Project Orion Abort Flight Test

PA-1 Flush Air Data Sensing Systems

Aliyah N. Ali
NASA Dryden Flight Research Center

Jerry Borrer
NASA Johnson Space Center

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Introduction

- PA-1 Trajectory
- Overview PA-1 FADS systems
- Orientation angle definitions
- Nose Cap FADS
- Heat Shield FADS
- Summary

Picture showing orientation of Crew Module and Launch Abort System just after LAS jettison

PA-1 Trajectory

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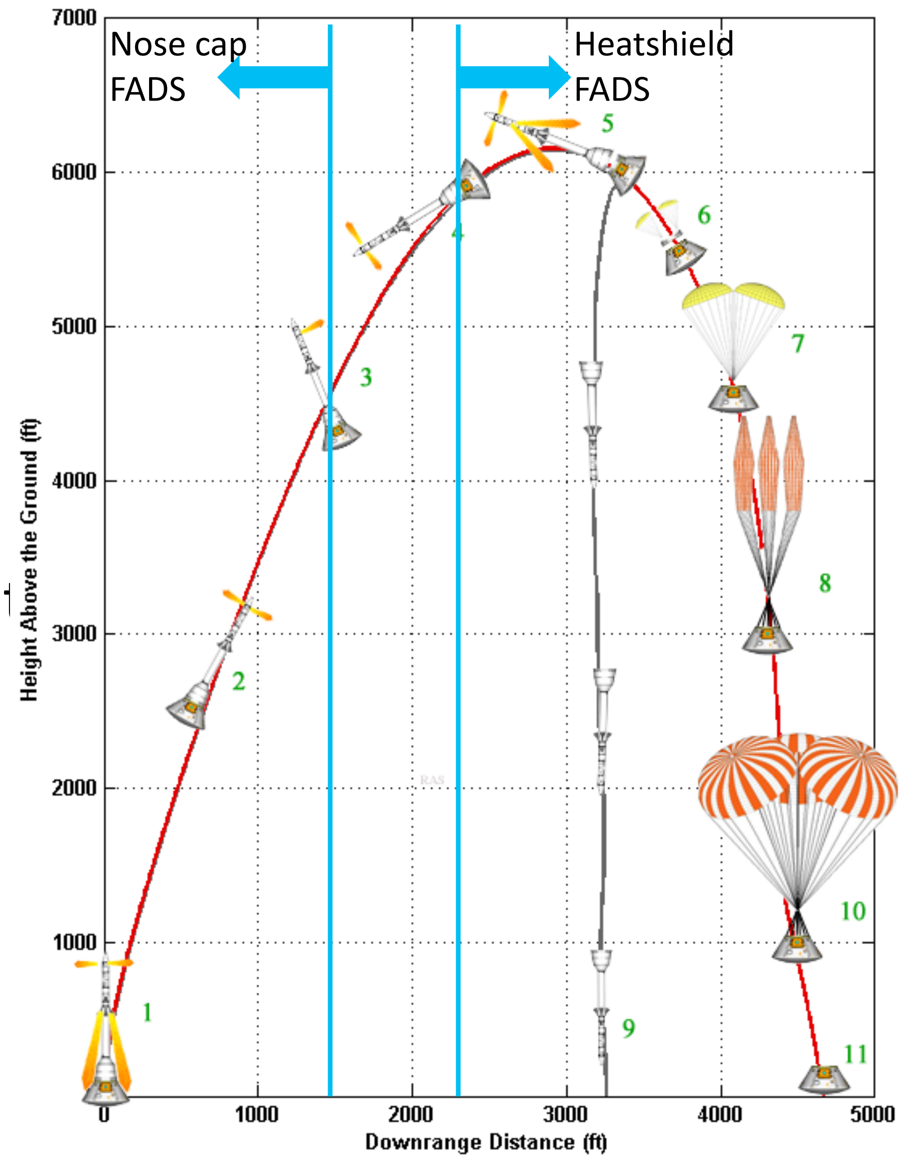
1. Launch
2. Abort Motor Burnout
3. Reorientation Started
4. Reorientation Completed
5. LAS Jettison
6. FBC Jettison
7. Drogue Parachute Deployment
8. Main Parachute Deployment
9. LAS Touchdown
10. Main Parachute Full Inflation
11. CM Touchdown



PA-1 Flush Air Data Sensing Systems

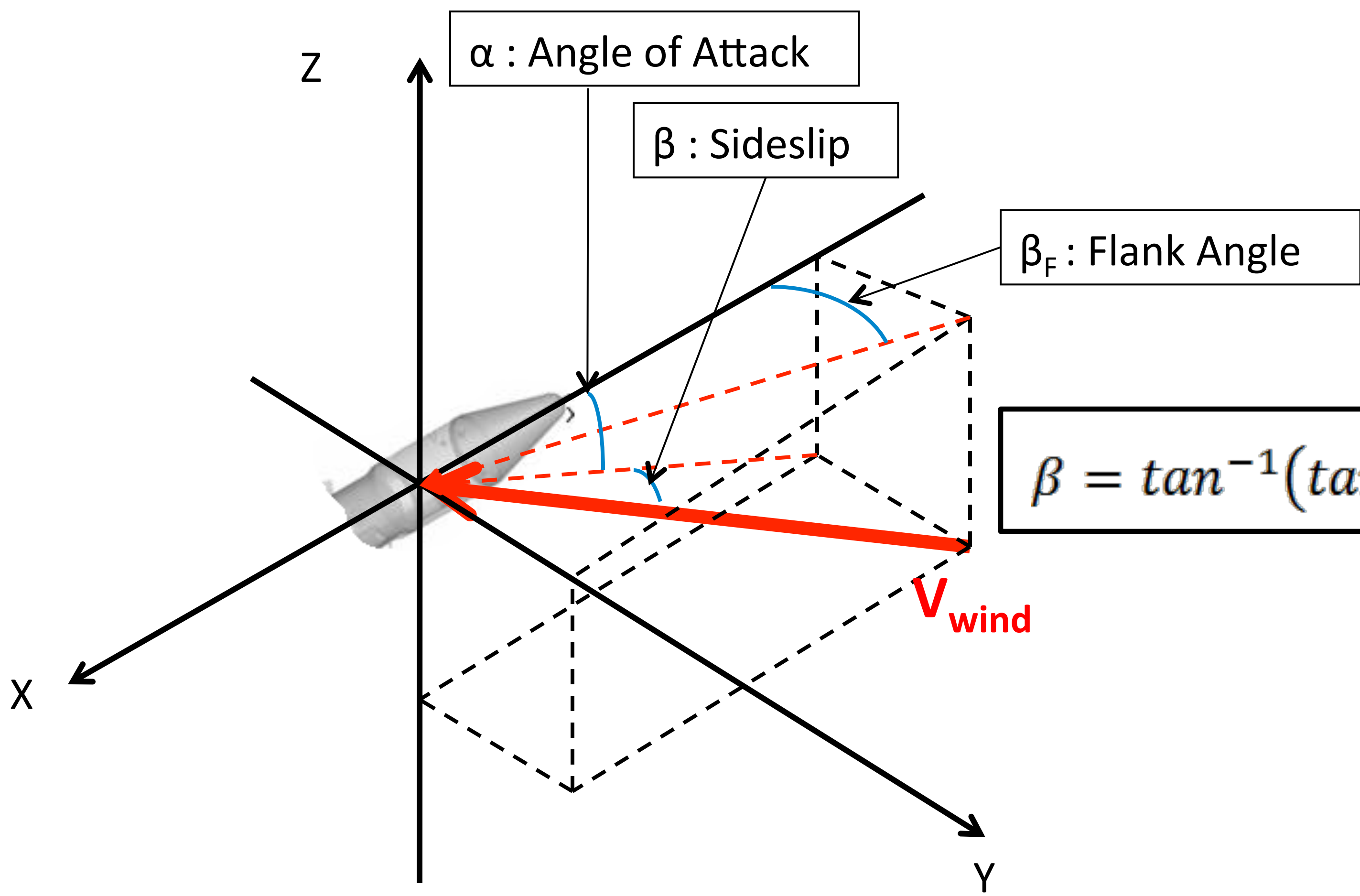
- Matrix of pressure ports arranged in an X pattern
- Ports flush with the surface of the vehicle
- Uses pressure data to calculate angle of attack, sideslip, dynamic pressure, free stream pressure and mach
- Two Systems
  - Nose cap FADS
    - 9 ports
    - For calculating air data parameters from Launch up to the start of reorientation
  - Heat shield FADS
    - 8 ports – structural constraints
    - For calculating air data parameters from the completion of reorientation to CM touch down
- Experimental system
  - Not used for control
  - all data post processed

Nose cap FADS
9 ports

Heat shield
FADS
8 ports

PA-1 Vehicle Just after
Start of reorientation

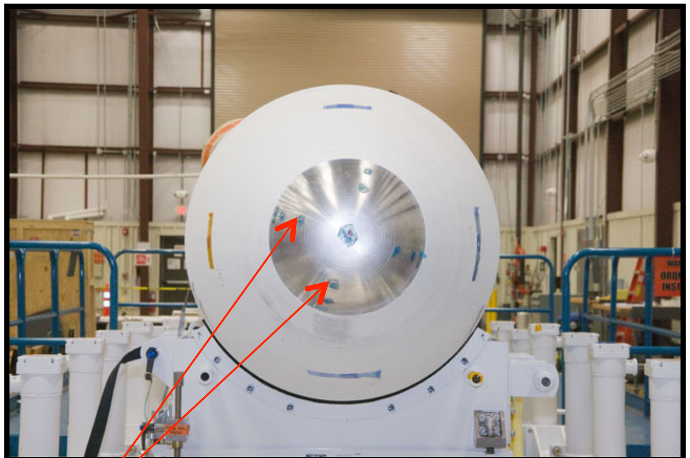
Angle of Attack, Flank Angle and Sideslip Definition



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

Nose cap FADS system

Nose Cap FADS Port Locations Relative to Motors

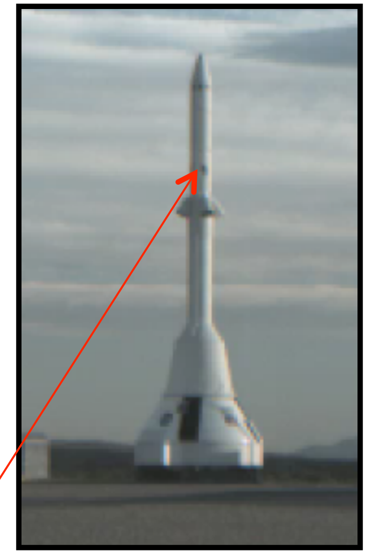


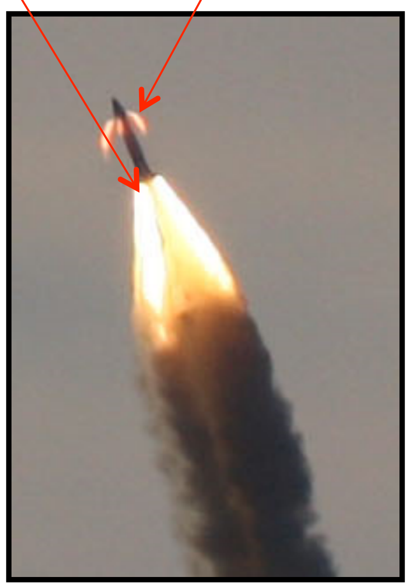
~ 48”

Ports

Abort Motors

Attitude Control Motors (ACM’s)



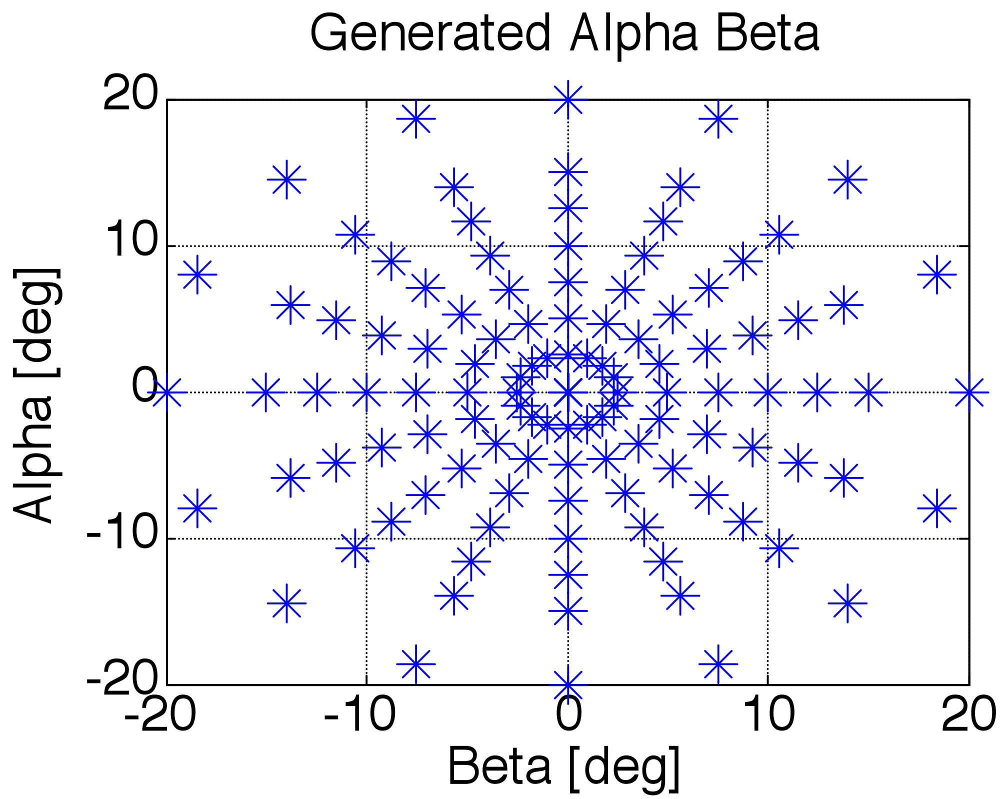


Jettison Motors (JM)

Calibration Data

Nose cap: CFD

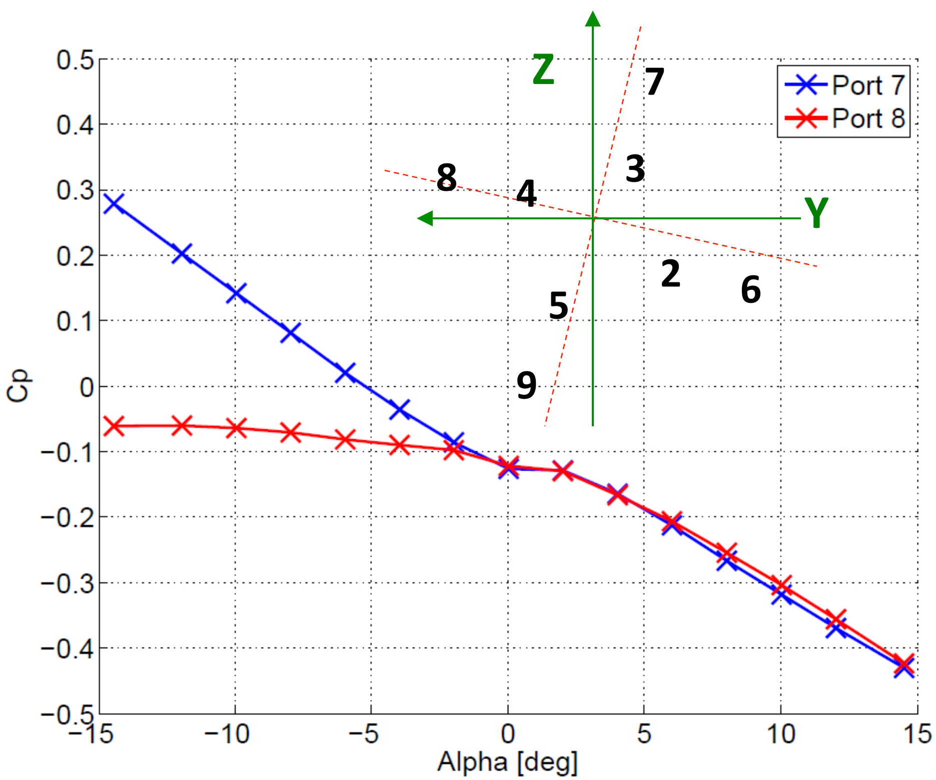
- Mach {0.2, 0.4, 0.5, 0.6, 0.7}
- Alpha {0.0, 2.5, 5.0, 7.5, 10, 12.5, 15, 20}
- Beta {0.0}
  - Took advantage of symmetry to algebraically generate data at varying beta
- ACM's turned off



Calibration Data

Nose cap: Wind Tunnel

- Data available but not used
  - Ports installed at incorrect cone angles (λ)
    - For calibration to work, cone angles on wind tunnel model must match vehicle
  - Anomalies in Data



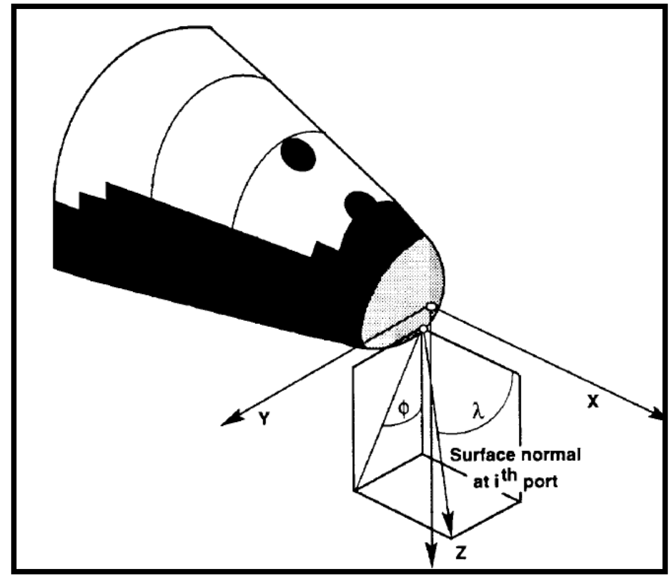
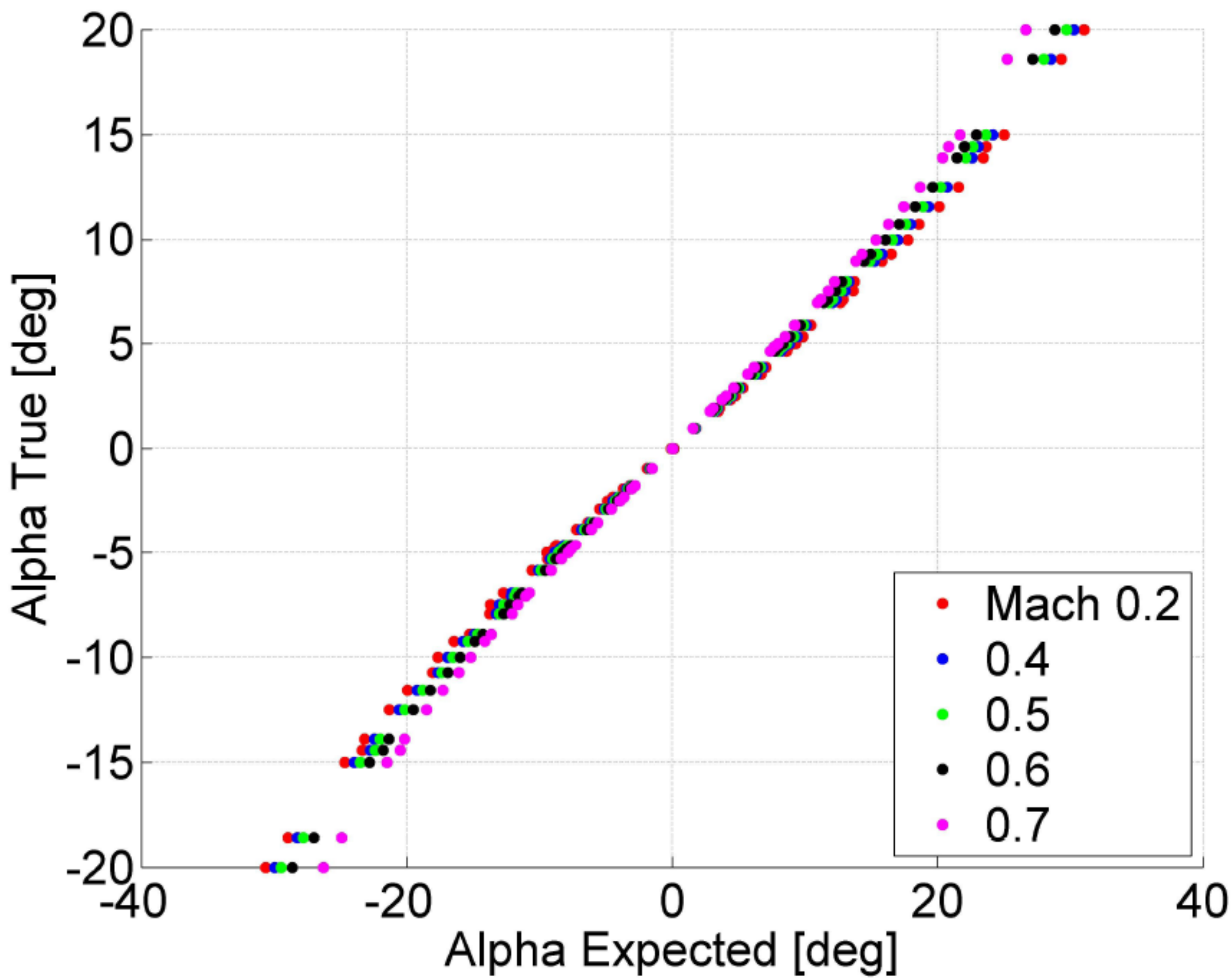


Figure Illustrating clock(Φ) and cone(λ) angle

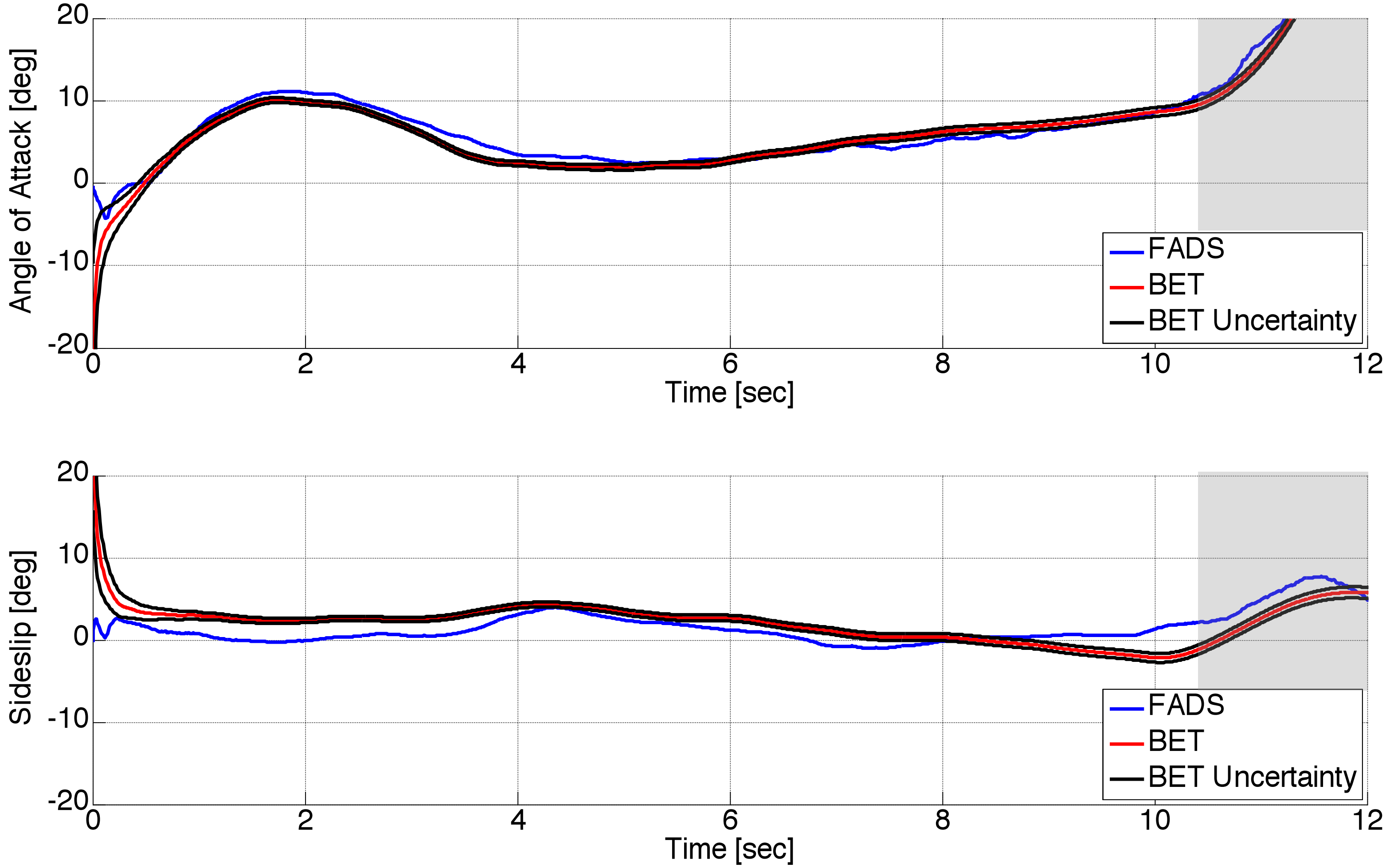
Calibration Data

Nose cap; $\alpha(\alpha_e, \beta_{fe}, M_\infty)$



Flight Data Comparison: Nose Cap FADS Angle of Attack and Sideslip to the Best Estimated Trajectory(BET)

Reorientation
Start : 10.27sec



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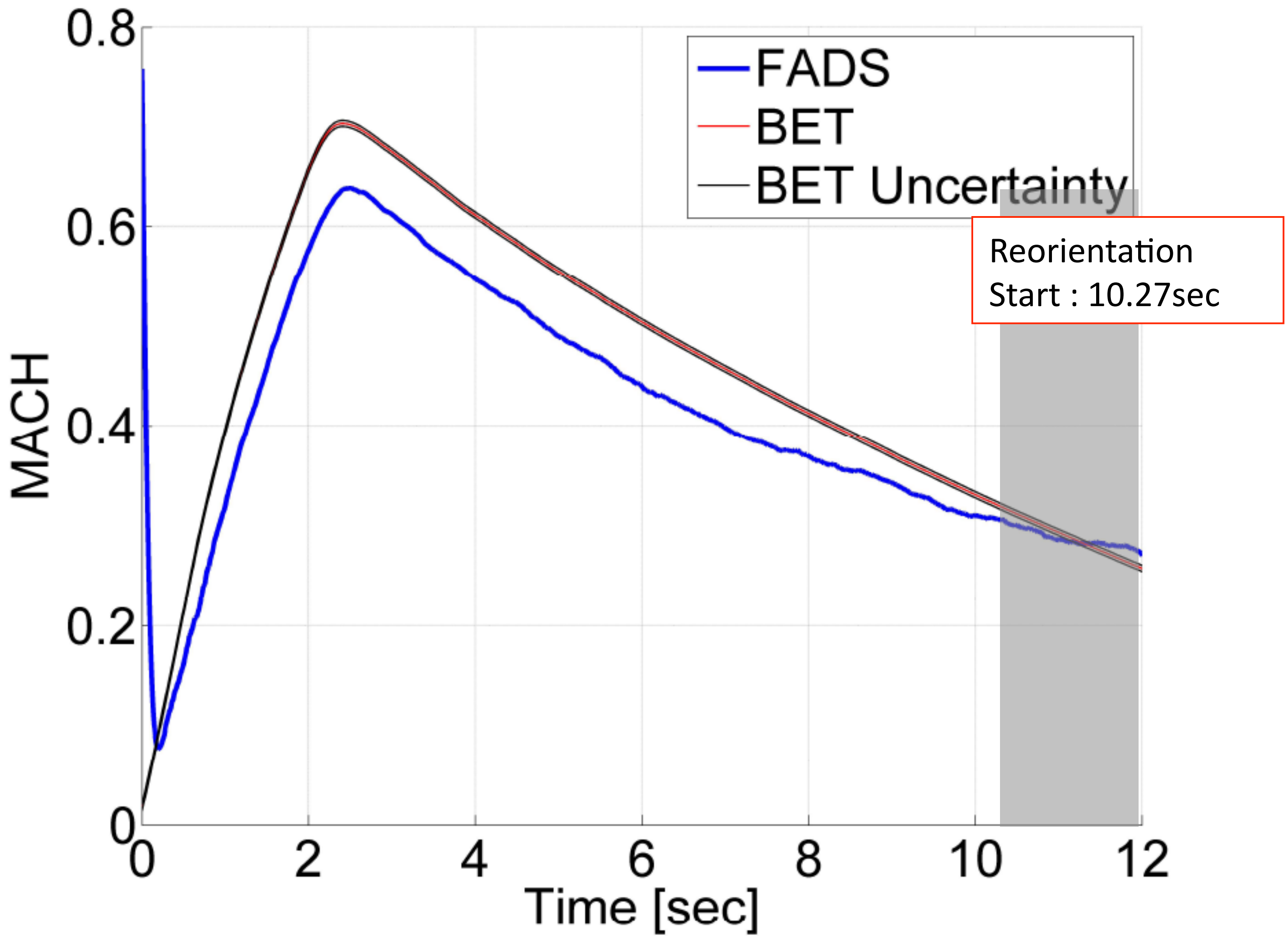
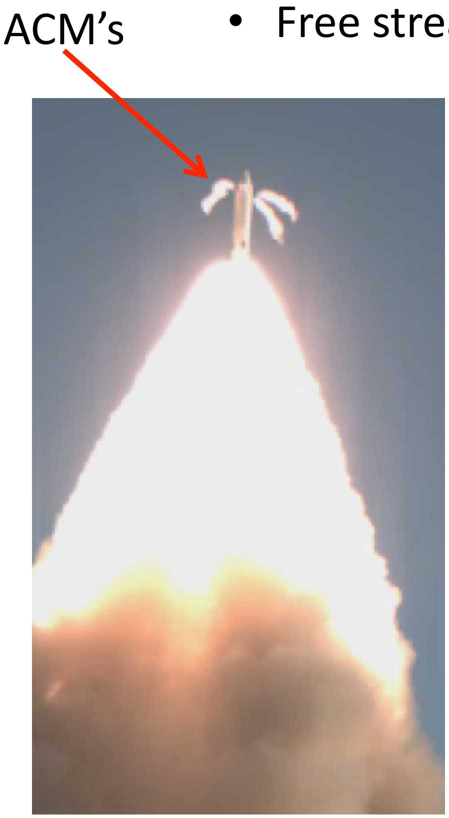
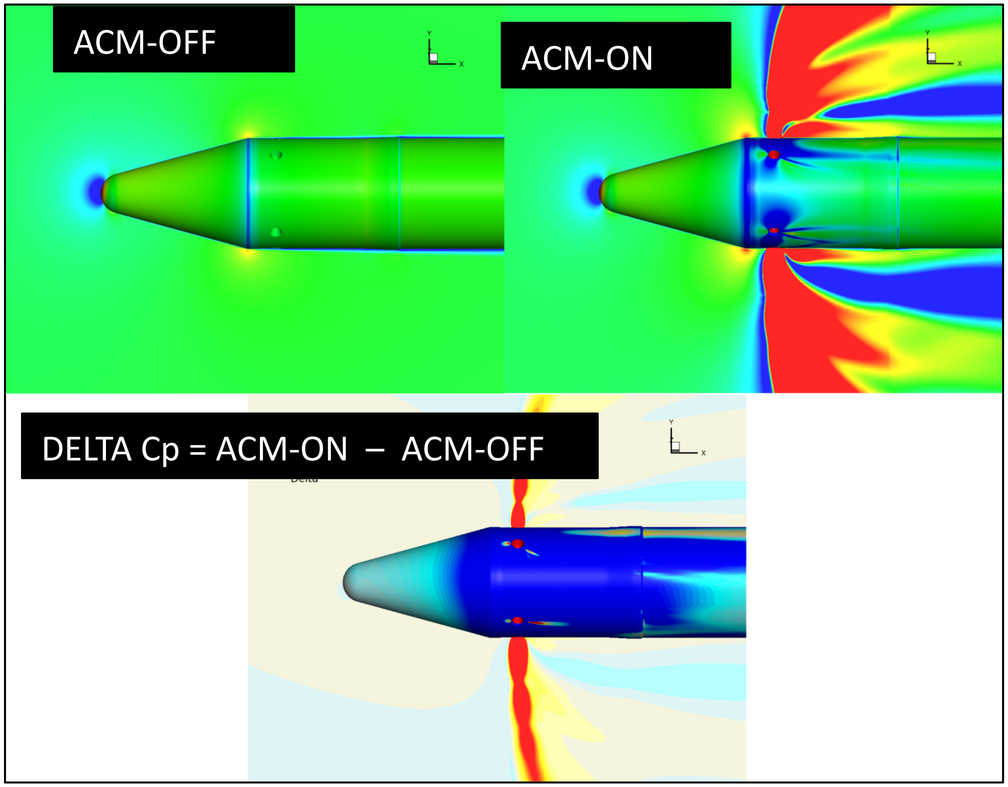
Flight Data Comparison: Nose cap FADS Mach number to the Best Estimated Trajectory(BET)



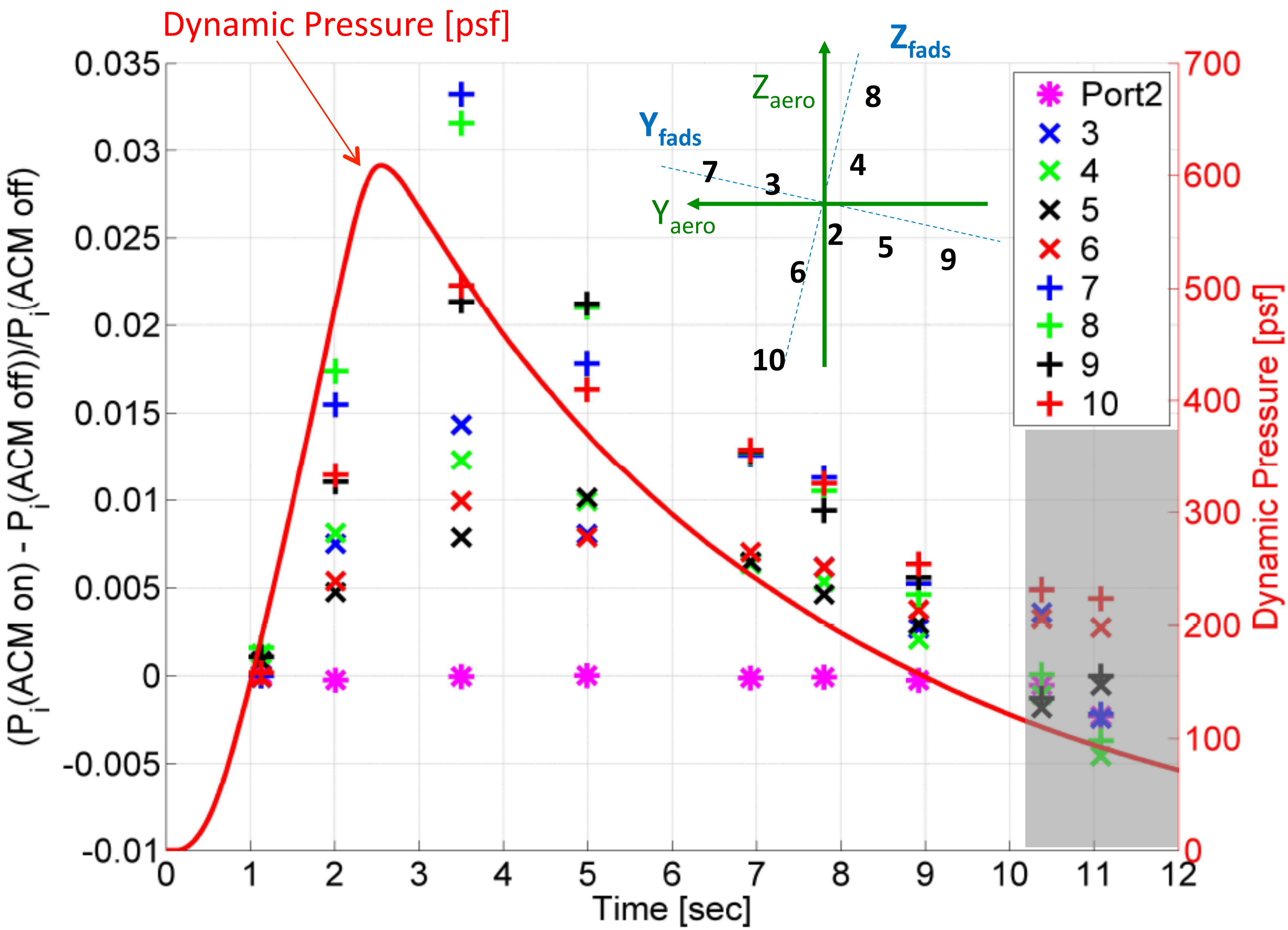
ACM Jet Interaction With FADS Ports

- 10 Points considered along the flight trajectory prior to reorientation
- 20 CFD cases run using overflow: 10 cases ACM on, 10 cases ACM off
  - Input
    - Alpha, Beta from FADS
    - Mach from BET
    - Free stream pressure from Balloon data



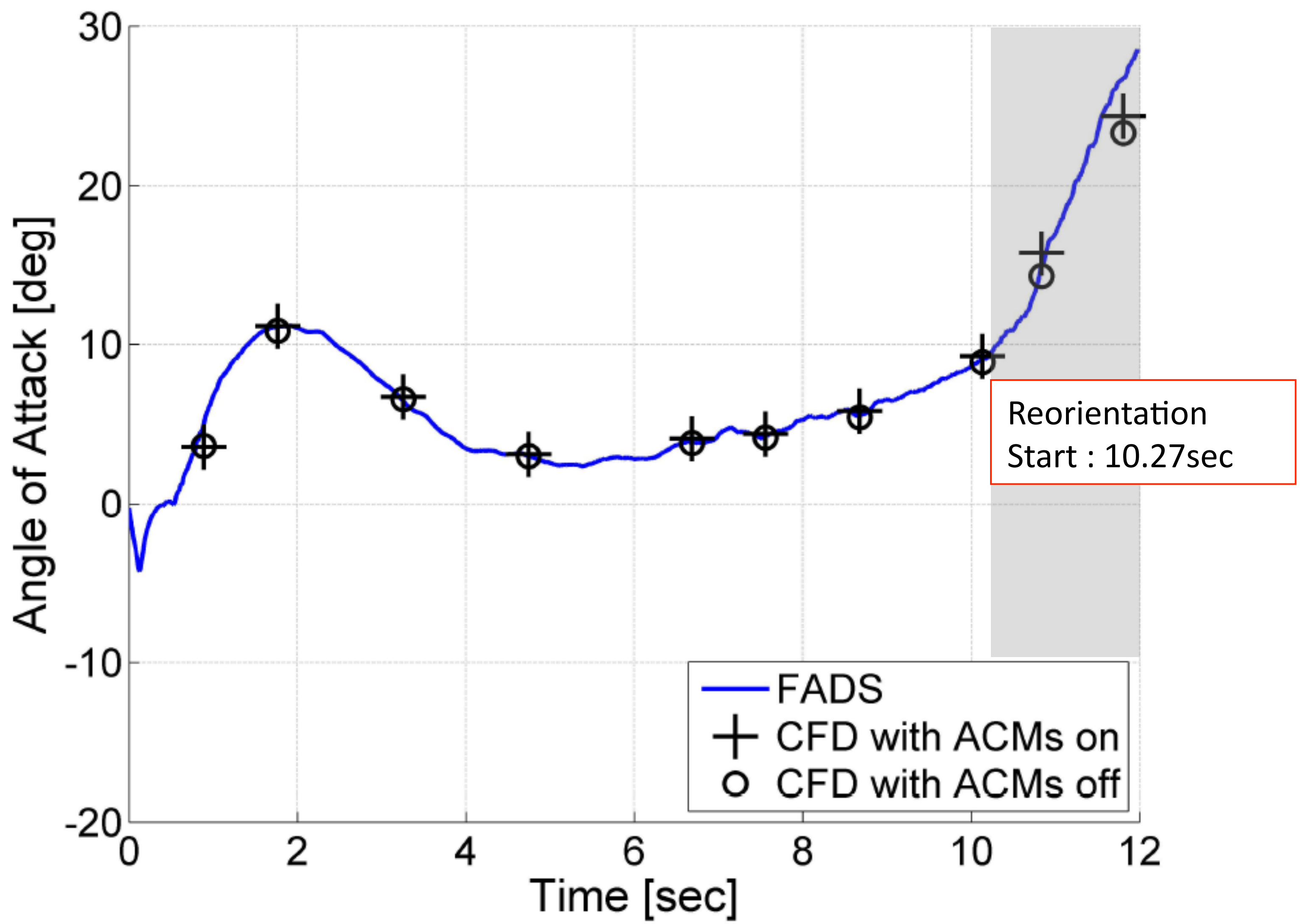


Effect of Attitude Control Motors on FADS Ports



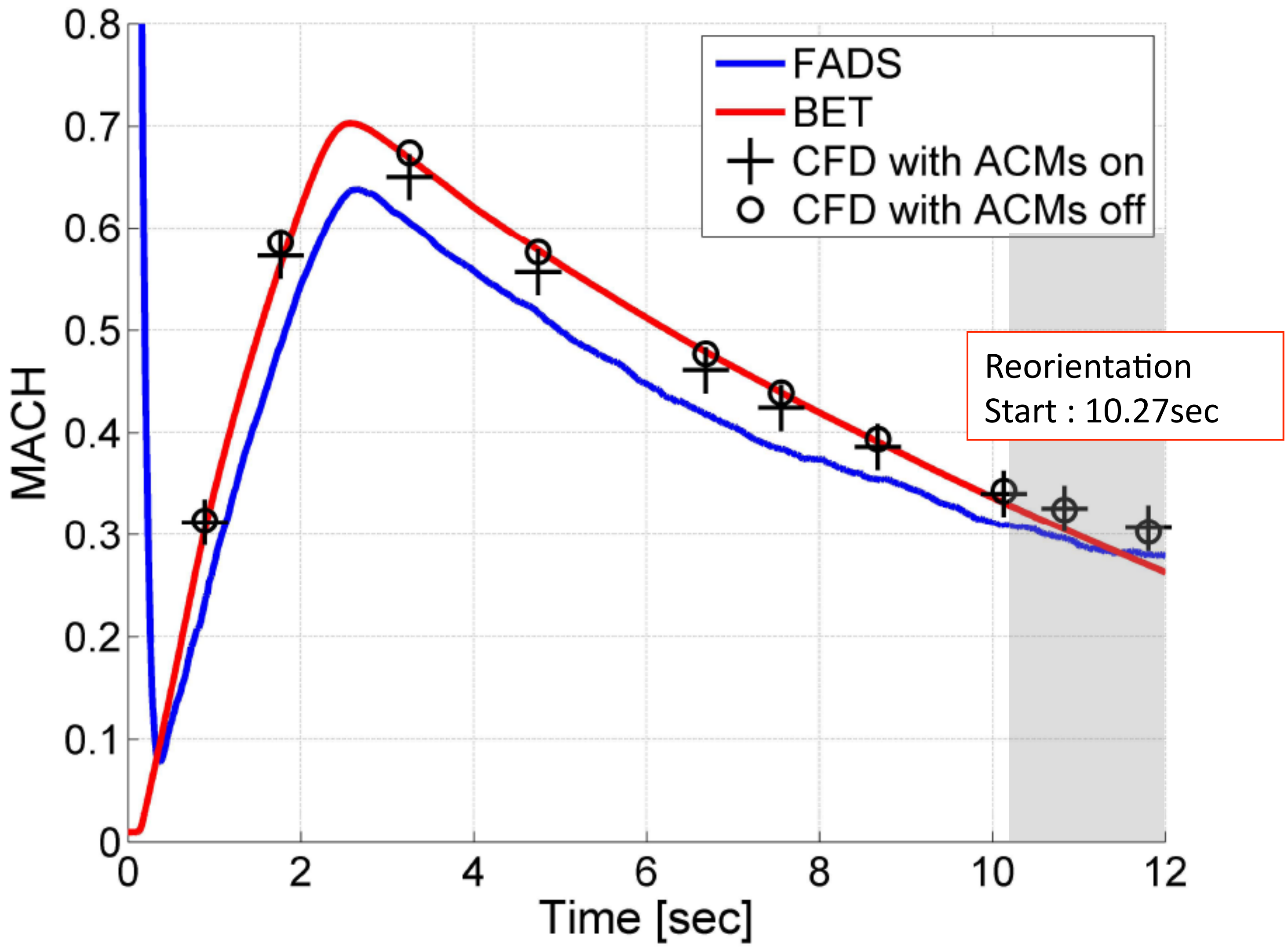
ACM Jet Interaction With FADS Ports

- Very little effect on angle of attack and sideslip results



Effect of Attitude Control Motors on FADS output

- Under-prediction of Mach

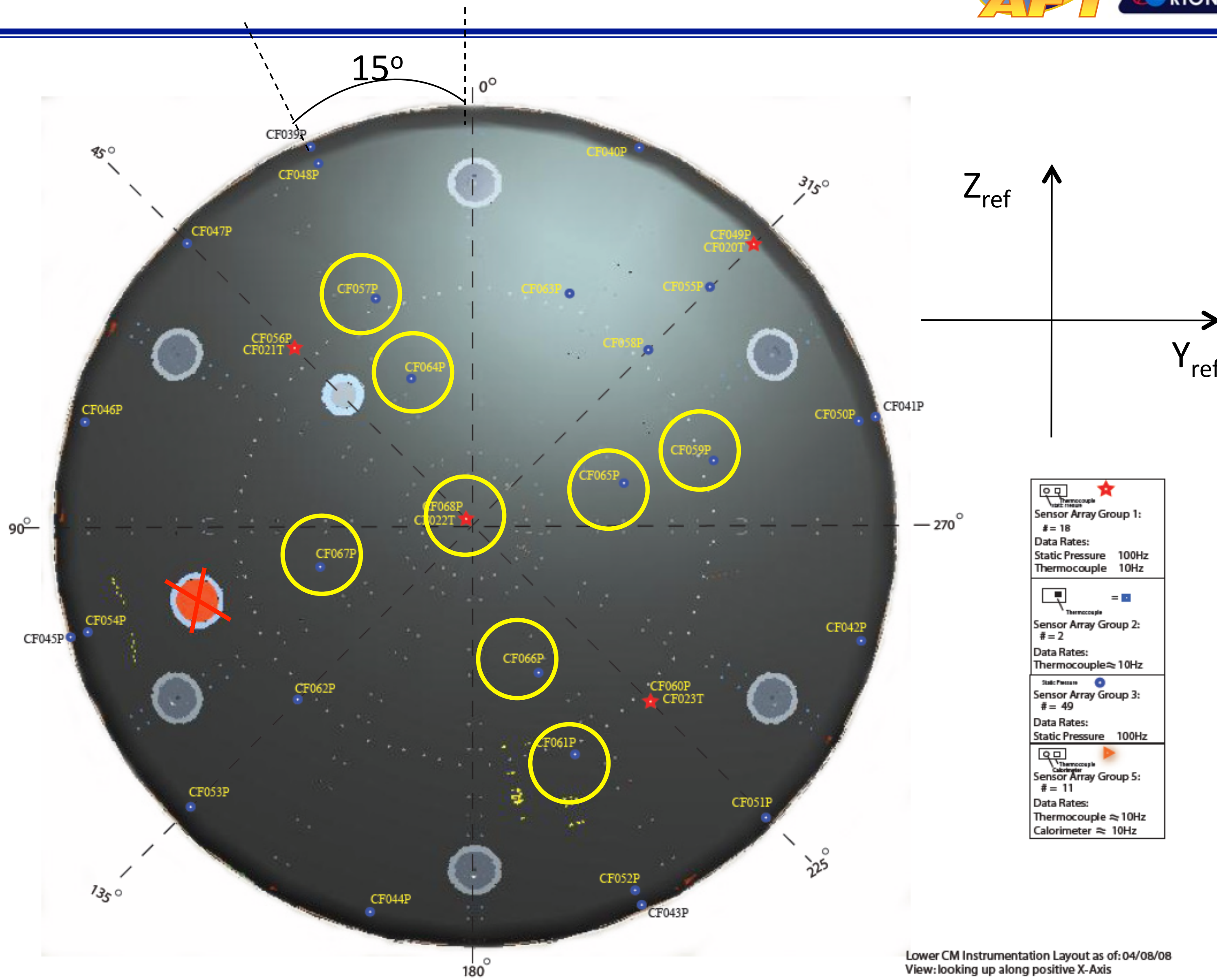


Heat Shield FADS System

Heat Shield FADS

- 8 pressure ports
  - Structural constraints
- Operating range of the pressure sensors on the heat shield was too large (+/- 720 psf) for the low dynamic pressure during parachute flight (~ 2 psf) from ~50 sec to landing to give completely accurate results.
  - Large scatter in the computed FADS data required visual inspection and selection of reasonable parameters for data smoothing process.
  - Pitch, and Yaw rates difficult to quantify during chute transient times while CM rotates with regards to its CG.

Orientation of Ports on Heat Shield



Lower CM Instrumentation Layout as of: 04/08/08
View: looking up along positive X-Axis

Calibration Data

Heat Shield

- CFD
  - AR92
    - Mach 0.2
      - Alpha = {120 150 155 160 165 170 175 180}
      - Beta = 0
    - Mach 0.3
      - Alpha = {140 145 150 155 160 165 170 175 180}
      - Beta = 0
- Wind Tunnel
  - Mach 0.131
  - {190 184 182 180 178 176 172 170 166 164 160 155 150 140}
  - Beta = 0

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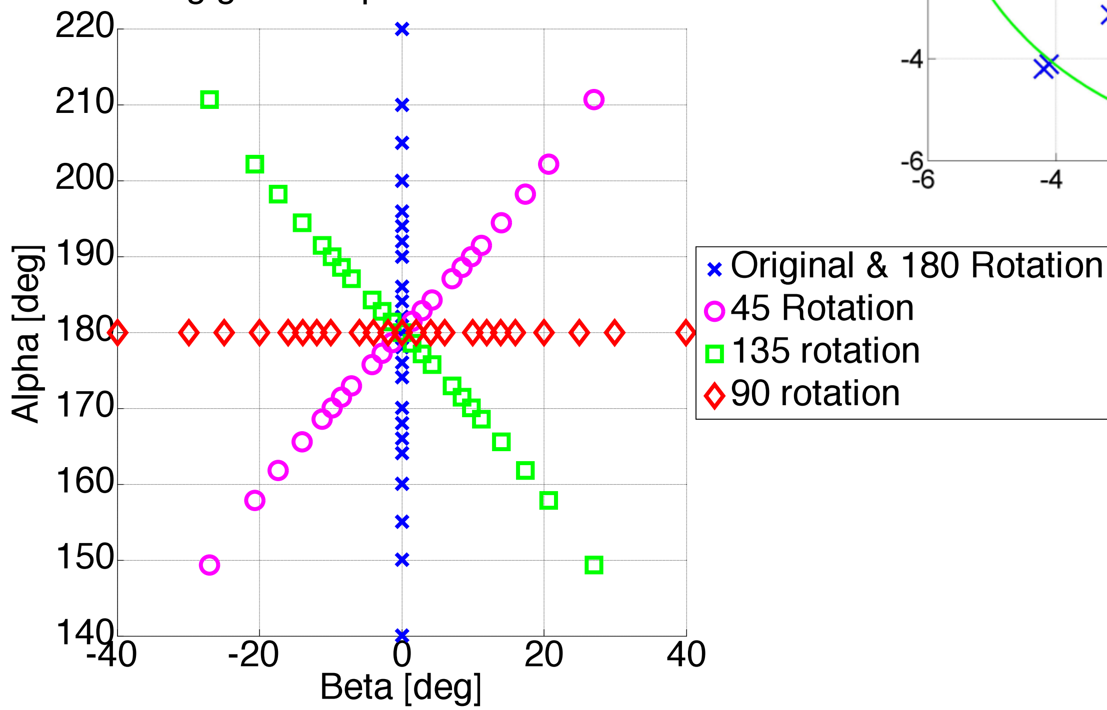
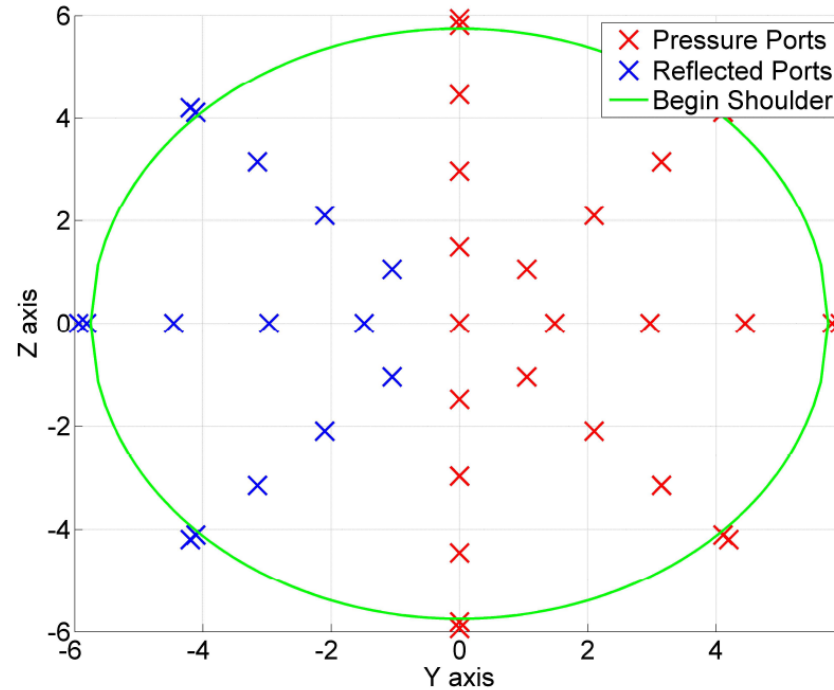
Wind Tunnel Pressure Port Layout and Data Expansion

- ½ of heat shield instrumented
  - Data at 0 beta reflected to complete heat shield
  - Interpolated to correct port location
  - Rotated in 45 degree increments to generate beta

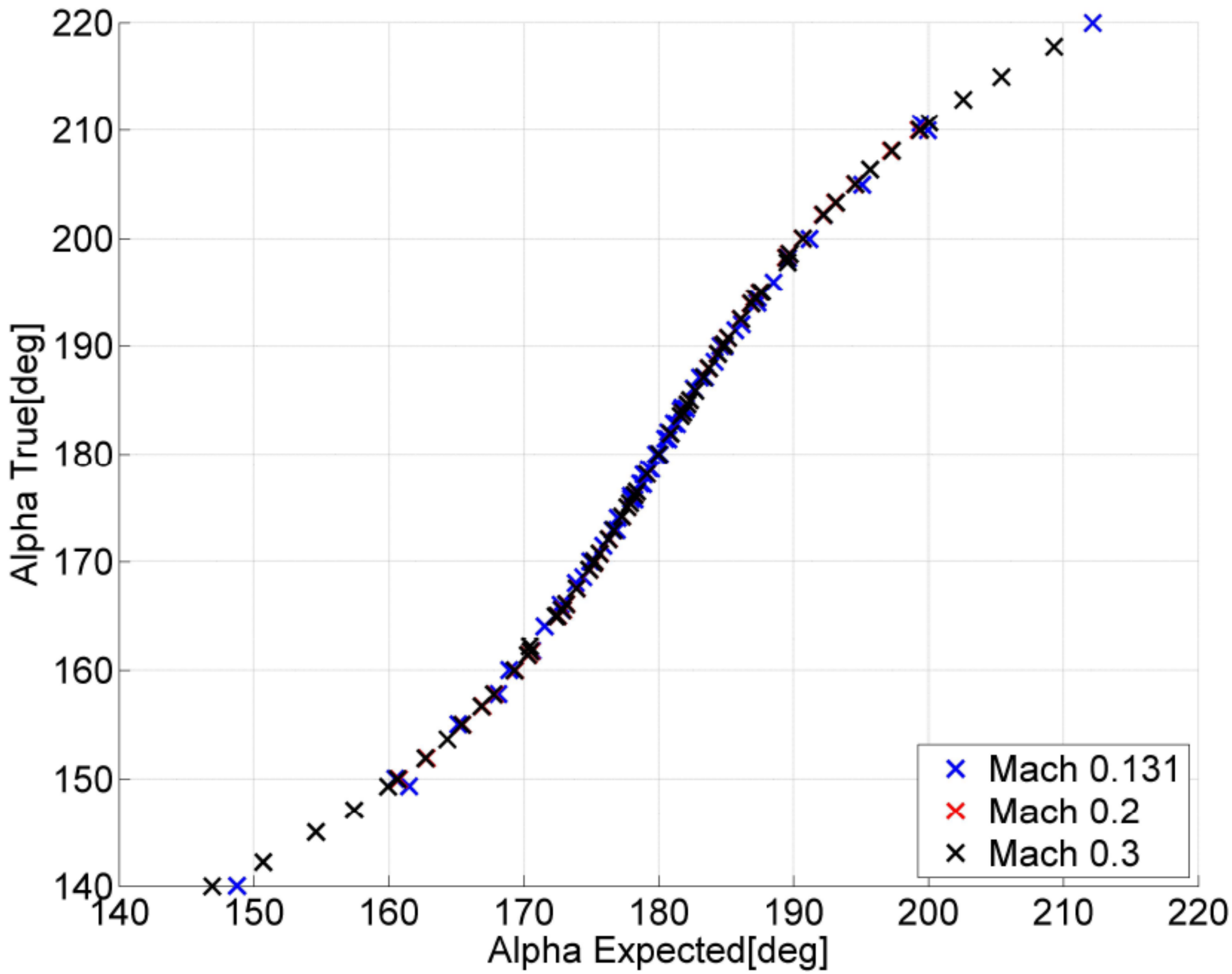
Plot showing gain in alpha and beta from rotations





Calibration Data

Heat Shield $\alpha(\alpha_e)$



Mach, Free stream Pressure, Impact Pressure Heat Shield

- Prandtl Glauert approximation:

$$C_{p0i}(\alpha,\beta,port_i) = C_{pi}(\alpha,\beta,port_i)\sqrt{1-M_\infty^2}$$

- Use calibration data at Mach 0.3 to generate interpolation surface for C_{p0i} $(\alpha,\beta,port_i)$ => C_p at Mach 0.0
- Use data from two ports to simultaneously solve for q_c and P_∞ while iteratively solving for M_∞
  - Less than 5 iterations to converge
  - Tol = 1E-6

$$C_{P1} = \frac{C_{P01}}{\sqrt{1-M_{\infty\,iter}^2}} \qquad C_{P2} = \frac{C_{P02}}{\sqrt{1-M_{\infty\,iter}^2}}$$

$$C_{P1} = \frac{P_1 - P_\infty}{q_c} \qquad C_{P2} = \frac{P_2 - P_\infty}{q_c}$$

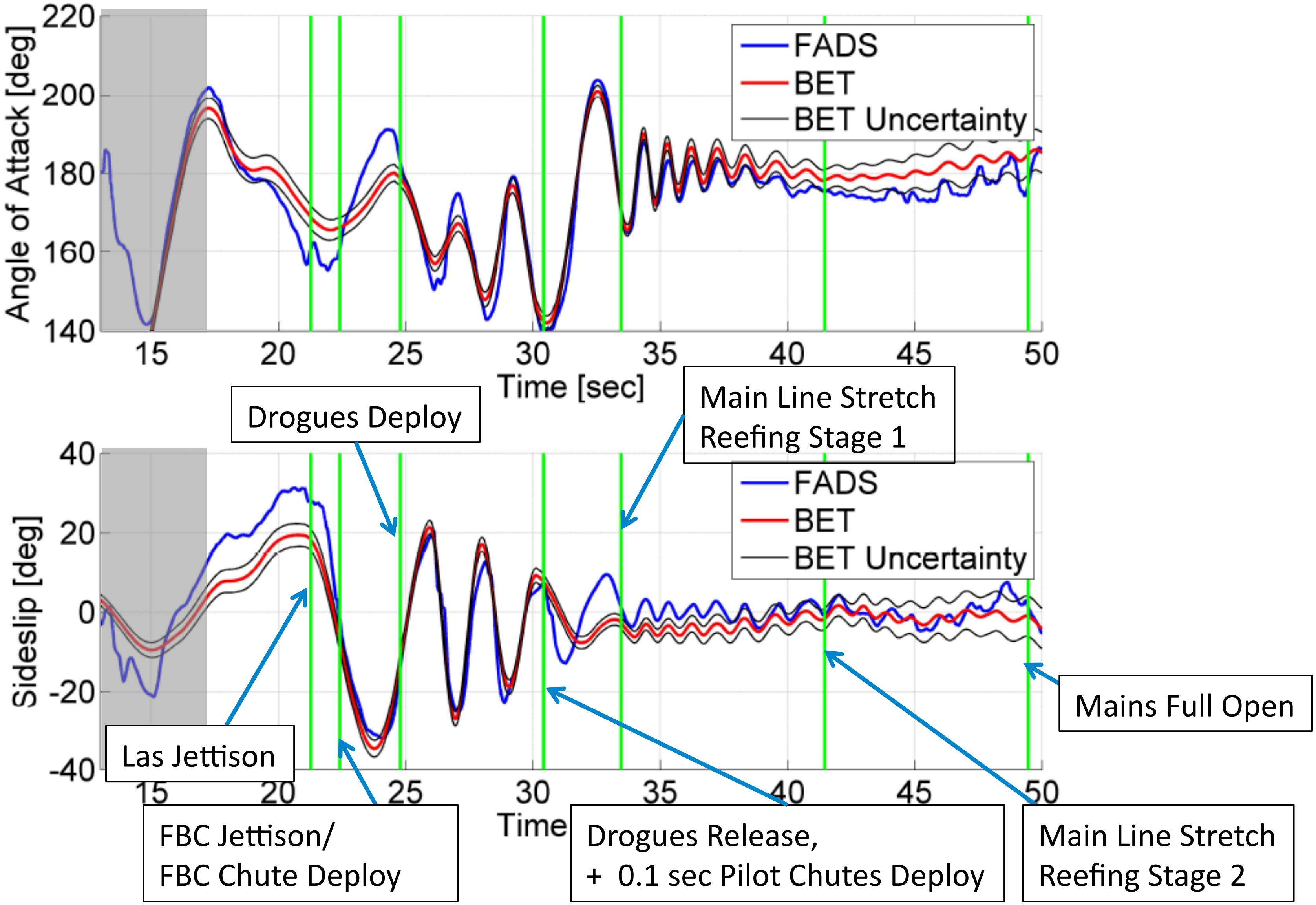
$$q_c = \frac{P_1 - P_2}{C_{p1} - C_{p2}}$$

$$P_\infty = P_1 - q_c C_{P1}$$

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

Flight Data Comparison of Heat Shield FADS Angle of Attack and Sideslip to the Best Estimated Trajectory(BET): Main Events

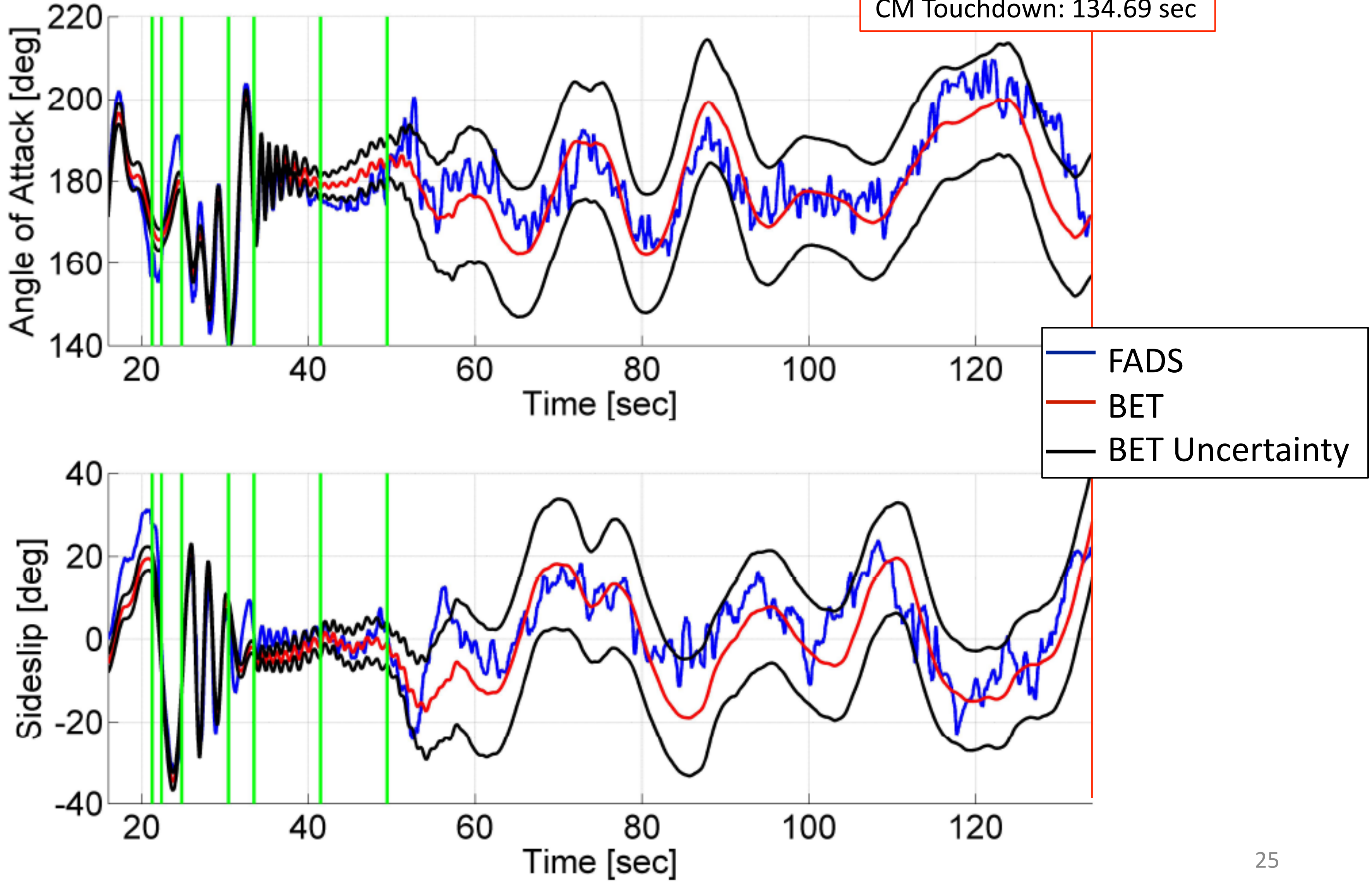
Reorientation End : 17.42 sec



Flight Data Comparison of Heat Shield FADS Angle of Attack and Sideslip to the Best Estimated Trajectory(BET)

Reorientation End : 17.42 sec

CM Touchdown: 134.69 sec



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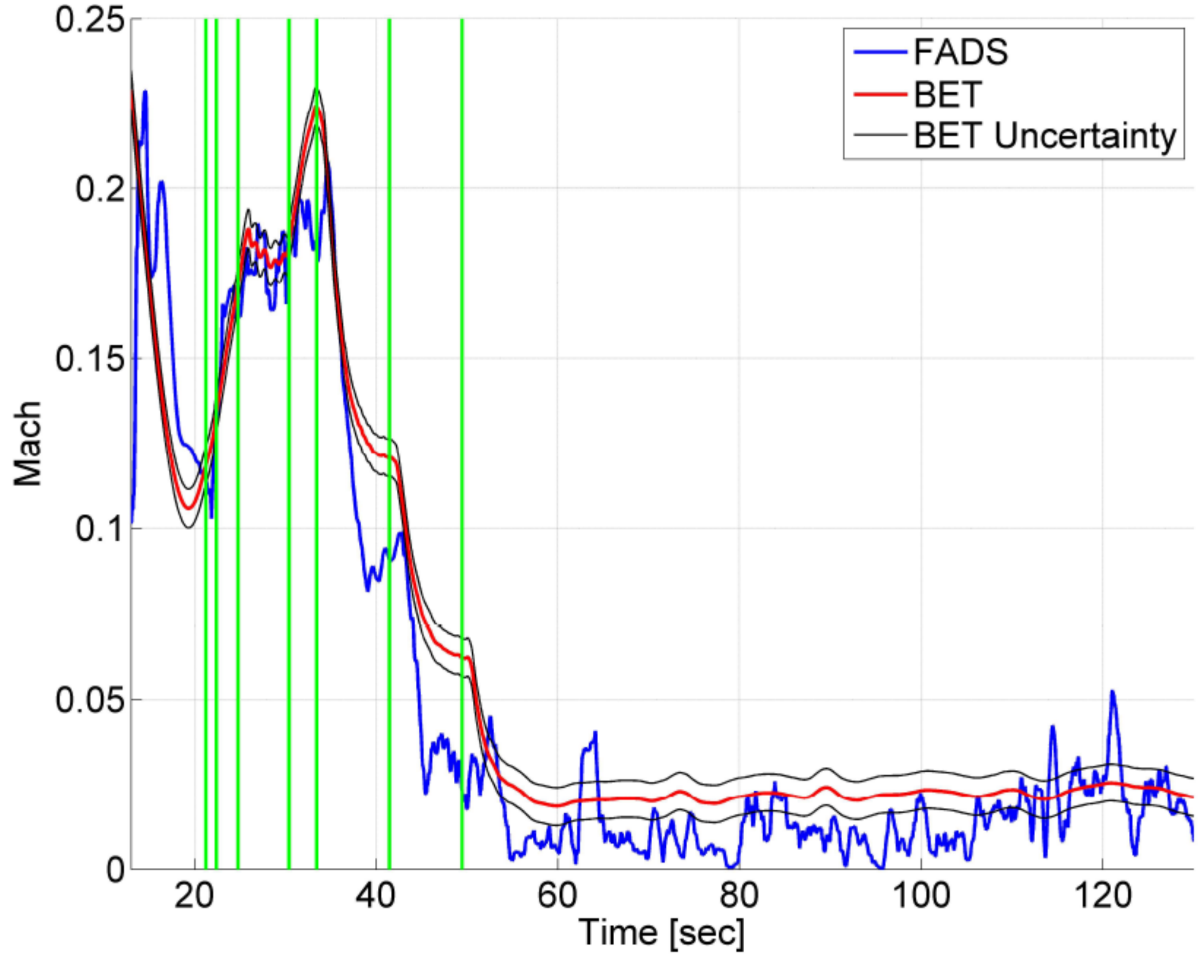
Comparison of heat shield FADS Free Stream Mach number to the Best Estimated Trajectory(BET)

Reorientation End : 17.42 sec



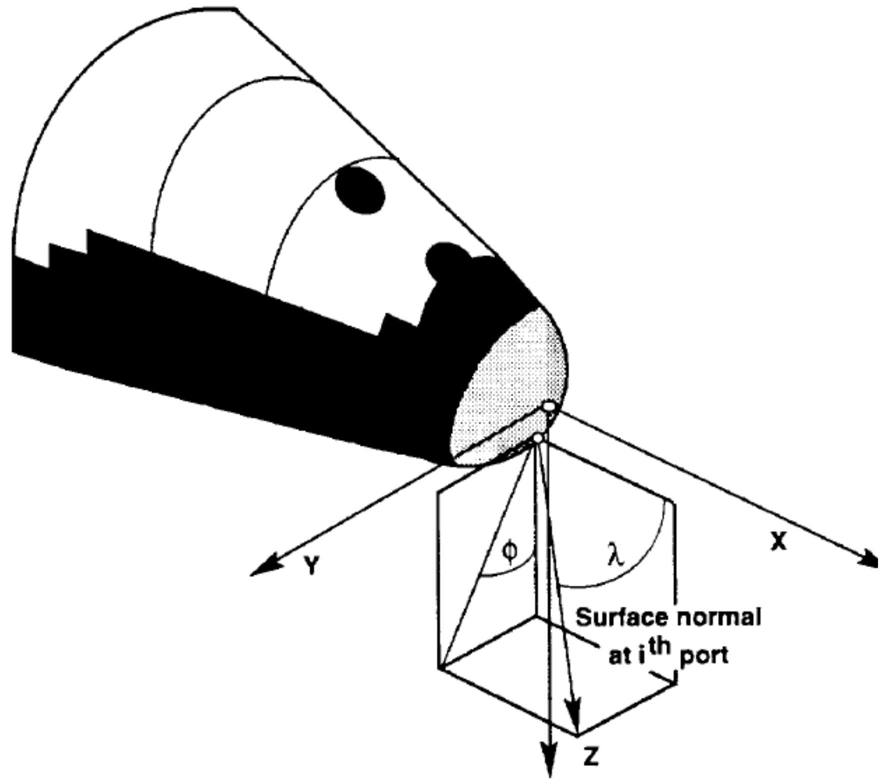
Summary

- Nose cap FADS
  - CFD showed very little effect on angle of attack and sideslip by ACM's
  - Presence of ACM's did affect ability of FADS system to calculate Mach, dynamic pressure and free stream static pressure
- Heat shield FADS
  - Prandtl Glauert approximation used to calculate Mach, dynamic pressure and free stream pressure
    - Typical least squares solution of FADS governing equation used to calculate Mach, dynamic pressure and free stream pressure would not converge
  - Poor data quality; sensors lacked sensitivity

BACK-UP

Clocking and Cone Angle Definition

- ϕ_i: clocking angle
  - Clockwise angle looking nose to tail starting from the z-axis as illustrated
- λ_i: cone angle
  - Angle that the normal to the surface, at the ith port, makes with the x-axis



Governing Aerodynamic Model

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

$$\begin{aligned} cos(\theta_i) = {} & cos(\alpha_e)cos(\beta_e)cos(\lambda_i) \\ & + sin(\beta_e)sin(\phi_i)sin(\lambda_i) \\ & + sin(\alpha_e)cos(\beta_e)cos(\phi_i)sin(\lambda_i) \end{aligned}$$

- Combination of
  - Closed form potential flow solution for a blunt body; applicable at low subsonic speeds
  - Modified Newtonian flow model; applicable at hypersonic speeds

- P_i : pressure at each port
- q_c: impact pressure = P_0 - P∞
- θi : flow incidence angle between the surface normal at the ith port and the velocity vector
- P_∞: Free stream static pressure
- α_e: angle of attack predicted by model; alpha expected
- β_e: sideslip predicted by model
- ϕ_i: clocking angle
- λ_i: cone angle
- Є: calibration parameter; blends potential flow solution and Newtonian flow model => model applicable to large range of mach numbers

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

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

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

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

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

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

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

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

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

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

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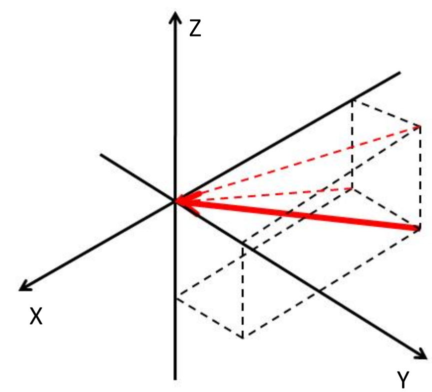
Triples Algorithm
Sideslip

- Took advantage of the fact that β_F and α are contained in orthogonal planes
  - Flank angle was calculated in a similar manner as angle of attack by
    - replacing the respective values for clocking angle, ϕ $(3\pi/2, \pi/2) \rightarrow (0, \pi)$
    - Using ports along Y axis to construct triples
    - Maintaining correct sign convention
- Resulting β_{fe} is calibrated to wind tunnel data and/or CFD data to get to get β_f
- β_f combines with α to get β

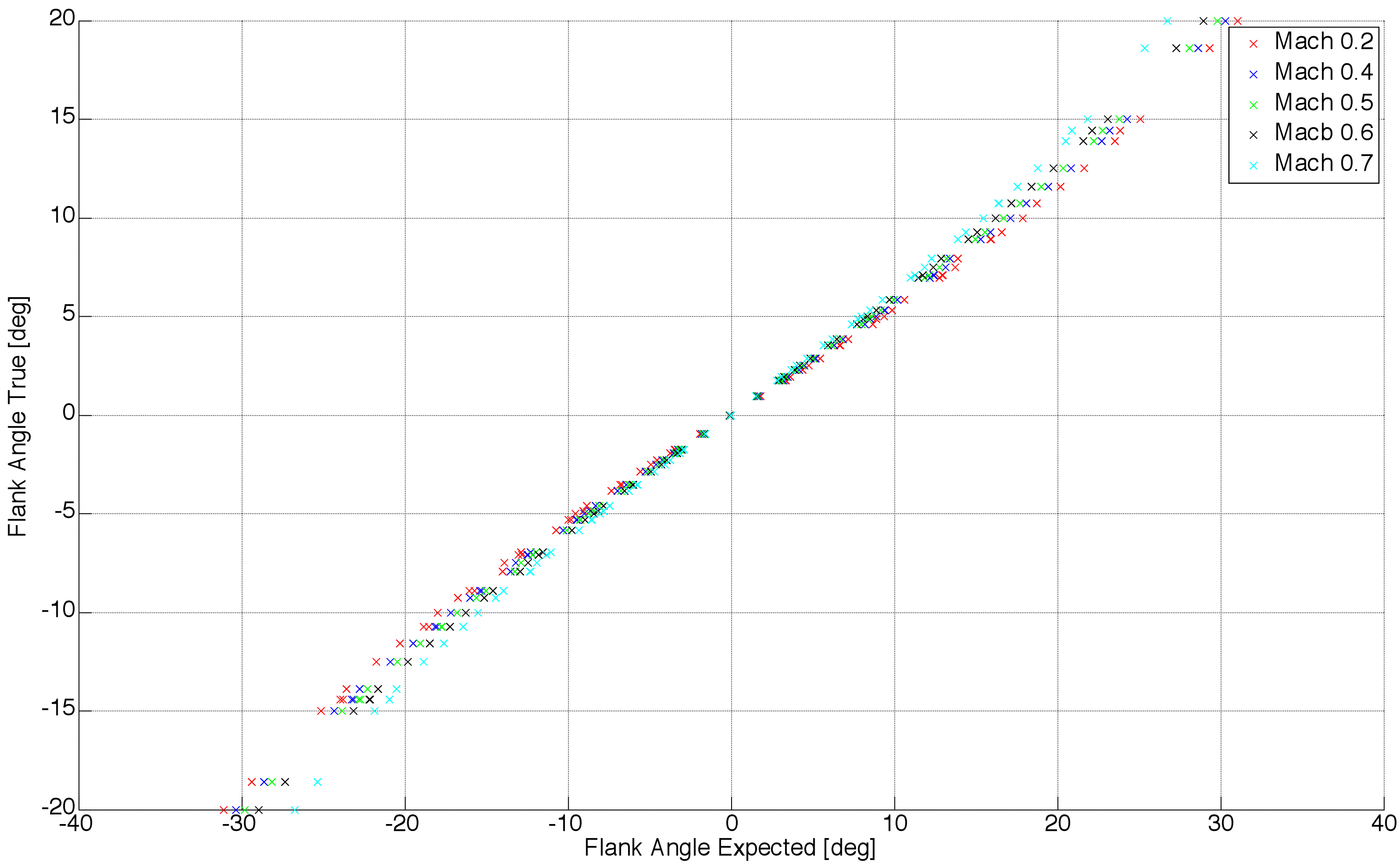
$$\beta = tan^{-1}\left(tan(\beta_F)cos(\alpha)\right)$$



Nose cap FADS system back-up

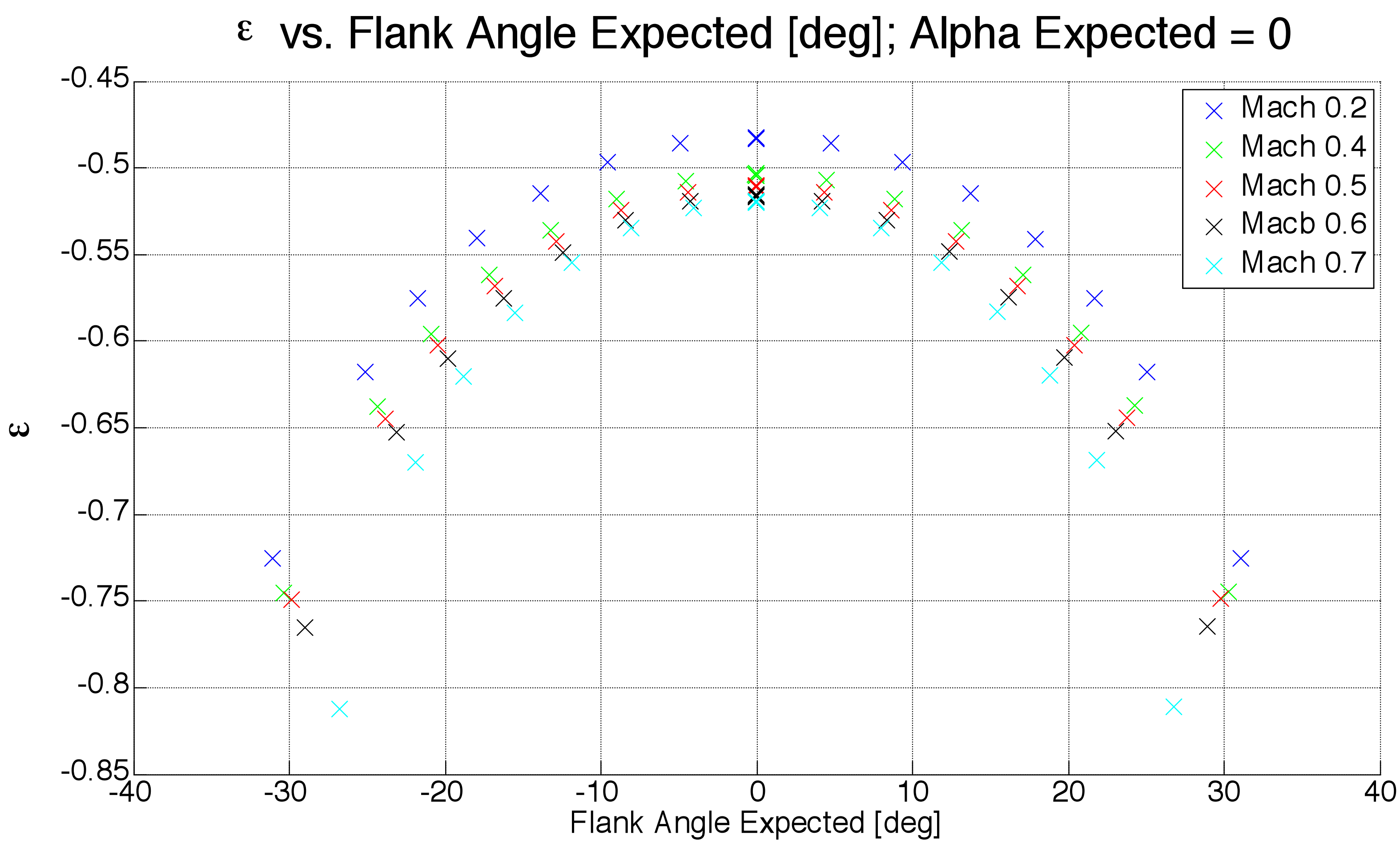
Calibration Data

Nose cap; $\beta_f(\alpha_e, \beta_{fe}, M_\infty)$



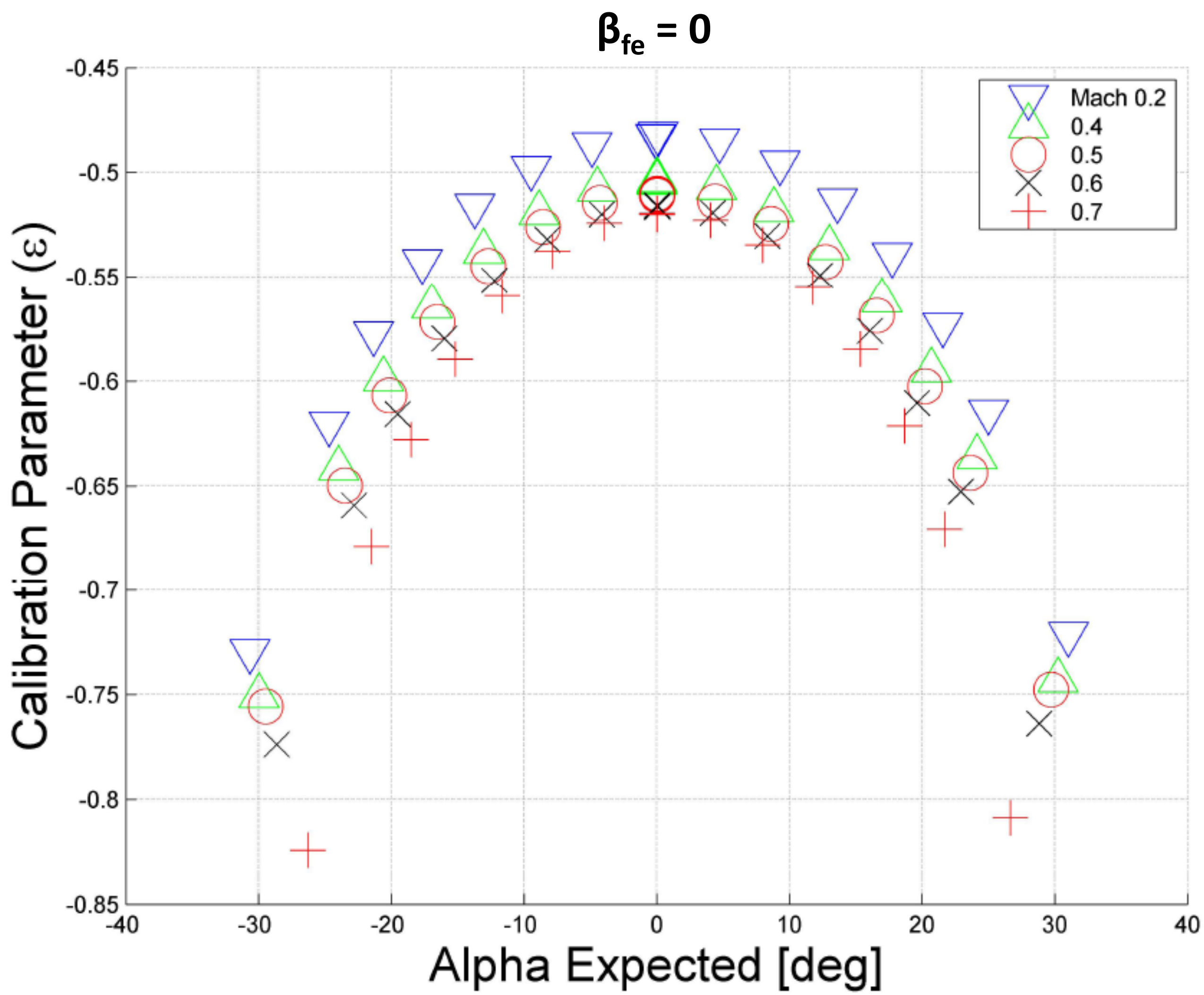
Calibration Data

Nose cap; $\epsilon(\alpha_e, \beta_{fe}, M_\infty)$



Calibration Data

Nose cap; $\epsilon(\alpha_e, \beta_{fe}, M_\infty)$



Mach, Free stream Pressure, Impact Pressure: Nose Cap

- Given: $P_i = q_c\,[cos^2(\theta_i) + \epsilon\, sin^2(\theta_i)] + P_\infty$

- For all n = 9 ports: $\begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix} = \begin{bmatrix} \left(cos^2(\theta_1) + \epsilon sin^2(\theta_1)\right) & 1 \\ \vdots & \vdots \\ \left(cos^2(\theta_n) + \epsilon sin^2(\theta_n)\right) & 1 \end{bmatrix} \begin{bmatrix} q_c \\ P_\infty \end{bmatrix}$

- Let: $\zeta_i = cos^2(\theta_i) + \epsilon\, sin^2(\theta_i)$

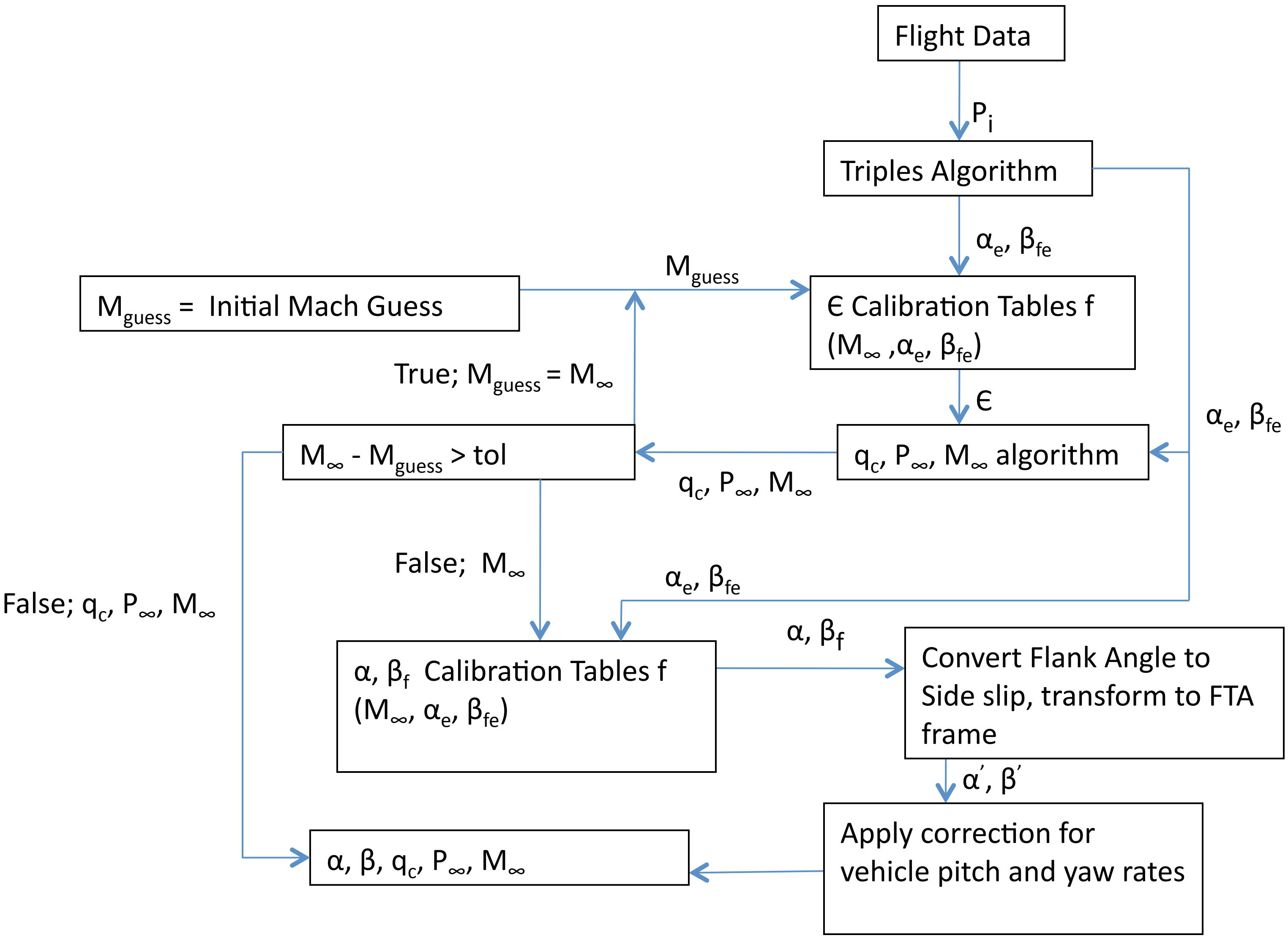
- Apply least squares to system of n equations
  - First with respect to qc and then with Pinf
- Solve resulting simultaneous equations for q_c and P_∞
- Use resulting values to solve for mach(M_∞), with the isentropic flow laws

$$q_c = \frac{\left(\frac{1}{n}\sum_{i=1}^{n} P_i\right)\left(\sum_{i=1}^{n} \zeta_i\right) + \sum_{i=1}^{n} P_i \zeta_i}{\sum_{i=1}^{n} \zeta_i^2 - \left(\frac{1}{n}\sum_{i=1}^{n} \zeta_i\right)\left(\sum_{i=1}^{n} \zeta_i\right)}$$

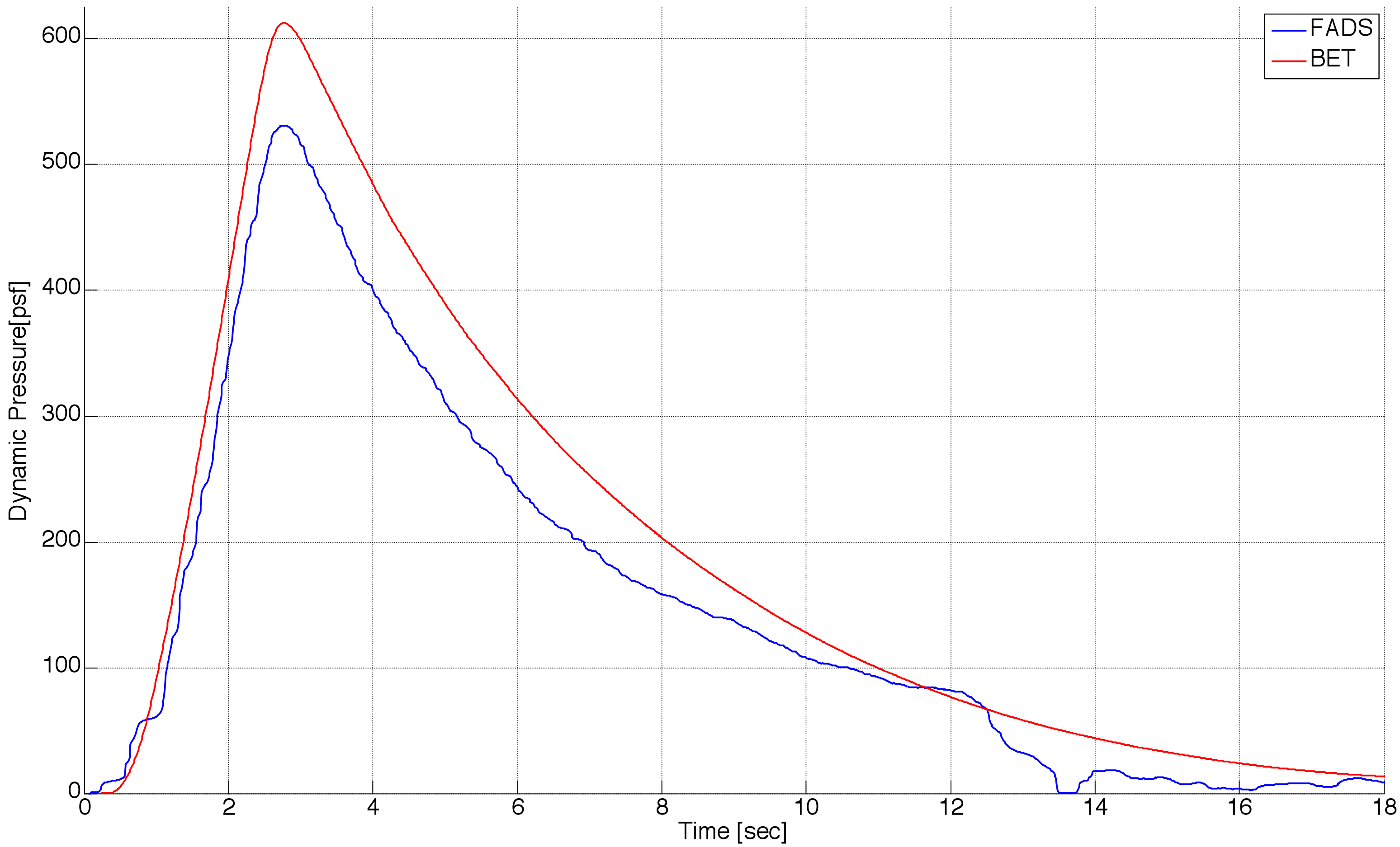
$$P_\infty = \sum_{i=1}^{n} \frac{P_i}{n} - \frac{q_c}{n}\sum_{i=1}^{n} \zeta_i$$

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

Nose cap FADS algorithm



Comparison of nose cap FADS Dynamic Pressure [psf] to the Best Estimated Trajectory(BET)



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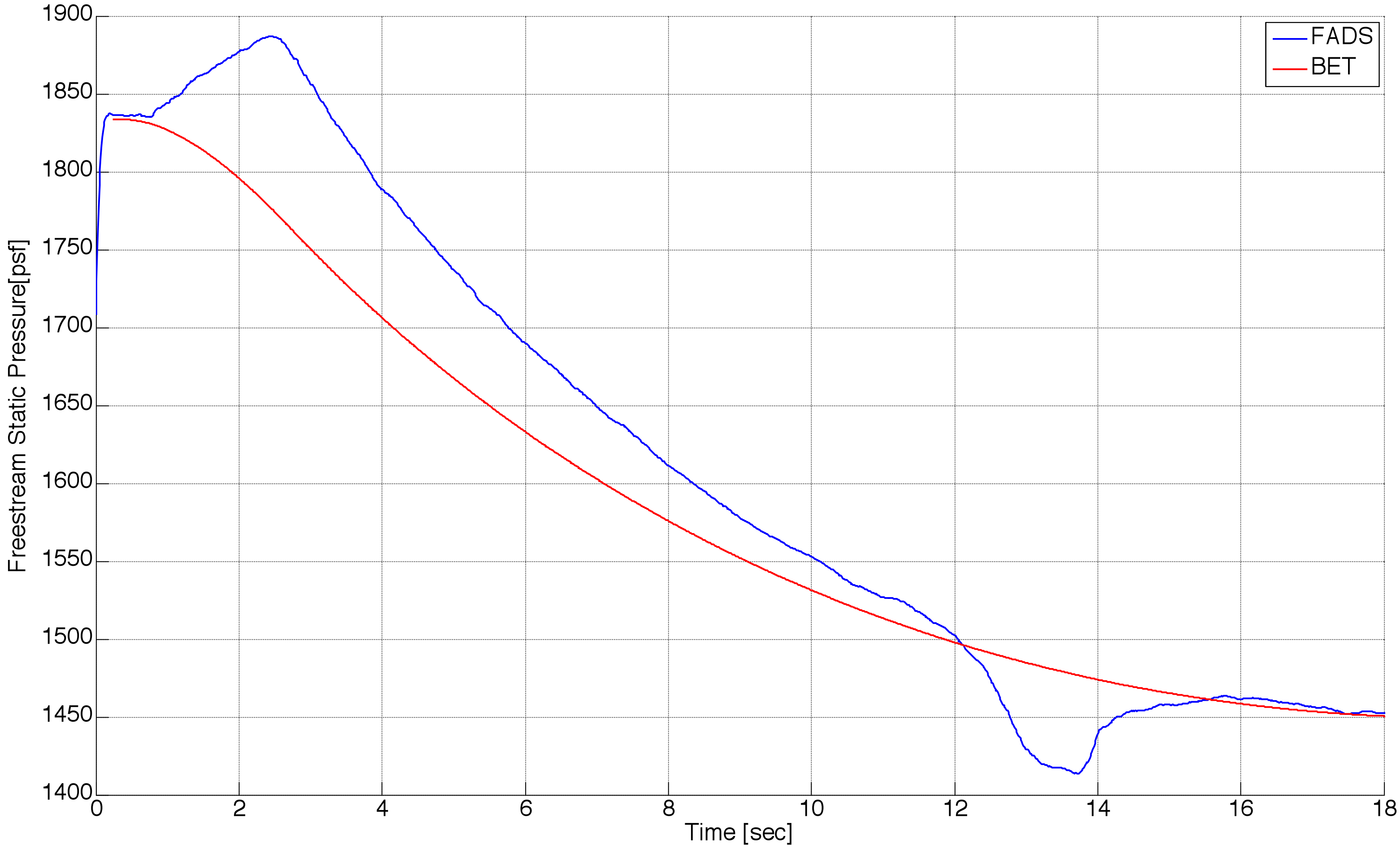
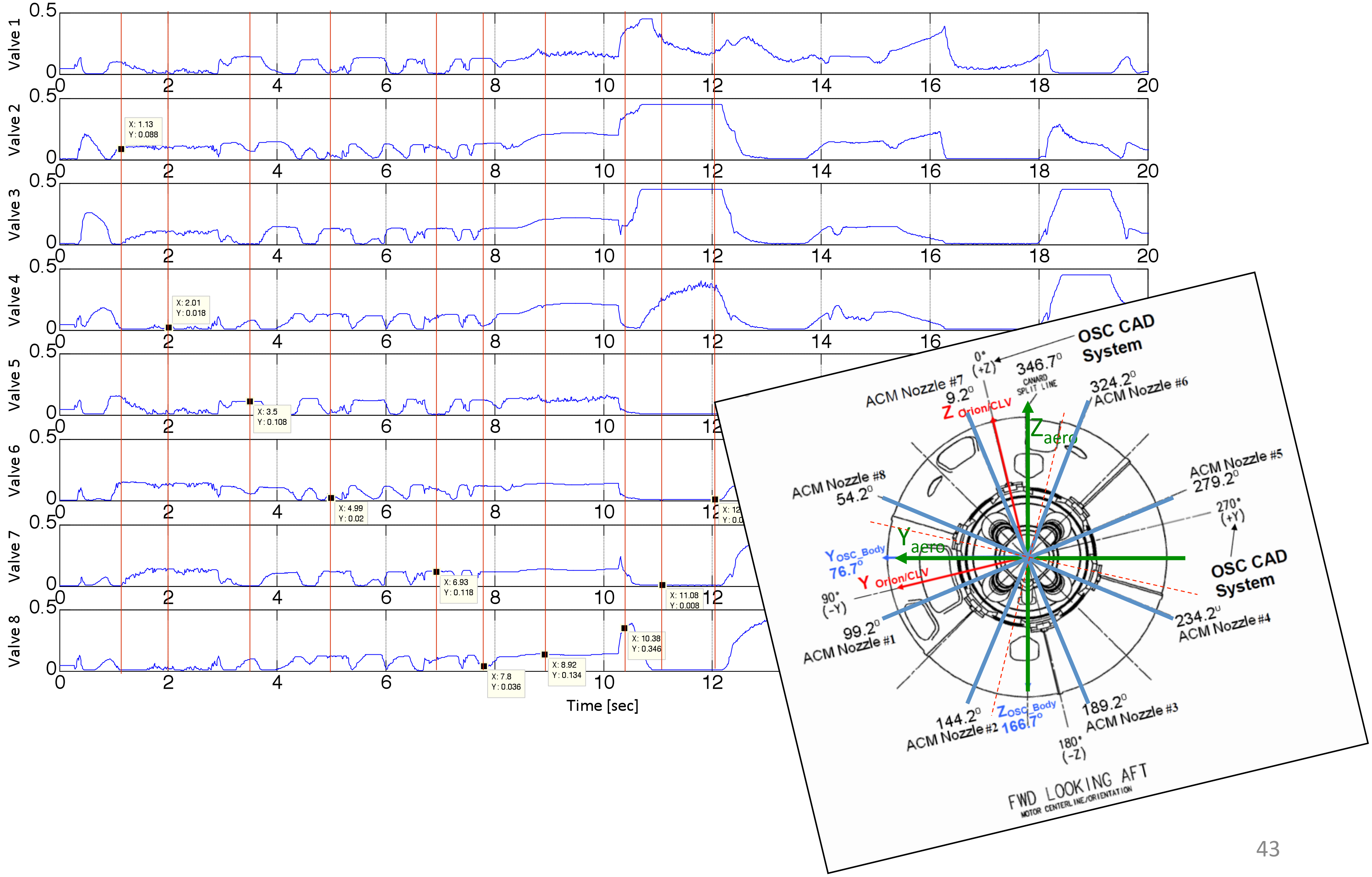
Comparison of nose cap FADS Freestream Static Pressure[psf] to the Best Estimated Trajectory(BET)



ACM Pintle Positions



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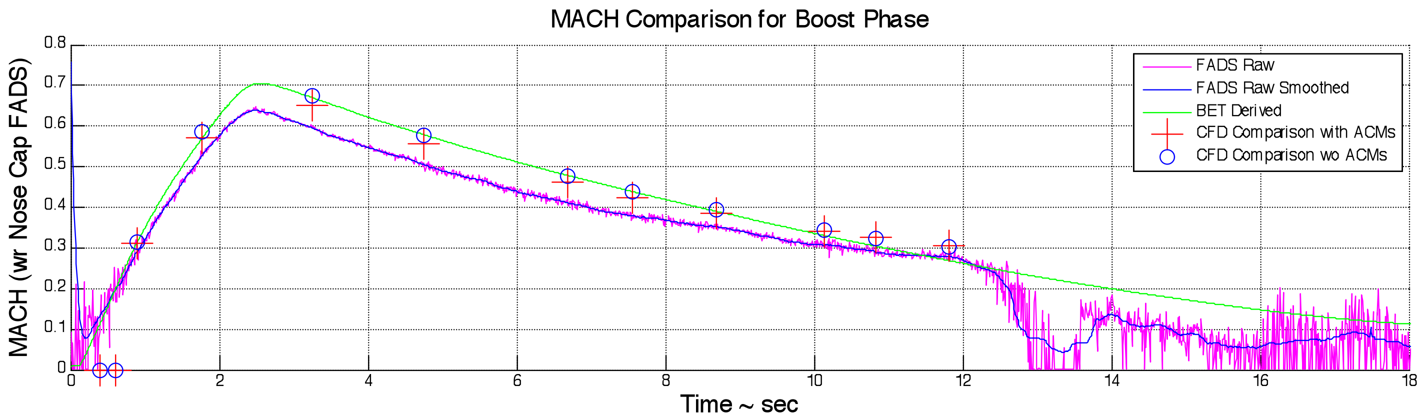

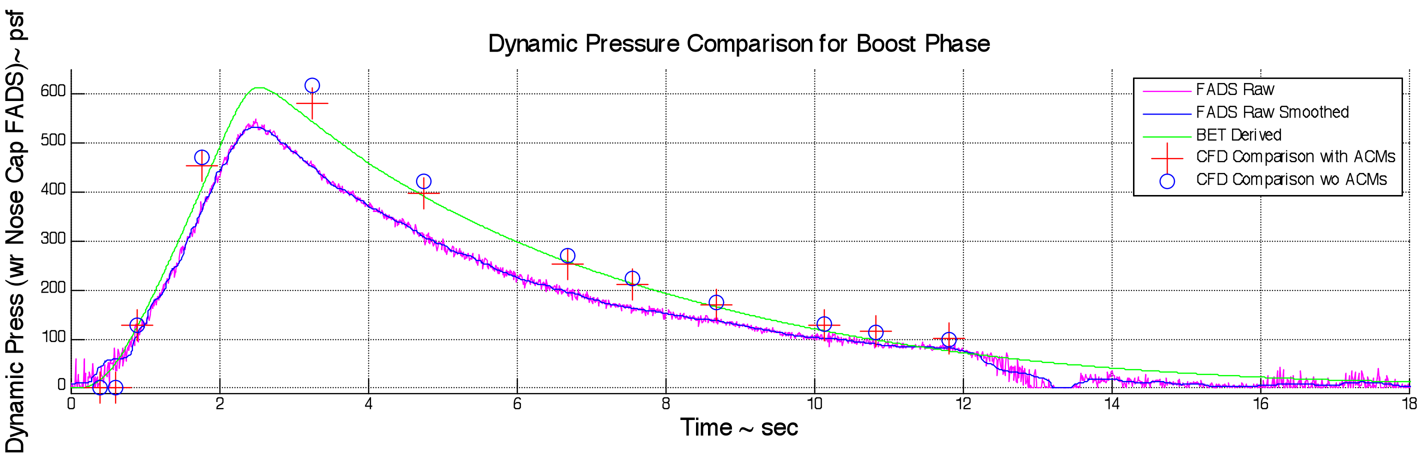

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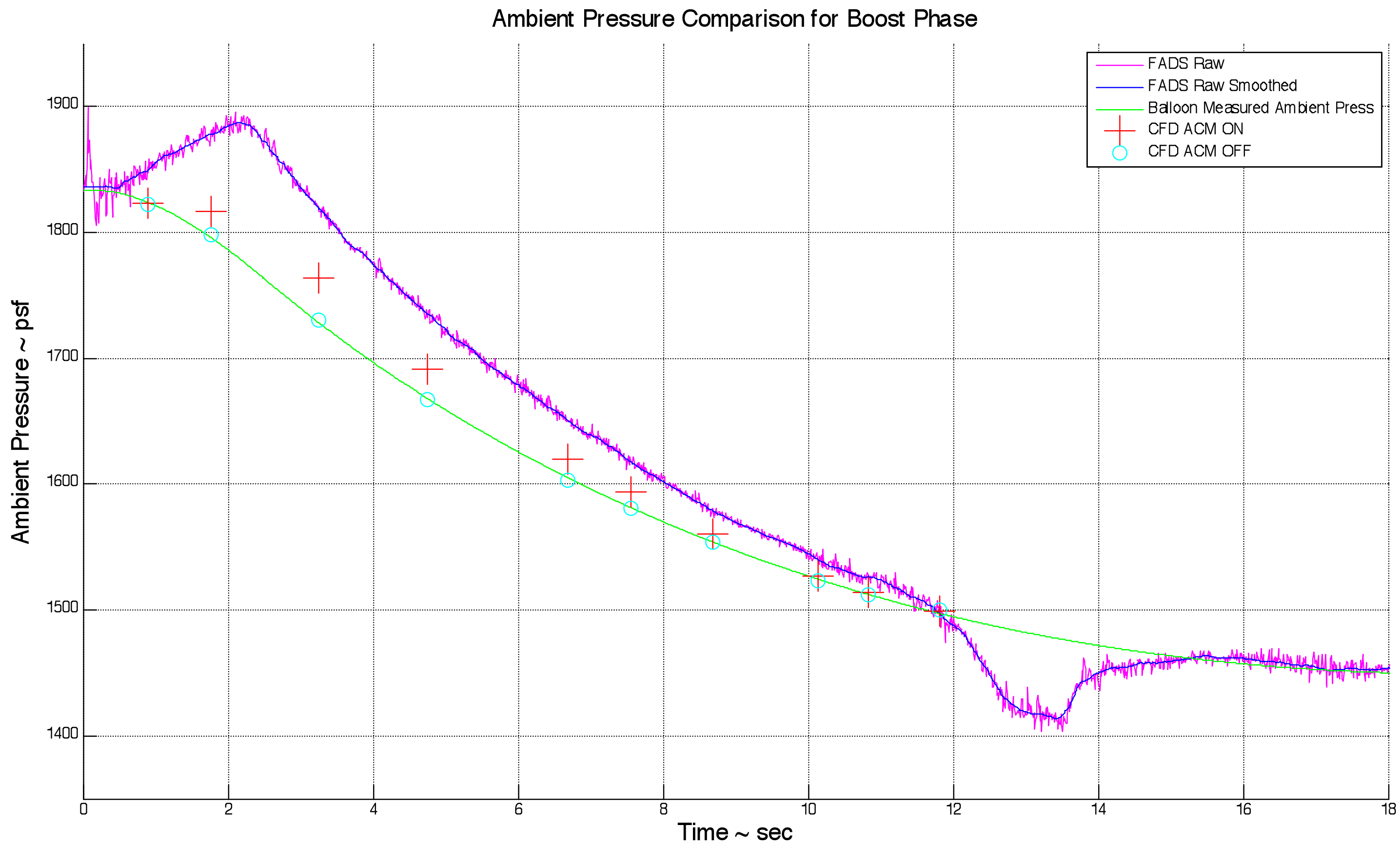
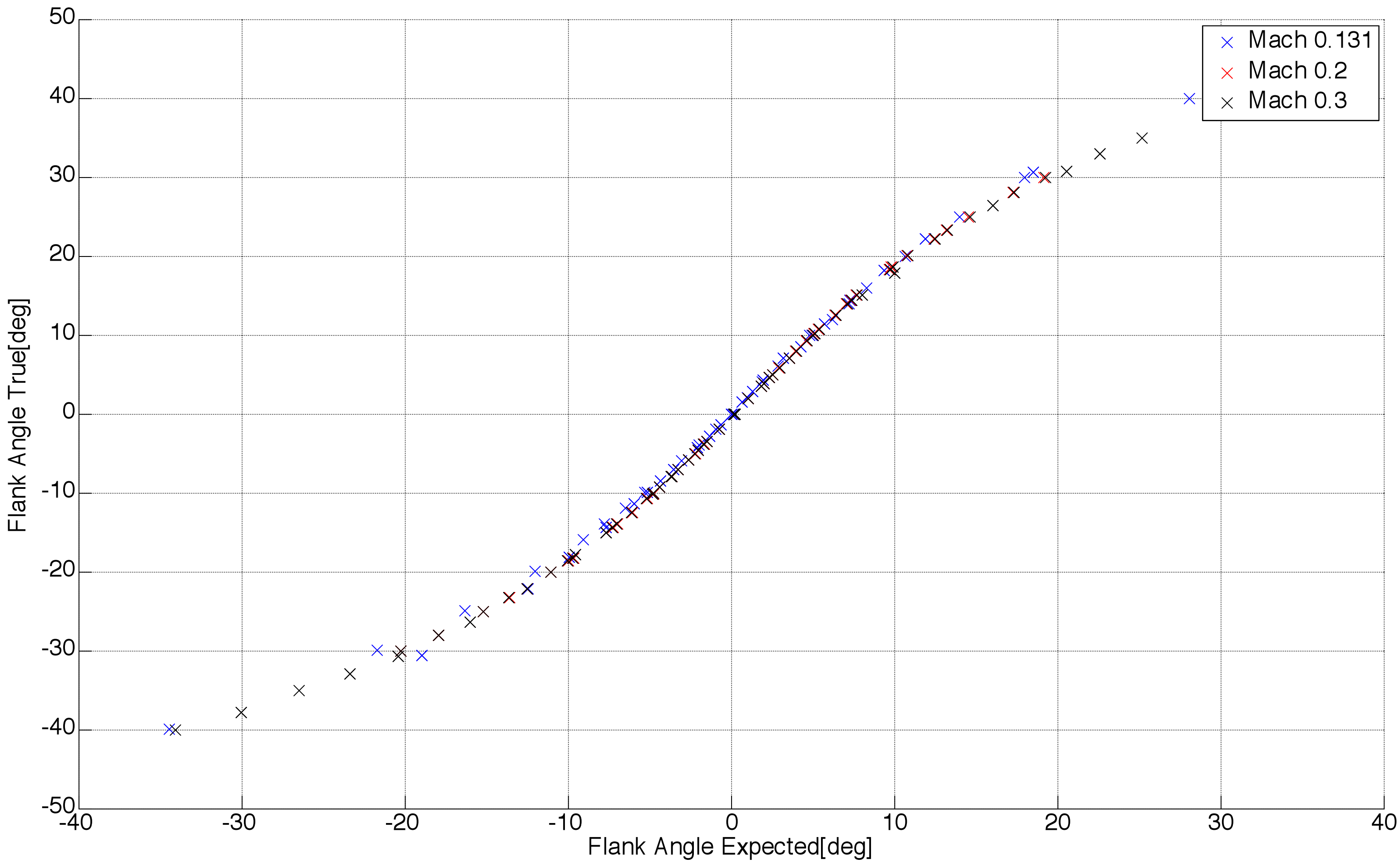


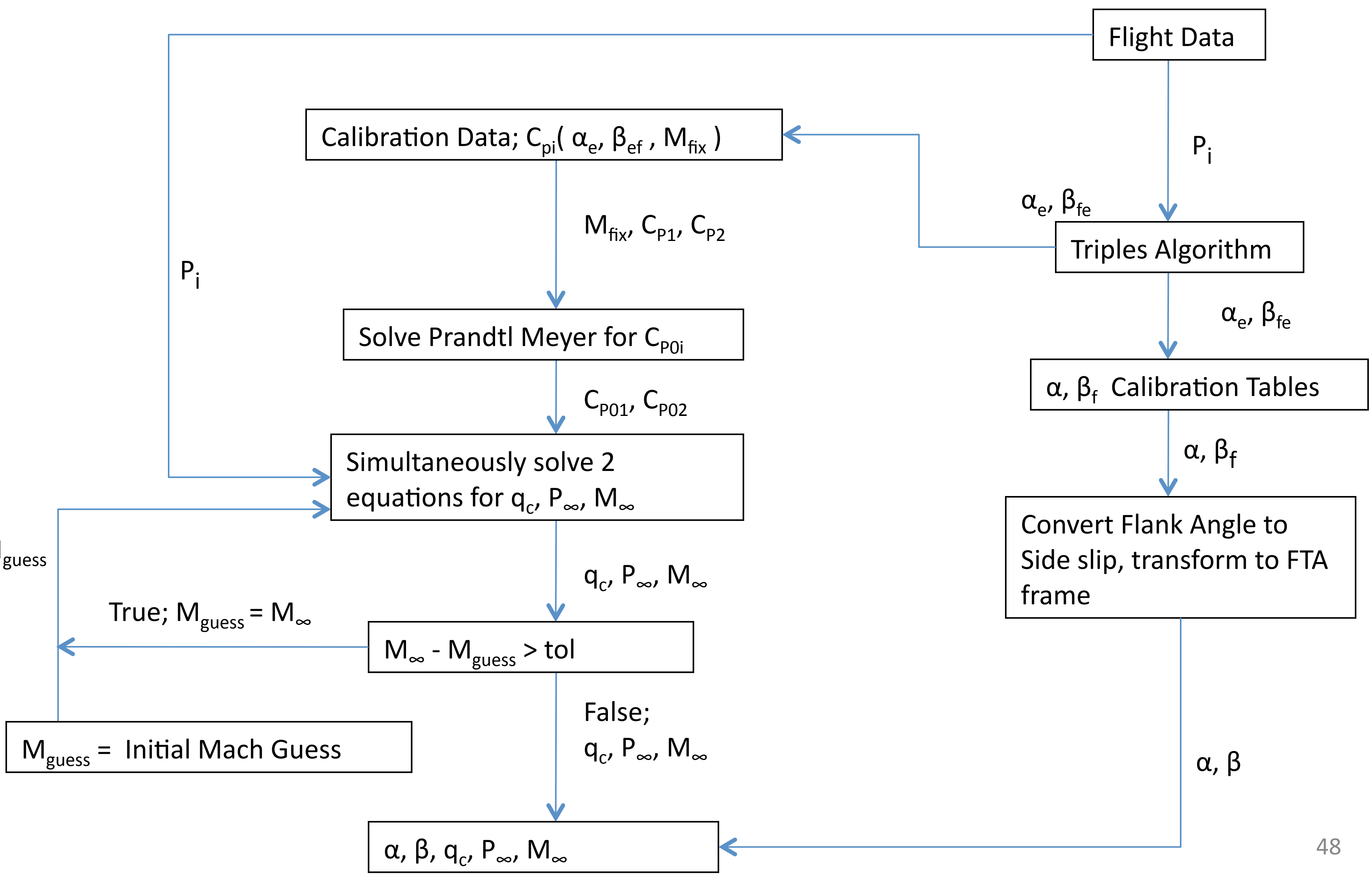
Heat Shield FADS System back-up

Calibration Data

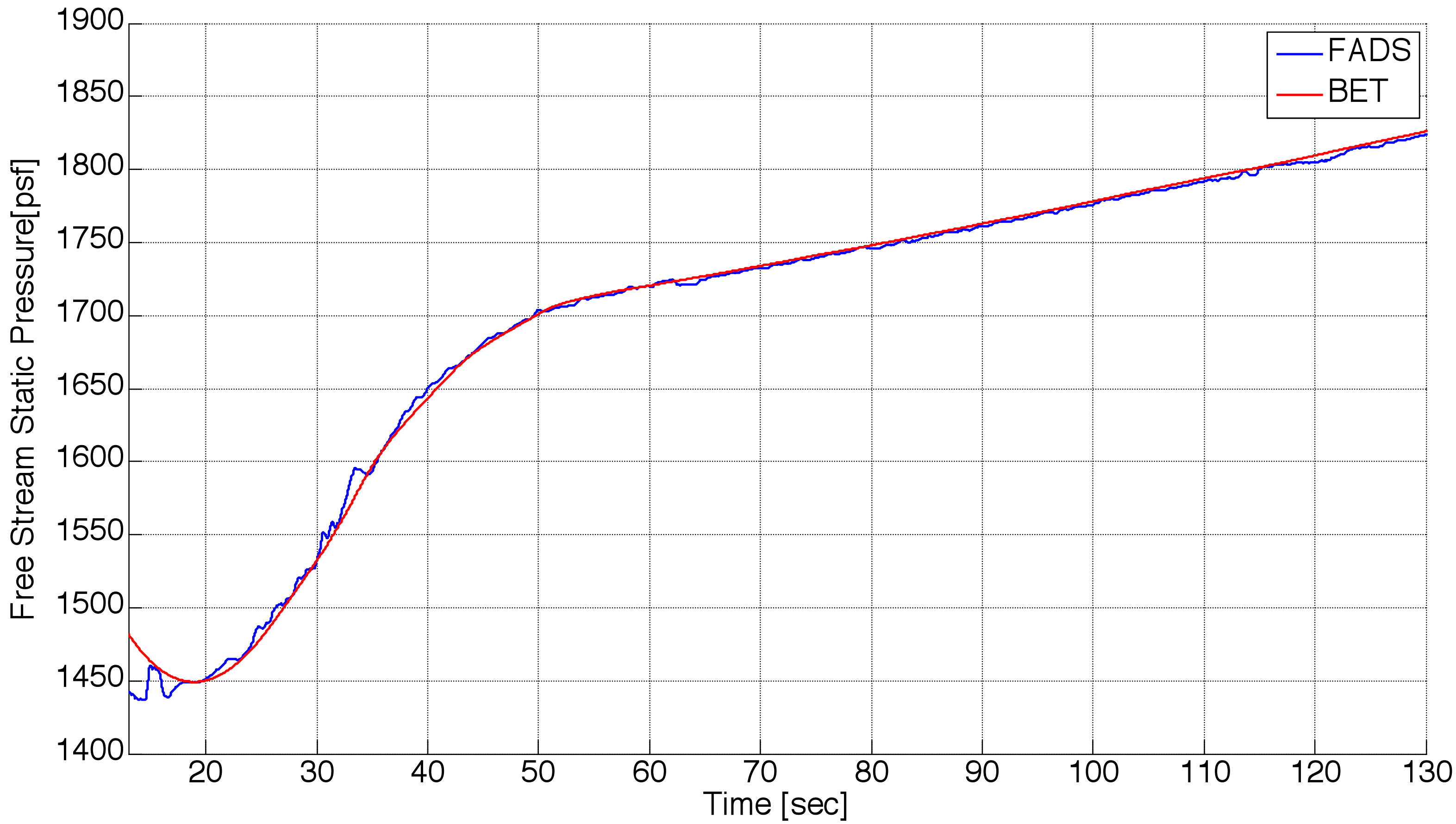
Heat Shield $\beta_f(\beta_{fe})$



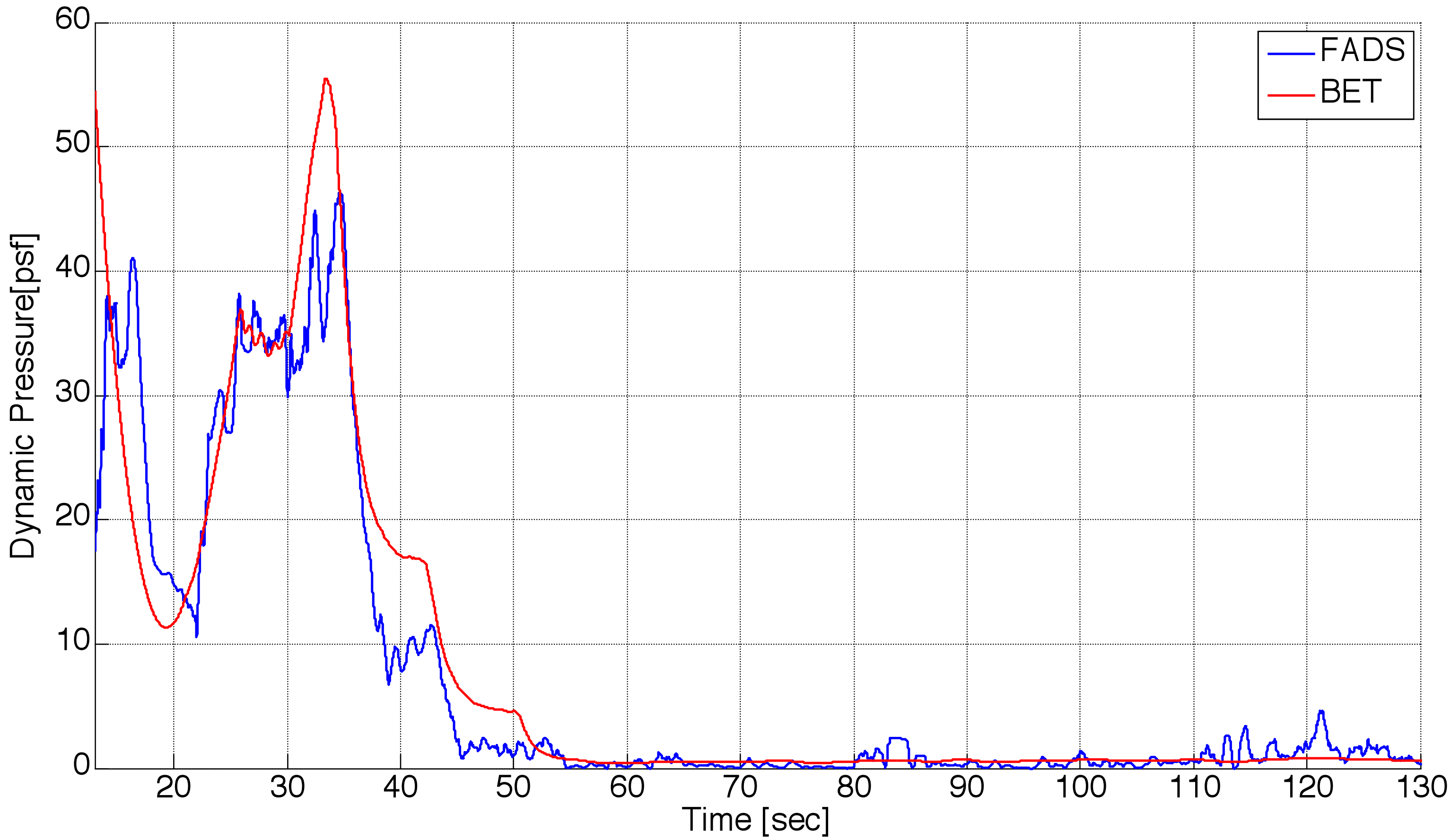
Heat Shield FADS algorithm



Comparison of heat shield FADS Free Stream Static Pressure to the Best Estimated Trajectory (BET)



Comparison of heat shield FADS Dynamic Pressure to the Best Estimated Trajectory(BET)



Main Events after Launch

- Reorientation Complete: 17.42 sec
- LAS Jettison: 21.27
- FBC Jettison/FBC Chutes deployed: 22.41
- Drogues Deploy: 24.8
- Drogues Release: 30.41
- Pilot Chutes Deploy 30.42
- Main Line Stretch/Reefing Stage 1: 33.47
- Main Line Stretch Reefing Stage 2: 41.47
- Mains Full Open: 49.47
- CM touch down 134.69