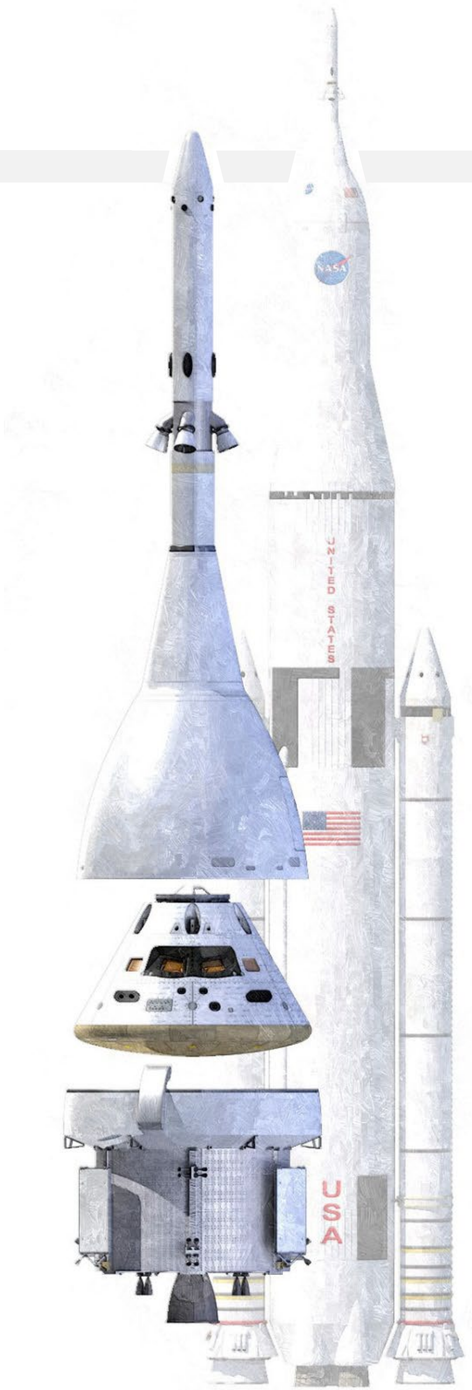

46th Rocky Mountain AAS GNC Conference

Historical Retrospective on Orion GNC Design

Robert Gay

February 6, 2024

Outline

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- Navigation – First things First
  - Navigation Architecture Upgrade – EFT-1 to Artemis I
  - "Navigation Base" – Compromises Hurt
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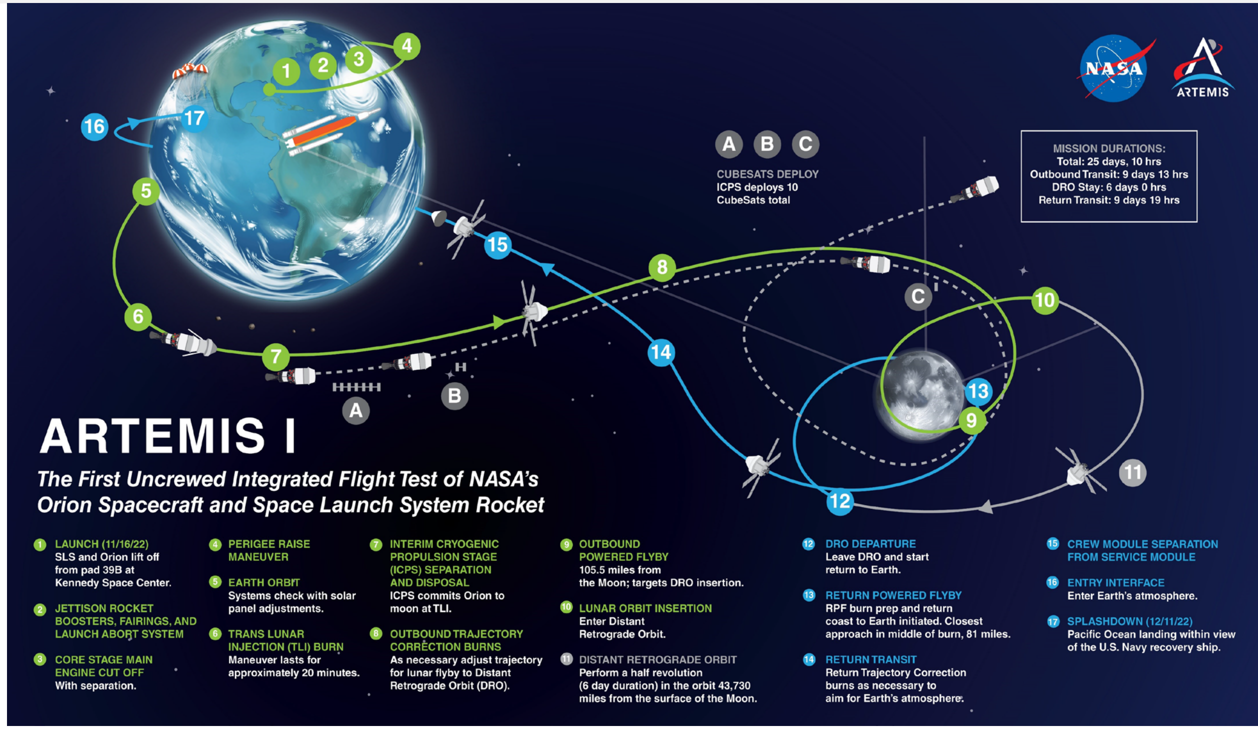
Introduction



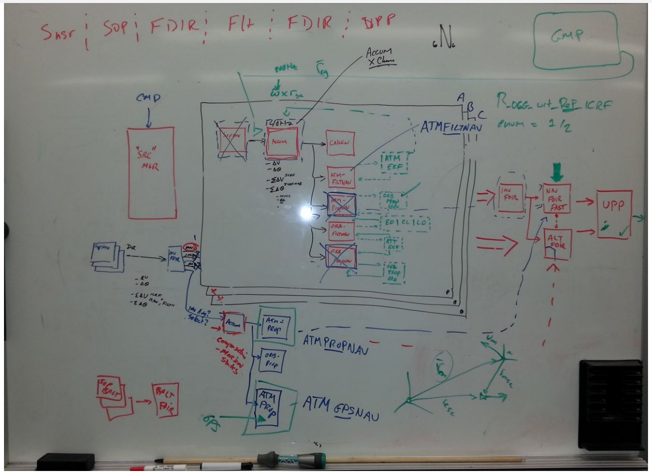
Artemis I – First human-rated vehicle back to the moon in fifty years

- Paper is a sampling of key Orion GNC design decisions over 17+ years leading up to Artemis I.
- Author started on Orion in November of 2005 just prior to contract award to Lockheed Martin in 2006.
  - Early Orion simulation development (2005)
  - Entry Descent and Landing (EDL) Navigation Subsystem Manager (2006)
  - Navigation System Manger and MODE Team Lead (2011)
  - VIO Program Lead Engineer (2016), SMI Program Lead Engineer (2020)
  - Orion Spacecraft Chief Engineer / Deputy Program Chief Engineer – (2024)

Navigation – First things First

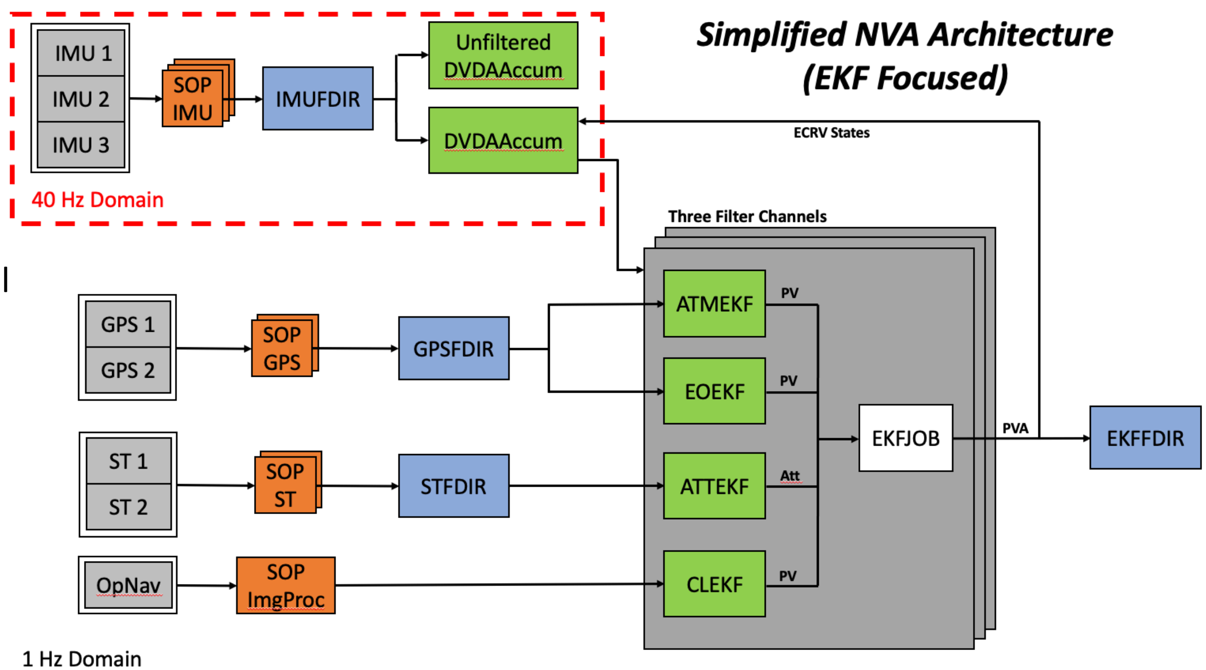
I never understood why Guidance came before Navigation in GNC? You must know where you are (Navigation) before you can decide where to go (Guidance) and how to get there (Control), - right? Ok, I'm biased. I'm a Nav guy. On to the story…

Navigation Architecture Upgrade – EFT-1 to Artemis I



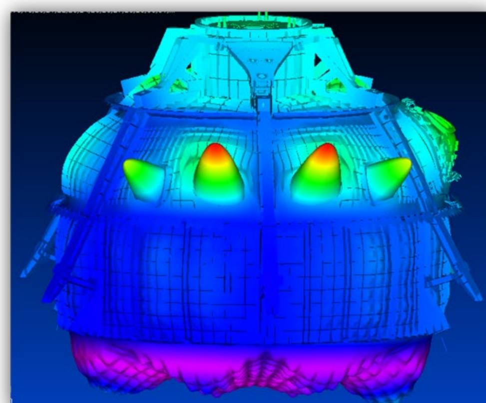
- EFT-1 was a great success, but due to changing political priorities and resulting schedule pressures, the Nav code needed an overall to handle additional hardware and be more extensible for future missions.
- Nav team held multiple TIMs to redesign the base architecture to support future needs.
- Resulted in an historic achievement captured at the end of the last TIM on Nov 21, 2014.

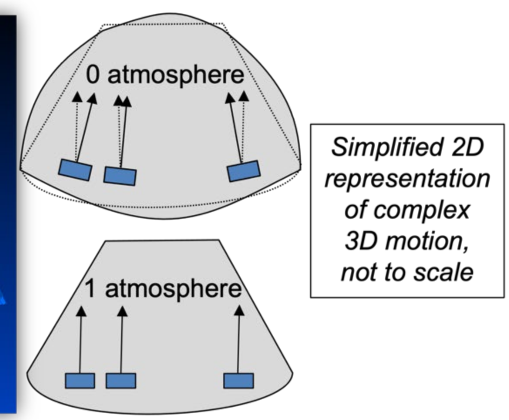
- Image above: Whiteboard sketch detailing the fundamentals of the 4-Channel architecture.
- Image right: Documentation of Artemis I Nav implementation
- 3 – Aided channels + 1 – Inertial propagation only channel
- 4 – Modular EKFs for all flight phases (easy to add more as needed)
- Sensor SOPs and FDIR + EKF FDIR
- Source select and Altitude select logic



“Navigation Base” – Compromises Hurt

- Most spacecraft have a rigid “Nav Base” with co-located IMUs and Star Trackers (STR).
  - Allows for stable alignment between sensors needed for attitude and gyro error estimation
- IMUs are needed for the entire mission so they must be located on the Crew Module (CM).
- STRs need a sun shield to protect optics and need to penetrate the outer mold line to see stars.
  - Sun shield that could withstand the heat of entry would be very heavy
- Nav Team challenged to put the STR on the Crew Module Adaptor (CMA).
- In addition, configurators required one of the IMUs had to be located on the opposite side of the vehicle.
- A successful design was implemented to estimate the STR-IMU alignment by processing STR measurements while rotating the vehicle.
  - Assumes reasonably stable structure between alignment maneuvers
- Later discovered that the pressure vessel deflected (ballooned) in vacuum and from aerodynamic loading during entry
- Mostly impacted IMU FDIR – had to increase thresholds and persistence
- On-orbit alignment process still worked well, and the vehicle structure was stable between maneuvers
- Lesson: have a ”Nav Base” if possible.



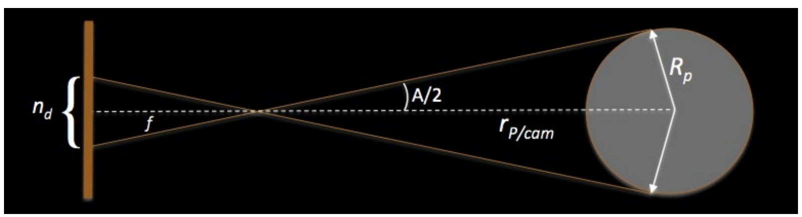


Return with Permanent Comm Loss – What?

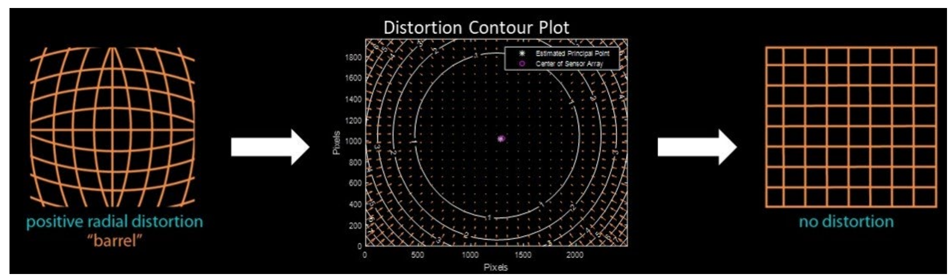
Orion has a requirement to return the crew home safely to Earth without communications with the ground. This core requirement drives Orion to be one of the most autonomous and automated vehicles to ever fly in space. Two primary capabilities evolved to satisfy this requirement: Optical Navigation (OpNav) and Onboard targeting and burn execution.

Autonomous Optical Navigation – First Time Ever

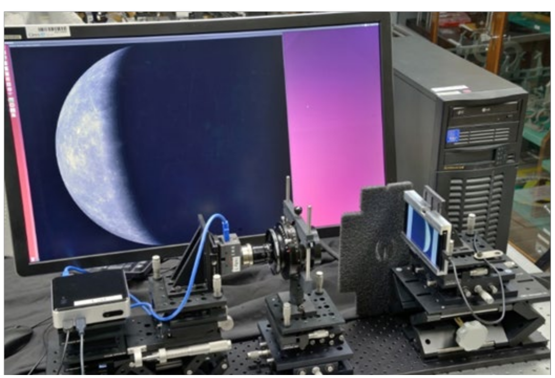
- In place of conventual Earth-based ground tracking navigation, OpNav is the process of computing a bearing and range measurement to a known celestial object like a planet or moon.
- General technique demonstrated on Apollo but with humans using a sextant (star-limb meas).
- Executed in various forms for un-maned spacecraft with most of the processing done on the ground.
- Orion OpNav uses a special camera and custom image processing and lens calibration to derive the bearing and rang to the Earth or Moon.
  - Also provides backup to star tracker for inertial attitude (ground process for Artemis I, onboard for Artemis II+)
  - Successfully certified during Artemis I and demonstrated the first-ever fully autonomous Optical Navigation capability.

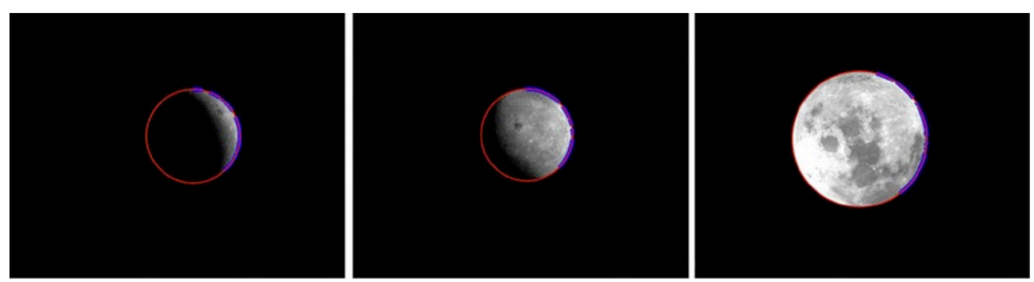


Basic OpNav Measurement Geometry



Lens Calibration

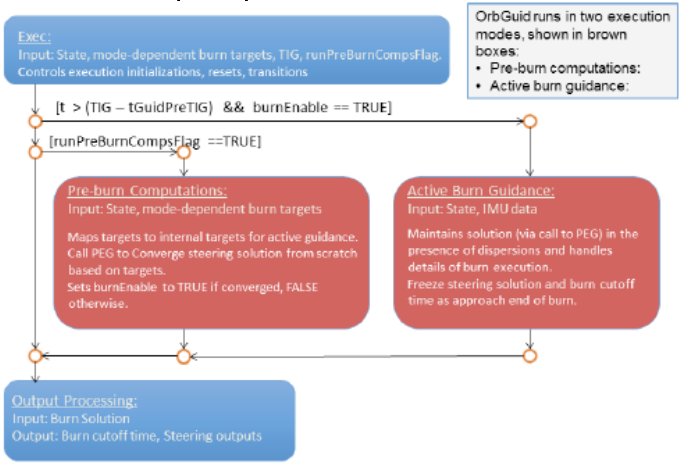

HW-in-the-loop


Artemis I Detected Limb and OpNav solution projected over lunar image

Autonomous Onboard Targeting and Burn Execution – Most Sophisticated Ever

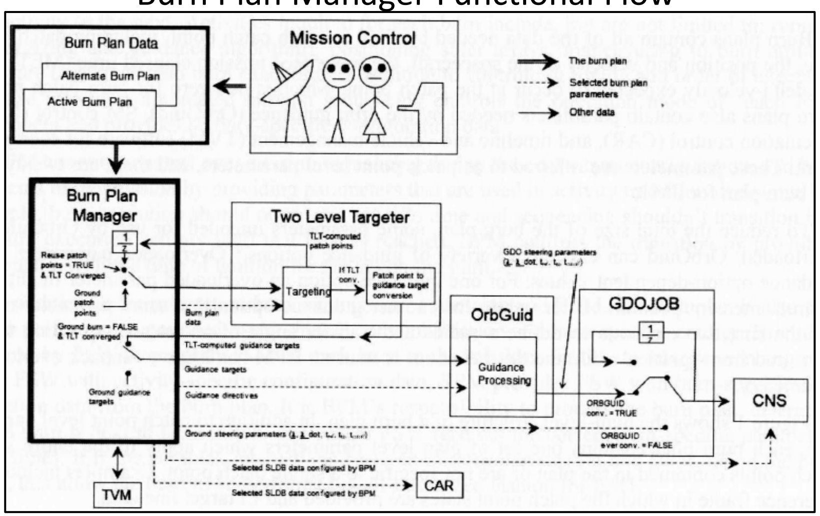
- Without ground support, Orion must plan, target, and execute all burns needed to get home.
- Burn Plan Manager (BPM) uses Burn Plan (BP) data to drive onboard Two-Level-Targeter (TLT) to generate targets for orbit guidance (Orbguid).
- During burn execution Orbguid provides steering commands to Service Module (SM) Control (CNS).
- Timeline Vehicle Manager (TVM) uses BP data to control events, Solar Array Wing (SAW) positioning (CAR), and FSW configuration.
- Artemis I had two BPs available: one for nominal and one for the PCL scenario.

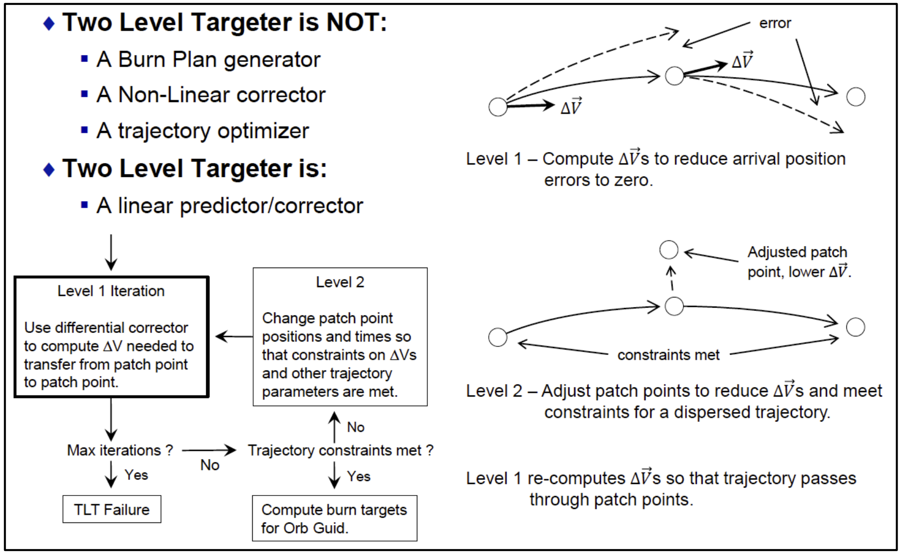
Orbguid: Executive drives core Power Explicit Guidance (PEG) with desired burn solution type.



TLT: Loop 1 iterates on position, Loop 2 applies additional constraints, repeat loops till converged

Burn Plan Manager Functional Flow



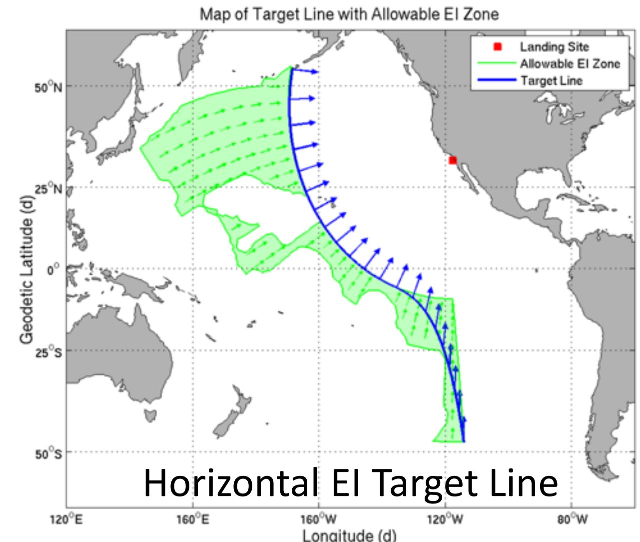


Time to Come Home – Returning to Earth

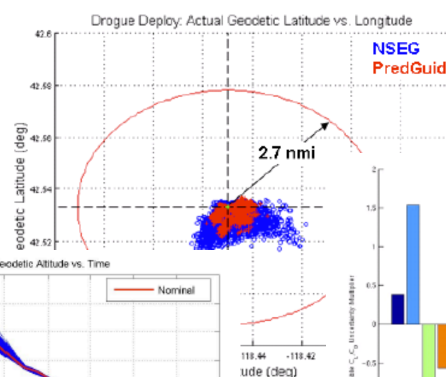
After a long journey to the Moon and back, Orion returns to Earth at incredible speed. All that energy must be dissipated to slow the vehicle down so parachutes can be deployed, and Orion can descend to a gentle splashdown in the Pacific Ocean off the coast of California.

Skip Entry Guidance – First Ever "Real" Skip Flown

- Skip entry enables Orion to return from the Moon with a variety of Earth-Moon geometries and still land off the coast of San Diego, California near Naval recovery forces.
  - Lift vector rolled up/down to control range (with a little cross range capability too)
  - Special Entry Interface (EI) target line utilized to setup approach.
- Early in the Orion Program there was a flyoff between NASA's Numerical Skip Entry Guidance (NSEG) algorithm and Draper's PredGuid algorithm.
  - Flyoff turned into more a merger and in the end PredGuid was chosen (though performance was similar).
- CM raise burn executed between CM/SM sep and EI used to fine tune the flight path angle (FPA) at EI.
  - FPA is very critical for Orion due to mass-optimized heat shield



Horizontal EI Target Line



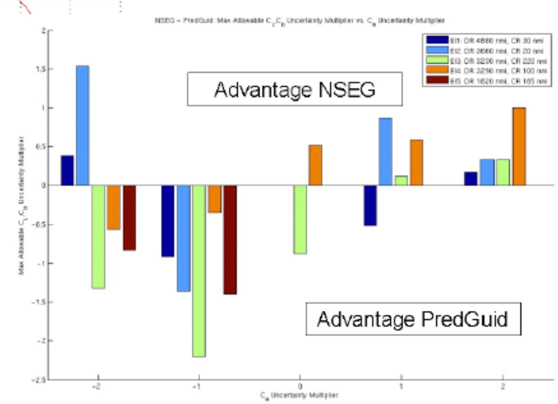
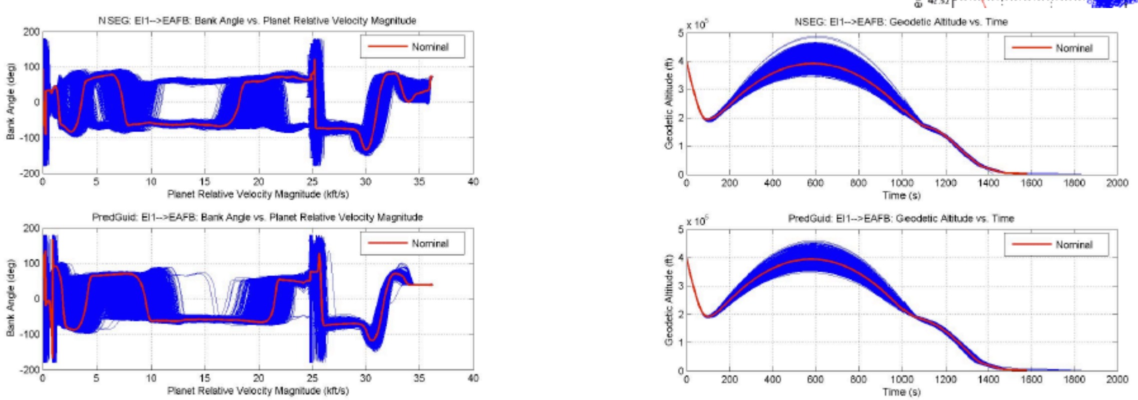


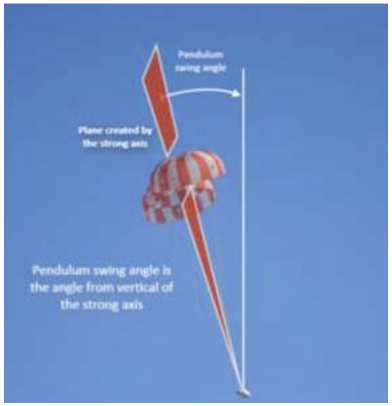
Figure 35. Aerodynamic Delta Figure-of-Merit.



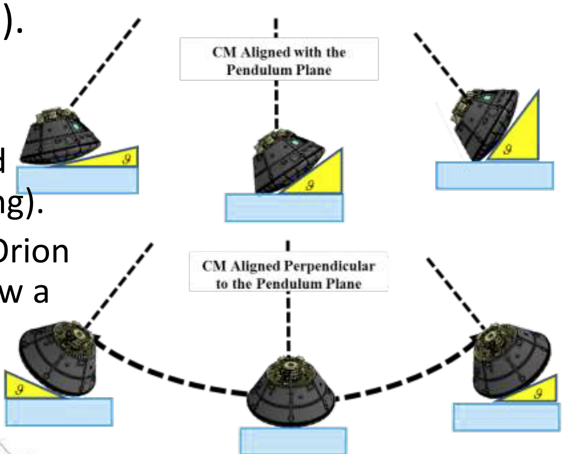
NSEG vs PredGuid Flyoff

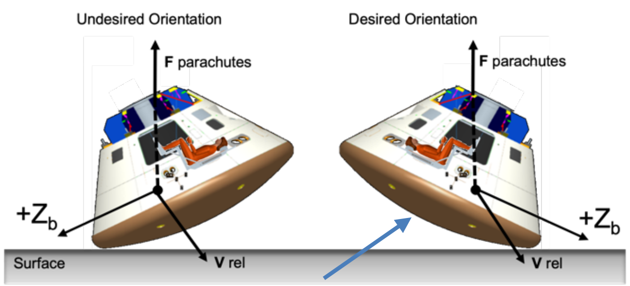
Touchdown Roll Control

- Orion must perform “Roll Control” or (Heading Control) under main parachutes to ensure CM impacts the water at a certain orientation.
  - Localizes impact loads to reduce structural mass and allows for seat stroke in a specific direction (only enough room in that direction and better for crew).
- The main parachute attach point is offset to produce a hang angle so Orion ”knifes” into the water.
  - Additional load reduction to save mass
- Roll Control points the vehicle in the direction of travel to slice into the water at the proper orientation (CM +Z Body axis).
- Just prior to EFT-1, a pendulum mode was discovered if descending under two parachutes (nominally there are three – requires a failure).
  - Could produce velocity direction changes too rapid for Roll Control to function.
  - Pendulum Observer developed to track the swing and remove the added velocity from the general direction of travel (controller can follow heading).
  - New control mode engaged if pendulum motion is present that orients Orion CM +Z Body perpendicular to the swing plane (if horizontal velocity below a threshold).
  - +Z Perpendicular to the swing plane reduces impact loads.

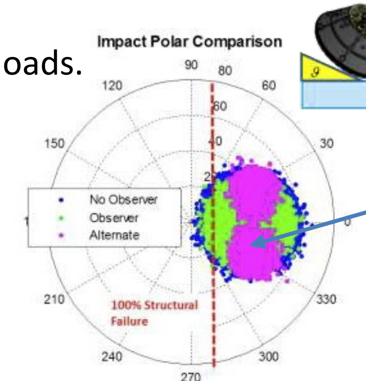


Pendulum Motion Under 2 Chutes





Desired Impact Orientation Relative to Direction of Travel



+Z Body perpendicular to Swing Plane (Alternate) moves impact point further to the edge of the Heat Shield reducing loads.

Questions?