SPACE LAUNCH SYSTEM

Tested, Proven,
Ready to Explore

Base Aerodynamics Post-Flight Reconstruction for Artemis I

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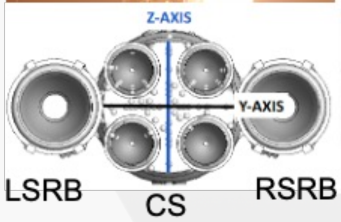
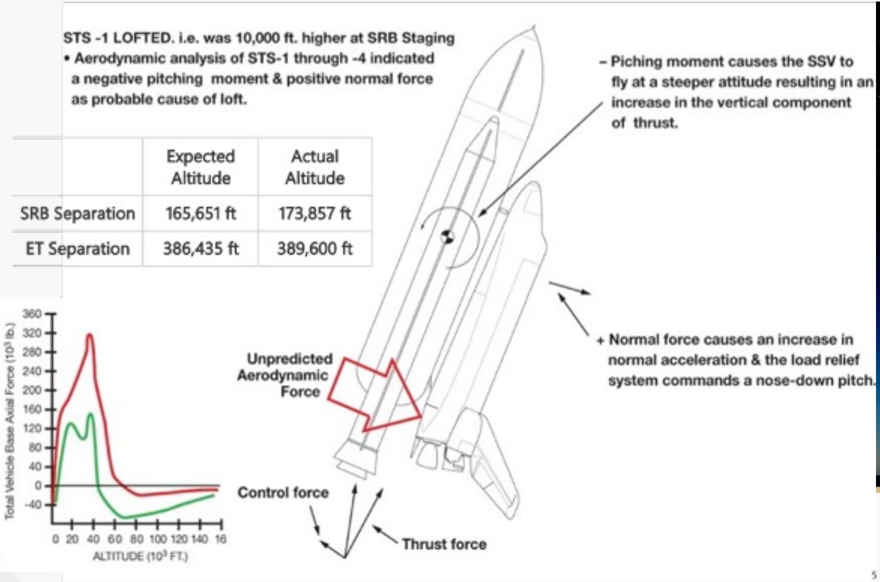
Agenda

- **AR01 Flight Summary**
  - Mission Profile
  - Flight Reconstruction Approach
- **AR01 Core Stage (CS) Base Aerodynamics**
- **AR01 Solid Rocket Booster (SRB) Base Aerodynamics**
- **Conclusions**

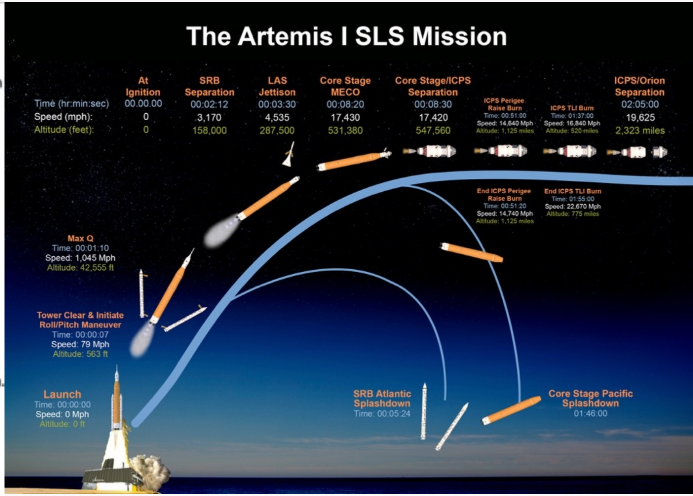
AR01 Mission Profile

- No aero anomalies observed due to plume-induced base environments
- All base environment model anchoring objectives satisfied

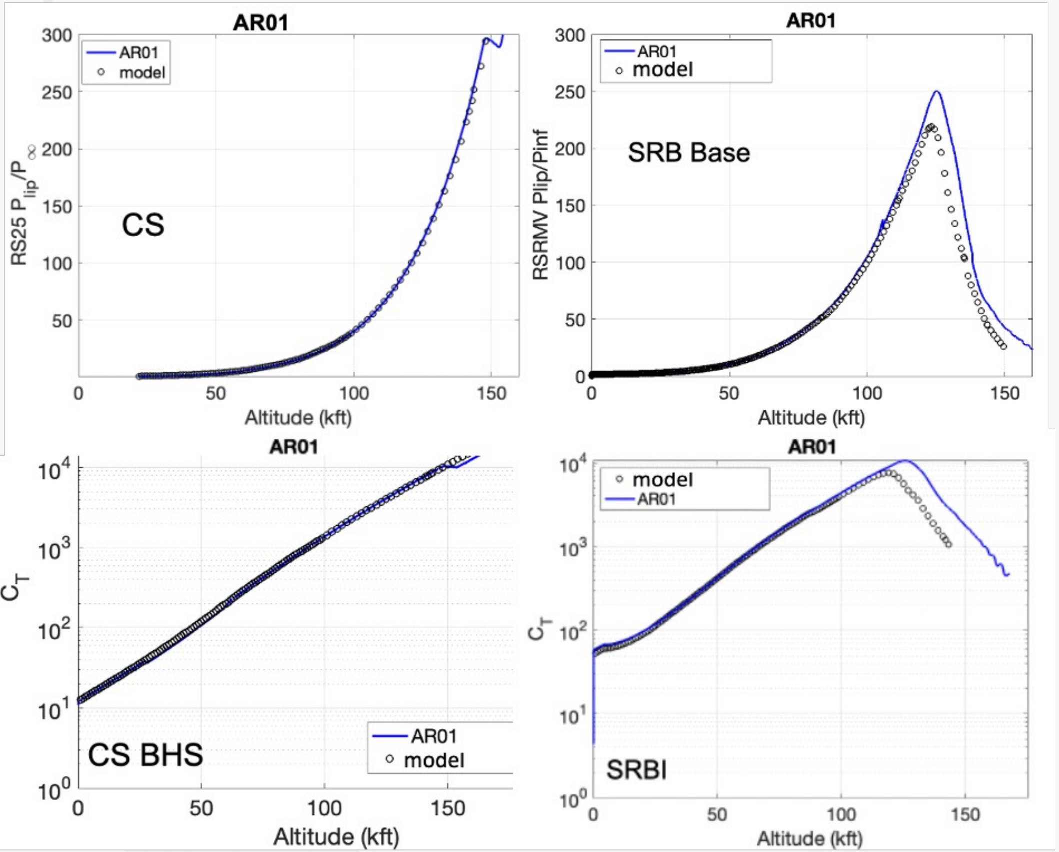




	Expected Altitude	Actual Altitude
SRB Separation	165,651 ft	173,857 ft
ET Separation	386,435 ft	389,600 ft



SLS Propulsion Characteristics

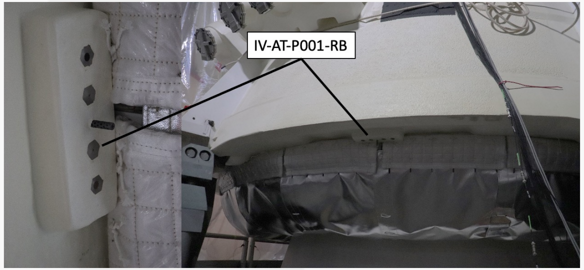


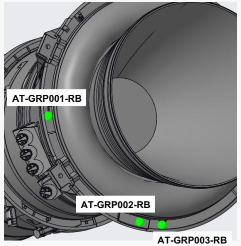
- Good agreement between BET models and post-flight reconstructed propulsion characteristics
- RSRMV P_{lip}/P_{inf} and thrust coefficient (C_T) higher at lower altitudes than RS-25 propulsion characteristics
- Model provides base force as a function altitude with a +3 sigma uncertainty bound
  - **Below 50 kft**: The Boyle and Pace semi-empirical model was used, which was derived from historical launch vehicles (Saturn to Shuttle)
  - **From 50 kft to MECO:** ATA-002 SLS base heating shock tunnel test program (tunnel data to 210 kft and extrapolated to MECO).
  - 3-sigma uncertainty bound intended to represent flight-to-flight variation below 50 kft, configuration driven sensitivities, and measurement uncertainties for the region of the tunnel derived profile

SLS Base Aero: Development Flight Instrumentation

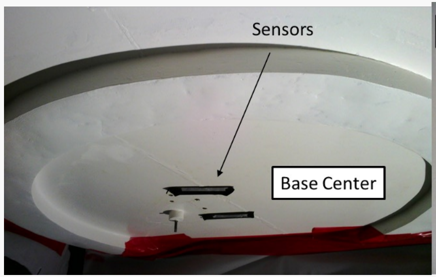
- **Development Flight Instrumentation (DFI)**
  - All Core Stage and SRB base pressure DFI were nominal for AR01 flight
  - A total of 8 CS and SRB base static pressure sensors were used in base force/pressure flight reconstruction

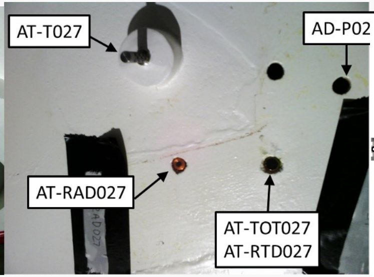
Sensor	Type	Component	Sample Rate (Hz)	Status	Notes
AD-P027	Static Pressure	CS Base Heat Shield (Center)	50	Good	
AD-P030	Static Pressure	CS Base Heat Shield (Periphery Near SRB)	50	Good	
AD-P032	Static Pressure	CS Base Heat Shield (Periphery Near CAPU)	50	Good	
AD-P033	Static Pressure	CS Base Heat Shield (Between E3 & E4)	50	Good	
AD-P034	Static Pressure	CS Base Heat Shield (Between E2 & E3)	50	Good	
IV-AT-P001-RB	Static Pressure	RH SRB Aft-Lip of Aftskirt	50	Good	
IV-AT-P002-RB	Static Pressure	RH SRB Aft-Lip of Aftskirt	50	Good	
IV-AT-P003-RB	Static Pressure	RH SRB Aft-Lip of Aftskirt	50	Good	Bad data between T+75 s and T+100 s

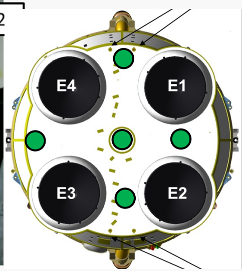




RH SRB Aft-lip Aftskirt (Base)







Core Stage Base Heat Shield

Base Pressure Reduction

- **Used serial calibration coefficients to convert raw counts to engineering units (psia)**

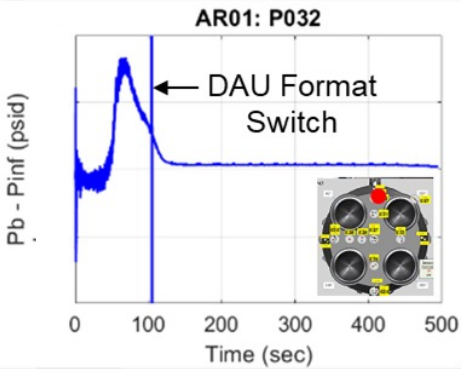
- **Determined the pressure off-set by comparing the pre-launch base pressure values prior to CAPU operations with BET trajectory**
  - All Core Stage& SRB base pressure DFI needed to be corrected

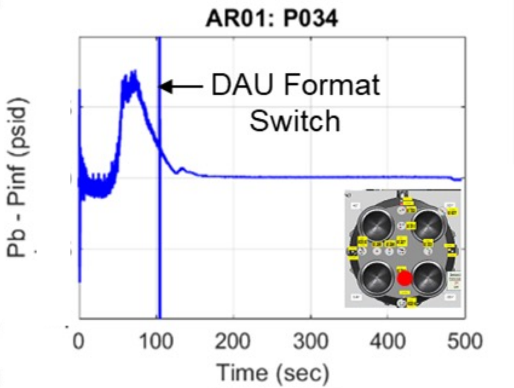
- **Temporal sync of all base pressure data to the freestream pressure (BET) trajectory to estimate P_b - P_{inf}**

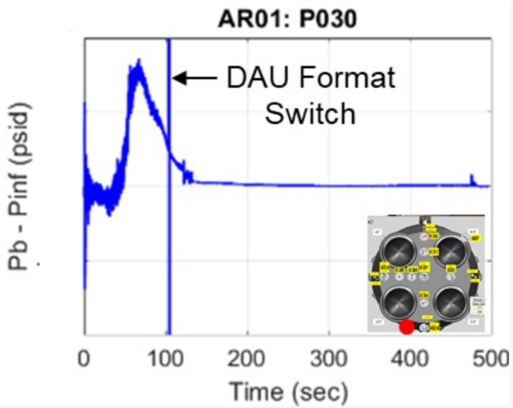
- **For SRB base pressure data, used the Time of Validity extraction approach recommended by Todd Honeycutt (not needed for Core Stage base pressure)**

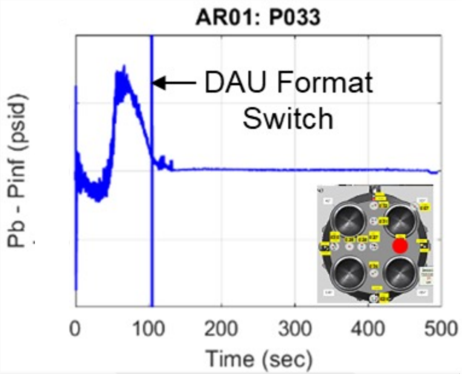
- **Applied a low-pass digital filter to both the CS and SRB environments to reduce noise**

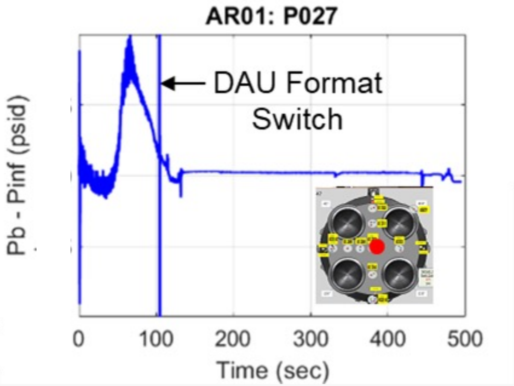
CS Base Aero: Reduced Raw Pressure Data



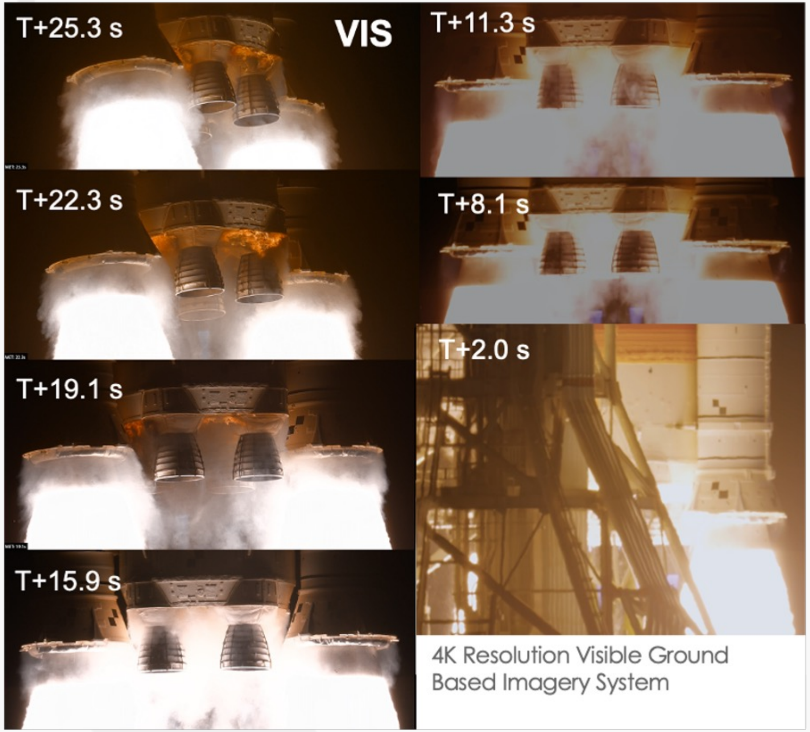




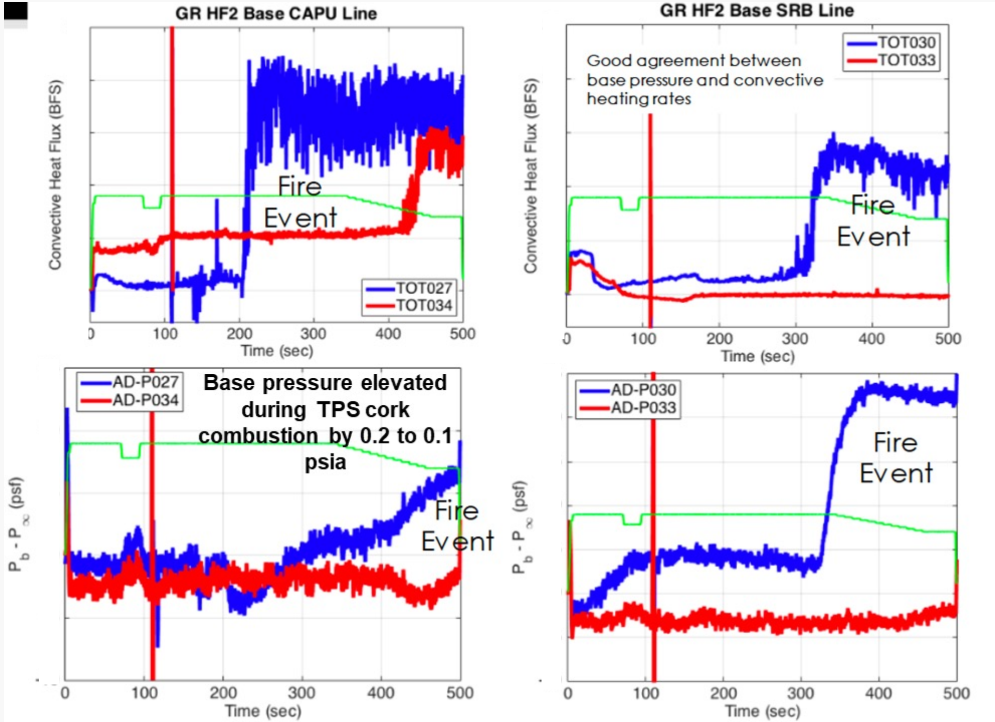




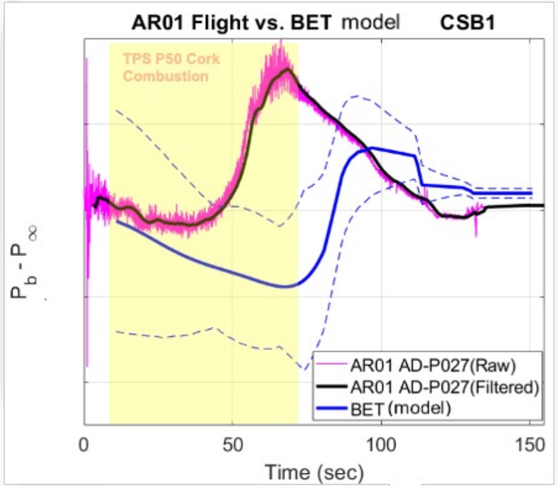
CS Base Aero: TPS Cork Combustion

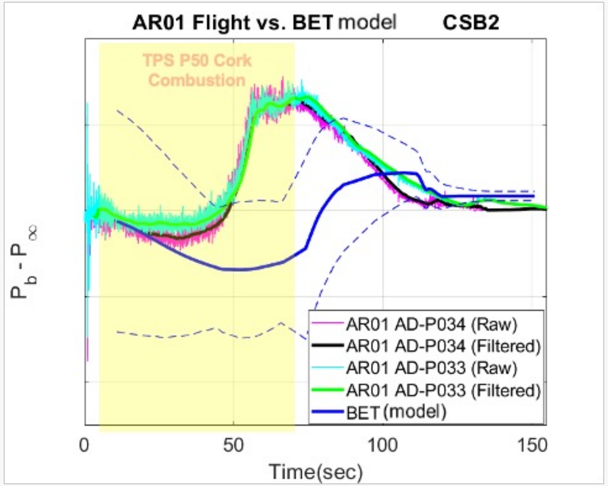


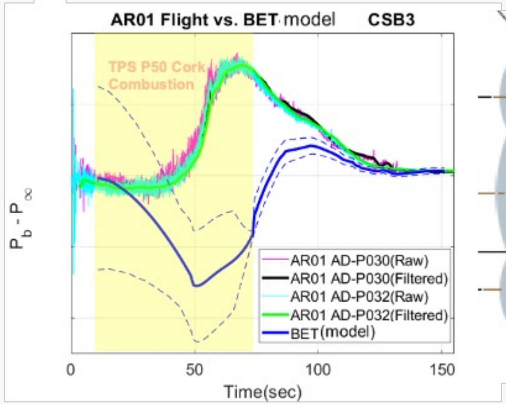
4K Resolution Visible Ground Based Imagery System

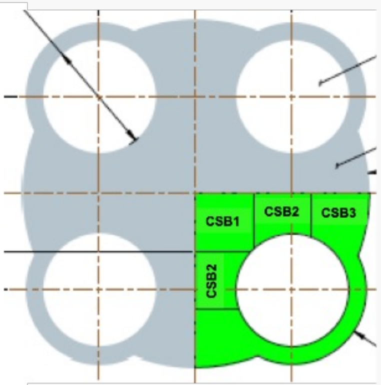


CS Base Aero: BET vs. Post-Flight Data







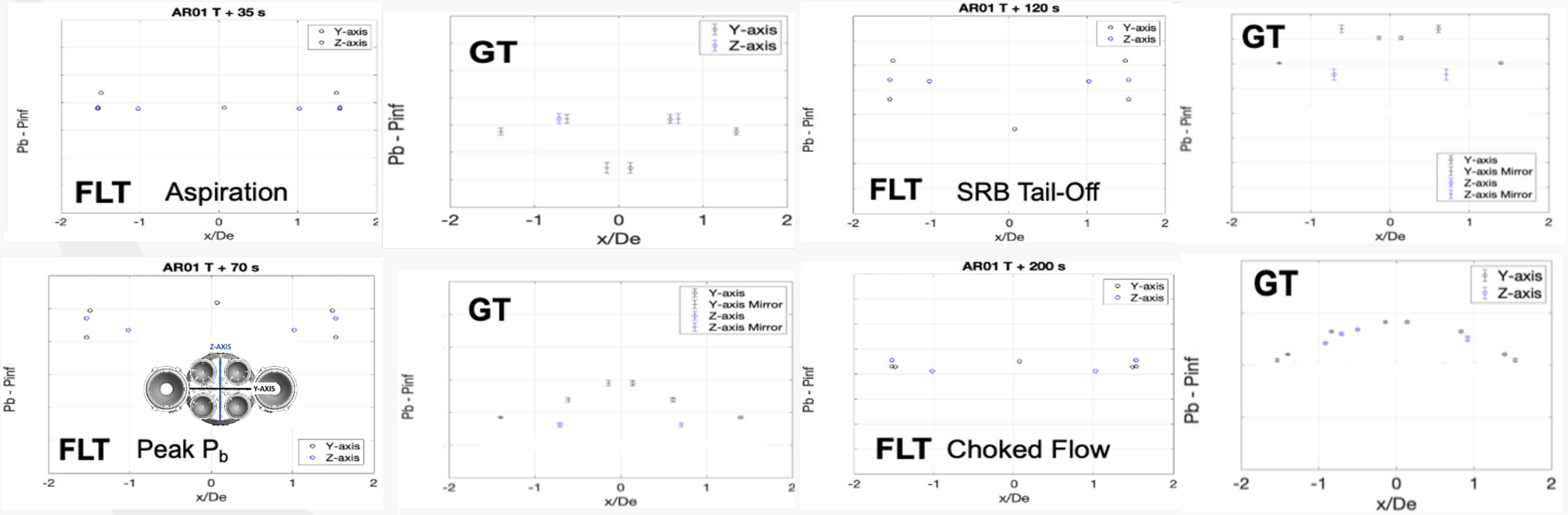


- Observe similar general trends to the pre-flight BET models
- Good agreement in core-only flight
- Base flow transition earlier than predicted by models by ~30 seconds
  - TPS combustion/early RSRMV-RS-25 plume-plume interactions
- Negative base pressure was lower than predicted (bounded)
- Positive base pressure was higher than predicted (not bounded)
  - Especially CSB3 region
- Correction for cork combustion environments at low altitudes may be needed
- EV33 CFD shows better agreement in trends and transition point with reconstructed flight data

CS Base Aero: GT vs. Post-Flight Data

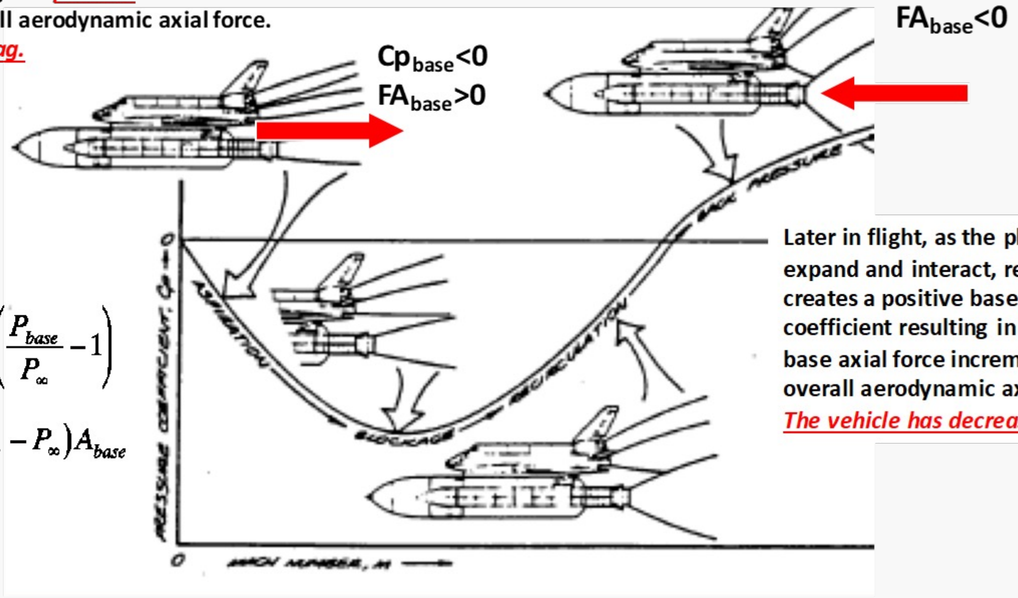
- On average, qualitatively similar spatial distributions between ground test data scaled to flight and AR01 flight reconstructed data for the four base flow regimes

- Notable observations:
  - During peak recirculation, ground test data (GT) shows a Gaussian-like surface pressure distribution where in flight (FLT) the surface pressure is more uniform across the whole base **(this leads to much more significant flight base force loads than the model environment)**
  - Both GT and FLT data show higher surface pressure near the SRB than in the center during SRB thrust tail-off due to plume-plume interactions between the SRB and RS25
  - Both GT and FLT data show normal-like distribution during choke flow regime



Base Force Schematic and Nomenclature

Early in flight, jet pumping creates a negative base pressure coefficient resulting in a ***positive*** base axial force increment to the overall aerodynamic axial force. ***The vehicle has increased drag.***



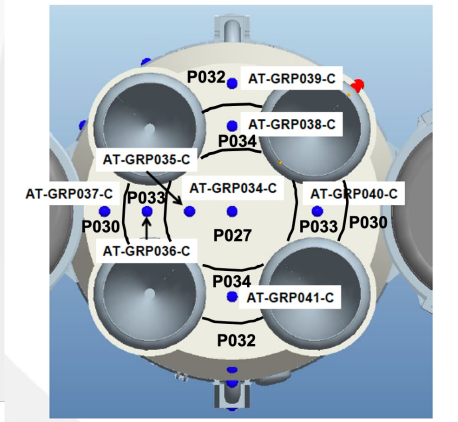
$$Cp_{base} = \frac{2}{\gamma M_\infty^2}\left(\frac{P_{base}}{P_\infty} - 1\right)$$

$$FA_{base} = -\left(P_{base} - P_\infty\right)A_{base}$$

Later in flight, as the plumes expand and interact, recirculation creates a positive base pressure coefficient resulting in a ***negative*** base axial force increment to the overall aerodynamic axial force. ***The vehicle has decreased drag.***

Positive base drag (negative thrust increment) decreases payload mass performance at lower altitudes. Negative base drag (positive thrust increment) increases payload mass performance at higher altitudes.

CS Base Aero: Base Force



$$F_{P032} = -\Delta P_{032} 2A_{032,3} \quad (1)$$

$$F_{P027} = -\Delta P_{027} 4A_{027,1} \quad (2)$$

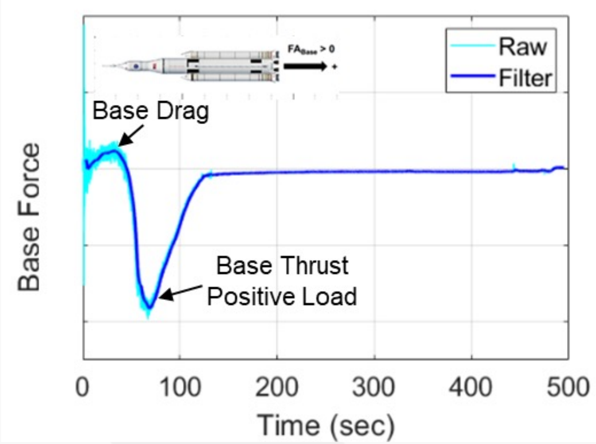
$$F_{P033} = -\Delta P_{033} 4A_{033,2} \quad (3)$$

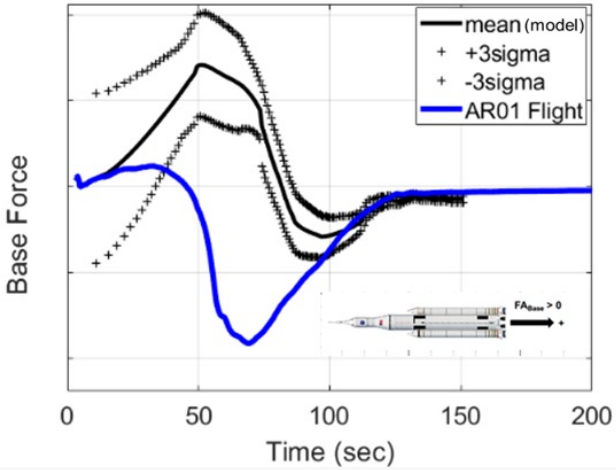
$$F_{P034} = -\Delta P_{034} 4A_{034,2} \quad (4)$$

$$F_{P030} = -\Delta P_{030} 2A_{030,3} \quad (5)$$

(6)

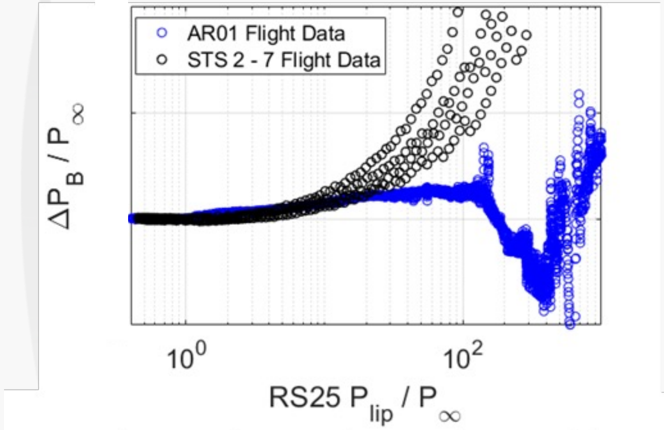
$$F_{CORE} = F_{P032} + F_{P033} + F_{P034} + F_{P027} + F_{P030} \quad (7)$$

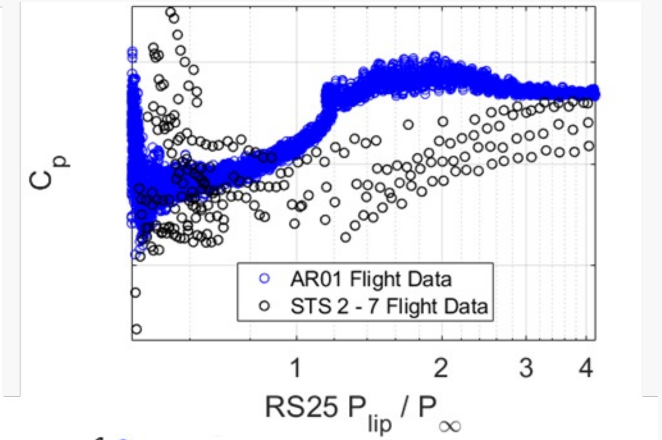


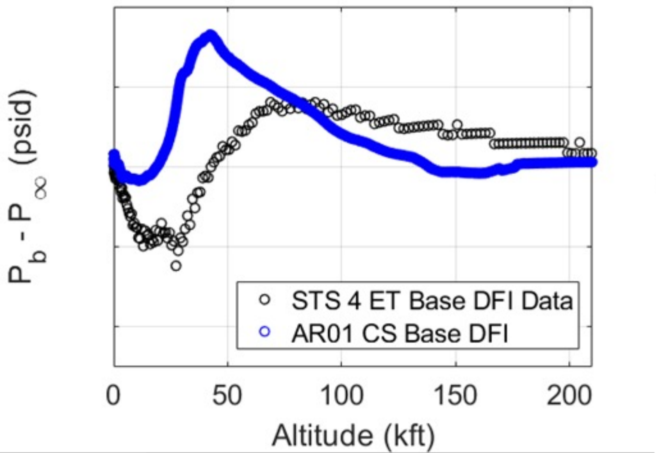


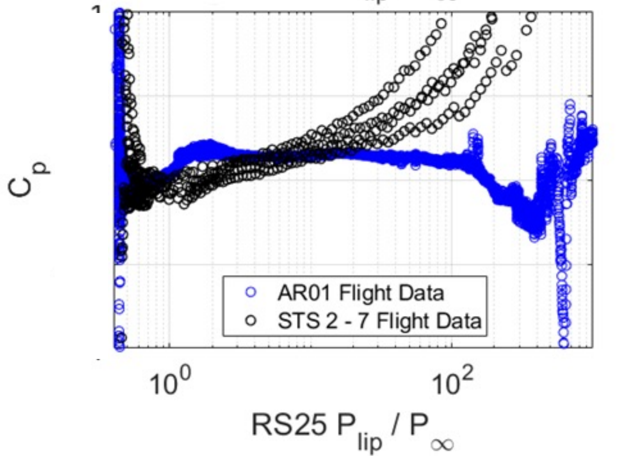
- **General observations**
  - AR01 shows good agreement with BET model between T+0 to T+25 s and T+90 s to T+495 s
  - AR01 transition point occurs at lower altitude(18 kft) and earlier time(T+45 s) for AR01 compared to BET model (60 kft and T+81 s)
  -
  - AR01 peak base force occurs ~30 s earlier as well but amplitude is higher by 3x
  - Good agreement for core-only flight regime

CS Base Aero: SLS vs. STS Comparisons



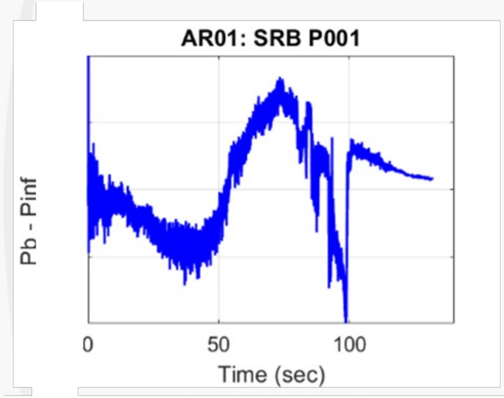


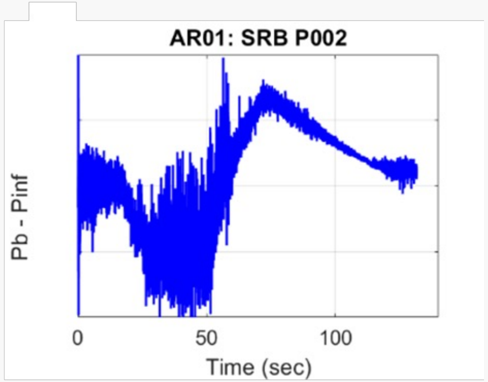


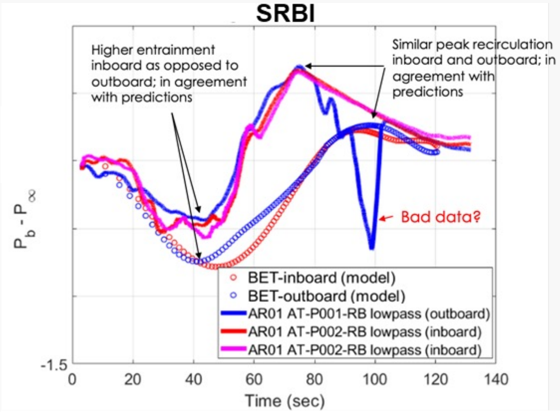


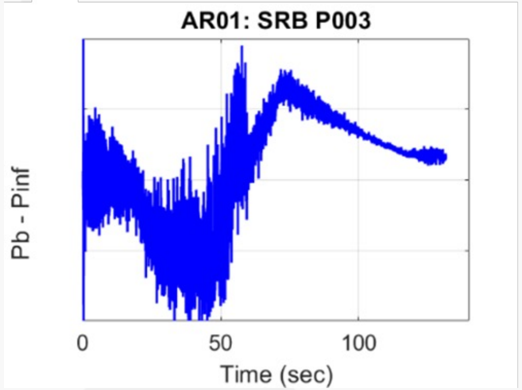
- Earlier peak base pressure on the CS than observed on the STS External Tank
- Higher base pressure (P_b/P_{inf} and C_p) observed on CS than on the ET due to higher number of exhaust plumes in the vicinity of the base

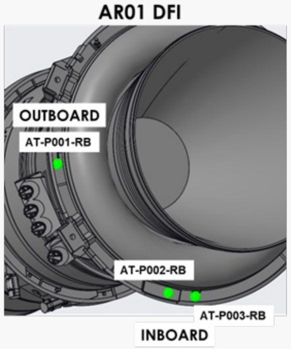
SRB Base Aero: Reduced Raw Pressure Data

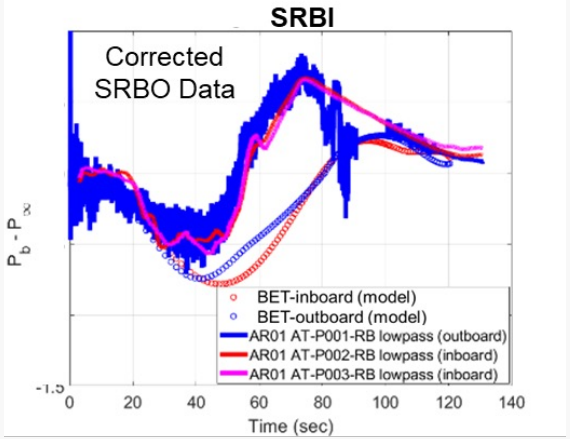




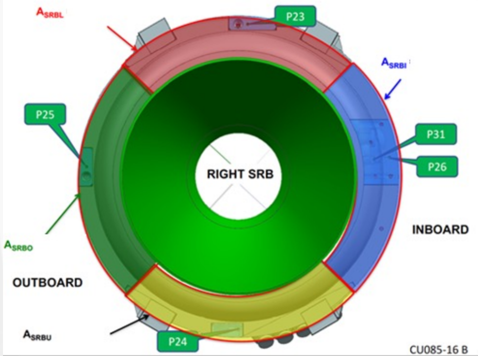








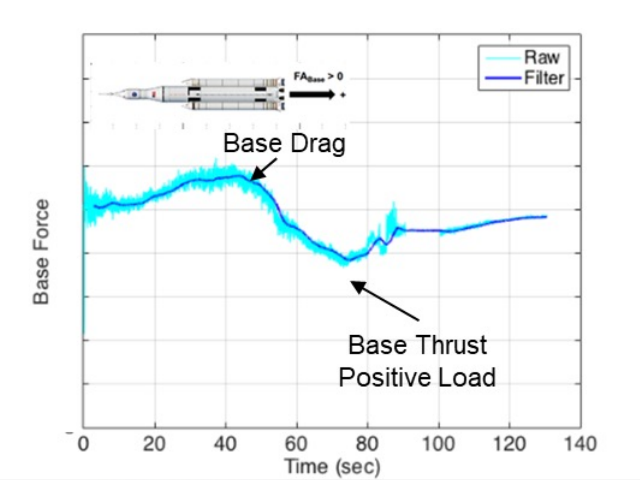
SRB Base Aero: Base Force

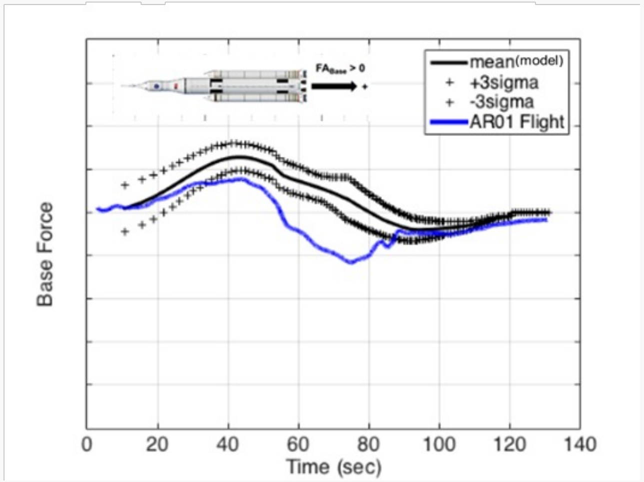


$$F_{P,SRBI} = -0.5(\Delta P_{001} + \Delta P_{002})A_{SRBI} \quad (8)$$

$$F_{P,SRBO} = -\Delta P_{003}\ A_{SRBO} \quad (9)$$

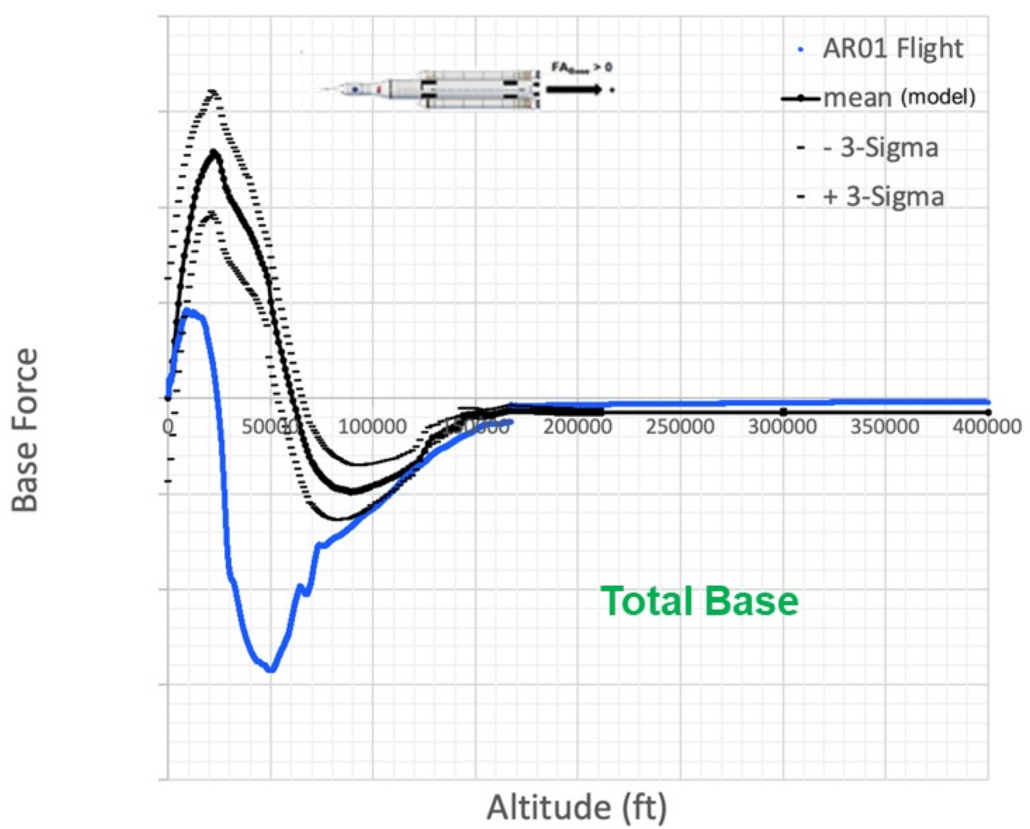
$$F_{SRB} = F_{SRBI} + F_{SRBO} \quad (10)$$





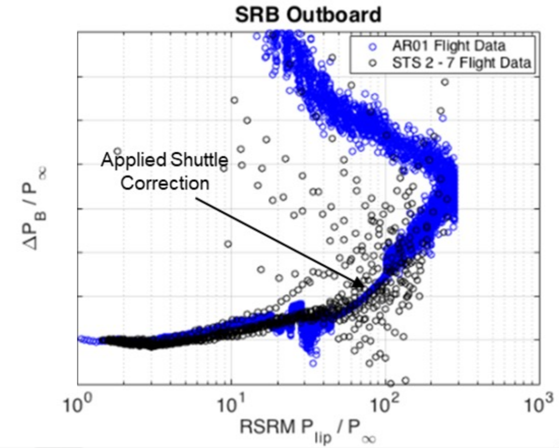
- **Overpredicted drag**
  - AR01 peak drag relatively in family with BET model
  - Optimal from vehicle performance
- **Underpredicted peak base force load**
  - AR01 peak base force load is ~3x the predicted nom value
  - Optimal for vehicle performance

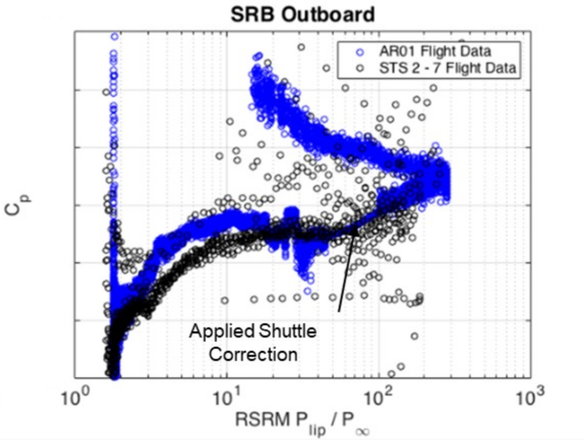
SLS Total Base Force Profile

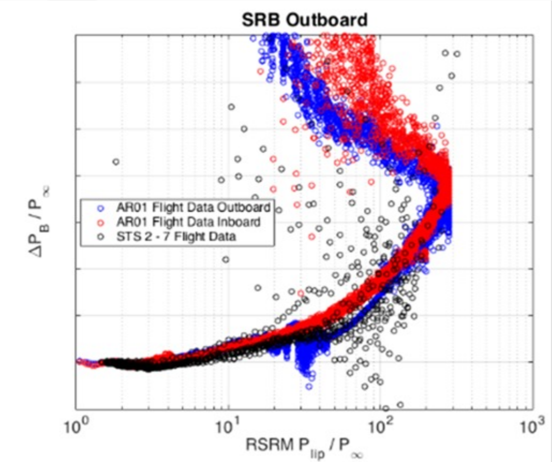


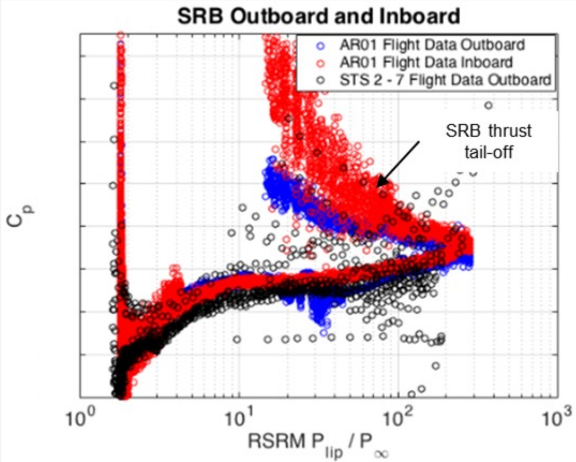
- **Net effect**
  - Preflight database produced overall drag effect and reduction in performance in trajectory simulations
  - Artemis I data shows that base force has an overall “thrust” effect and should result in increased vehicle performance (relative to pre-flight predictions)

SRB Base Aero: SLS vs. STS Comparisons









- General Shuttle SRB outboard (SRBO) data trends are in good agreement with AR01 SRBO base pressure data (prior to thrust tail-off)
- Applied Shuttle correction to AR01 SRBO data where data is circumspect
- Observe higher delta P_b and C_p for the SRB inboard (SRBI) than the SRBO region after base flow transition (most notable after SRB thrust tail-off)
- AR01 SRBI transition on the average occurs at a lower P_{lip}/P_{inf} and freestream Mach number than Shuttle

Conclusions

- CS BHS: Transition point (between aspiration to recirculation) occurs at a lower altitude and earlier time for AR01 reconstructed data compared to the BET models (AR01 CS BHS has transition about 30 seconds earlier than predicted)

- CS BHS: Reconstructed peak heat shield loads (positive thrust) are higher by a factor of 3 compared to prediction (improves performance if loads can be accommodated)

- CS BHS: Good agreement between reconstructed profiles and model environments in base force comparisons with core-only flight regime

- CH BHS: Much less base drag experienced in flight compared to BET model environments (improves vehicle performance)

- SRB base: Reconstructed force and pressure profiles show much better agreement with the BET model environments and more adequately fall within the mean + 3-sigma model environments than observed for the CS base

- SRB base: Less base drag experienced in flight compared to BET model environments, but higher force loads observed during peak recirculation, similar to CS BHS but much smaller effect

Lessons Learned

- Most significant lesson learned is that accurately predicting launch vehicle base environments are challenging and acquiring flight data is seminal to reduce risk related to power-on multi-engine base aerodynamics

- Equally important is to heavily instrument all flight-scale ground test campaigns to investigate these extreme environments prior to flight

- Fully understand the sensitivity of the freestream effects on the base during ascent while performing power-on shock-tunnel and wind-tunnel test programs

- Fully investigate environments through computational approaches and available ground test and flight-scale data