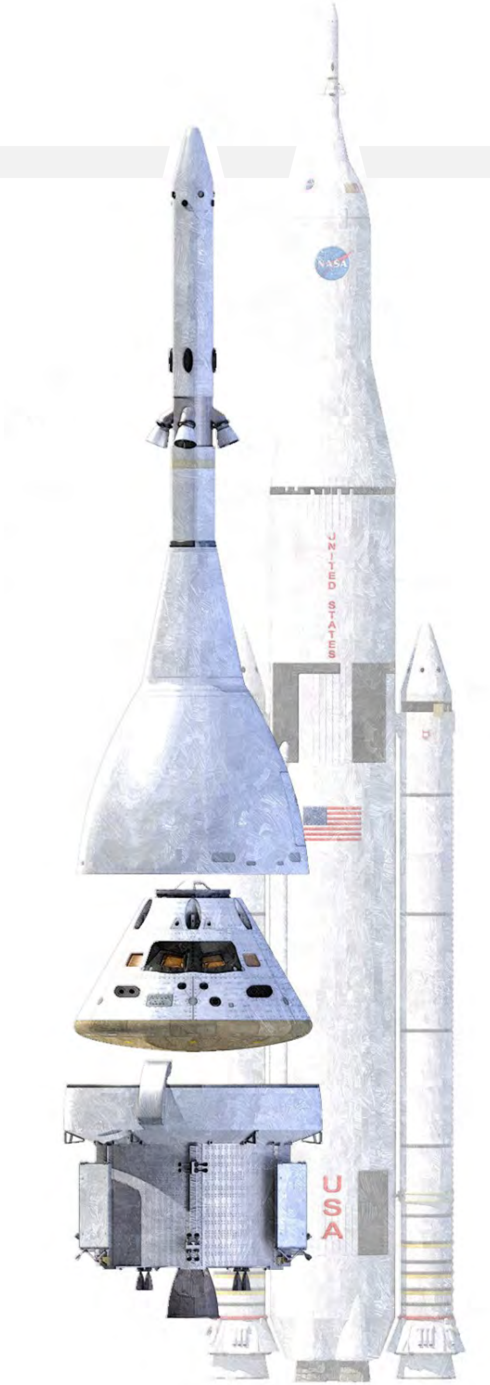


Overview of Orion Aerodynamics: Database Development and Flight Test Comparisons

Karen L. Bibb, *NASA, Langley Research Center*

MPCV Aerosciences, CM Static Aerodynamic Database Technical Lead

15th International Planetary Probe Workshop

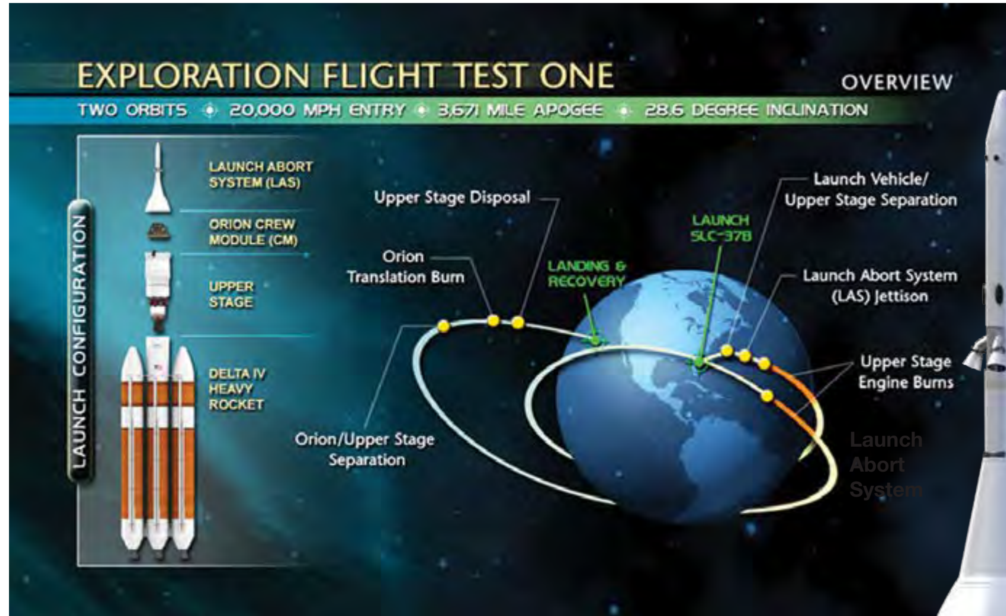
June 11-15, 2018

Why talk about Orion Aerodynamics?

EFT-1 flight test provided a well-instrumented EDL test
- Trajectory reconstruction
- Aerodynamic reconstruction

Orion-like heatshield proposed for 2026 Mars Sample Return Lander mission
- Aerodynamic database design
- Compare and contrast with typical planetary

Orion has three upcoming test flights
- Instrumentation has been modified based on EFT-1 lessons learned

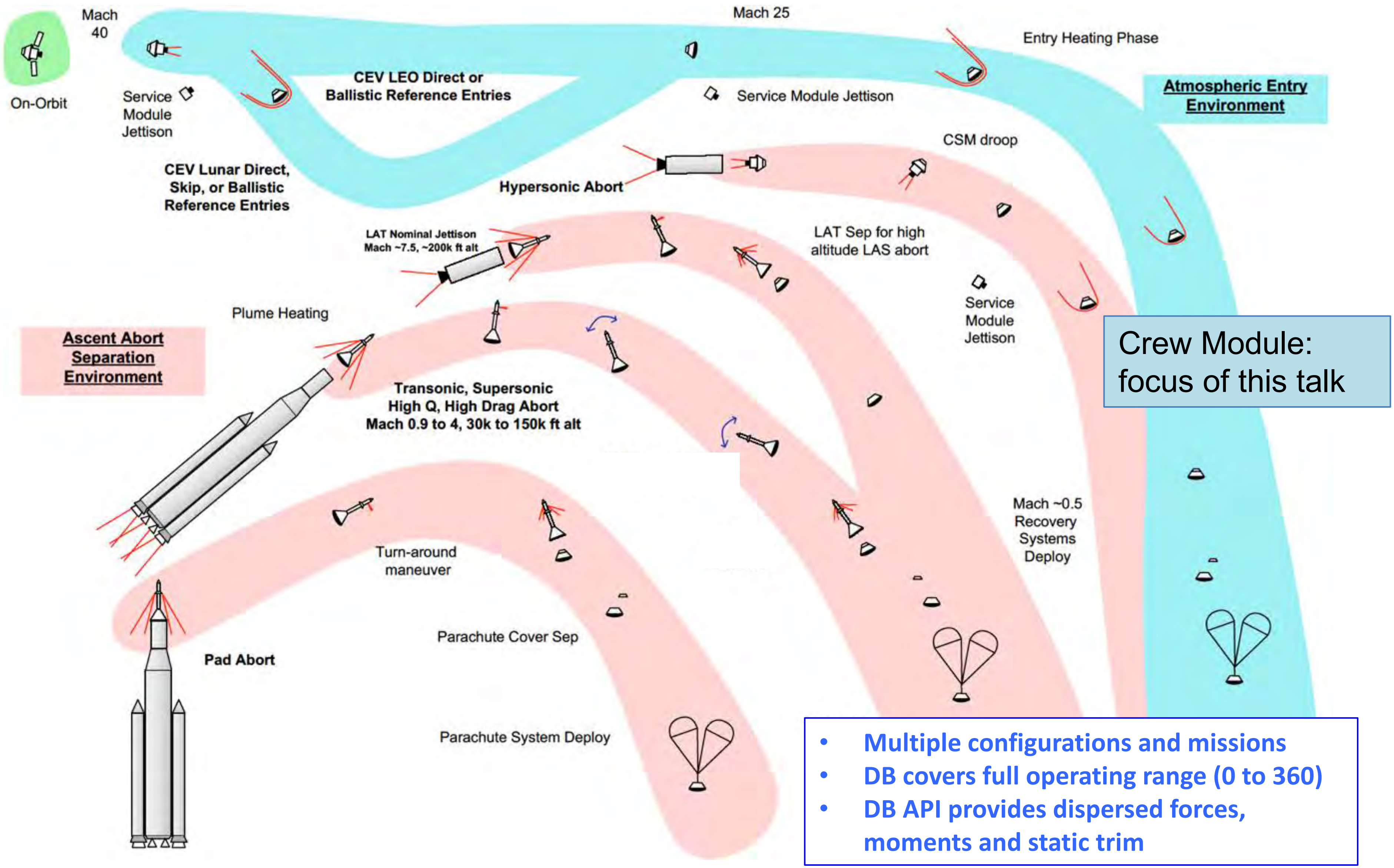


Crew Module Configuration
- 2005 – present
- Orion capsule is Apollo-like
  - Larger diameter, slightly larger backshell angle (30° vs. 32.5°)
  - Apollo heritage data informs some of the dynamic aero uncertainties, but is not used directly for static
- Heatshield design is tailored to heating environment to minimize TPS weight
  - Aerodynamic database versions are for specific heatshield configurations
  - ITAR / EARS restrictions on data with asymmetric heatshield.

Crew Module

Service Module

Orion Aerodynamic Database Overview



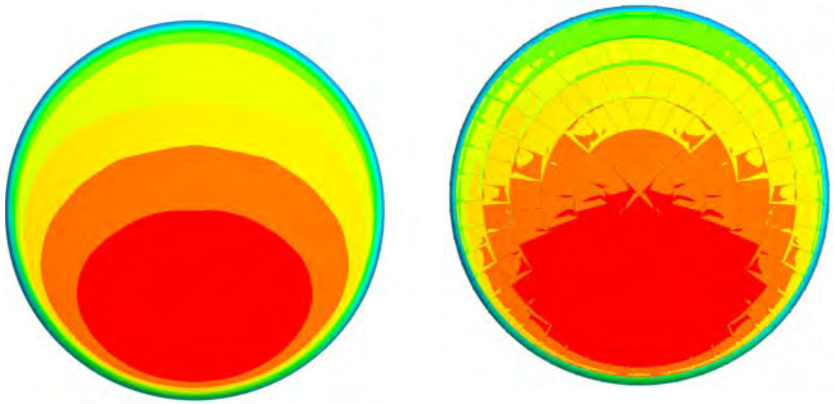
Crew Module: focus of this talk

- Multiple configurations and missions
- DB covers full operating range (0 to 360)
- DB API provides dispersed forces, moments and static trim

Orion Crew Module Aerodatabase

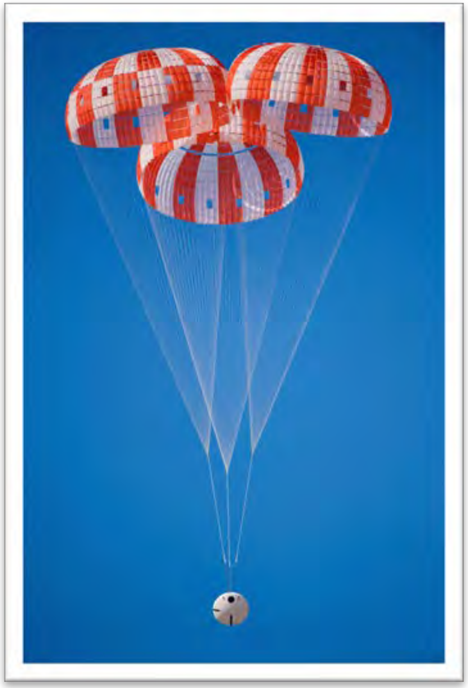
- Developed using computational, wind tunnel, and flight data
  - CFD primary for hypersonic
  - WT primary for subsonic
- Static aero developed in 2 parts
  - Axisymmetric baseline
  - Increment to account for shape changes as program progresses
    - Asymmetric heatshield
    - Recession
- Uncertainty formulation strategy is shared with SLS
  - Built-up from uncertainties in underlying analyses
  - Dispersed as uniform uncertainties
  - Planetary (MSL, etc) uncertainties developed to 'cover' heritage data, and are dispersed as normal distributions.

Current CM Aerodynamic Issues



Block avcoat fence/gap effects

- Subsonic drag increase
- FADS pressure database will need to include localized effects
- Uncertainty in both recessed shape and aerodynamic increment for a given shape
- High Re test (LaRC, NTF) proposed to address subsonic range



Drag damping

- PTV tests show a hysteresis that is not resolved with 'standard' pitch and yaw damping terms
- Investigating inclusion of a C_{Aq} term in aero buildup

Slope uncertainties

- Slope uncertainties for pitching and yawing moments are being implemented
  - Current database only provides 'adder' type uncertainty

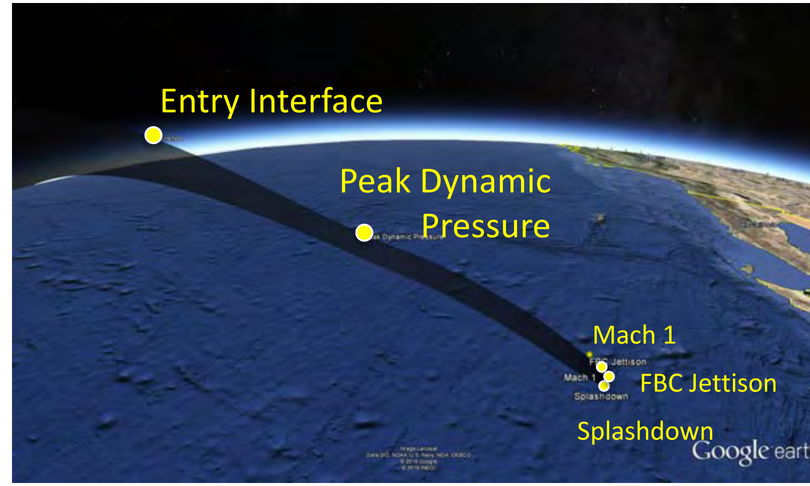
EFT-1 Flight Profile

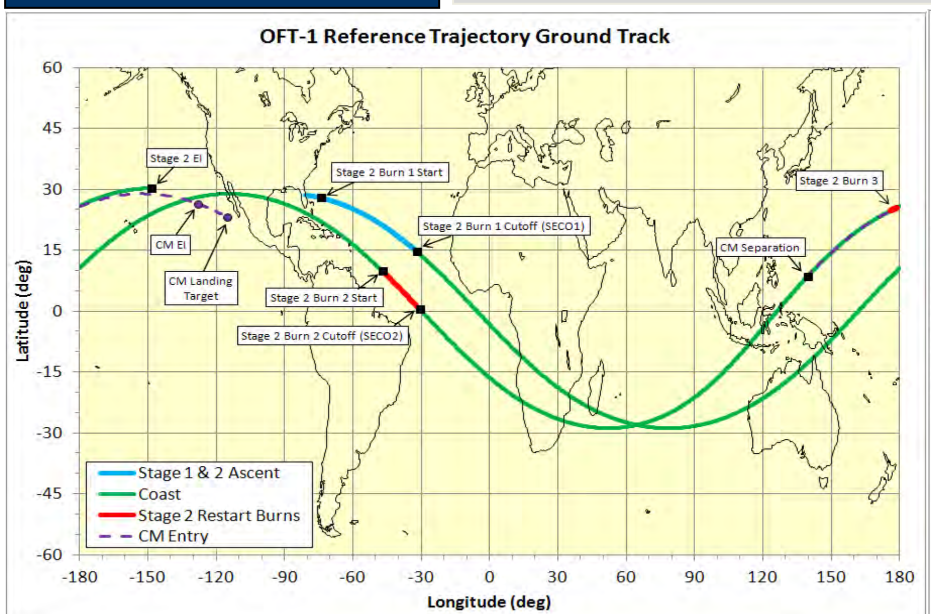
Mission Overview

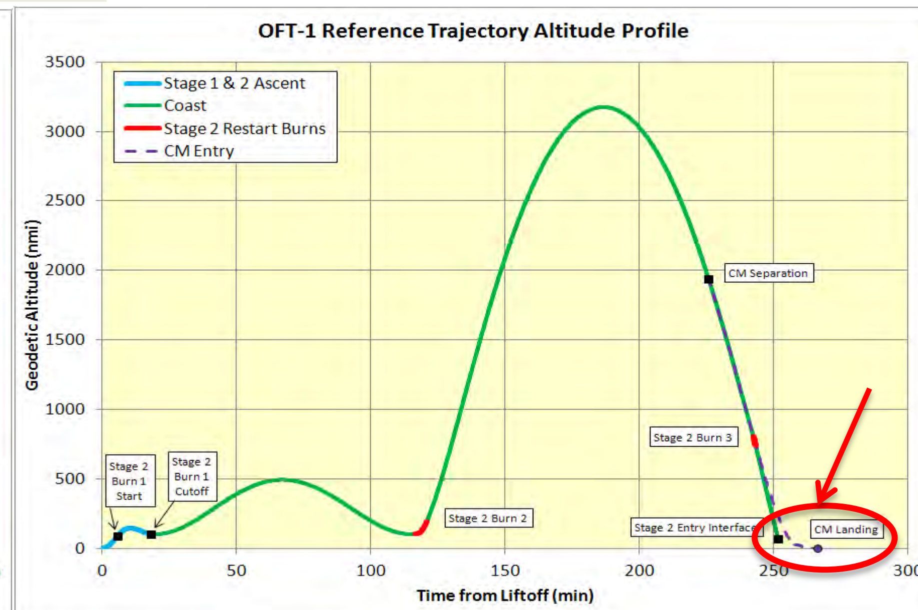
- Launch: 5 December, 2014
- Landing: Pacific Ocean, near Baja peninsula
- Mission duration: 4.4 hrs
- Max altitude: 3,188 nm
- 2 Rev, high energy entry (28kft/s)
- LV controlled flight until CM sep
- On-orbit BBQ roll attitude

Sequence of Events

00:00:00	Launch
00:05:57	SM Fairing Panel jettison
00:06:02	LAS jettison
03:45:42	CM/SM + Stage II separation
03:49:12	CM raise burn
04:15:43	**CM entry interface**
04:21:40	**FBC jettison**
04:21:42	**Drogue Chute Deploy**
04:22:38	**Main Chute Deploy**
04:25:51	**Landing**
04:40:51	Vehicle Safing Complete

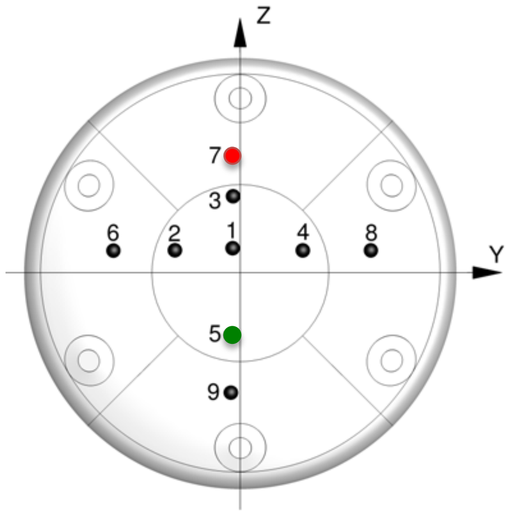


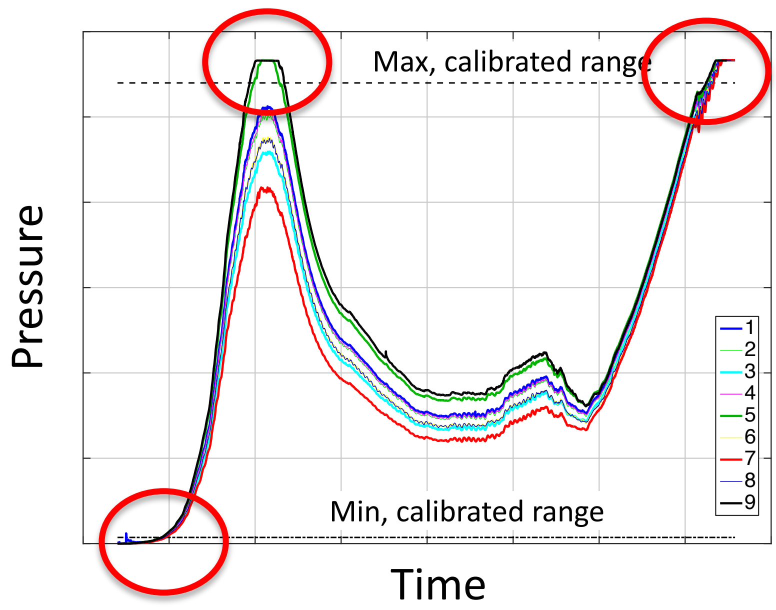




Flight test data

- Aerosciences DFI sensors (342 total/338 with usable data)
  - **9 FADS ports**
    - Honeywell PPTs,
      - Calibrated to measure between 0.1 psia and 7.5 psia
      - Data unreliable outside of range
    - Data rate expected to be 46.5Hz, was actually 23.25Hz
  - 33 Kulite pressures on backshell
  - Thermocouples and radiometers
- Trajectory development data
  - navBET inertial reconstruction (Kalman filter/FreeFlyer)
    - IMU, gyros for attitude, rates, accelerations
    - GPS, radar for additional positioning
  - Additional data provided in navBET
    - GRAM, balloon data, initial FADS density for atmosphere
    - RCS firing history
    - Pre-flight mass, inertias





aeroBET Development

- **navBET**
  - Program developed BET
  - Core: inertial reconstruction
  - Additional: discipline-specific data
- **FADS Methodology**
  - Fits pressure data to calibration database (CFD) using least squares methods
  - Similar to MSL / MEADS methodology
- **aeroBET** - Aerosciences developed BET
  - Replaced aerodynamic data in navBET with FADS-derived data
    - Consistent set of atmospheric variables
    - Vehicle attitude (α, β)
    - Winds and Mach number between Mach ~1 and drogue deploy
  - Used aeroBET for aerodynamic and aerothermal analysis of EFT-1 flight data

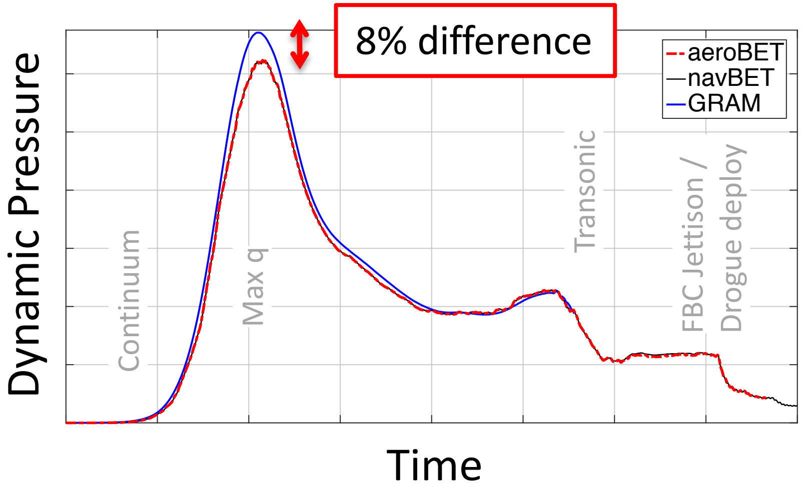
Flight data required for aerodynamic reconstruction and comparisons to predictions

Trajectory Parameter	navBET	aeroBET
planet-relative velocity	✓	
linear acceleration (a_x, a_y, a_z)	✓	
angular rate, $\omega = \{p, q, r\}^T$	✓	
angular acceleration, $\dot{\omega} = \{\dot{p}, \dot{q}, \dot{r}\}^T$	✓	
temperature (T_∞)	✓	✓
α, β	✓	✓
density (ρ)	✓	✓
dynamic, static pressure $(\bar{q},\ P_\infty)$	✓	✓
wind velocity	✓	✓
freestream velocity (V_∞)	✓	✓
Mach number (M)	✓	✓
mass, c.g. location, moments of inertia	✓	
RCS firing history	✓	

aeroBET / FADS Improvements to navBET

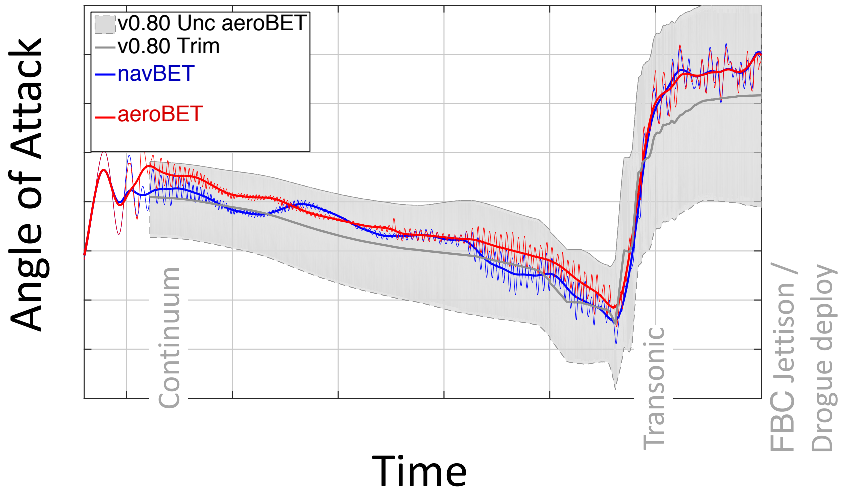
Final navBET replaced density derived from GRAM with density from the FADS analysis, from near entry down to near Mach 1

- FADS analysis provided significant improvement over initial GRAM estimate of density (as seen in dynamic pressure)
  - GRAM differences are ~8% at t=105s, ~50 psf.



(α, β) from the navBET show a long-period oscillation through hypersonic range, relative to the aeroBET.

- Oscillation correlates with bank angle
  - Suggests error in transformation from IMU-based planet-relative orientation to (α, β).
  - Efforts to uncover source were unsuccessful
- Maximum difference of ~1.0° in α
- α_{trim} for navBET does not follow expected monotonic decrease with decreasing Mach number
  - Trim angle change with Mach number is rooted in the 'real gas effects' seen at hypersonic speeds



Aerodynamic Reconstruction and Database Comparisons

Reconstructed aerodynamic coefficients

- Force and moment coefficients are reconstructed from accelerometer data, angular rate and acceleration data (navBET), with mass properties (navBET) and dynamic pressure (aeroBET)

$$\begin{Bmatrix} C_A \\ C_Y \\ C_N \end{Bmatrix} = \frac{m}{S\bar{q}} \begin{Bmatrix} -a_x \\ a_y \\ -a_z \end{Bmatrix}$$

$$\begin{Bmatrix} C_l \\ C_m \\ C_n \end{Bmatrix} = \frac{I\dot{\omega} + \omega \times I\omega}{SL\bar{q}}$$

Orion aerodatabase coefficients

- Trajectory parameters (aeroBET) used to query v0.80 Orion Aerodynamic Database
  - Angle of attack, angle of sideslip
  - Mach, velocity, c.g. location
  - Angular rates (for dynamic damping terms)

$$C_{A,Y,N} = f(M, V_\infty, \alpha, \beta)$$

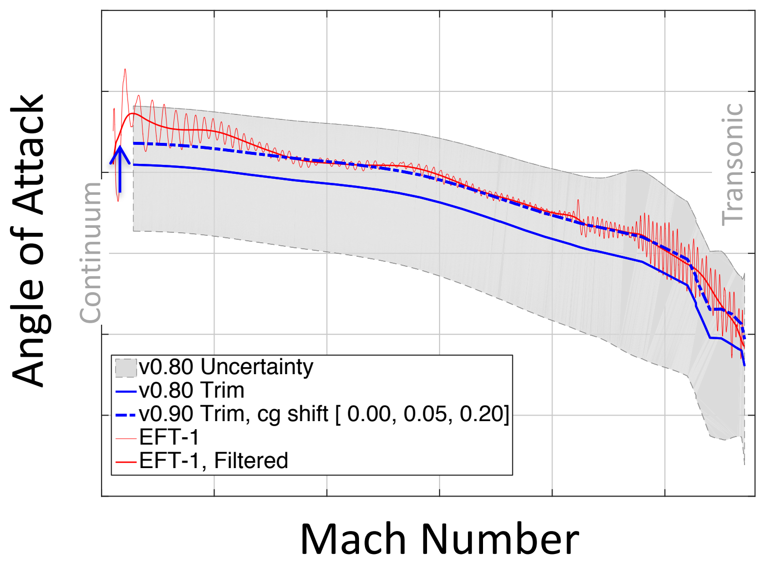
$$C_{l,m,n} = f(M, V_\infty, \alpha, \beta, cg, \omega)$$

$$\alpha_{trim}, \beta_{trim} = f(M, V_\infty, cg)$$

EFT-1 Comparisons to Aerodatabase

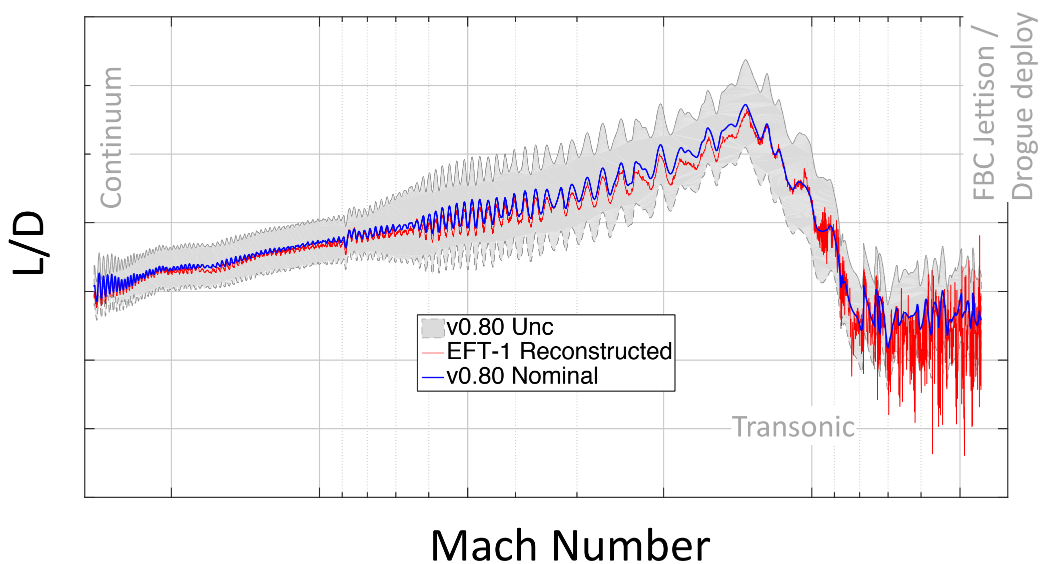
Trim angle shift likely due to c.g. shift

- Predicted trim (α, β) from ADB API compared to aeroBET
  - f(M, V_∞, c.g.)
  - navBET provides discrete changes in c.g. location, mass properties.
- Vehicle oscillated about a trim angle in flight
  - Seen in pitch, yaw moment reconstructions
- Adjustment in c.g. location of (0in,0.05in, 0.2in) provides reasonable trim agreement in hypersonic range
  - Well within c.g. location uncertainties of +/- 0.4in



Lift-to-Drag Ratio

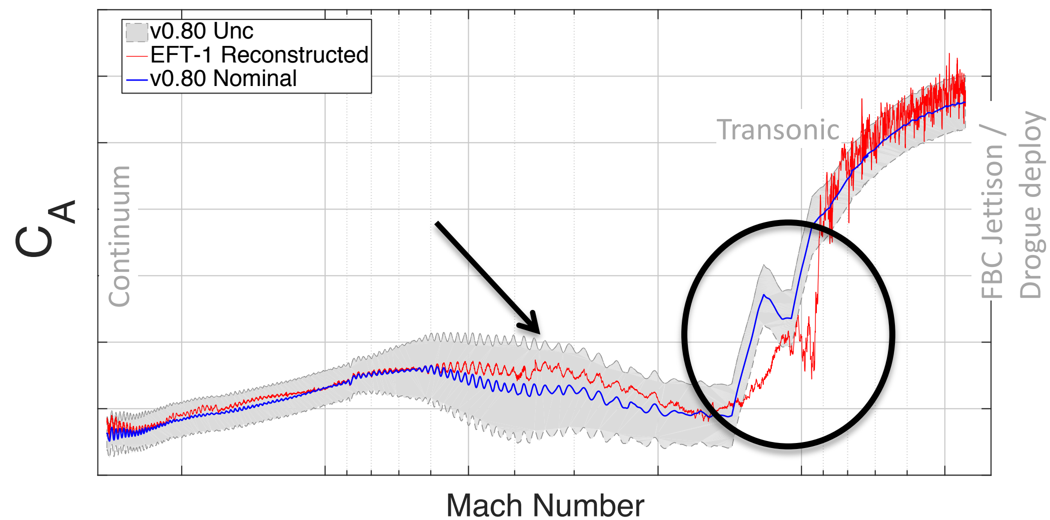
- L/D differences are well within ADB uncertainties for most of flight.
  - Largest differences in subsonic regime
  - Dynamic variation in subsonic regime is outside uncertainties
- L/D comparison is independent of qbar, but not (α, β)



EFT-1 Comparisons to Aerodatabase

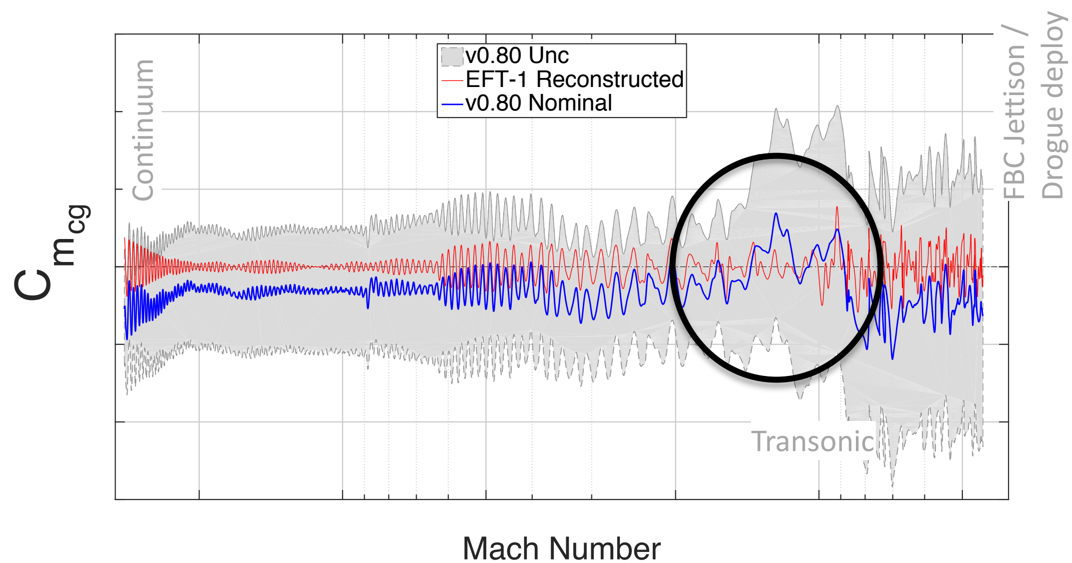
Axial Force

- C_A, C_D are the only coefficients that are outside ADB uncertainties.
  - Transonic range only
  - Due primarily to sparse Mach number coverage coupled with steep gradients
- ADB adjusted to cover flight data (v0.90 and v0.92 updates)
- Supersonic range (6 ≤ FMV ≤ 1.6) shows some divergence in C_A, C_D, but within database uncertainties



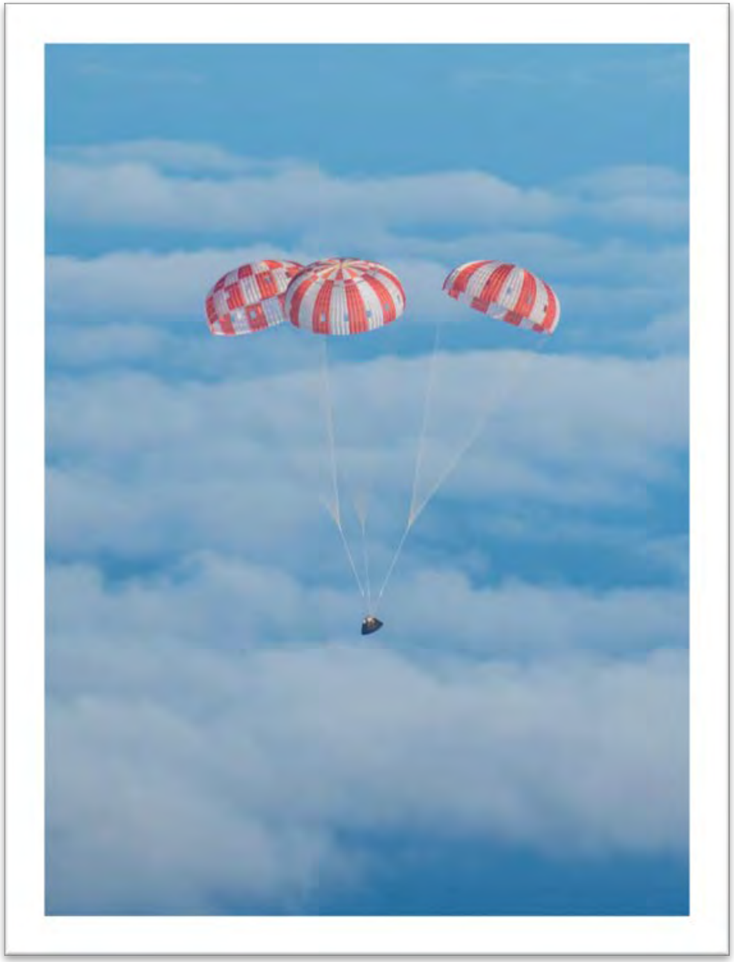
Pitching Moment

- Flight pitching moment is within database uncertainties for entire flight
- Predicted C_{mcg} closer to flight when 0.2 in shift in z_{cg} is applied.
- Nominal ADB values were adjusted in the transonic region for v0.90, and are now more 'in family' with supersonic and subsonic C_{mcg}

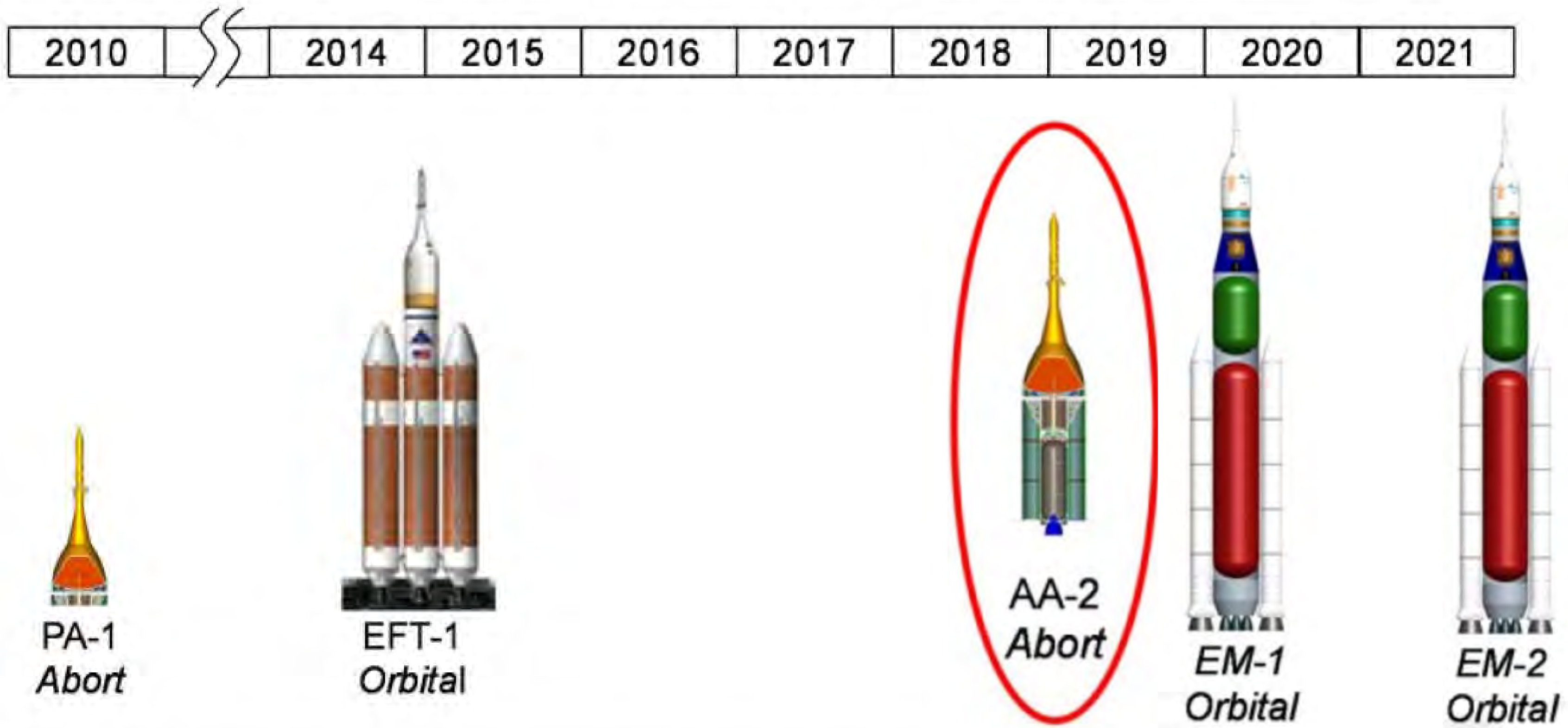


EFT-1 Comparison summary

- **Hypersonic trimmed L/D (function of α_{trim}) predicted very well.**
  - primary driver of downrange targeting
  - landed within 1.53nm of target (0.6nm before chutes deployed)
- **OVERALL vehicle performance was within the predicted ADB uncertainty over the broad range of continuum flight**
  - Flown angles of attack and sideslip were within expectations
    - Shift in c.g. location improves trim comparisons
  - Aerodynamic coefficients were generally within expectations
    - Comparisons with ADB were outside uncertainties for 1.4>M>0.8
- No strong RCS jet interaction was observed (or expected)
- **MPCV Orion ADB was updated for M<1.6 to account for flight data.**

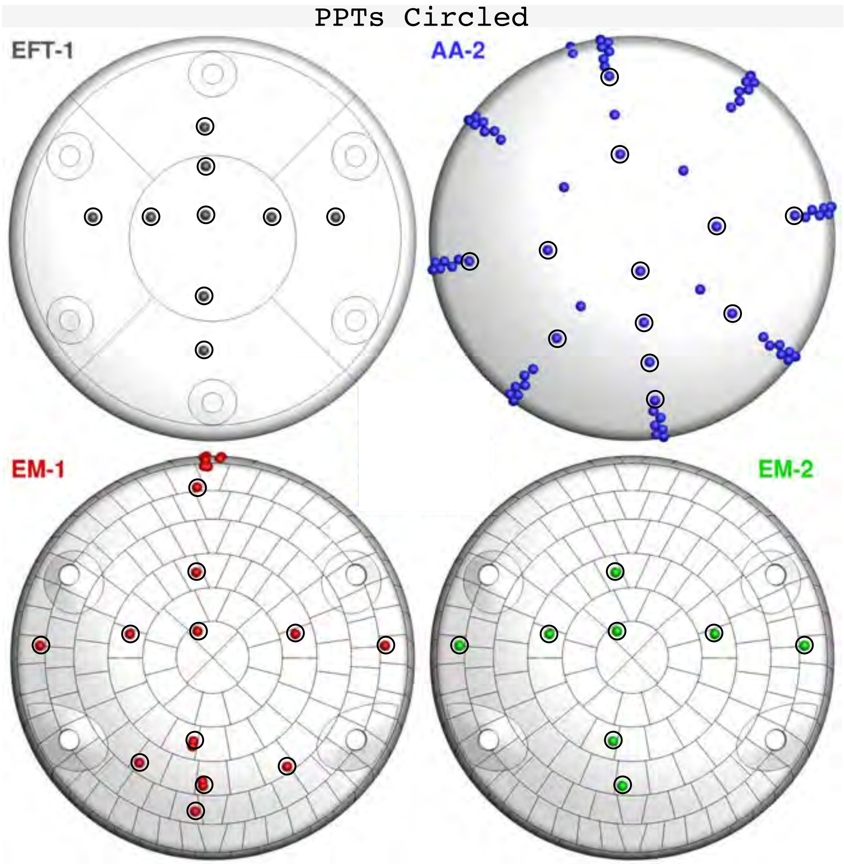


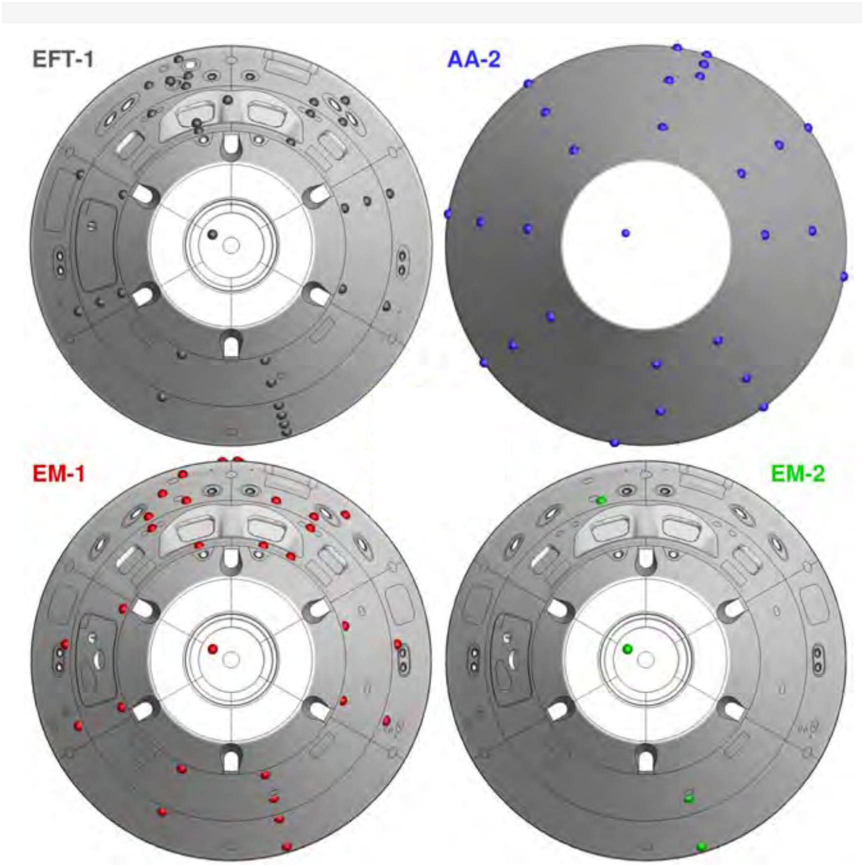
ESD Developmental Flight Test Program



PA-1	Pad Abort 1	Launch Pad Abort	May 6, 2010
EFT-1	Exploration Flight Test 1	LEO Return	Dec 5, 2014
AA-2	Ascent Abort 2	Transonic Abort	Apr 2019
EM-1	Exploration Mission 1	Un-crewed DRO	2019 / 2020
EM-2	Exploration Mission 2	Crewed Circumlunar	~2022

Pressure port layouts / aerosciences data





- AA-2 and EM-1 have improved pressure instrumentation
  - Additional FADS ports
  - Shoulder taps
  - Multiple calibration ranges

- EM-2 (and beyond) is expected to have significantly reduced instrumentation

Wrap-up

- Aerodynamics for the Orion Crew Module are well characterized with reasonable uncertainties
  - Database API provides consistent application of database
  - **Key differences with planetary aerodatabases: scope, uncertainty formulation**
- EFT-1 flight test provided general validation of database for a nominal entry
  - FADS-based aeroBET & aero reconstruction developed by Orion aerosciences
  - **Generally good agreement with database, except in transonic regime**
  - Aerodatabase adjusted accordingly.
- Upcoming flight tests will provide further aerosciences validation
  - **AA-2 abort test, focus on CM dynamics**
  - **EM-1, high heating 10.5km/s earth entry**
  - EM-2 and beyond will have limited aerosciences data (primarily FADS)

- Orion heatshield, aero, and database approach are being utilized by other programs
  - Boeing Commercial Crew vehicle is similar in shape and utilized Orion aerodatabase as a starting point.
  - **Mars 2026 (Sample Return Lander) is planning on a spherical heatshield (Orion-like) instead of traditional 70° sphere/cone.**

Bibliography

- Program docs
  - MPCV-72167 Orion Aerodynamics Databook
  - NASA-EG-CAP-13-21 Orion MPCV Aerodynamic Substantiation Report
  - NASA-EG-CAP-06-37 Formulation of the Orion MPCV Aerodynamic Database
  - Aerothermal Substantiation Report
- AIAA Applied Aerodynamics, 2011. 3 sessions
  - Papers on wind tunnel test data, CFD simulations, dynamic aero, uncertainty quantification
  - Development of the Orion Crew Module Static Aerodynamic Database
    - Part I: Hypersonic, AIAA-2011-3506
    - Part II: Supersonic/Subsonic, AIAA-2011-3507
- AIAA AVIATION 2016 (**ITAR**): EFT-1 results, 4 sessions
  - FADS BET development (AIAA-2016-3989), Aerodynamic reconstruction comparisons (AIAA-2016-3989)
  - Aerothermal comparisons and TPS analysis

Orion Aerodatabase

- Key database features
  - Covers large range of missions for multiple configurations
    - **CM entry (CM: FBC-on, FBC-off)**
    - Aborts (LAV, LAS/LAT, CM jettison)
    - On-orbit
  - Full operating range provided
    - $0° \leq \alpha \leq 360°$, $-90° \leq \beta \leq 90°$
    - Higher fidelity over typical operating range
  - ADB does NOT provide
    - RCS thrust or interaction
    - Parachute loads
  - Developed using computational, wind tunnel, and flight data
  - Uncertainty formulation strategy is shared with SLS
    - Built-up from uncertainties in underlying analyses
    - Dispersed as uniform uncertainties

- Provided to customers (GNC, etc) as an API
  - User provided interface module sets parameters (Mach, alpha, beta, …), calls the getCevAero() function, and retrieves the aero coefficients
    - Mach, alpha, beta, thrust level for aborts, etc.
    - Uncertainty factors (UF) for each coefficient
  - API returns
    - Dispersed forces and moments, coefficients and dimensional
      - UF=0 for nominal
    - Static trim (α, β) as a function of Mach number and c.g. location
  - Database tables initialize API to provide aerodynamic coefficients, uncertainties
    - 170+ tables (654Mb) currently (up to 7-dimensions)
      - 49 CM specific
    - Allows for database to be easily updated
    - All interpolation in table is linear
  - Coded in C, Matlab interface available

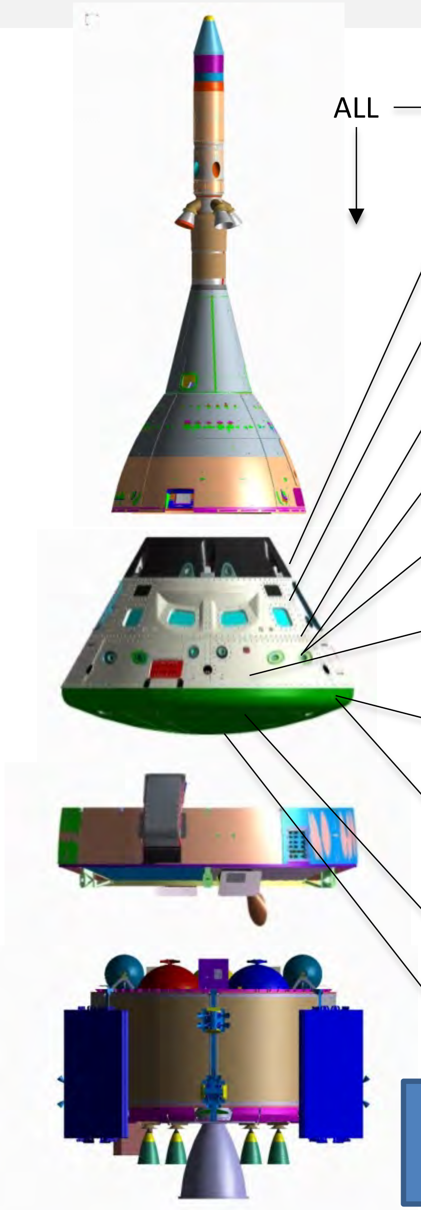
aeroBET Development

- Program developed BET (navBET)
  - Kalman filter inertial reconstruction
    - FreeFlyer COTS software
    - Position, rates, and accelerations
  - 'Discipline' related data added as post-processing step
    - Wind relative attitude (α, β)
    - Atmosphere (density, dynamic pressure, winds)
      - from GRAM, balloon data, and FADS
    - Mass properties (pre-flight), RCS firing
  - Full Kalman-filtered type BET not developed using FADS data
- FADS Methodology
  - Fits pressure data to calibration database (CFD) using least squares methods
  - Variations in methodology required for different segments of the trajectory
    - 4-parameter $(\alpha, \beta, \bar{q}, P_\infty)$
    - 3-parameter $(\alpha, \beta, \bar{q})$
    - CFD look-up (ρ)
- Aerosciences developed BET (aeroBET)
  - Replaced aerodynamic data in navBET with FADS-derived data
    - Consistent set of atmospheric variables
    - Vehicle attitude (α, β)
    - Winds and Mach number between t=287 and drogue deploy
  - Used aeroBET for aerodynamic and aerothermal analysis of EFT-1 flight data

Flight data required for aerodynamic reconstruction and comparisons to predictions

Trajectory Parameter	navBET	aeroBET
planet-relative velocity	✓	
linear acceleration (a_x, a_y, a_z)	✓	
angular rate, $\omega = \{p, q, r\}^T$	✓	
angular acceleration, $\dot{\omega} = \{\dot{p}, \dot{q}, \dot{r}\}^T$	✓	
temperature (T_∞)	✓	✓
α, β	✓	✓
density (ρ)	✓	✓
dynamic, static pressure $(\bar{q}, P_\infty)$	✓	✓
wind velocity	✓	✓
freestream velocity (V_∞)	✓	✓
Mach number (M)	✓	✓
mass, c.g. location, moments of inertia	✓	
RCS firing history	✓	

EM Vehicle Design Benefits from EFT-1 Flight Data



Change	Benefit
Update loads models & reduce uncertainties	Lower loads & environments
Reduced heating in LAS wells	Mitigate risk of needing to add Avcoat
Updated backshell transition model (later transition)	**Lower heating, reduced tile thickness, mitigate FBC/Panel C Avcoat risk**
Implemented RCG tile surface catalysis model	**Lower heating, reduced tile thickness, mitigate FBC/Panel C Avcoat risk**
CM RCS Cat Bed temp model	Reduced thruster pulse count
Lower separated backshell heating	Reducing risk of exceeding tile temp limits due to RCS JI
Updated GPS & BALT models	Improved performance, deletion of velocity trigger backup
Reduced hypersonic static & dynamic stability uncertainties	Lower prop consumption
Increased CM damping (30-50% slower roll rate ramp-up) while under chutes	**Lower prop consumption, improved HSIR performance (e.g., cross-coupled rotational accel)**
Updated heat shield transition model (later transition)	Reduced Avcoat mass
Updated CM/SM sep model	Lower prop consumption (4-5 lb)

Performance benefits of Aeroscience databases implemented in time to impact CDR in Fall 2015 – direct link to DFI being flown on AA-2, EM-1 and EM-2

AA-2 Flight Test Trajectory & Events

<u>Event</u> <u>Description</u>

1. ATB ignites.
   Vehicle departs on eastward trajectory.
   ATB boosts the FTA to the test condition.

2. Test Condition is reached.
   ATB sends signals to the FTA.
   CM triggers the abort event.
   CM sends signals to ignite LAS AM and ACM.
   CM separates from SR.
   LAS propels CM away from ATB.

3. LAS AM burns out.
   CM/LAS continue coasting to apogee.
   While coasting, ACM reorients CM heat-shield forward.

4. CM/LAS reorientation is completed.

5. CM sends signals to ignite LAS JM.
   CM separates the LAS from the CM.
   LAS is jettisoned away from the CM.

6. ATB, LAS, and CM free-fall into the ocean.
   Flight Test is completed.

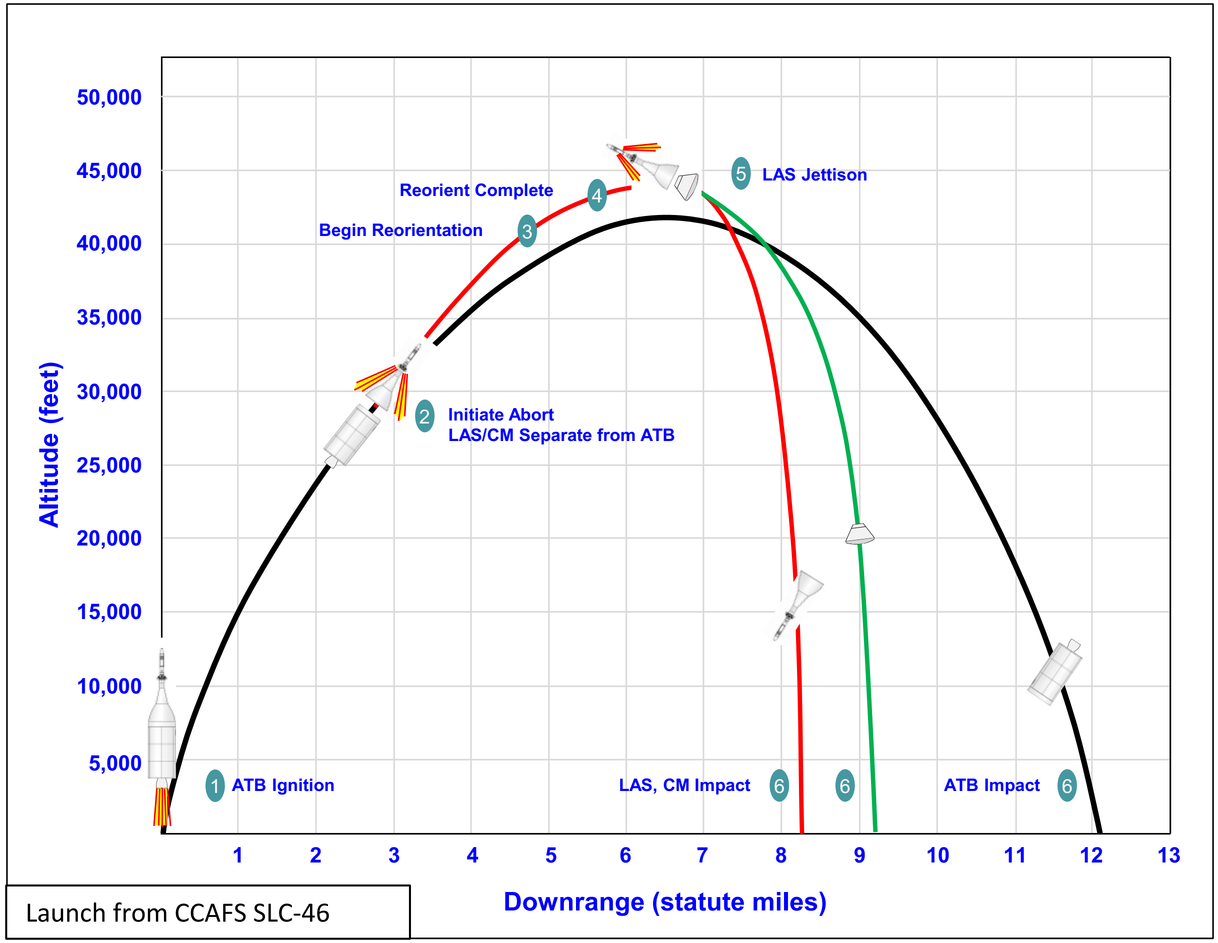
No planned recovery. Will dispose of items that are hazards to marine navigation.

MPCV 72465
BASELINE
RELEASE DATE: JUNE 4, 2013

TABLE 3.2-1 - ASCENT ABORT 2 TEST CONDITIONS

AA Test Conditions	Parameter
Dynamic Pressure (psl)	650 +30/-50
Mach Number	1.15 +0.1/-0.05
Total Angle of Attack (deg)	Less than 4°, targeting 1°
Body Lateral Rate (deg/sec) = RSS(q,r)	Nominal ± 1.0
Axial Acceleration (g)	0.0 - 1.8
Flight Path Elevation (deg)	>0.0

AA-2 demonstrates that Orion's Launch Abort System (LAS) can safely separate and maneuver the Crew Module (CM) away from a launch vehicle during an abort in near-transonic conditions.



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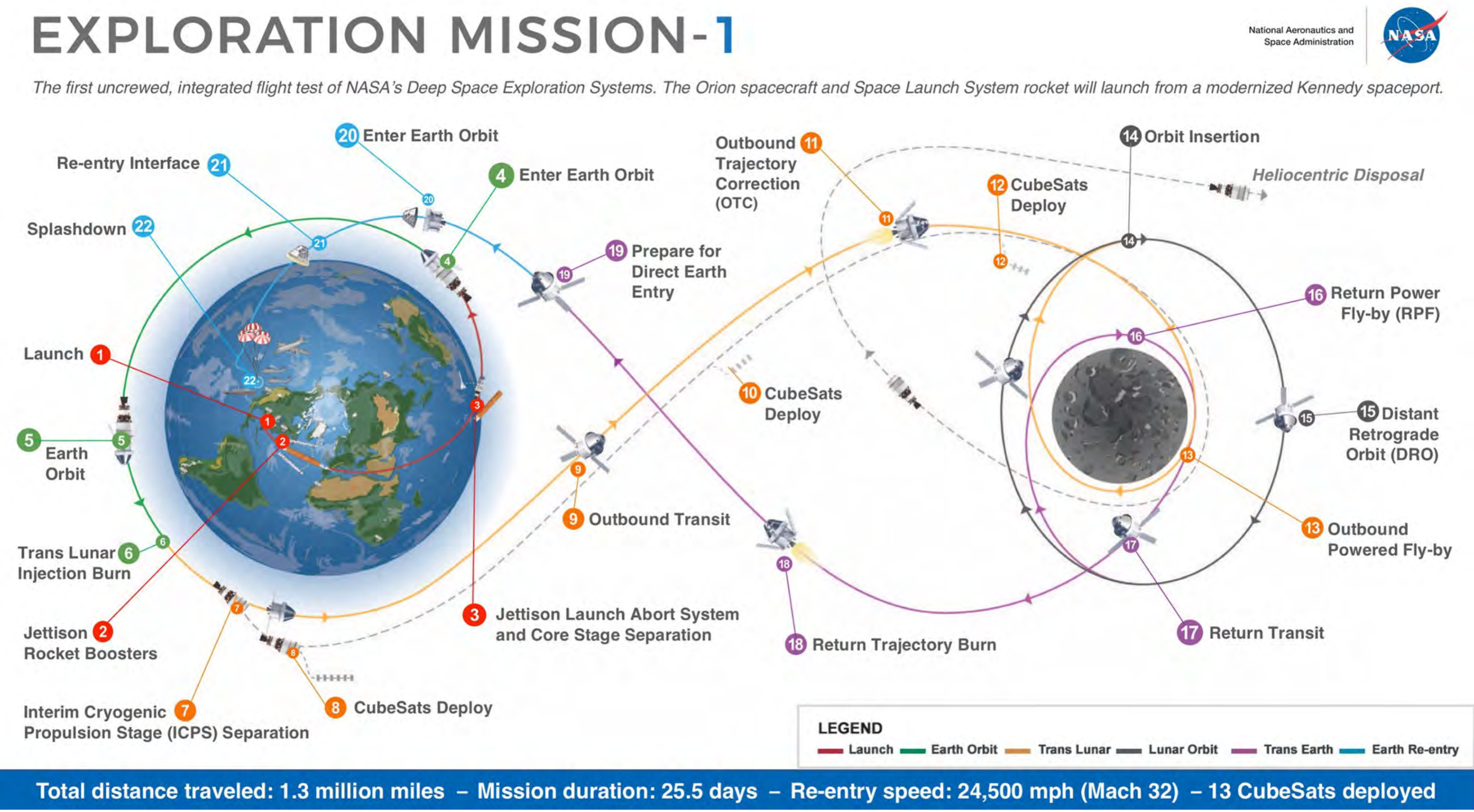
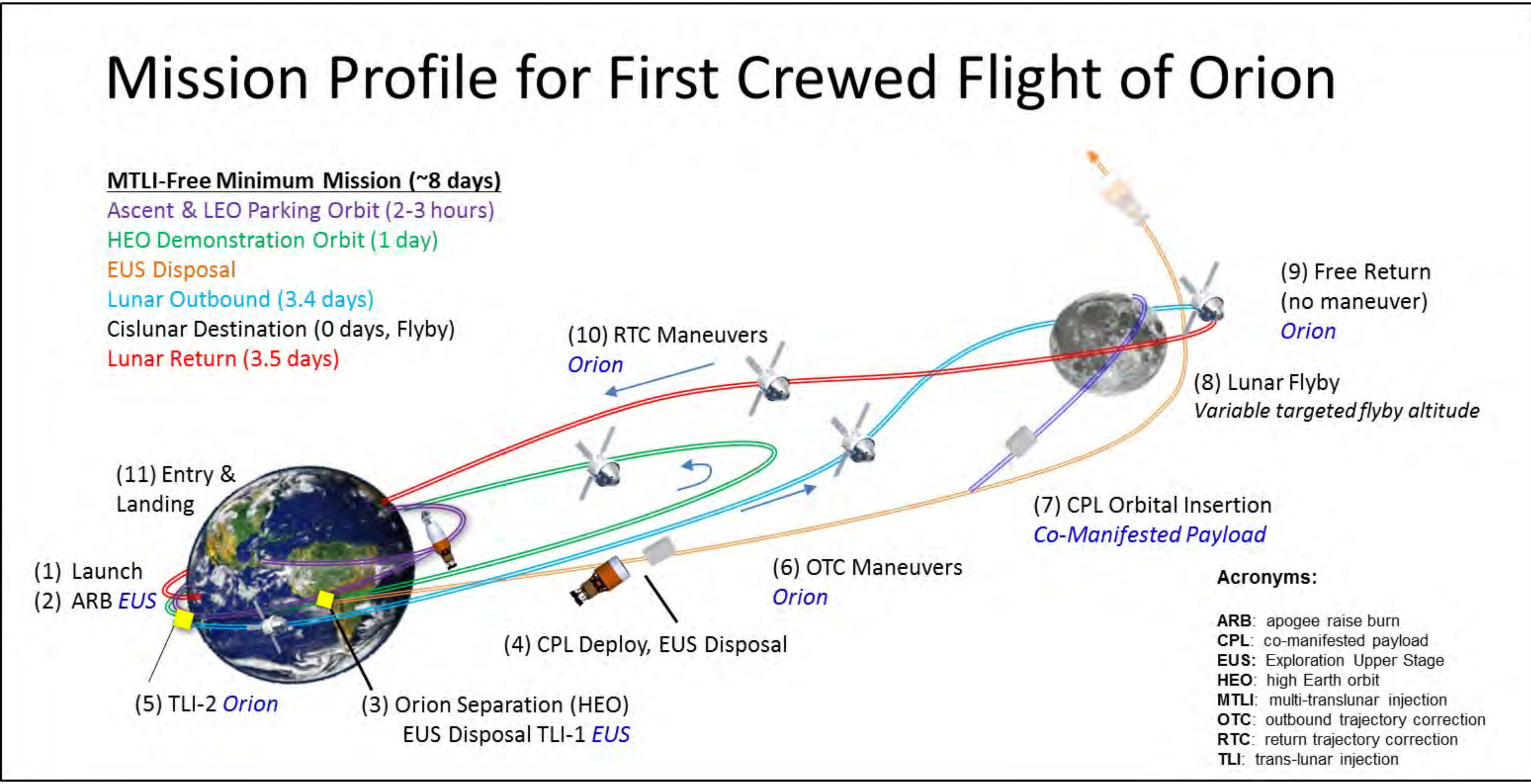


https://www.nasa.gov/image-feature/exploration-mission-1-map

EM-2



https://www.nasa.gov/sites/default/files/thumbnails/image/em_2_mission_profile_update.jpg