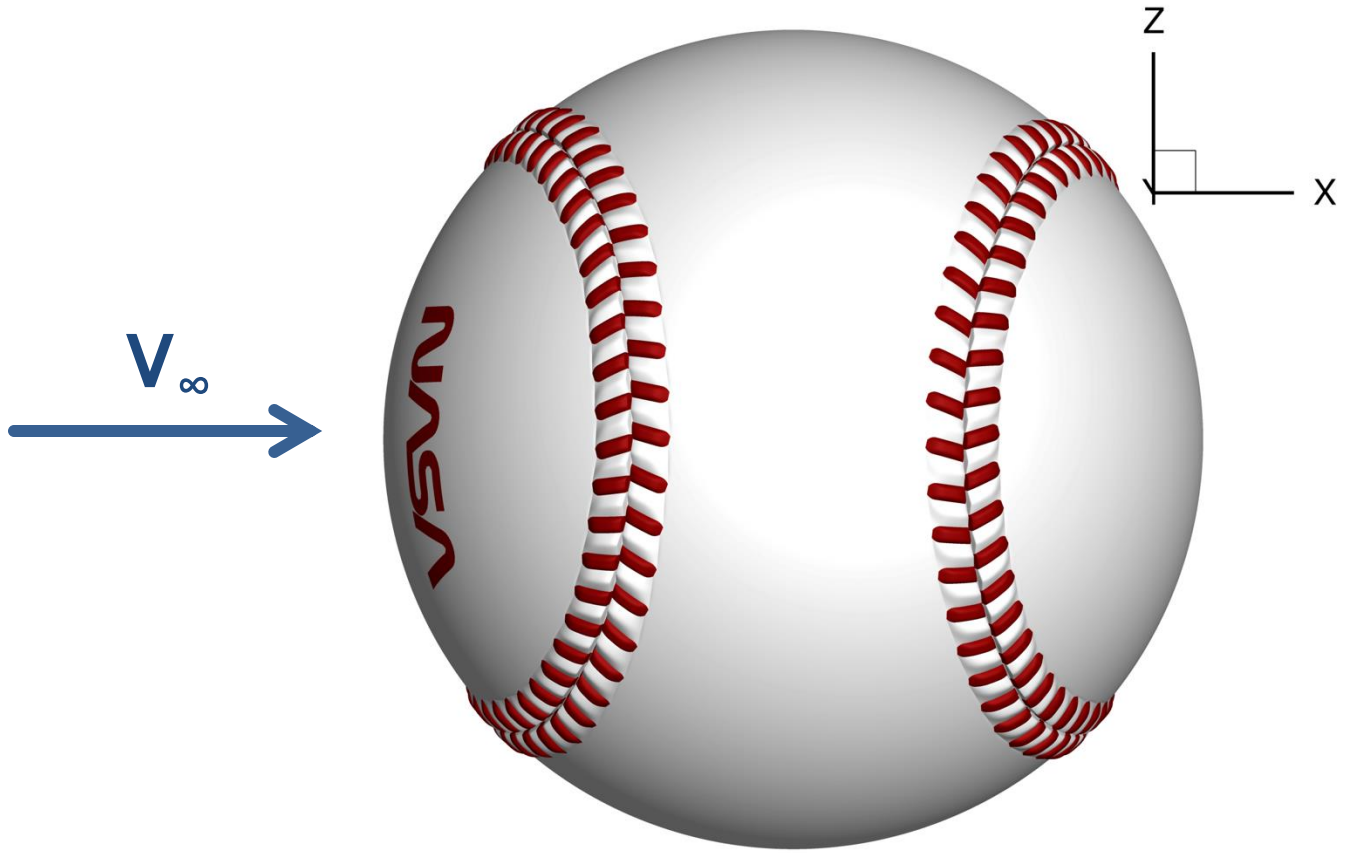


Computational Coordinate System



Baseline Solution

- **Static, fully turbulent, and perfectly smooth at 95.0 mph (very fast four-seam knuckleball)**



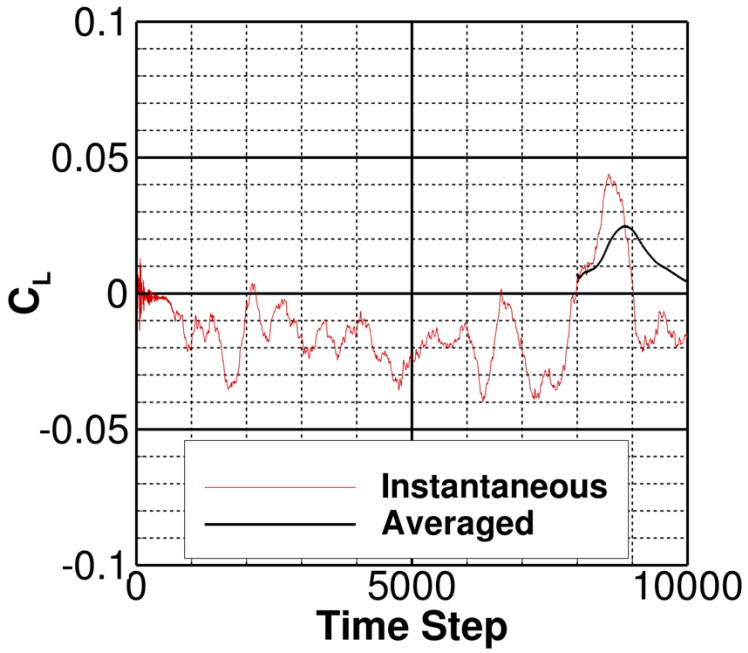
First base view

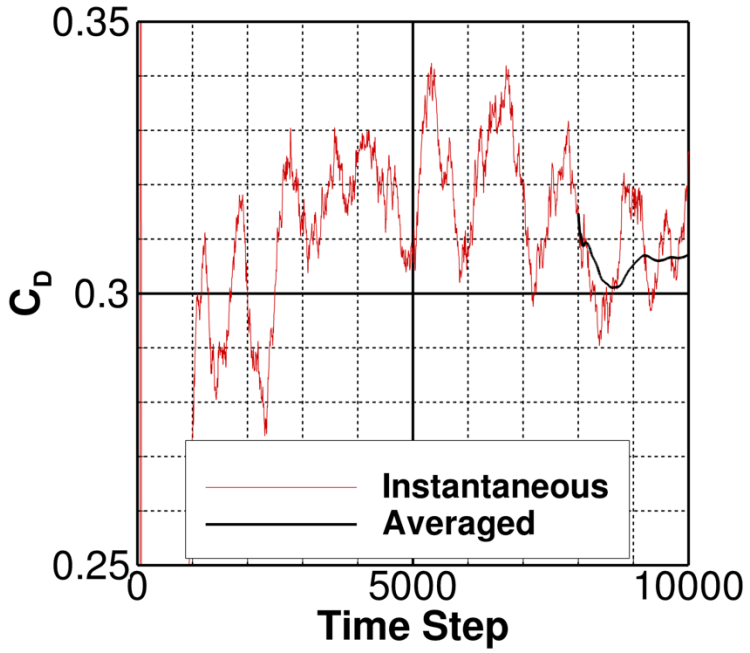
Static, Fully Turbulent – F&M

- **Static, fully turbulent, and perfectly smooth at 95.0 mph (very fast four-seam knuckleball)**
- **Periodic changes in C_D**
  - About 1100 iterations (0.011 sec, 6.25 D_{ball})
  - For reference: ball travels ~230 diameters from mound to batter



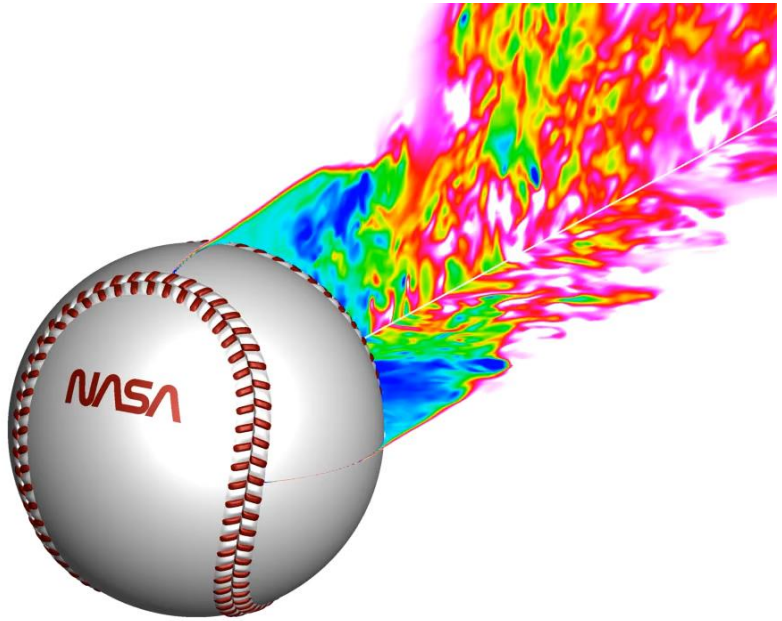
First base view



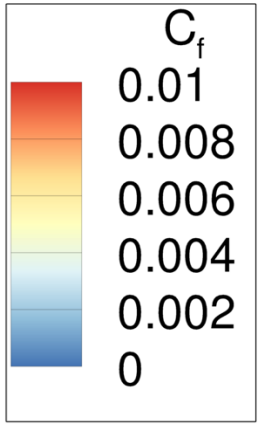


Static, Fully Turbulent – Flow Separation

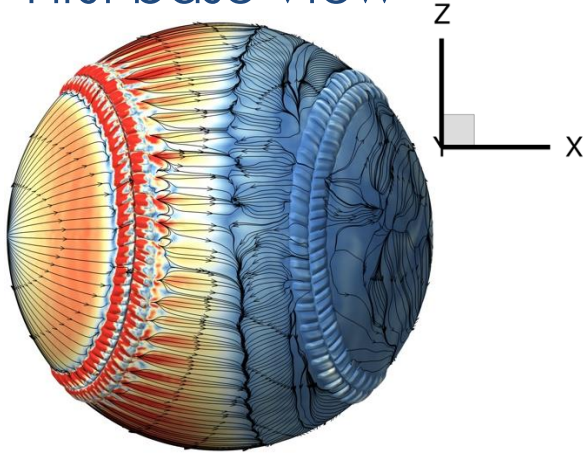
- **Stitches have significant effect**
  - Promote attachment or separation
  - Behavior depends on stitch location
  - Attachment promoted by vortex generator (VG)-like behavior



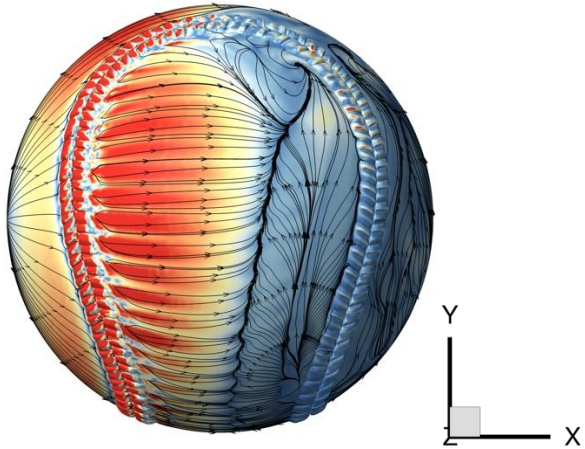
Total pressure coefficient
Measure of momentum loss



First base view

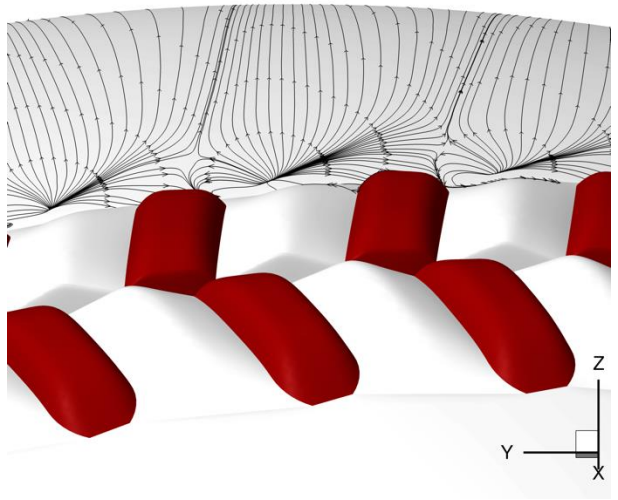


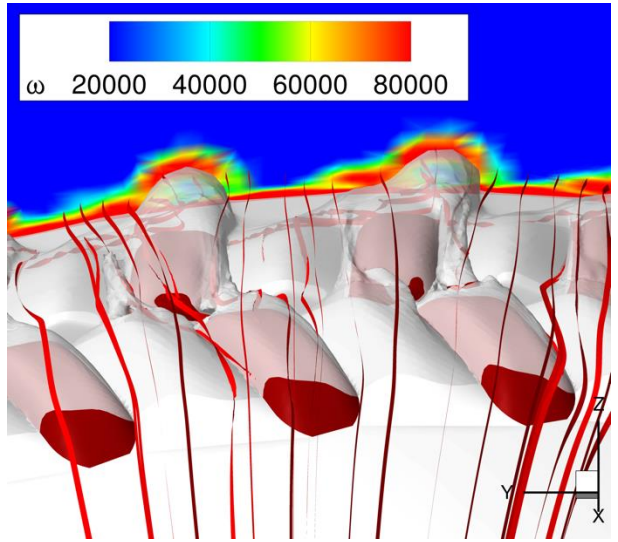
Top view



Static, Fully Turbulent – Flow Separation

- **Stitches have significant effect**
  - Promote attachment or separation
  - Behavior depends on stitch location
  - Attachment promoted by vortex generator (VG)-like behavior
- **Separation pattern driven by complex stitch/puff interactions**
- **Attachment/separation pattern may be leveraged for increased pitch control**



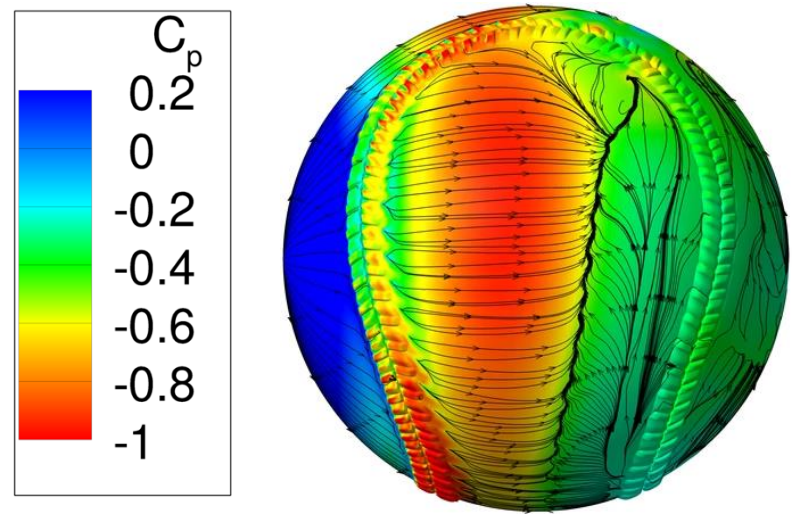


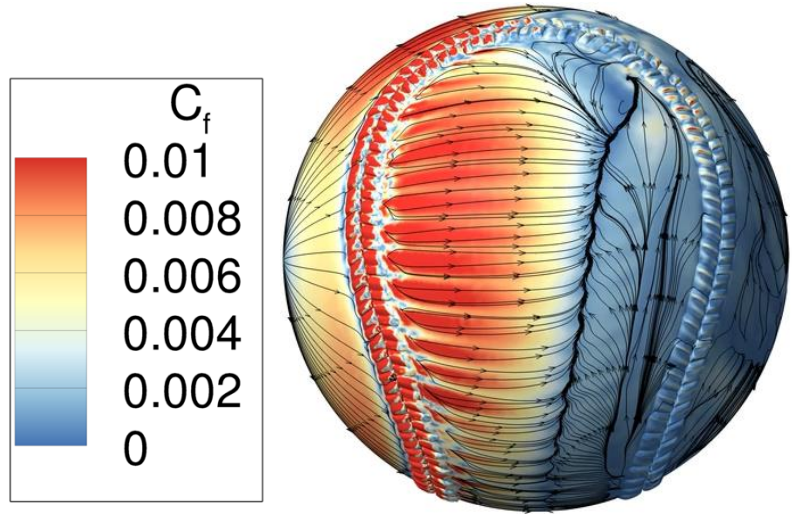
Isosurface of $C_{p,t}$
Slice of ω

Static, Fully Turbulent – Surface Fluctuations

- **Unsteady variation observed**
  - Evidenced by both C_p and C_f
  - Largest differences near top of horseshoe
  - Accentuated by streamline pattern
  - Separation varies by seam width (~0.28 in)
- **Variations in pattern must be considered when performing experimental comparisons**
- **Animations shown every 0.01 sec**

Top view





Kestrel Free-Transition Model

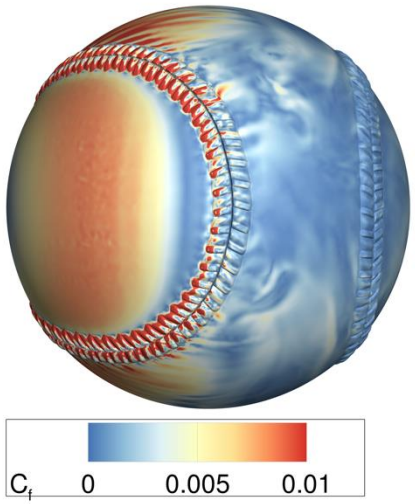
- **One-equation Menter intermittency transport equation**
  - Galilean invariant, Spalart-Allmaras (SA) or Menter
  - Freestream turbulence values can have a significant impact
  - No wall functions (requires $y^+ < 10$)
- **Multiple transition modes available**
  - Bypass, crossflow, separation-induced, and compressible second modes
  - Forced transition is also possible
  - Permits relaminarization
- **Turbulence intermittency indicates flow regime**

$$\gamma = \frac{\mu_t}{\mu_{t,\,model}} \quad \begin{cases} < 0.02 & \text{laminar} \\ > 0.03 & \text{turbulent} \end{cases}$$

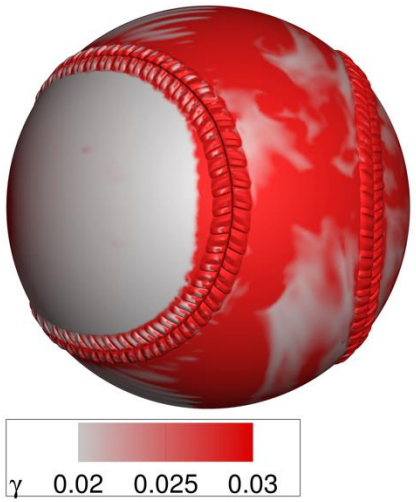
Static, Free-Transition Results

- **First base view (ball rotated 30 deg)**
  - Transition scheme does not affect separated flow upstream of stitches (expected)
  - Attached, turbulent flow observed near top and bottom of ball

First base view



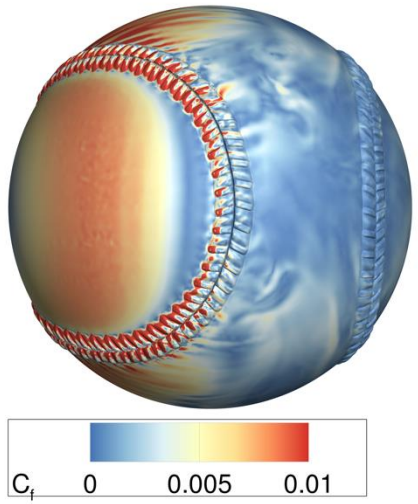
First base view



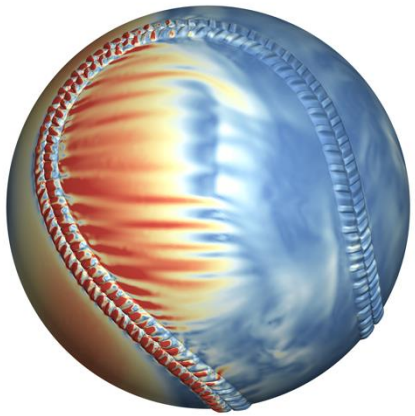
Static, Free-Transition Results

- **First base view (ball rotated 30 deg)**
  - Transition scheme does not affect separated flow upstream of stitches (expected)
  - Attached, turbulent flow observed near top and bottom of ball
- **Top View**
  - Stitches can promote attachment, cause transition, or separate the flow, depending on the location of the stitches
  - Separation still observed near top-most part of the horseshoe

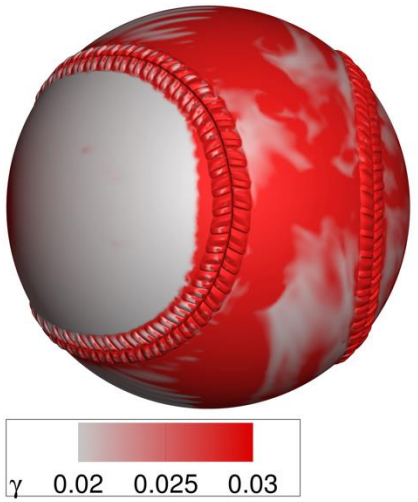
First base view



Top view



First base view



Top view



Flowfield Features at Three Ball Orientations

- **Top view**
- **Rotated about y axis by 0, 15 and 30 deg**

Causes transition and promotes attachment

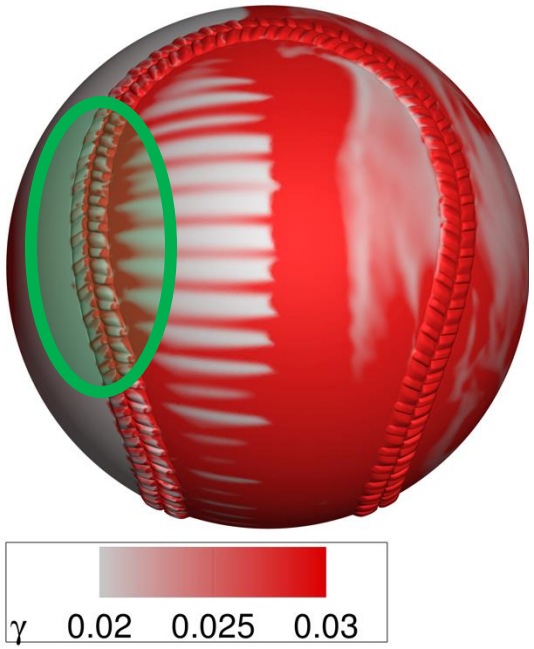
Slight effect upon flowfield

Causes separation

0 deg rotation

+15 deg rotation

+30 deg rotation



Effect of Turbulence Intensity



- **Freestream turbulence intensity affects transition predictions**
  - Significant effect previously observed over aircraft wings
  - Minimal investigations regarding separation patterns and turbulence

Effect of Turbulence Intensity

- **Freestream turbulence intensity affects transition predictions**
  - Significant effect previously observed over aircraft wings
  - Minimal investigations regarding separation patterns and turbulence
- **Sweep of cases from 1/10th baseline to 10 times baseline values**

1/10th baseline

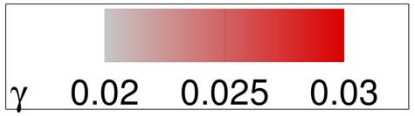


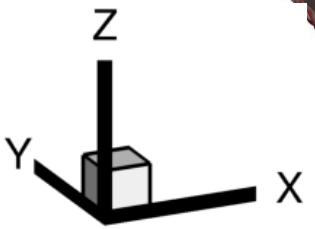
Baseline



10x Baseline







Ball Roughness

- **Various sources of surface damage**
  - Contact with ground
  - Contact with equipment
- **Lena Blackburne Rubbing Mud**
  - Acquired from shores of Delaware River
  - Changes color and roughness of ball
- **Enhanced grip ball being tested**




Rubbed


Unrubbed



Source (all): NASA

Surface Roughness Measurements

- **MLB roughness determined through profilometer measurements (WSU)[1]**
  - Six balls in data set, four profiles per ball
  - Converted to sand grain roughness (k_s) for Kestrel
  - Previously-developed relationships define roughness[2]

	Arithmetic Mean	Root Mean Square	Maximum Height
As Measured (thou)	0.288	0.394	5.249
Equivalent Sand Grain Roughness (thou)	1.69	1.22	5.14

NANOVEA ST500 Non-Contact Optical Profilometer



Source: NANOVEA
Used with Permission
nanovea.com

[1] Liu, F. *Analytical Report: Nanovea.* Washington State University Technical report PRO180301-26-P. 2018.

[2] Adams, T., Grant, C., and Watson, H. *A Simple Algorithm to Relate Measured Surface Roughness to Equivalent Sand-Grain Roughness*. International Journal of Mechanical Engineering and Mechatronics. 2012. Vol. 1, Is. 1. pp 61-71.

Kestrel Roughness Model

- **Methods leverage previously-developed models[1-3]**
- **Discrete element approach with modeling and calibration**
  - Modifies μ_t near wall to increase shear and skin friction (non-zero)
  - Coupled with reduction of turbulence damping
  - Model applied deep in laminar subregion without wall functions
- **Can be applied for SA and Menter models**
- **Implemented for RANS, URANS, and IDDES schemes**
- **Roughness can be declared patch by patch**

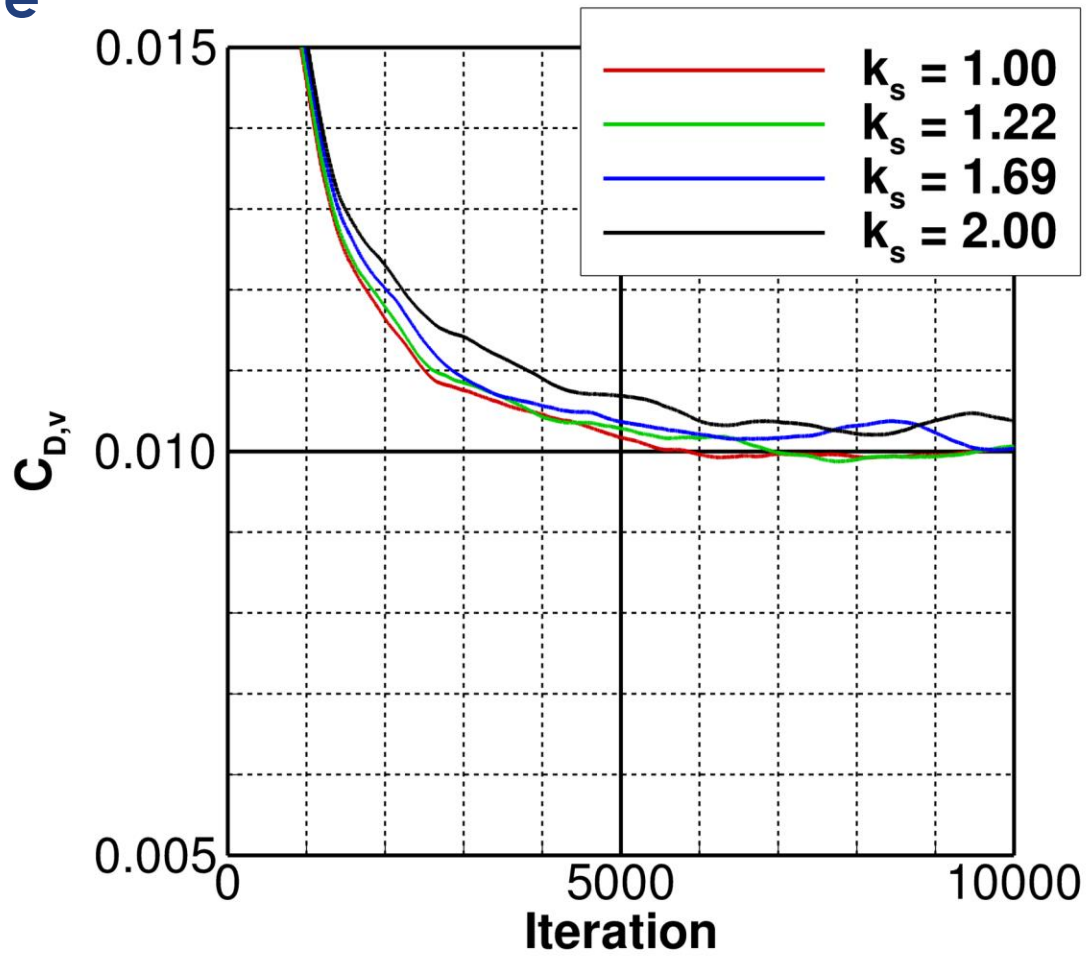
[1] Leasca, T., DeJong, A., and Engel, J. *Roughness Wall Modeling for Naval Applications in CREATE-AV Kestrel as Modified by Naval Surface Warfare Center, Carderock Division.* 2023 AIAA SciTech Forum. Paper 2023-0642.

[2] Knopp, T., Eisfeld, B., and Calvo, J. *A New Extension for k-ω Turbulence Models to Account for Wall Roughness.* International Journal of Heat and Fluid Flow. 2009. Vol. 30, pp 54-65.

[3] Aupoix, B. and Spalart, P. *Extensions of the Spalart-Allmaras Turbulence Model to Account for Wall Roughness.* International Journal of Heat and Fluid Flow. 2003. Vol. 24, pp 454-462.

Effect of Surface Roughness

- Computed in baseline knuckleball orientation
- Utilized selected freestream turbulence value
- Less than 5 counts different for four roughness values
- No significant effect upon separation behavior



Spin Angle Coordinate System

- **Axis of rotation defined by spin direction and gyro angles**
- **Spin direction (clock angle)**
  - Pure side spin
  - Positive vector points in direction of lift
- **Gyro angle**
  - Pure football spin
  - Positive for right-handed pitchers



12:00 spin axis



+90 gyro

Prescribed Rotation – Pure Backspin

- **Baseline tests to quantify effects of spin**
  - Data can be implemented in pitch models
  - Differences quantified between pitch types
- **Investigated effect of spin rate**
  - 78.1 mph (Re ~144,000)
  - Eight different spin factors (0.05-0.40)
  - MLB range ~0.22 ± 0.18

$$S = \frac{\omega r}{V_\infty}$$

- **Computations performed over two ball rotations after adequate flow setup**
- **Maintained constant time step between simulations**

Prescribed Rotation

- **Significant variation in rotation rate and axis of rotation**
  - Varies pitcher to pitcher, day to day, and season to season
  - Leveraged publicly-available axis of rotation data for baseline data[1]
  - Computations on fastballs and curveball (slider included for reference)

Pitch	Spin Rate	Clock Angle	Gyro Angle	Speed (mph)	Reynolds Number
4-Seam Fastball	2250-2350	12:30-1:30	0-10	95	215,000
2-Seam Fastball	2150-2200	1:00-2:00	10-20	95	215,000
Curveball	2500-2600	6:00-7:00	20-30	81	182,000
Slider	2400-2500	10:00-11:00	65-75	85	192,000

[1] Rapsodo. *MLB Data Guide: Pitch Design Chart-MLB Averages*. Device manual and guidance document.

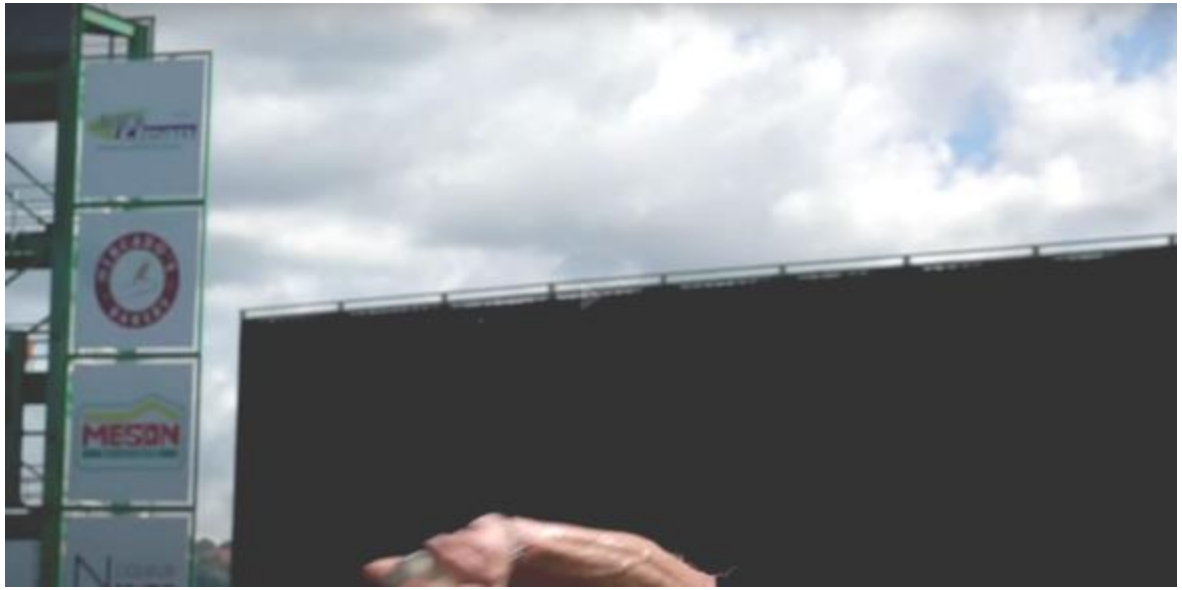
Fastball





Source (all): Robby Rowland
Used by permission

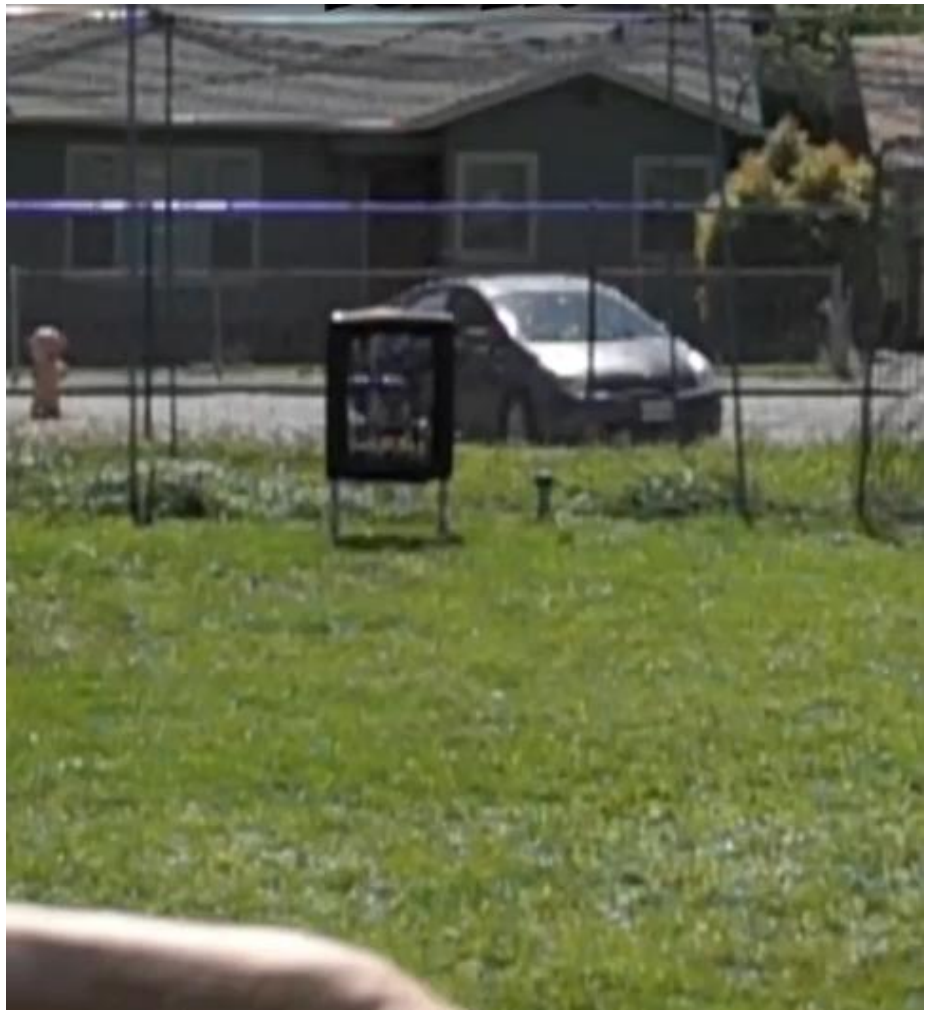
Curveball





Source (all): Robby Rowland
Used by permission

Slider





Source (all): Robby Rowland
Used by permission

Release Pitch Grips

Four-Seam Fastball



Curveball

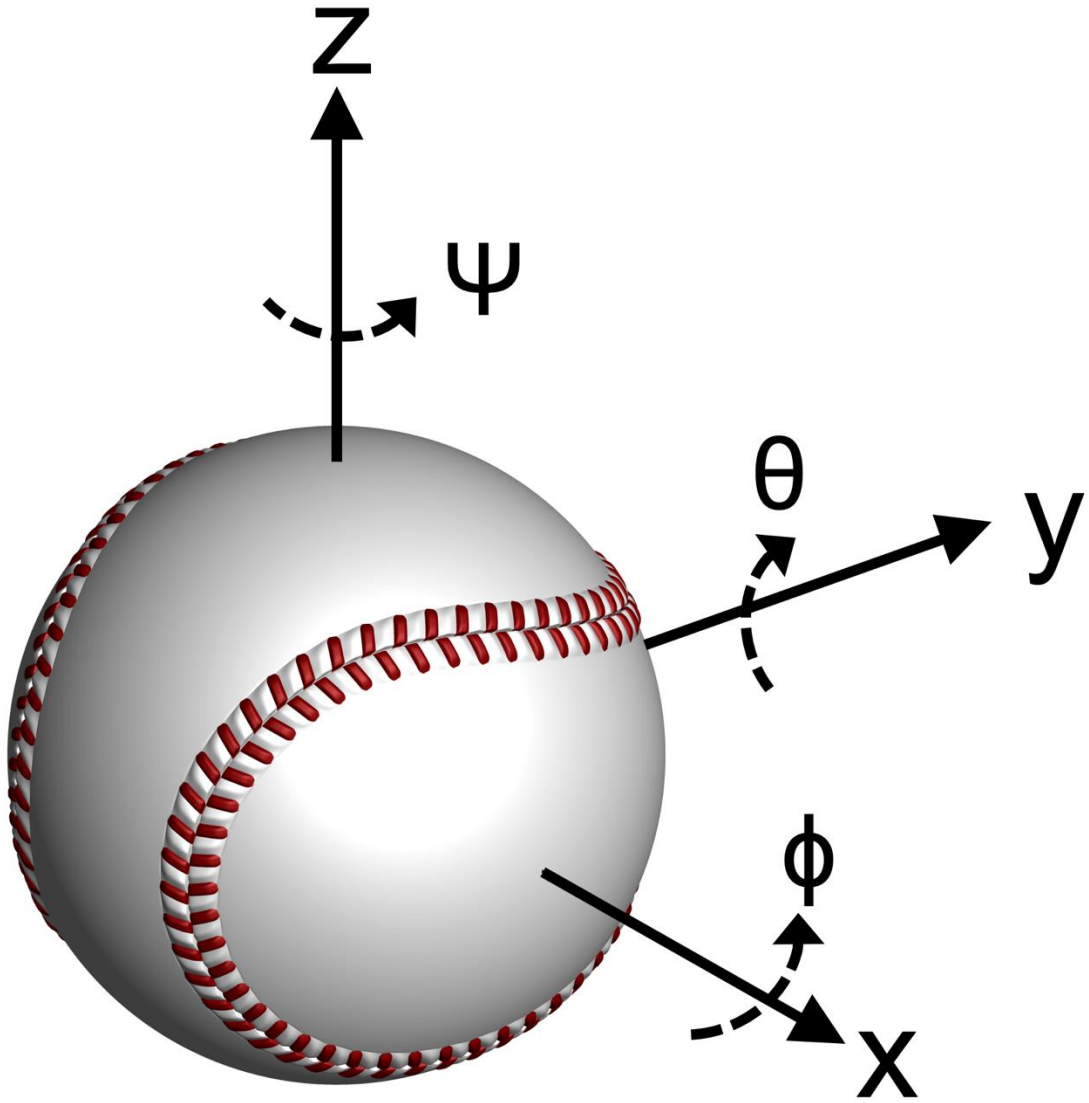


Slider



Source (all): Robby Rowland
Used by permission

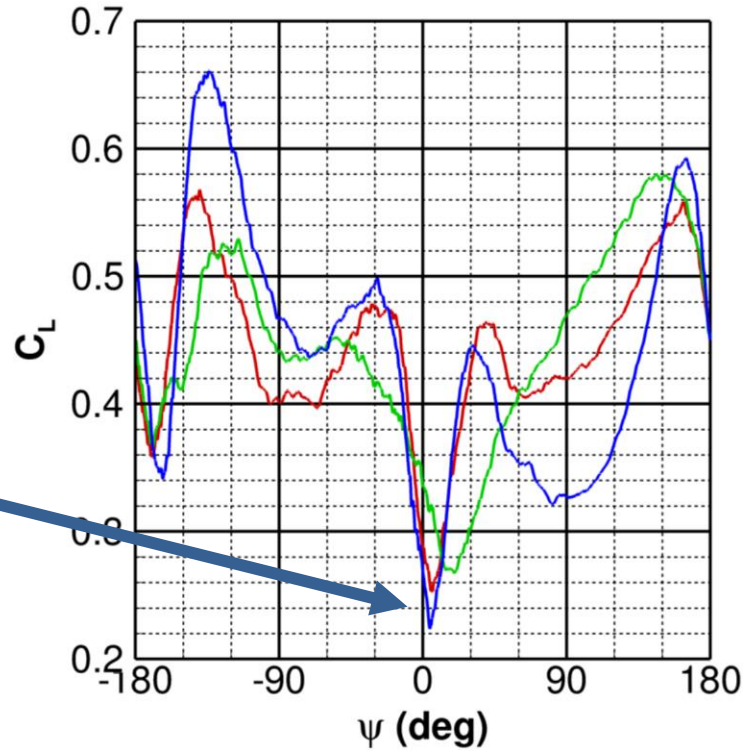
Rotational Axis Coordinate System

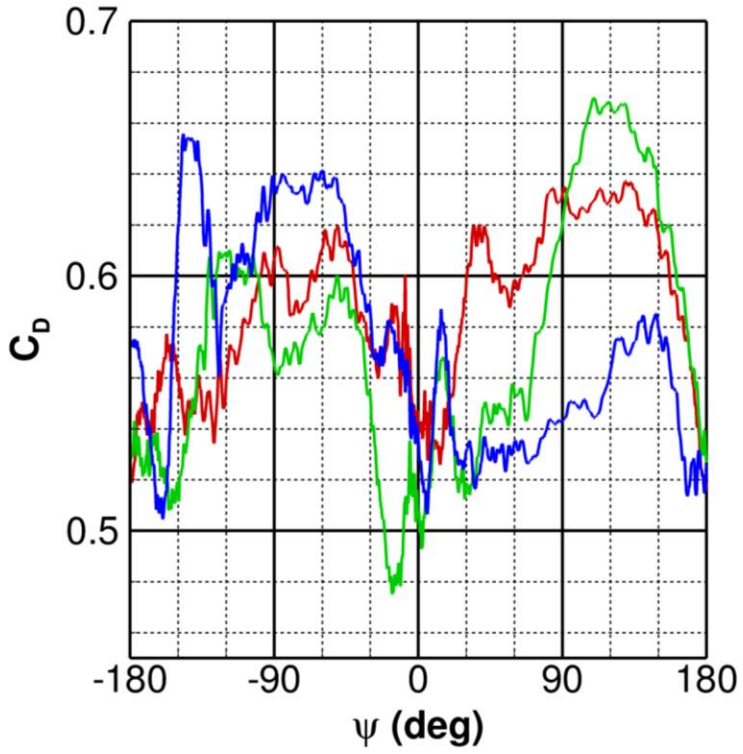


Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Aerodynamic forces through three rotations
- Presented as a function of the x-y plane angle
- Similar trends in C_L with larger variations in C_D

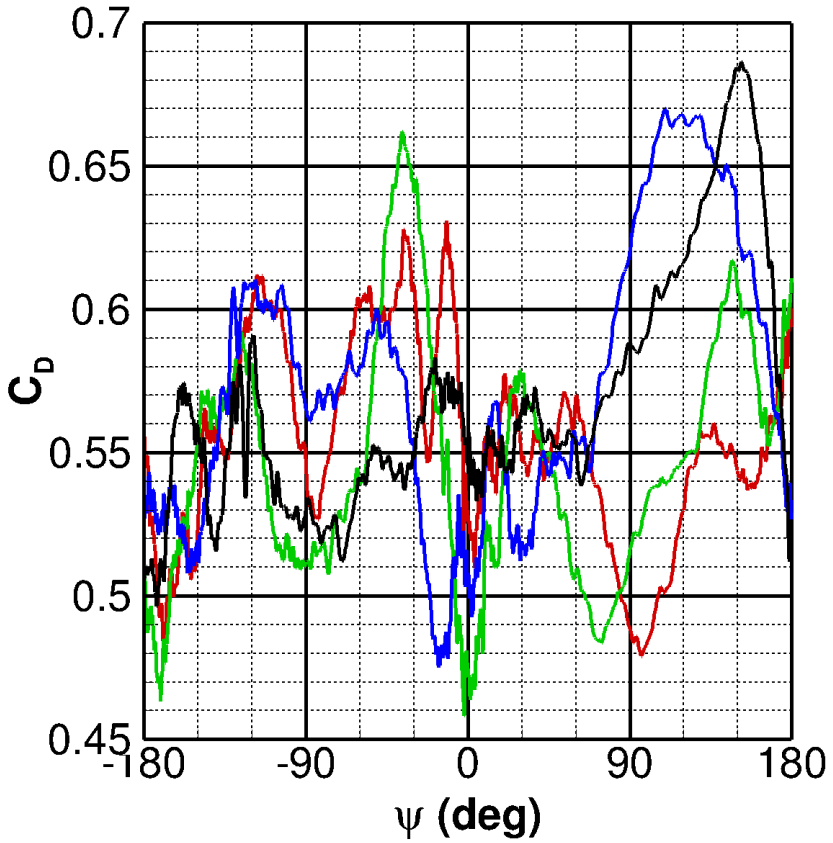






Four-Seam Fastball (1:00 clock, 10 deg gyro)

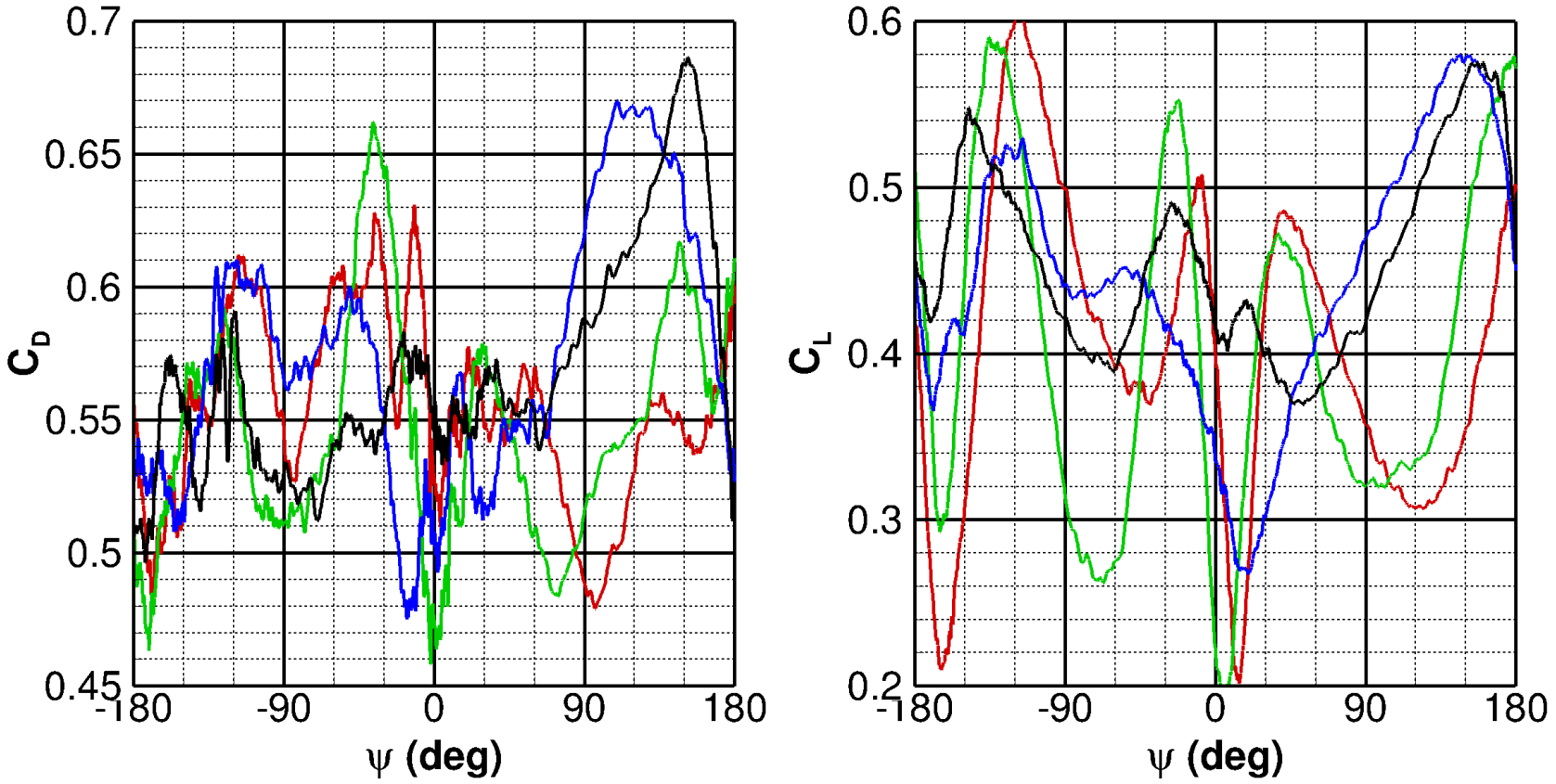
- Drag, lift, and side force for one rotation cycle
- Similar trends observed in C_D



1750 RPM
2000 RPM
2250 RPM
2500 RPM

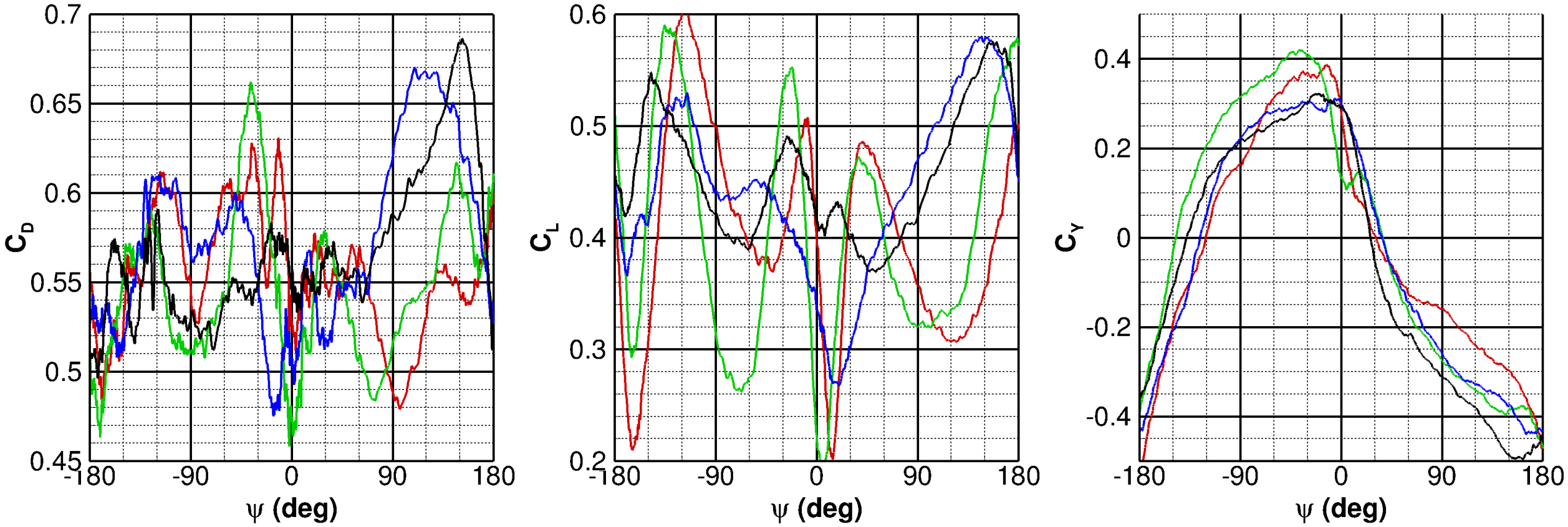
Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Drag, lift, and side force for one rotation cycle
- Similar trends observed in C_D and C_L



Four-Seam Fastball (1:00 clock, 10 deg gyro)

- Drag, lift, and side force for one rotation cycle
- Similar trends observed in C_D and C_L with minimal variations in C_Y

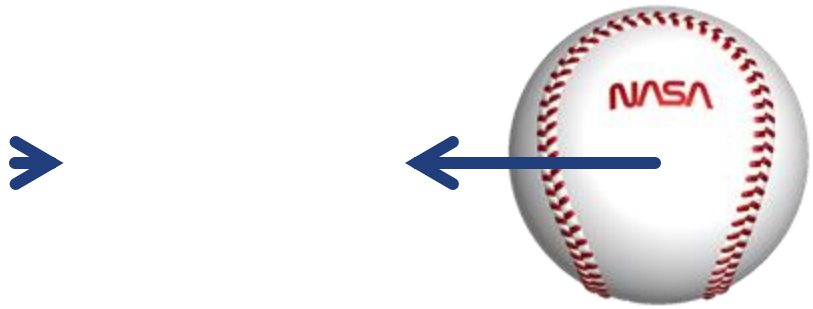


Two-Seam Fastball (1:00 clock, 20 deg gyro)



6DOF Responding Body Formulation

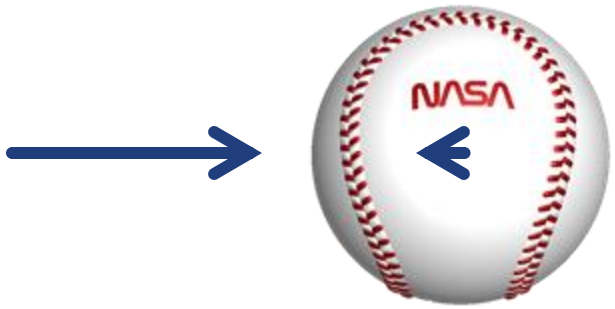
Real World



V_∞ = 0 mph

V_0 = x mph

Computational



V_∞ = x mph

V_0 = 0 mph

6DOF Responding Body Formulation

Real World



V_∞ = 0 mph V_0 = x mph

Computational

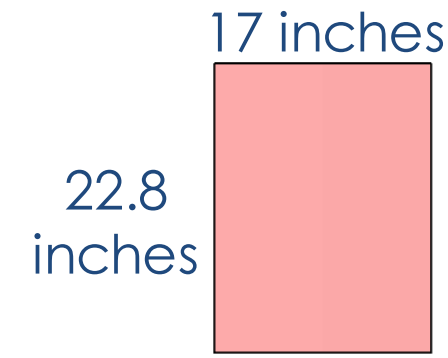


V_∞ = x mph V_0 = 0 mph

Physical Space Setup

- **Release**
  - Pitching rubber is 60’ 6” from home plate
  - Release is about 55’ from home plate
  - Vertical release about 8’ above ground level
- **Axis of rotation data provided by Rapsodo**
- **Strike zone for a representative infielder (6’ 0”)**

Pitch	Velocity (mph)	Spin Rate (RPM)
Fastball	95	2,250
Curveball	81	2,500
Slider	85	2,400

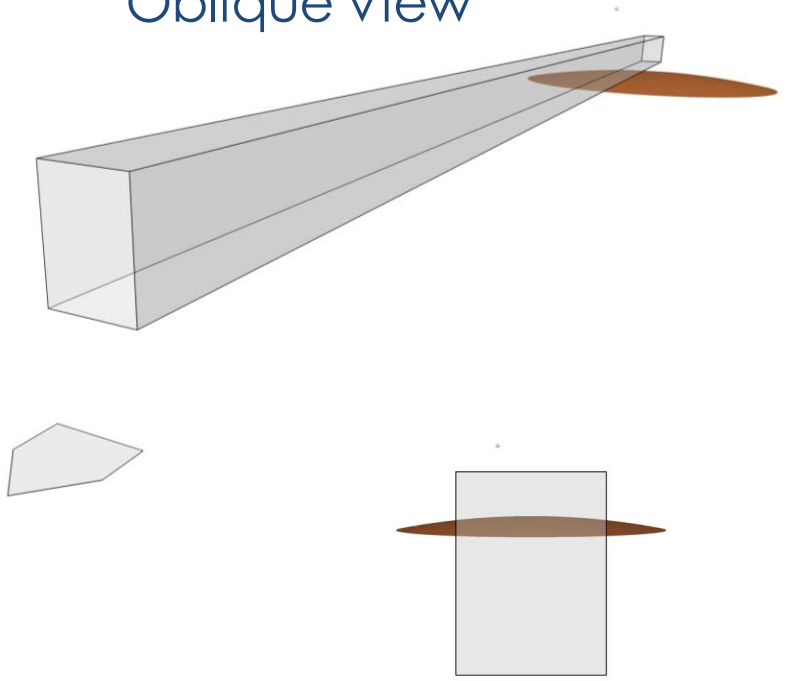


Strike zone for a 6’0” representative infielder

Fastball Six Degree of Freedom Movement

- **Ball released from representative pitcher's hand**
- **Trajectory shows expected movement**
  - Black line shows position history
  - Dots shown at constant time increments
- **Flight time ~0.42 seconds**
- **Additional work needed to accurately model pitches at various release angles**

Oblique view



Catcher's view

Future Work



- **Backspin comparison to flight and experimental data**
- **Determination and comparison of separation locations**
- **Non-idealized ball**
  - Off-center center of mass
  - Variable stitch/puff sizes
- **Investigation of curveball**
  - Curveball contains significant top spin
  - Slider has lots of gyro
  - Prescribed, ball joint response and 6DOF
- **Sensitivity to computational setup**
  - Turbulence model
  - Grid density and refinement
  - Order in spatial and temporal schemes

What It Took







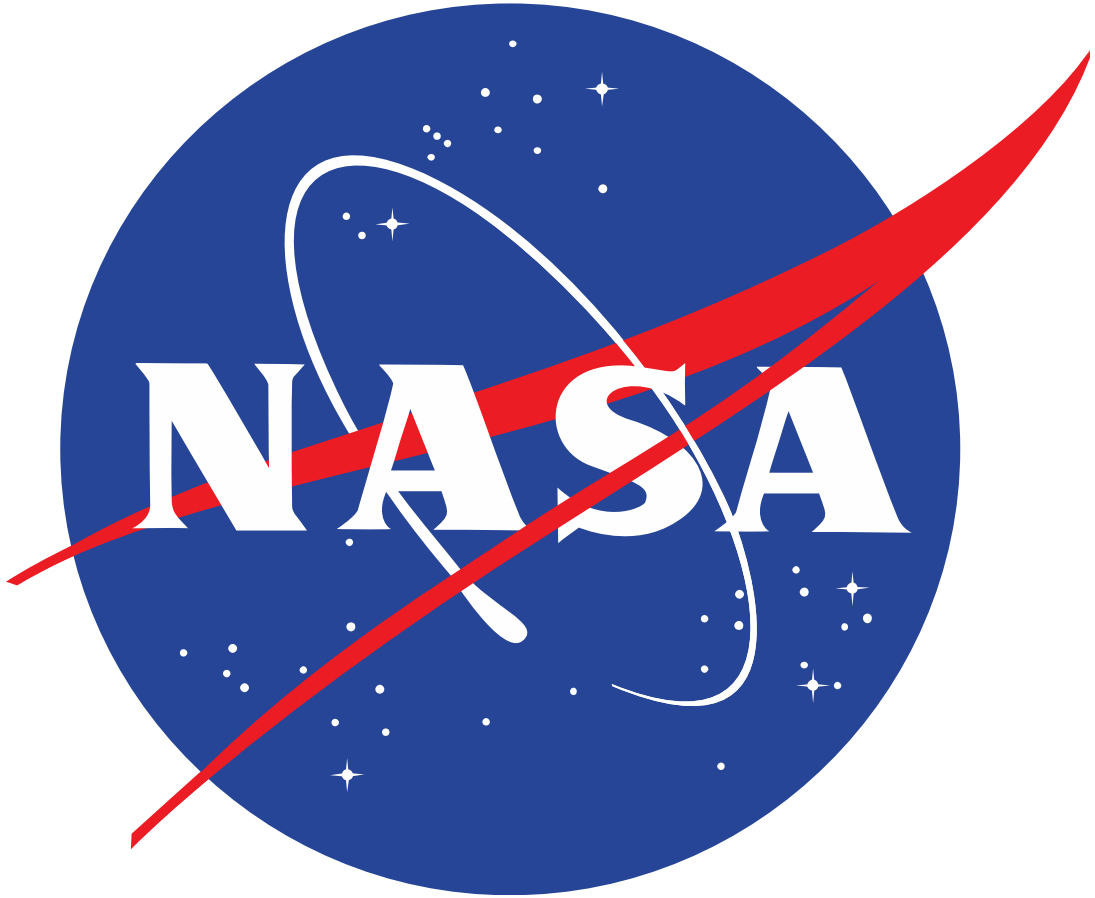


Source (all): NASA

Acknowledgments

- **Project leveraged individuals from many organizations**
- **NASA Langley – Key Team**
  - Richard Huang, intern
  - Sarah Langston, mentor
  - Steve Krist, mentor
- **NASA Langley – Support**
  - Meelan Choudhari
  - Mark Cagle
  - Kenny McNeil
  - Harlen Capen
- **Clay Nunnally, MLB**
- **Washington State University**
  - Lloyd Smith
  - Bin Lyu
  - Nick Smith
- **Bart Smith, Utah State University**
- **John Garrett, Rapsodo**
- **Alan Nathan, University of Illinois**

Questions?



brent.w.pomeroy@nasa.gov