



A Numerical Investigation of Parachute Deployment in Supersonic Flow

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AIAA Science and Technology Forum and Exposition 2020

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Outline



☐ Introduction and Motivation

- Overview, Problem Description

☐ Overview of FSI Method

- Immersed Boundary Method (CFD)
- Nonlinear Finite Element Method (CSD)
- Parallel loose coupling framework

☐ Developments

- Adaptive mesh refinement
- Parallel contact algorithm
- Robust flow field sampling
- Porosity interface condition

☐ Demonstration

☐ Conclusion and Outlook



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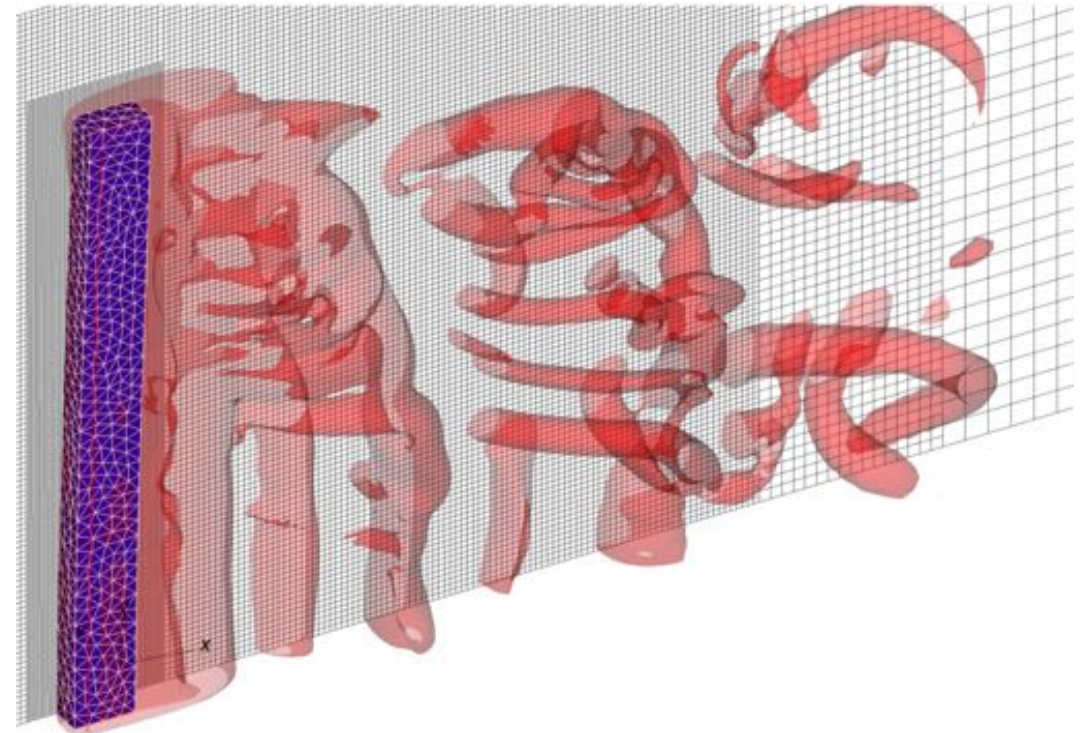
Introduction



- This is a continuation of a research effort studying supersonic parachute inflation with Immersed Boundary Methods (IBM) and Nonlinear Finite Element Methods (FEM)

“An Immersed Boundary Method for Solving the Compressible Navier-Stokes Equations with Fluid-Structure Interaction”

AIAA 2016 Aerospace Sciences Meeting
Brehm, C., Barad, Michael F., Kiris, Cetin C.





Introduction

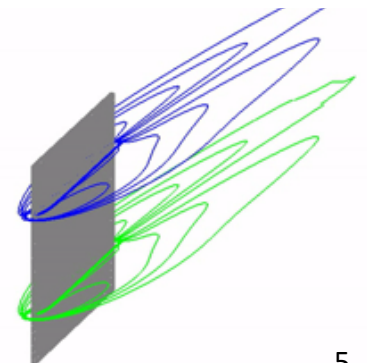
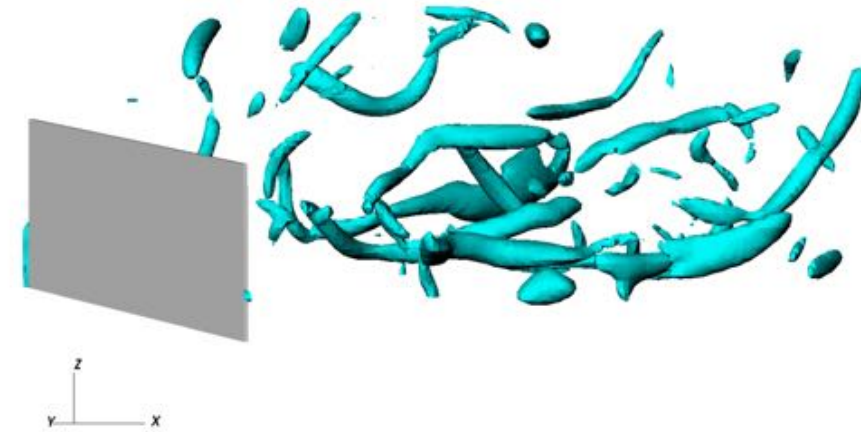
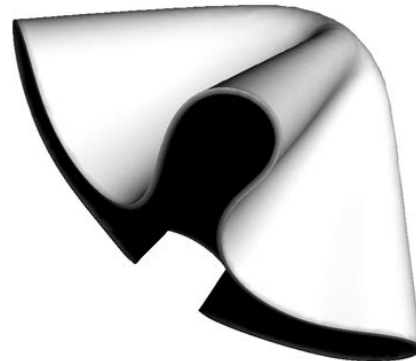
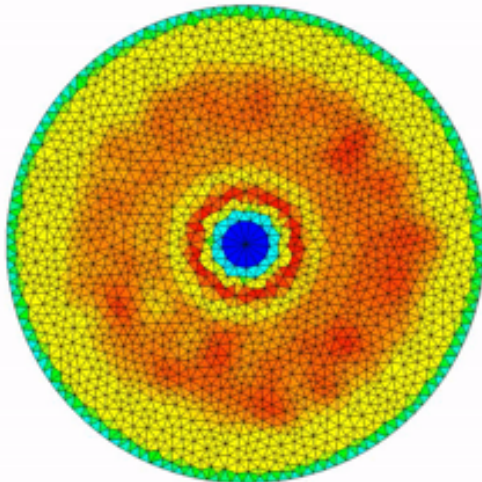


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“Fluid-Structure Interactions with Geometrically Nonlinear Deformations”

AIAA 2019 Science and Technology Forum and Exposition

Boustani, J., Browne, Oliver M. F., Wenk, Jonathan F., Barad, Michael F., Kiris, Cetin C., Brehm, C





Introduction

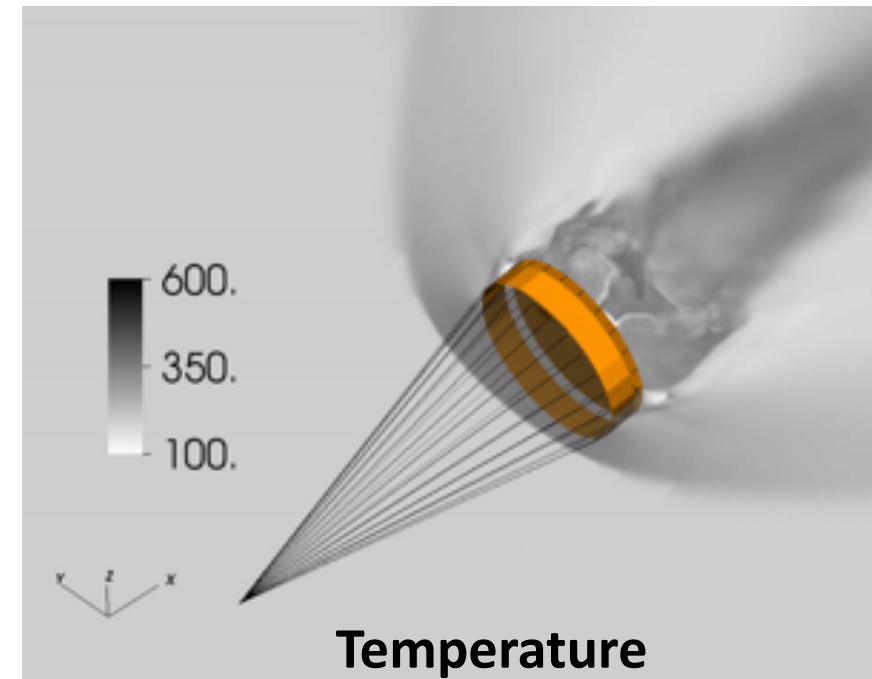
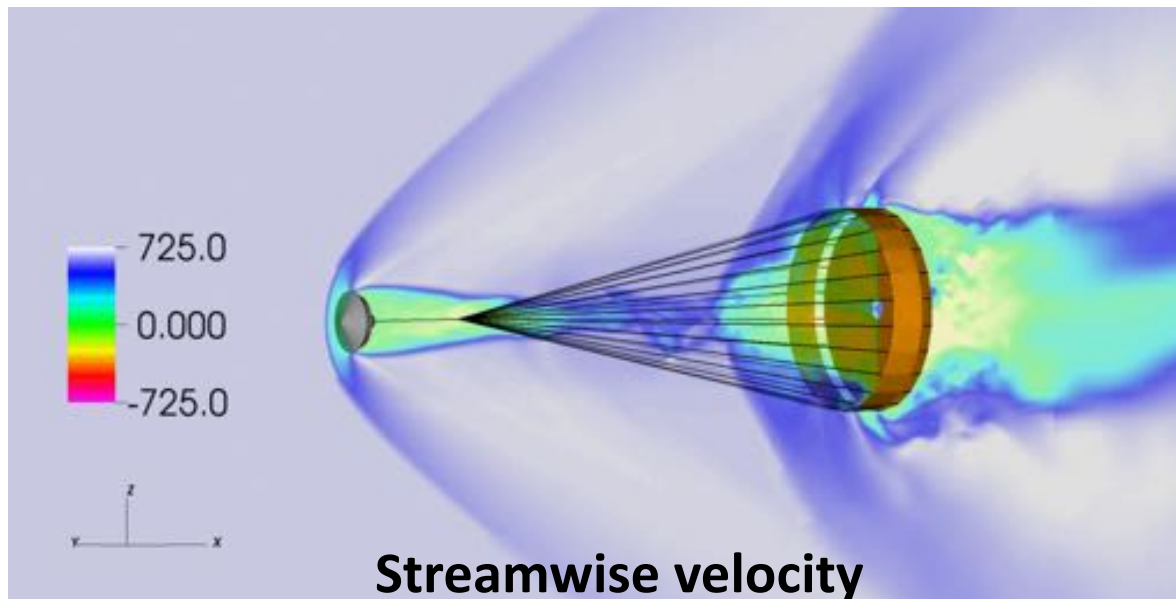


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“Fully-Coupled Fluid-Structure Interaction Simulations of a Supersonic Parachute”

AIAA 2019 Aviation Forum and Exposition

Boustani, J., Barad, Michael F., Kiris, Cetin C., Brehm, C





Introduction



- ❑ The goal of this effort is to develop computational methods for parachute performance prediction in supersonic conditions

- ❑ This work extends the validated computational FSI method to consider developments necessary for further studying supersonic parachute inflation
 - Robust sampling from the flow field onto the structure
 - A unique, parallel (self-) contact algorithm
 - A porosity interface condition
 - Adaptive mesh refinement



Motivation



□ The problem identified is two-fold:

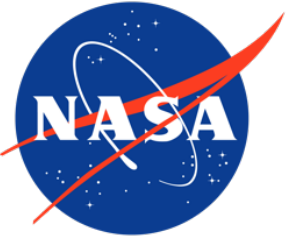
- I. There is a reliance on costly, time-consuming real-world drop tests and wind tunnel tests used for parachute qualification. Computational methods play, at best, a supporting role
- II. There is a knowledge gap in understanding how relevant broadcloth materials respond during the unsteady inflation process, where they are exposed to transient, unpredictable loading patterns — usually induced by the turbulent wake of some bluff upstream capsule



(NASA/JPL)



(O'Farrell *et al.* 2018)



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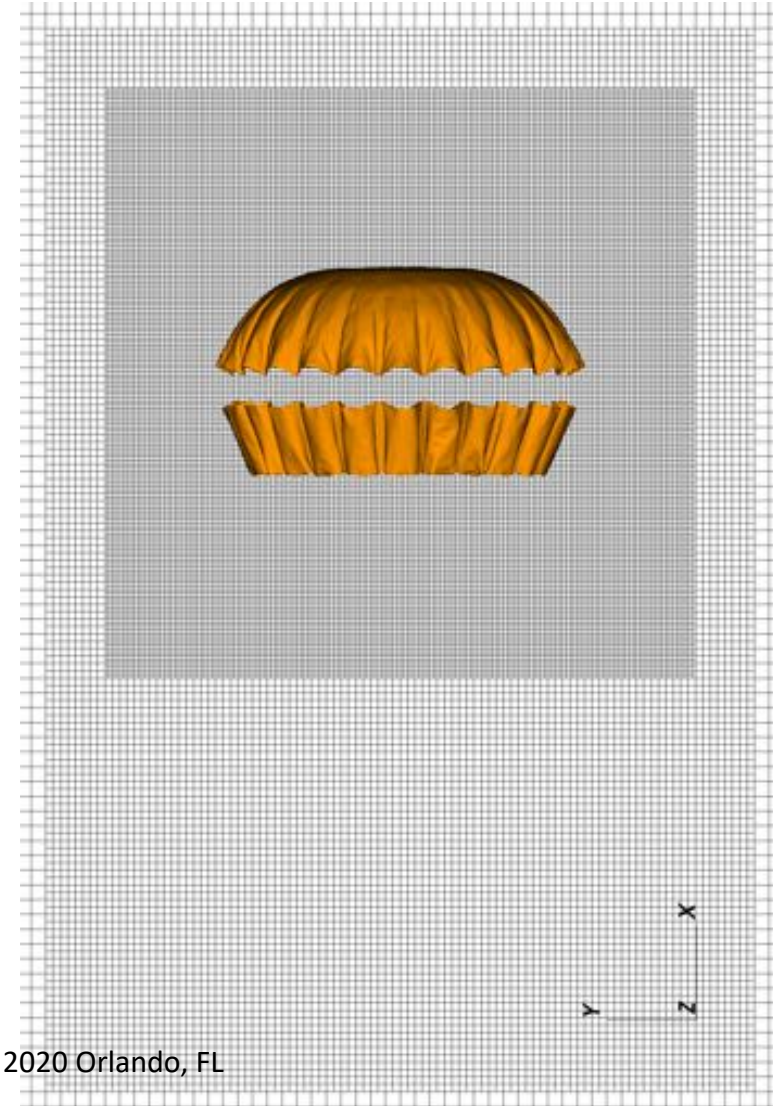
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Higher-Order IBM



- ❑ **Automatic volume mesh generation**
 - For any arbitrarily complex geometry
- ❑ **FD stencil coefficients at irregular grid points are locally optimized**
 - Improved global stability
- ❑ **Higher-order accurate**
 - 5th-order accurate WENO5 for convective terms
 - 2nd/4th-order RK explicit time integration

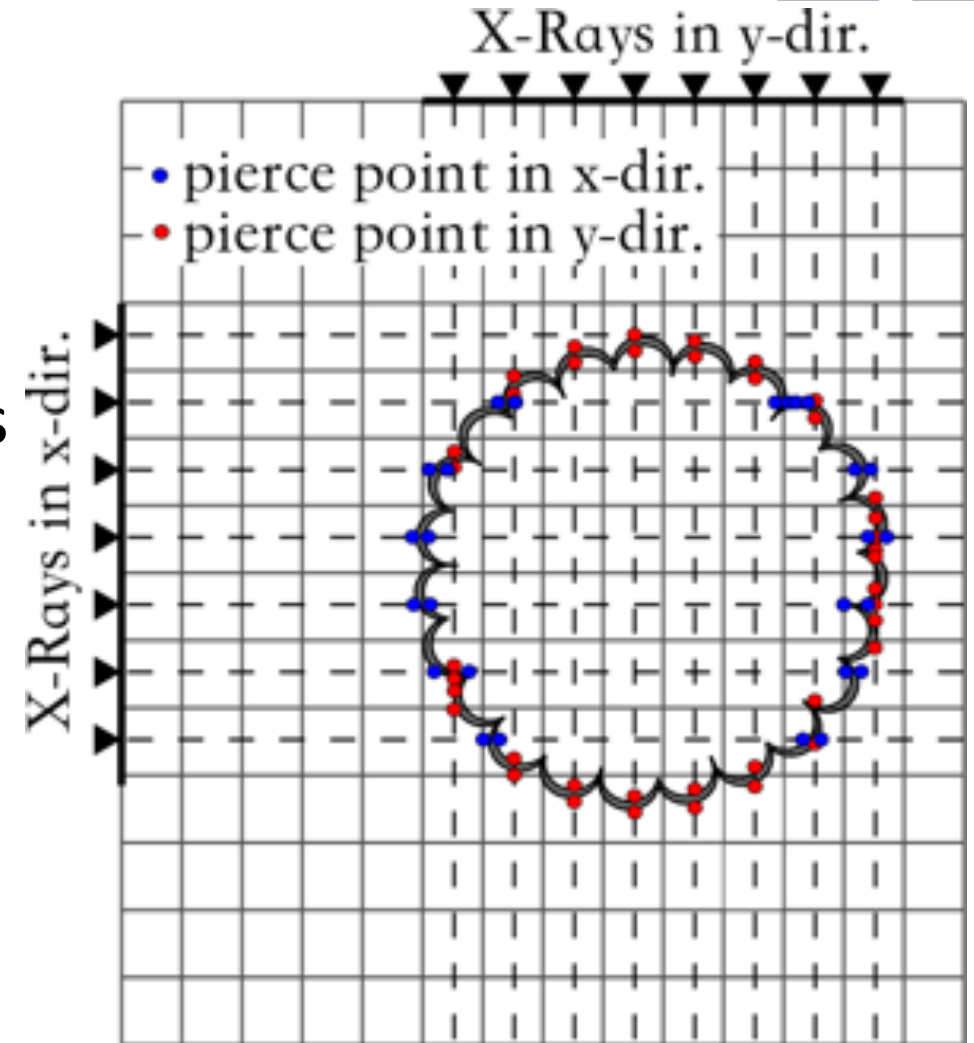




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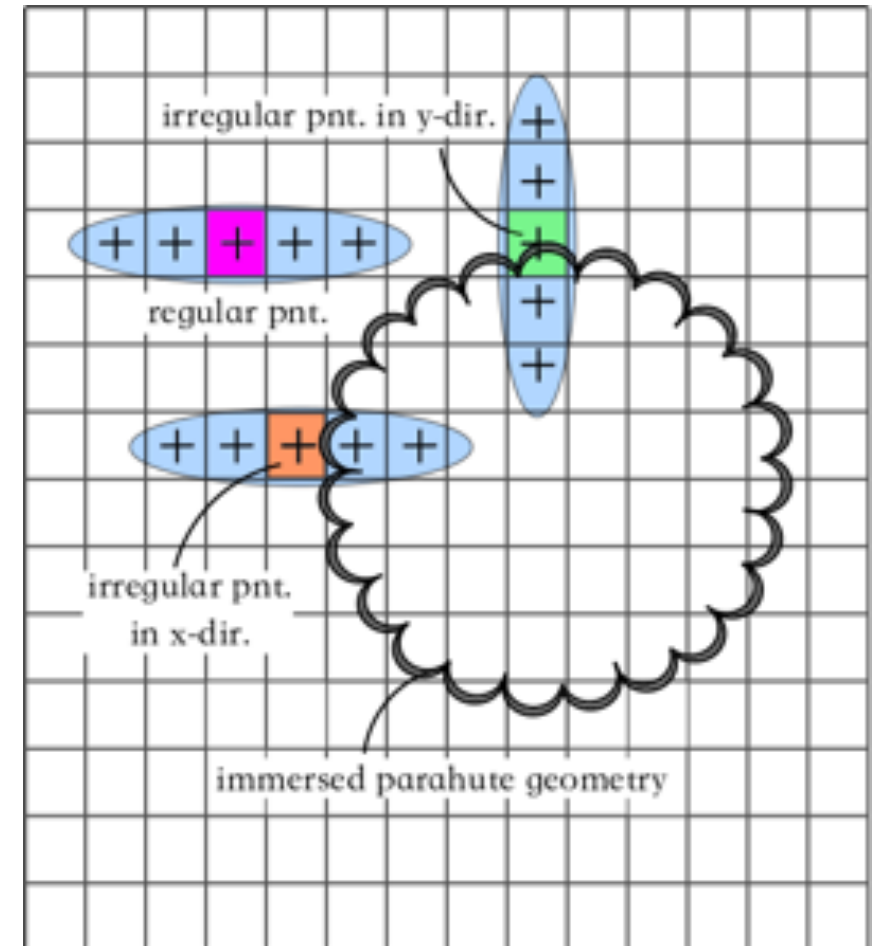




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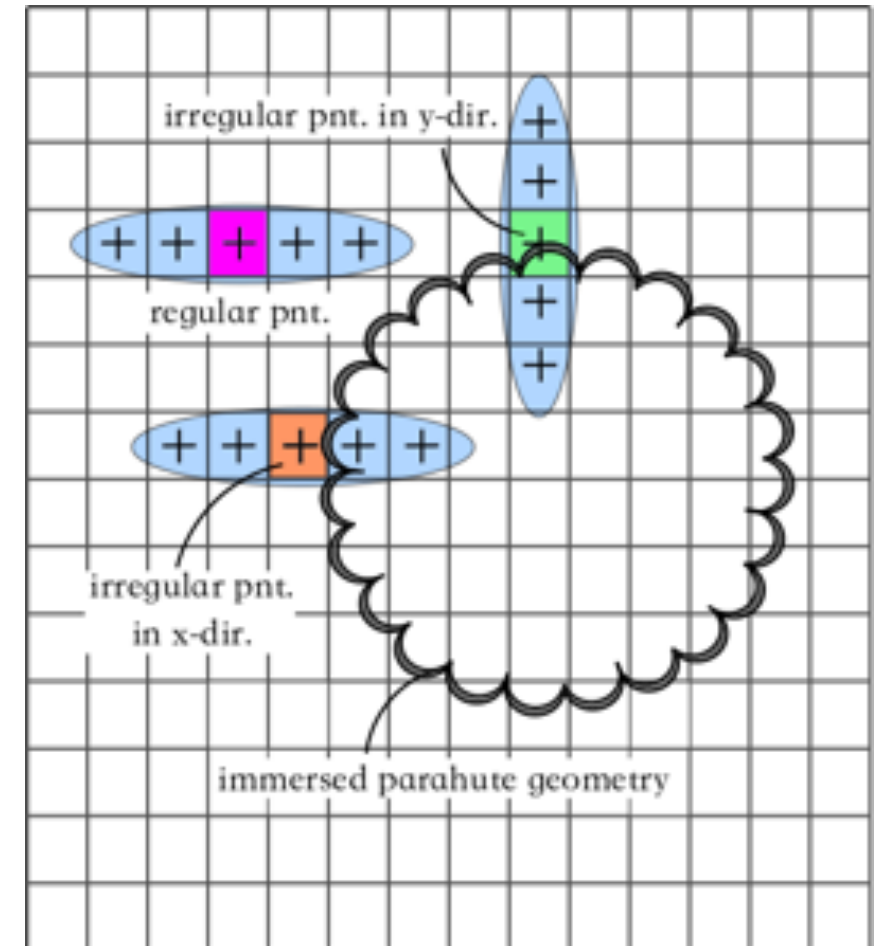


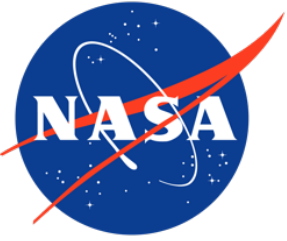


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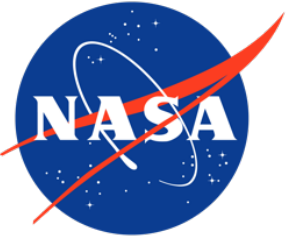
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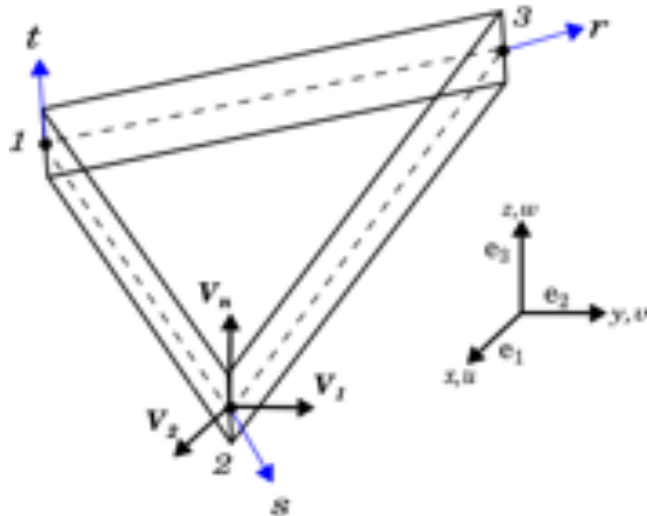
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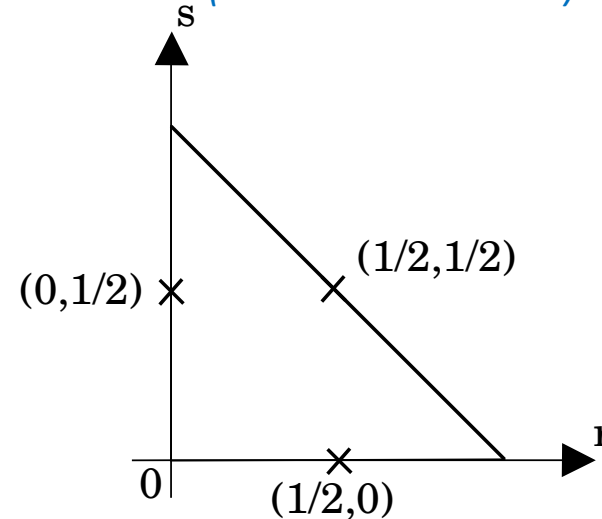
MITC3 Shell Element



- ❑ One method of assumed strain variation for shell and plate elements is the Mixed Interpolation of Tensorial Components (MITC)
 - The corresponding triangular shell element is the MITC3 *(Lee and Bathe 2004)*

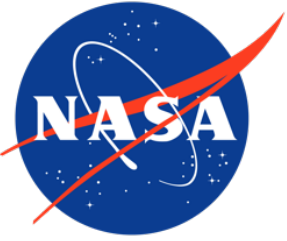


The MITC3 element and director vectors.
(Lee and Bathe 2004)



The tying points in the isoparametric basis.
(Lee and Bathe 2004)

- ❑ More details can be found in Boustani *et al.* SciTech 2019, Boustani *et al.* Aviation 2019



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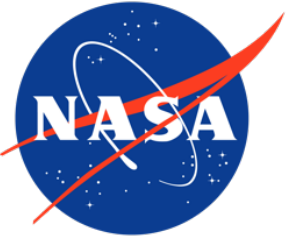
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FSI Method



❑ The method used in this work couples together

- I. A block-structured Cartesian, higher-order, sharp, immersed boundary method for the compressible Navier-Stokes equations

Brehm, C., Fasel, H., JCP 2013

Brehm, C., Hader, C., Fasel, H., JCP 2015

Kiris et al., Aerospace Sci. and Tech. 2016

Brehm, C., Barad, M. F., Kiris, C. C., JCP 2019

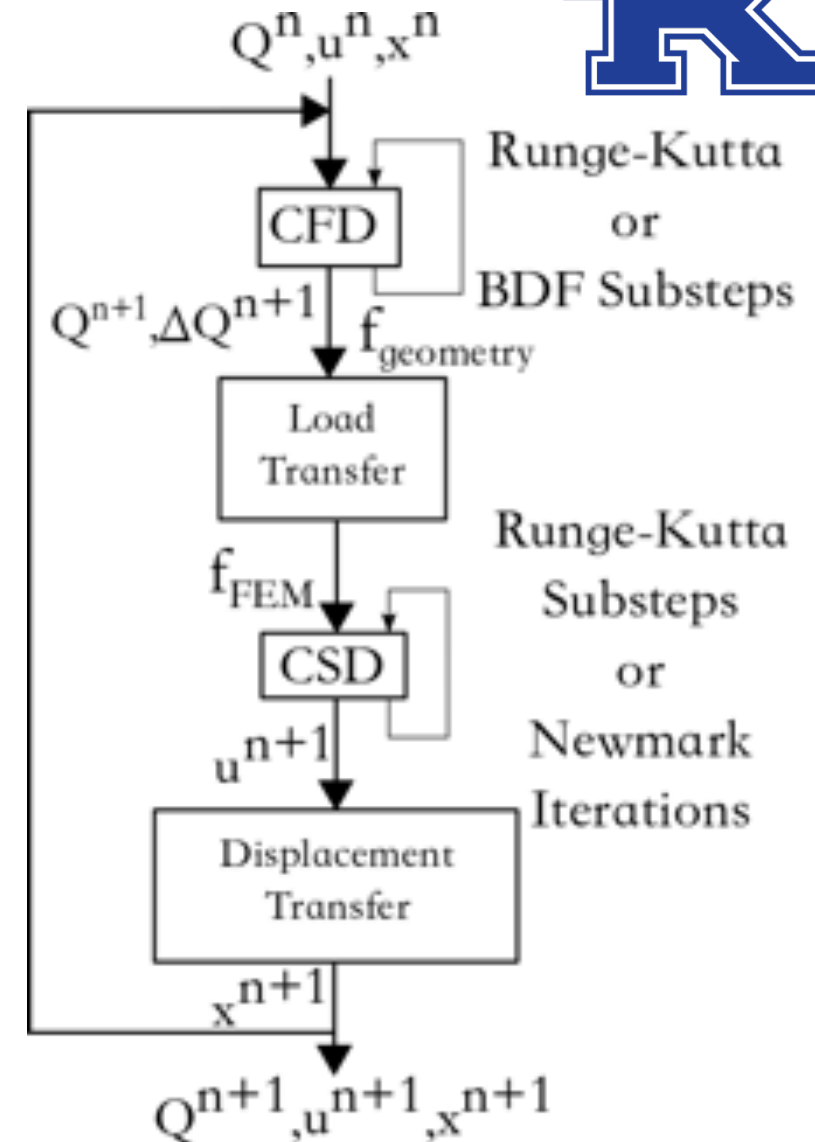
- II. A nonlinear structural finite element solver employing shell elements that utilize the Mixed Interpolation of Tensorial Components

Boustani et al., AIAA SciTech 2019

Boustani et al., AIAA Aviation 2019

Boustani et al., JCP 2019 (in progress)

❑ More details can be found in Boustani et al. SciTech 2019, Boustani et al. Aviation 2019





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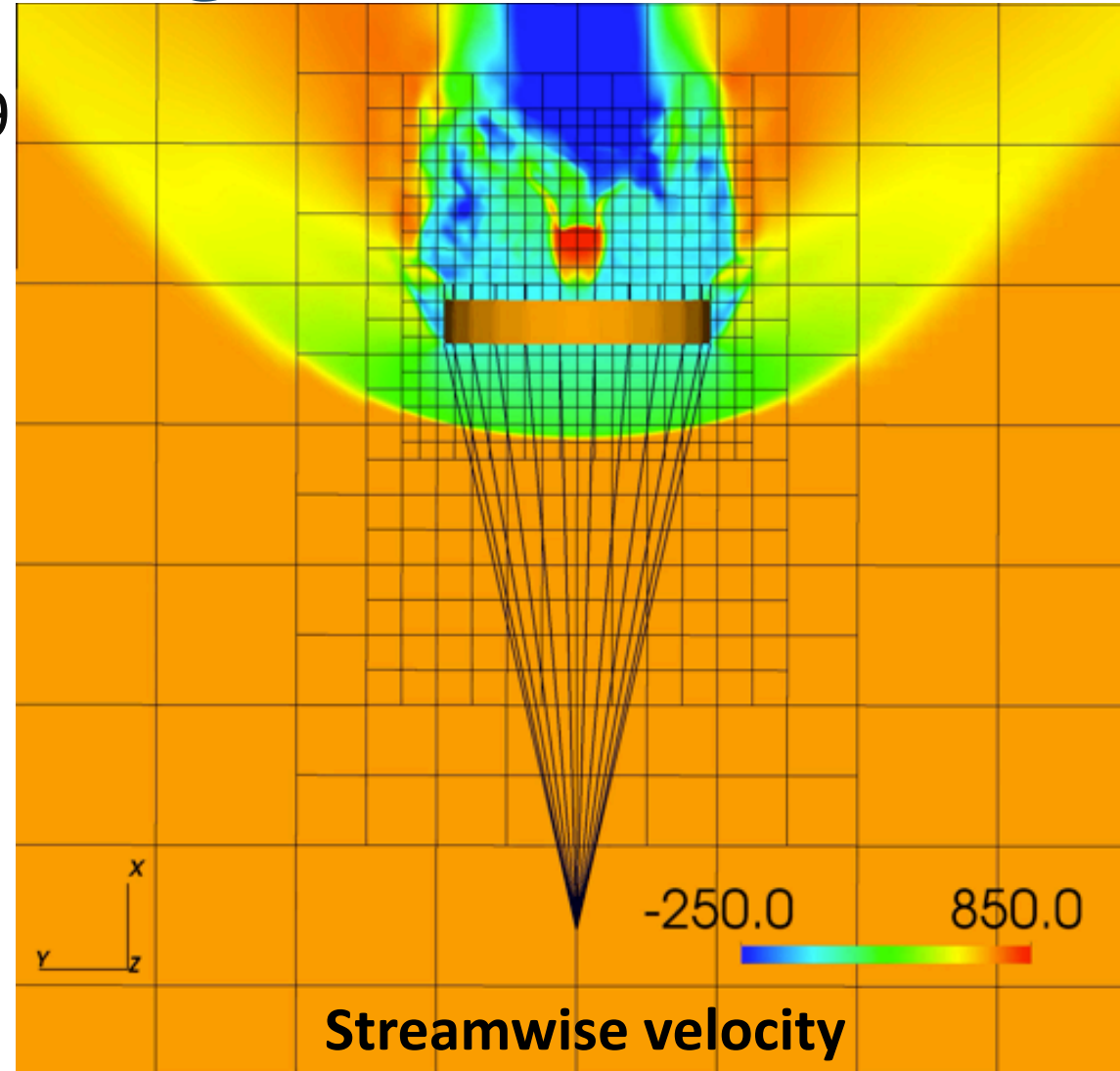
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Starting Point



- ☐ Ending point from Aviation 2019
- ☐ Sampling robustness
- ☐ Impermeable
- ☐ Contact not identified
- ☐ Static refinement box





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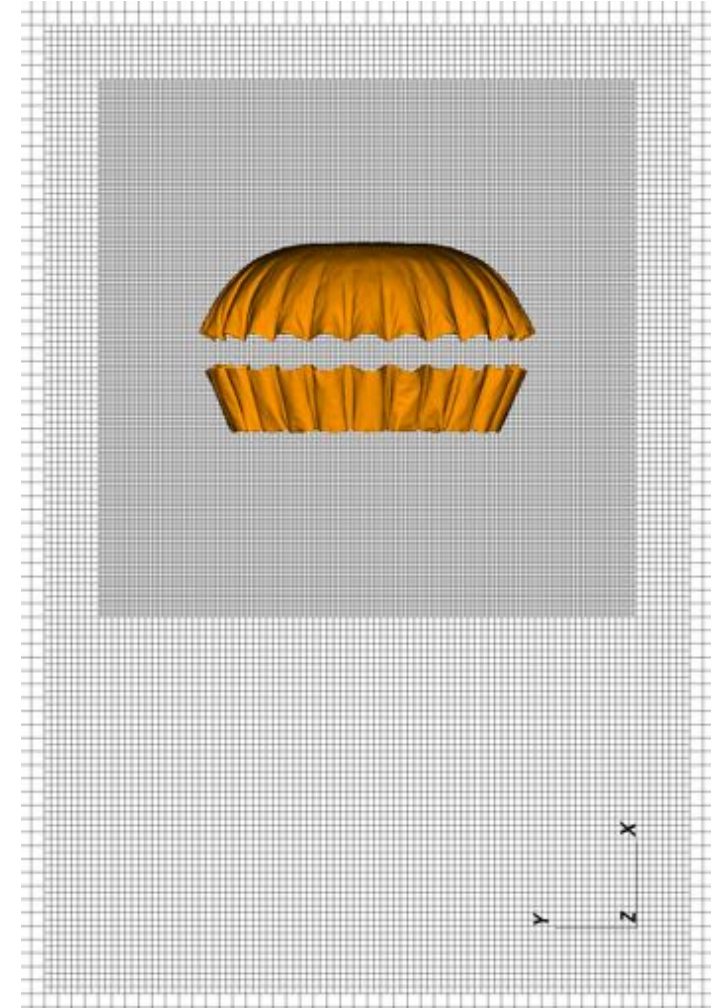
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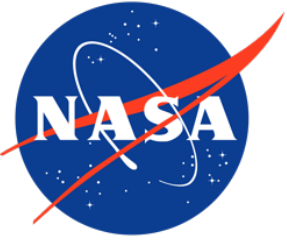


Adaptive Mesh Refinement



- ❑ Without adaptive mesh refinement (AMR), the finest level would have to be made *a priori* large enough to always contain the geometry
 - For X-Ray tracing and related procedures
- ❑ Inefficient to track the geometry
- ❑ Utilizing AMR also provides the ability to efficiently track flow features of interest





Adaptive Mesh Refinement



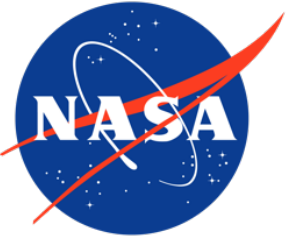
□ Two refinement criteria are used in this work:

1. Pressure gradient

- Uses second finest level
- Primary purpose is bow shock tracking

2. Geometry tracking

- Uses finest level
- Primary purpose is efficient tracking of arbitrarily large geometry displacements



Adaptive Mesh Refinement



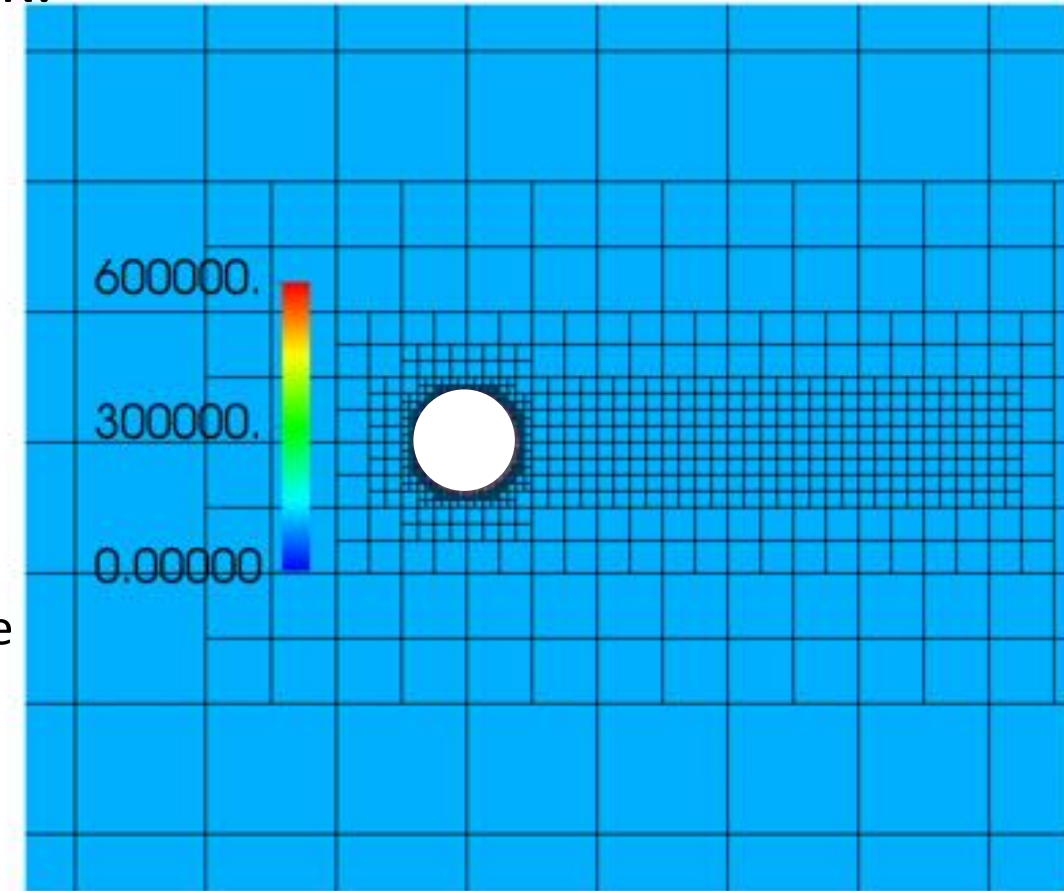
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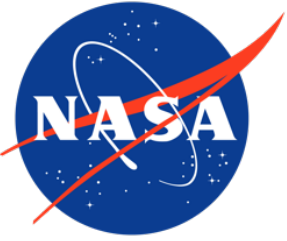
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AMR Demonstration on a Mach 2.0, 2D sphere



Adaptive Mesh Refinement



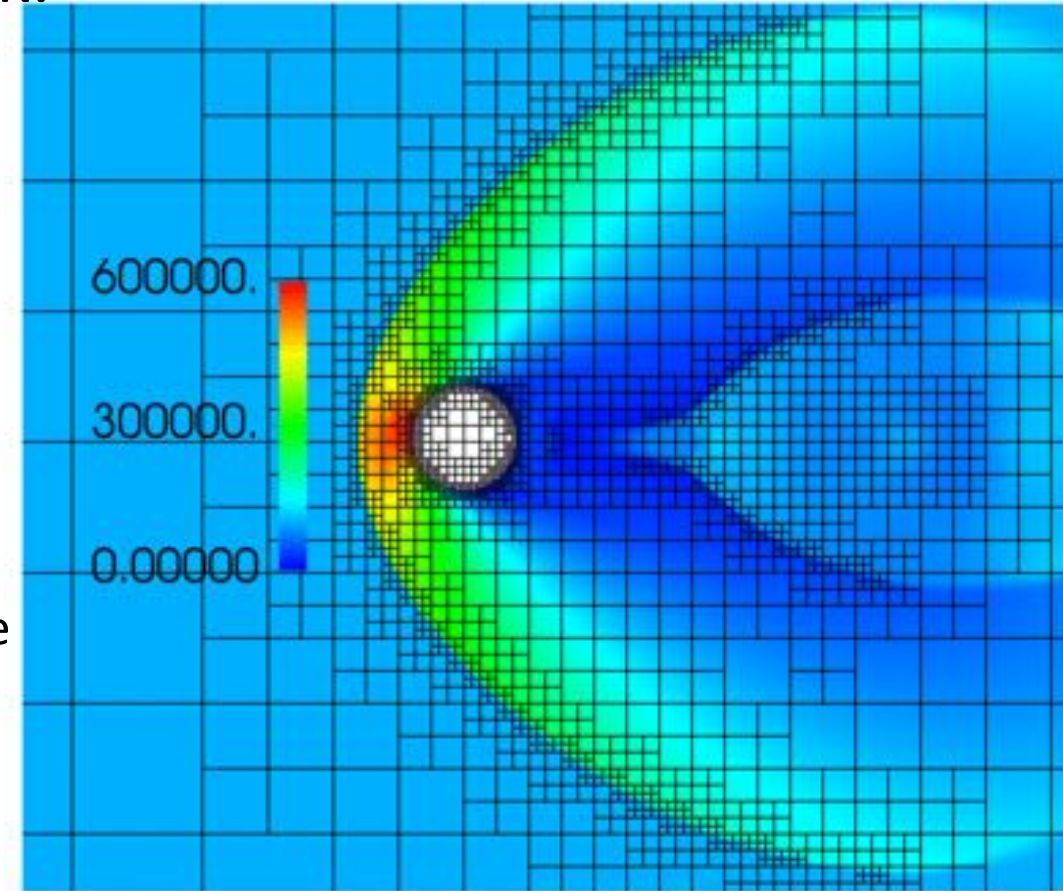
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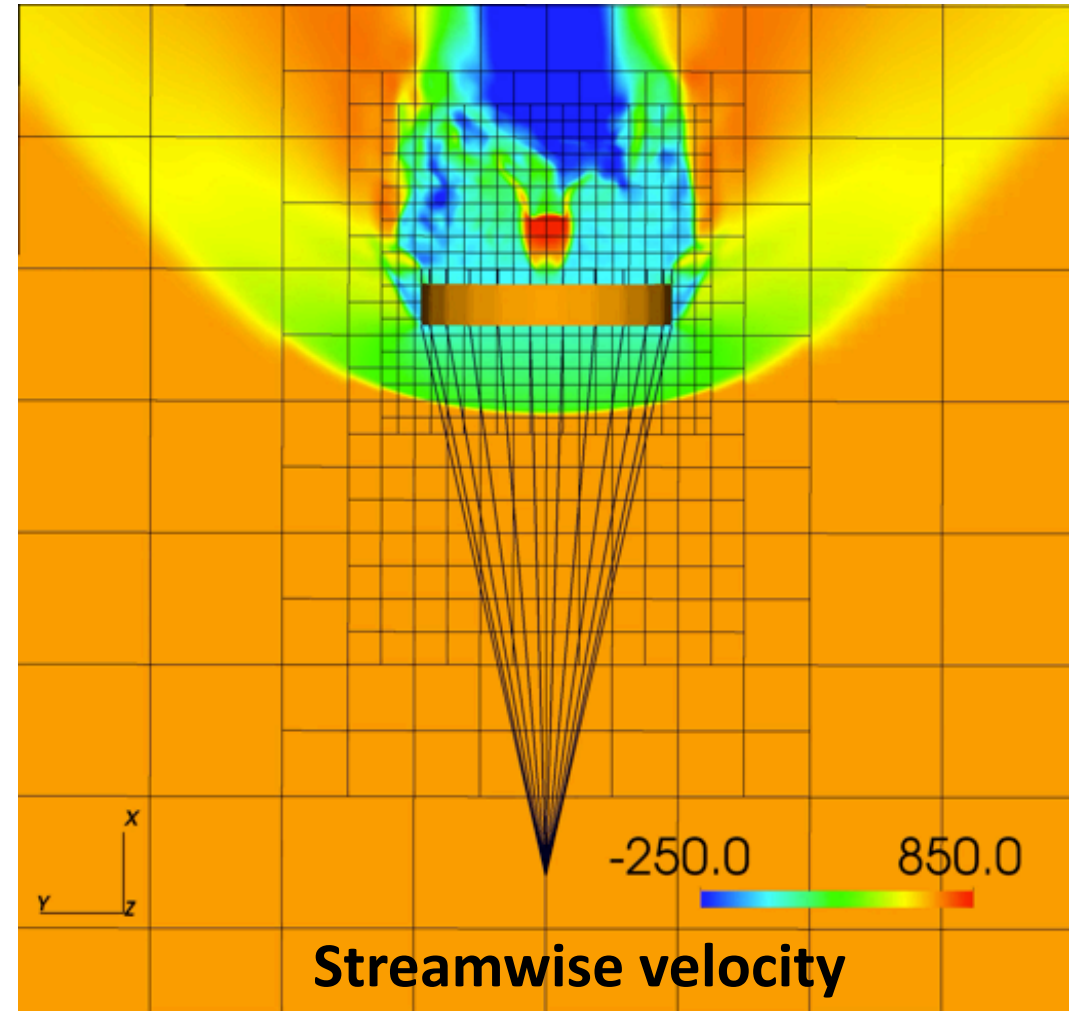
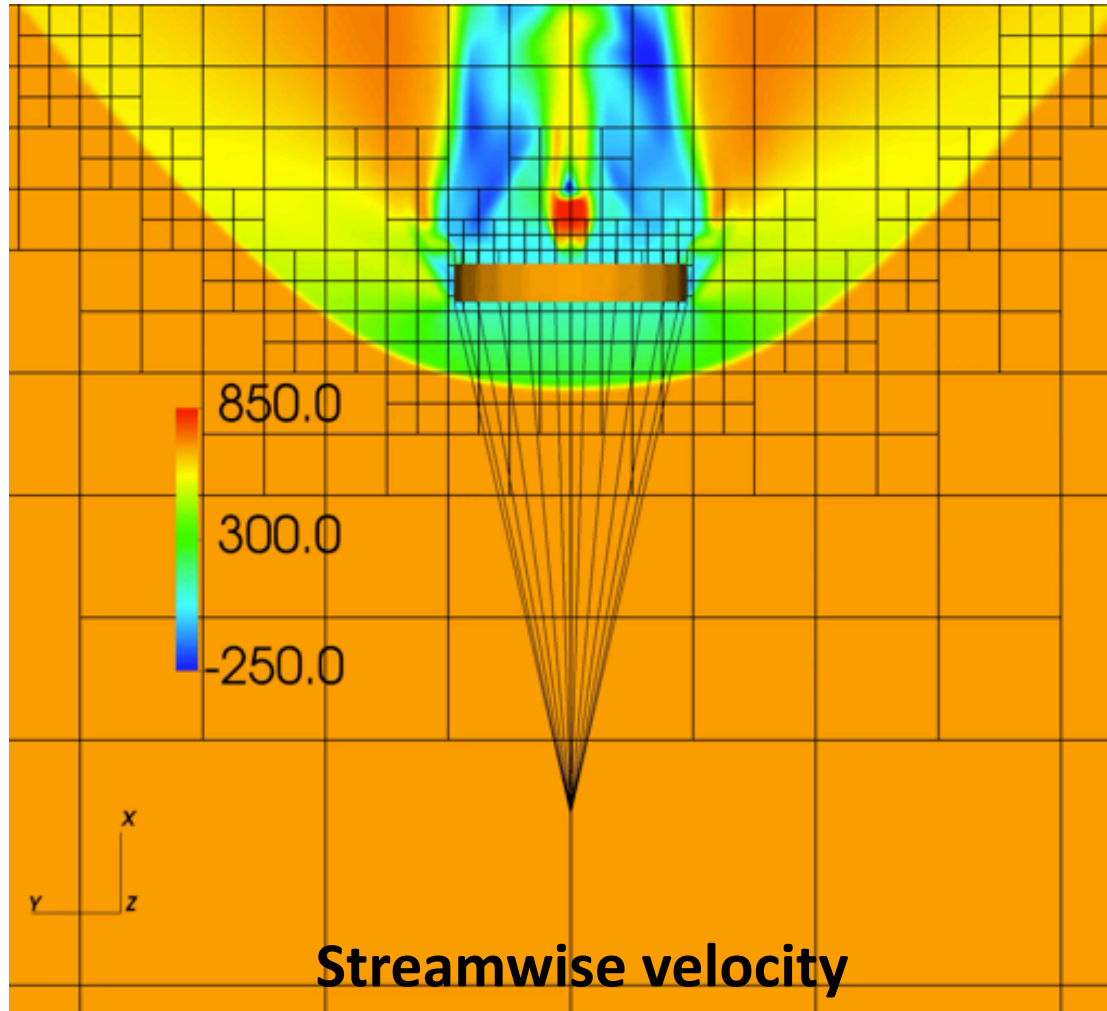
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AMR Demonstration on a Mach 2.0, 2D sphere



FSI with AMR





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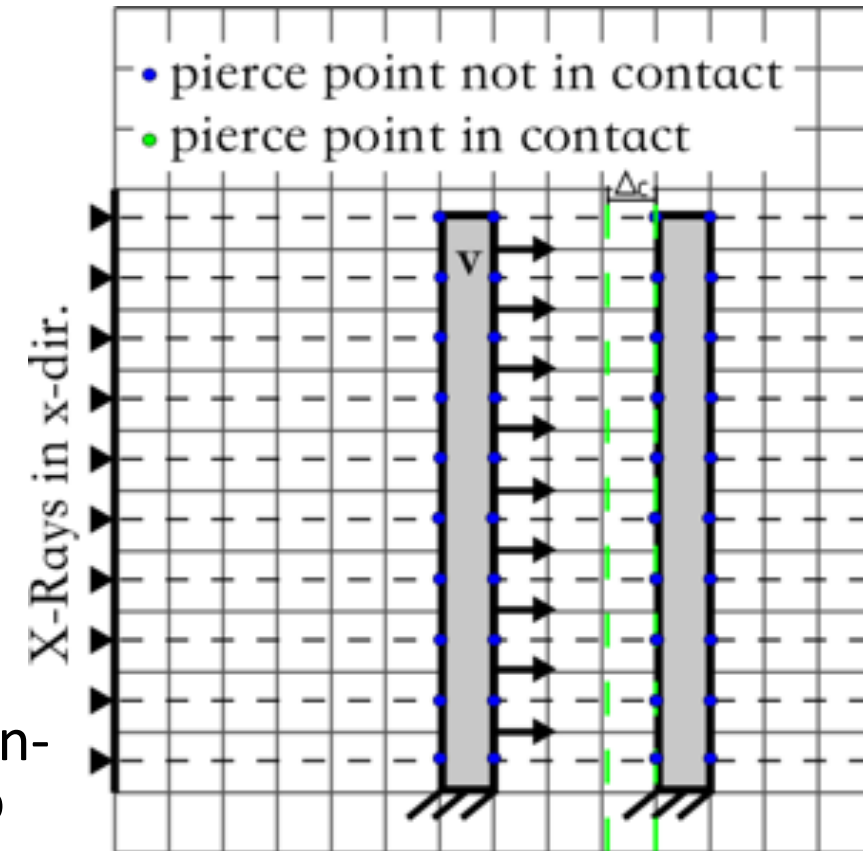


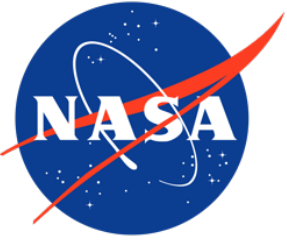
Parallel Contact Algorithm



Identification

- ❑ Contact identified in Eulerian-framework via the distance between pierce points, from x-ray tracing
 - x-ray process is already necessary, no extra cost
- ❑ Can identify contact outside each rank's partition
 - Contact identification extends into guard cells outside each partition
 - Give each rank access to the global triangulation
 - Can uniquely enforce on elements within your rank
- ❑ Only searching through pierced elements reduces Lagrangian-type search from possibly millions of elements to exactly two contacting elements





Parallel Contact Algorithm



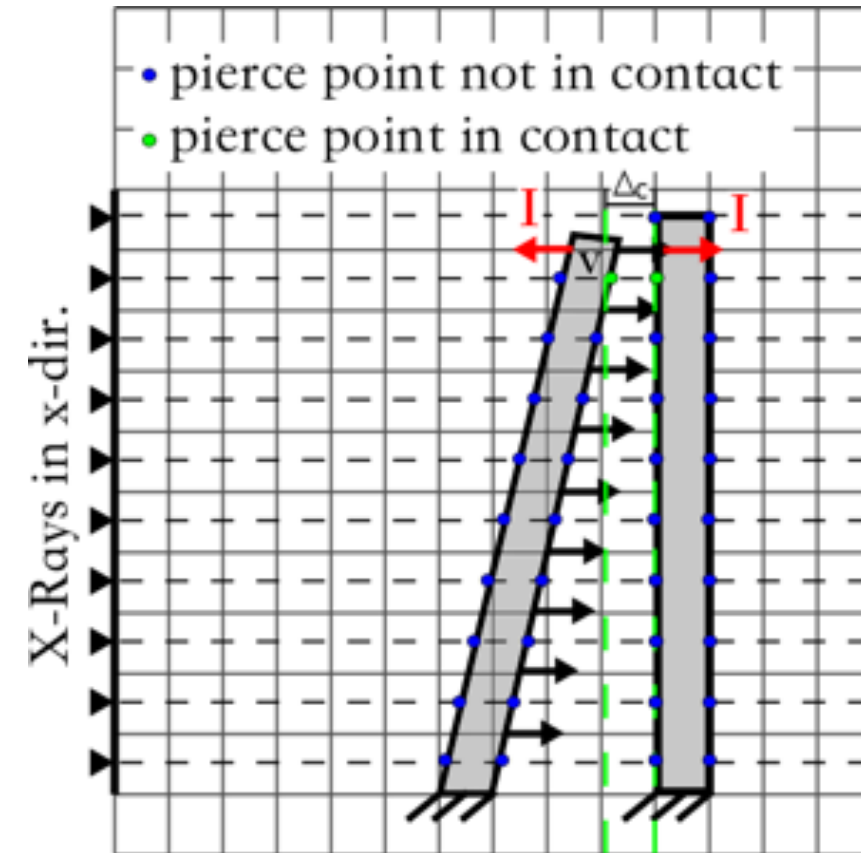
Enforcement

- ❑ Use the conservation of momentum to compute velocities after an inelastic collision

- ❑ Use linear impulse-momentum to compute the impulse required to enforce the velocity change

$$I_A = \int_t^{t+\Delta t} m_A (v_{A_f} - v_{A_i}) dt$$

- ❑ For 'self-contact', assume the contacting elements have the same mass

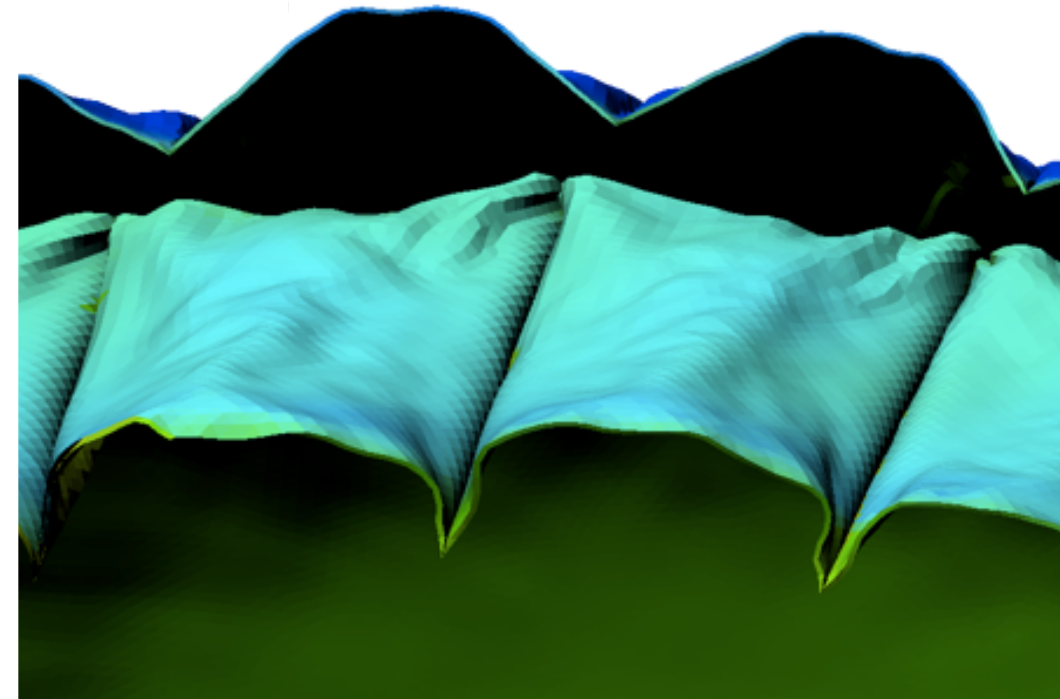




Parallel Contact Algorithm



- ❑ The contact impulse is given to the structural solver via the traction vector usually reserved for fluid dynamic tractions
- ❑ Thus, the structural solver enforces contact on the geometry representation secondhand
- ❑ Many ways to enforce, identification is the challenge



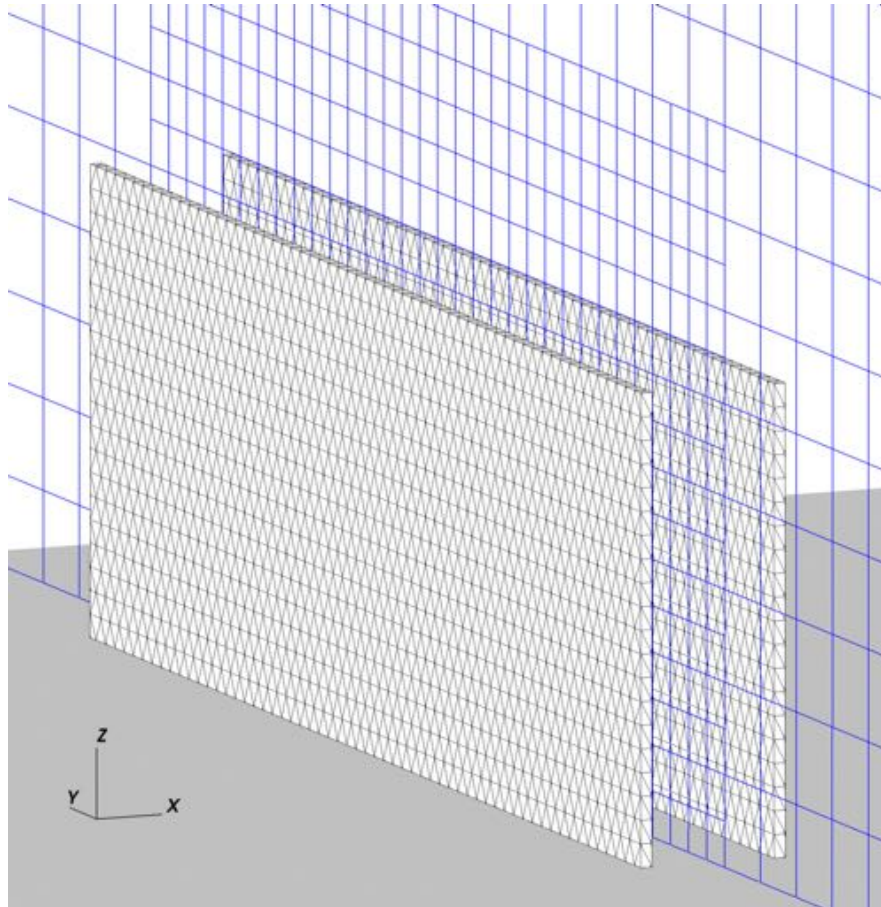
Demonstration in supersonic flow
Geometry is colored with pressure contours.



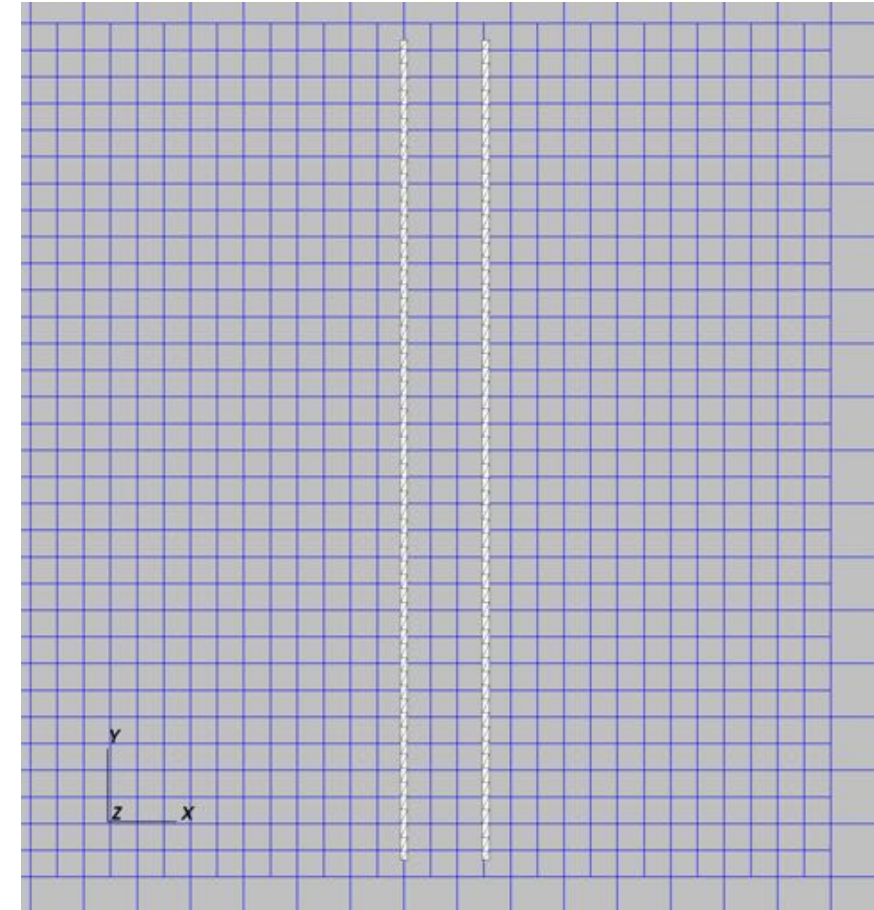
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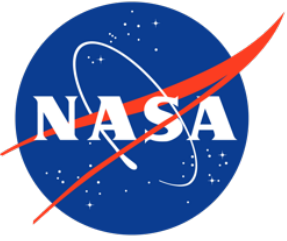
□ Demonstration of two colliding plates in a quiescent fluid:



Perspective view



Top-down view



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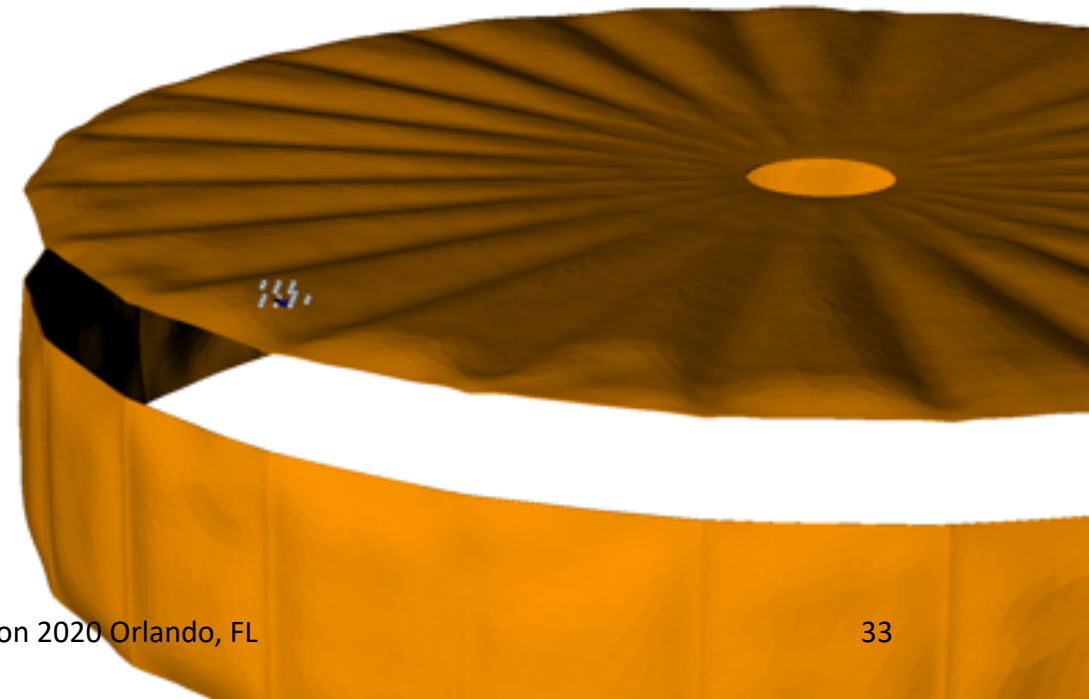
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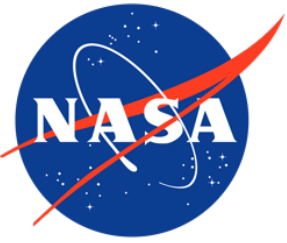


Robust Flow Field Sampling



- ❑ To obtain pressure and viscous tractions on the surface of the parachute, primitive flow field quantities are extrapolated from the flow field
- ❑ Each planar, triangular element of the geometry representation creates a 'cloud' of Cartesian grid points to use in WLSQR methods
- ❑ Usually, this is done by selecting a base point and building a cloud around it

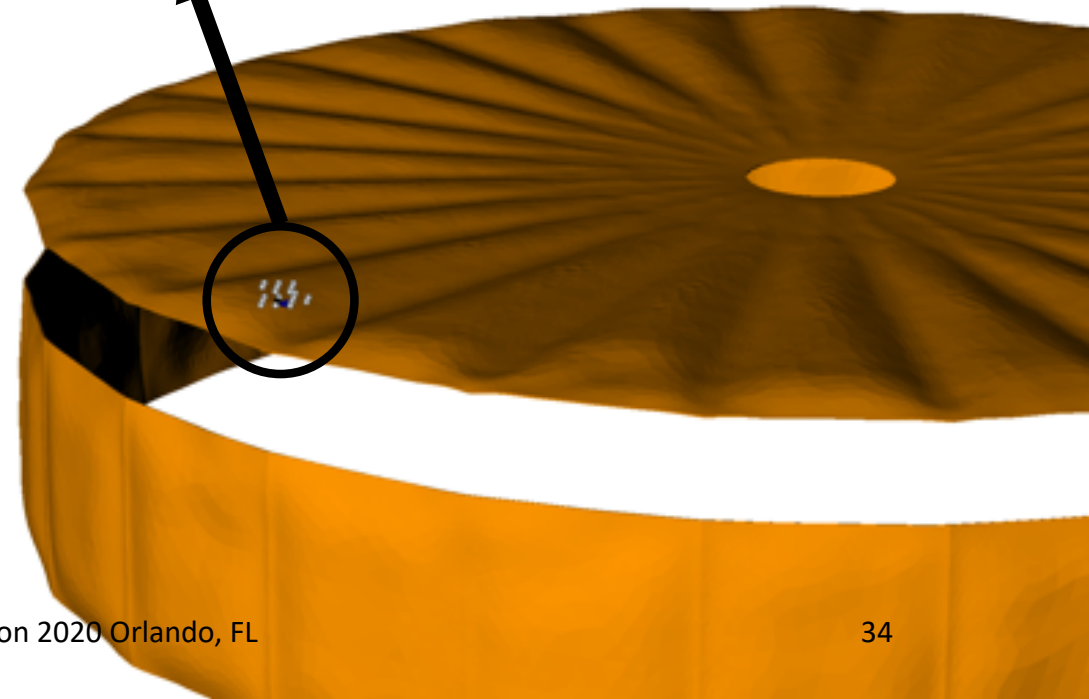
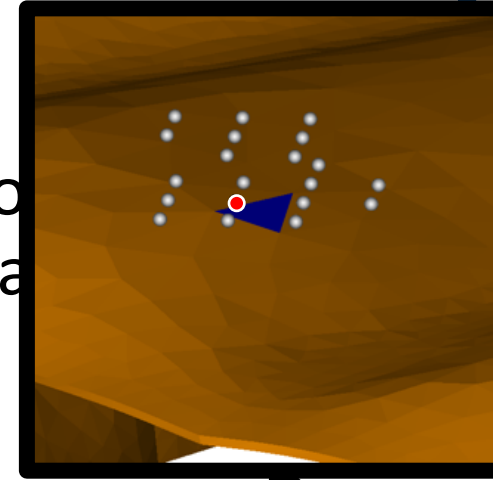




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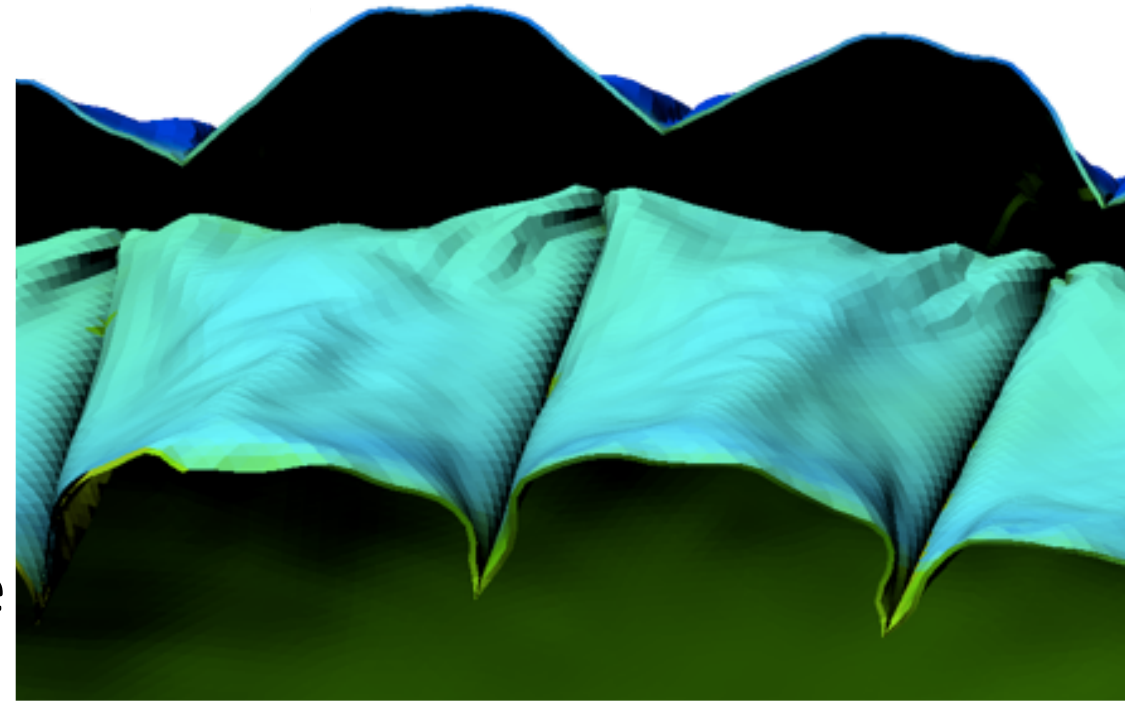




Robust Flow Field Sampling



- ☐ Selection of the base point, however, is not always straight forward
- ☐ The closest Cartesian grid point to the centroid is not always the best point
- ☐ The closest Cartesian grid point to a modified centroid location is not always the best point
- ☐ How can we reliably find a valid base point?

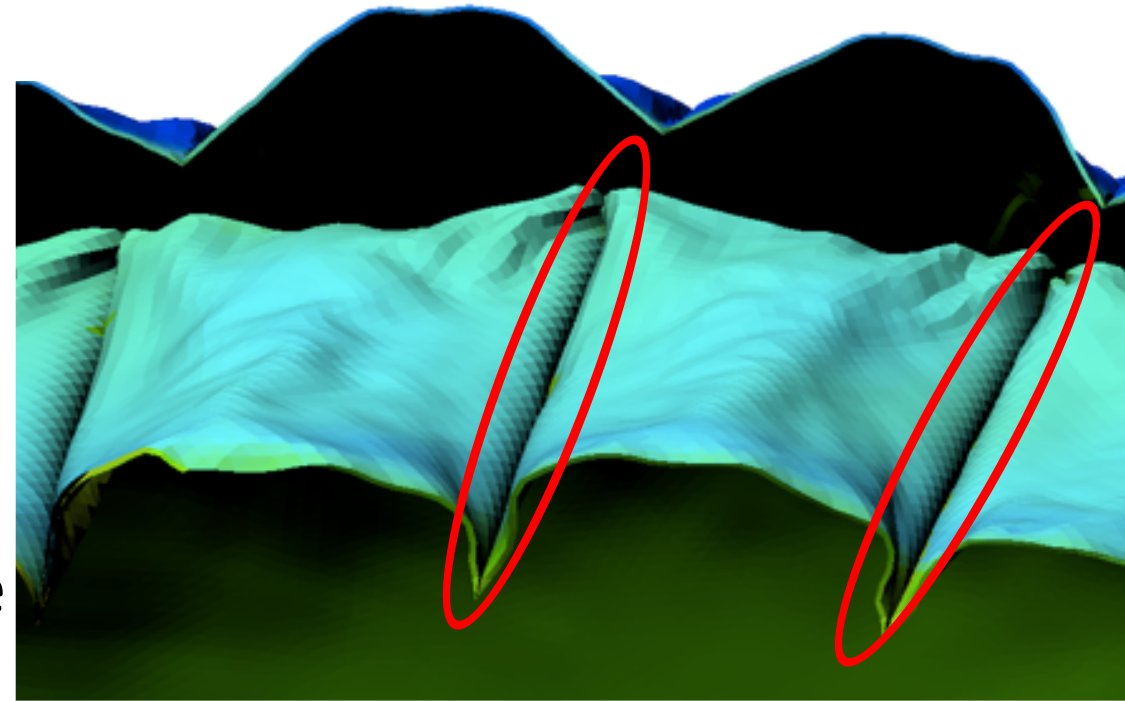


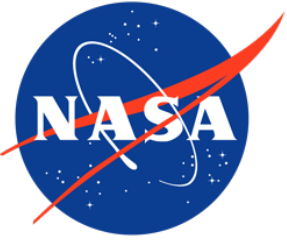


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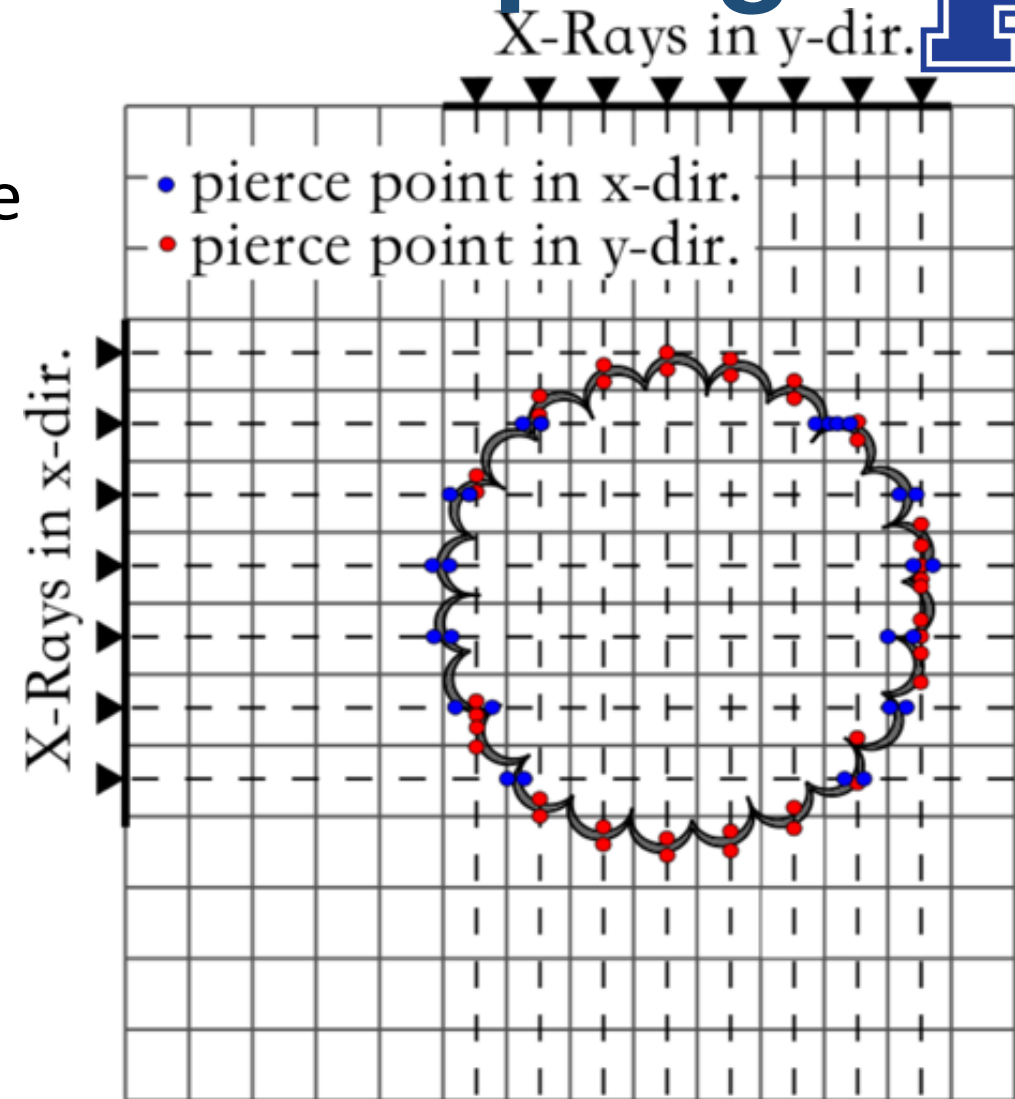


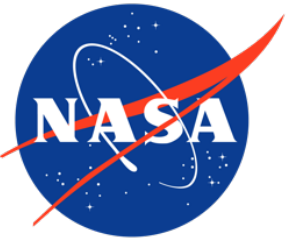


Robust Flow Field Sampling



- ❑ Irregular points are identified during the x-ray tracing process

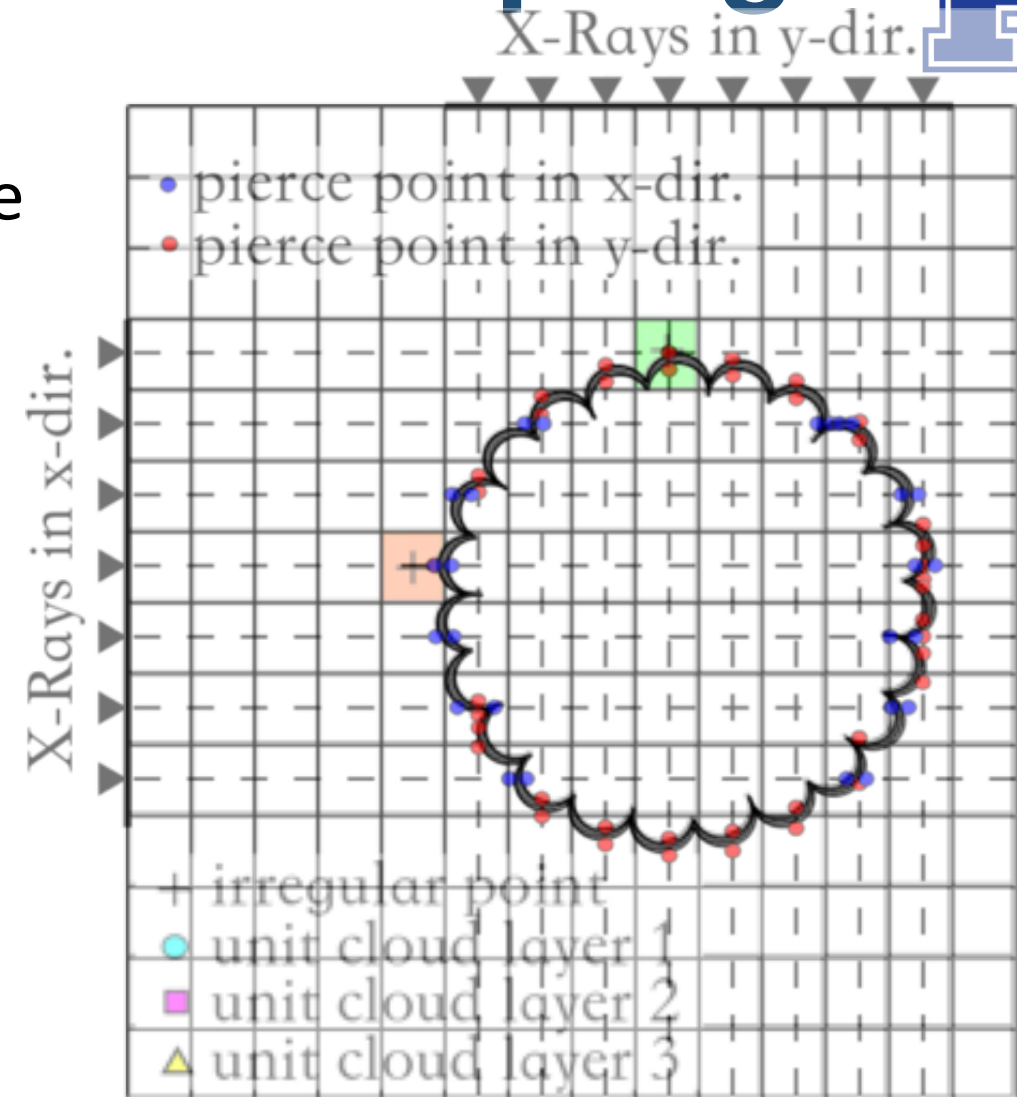




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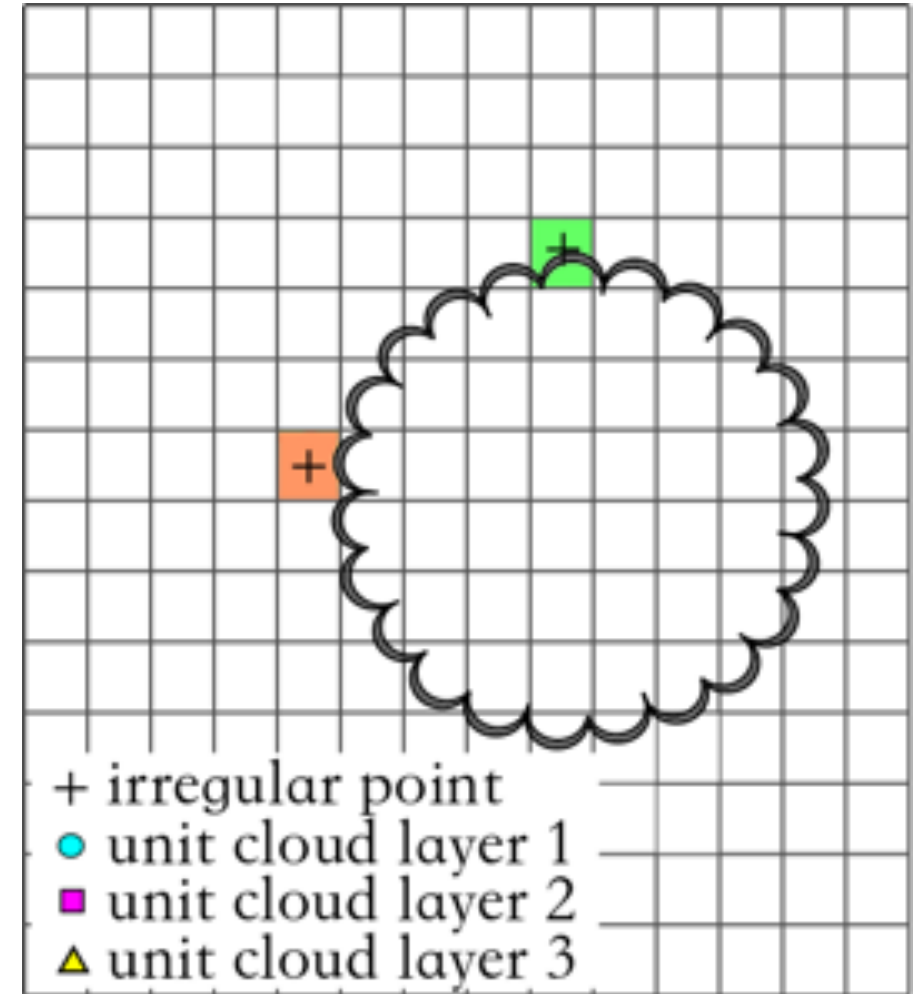


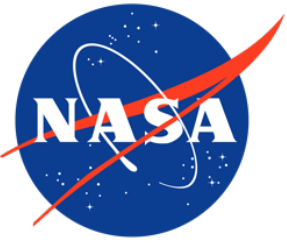


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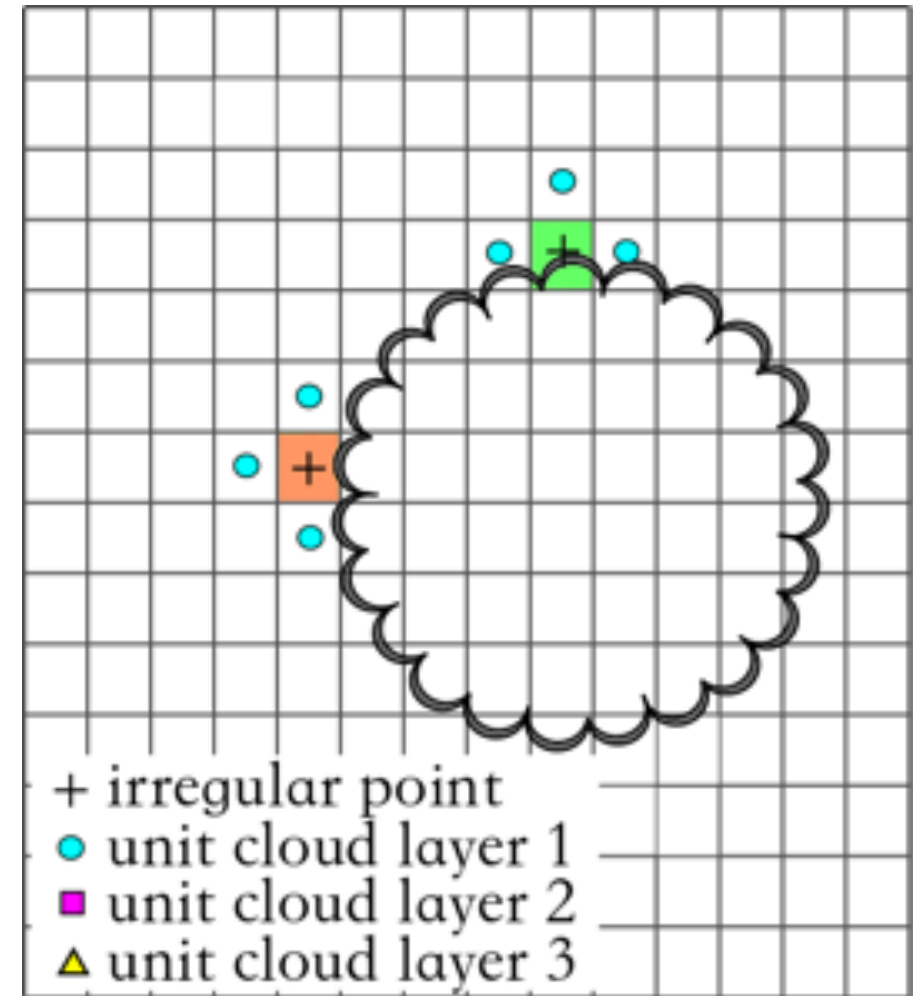


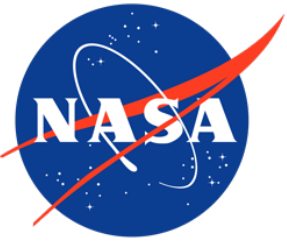


Robust Flow Field Sampling



- ❑ Irregular points are identified during the x-ray tracing process
- ❑ Utilize a careful graph walking approach to add the Cartesian grid points directly around the base point

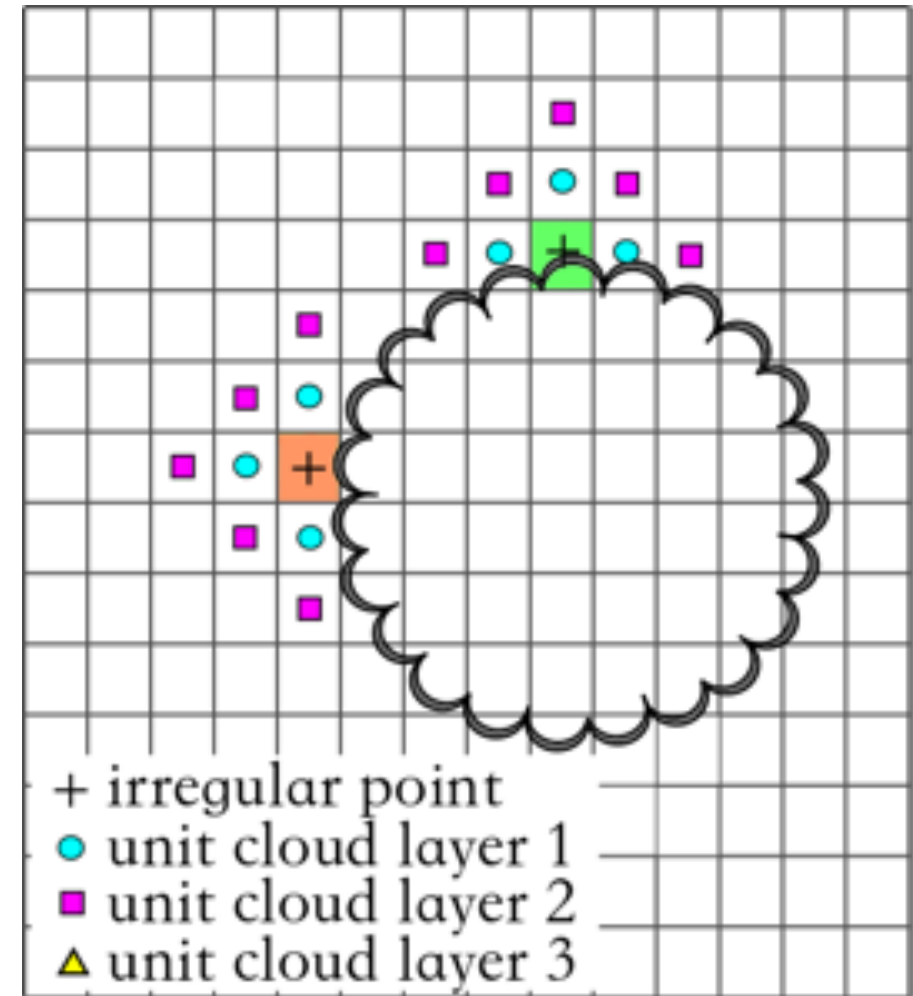




Robust Flow Field Sampling



- ❑ Irregular points are identified during the x-ray tracing process
- ❑ Utilize a careful graph walking approach to add the Cartesian grid points directly around the base point
- ❑ Repeat the graph walking approach on the first unit cloud layer

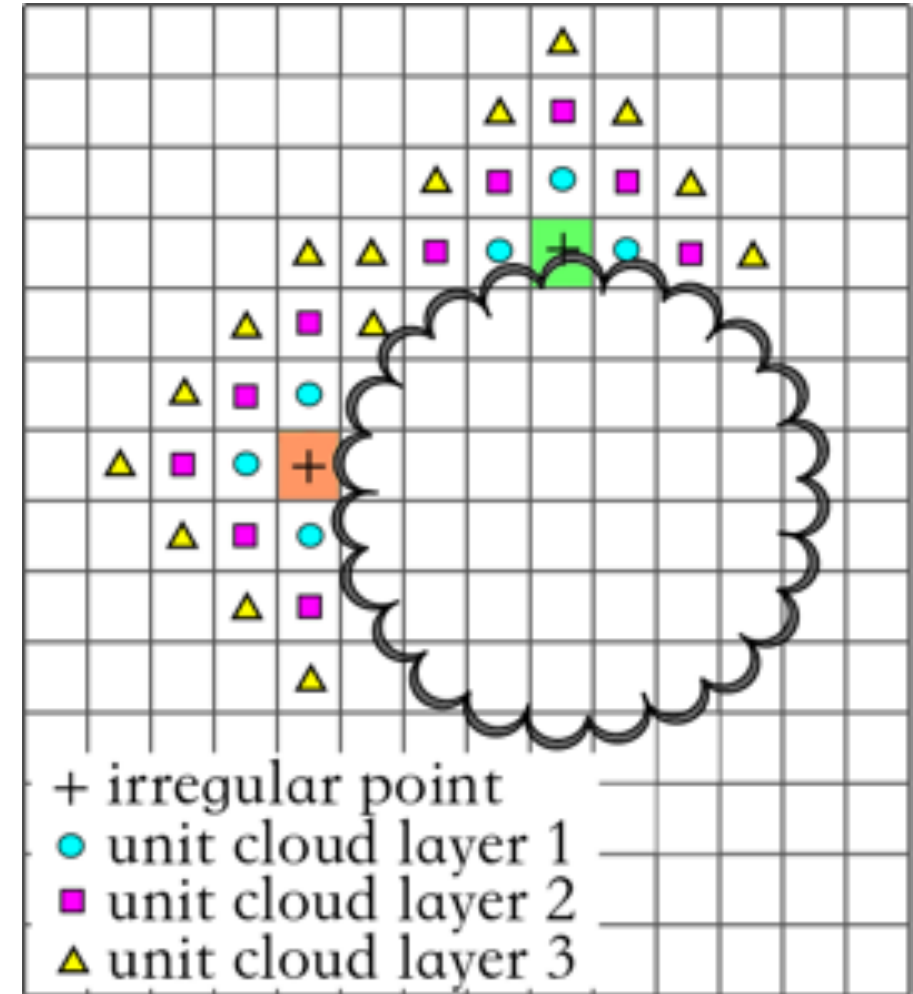




Robust Flow Field Sampling



- ❑ Irregular points are identified during the x-ray tracing process
- ❑ Utilize a careful graph walking approach to add the Cartesian grid points directly around the base point
- ❑ Repeat the graph walking approach on the second unit cloud layer

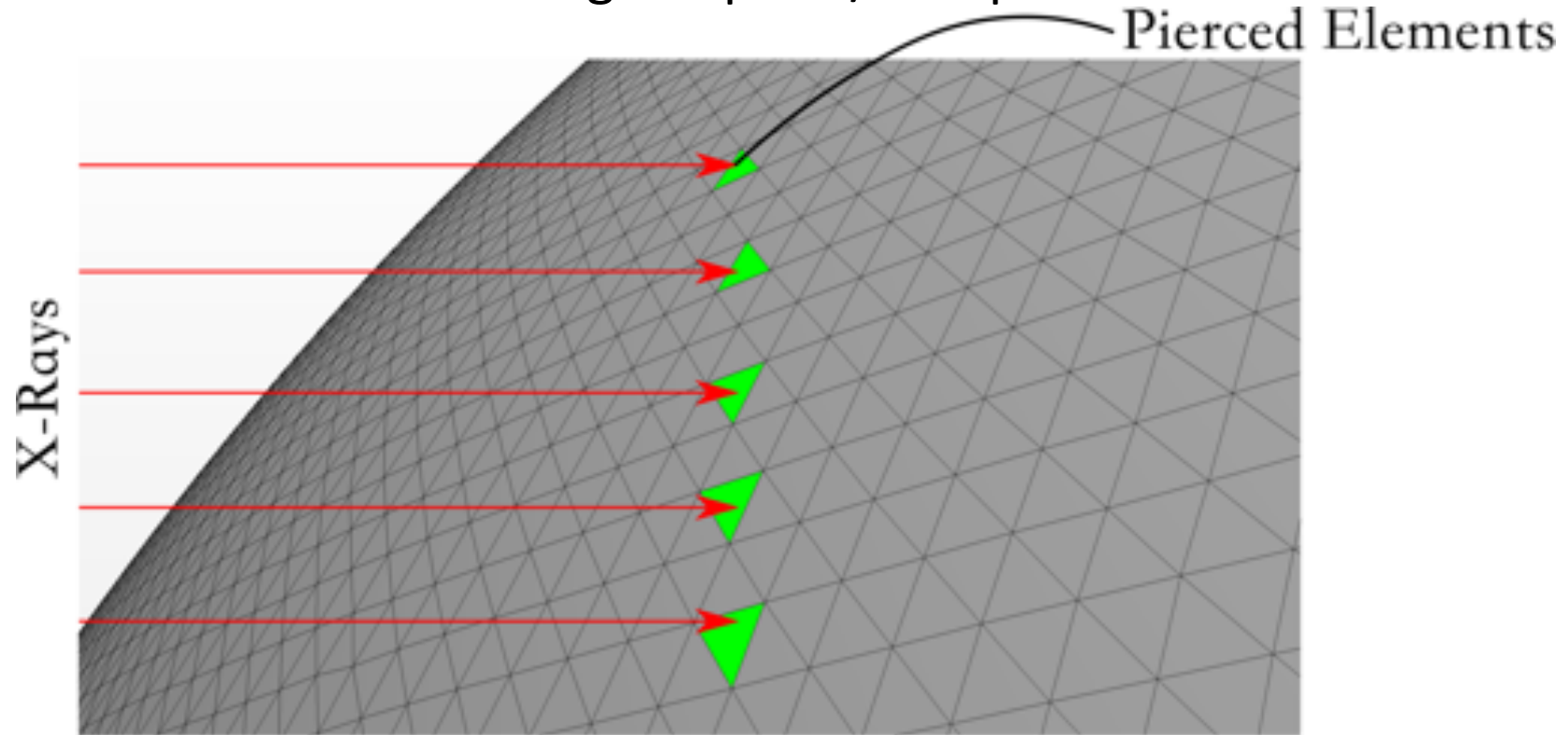




Robust Flow Field Sampling



- ❑ What about the elements on the geometry that were not pierced?
 - These points have no associated irregular point/interpolation cloud

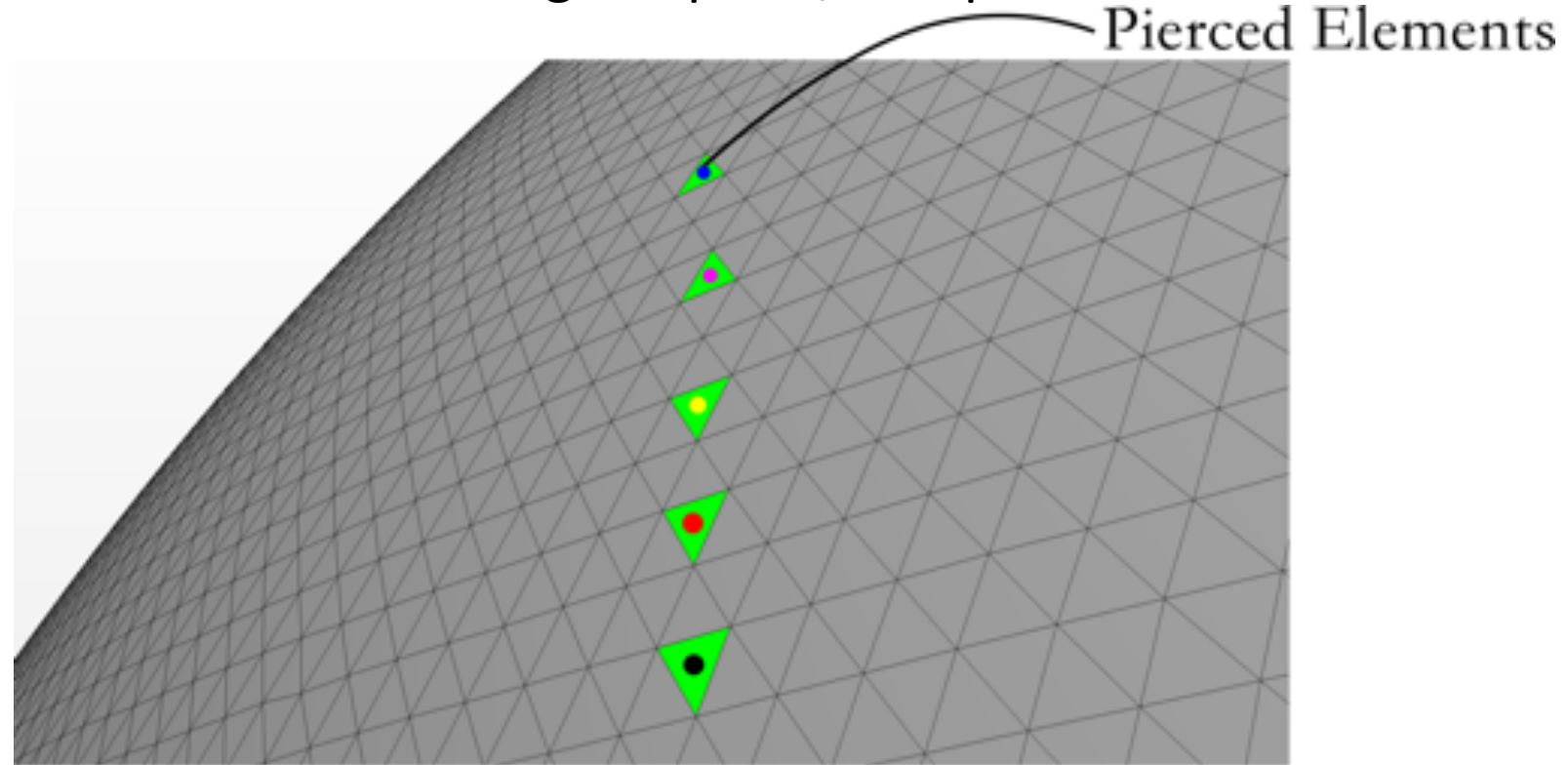




Robust Flow Field Sampling



- ❑ What about the elements on the geometry that were not pierced?
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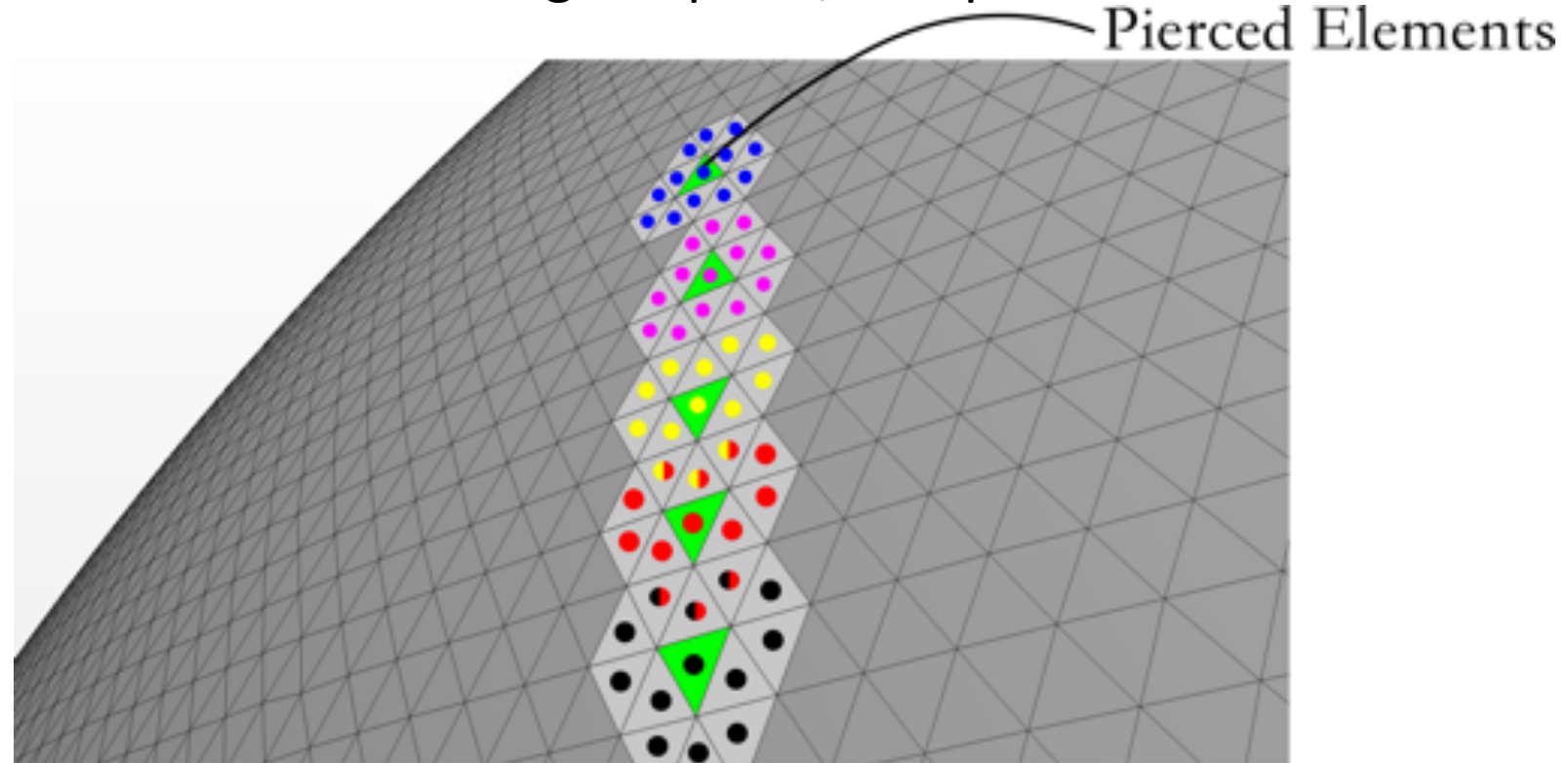




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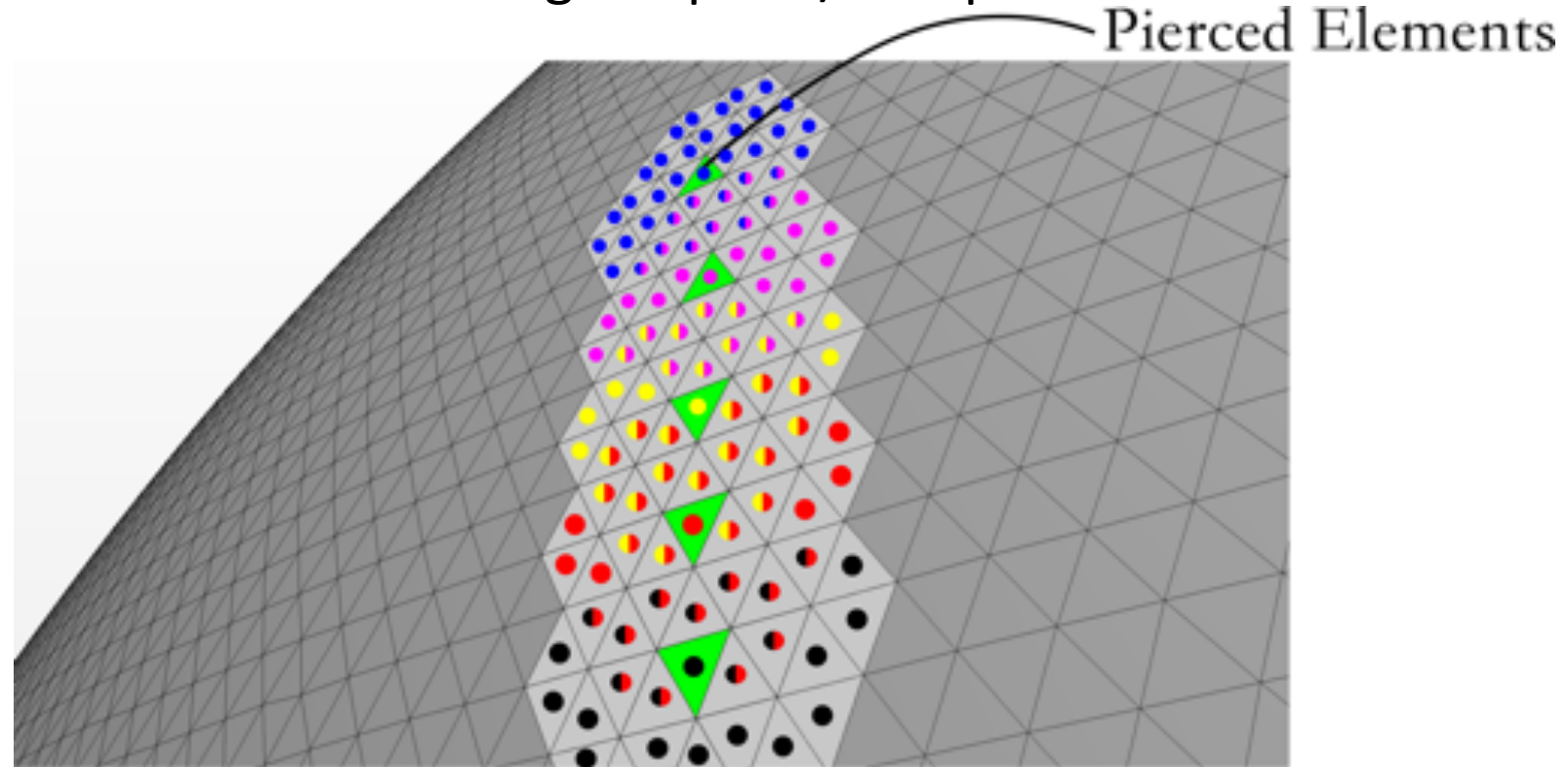


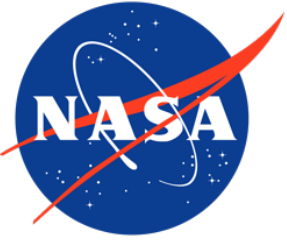


Robust Flow Field Sampling



- ❑ What about the elements on the geometry that were not pierced?
 - These points have no associated irregular point/interpolation cloud





Robust Flow Field Sampling



- ❑ Sampling should provide quality loading regardless of topological changes



Pressure distribution



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☐ Overview of FSI Method

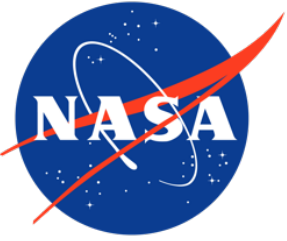
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- Parallel contact algorithm
- Robust flow field sampling
- Porosity interface condition

☐ Demonstration

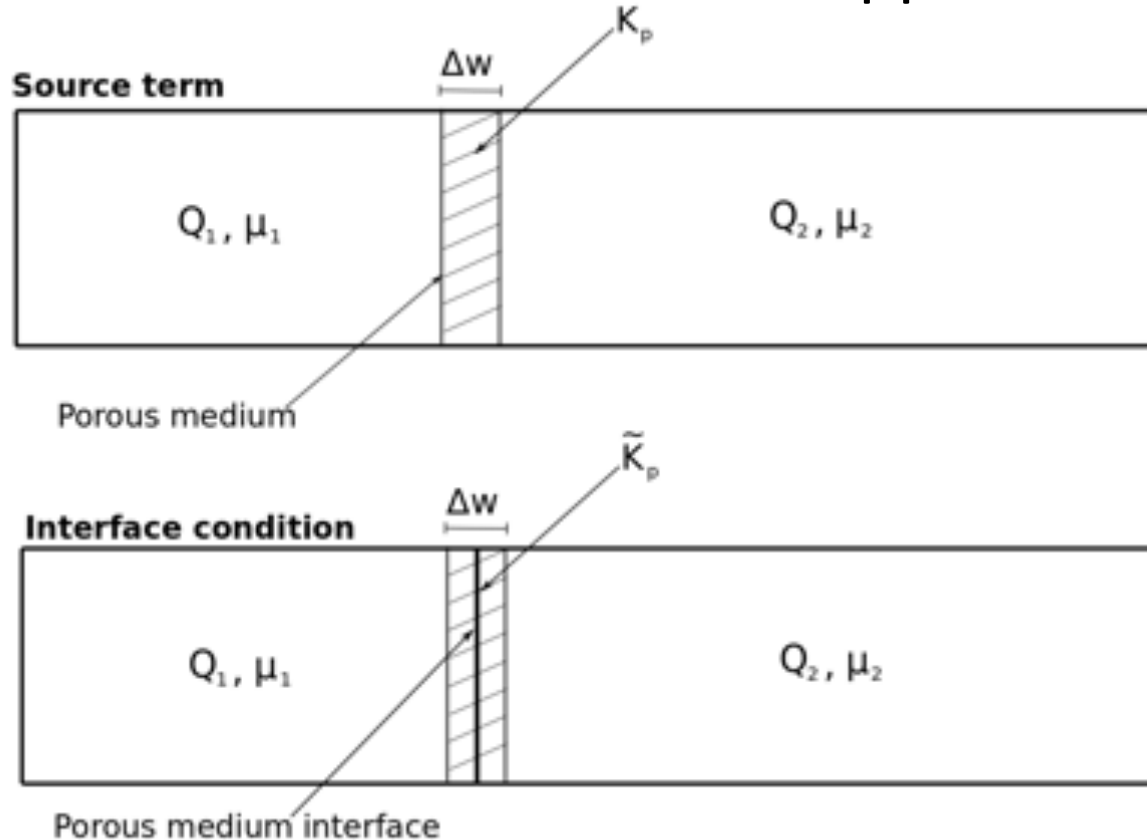
☐ Conclusion and Outlook

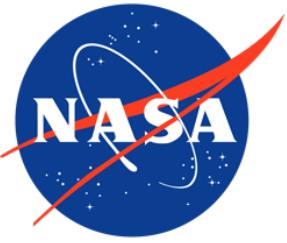


Porosity Interface Condition



- A conventional porosity model can be derived from Darcy-Forchheimer law and includes a source term applied to points resolving a porous medium

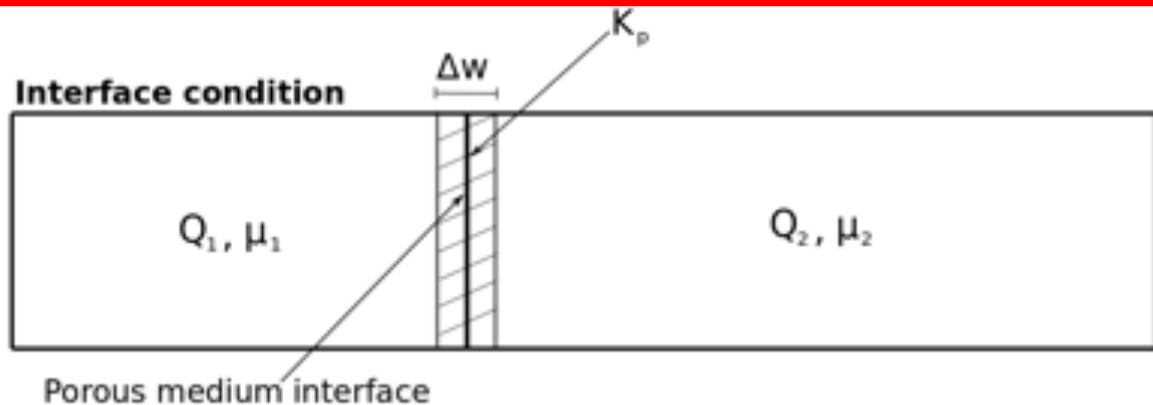
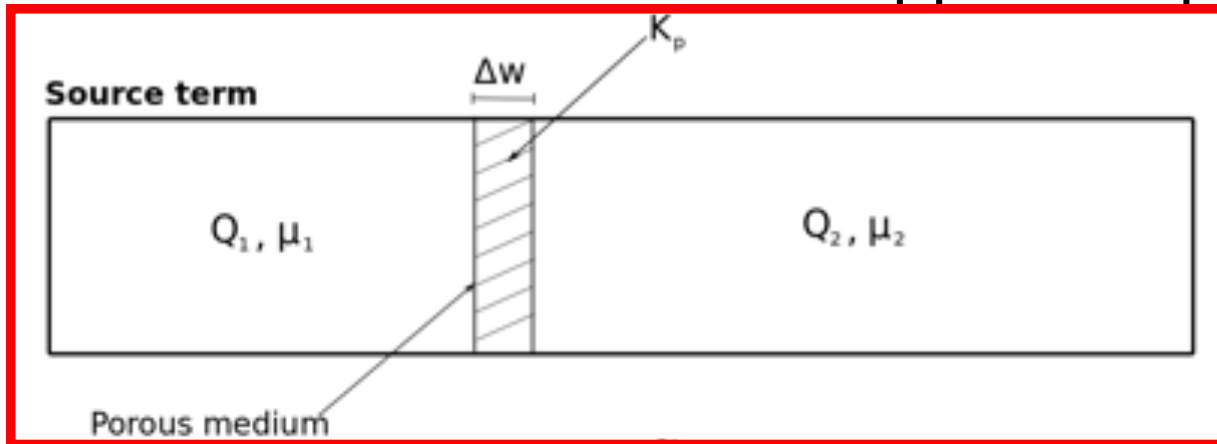




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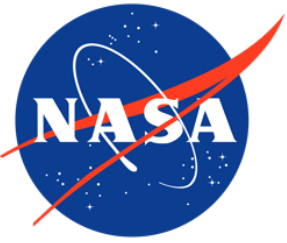


- ❑ A conventional porosity model can be derived from Darcy-Forchheimer law and includes a source term applied to points resolving a porous medium



$$\vec{S} = -\frac{\mu}{K_p} \vec{v} - \beta |\vec{v}| \vec{v}$$

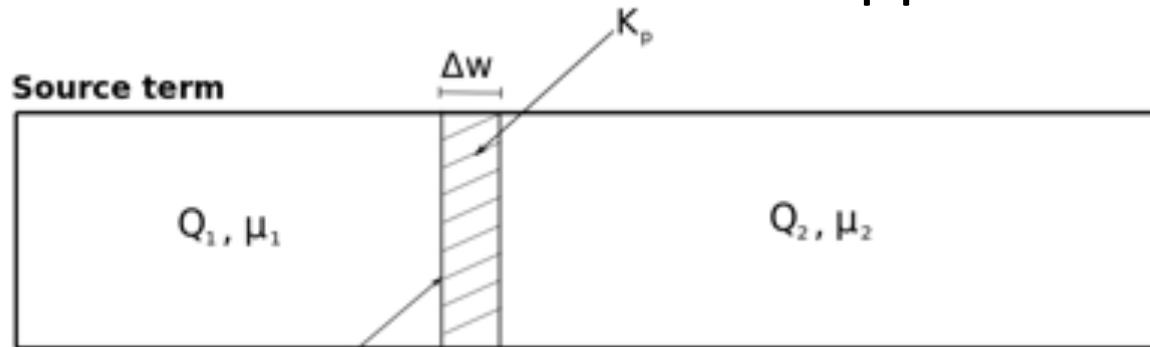
This requires enough resolution though the thickness of the porous medium



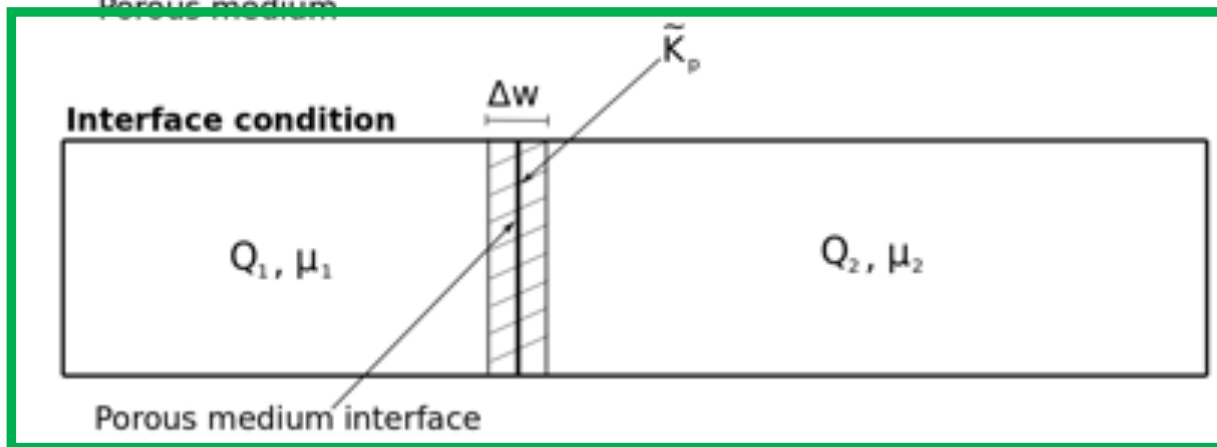
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Porous medium



Porous medium can be treated as an infinitesimally thin interface

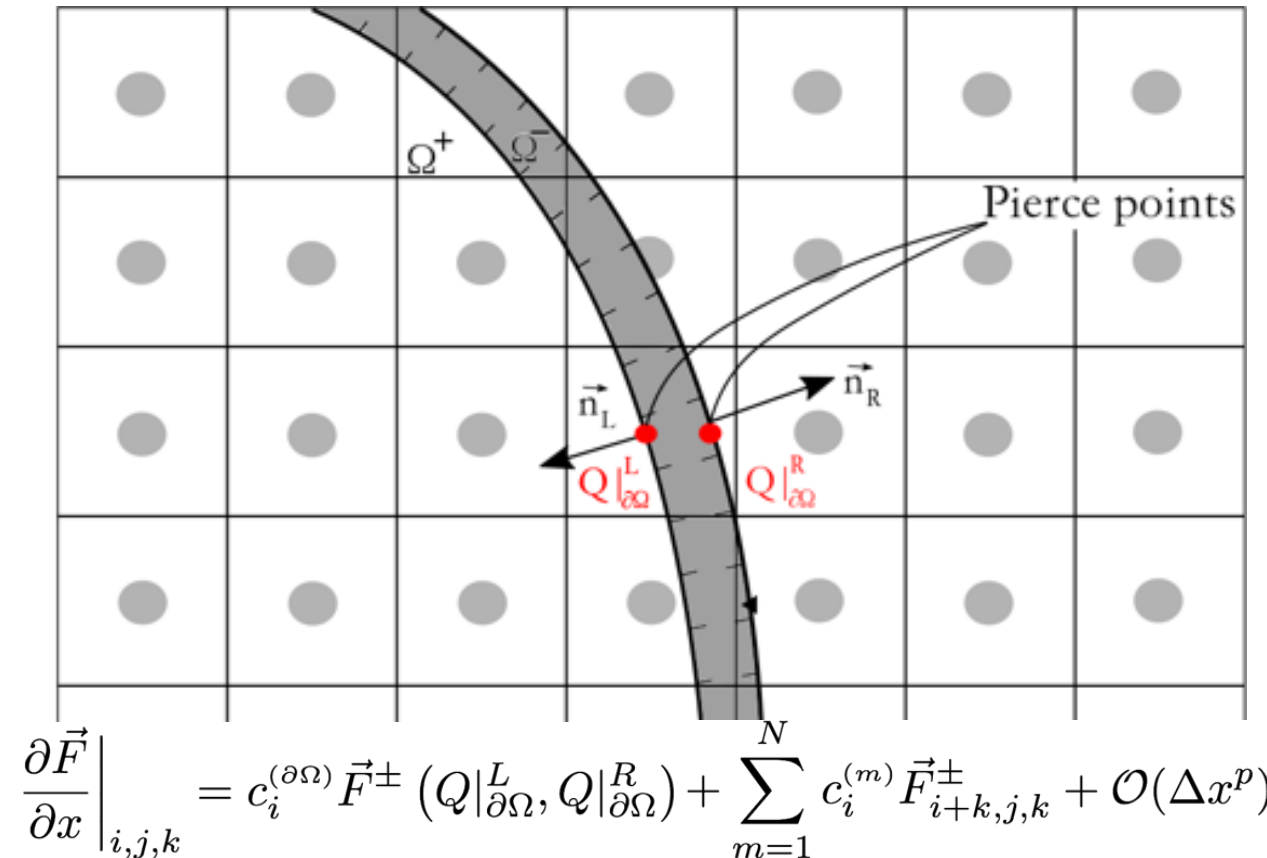
$$\frac{\partial p}{\partial n} = -\frac{\mu}{K_p} \vec{v} \cdot \vec{n} - \beta |\vec{v}| (\vec{v} \cdot \vec{n})$$

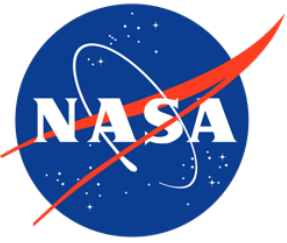


Porosity Interface Condition



- ❑ The state on both sides of the porous medium must be known
- ❑ Elements composing the geometry representation are paired together
- ❑ Pierced elements exchange the (sampled) state either side of the porous medium with their pair
- ❑ Compute mass flow through the porous medium rate to prescribe state

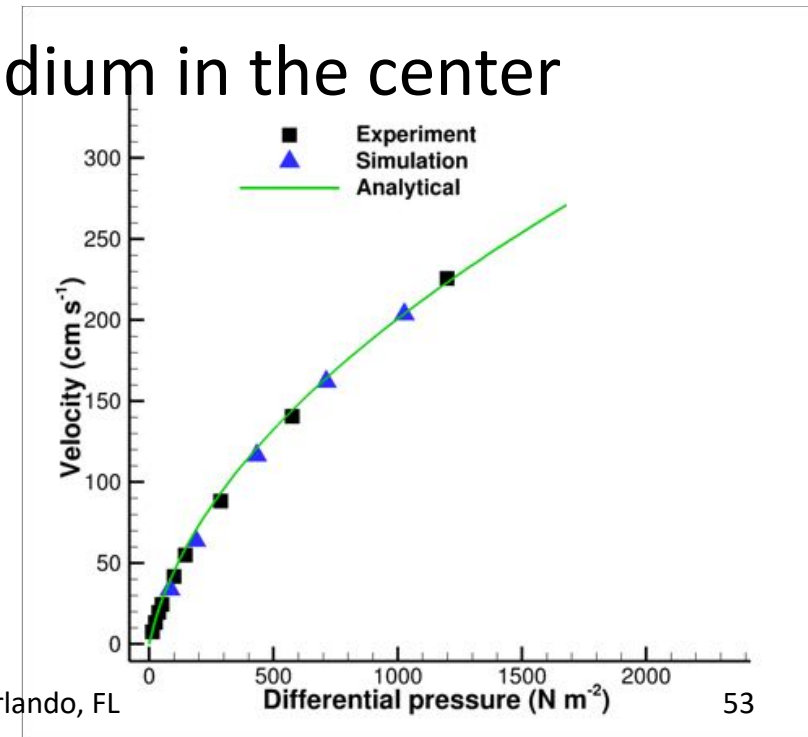
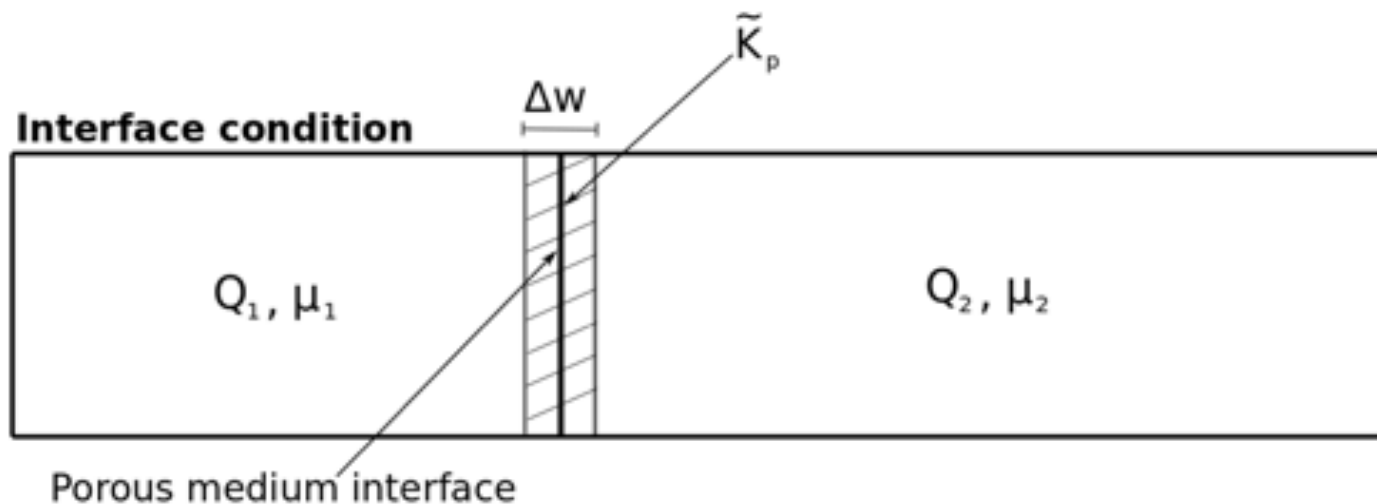




Porosity Interface Condition



- ❑ Test formulation and implementation with experiments by Cruz *et al.* AIAA 2017
- ❑ Supply pressure differentials across samples of PIA-C-7020D Type I broadcloth
- ❑ Simulations run in a 2D channel with a porous medium in the center

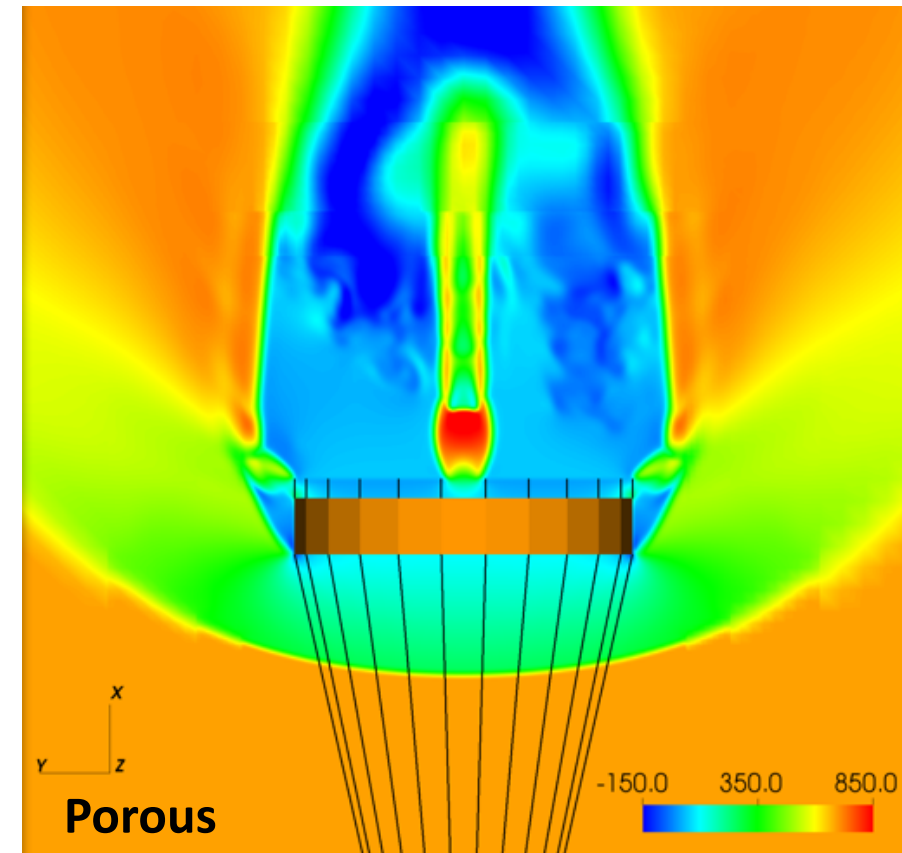
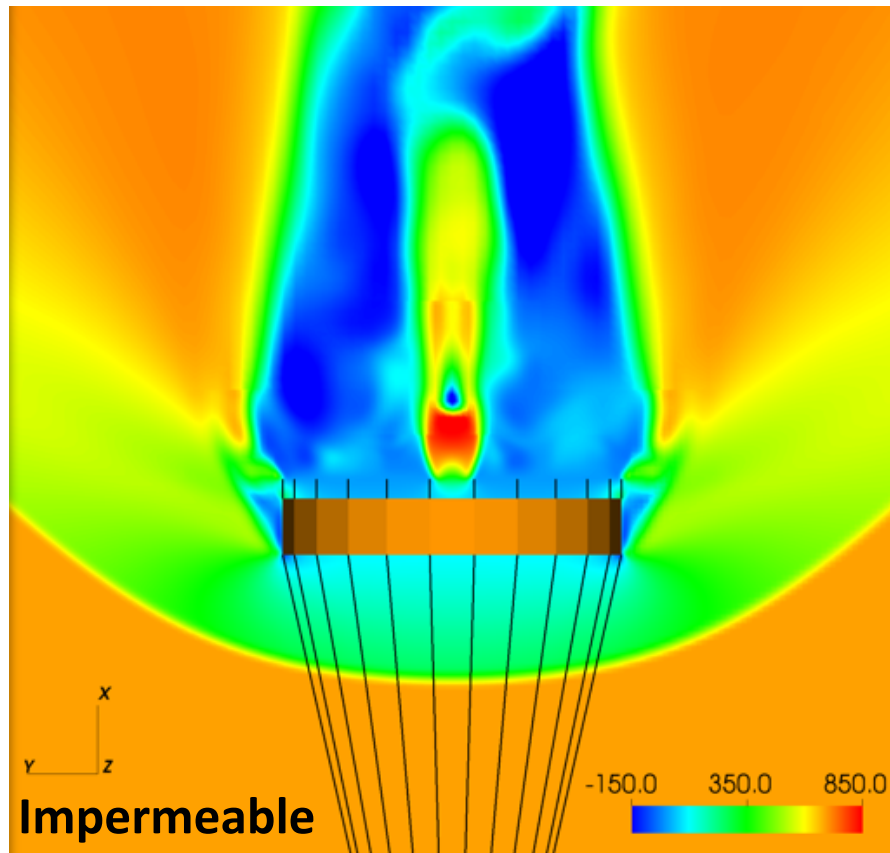




Porosity Interface Condition



- Demonstration in Mach = 2.0 flow on a parachute with PIA-C-7020D Type I broadcloth, comparison of streamwise velocity





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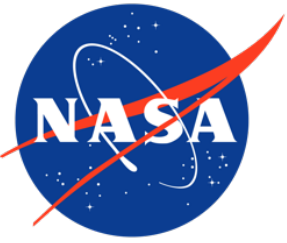
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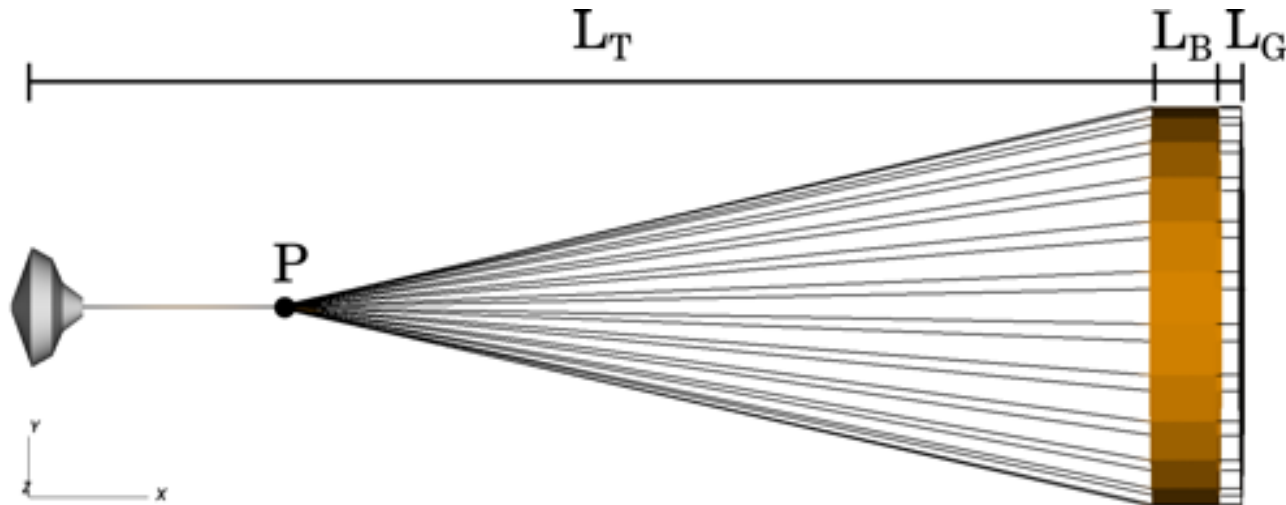
☐ Conclusion and Outlook



Problem Setup



- ❑ Setup is chosen in accordance with
 - **Experiments:** Sengupta *et al.* ([AIAA 2009](#))
 - **Simulations:** Karagiozis *et al.* ([JFS 2011](#)) and Yu *et al.* ([AIAA 2019](#))
- ❑ 0.8m D_0 DGB Parachute design is based off Reuter *et al.* ([AIAA 2009](#))
 - Sub-scale Viking parachute model ***with and without*** a sub-scale 70° Viking capsule



L_T	L_B	L_G
$\frac{x}{d} = 10.6$	$0.121D_0$	$0.042D_0$



Problem Setup



- Problem resembles spacecraft entry into the upper Martian atmosphere:

Fluid Properties

- $Re = \frac{\rho_{\infty} u_{\infty} d}{\mu_{\infty}} = 10^5$
- μ_{∞} via Sutherland's law at $T_{\infty} = 294.93K$
- $\rho_{\infty} = 0.0184527 \frac{kg}{m^3}$
- $u_{\infty} = 688.89 \frac{m}{s}$
- $M = \frac{u_{\infty}}{a_{\infty}} = 2.0$

Structural Properties

- $E_p = 878 MPa$
- $\nu = 0.33$
- $h = 6.35 \times 10^{-5} m$
- $\rho_p = 614 \frac{kg}{m^3}$
- $d_c = 0.99 \times 10^{-3} m$
- $E_c = 43 GPa$
- $\rho_c = 8.27 \times 10^{-4} \frac{kg}{m}$

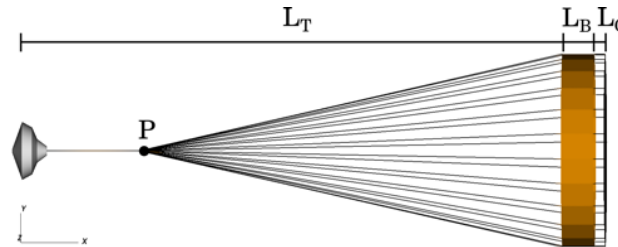
- Setup time: virtually none after CSD mesh is created

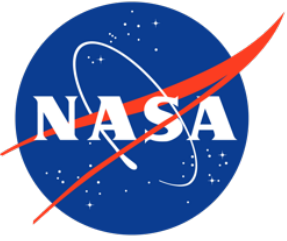


Problem Setup



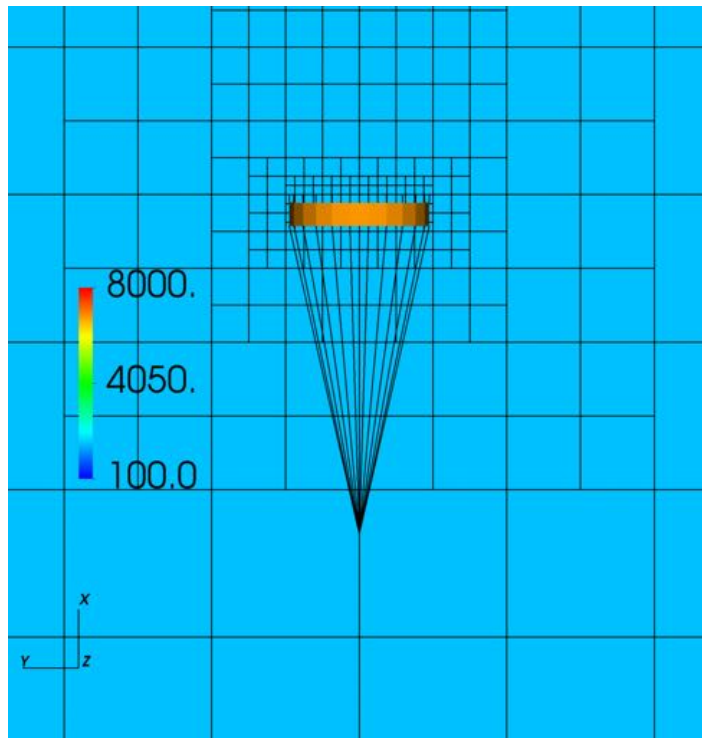
- ❑ Center of the vent hole is at $(0,0,0)$
- ❑ Domain: $[-6.25D_0, 6.25D_0] \times [-6.25D_0, 6.25D_0] \times [-6.25D_0, 6.25D_0]$
- ❑ Base case: $\Delta x_{min} = \Delta y_{min} = D_0/164$, **7-10 million CFD points**
- ❑ 600 geometrically nonlinear cable elements are used for the suspension lines
 - Fixed at point P
- ❑ **180,000 geometrically nonlinear shell elements** resolve the disk and canopy



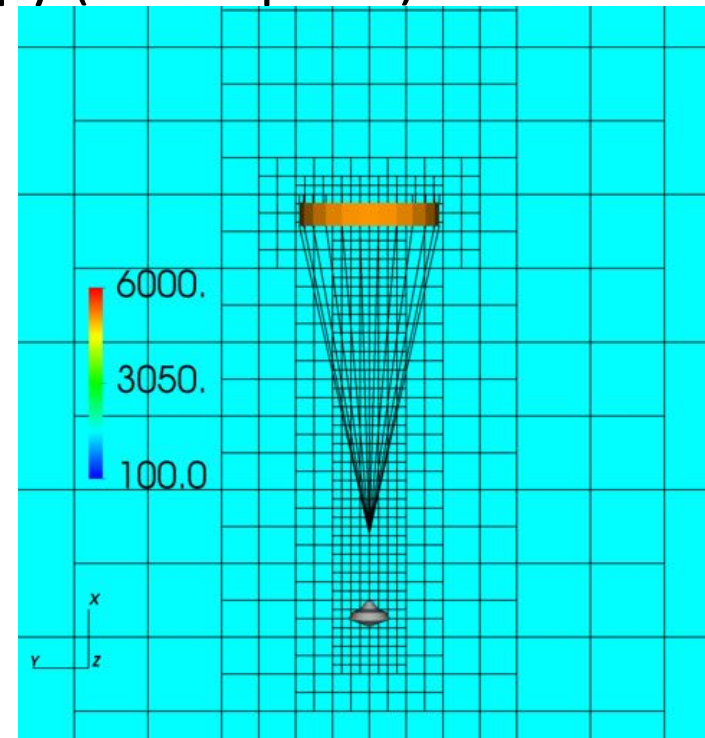


FSI Initial Condition

- ❑ A flow field is run to be used at the initial condition for FSI simulations
 - Develops the bow shock ahead of the canopy (and capsule) and the block arrangement

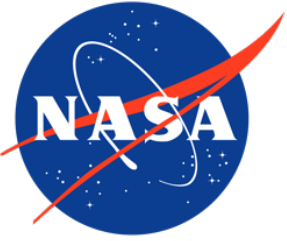


No capsule, Δx



Capsule, Δx

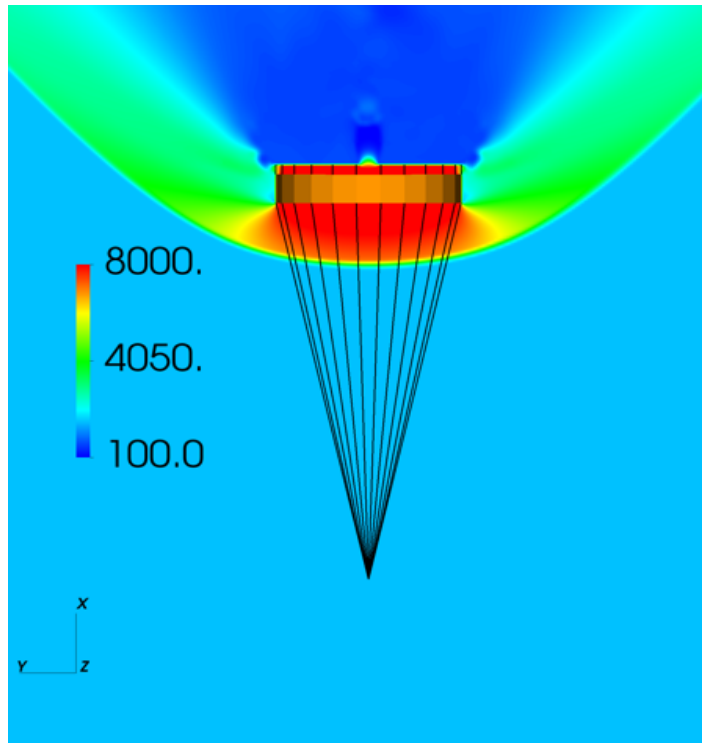
- ❑ The structural solver starts FSI simulations in an unstressed state



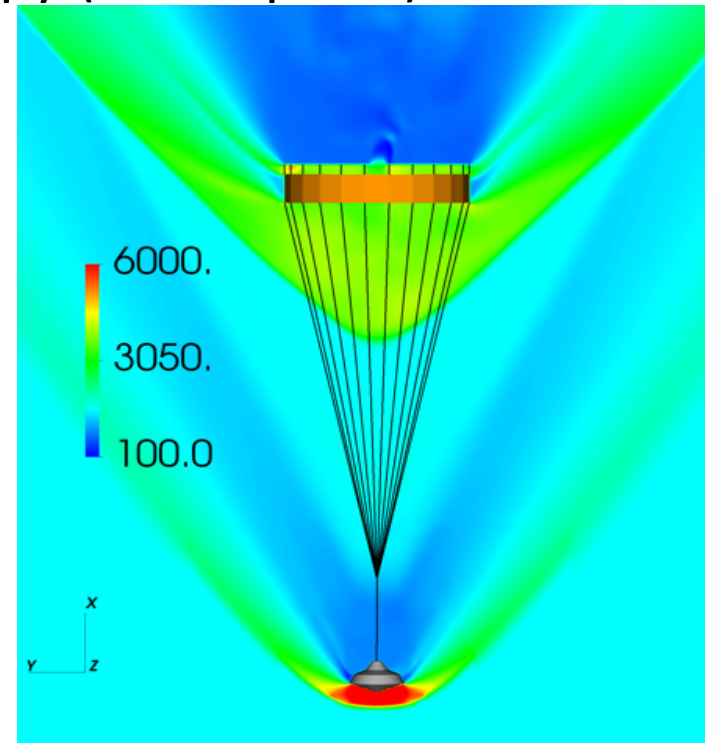
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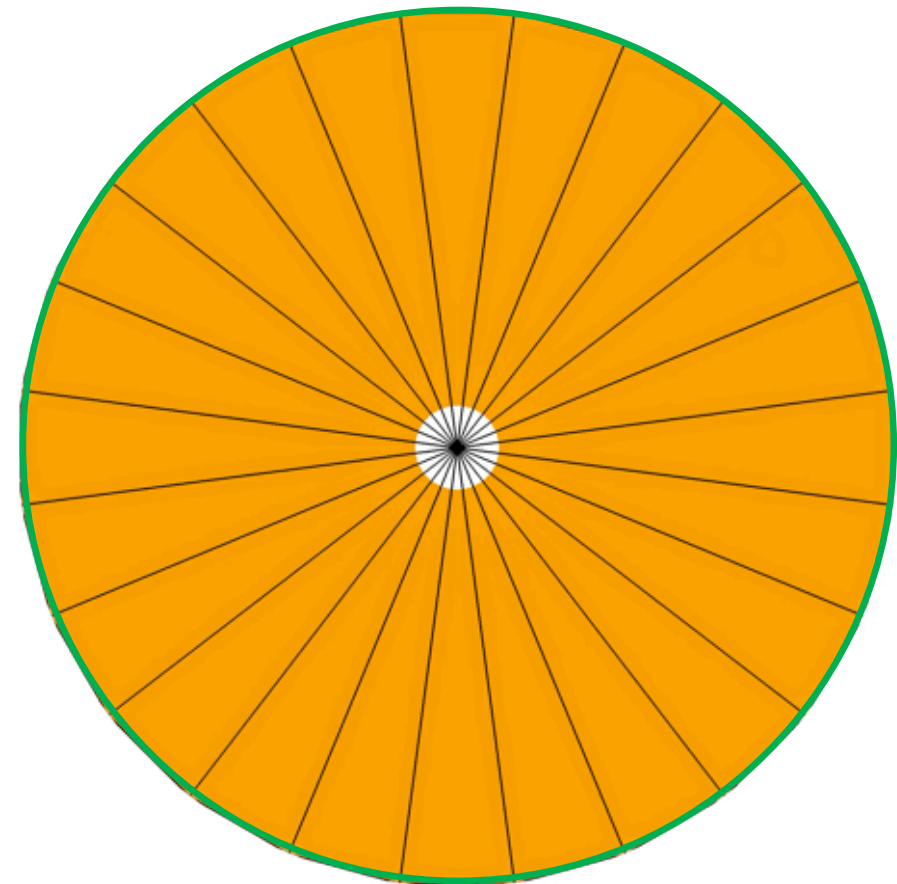
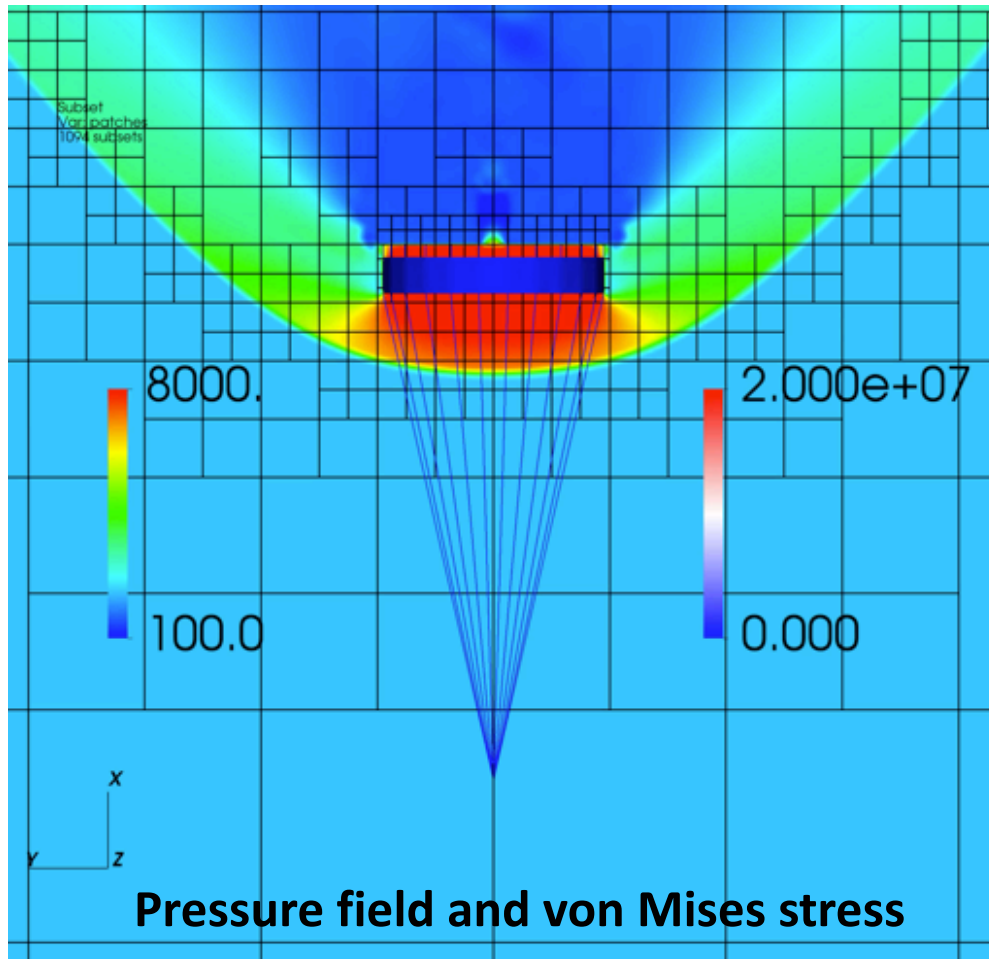
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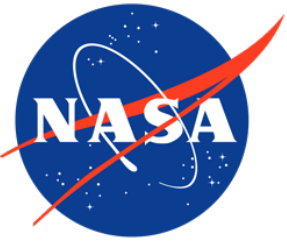
FSI Simulations



- ❑ The parachute is first considered without the leading Viking capsule



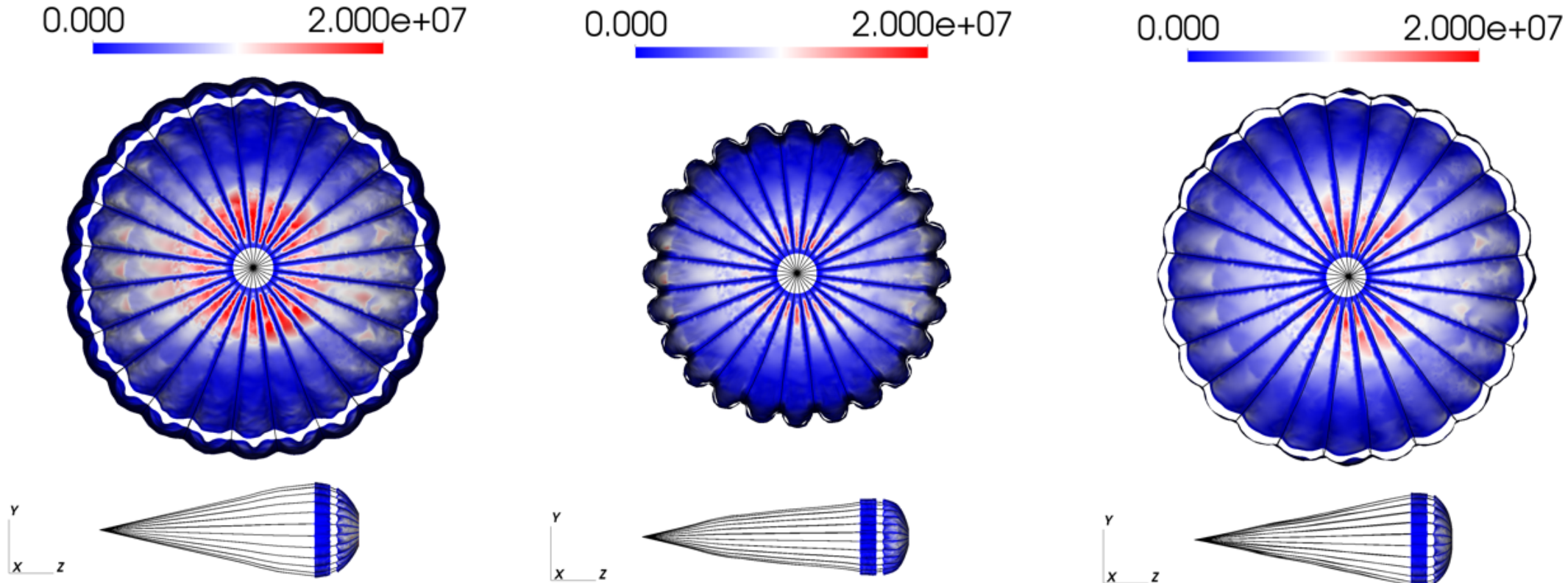
Streamwise view of parachute



FSI Simulations



- The von Mises stress on the parachute canopy sheds light on the high-stress/deviatoric strain regions of the parachute during the inflation process

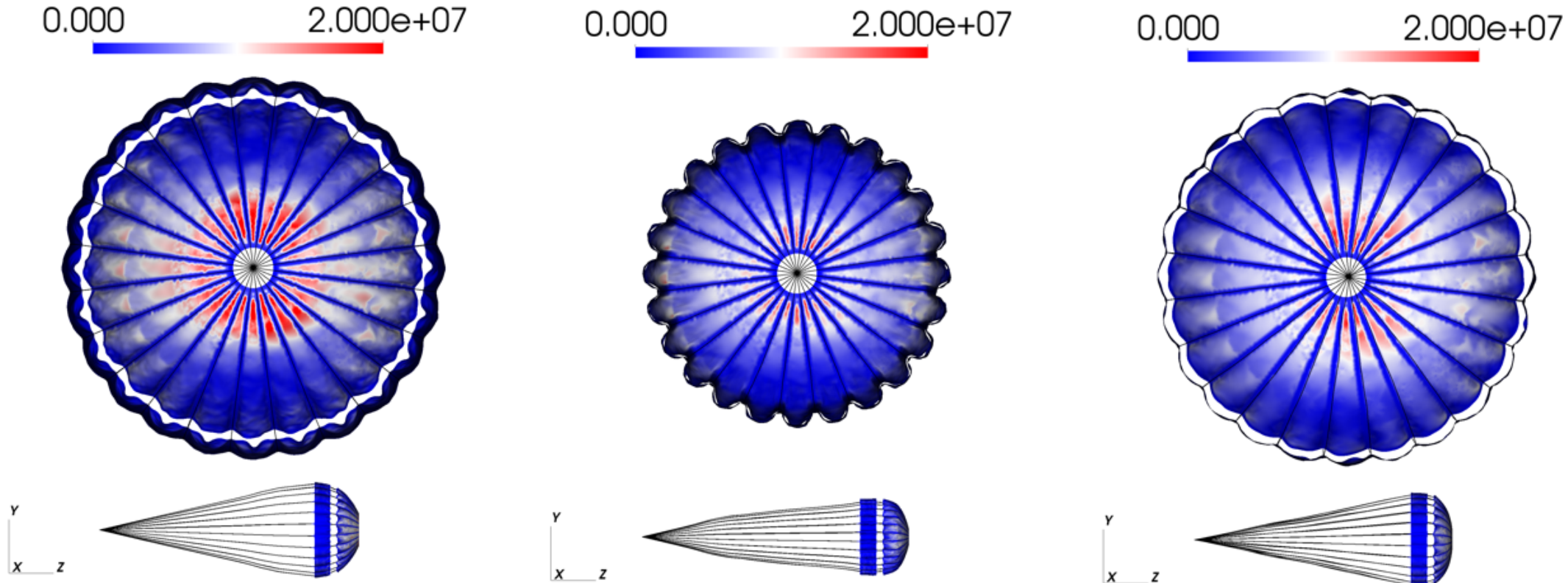


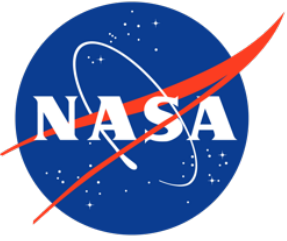


FSI Simulations



- ❑ ASPIRE SR01 saw broadcloth shearing along the radials near the vent hole

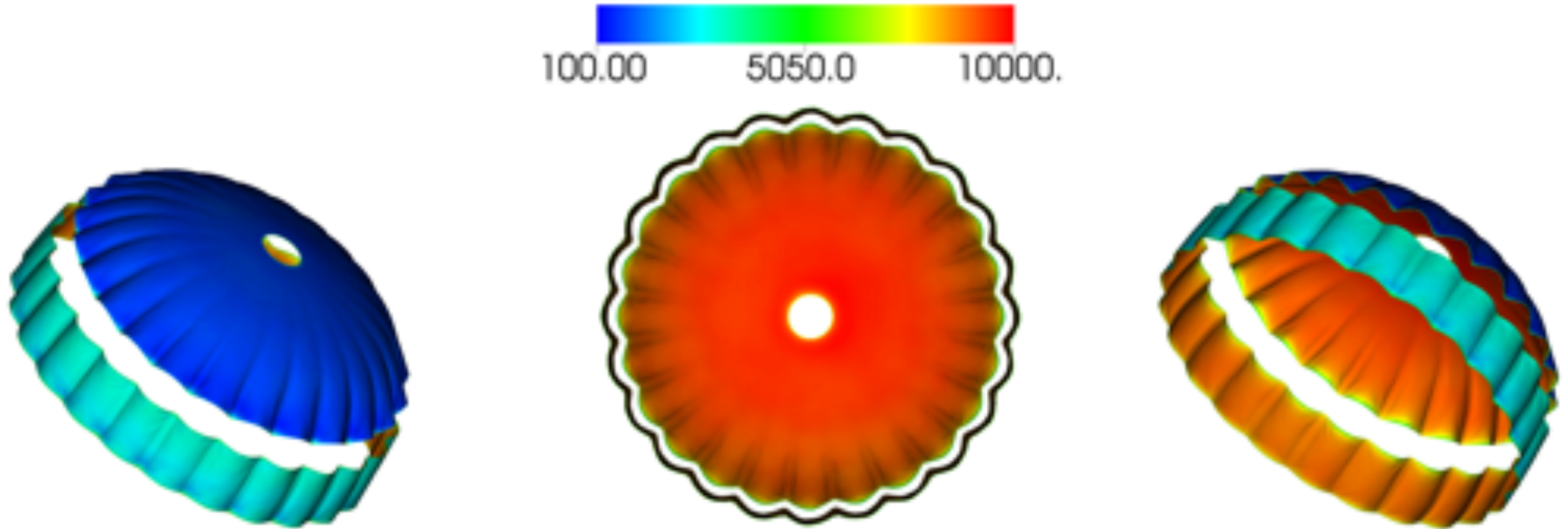




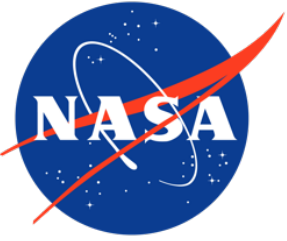
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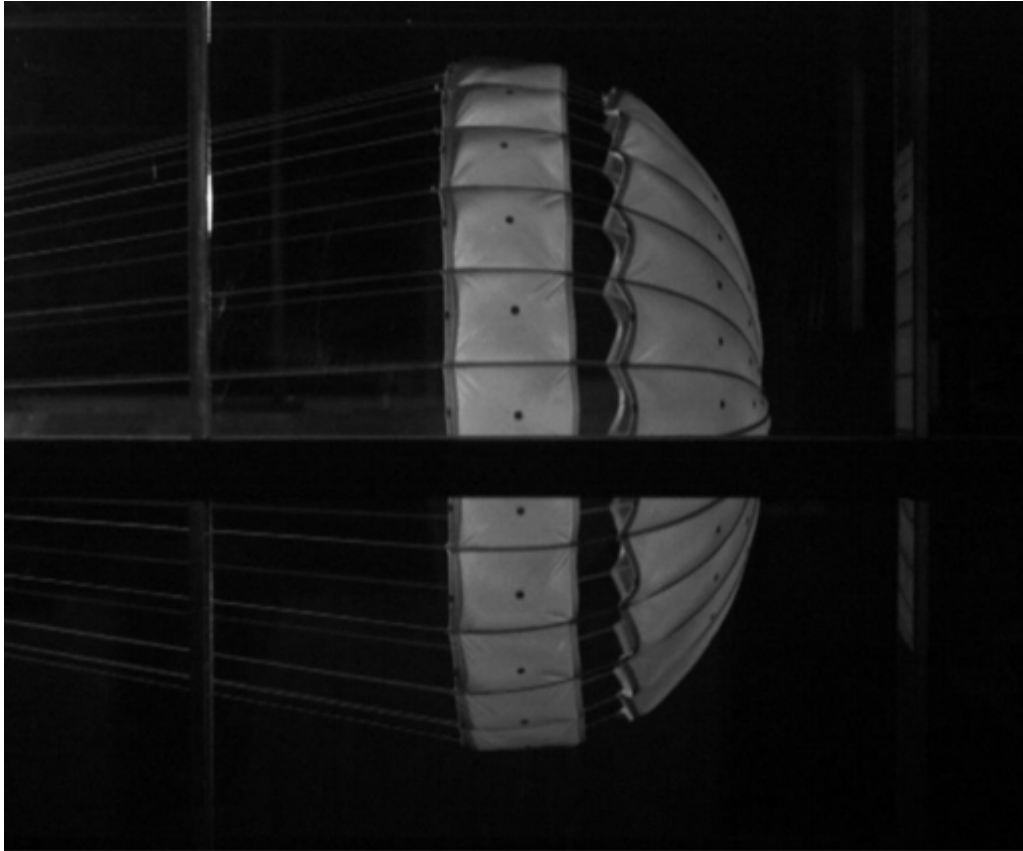
Pressure distribution on the parachute canopy



FSI Simulations

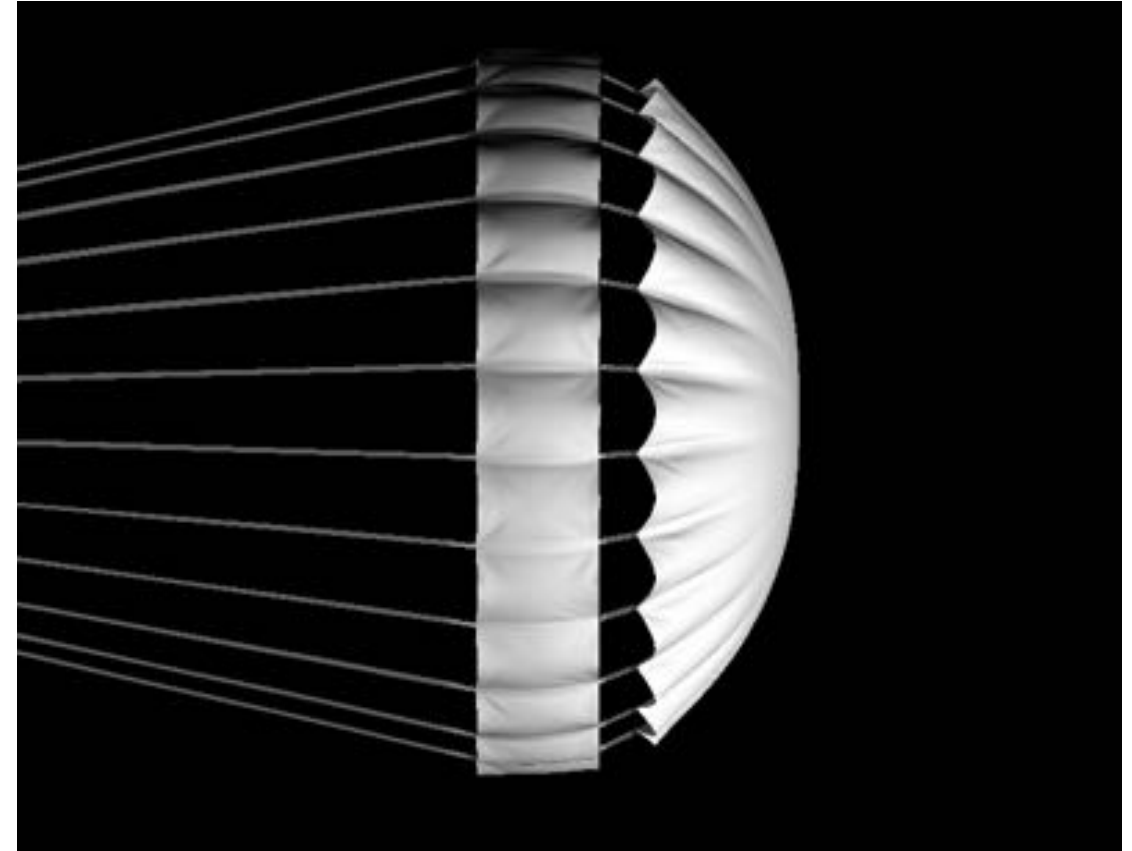


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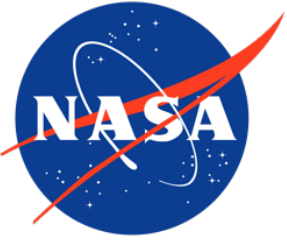


Experiment of sub-scale DGB

(Adjusted from Witkowski *et al.* AIAA 2009)



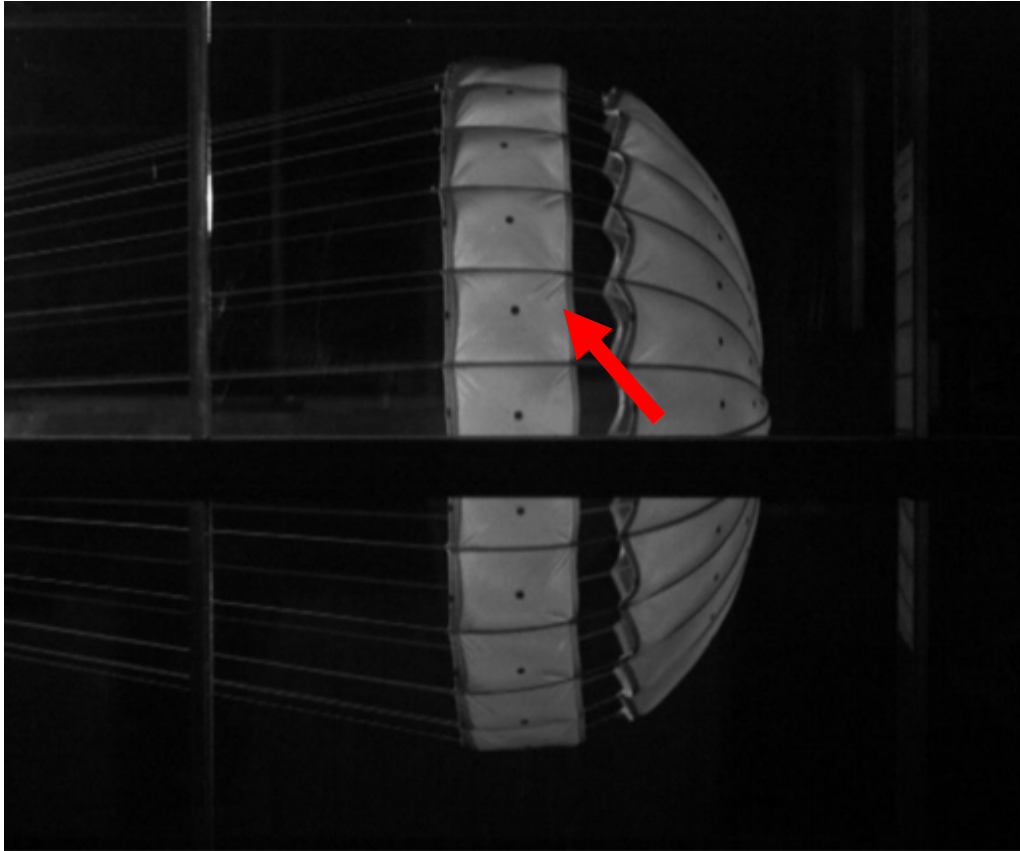
Simulations from the current work



FSI Simulations

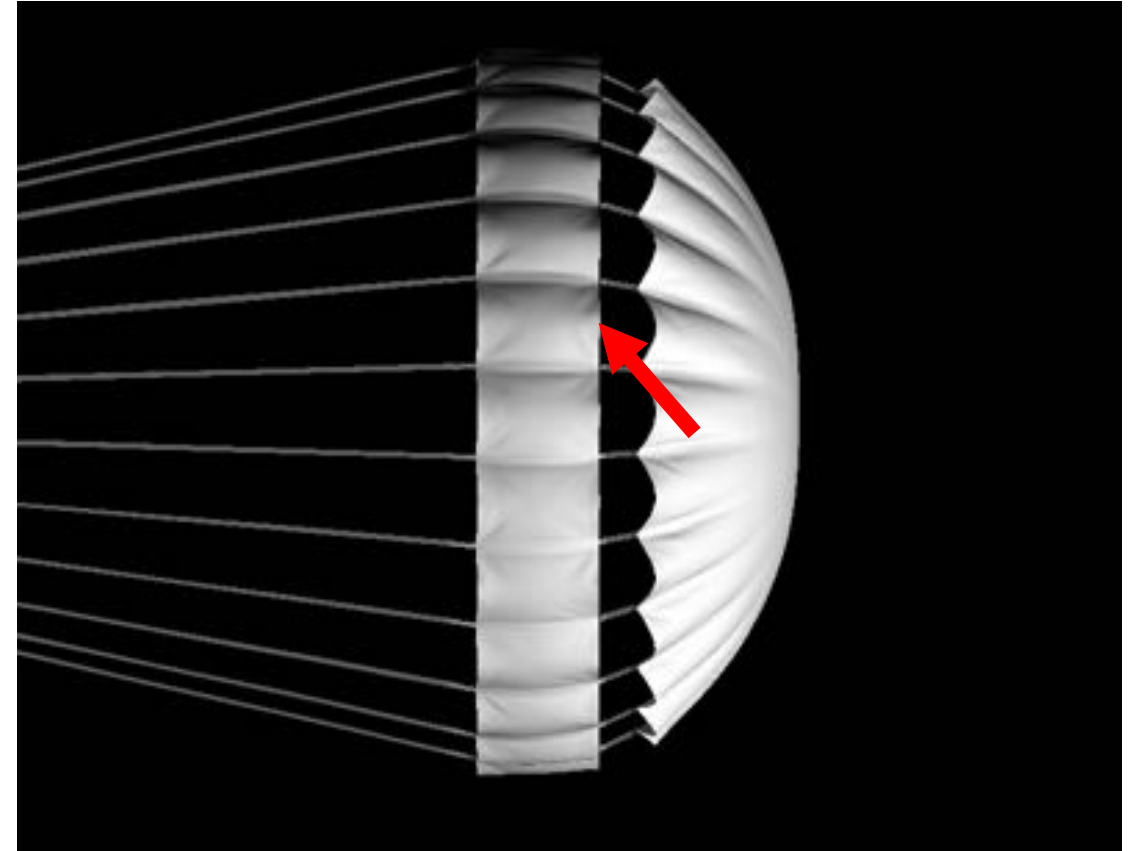


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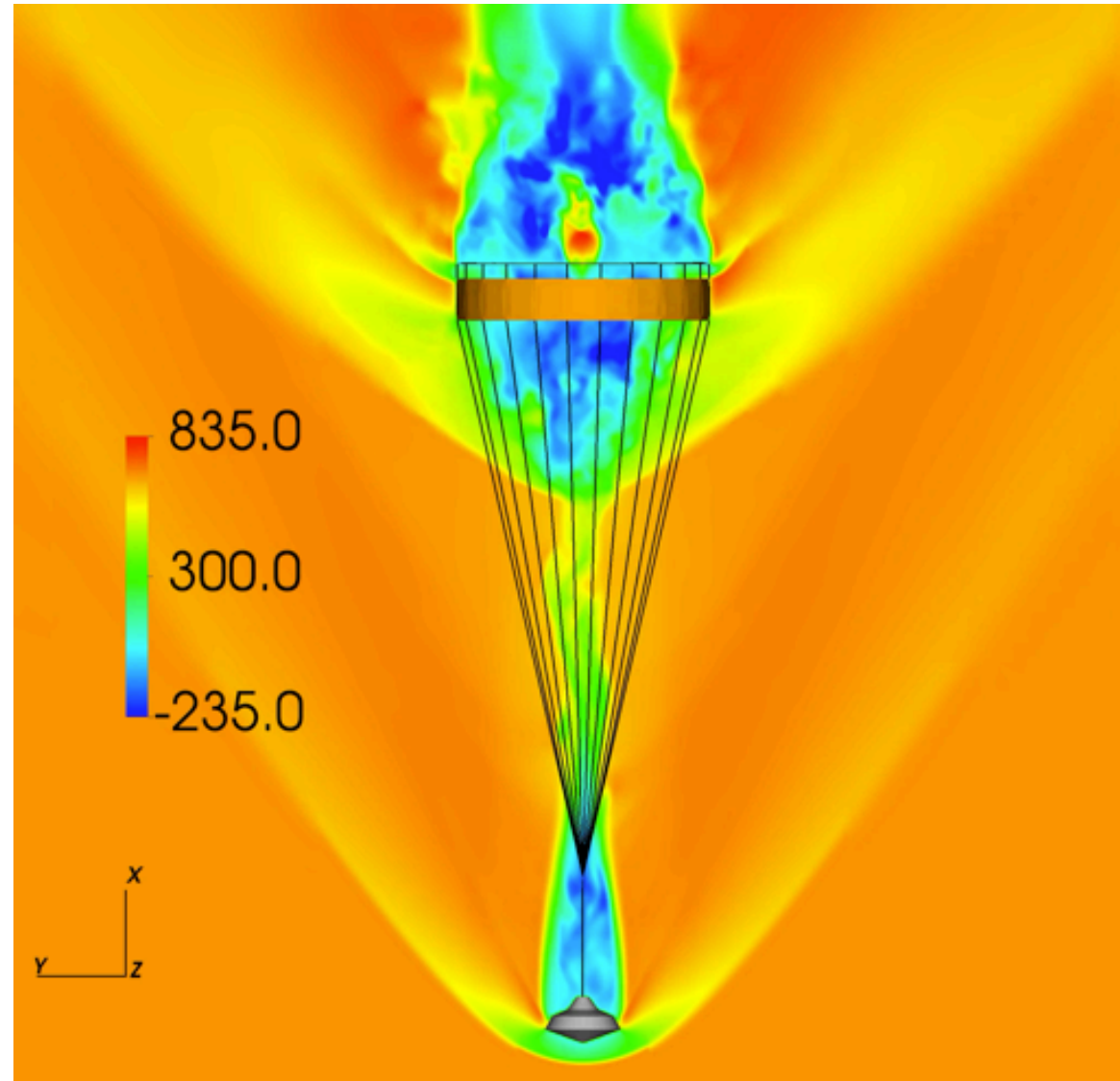
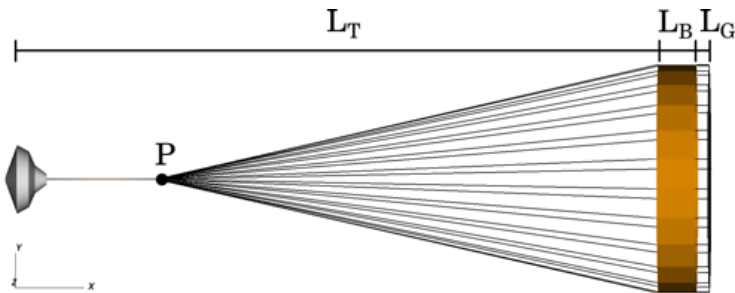
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FSI Simulations



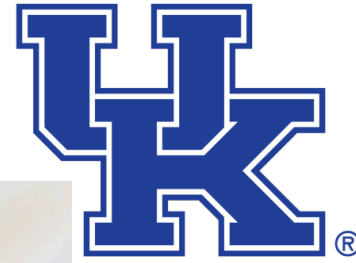
- ❑ Then the leading Viking capsule is included



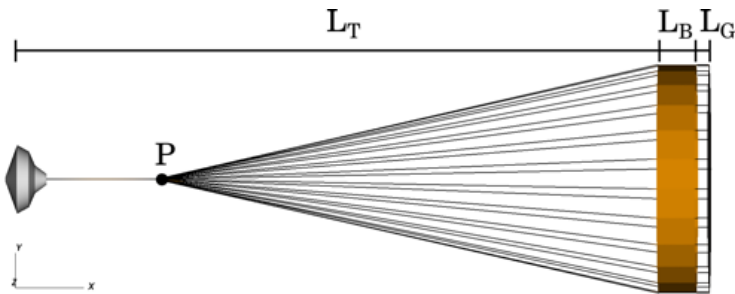
Streamwise Velocity and parachute geometry



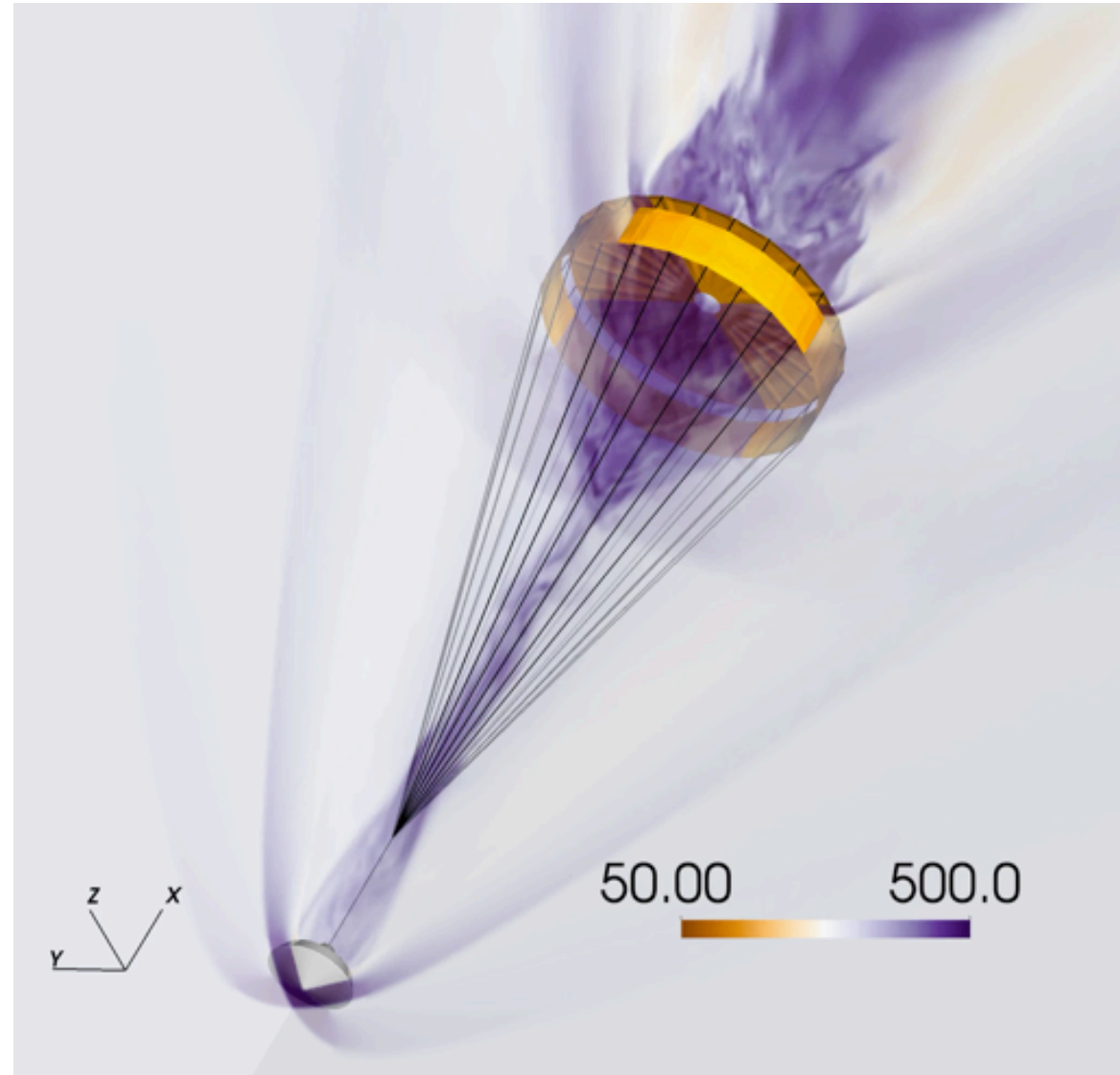
FSI Simulations

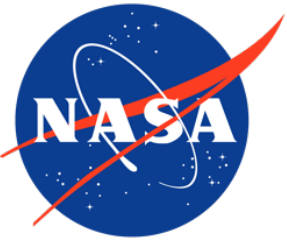


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Temperature field and parachute geometry

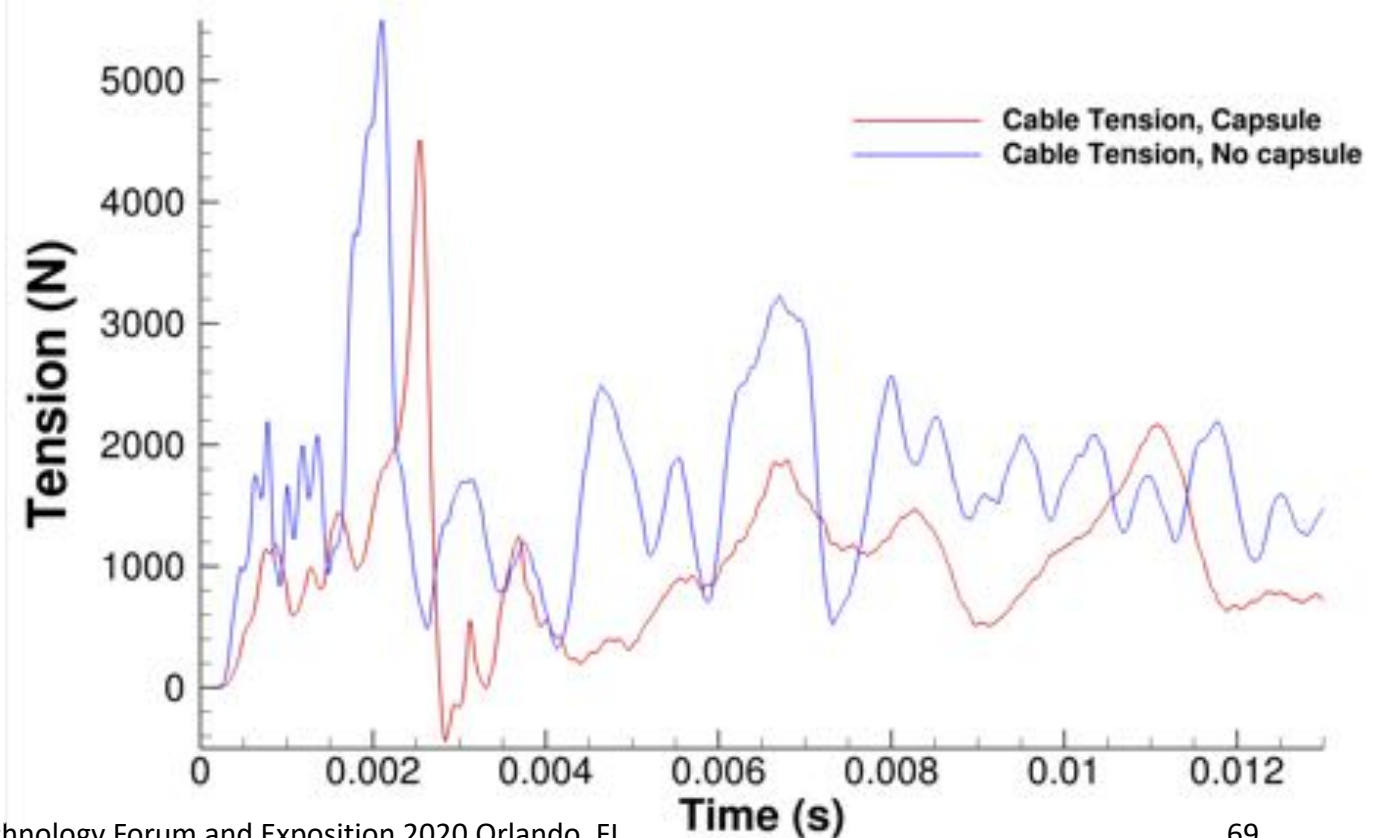




FSI Simulations



- ❑ The tensions in the suspension lines are recorded during the course of the simulation to investigate the loading vs. time during inflation
- ❑ Lower peak inflation load and slower inflation with capsule
- ❑ Low frequency, high amplitude oscillations with capsule





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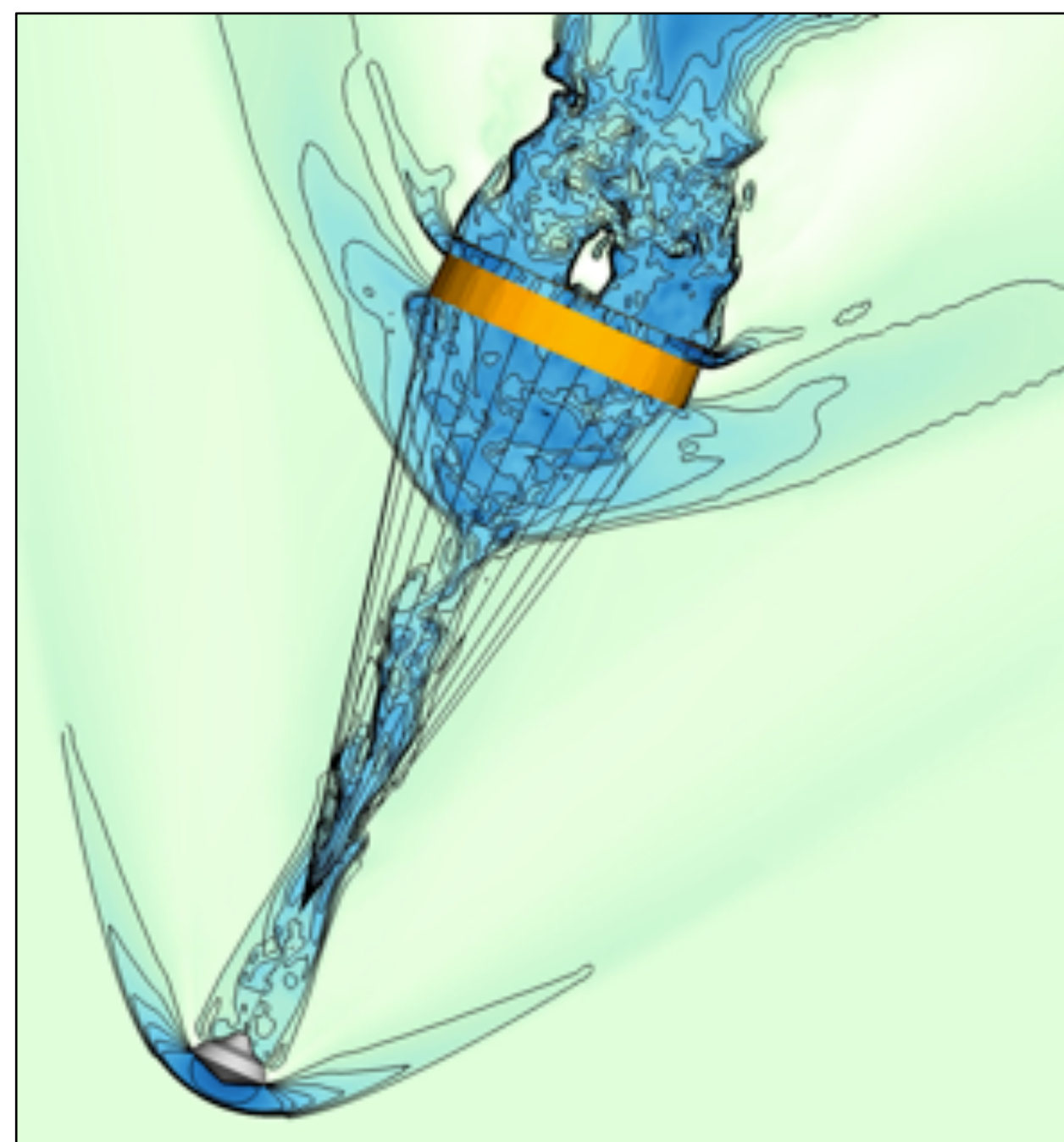
Acknowledgments



- ❑ This work is partially supported by NASA ARMD's Transformational Tools and Technologies project (T^3)
- ❑ Gokul Anugrah and Professor Brehm greatly acknowledge funding from the Computational Aerosciences Branch at NASA Ames Research Center
- ❑ Computing resources were provided by NASA Advanced Supercomputing (NAS) systems at NASA Ames Research Center

Conclusion

- ❑ A validated computational FSI method was extended to consider:
 - Robust flow field sampling for quality fluid dynamic loading on thin geometries
 - A unique, parallel contact algorithm for Eulerian frameworks
 - A porosity interface condition for compressible flows
 - Flow feature refining and geometry tracking adaptive mesh refinement
- ❑ The developments were demonstrated individually and then on a sub-scale DGB parachute in supersonic flow
- ❑ Some analysis of the parachute inflation demonstration case was presented



- ☐ Consider the effect of more interesting starting conditions
- ☐ Consider more representative, orthotropic, materially nonlinear constitutive relationships
- ☐ Move to full-scale MSL and ASPIRE parachutes and compare coefficient of drag, peak tension/loading, inflation times

