National Aeronautics and Space Administration

5 . . . 4 . . . 3 . . . 2 . . . 1 . . .

SPACE LAUNCH SYSTEM

PEG Modifications & Enhancements for SLS Block-1 and Block-1B Vehicles

Paul Von der Porten, MSFC
Naeem Ahmad, MSFC
Matt Hawkins, MSFC/ESSCA/Jacobs Engineering
Thomas Fill, Charles Stark Draper Laboratory

2018 AAS GNC Conference

Outline

- Introduction
- Block-1 Modifications to Powered Explicit Guidance (PEG) Since Shuttle
- Block-1B 1-target VS 2-target Ascent Guidance Problems
- Block-1-to-Block-1B Enhancements
- Conclusion

Introduction

- **Marshall Space Flight Center (MSFC) Guidance, Navigation, & Control (GN&C) Team has an expanded responsibility going from Space Launch System (SLS) Block-1 to Block-1B vehicles**
  - Characteristics of Block-1 ascent burn allow for use of a modified version of Space Shuttle's Powered Explicit Guidance (PEG) algorithm
  - Long-arc burns and the need to carry out Lunar Vicinity and Earth Escape missions require enhancements to PEG for Block-1B

MSFC	Block-1	Block-1B
GN&C Responsibility	Ascent Only	Ascent and In-space
Guided Burns	Core Stage (CS) Ascent Burn to Low Earth Orbit (LEO)	CS/EUS Ascent Burns to LEO, Apogee Raise Burn (ARB), Trans-Lunar Injection (TLI), Earth Departure Burn (EDB), Settling Motor Disposal Burn
Guidance Algorithm	Modified Shuttle PEG	Enhanced Shuttle PEG

Block-1 Modifications to PEG Since Shuttle

- **Block-1's ascent burn arc (~13°) similar size as Space Shuttle**
  - Allows for straight adaption of Shuttle's PEG with the ascent desired velocity mode
- **Modifications:**
  - Multi-phase PEG and PEG Phase Manager
    - Replaces Shuttle's algorithmic approach to switch between 3 phases for a data-driven approach
    - Moves calculation of most burn times and all mass-flowrate-to-initial-mass time constants out of time-to-go computation algorithm into an outer loop wrapper
  - Lofting parameter for Launch Abort System Jettison
    - Induces additional lofting by applying an altitude bias to the desired radius magnitude
  - Engine-Out Logic
    - Uses inertial velocity to decide if an alternate mission target is needed in response to a CS engine-out
  - Thrust Factor
    - Similar to Shuttle's FT_FACTOR
    - Provides updated propulsion knowledge to PEG

Modifications allow an outer loop to drive PEG for Block-1

Block-1B 1-target VS 2-target Ascent Guidance

- **Block-1B Ascent Profile**
  - Boost stage: Two Solid Rocket Boosters and CS engines burn to booster separation
  - CS burn: CS engines burn to intermediate point in ascent trajectory
  - EUS Ascent: EUS engines burn to LEO insertion
- **Two flight techniques studied early in Block-1B design:**

	1-target	2-target
CS Burn Approach	Burn to completion	Targeted burn with flight performance reserve
EUS Ascent approach	Targeted burn with flight performance reserve	Targeted burn with flight performance reserve
PEG Modeling	Entire burn arc (~50°) from booster separation to LEO	Separate targeted burns for CS and EUS Ascent (i.e. PEG reset for EUS Ascent burn)

- **2-target baselined for Block-1B**
- **1-target presented several convergence issues that led to several bullet-proof enhancements to PEG kept for Block-1B**

Challenging 1-target guidance problem led to several bullet-proofing enhancements for PEG

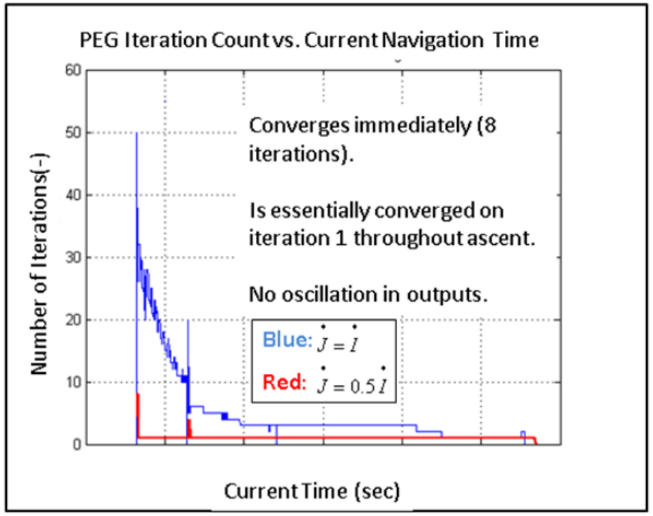
Block-1-to-Block-1B Enhancements

- **Safeguards for Constructing Turn Rate Vector**
  - Limiting Tangent of Thrust Angle
    - Useful initial strategy to limit turn rate magnitude
    - Bullet-proof enhancement from 1-target problem
  - Elevation-limit
    - Shuttle heritage
    - Ensures thrust direction from PEG's steering law does not have a component retrograde compared to cutoff radial direction
    - Required to close engine-out 2-target scenarios
  - Sign Reversal of Thrust Turning Rate Vector
    - Constructs augmented coordinate frame to protect orthogonality constraint from yielding a thrust turning rate sign reversal
    - Bullet-proof enhancement from 1-target problem

Safeguards developed for Turn Rate Vector to address stress situations due to long-arc burns

Block-1-to-Block-1B Enhancements

- **Scaling Identity Jacobian in PEG Corrector**
  - Applies a contraction factor to PEG's traditional Identity matrix Jacobian as a simplified scheme to improve PEG's convergence for long-arc burns
  - Bullet-proof enhancement from 1-target problem
- **Plane Constraint Strategy**
  - Strategy to unify plane constraint for both ascent and in-space burns
  - PLANE_OFF, RV_NULL, V_NULL, INTERCEPT
- **New Desired Velocity Routines**
  - Linear Terminal Velocity Constraint
    - Shuttle heritage
    - Used for ARB and TLI burns
  - Hyperbolic Target

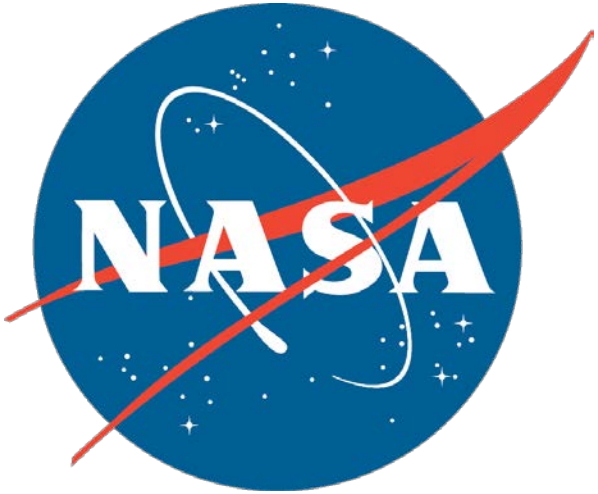


Additional enhancements bullet proof PEG and make PEG capable of carrying out Block-1B missions

Conclusion

- Space Shuttle PEG modified to accommodate initial evolution of SLS, Block-1
- Several enhancements to PEG required going from Block-1 to Block-1B to carry out demanding Block-1B missions
- Improvements make PEG capable for use on the SLS Block-1B vehicle as part of the GN&C System

Thank you!



Any questions?

National Aeronautics and Space Administration

5 . . . 4 . . . 3 . . . 2 . . . 1 . . .

SPACE LAUNCH SYSTEM

BACKUP

PEG Linear Tangent Guidance Geometry