NASA Fundamental Aeronautics Program

SUP4.0 Cruise Efficiency - Airframe: Milestone Summary

MS S4.03.002 – Adjoint-Based Design for Configuration Shaping

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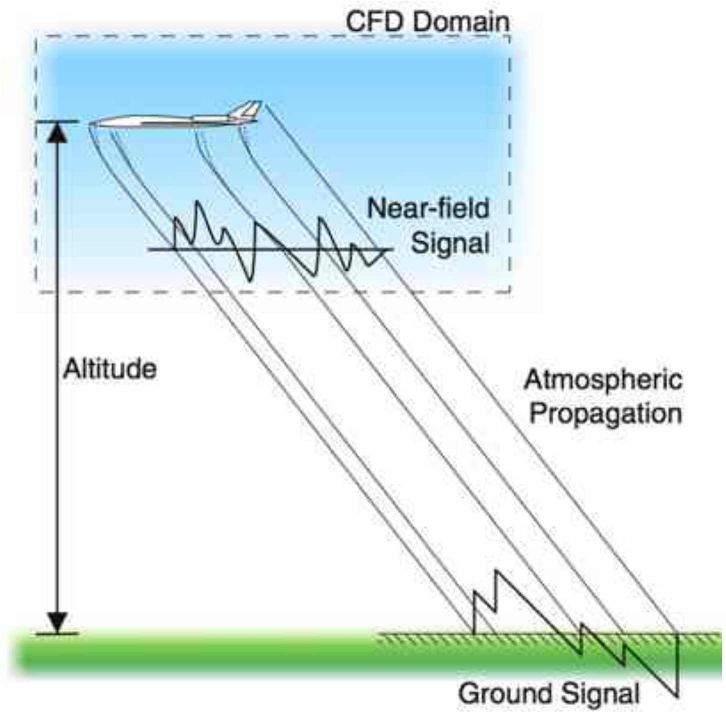
MS S4.03.002 - Adjoint-Based Design for Configuration Shaping

Goal: Drive vehicle shape by prescribing quieter near-field signals

Approach:

- **Use adjoint method** to determine objective function gradients with quasi-newton (BFGS) optimizer
- **Inverse design:** Determine shape to produce a prescribed near-field signal
- **Cart3D:** Robust, scalable inviscid flow-simulations & discrete-adjoint using fully-automated Cartesian meshing with cut-cell boundaries
- **Parametric CAD-based** design framework using XML dataflow for shape sensitivities and control of CAD parameters
- **CAD-in/CAD-out:** Result of design is updated parametric CAD model with feature-tree intact



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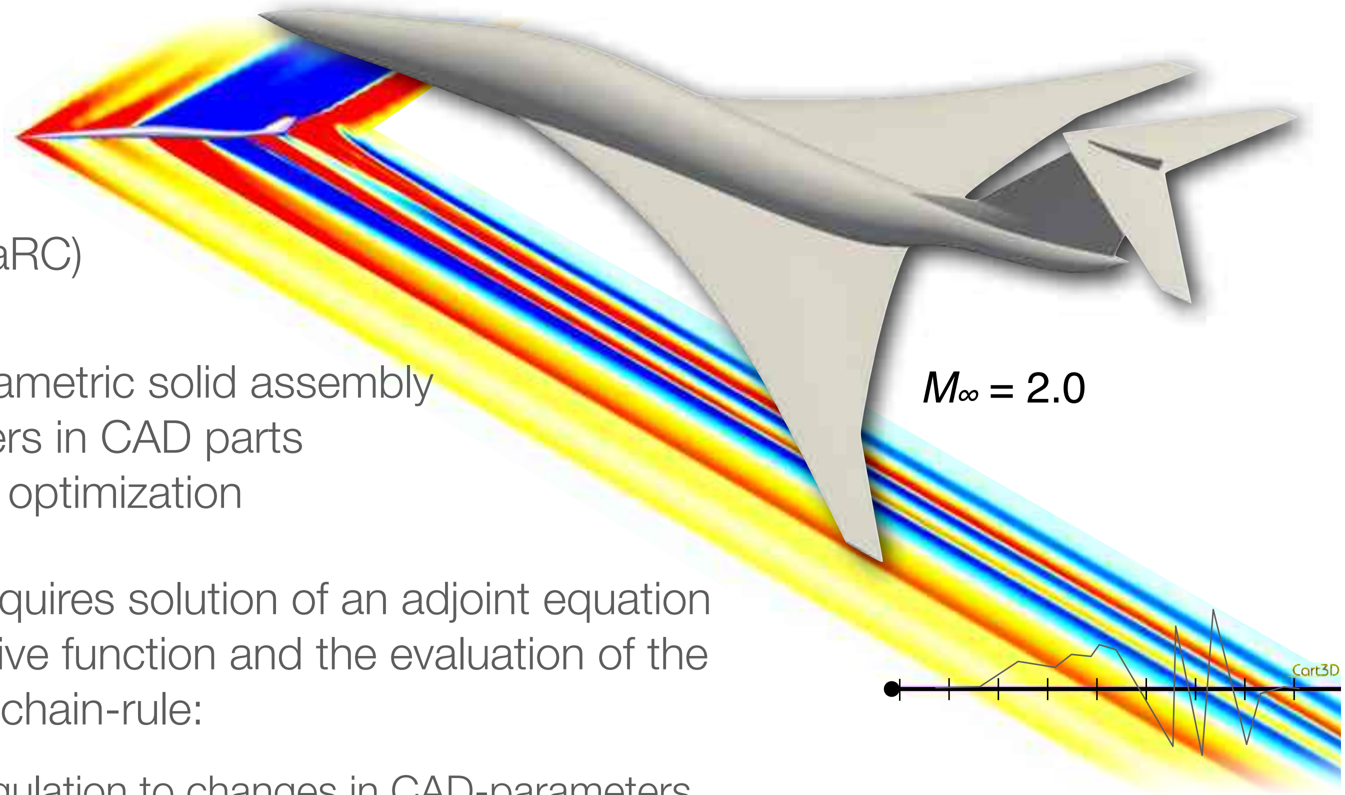
Exit Criterion: Demonstrate adjoint-based design for sonic boom mitigation through design optimization of a configuration completed in two weeks



- **Baseline configuration** provided by Aeronautics Systems Analysis Branch (LaRC)
- **CAD-Model:** Construct parametric solid assembly in Pro/ENGINEER. Parameters in CAD parts become design variables for optimization
- **Gradient Computation:** Requires solution of an adjoint equation for the inverse design objective function and the evaluation of the following sensitivities via the chain-rule:
    - Sensitivity of surface triangulation to changes in CAD-parameters
    - Sensitivity of mesh to changes in surface triangulation
    - Sensitivity of near-field signal to changes in vehicle shape and mesh

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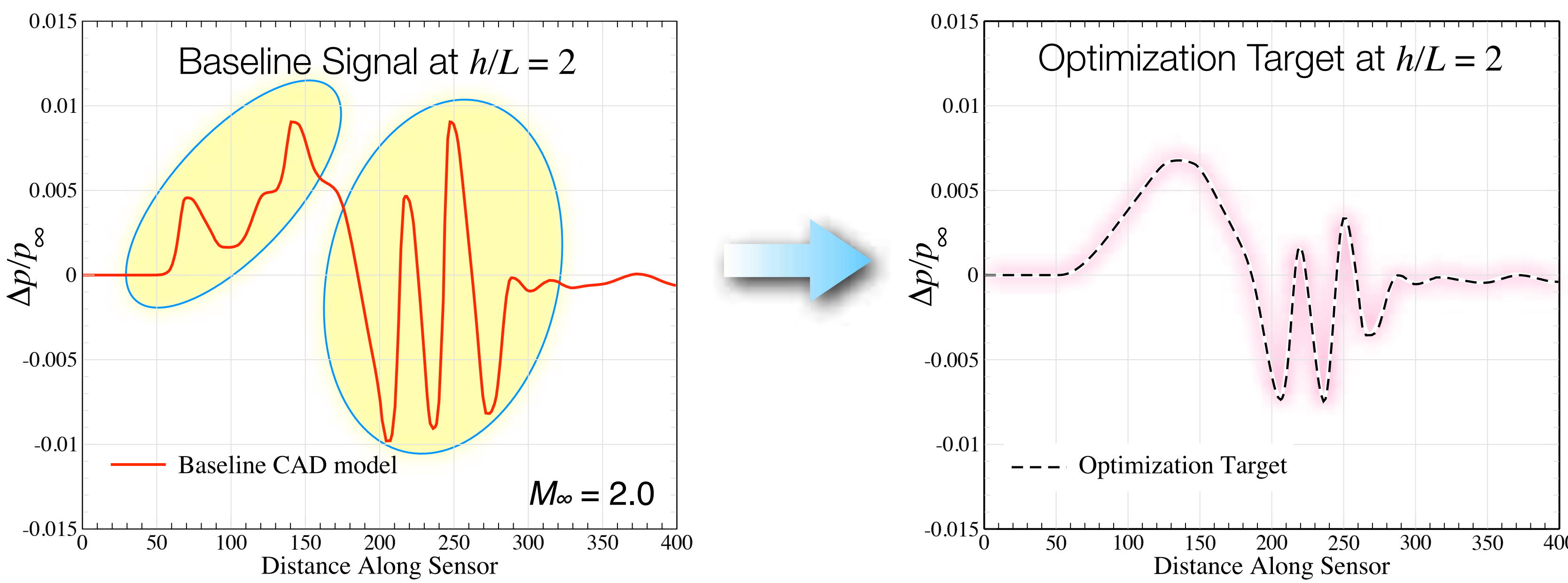
Optimization Goals:

- Inverse design to pre-specified target-signal measured two body-lengths away from the vehicle ($h/L = 2$)
- Smooth forebody ramp compression
- Decrease amplitude of rise at main wing
- Tailor aft-signal to reduce peaks
- Produce optimized CAD assembly with full feature tree intact
- Focus is on matching specified target near-field signal (no propagation to ground yet)



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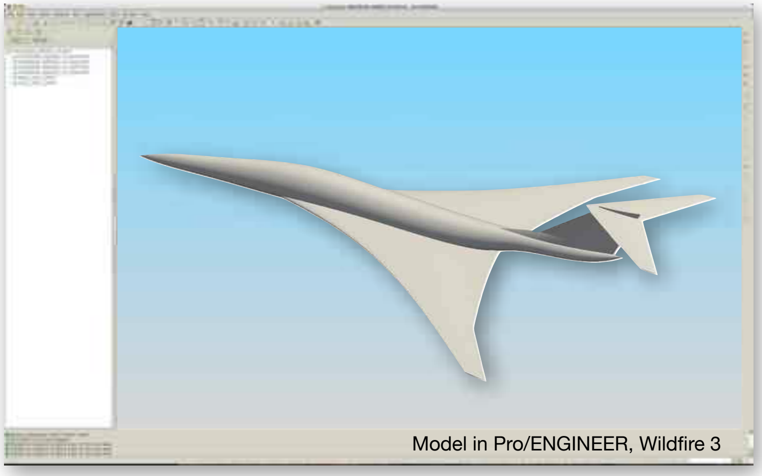
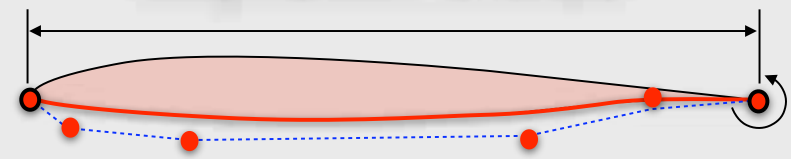
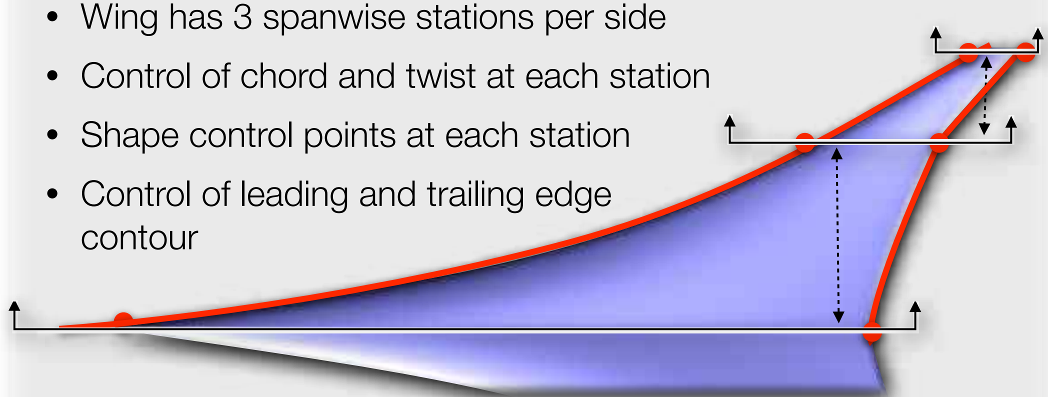
Shape Parameters in CAD-model:



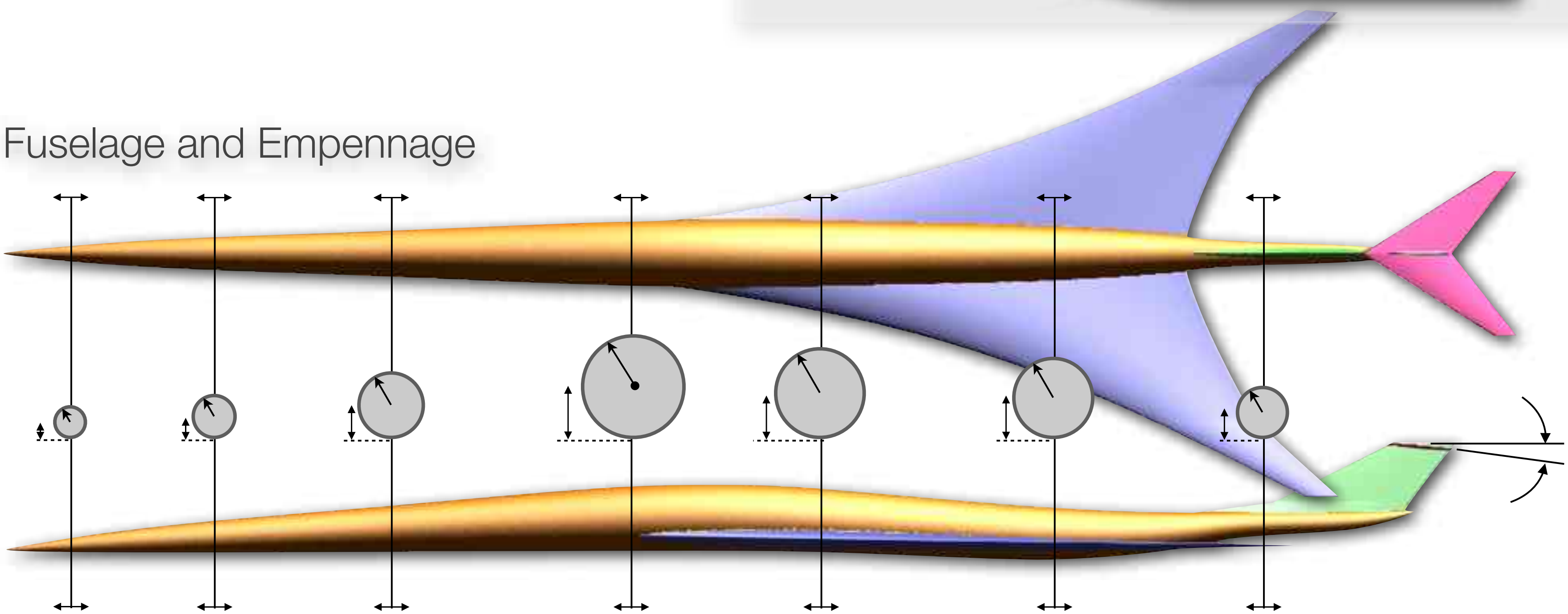
Wing Planform & Shape



- Wing has 3 spanwise stations per side
- Control of chord and twist at each station
- Shape control points at each station
- Control of leading and trailing edge contour



Fuselage and Empennage



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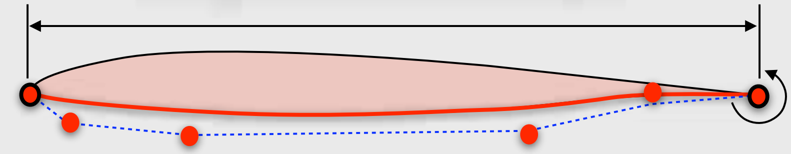
Design Variables Used

- CAD model controlled by ~100 independent parameters
- Selected 18 of the CAD-parameters to be Design Variables (DVs) for this particular inverse design case
  - **Fuselage Shape:** (9 DVs) radii and location of circular fuselage cross-sections
  - **Main Wing:** 4 airfoil shape parameters at 2 wing stations on lower surface
  - **Horizontal Tail:** Angle of incidence, $\theta_{\text{H-tail}}$

Wing Planform & Shape



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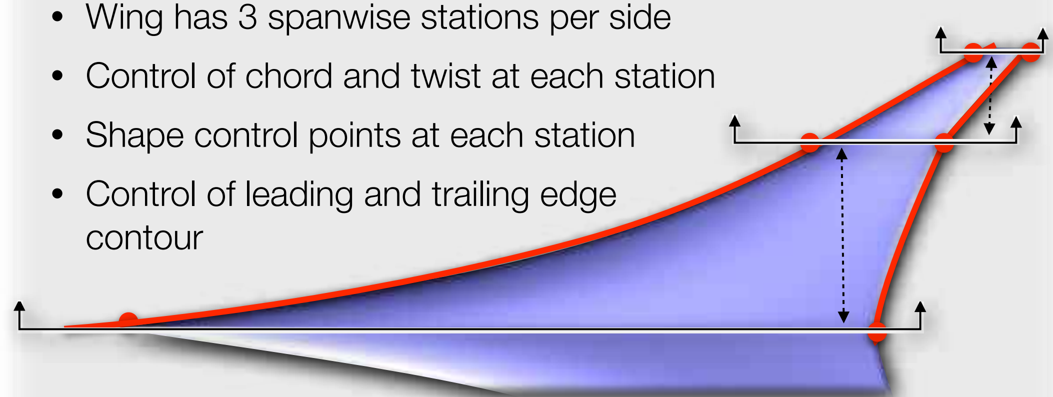

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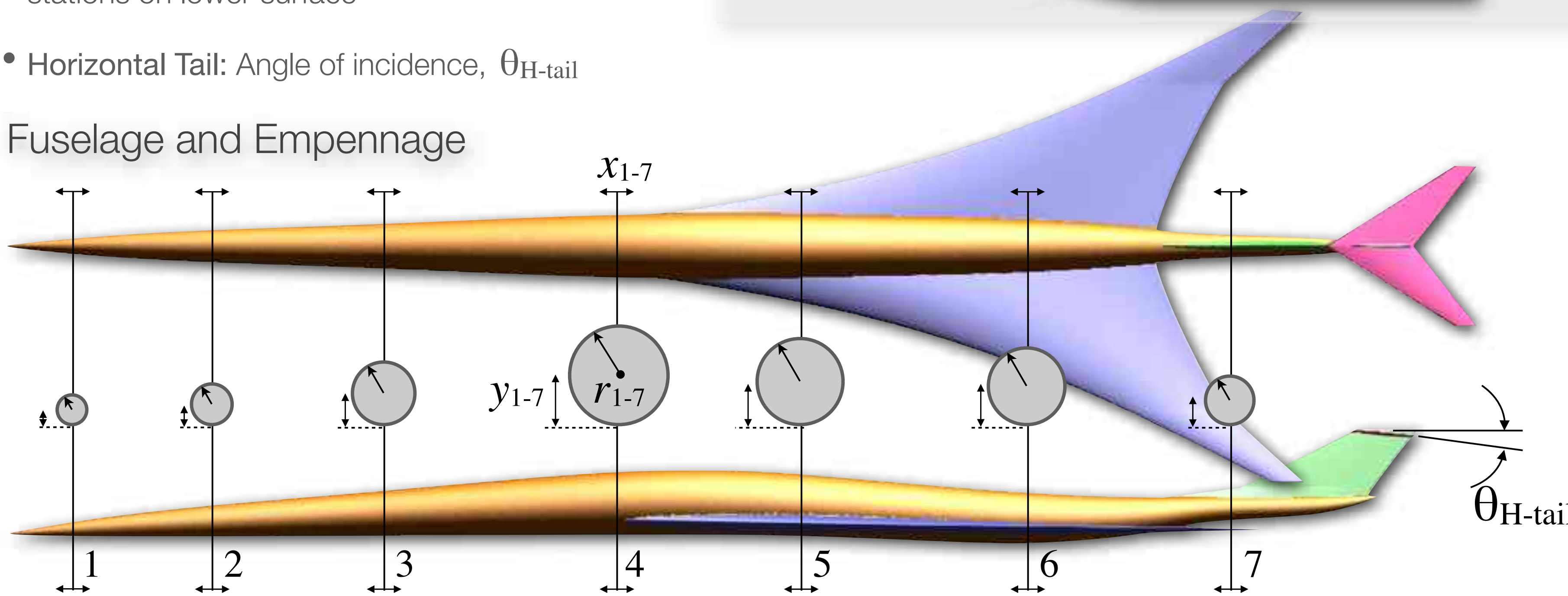

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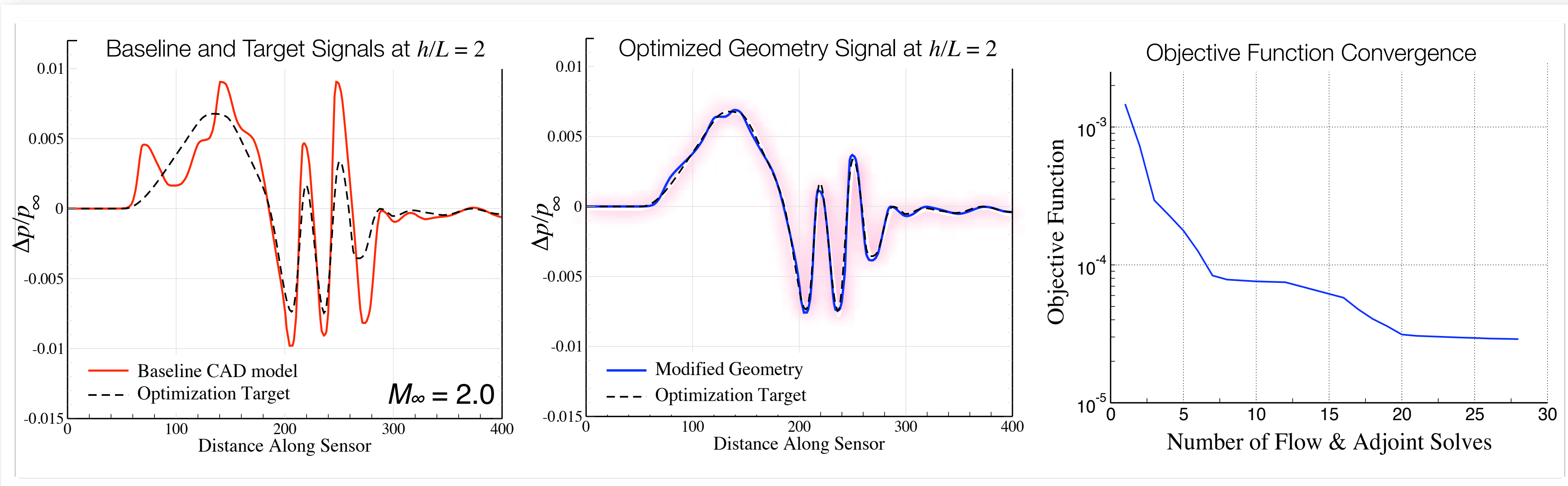
Optimization:

- Goal is to shape body using target pressure signal specified at h/L = 2
  - Objective function: Minimize $J = \int (P - P_{\text{target}})^2 dS$ at $h/L = 2$
- 18 Design variables
- Gradient-based optimizer used 19 search directions and a total of 28 objective function evaluations before flattening out
- Outcome is optimized CAD assembly with full feature-tree intact



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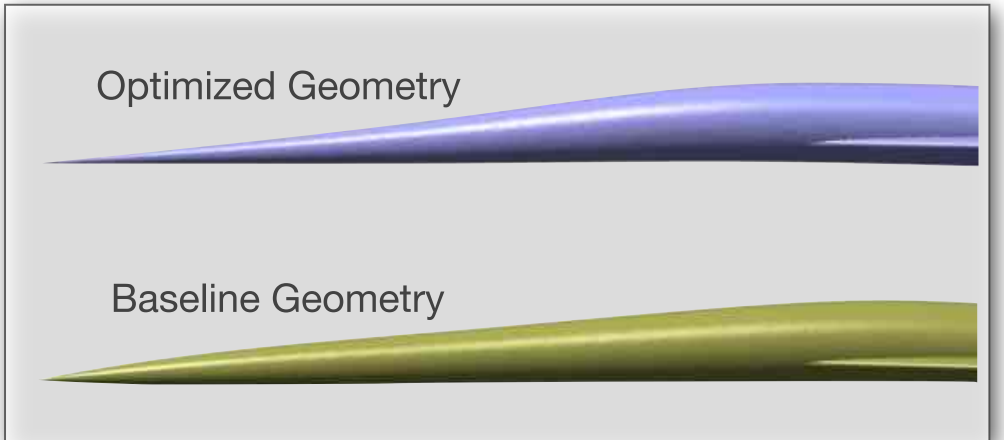
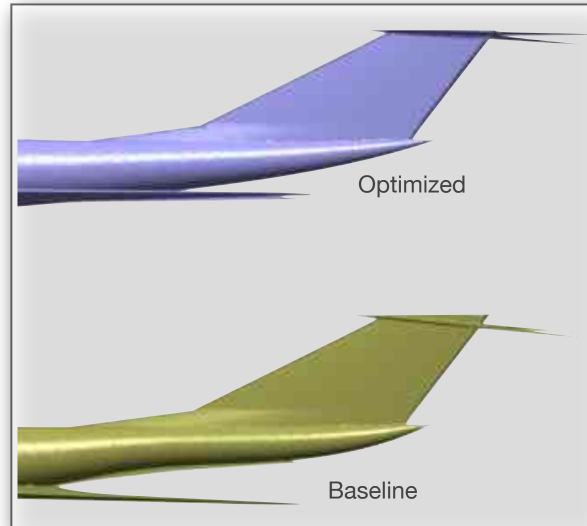
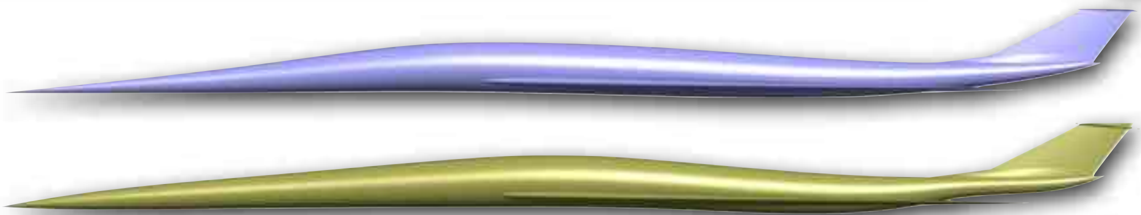
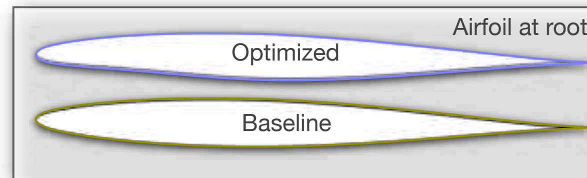
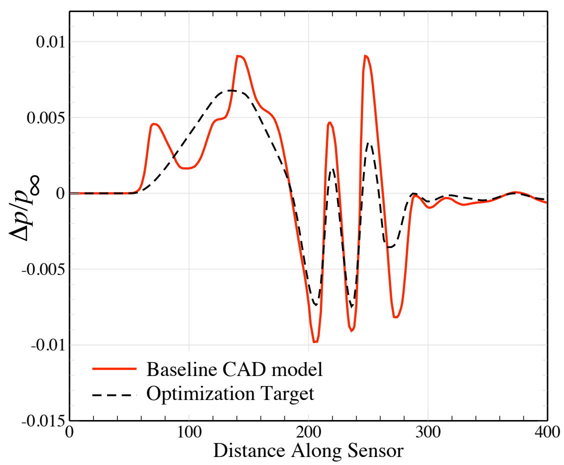




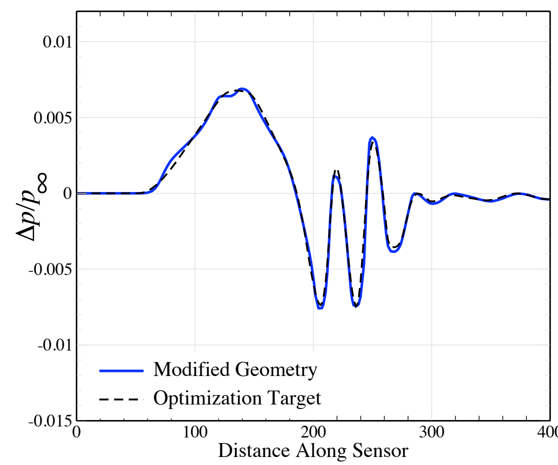




Baseline Geometry Signal at $h/L = 2$



Optimized Geometry Signal at $h/L = 2$



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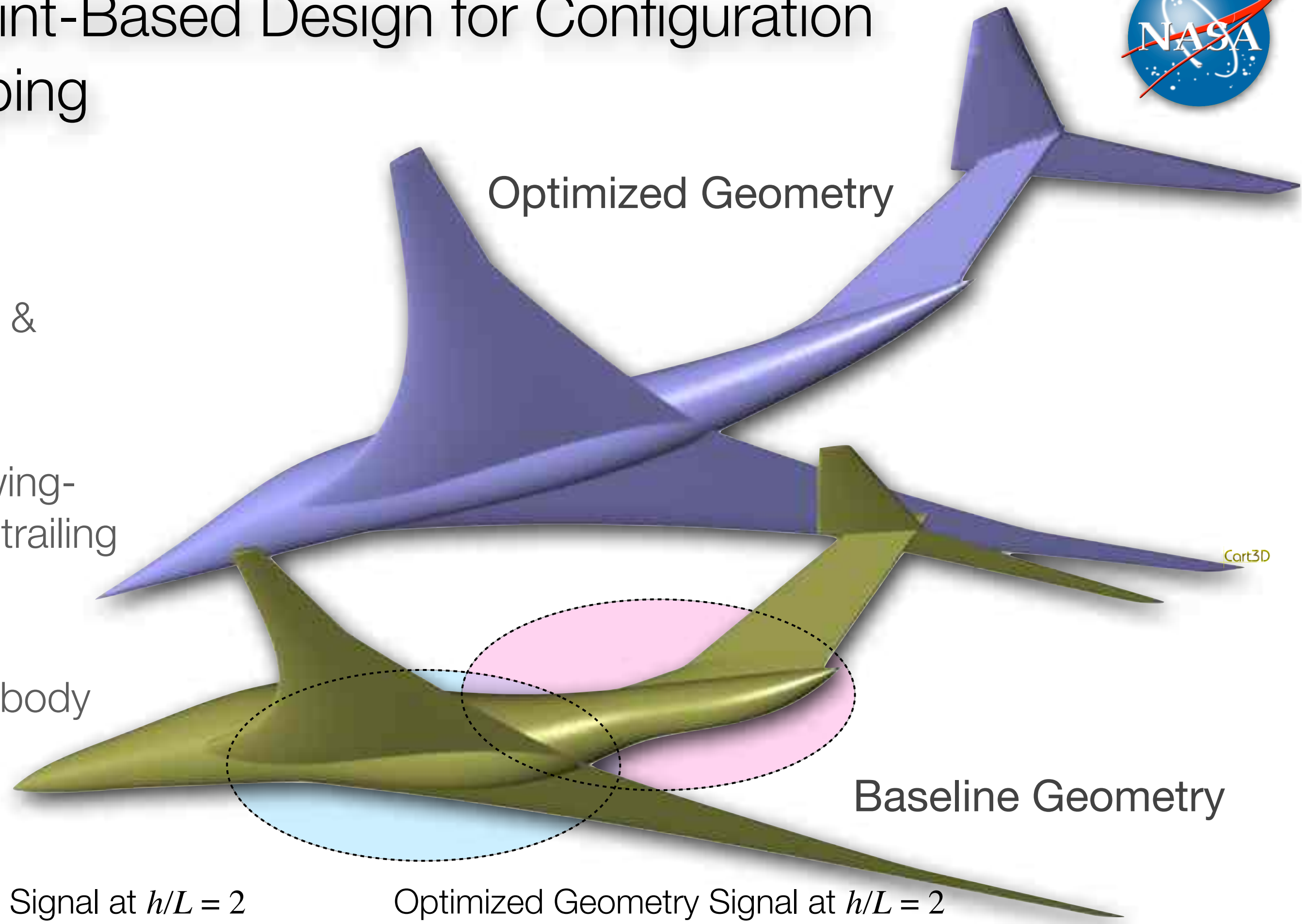
- Re-contouring of aft fuselage & underbelly
- Re-contouring of airfoil and wing-body juncture at leading and trailing edges
- Topology change at aft wing-body juncture



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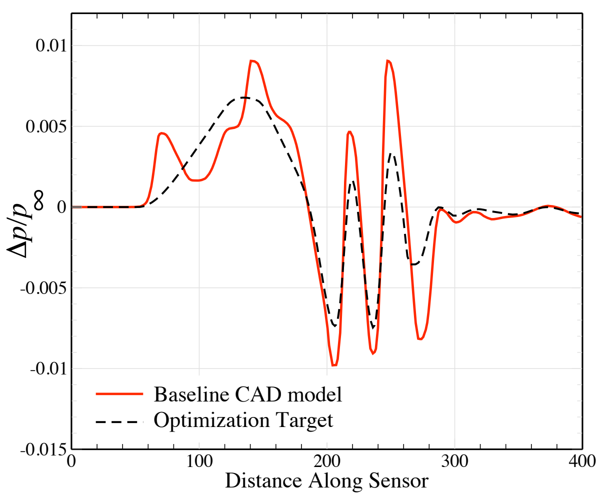

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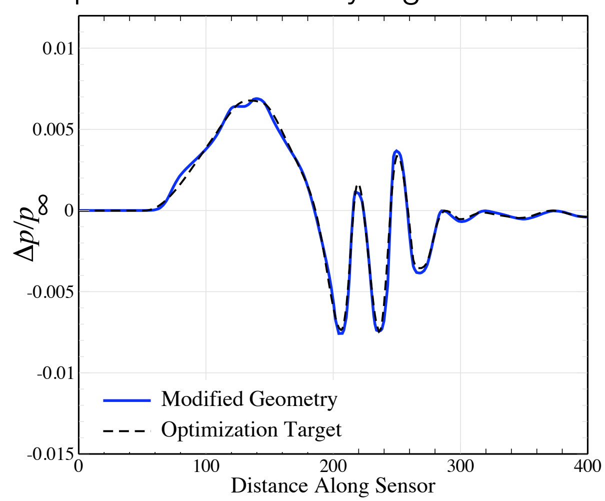

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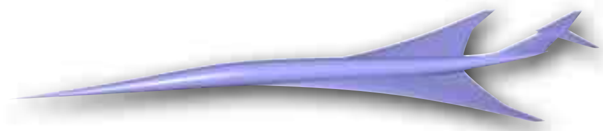
Baseline Geometry



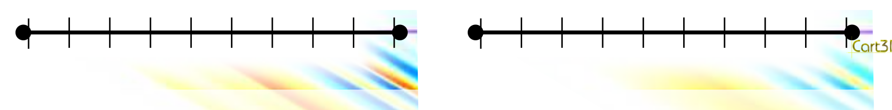
Optimized Geometry

$M_\infty = 2.0$

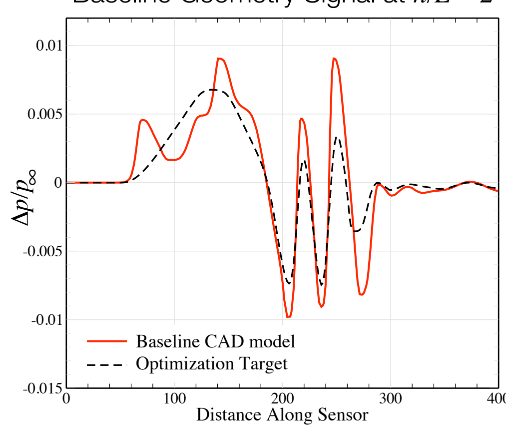
Isobars

$M_\infty = 2.0$

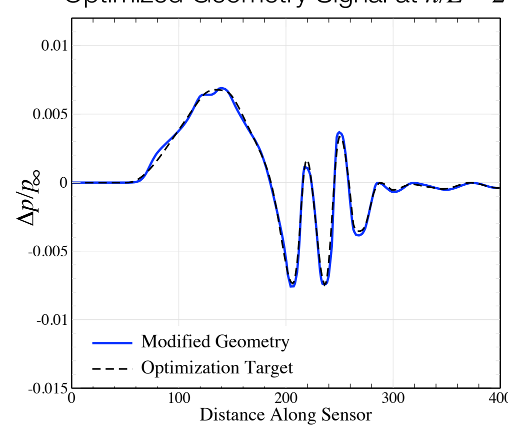
Scaled Isobars



Baseline Geometry Signal at $h/L = 2$



Optimized Geometry Signal at $h/L = 2$



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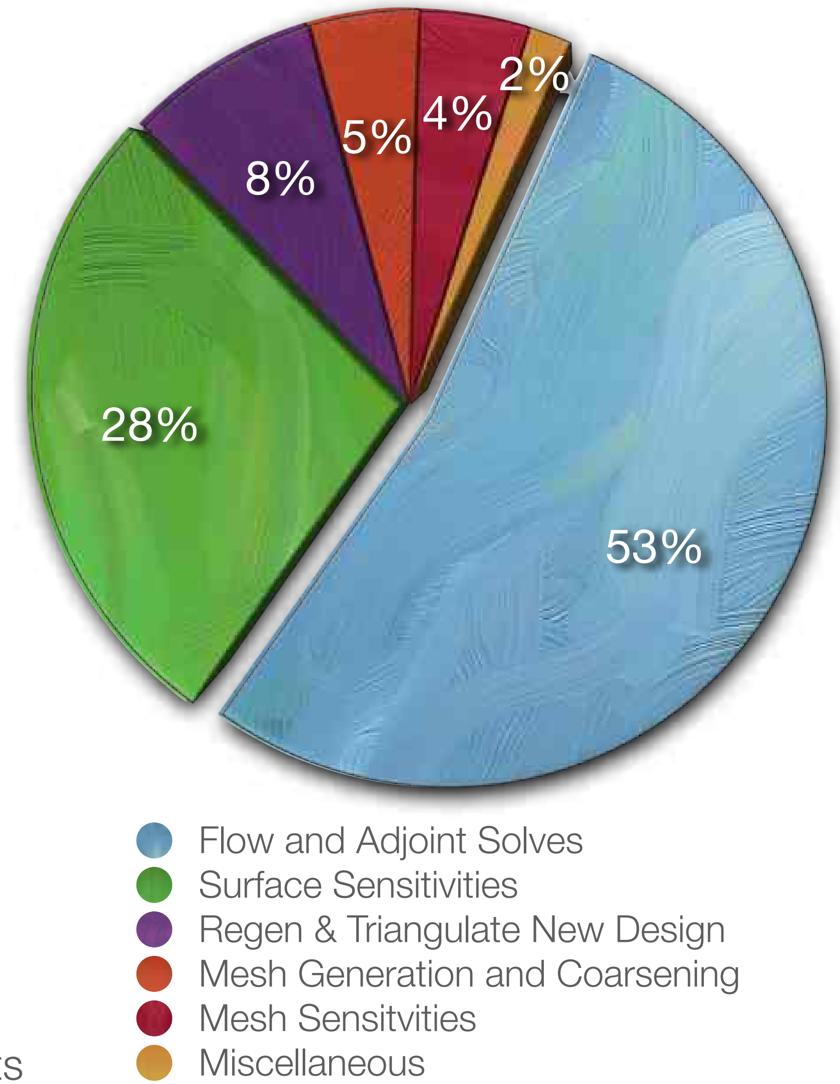
Timing and Performance:

- Optimization was carried out on 32 CPUs of Columbia and required ~1100 seconds of wall-clock-time per design iteration
- 18 Design Variables (nDV=18). Each iteration required
  - ✓ 1 flow & 1 adjoint solve
  - ✓ 3 x nDV re-generations of the geometry
  - ✓ 3 x nDV tessellations of the geometry
  - ✓ nDV surface sensitivities
  - ✓ nDV mesh sensitivities
  - ✓ Gradient formation and optimization step
- 5 CAPRI CAD-servers (running Pro/ENGINEER) provided geometry using "http://" protocol
- Design process used 19 search directions with 28 objective function & gradient evaluations
- ~20 x fewer resources than finite-difference gradients
- Total = 8.5 hrs wall-clock time



Total = ~18 mins./design cycle

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Summary

- Demonstrated adjoint-based design for sonic boom mitigation through design optimization of a complete configuration provided by LaRC in under 2 weeks (8.5 hrs on 32 Columbia CPUs)

- An inverse-design approach was used to shape a vehicle to match user-prescribed near-field pressure signature at a distance of 2 body-lengths away from vehicle

- Design approach uses adjoint-based gradients for mesh and flow field sensitivities in conjunction with a non-body-fitted Cartesian method for automation and efficiency

- First demonstration of accurate objective function gradients for remote functionals of full configurations using non-body-fitted methods

- Prototype Cart3D design framework has undergone extensive V&V and developers are working toward beta-release

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Further Development

- Incorporate knowledge of signal after propagation to ground in near-field objective function
- Port Cart3D design framework to distributed memory platforms
- Incorporate adjoint-based adaptive meshing (Cart3D AERO module)
  - Extend AERO module to output mesh sensitivities
- Need to develop hooks for non-CAD modelers (Rage, Sculptor, VSP, in-hose modelers etc..)
- CAPRI CAD servers - $O(nDV^2)$ Regens and tessellation emphasize robustness & speed
  - Streamline surface tessellation and sensitivity calculations
  - Revisit CAD model construction for improved efficiency in regeneration & tessellation
  - Investigate analytic CAD sensitivities
- Examine alternative optimization strategies including those which trade design improvement with level of functional accuracy to accelerate convergence