ORION ARTEMIS I ENTRY PERFORMANCE

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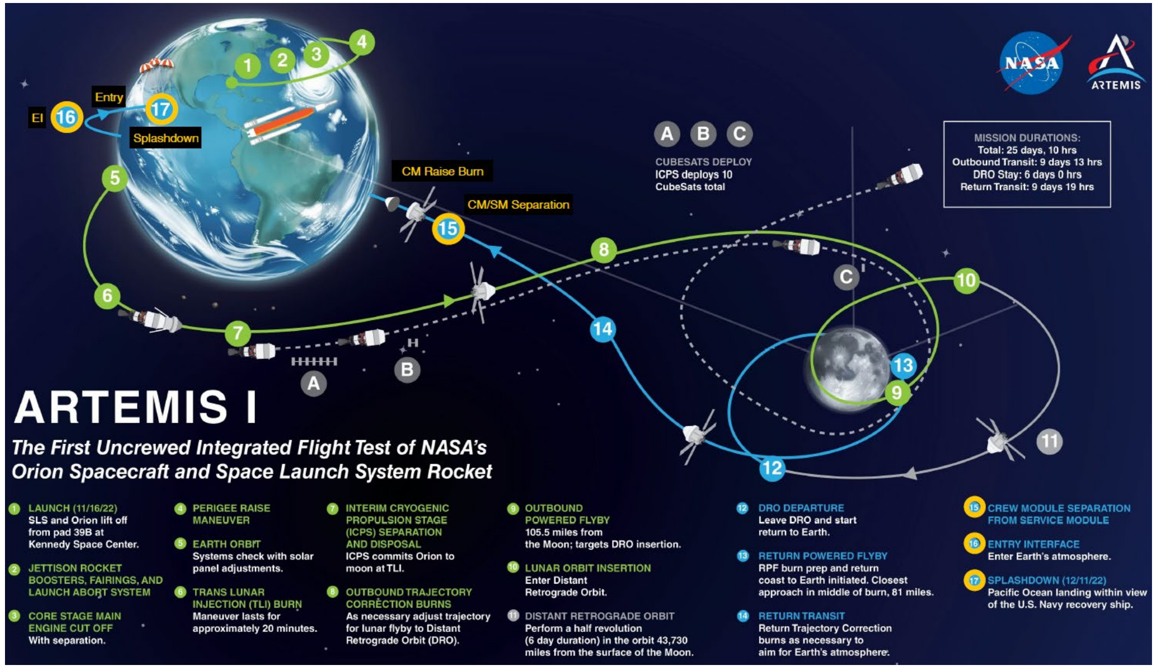
ARTEMIS I

- **Launched**
  - November 16, 2022 at 1:47 am
- **Mission Duration**
  - 25 days, 10 hours, 53 minutes
- **Primary landing zone near San Diego**
  - Skip entry allows access across lunar month
  - Artemis I shifted 300 nmi south due to weather
  - EI to splashdown range ~3200 nmi



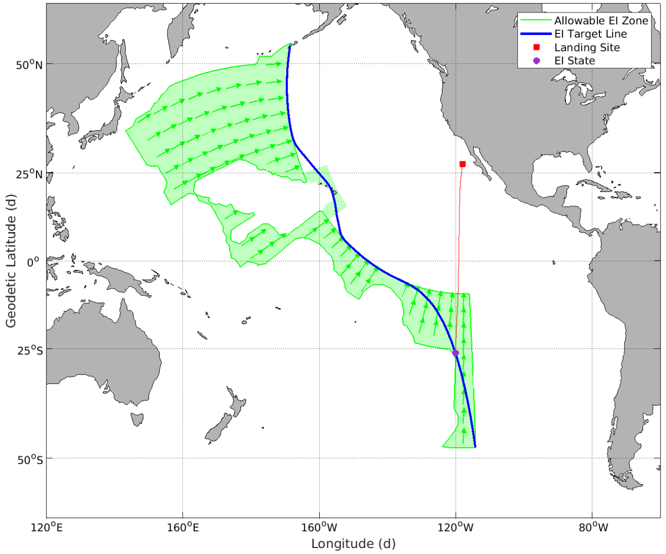
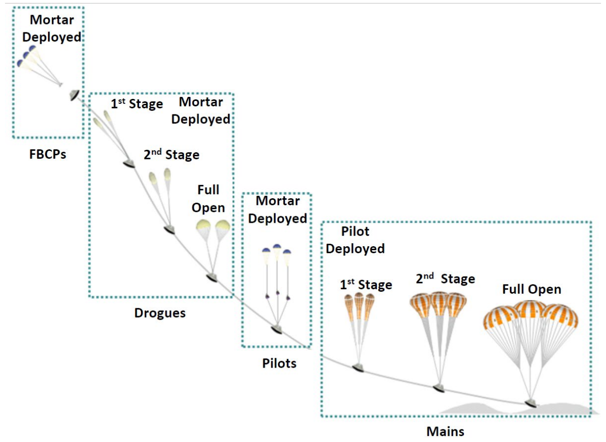


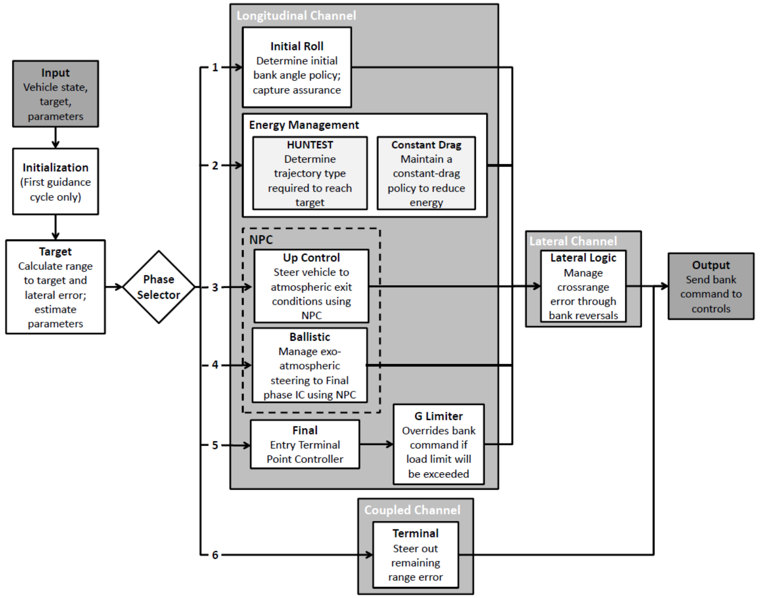
Table 1: Artemis I Entry Interface State

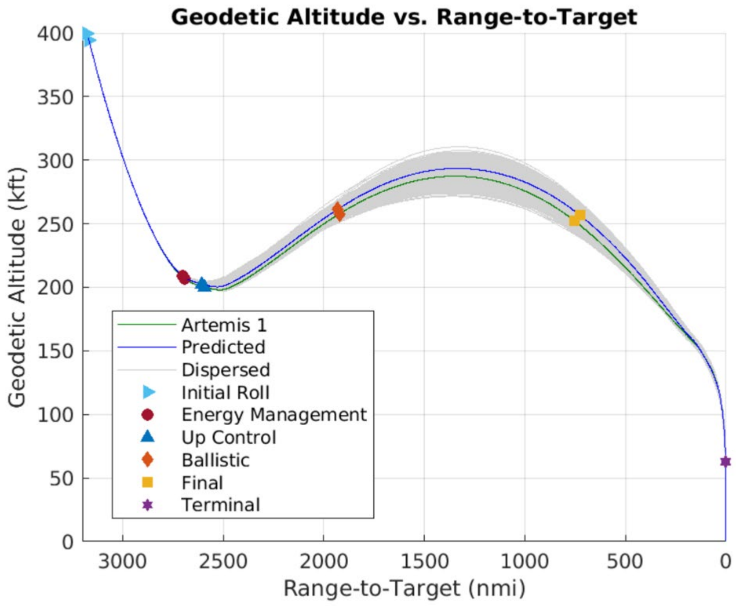
Parameter	Units	Artemis I
Geodetic Altitude	ft	400000.0
Geodetic Latitude	deg	-25.82847
Longitude	deg	-120.08071
Inertial Velocity Magnitude	ft/s	36062.65680
Inertial Topocentric Flight Path Angle	deg	-5.66367
Inertial Topocentric Azimuth	deg	4.65389
Total Range-to-Target	nmi	3176.65
Lateral Angle	deg	0.94018



PREDGUID ENTRY GUIDANCE

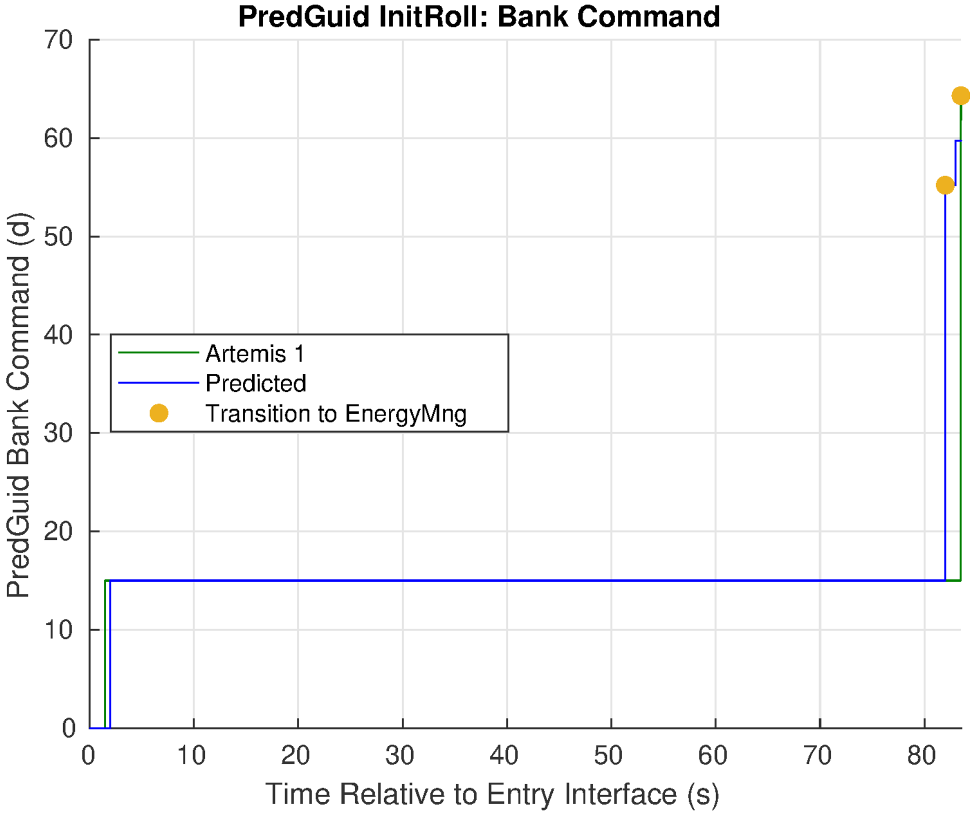
- **Generates bank command to achieve target**
- **Based on Apollo entry guidance, with changes only where needed to improve performance**
  - Numerical Predictor-Corrector (NPC) for range prediction, rather than analytic methods, in early entry guidance phases
  - In-flight estimation of atmospheric density and vehicle lift-to-drag ratio (L/D)
  - Interpolation of the Final phase reference trajectory, rather than nearest-neighbor
  - Addition of Terminal phase steering
- **Decoupled downrange and crossrange channels**
- **NPC taken from Aeroassist Flight Experiment**
  - Propagates constant bank angle solution
  - Iterates on bank angle to converge on range
- **Six phases**

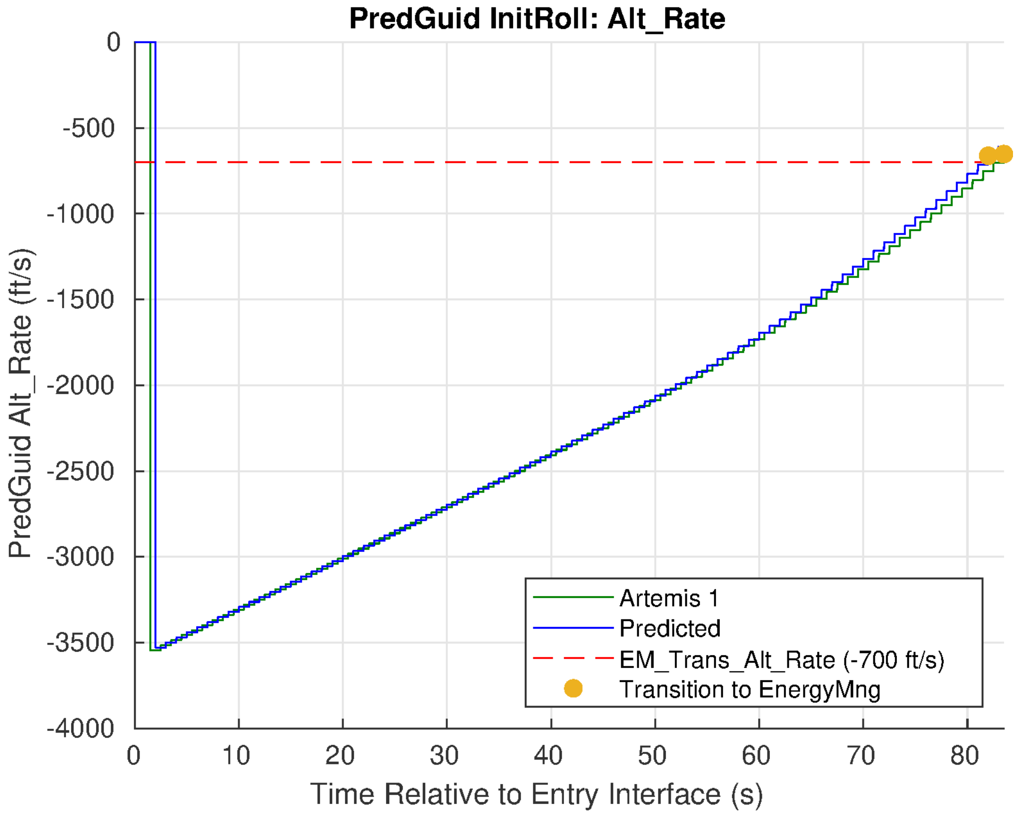




PREDGUID PHASE 1: INITIAL ROLL

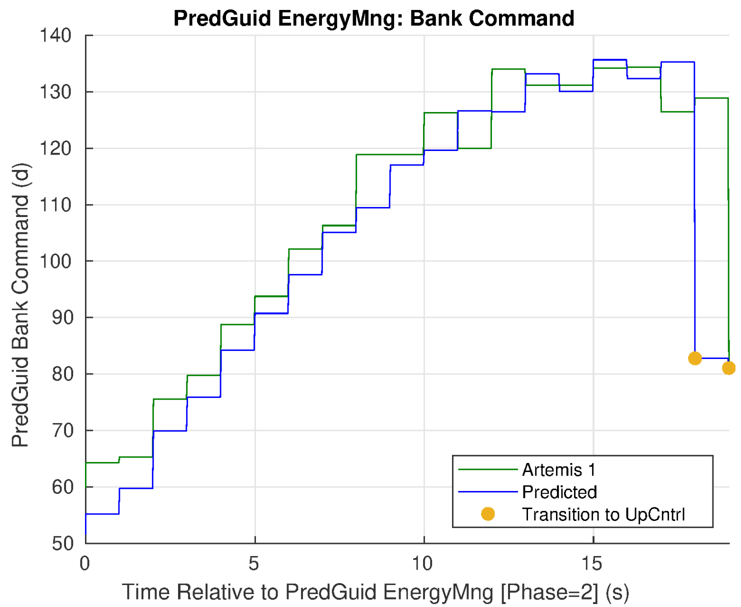
- **Holds pre-selected bank angle**
- **Includes skip out protection to command full lift-down if entry is too shallow**
  - Skip out protection was not triggered during Artemis I
- **Transitions to Energy Management phase when altitude rate goes above -700 ft/s**

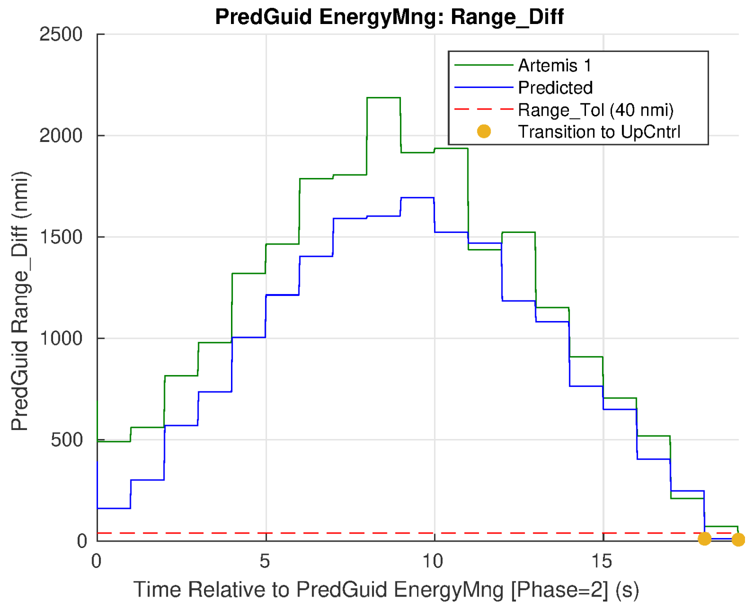




PREDGUID PHASE 2: ENERGY MANAGEMENT

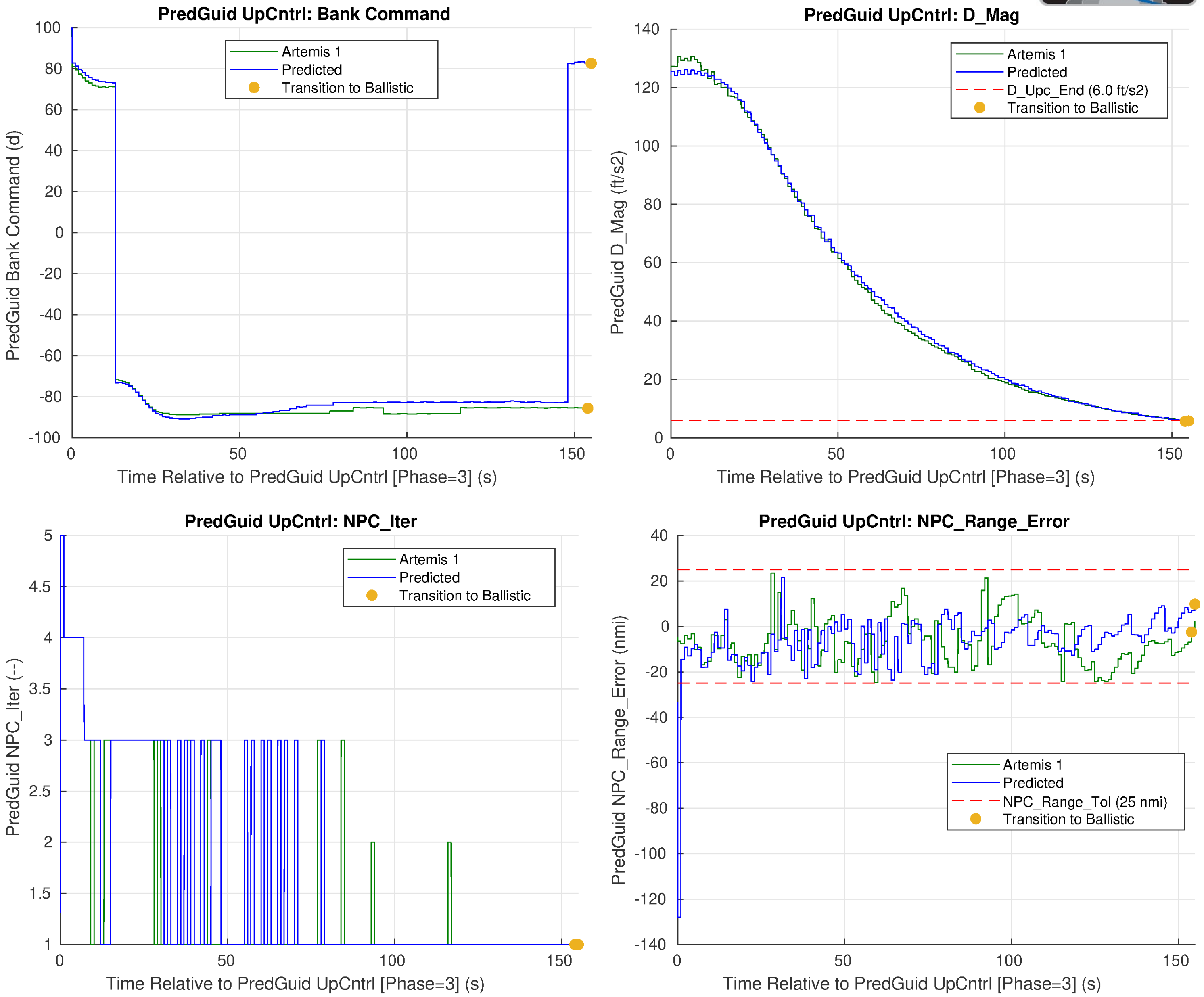
- **Retains original Apollo formulation of analytic predictor-corrector**
- **Two subphases**
  - Huntest
    - Analytically propagates a constant vertical L/D to find the range between current state and the initiation of the Final phase
    - Iterates on speed to converge on the range
  - Constant Drag
    - Selects the bank needed to bleed off energy to achieve the speed
- **Transitions to Up Control when the range converges**
- **Differences between the predicted and actual trajectories are due to atmospheric and vehicle variations**





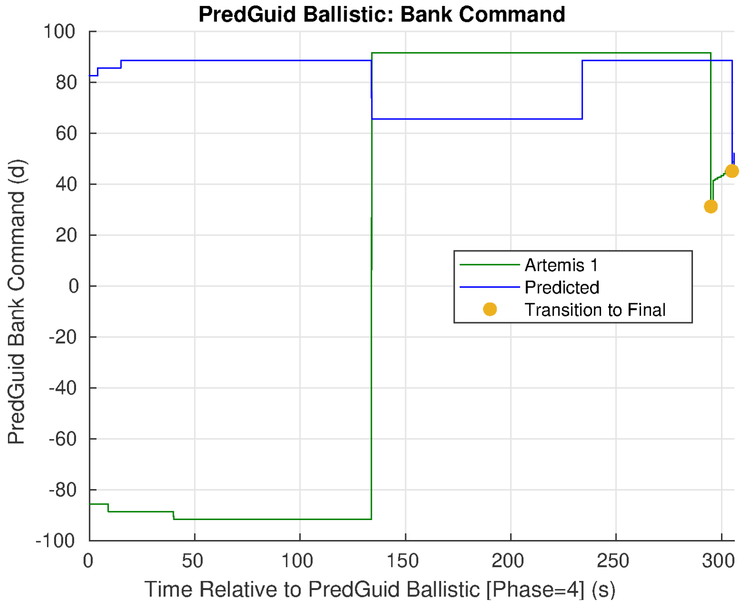
PREDGUID PHASE 3: UP CONTROL

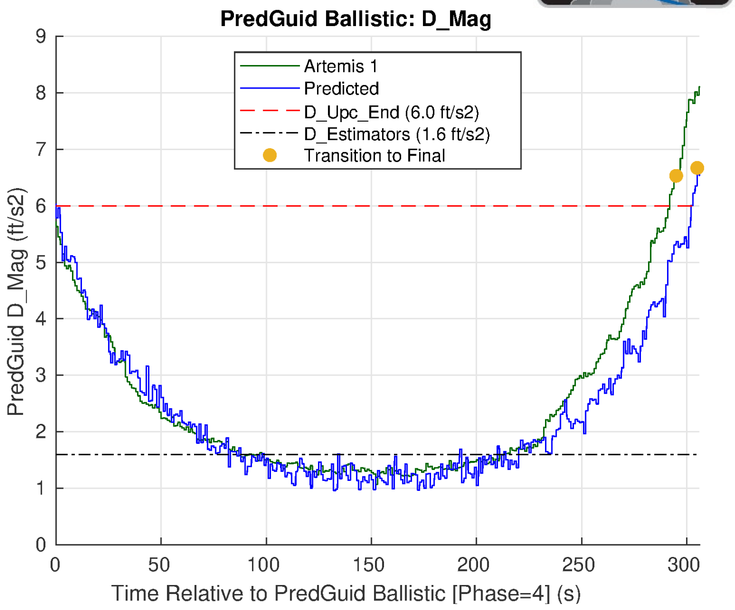
- Numerical Predictor Corrector
- Uses in-flight estimated density and L/D
- Transitions to Ballistic phase upon exit of sensible atmosphere

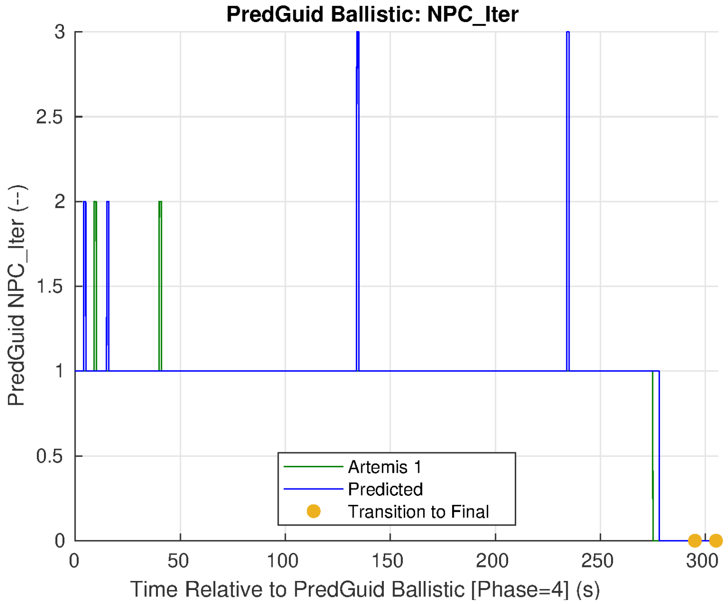


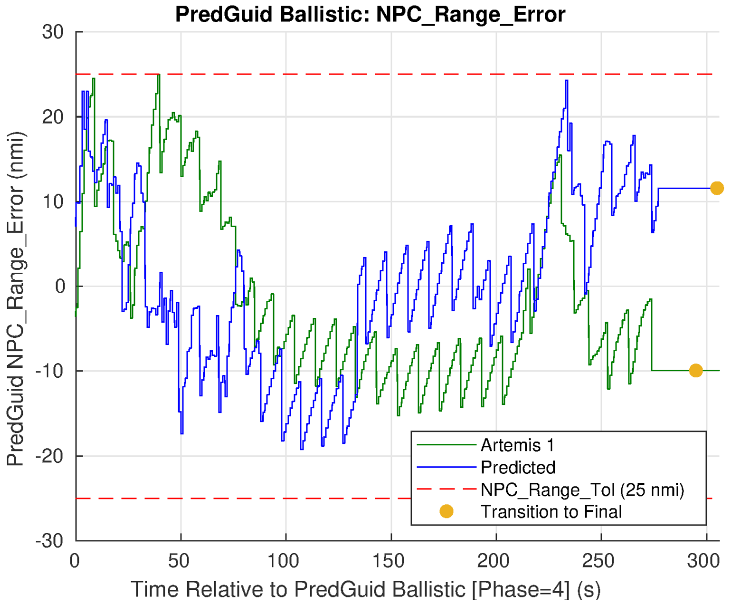
PREDGUID PHASE 4: BALLISTIC

- Low drag phase of flight
- Numerical Predictor Corrector
- Continues to update guidance command
- Uses in-flight estimated density and last estimated L/D before atmospheric exit



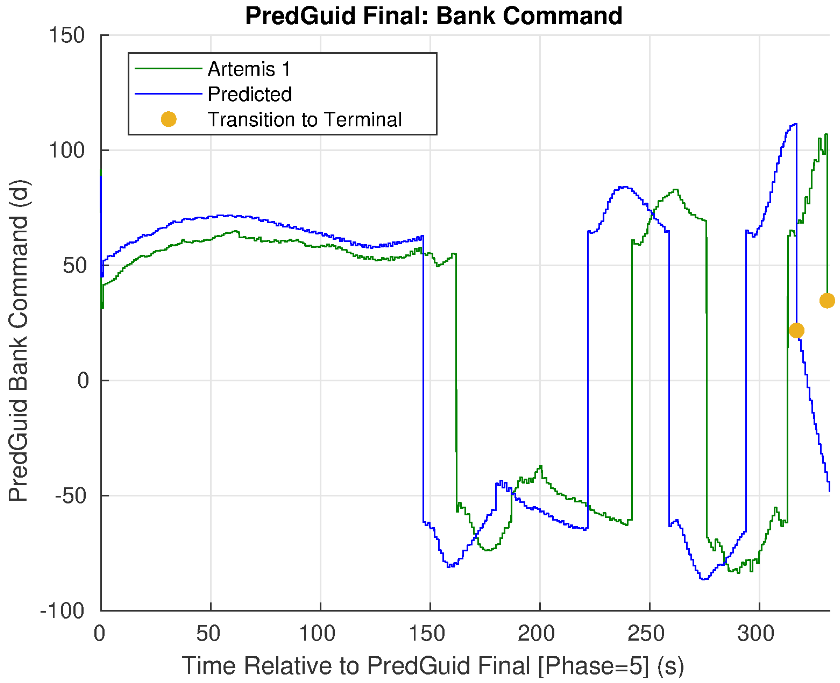






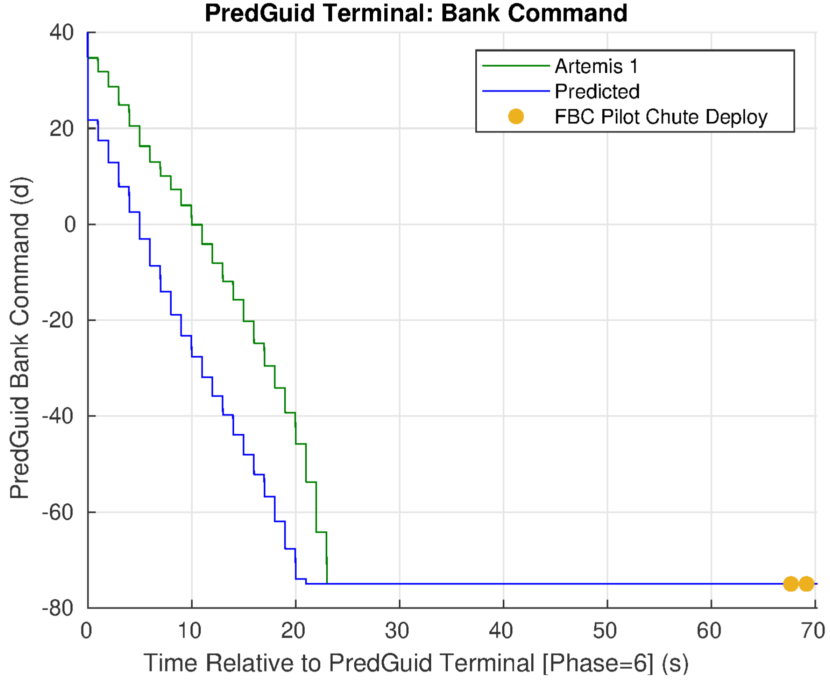
PREDGUID PHASE 5: FINAL

- Uses Apollo formulation of Entry Terminal Point Controller
  - Stored reference trajectory and gains
- Includes g-limiter to alter bank angle in high gload scenarios
  - G-limiter was not triggered during Artemis I
- Transitions to Terminal phase when speed drops below 1000 ft/s



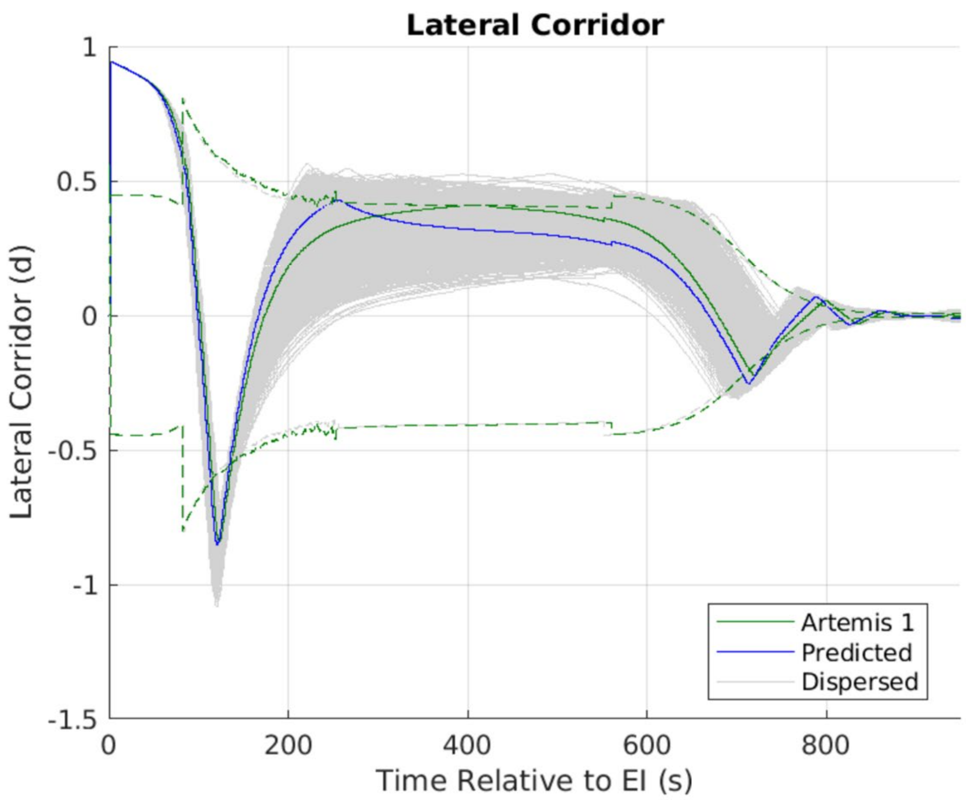
PREDGUID PHASE 6: TERMINAL

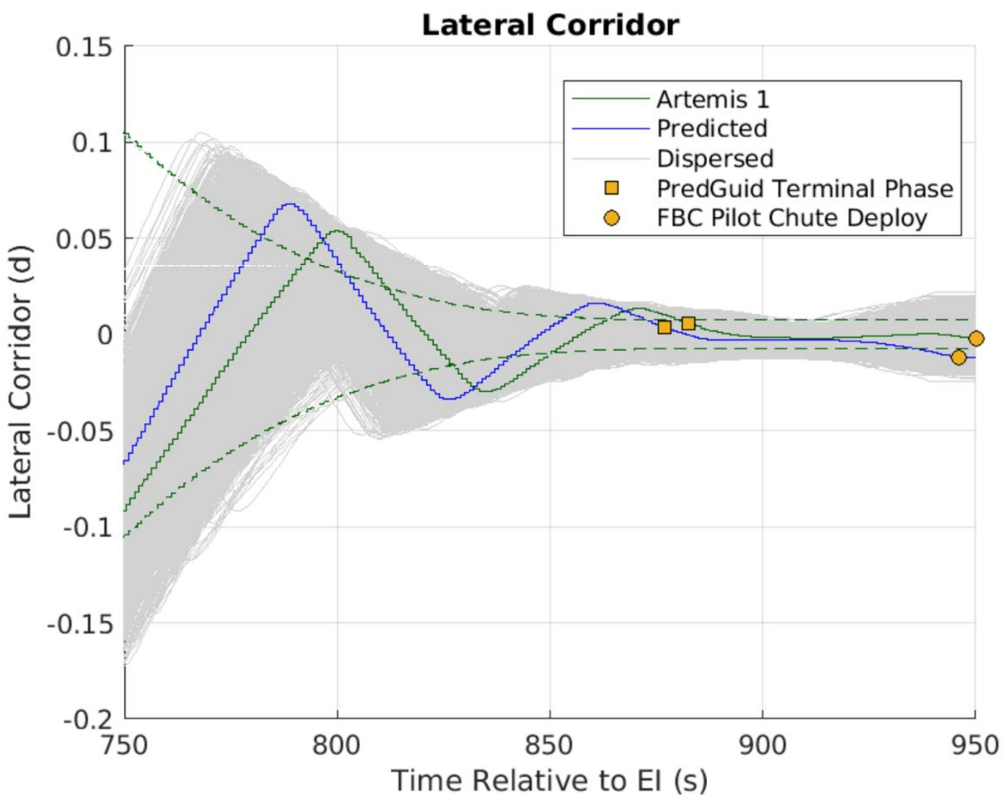
- **Simple proportional guidance based on heading error**
  - Points at the target
  - Holds command if vehicle flies past target
- **Active guidance ends at beginning of chute sequence**
  - Forward Bay Cover (FBC) pilot chute deploy



LATERAL CORRIDOR PERFORMANCE

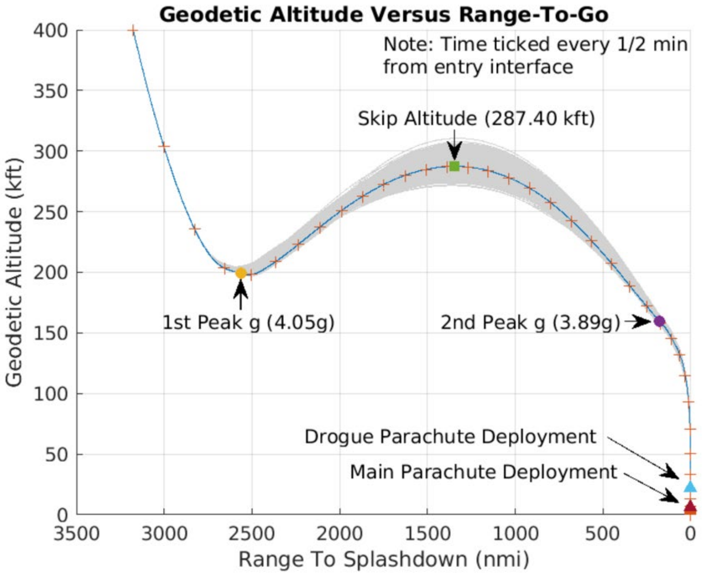
- **Lateral channel controls crossrange using bank reversals**
  - Lateral deadband based on speed and L/D
- **Guidance commanded 6 bank reversals during flight**

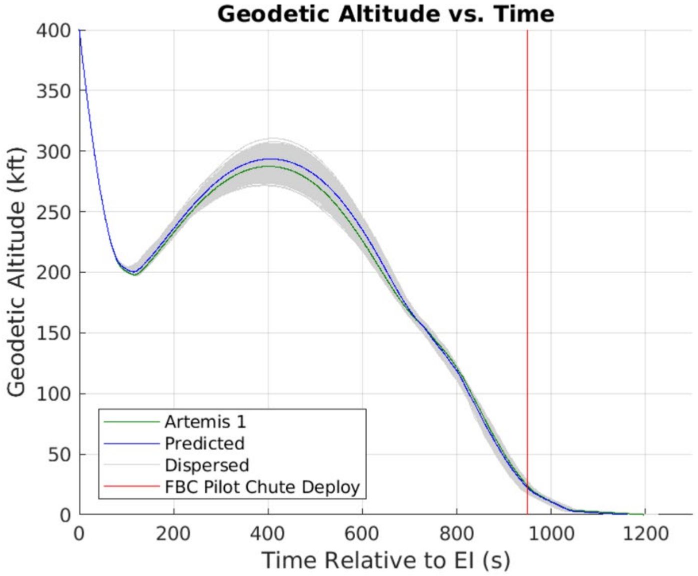


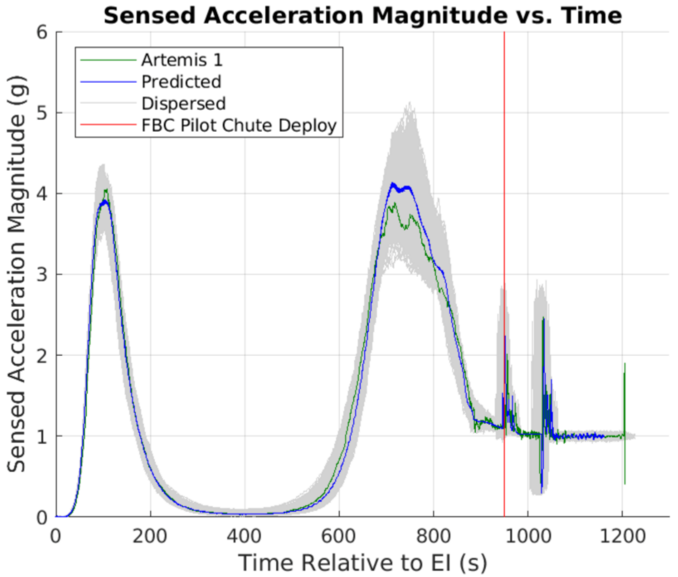


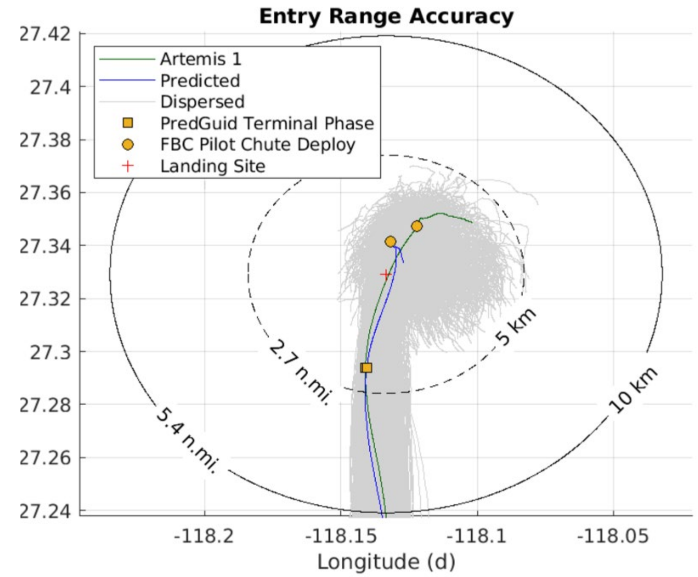
GUIDANCE RESULTS

- **During Artemis I flight, the Orion entry guidance operated as expected and achieved the targeted landing site within the required accuracy**
- **The Artemis I flight did not skip as high as predicted**
  - Predicted skip apogee: 293.5 kft
  - Actual skip apogee: 287.4 kft
  - Likely due to a less dense atmosphere during the first pass and slightly less lift-to-drag (L/D) than predicted.
- **This data shows a successful skip entry**



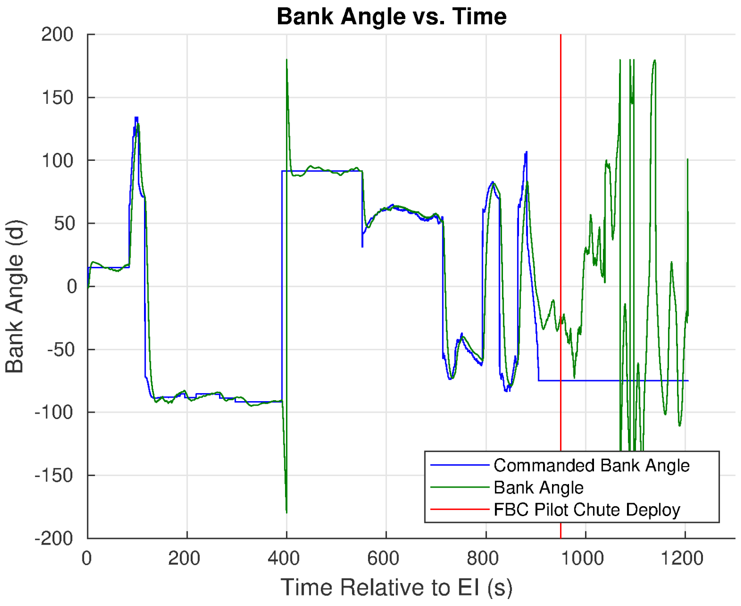


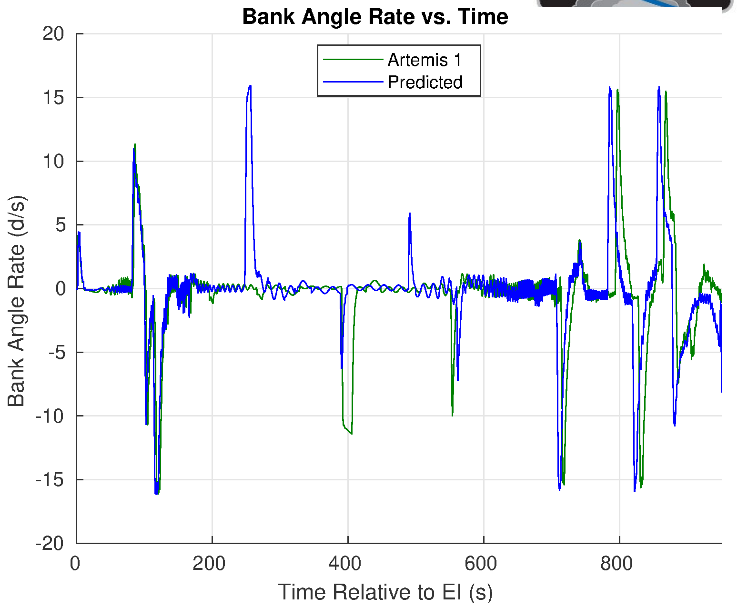


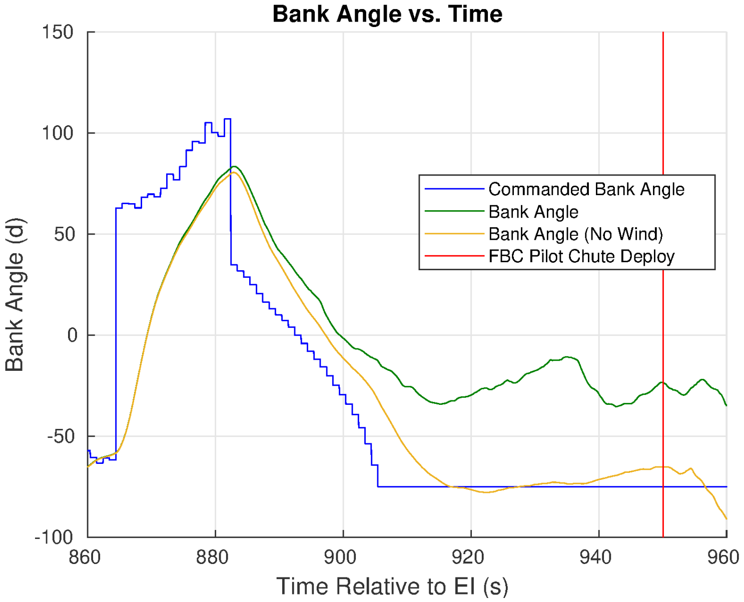


BANK ANGLE

- **Navigated bank angle tracks commanded bank angle very well until the last 90 seconds of guided flight**
- **Navigated bank angle assumes no wind**
  - As the vehicle slows down, the wind speed becomes significant relative to the speed of the vehicle
  - Assumption to ignore wind in the on-board computation of bank angle breaks down
- **Contributing factor to the miss distance at chute deploy**

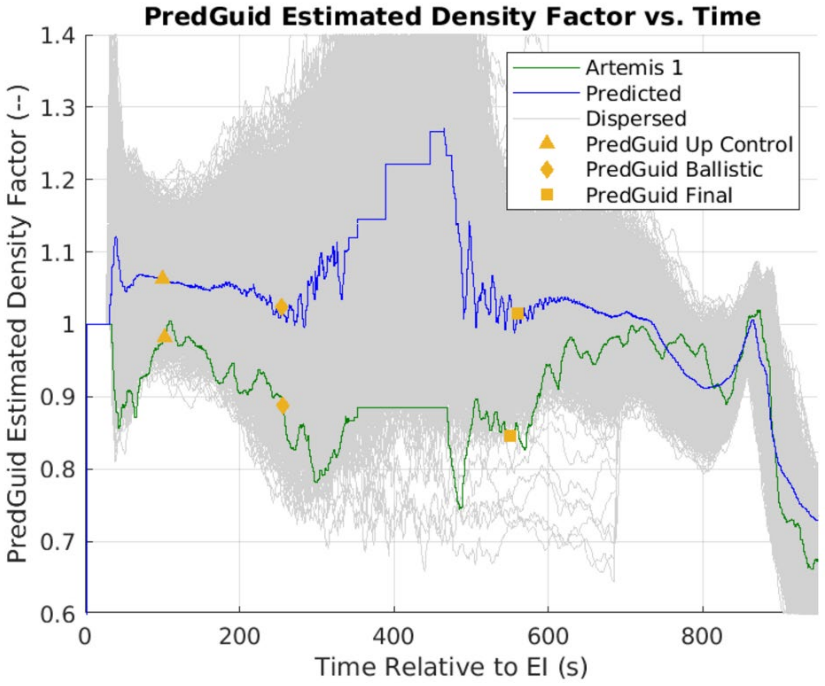


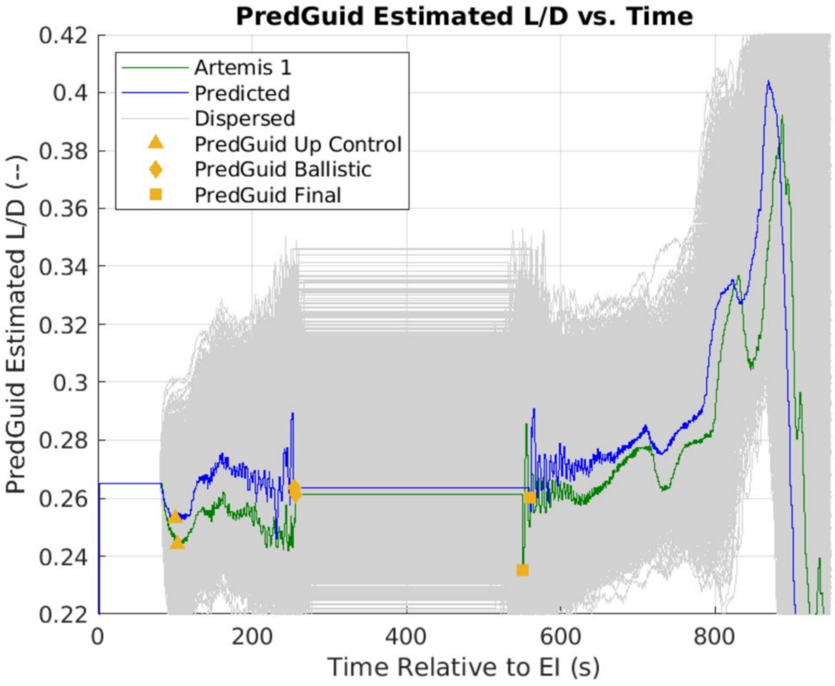




DENSITY AND L/D ESTIMATOR PERFORMANCE

- **Measured acceleration used to estimate:**
  - Density scale factor applied to on-board 1976 standard atmosphere
  - Lift-to-drag ratio
- **Artemis I flight experienced ~10% less dense atmosphere and ~5% less L/D than predicted**
  - Within expected dispersion envelope
  - Most likely cause of differences between predicted and actual flight



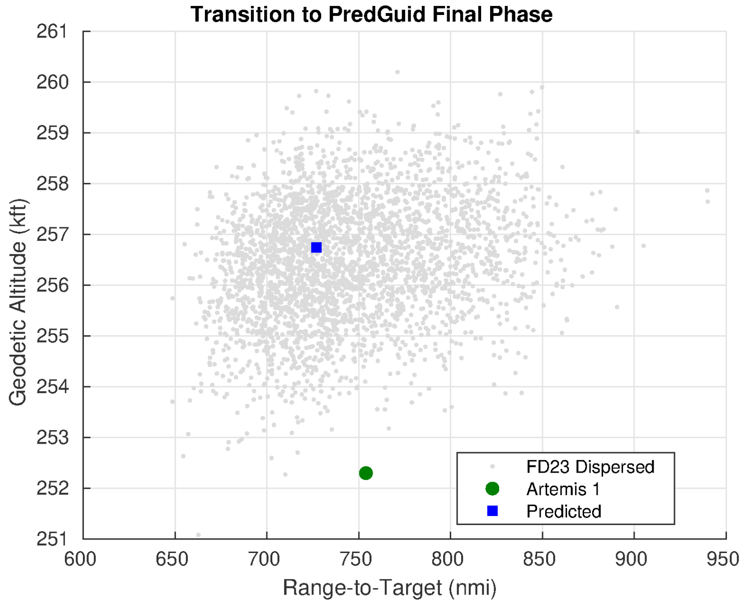


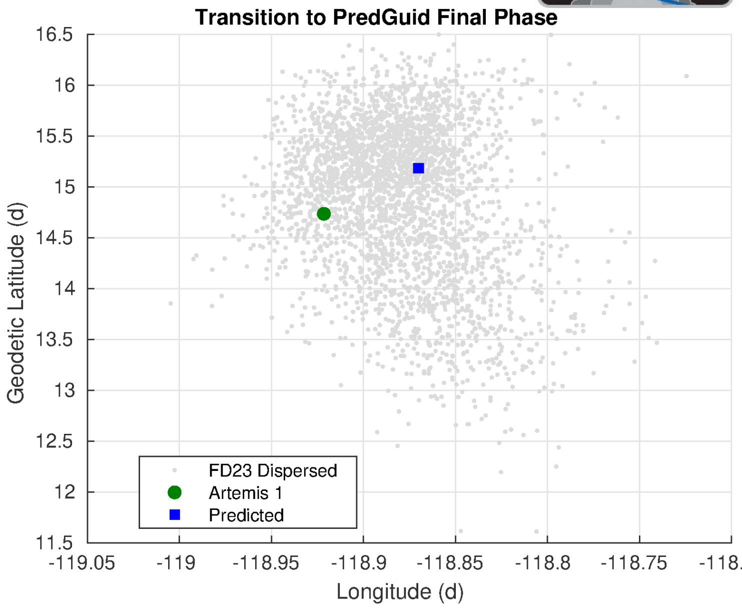
TRANSITION TO FINAL PHASE

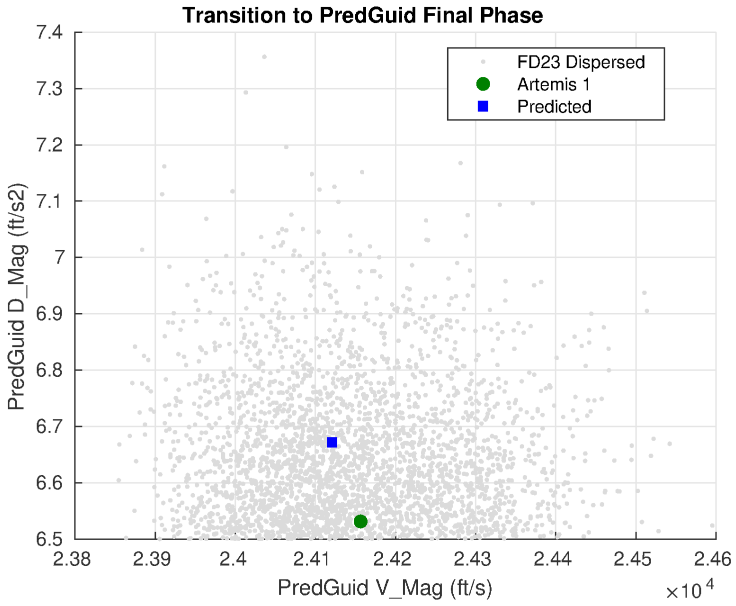
- **Transition to Final phase is an important measure of the guidance performance**
  - Effectively at the second atmospheric entry since this is the point where the drag acceleration begins to increase

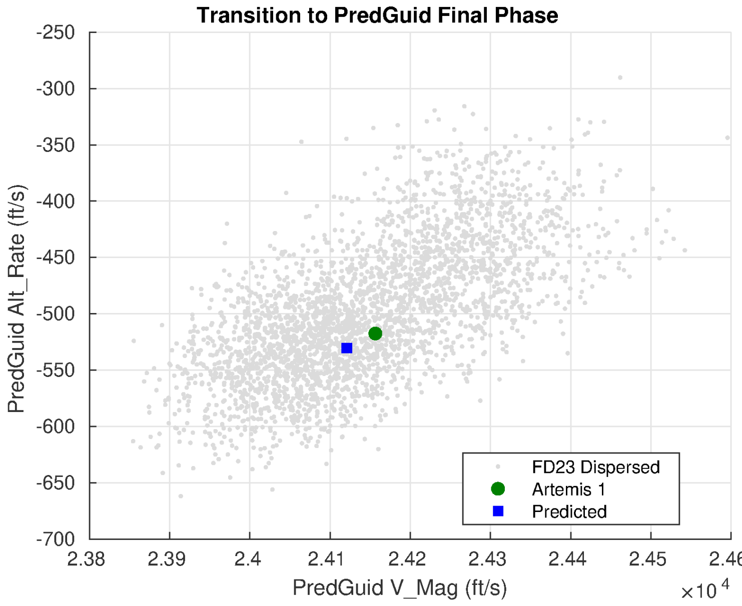
- **As noted, the Artemis I flight did not skip as high as predicted**

- **Geodetic altitude is not used during the Final phase and thus does not impact performance**



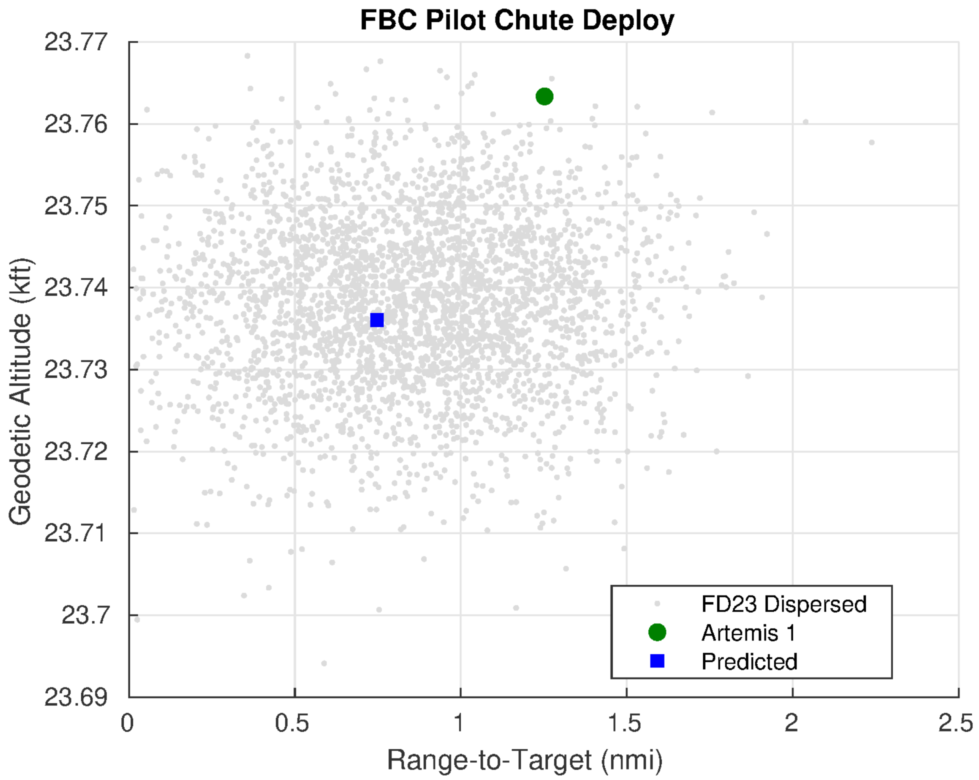


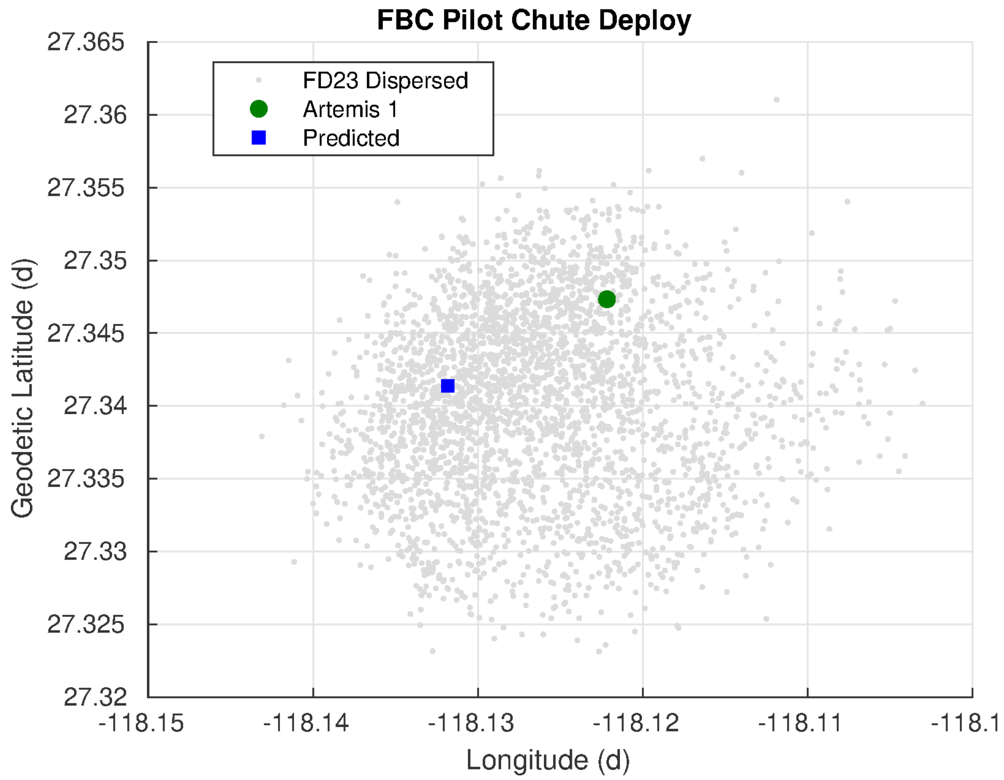




FORWARD BAY COVER PARACHUTE DEPLOY

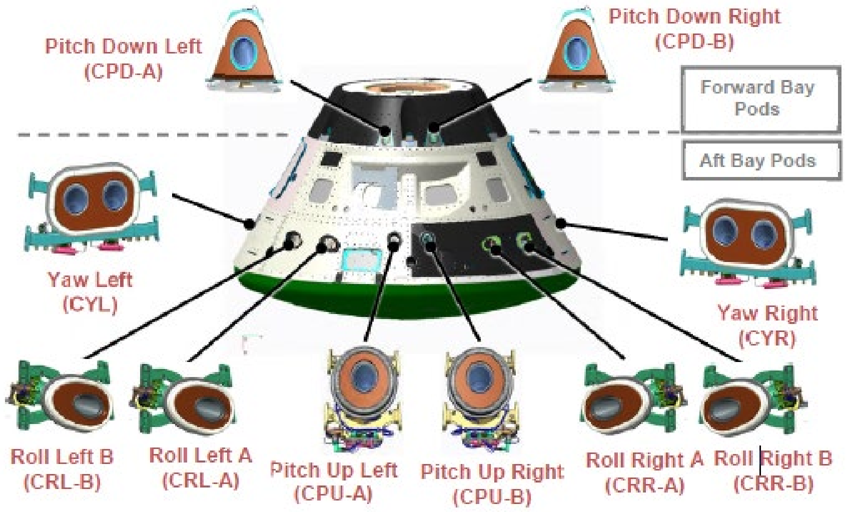
- Forward Bay Cover (FBC) parachute deploy is the end of active entry guidance



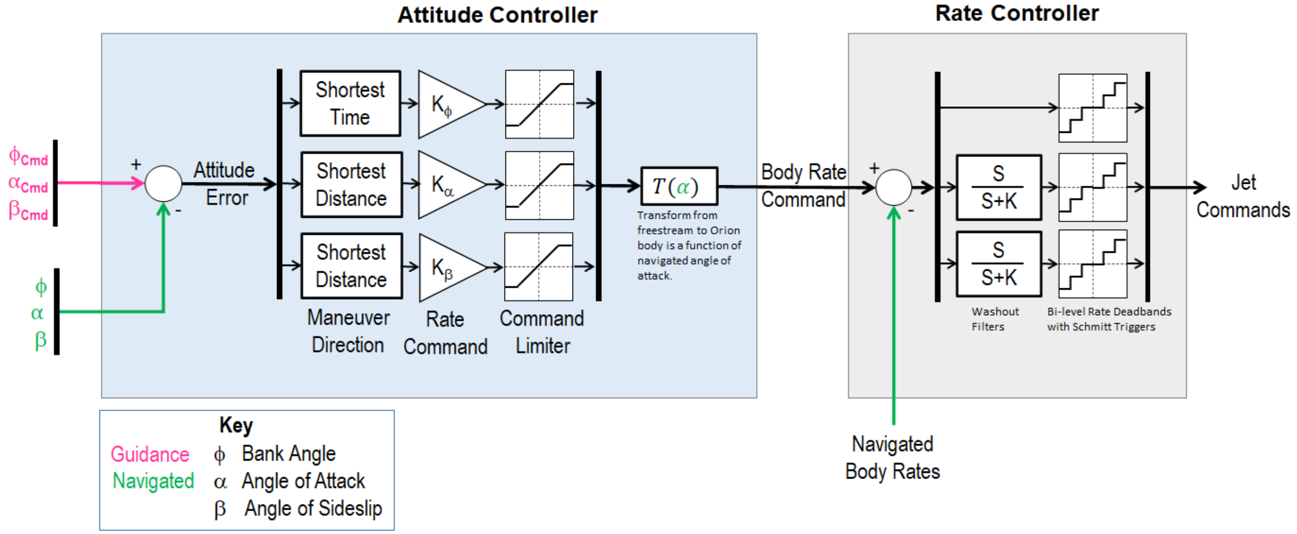


ENTRY CONTROL OVERVIEW

- **Crew Module Reaction Control System (RCS)**
  - Attitude control is achieved by commanding reaction control thrusters that produce torque about the vehicle body axis
    - Two fully redundant strings of thrusters
    - Six thrusters per string
    - Each thruster produces a nearly pure torque in one direction about the primary body axis

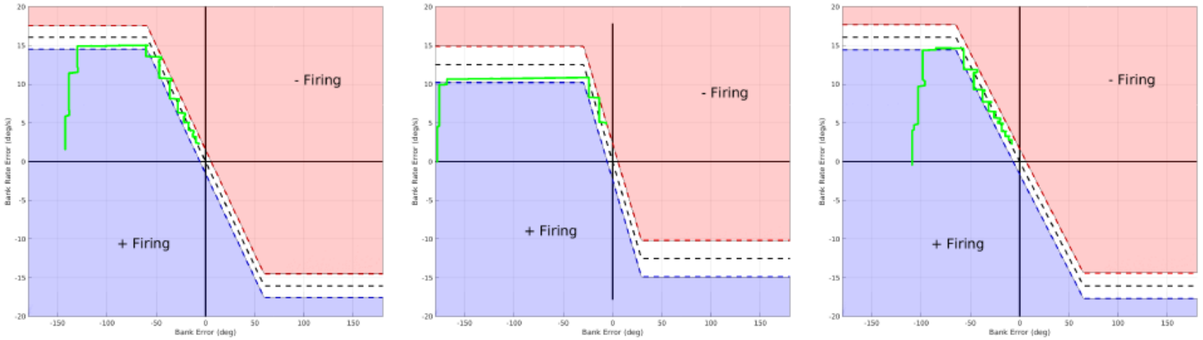


- **Control Design**
  - The Crew Module control system (CNC) is a digital controller that operates at 40Hz
  - 3-axis attitude control is performed during exo-atmospheric flight
    - Transition between exo-atmospheric and atmospheric gains is scheduled on acceleration magnitude
  - Attitude maneuvering in atmosphere is limited to bank
    - Angle of sideslip and angle of attack are aero stabilized
  - Atmospheric control gains are scheduled on velocity magnitude and are tailored for hypersonic, supersonic, transonic, and subsonic phases of flight

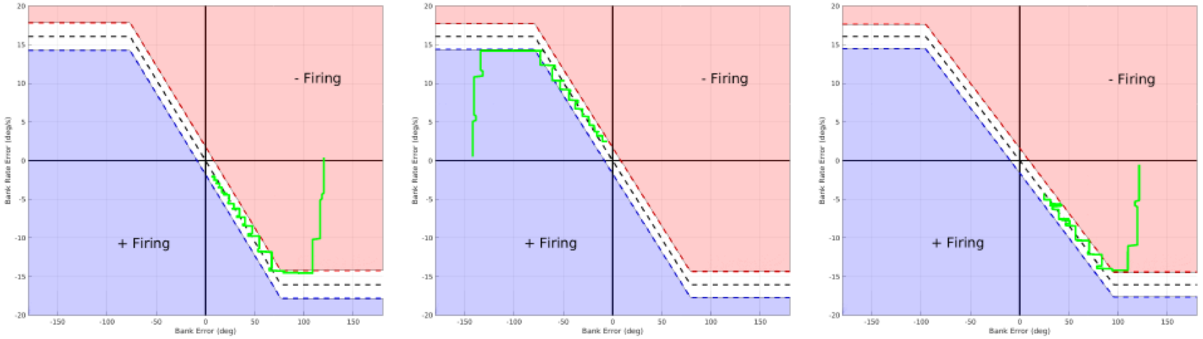


ENTRY CONTROL PERFORMANCE

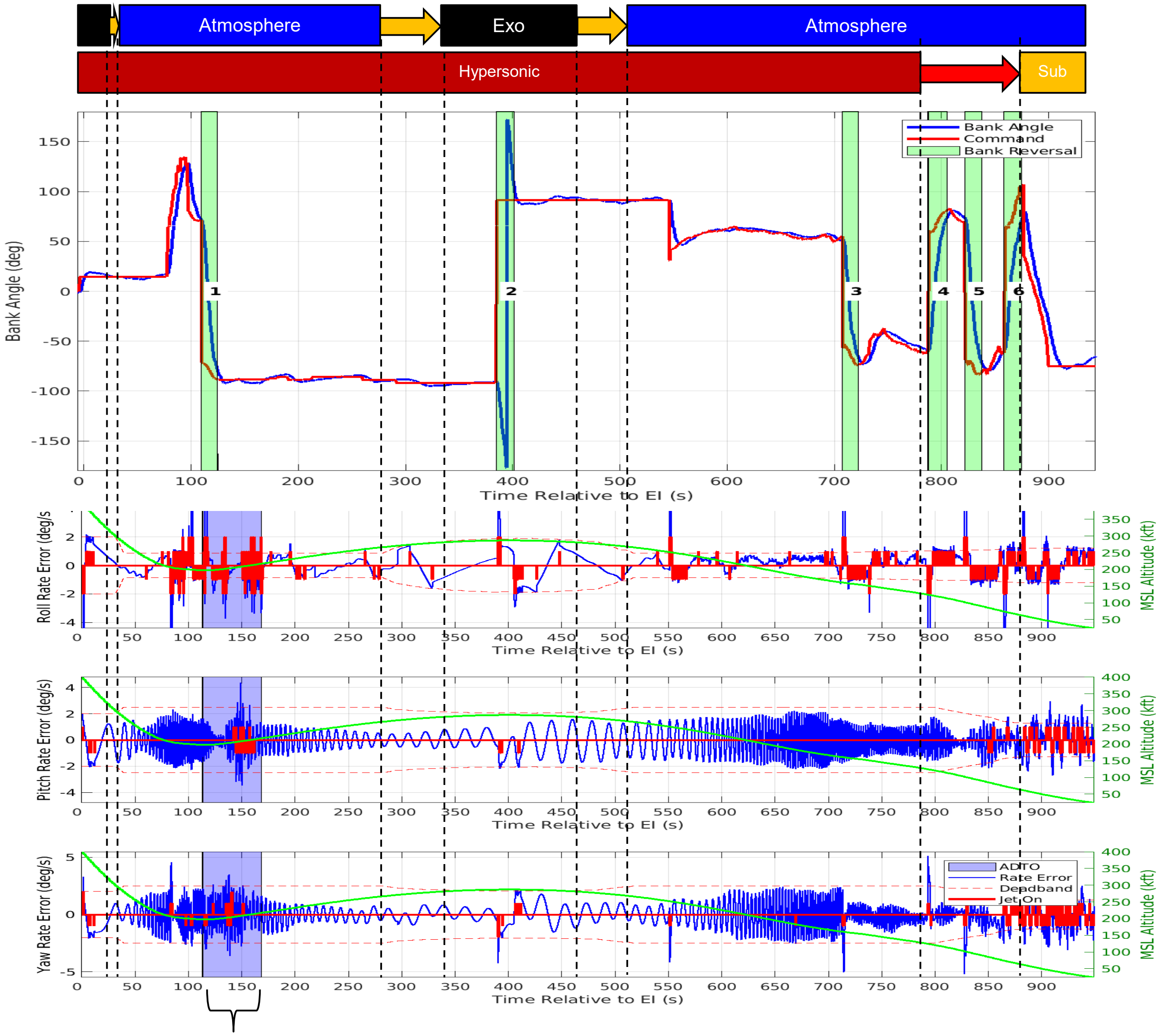
- Entry control tracked the bank angle command well during flight
- Attitude rates required little correction to stay within deadbands
  - Aero stability decreases during subsonic flight requiring more control corrections near the time of Forward Bay Cover (FBC) jettison
- Bank reversal maneuvers were well behaved and followed the control phase plane indicating CM RCS thrusters performed as expected



(a) Bank Reversal 1 Phase Plane (b) Bank Reversal 2 Phase Plane (c) Bank Reversal 3 Phase Plane



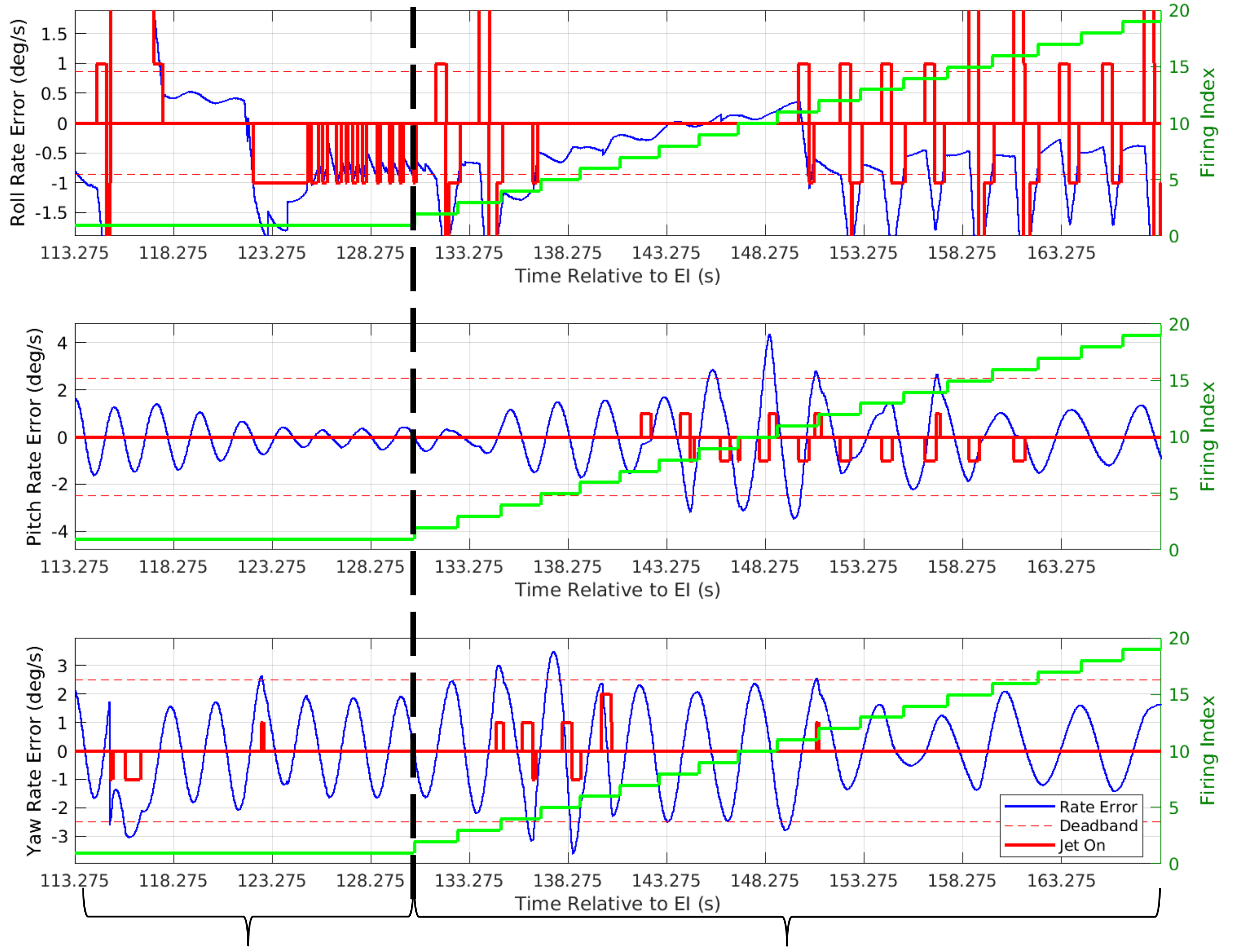
(d) Bank Reversal 4 Phase Plane (e) Bank Reversal 5 Phase Plane (f) Bank Reversal 6 Phase Plane



Period of Aerothermal Detail Test Objective (ADTO) Activity

AEROTHERMAL DETAILED TEST OBJECTIVE

- **Aerothermal Detailed Test Objective (ADTO)**
  - Series of RCS commands executed during hypersonic flight in the atmosphere
  - Temperature sensors included on the CM back-shell measured the effect of RCS firings on heating for aerothermal model validation
  - Unique to the Artemis I mission
  - Open-loop firings
    - Prior to the firing a quiescent period is enforced
    - Post firing the control system corrects resulting disturbance
    - Firings are suspended by bank reversals or if significant attitude or rate disturbances are detected
      - The ADTO was suspended due to the 1st bank reversal
      - Attitude and attitude rate was well behaved during the ADTO. Minor excursions occurred due to ADTO firings but did not result in further suspension of the ADTO



ADTO Suspended due to 1st bank reversal

ADTO Completes all pre-planned firing patterns with no further interruptions

CONCLUSION

- **Artemis I flight was within the predicted dispersed flight envelope**
  - Differences between flight and best prediction due to 10% less dense atmosphere and 5% less L/D from predictions
  - Even with these differences, the flight was close to the pre-flight predictions

- **Artemis I is the first successful demonstration of a skip entry for a human rated vehicle**

- **Acknowledgements**
  - Original Apollo engineers
  - Former team members Tim Crull, Mike Tigges, Gregg Barton, Zach Putnam, Andy Barth, and Travis Bailey