Analysis and Results from a Flush Airdata Sensing (FADS) System in Close Proximity to Firing Rocket Nozzles

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Introduction

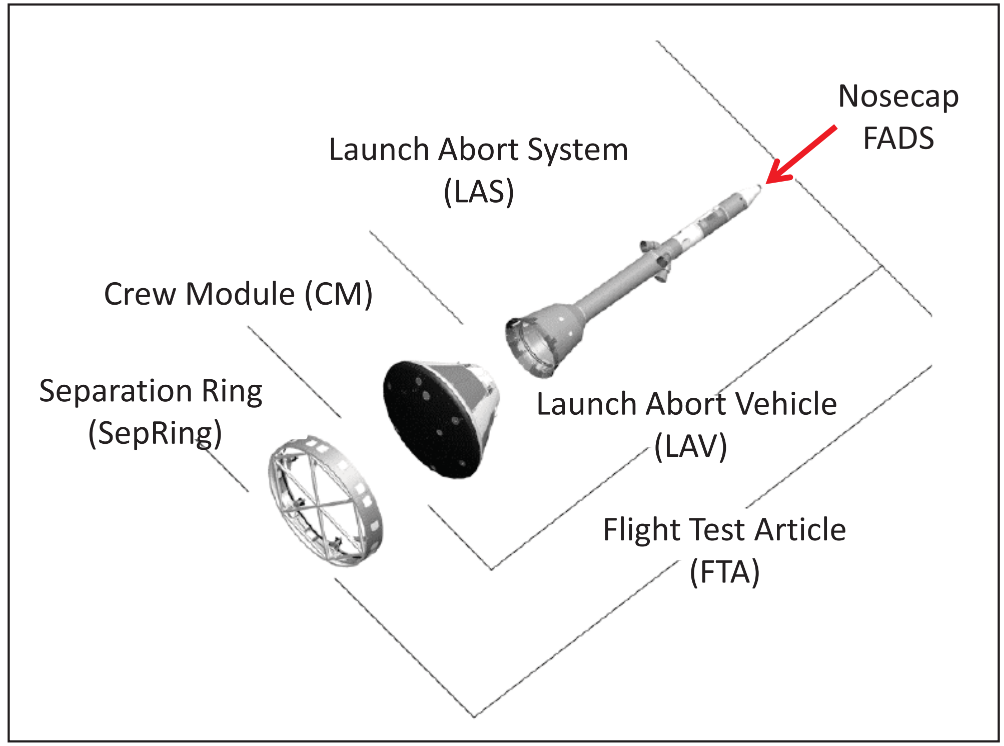
- PA-1 overview
- FADS system overview
- PA1 trajectory results
- CFD study
- Summary

Orion Pad Abort One

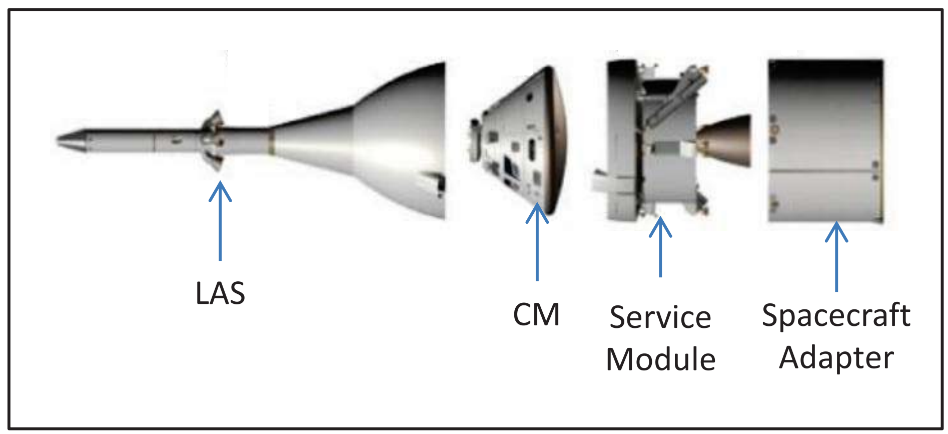
PA-1

- First in a sequence of atmospheric flight tests for developing the Orion Crew Exploration Vehicle (CEV); a component of the now deactivated Constellation
- **Purpose**: To demonstrate capability of the LAS and boilerplate CM to abort from the launch pad and safely return the CM to the ground using the parachute recovery system.
- Orion CEV now Multi Purpose Crew Vehicle (MPCV)

Artist's rendition of Space Launch System



PA-1 Flight Test Article

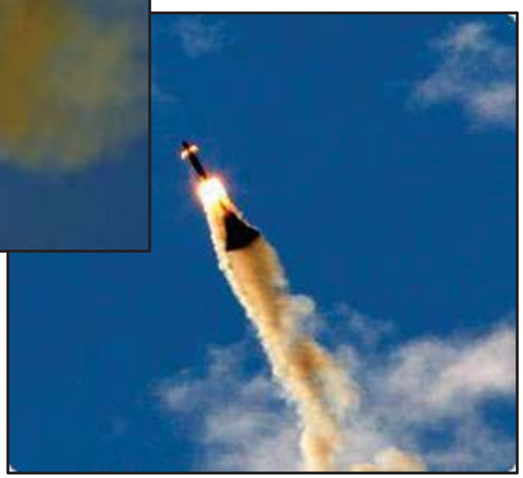


Expanded view of the Orion CEV

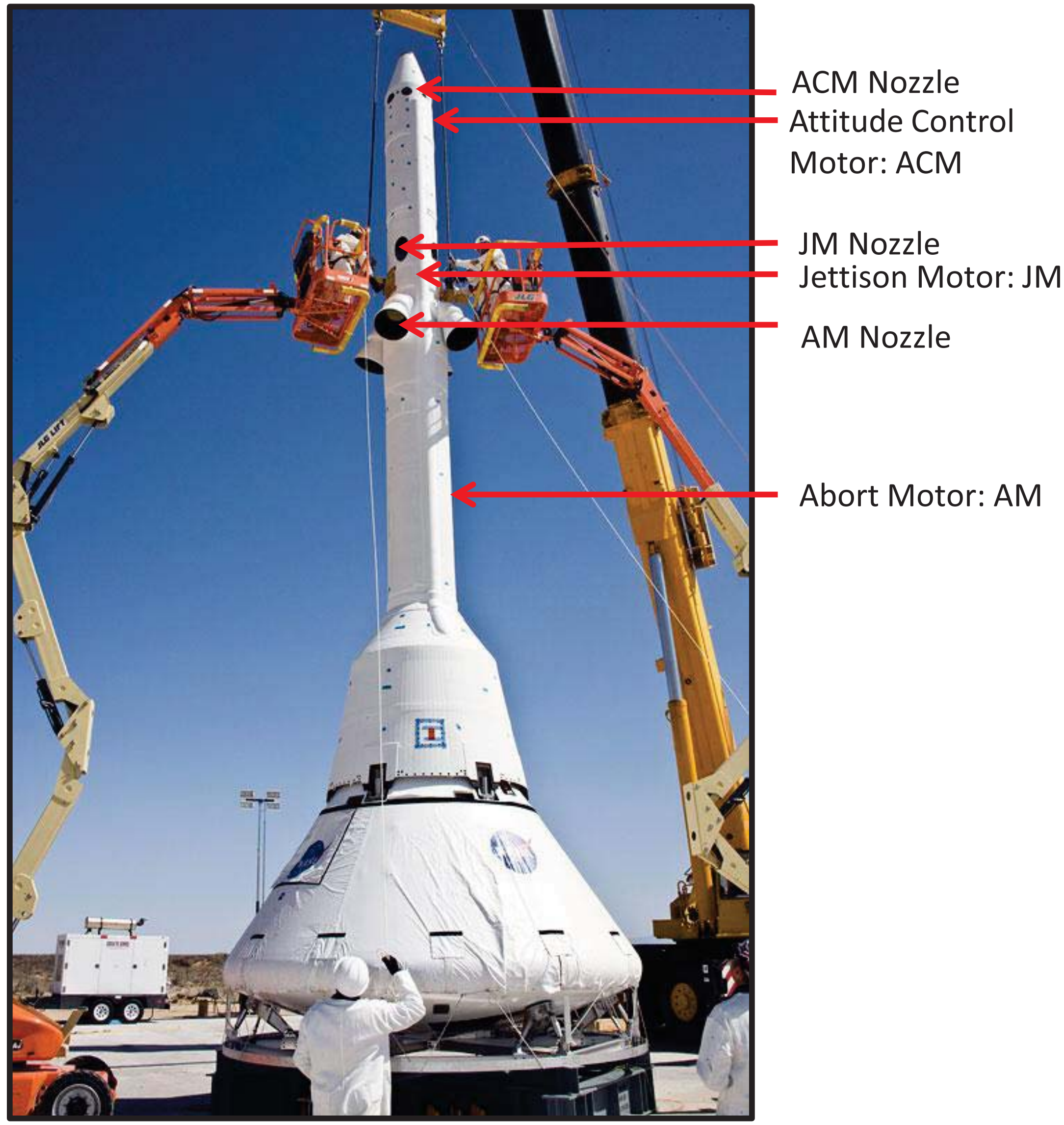
PA-1 Launch Abort System

- **Attitude Control Motor:** provided omnidirectional control for the LAV
  - Max thrust 6.5×10^3 lbf
  - 8 nozzles
- **Jettison Motor:** responsible for pulling the LAS away from the CM
  - Max thrust 4×10^4 lbf
  - 4 nozzles
- **Abort Motor:** responsible for pulling the LAV away from the launch pad
  - Max thrust 5×10^5 lbf
  - 4 nozzles

Separated LAS and CM



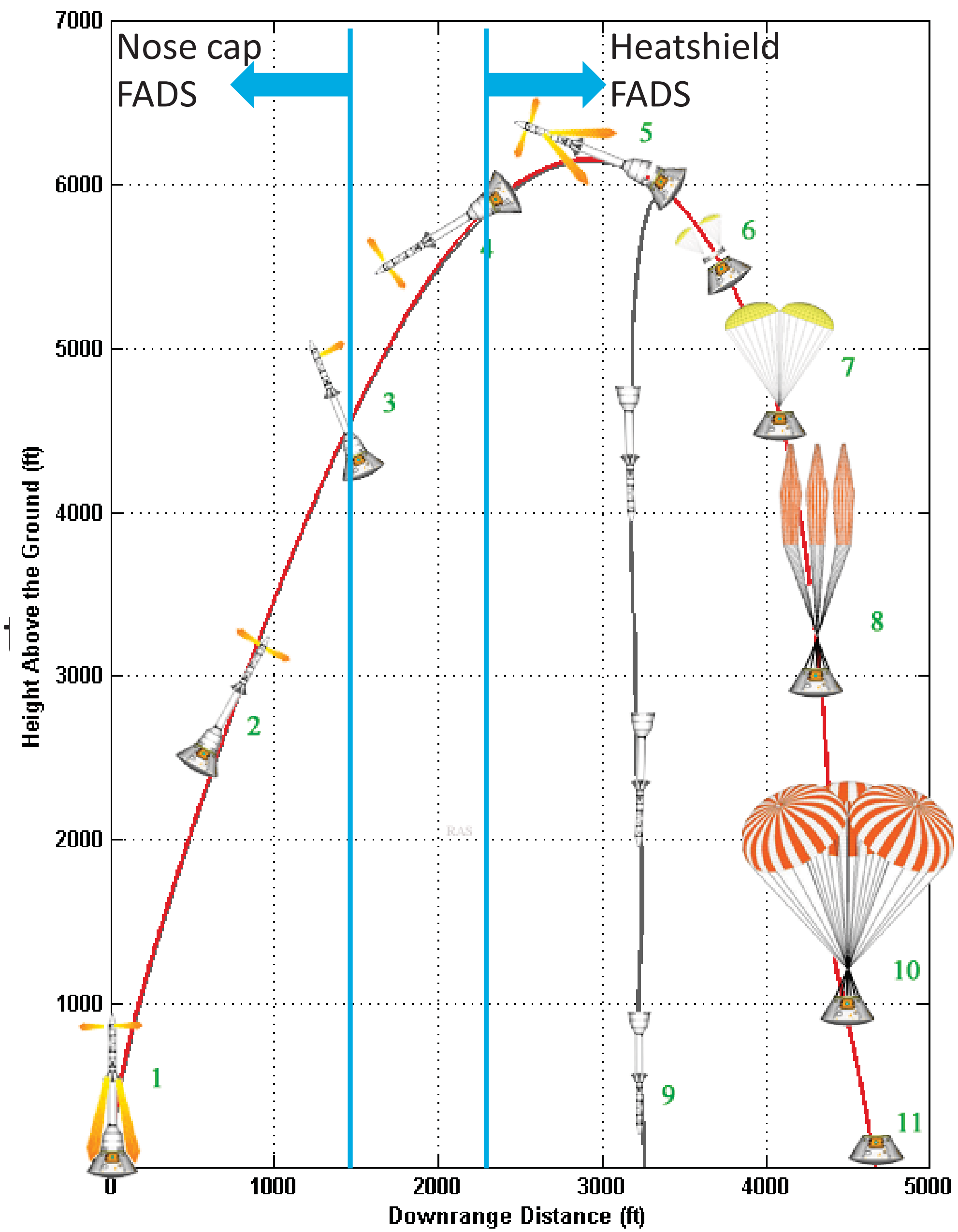
LAV



PA-1 Flight Test Article

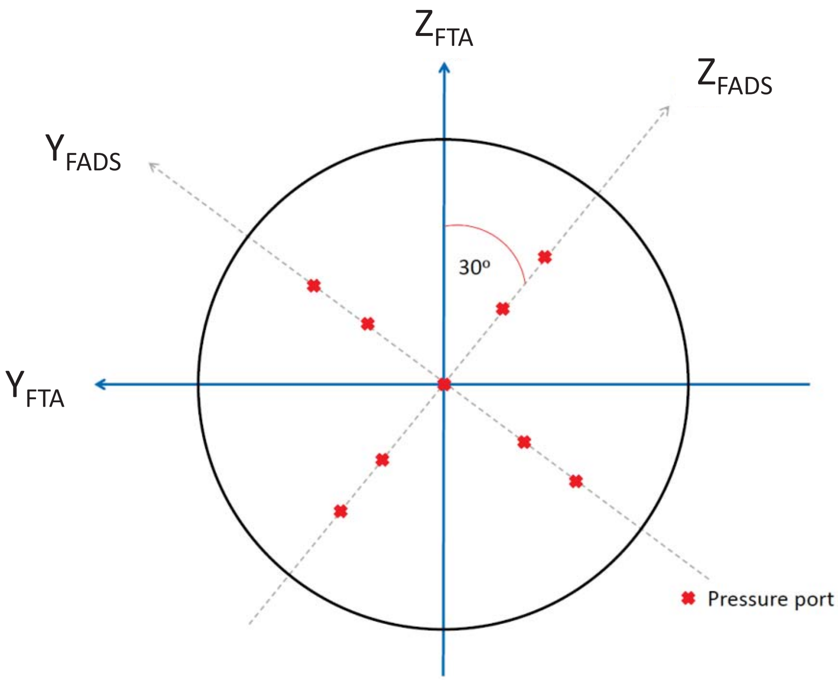
PA-1 Trajectory

1. Launch
2. Abort Motor Burnout
3. Reorientation Started
4. Reorientation Completed
5. LAS Jettison
6. FBC Jettison
7. Drogue Parachute Deployment
8. Main Parachute Deployment
9. LAS Touchdown
10. Main Parachute Full Inflation
11. CM Touchdown



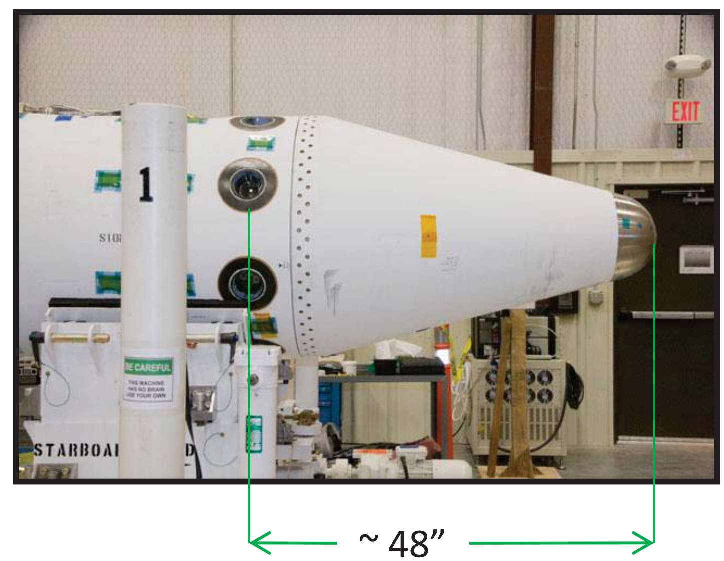
Flush Airdata Sensing System

- Pressure data collected from pressure ports flush with the surface
  - Used to calculate angle of attack, sideslip, impact pressure, free stream pressure and Mach
- Estimated air data parameters from Launch up to the start of vehicle reorientation
- Experimental system
  - Not used for control
  - all data post processed



FADS Reference Frame Relative to Flight Test Article Reference Frame

FADS pressure ports on LAS (protective covering on)



Distance of FADS ports from ACM nozzles

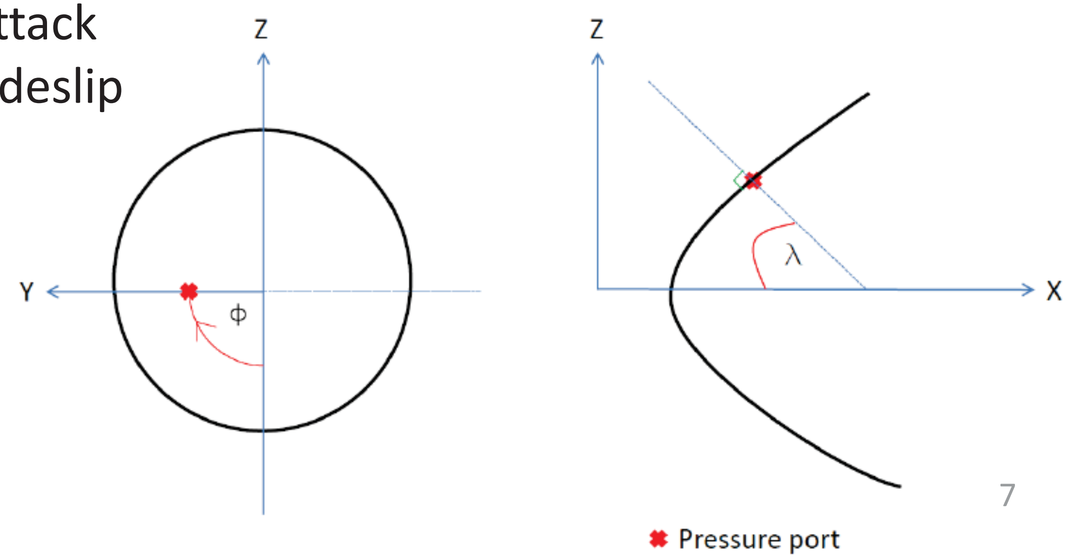
FADS Aerodynamic Model

- Aerodynamic Model
  - Combination of closed form potential flow solution for a blunt body and modified Newtonian flow model

$$p_i = q_c[cos^2(\theta_i) + \epsilon\, sin^2(\theta_i)] + P_\infty$$

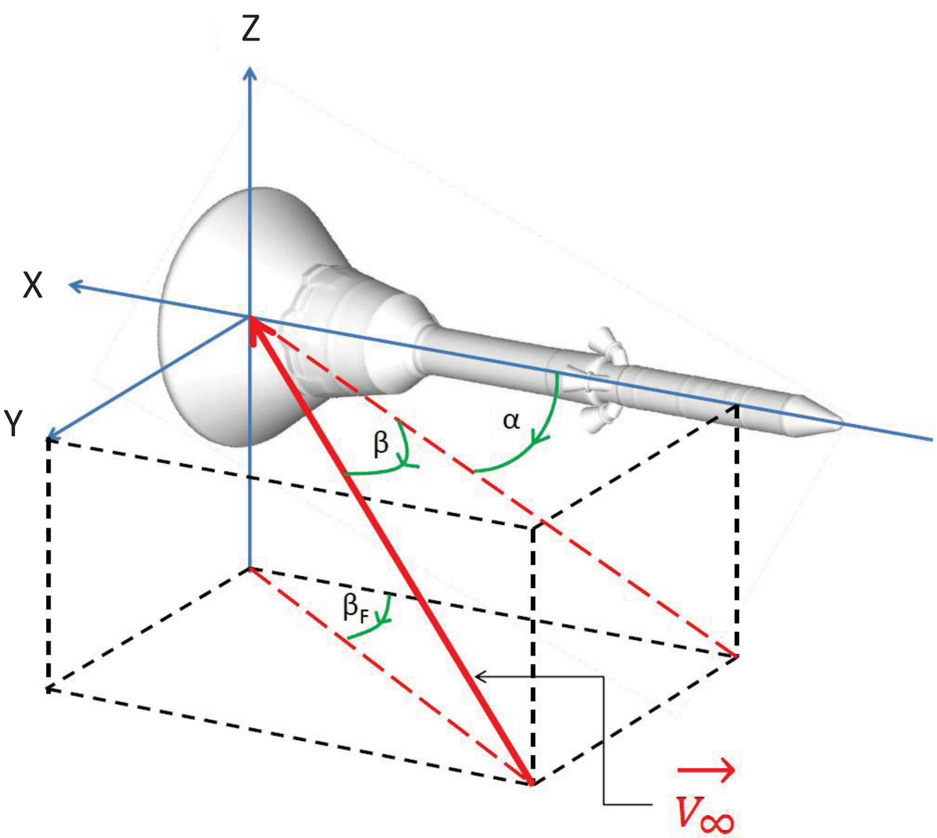
$$cos(\theta_i) = cos(\alpha_e)cos(\beta_e)cos(\lambda_i) + sin(\beta_e)sin(\phi_i)sin(\lambda_i) + sin(\alpha_e)cos(\beta_e)cos(\phi_i)sin(\lambda_i)$$

  - p_i: port pressure, q_c: impact pressure, P_∞ : freestream static pressure, ϵ: calibration parameter
  - θ_i: angle velocity vector makes with normal to i'th port
  - α_e : effective or local angle of attack
  - β_e : effective or local angle of sideslip
  - ϕ_i : clocking angle of i'th port
  - λ_i : cone angle



Angle of Attack, Sideslip & Flank Angle

- Angle of Attack
  - Contained in XZ plane
  - Used triples algorithm (NASA/TM-1998-206540: Whitmore, Cobleigh, Haering) which uses differences of three distinct surface pressures from ports aligned with Z_{FADS} axis
- Flank Angle
  - Contained in XY plane
  - Applied 90^0 counterclockwise rotation to clocking angles of ports on Y_{FADS} axis
  - Used triples algorithm to calculate flank angle
- Sideslip
  - $\beta = tan^{-1}(tan(\beta_F) \times cos(\alpha))$



Calibration Parameter: ϵ

Project Orion Abort Flight Test

- Applied least squares to system of equations defining pressures at all nine ports

$$\begin{bmatrix} p_1 \\ . \\ . \\ . \\ p_9 \end{bmatrix} = \begin{bmatrix} (\cos^2(\theta_1) + \epsilon \sin^2(\theta_1)) & 1 \\ . & \\ . & \\ . & \\ (\cos^2(\theta_9) + \epsilon \sin^2(\theta_9)) & 1 \end{bmatrix} \begin{bmatrix} q_c \\ P_\infty \end{bmatrix}$$

$$\epsilon = \frac{\sum_{i=1}^{9} \sin^2\theta_i \left(C_p - \cos^2\theta_i\right)}{\sum_{i=1}^{n} \sin^4 \theta_i}$$

Impact Pressure, Freestream Static Pressure, Mach

- Impact pressure (q_c) and freestream static pressure (P_∞)
  - Iterative estimator (NASA/TM-1998-206540: Whitmore, Cobleigh, Haering)

$$\begin{bmatrix} q_c \\ P_\infty \end{bmatrix}_{(j+1)} = \left\{ \left[M_{(j)}^T Q M_{(j)} \right]^{-1} M_{(j)}^T Q \right\} \begin{bmatrix} p_1 \\ \cdot \\ \cdot \\ \cdot \\ p_n \end{bmatrix}$$

$$M_{(j)} = \begin{bmatrix} \left(cos^2(\theta_1) + \epsilon_{(j)}\ sin^2(\theta_1)\right) & 1 \\ \cdot & \\ \cdot & \\ \cdot & \\ \left(cos^2(\theta_n) + \epsilon_{(j)}\ sin^2(n)\right) & 1 \end{bmatrix}$$

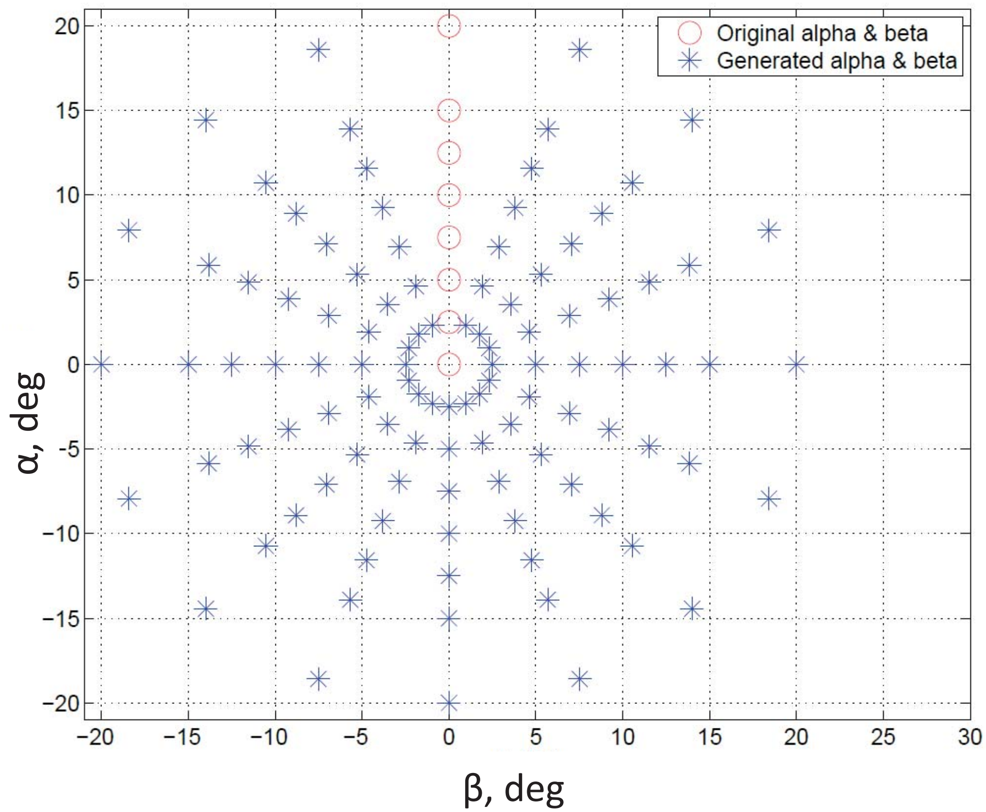
$$Q = \begin{bmatrix} q_1 & \cdot & \cdot & \cdot & 0 \\ \cdot & \cdot & & & \cdot \\ \cdot & & \cdot & & \cdot \\ \cdot & & & \cdot & \cdot \\ 0. & \cdot & & \cdot & q_n \end{bmatrix}$$

- Mach number
  - Isentropic flow relation for subsonic flow

$$\frac{q_c}{P_\infty} = \left(1 + \frac{\gamma - 1}{2} M_\infty^2\right)^{\frac{\gamma}{\gamma - 1}} - 1$$

Calibration Data

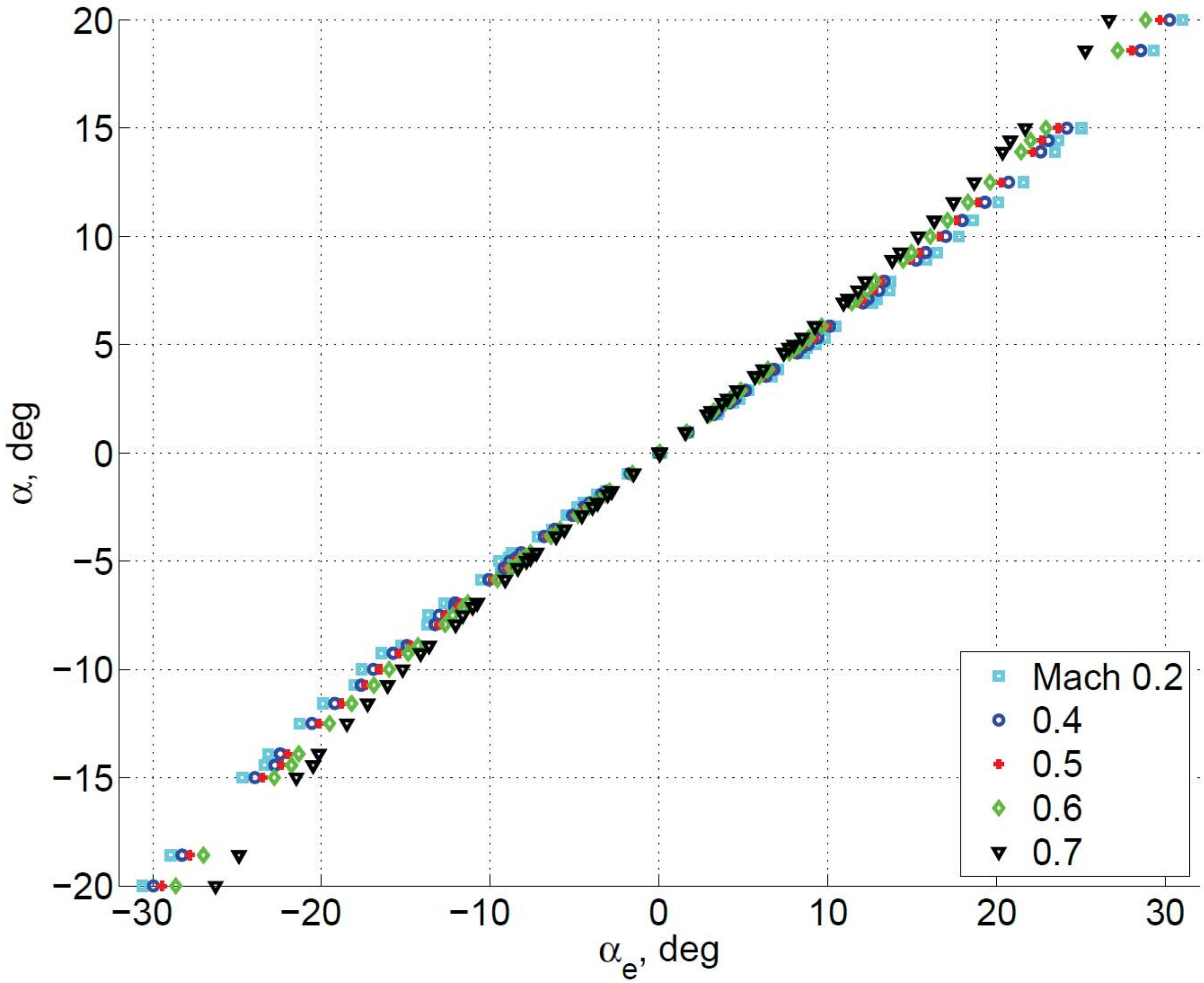
- Database made up entirely of CFD data generated with OVERFLOW; a Navier Stokes flow solver
- The portion of vehicle forward of the AM nozzles was modeled in the CFD
- ACM was not modeled
- Mach range
  - {0.2, 0.4, 0.5, 0.6, 0.7}
- Alpha range
  - {0.0, 2.5, 5.0, 7.5, 10, 12.5, 15, 20}
- Beta range
  - {0.0}
- Took advantage of vehicle axisymmetry to algebraically expand the database



Project Orion Abort Flight Test

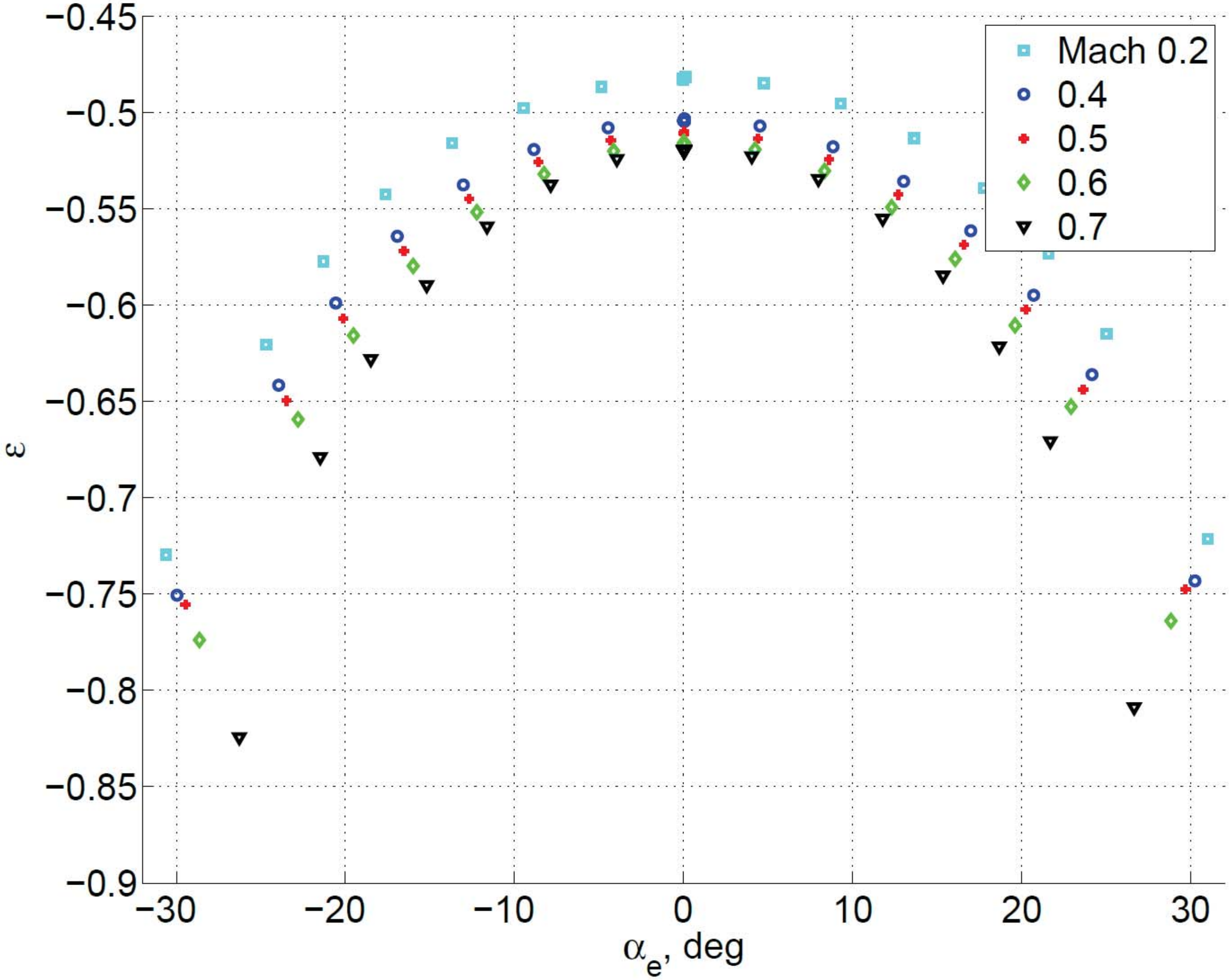
Calibration Data

$\alpha(\alpha_e, \beta_{fe}, M_\infty)$, $\beta_{fe} = 0$



Calibration Data

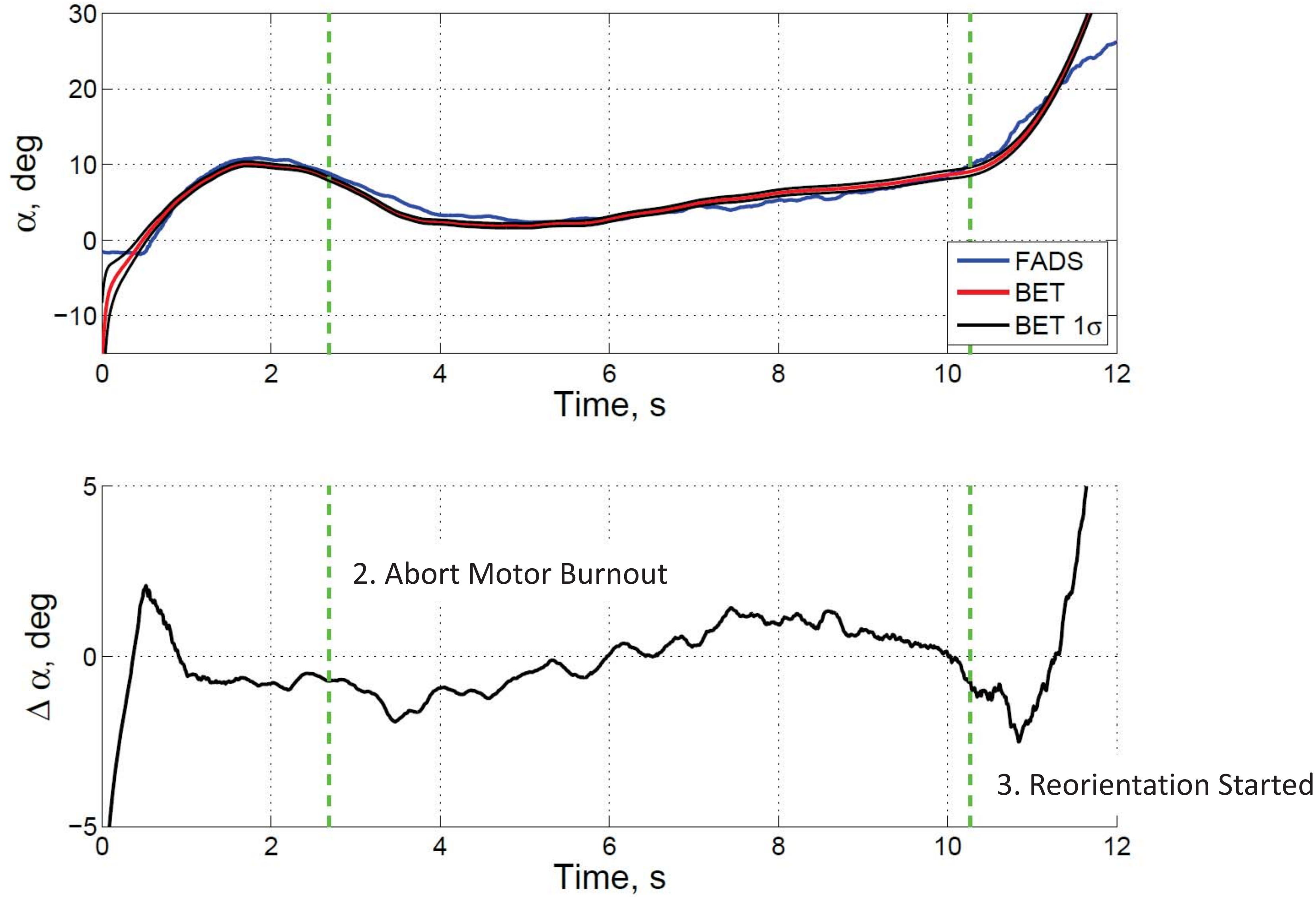
$\varepsilon(\alpha_e, \beta_{fe}, M_\infty)$, $\beta_{fe} = 0$



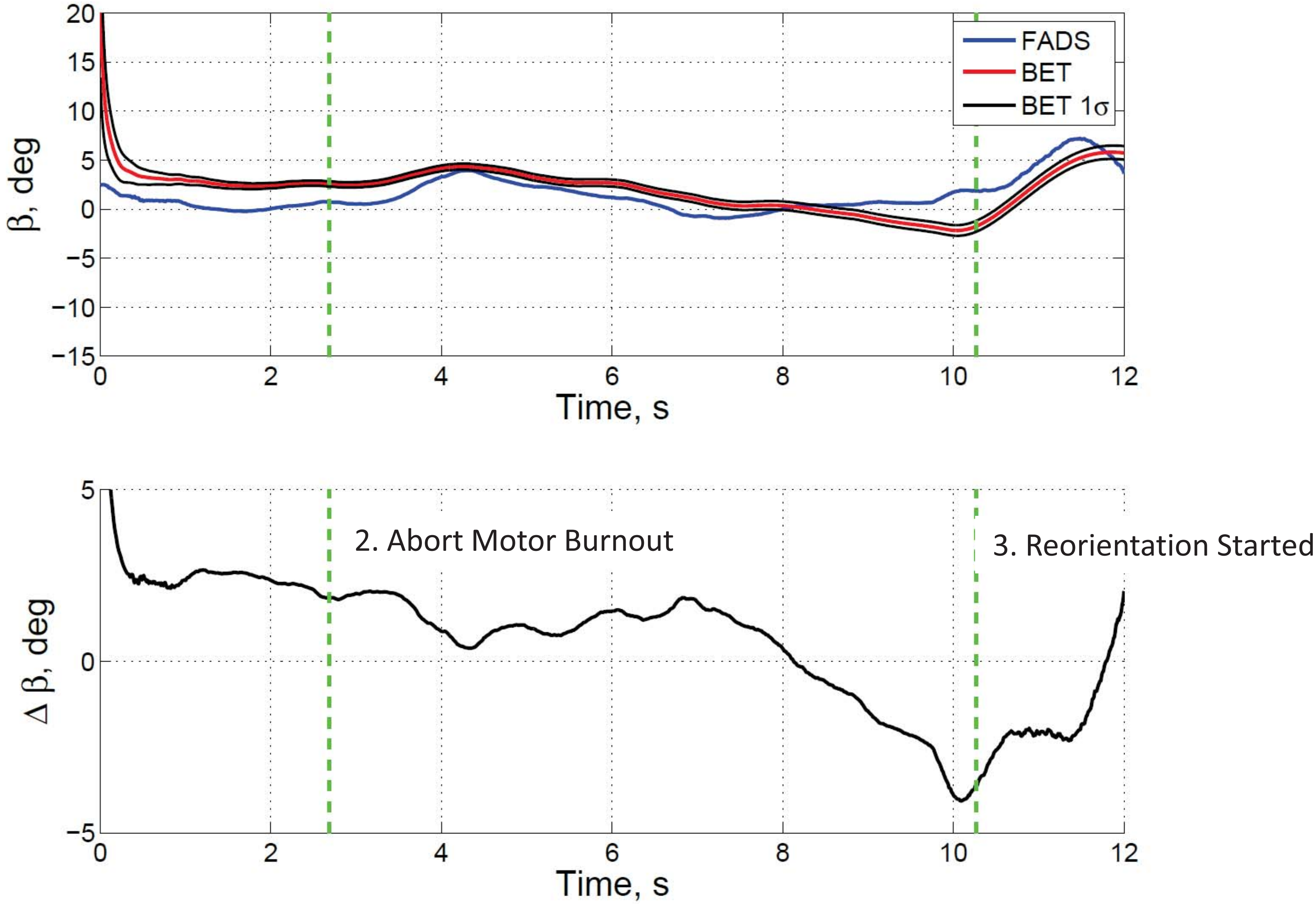
Best Estimated Trajectory: BET

- Used combination of:
  - Inertial data
  - radar tracking
  - optical observations
  - day of flight atmosphere profile
- To determine data parameters of the vehicle along its trajectory

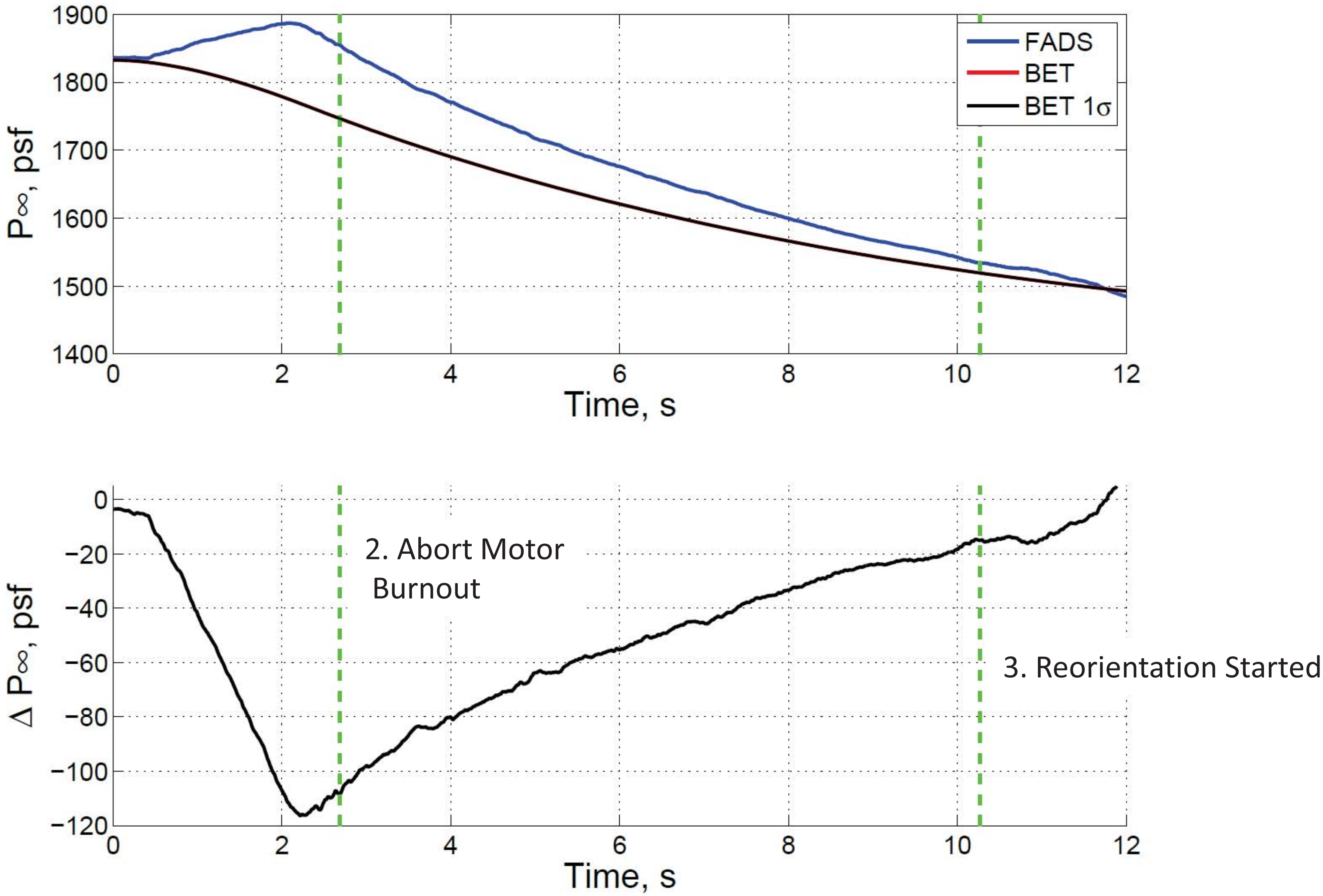
Flight Data Comparison: Angle of Attack



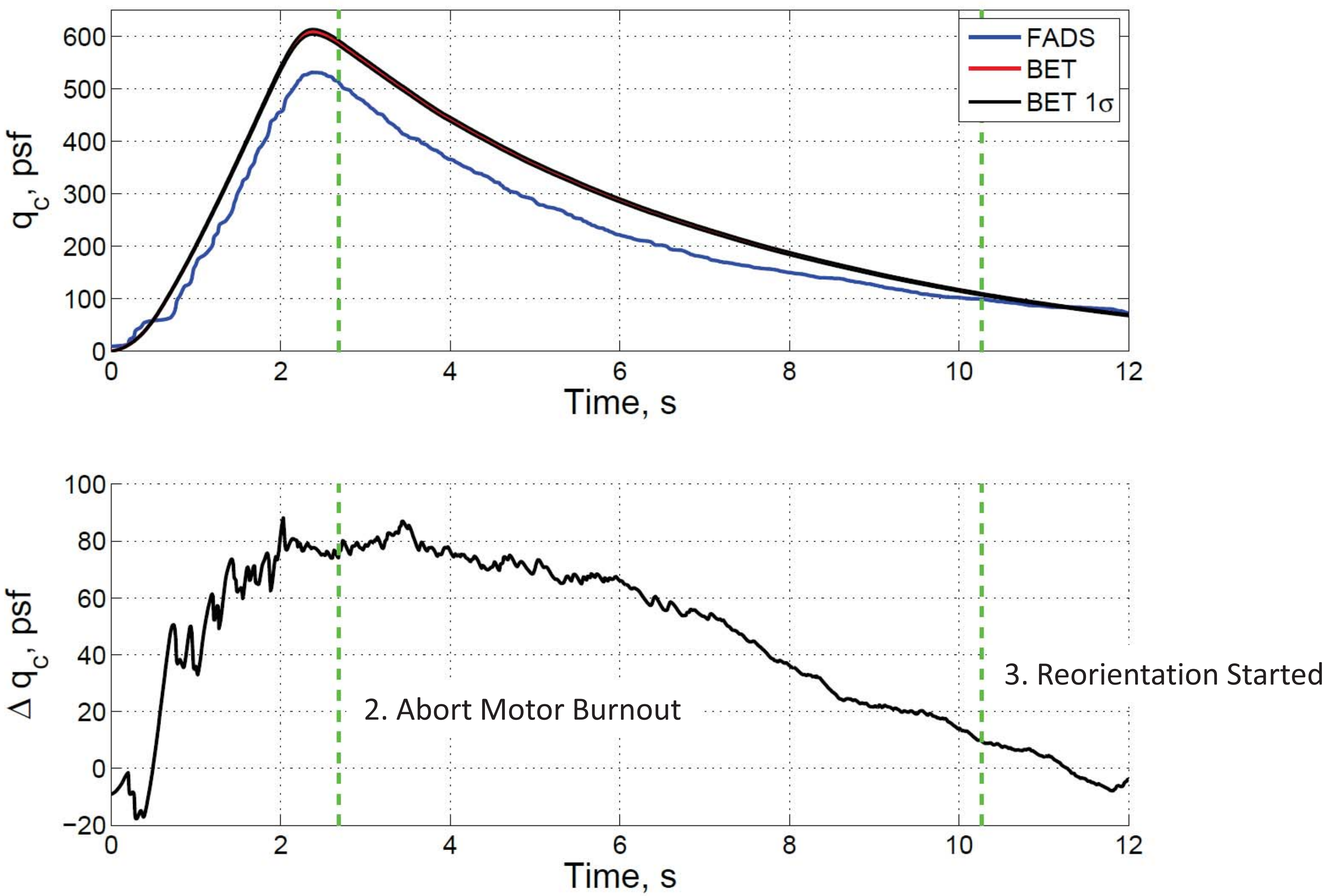
Flight Data Comparison: Sideslip



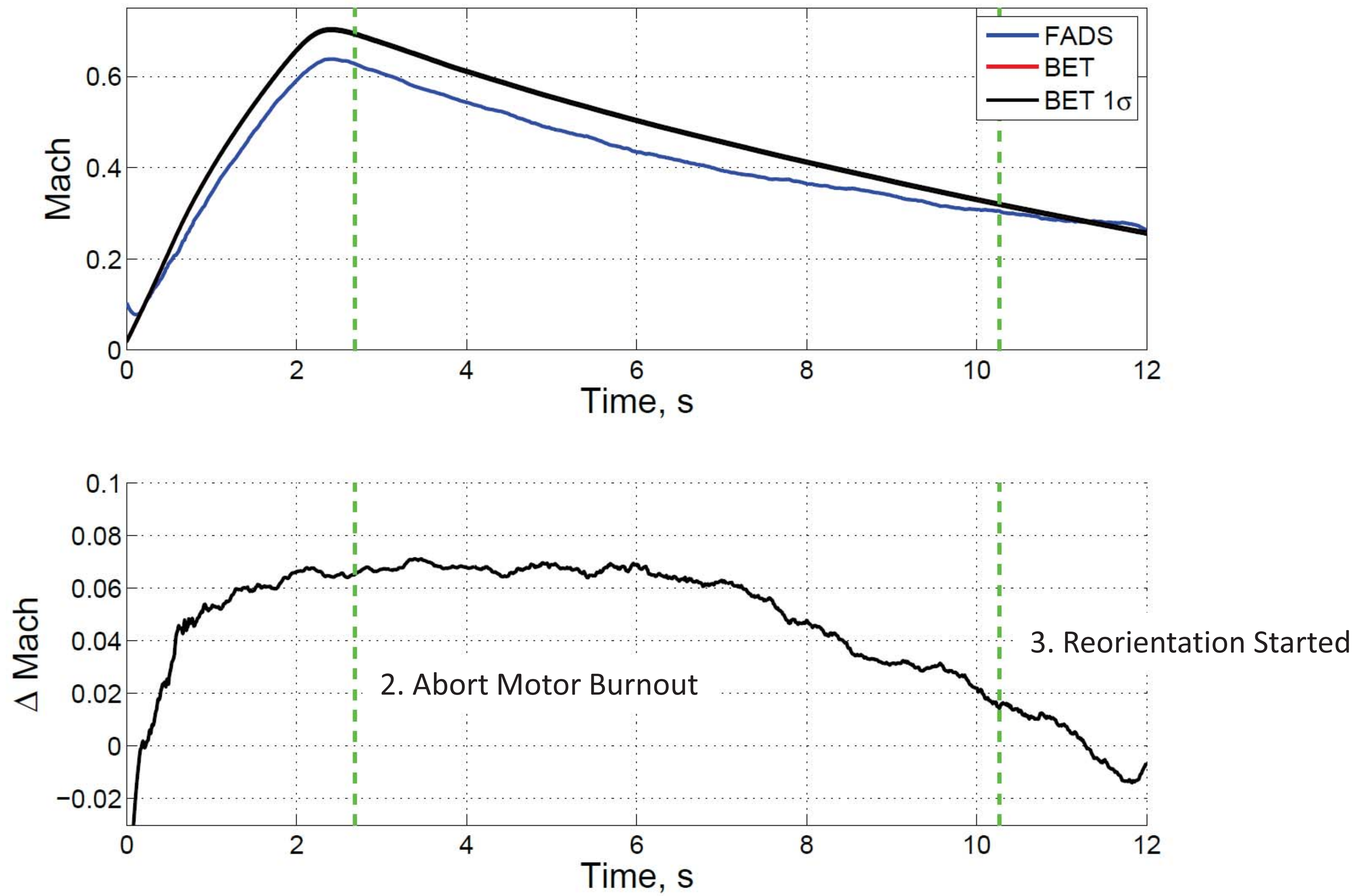
Flight Data Comparison: Freestream Static Pressure



Flight Data Comparison: Impact Pressure

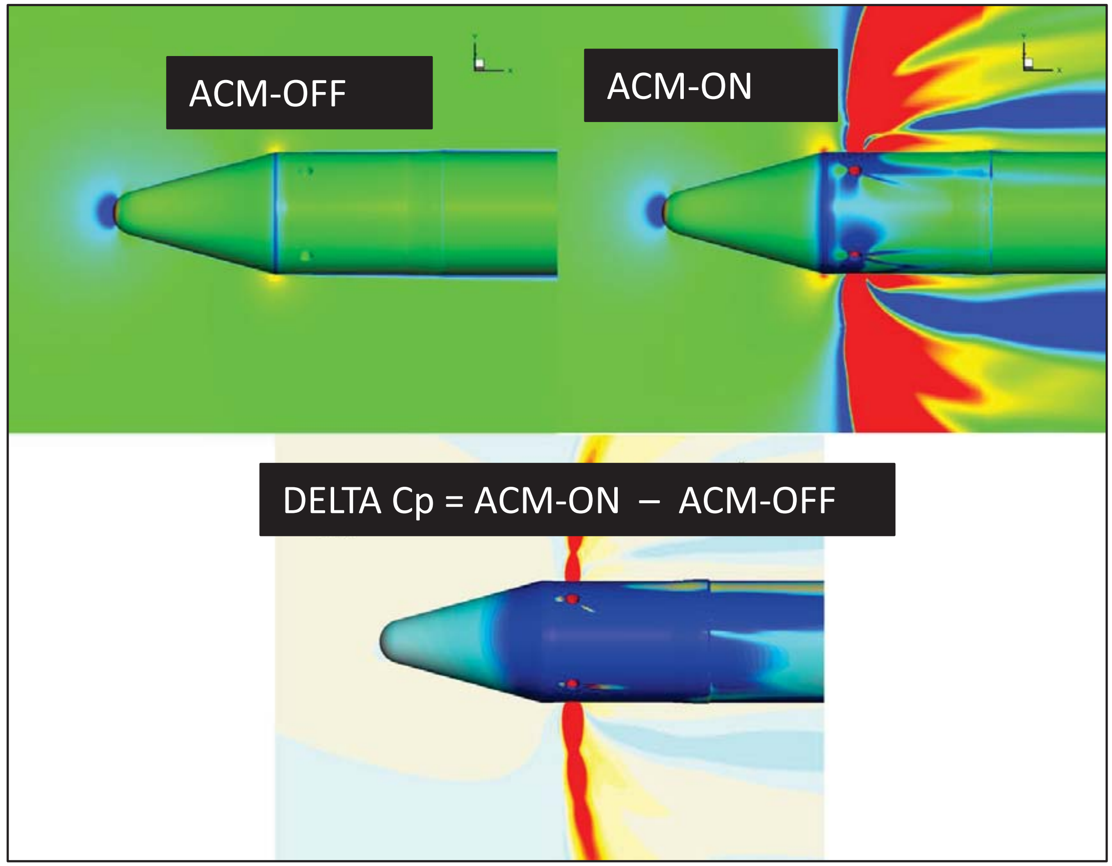


Flight Data Comparison: Mach Number

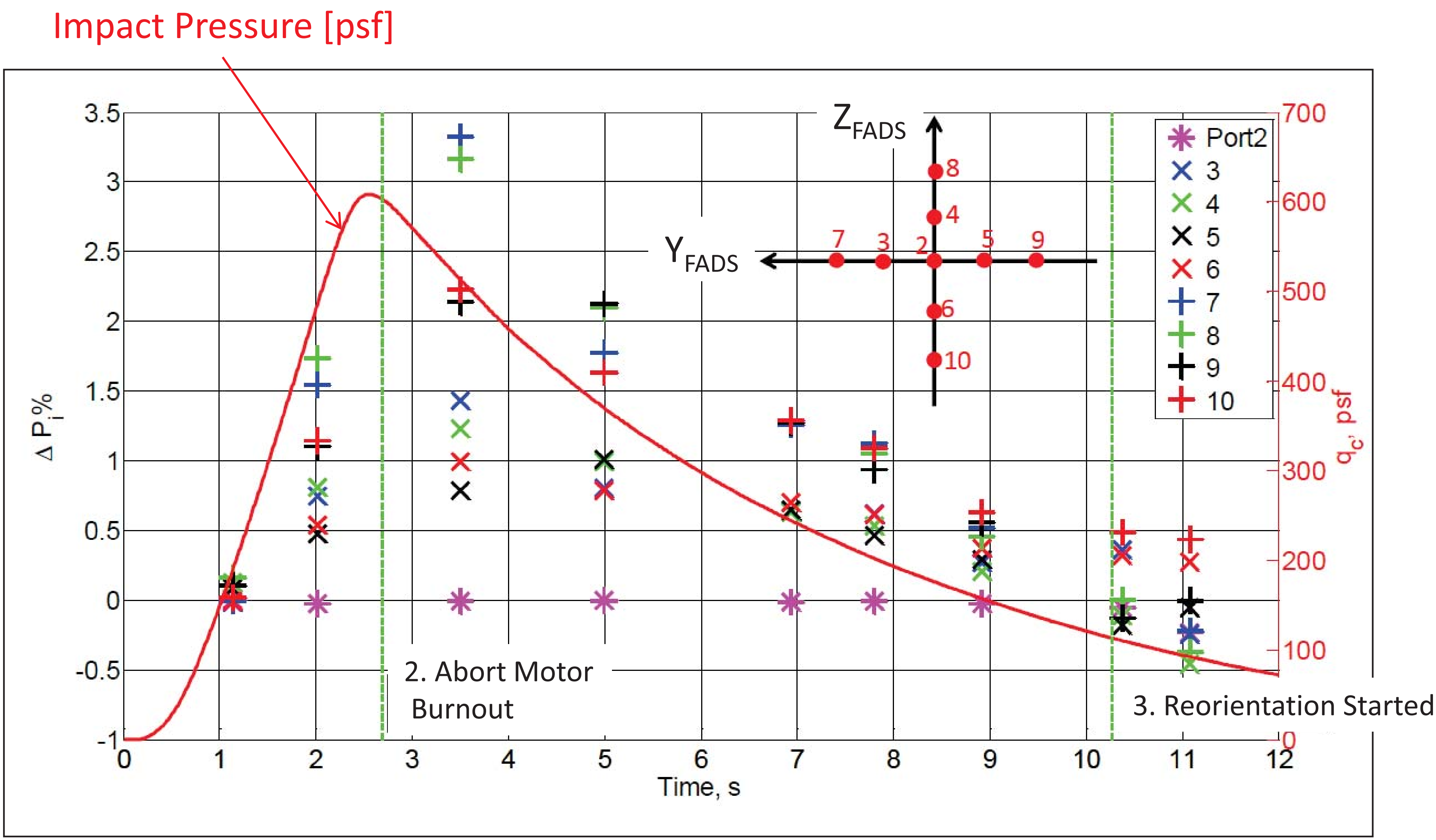


ACM Jet Interaction With FADS Ports

- 9 Points considered along the flight trajectory prior to reorientation
- 18 CFD cases run using OVERFLOW: a Navier Stokes Flow Solver
- 9 cases ACM on, 9 cases ACM off
  - Input
    - Alpha, Beta from FADS
    - Mach from BET
    - Free stream pressure from Balloon data
- Only portion of vehicle forward of AM nozzles modeled



Effect of Attitude Control Motors on FADS Ports



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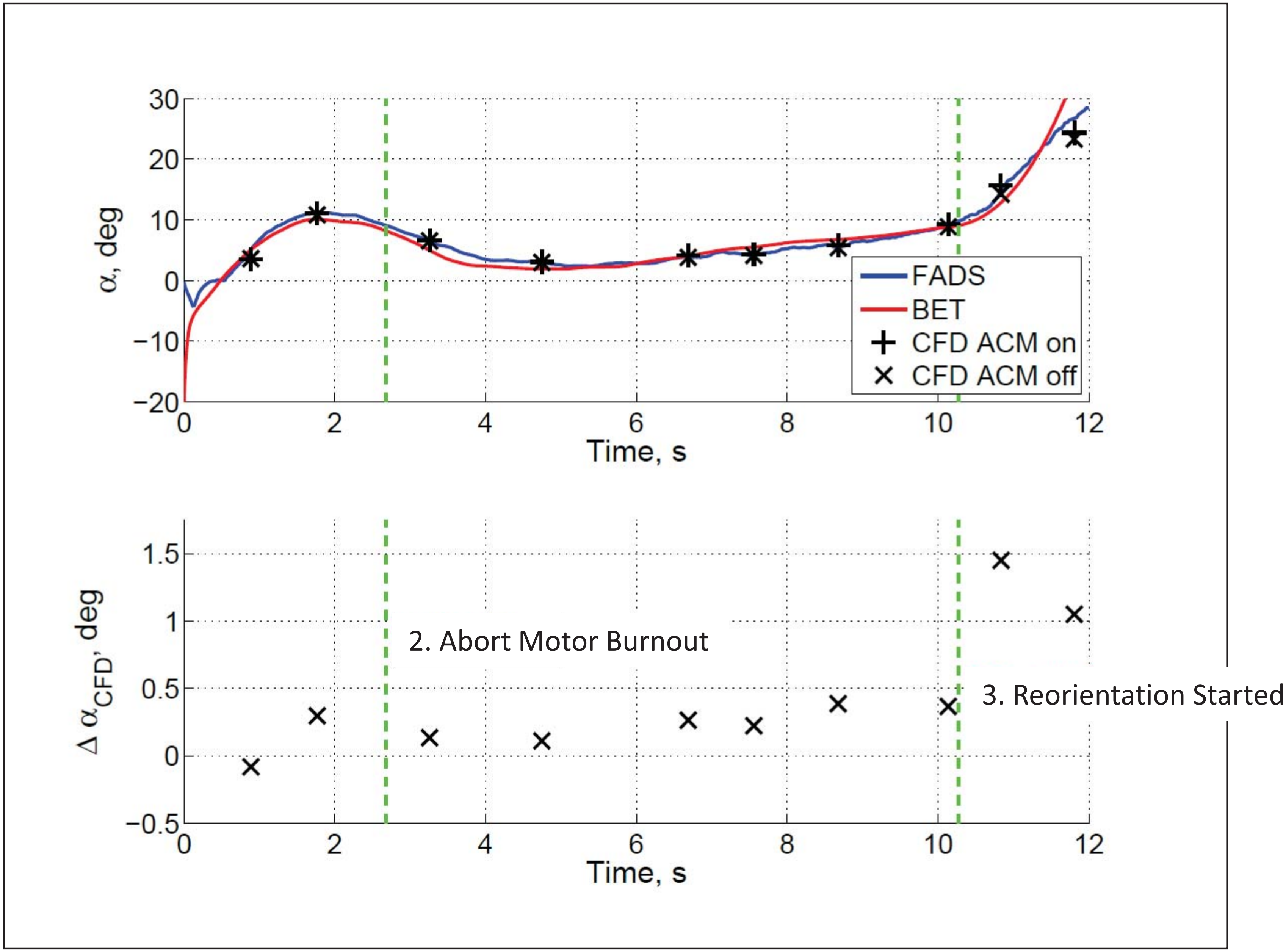
CFD to Flight Data Comparison: Angle of Attack



CFD to Flight Data Comparison: Sideslip

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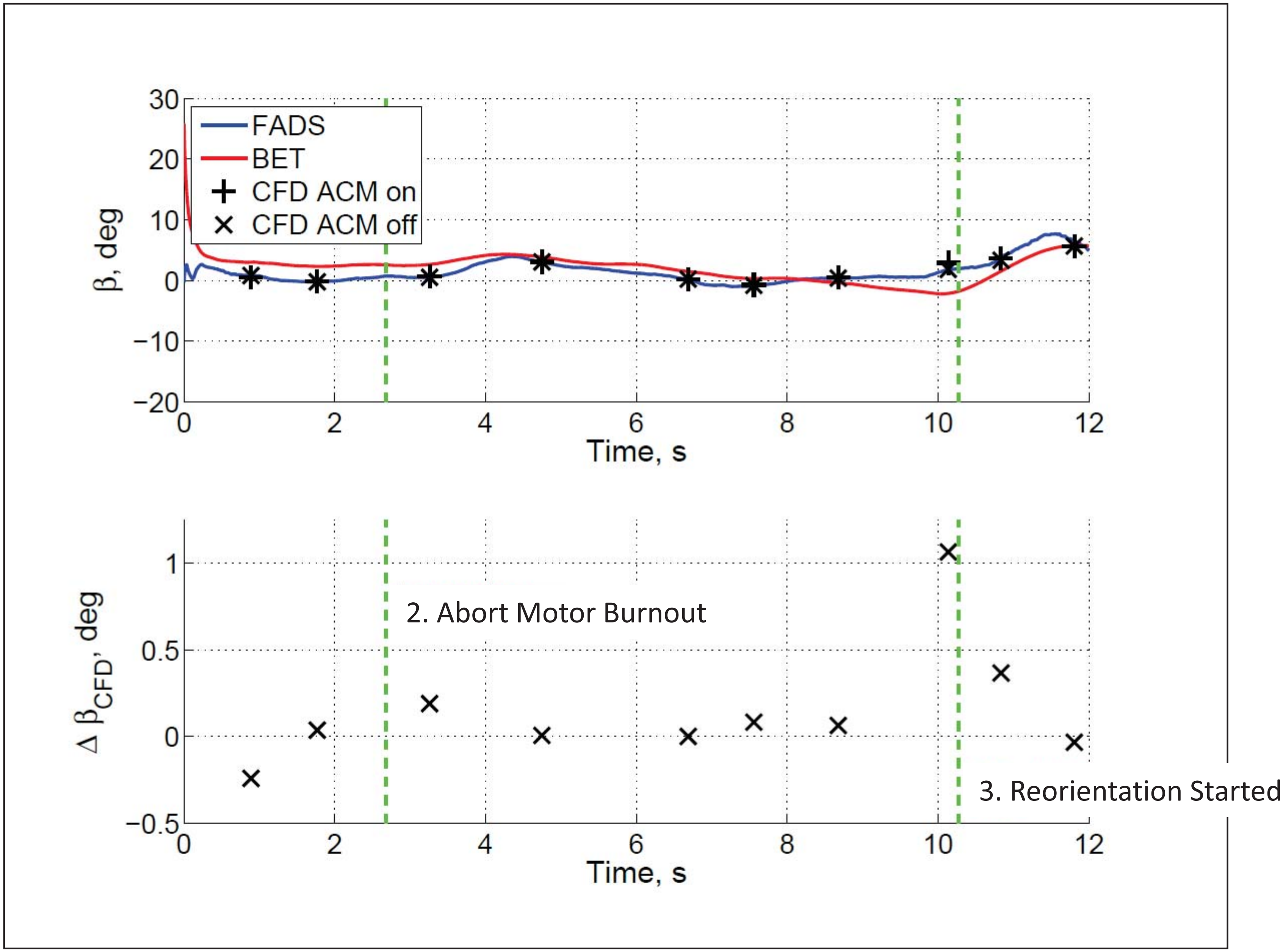
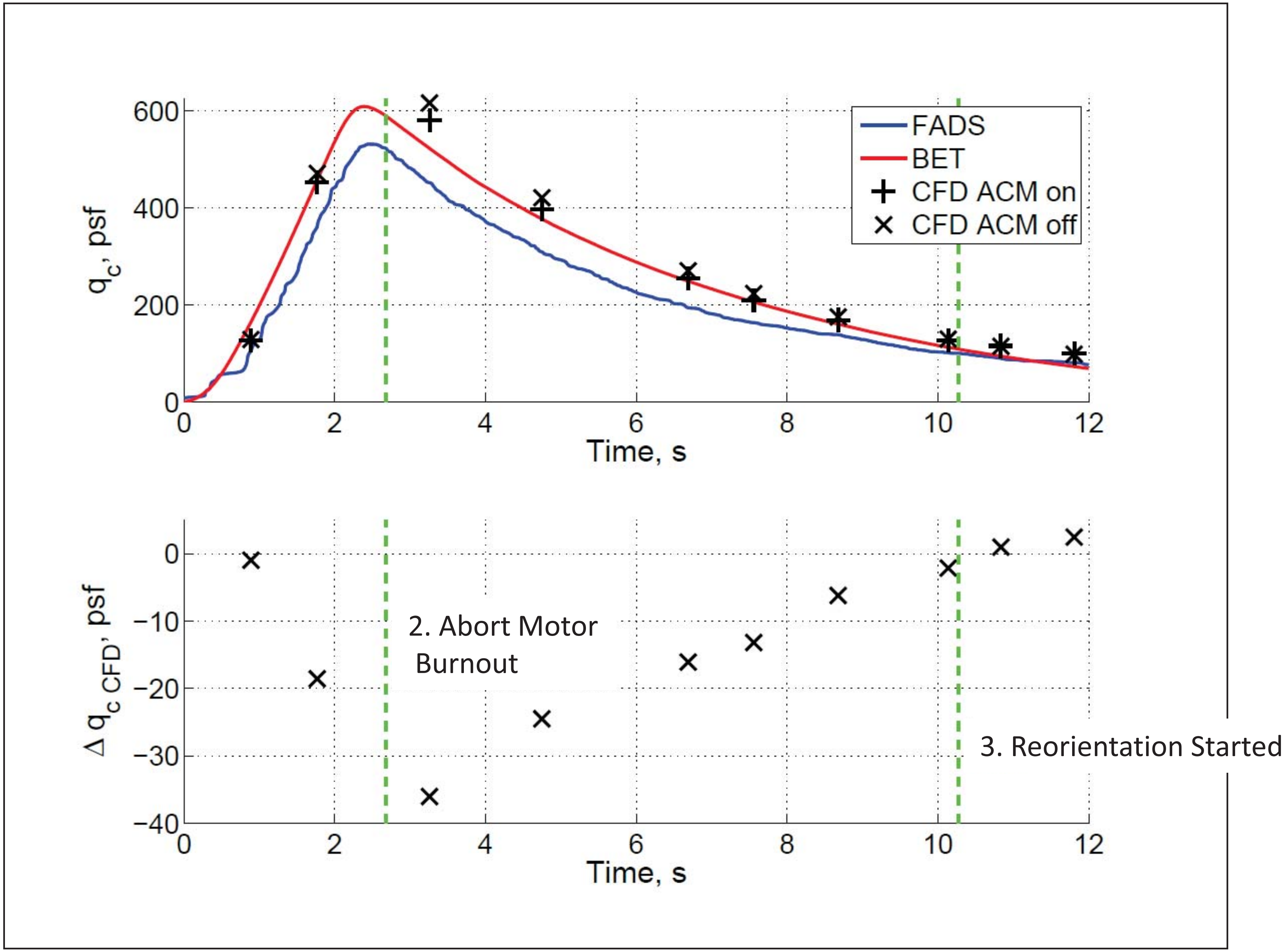
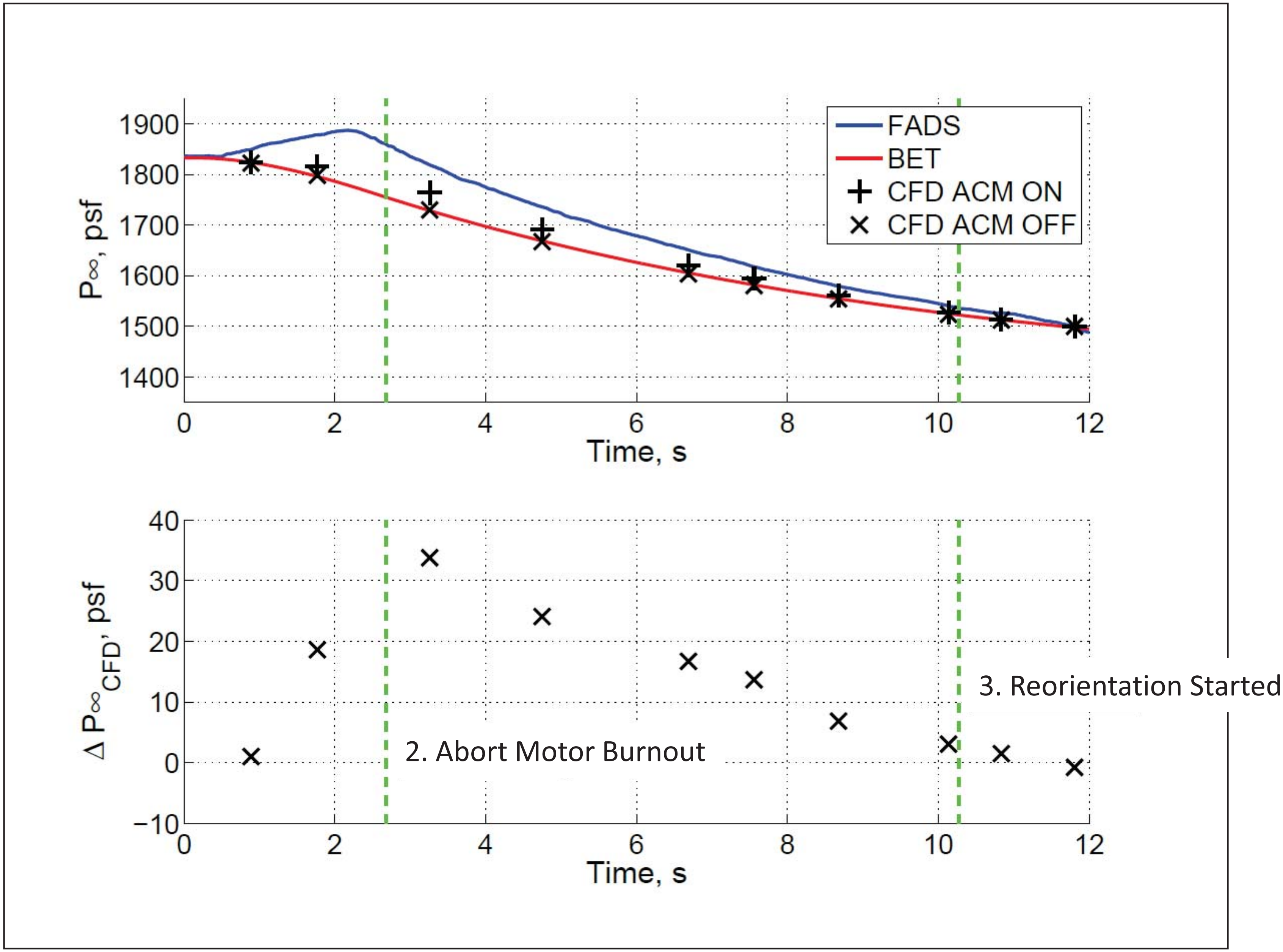


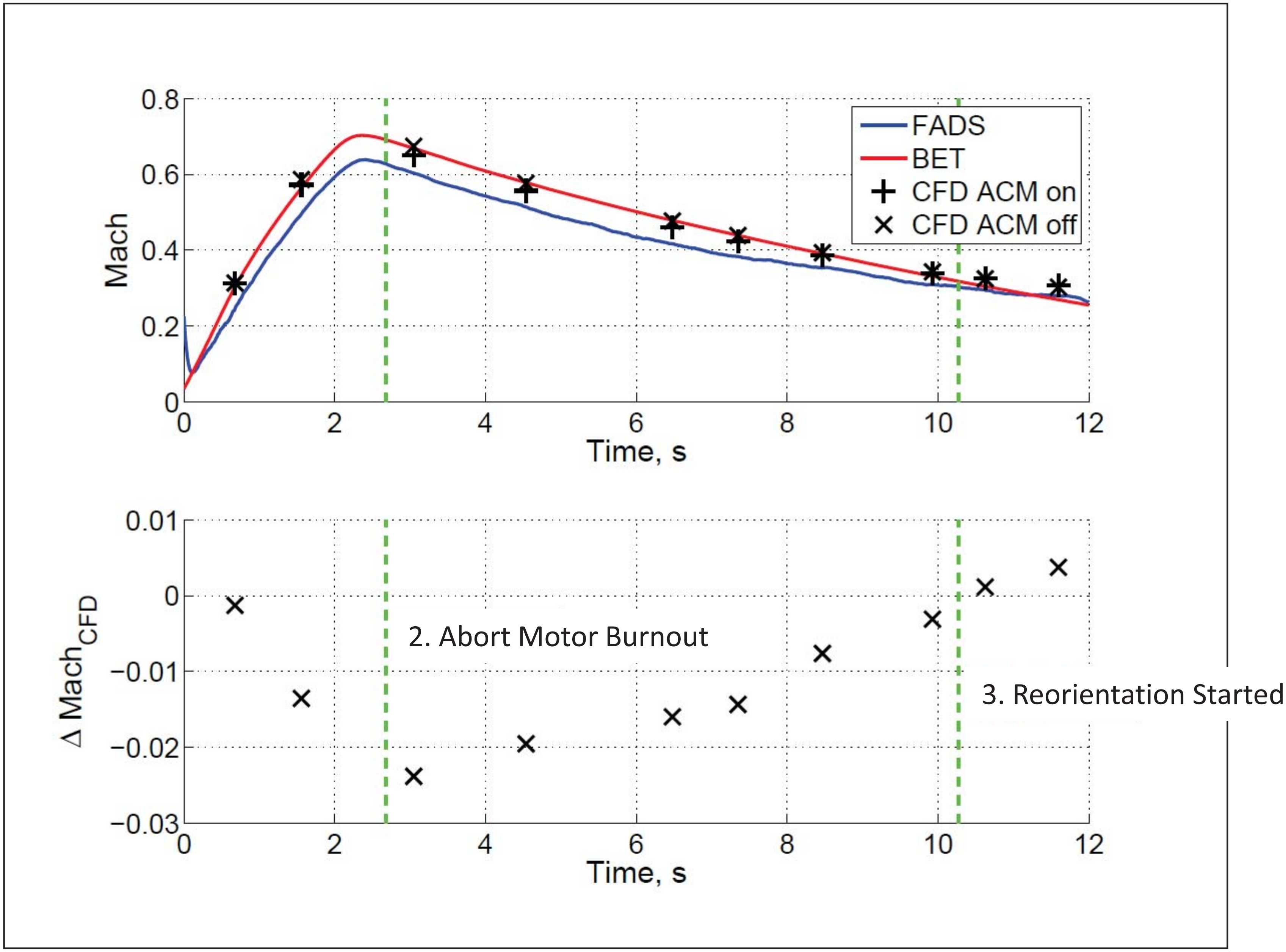
CFD to Flight Data Comparison: Impact Pressure



CFD to Flight Data Comparison: Freestream Static Pressure



CFD to Flight Data Comparison: Mach Number



Summary

- PA1 airdata estimates from the FADS system showed influences of the adjacent firing rocket motor nozzles
- CFD study showed less influence of the ACM than expected given the PA1 BET to FADS comparison
- New calibration database necessary
  - minimum required: CFD which models complete vehicle
  - desired: combination of Wind tunnel and CFD which incorporate ACM and AM
- New CFD study needed with model of complete vehicle including ACM and AM models

PA1 Movie

http://www.youtube.com/watch?v=wzIcDDJyTRI
(Space City Films)

BACK-UP

Triples Algorithm

- Uses combinations of pressures from three distinct ports along the axis of interest
- Angle of attack(α)
  - Use pressure readings from ports along Z-axis
- Flank angle(β_f)
  - Use pressure readings from ports along Y-axis
- Side slip(β)

$$\beta = tan^{-1}\left(tan(\beta_F)cos(\alpha)\right)$$

Triples Algorithm

Angle of Attack

- Let: $\Gamma_{ik} = \mathrm{p_i} - \mathrm{p_k}$

$$\Gamma_{ji} = p_j - p_i$$

$$\Gamma_{kj} = p_k - p_j$$

$$A = \Gamma_{ik} sin^2 (\lambda_j) + \Gamma_{ji}\, sin^2(\lambda_k) + \Gamma_{kj} sin^2 \lambda_i$$

$$B = \Gamma_{ik} cos(\phi_j)\, sin(\lambda_j) cos(\lambda_j)$$

$$+ \Gamma_{ji}\, \cos(\phi_k) sin(\lambda_k)\, cos(\lambda_k)$$

$$+ \Gamma_{kj} cos(\phi_i) sin(\lambda_i) cos(\lambda_i)$$

$$\alpha_e = \frac{1}{2}\, tan^{-1}\left(\frac{A}{B}\right) \qquad |\alpha_e| \leq \frac{\pi}{4}$$

$$\alpha_e = \frac{1}{2}\left[\pi - tan^{-1}\left(\frac{A}{B}\right)\right] \qquad |\alpha_e| > \frac{\pi}{4}$$

Triples Algorithm
Angle of Attack

- Used ports along the Z axis: $\phi = 0, \pi$
- All combinations of three distinct ports were considered (i, j, k).
- By taking the differences in pressure;

$$\frac{p_i - p_j}{p_j - p_k}$$

q_c, P_∞ and ϵ are decoupled from equation

- With $\phi = 0, \pi$; sideslip is also removed from the equation
- Resulting α_e is calibrated to wind tunnel data and/or CFD data to get α