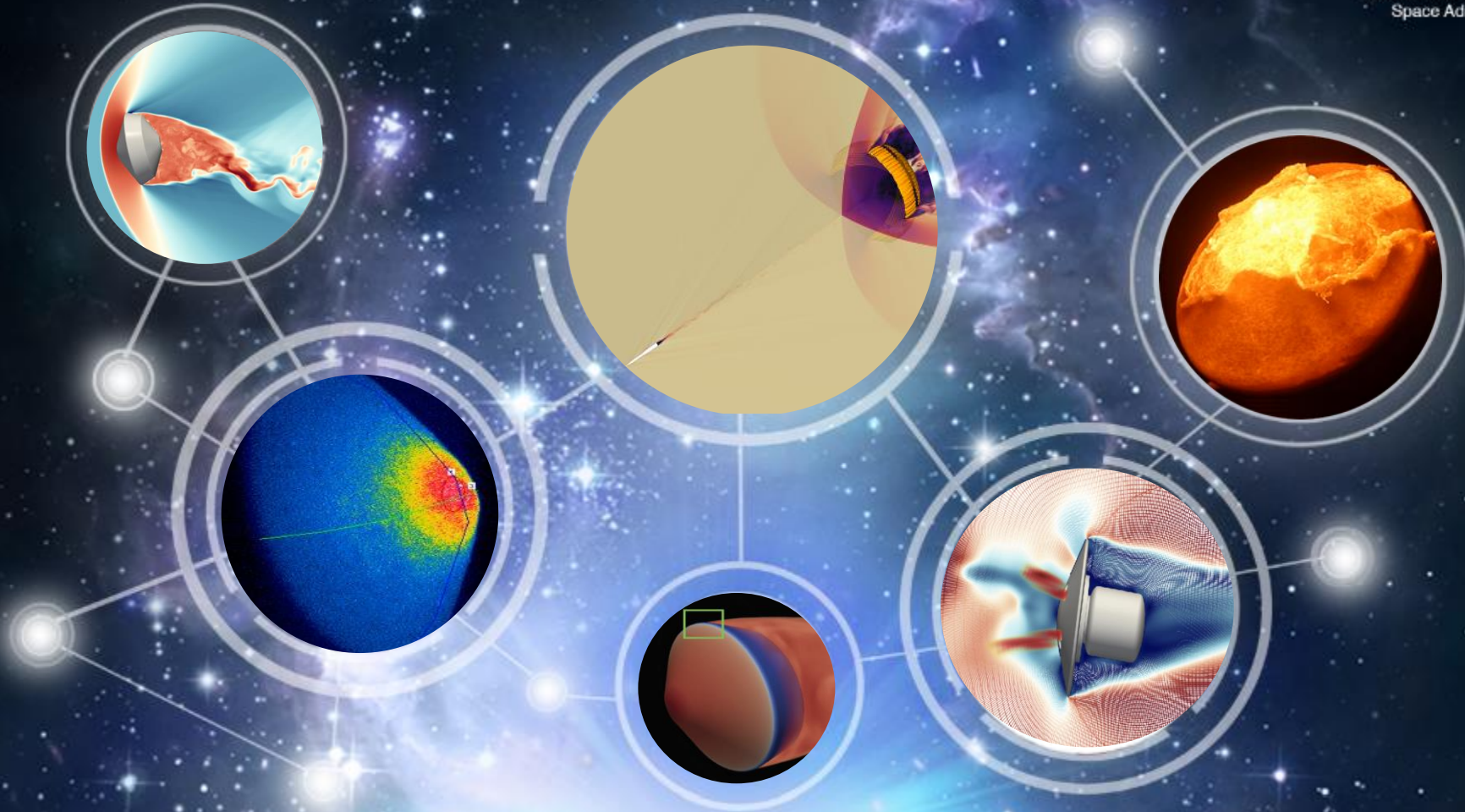


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National Aeronautics and
Space Administration



Performance Analysis of SmallSat Aerocapture at Venus

Rafael Lugo & Soumyo Dutta (NASA Langley Research Center)

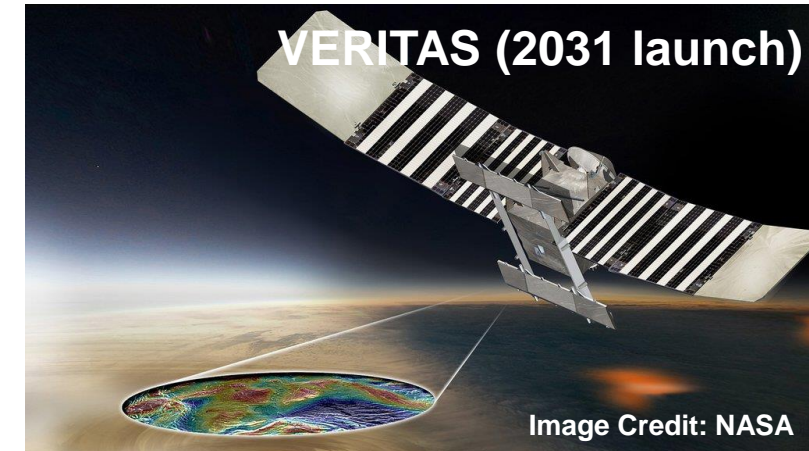
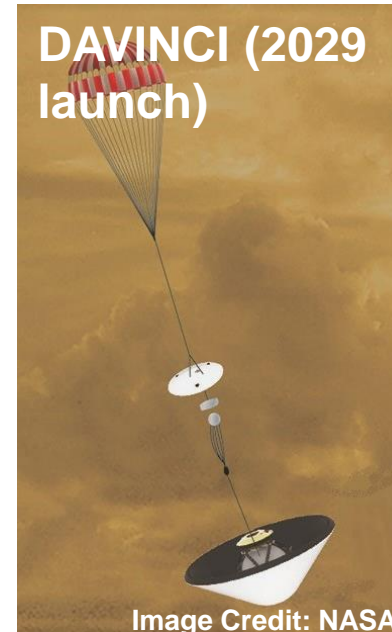
Daniel Matz & Breanna Johnson (NASA Johnson Space Center)

Alejandro Pensado, Evan Roelke, John Aguirre, and Richard Powell (Analytical Mechanics Associates)

AIAA SciTech Forum | 23-27 January 2023

Overview

- **Increased scientific interest in exploration of Venus**
 - Two NASA missions approved in 2021
- **Entry Systems Modeling (ESM) project**
 - Tasked with advancing understanding of atmospheric entry system performance across NASA through modeling & simulation
- **Use this opportunity to construct a guidance flyoff framework**
 - Test novel guidance algorithms and architectures in multiple simulations
 - Identify processes needed to get to “apples-to-apples” simulation setup
 - Demonstrate initial cross-simulation flyoff verification & validation (V&V)
 - Utilize POST2 (LaRC) and Genesis (JSC) simulation environments
- **Application: Venus Aerocapture with notional “piggyback” smallsat (150 kg)**
 - Smallsat carried as secondary payload that is deployed/jettisoned



POST2: Program to Optimize Simulated Trajectories II

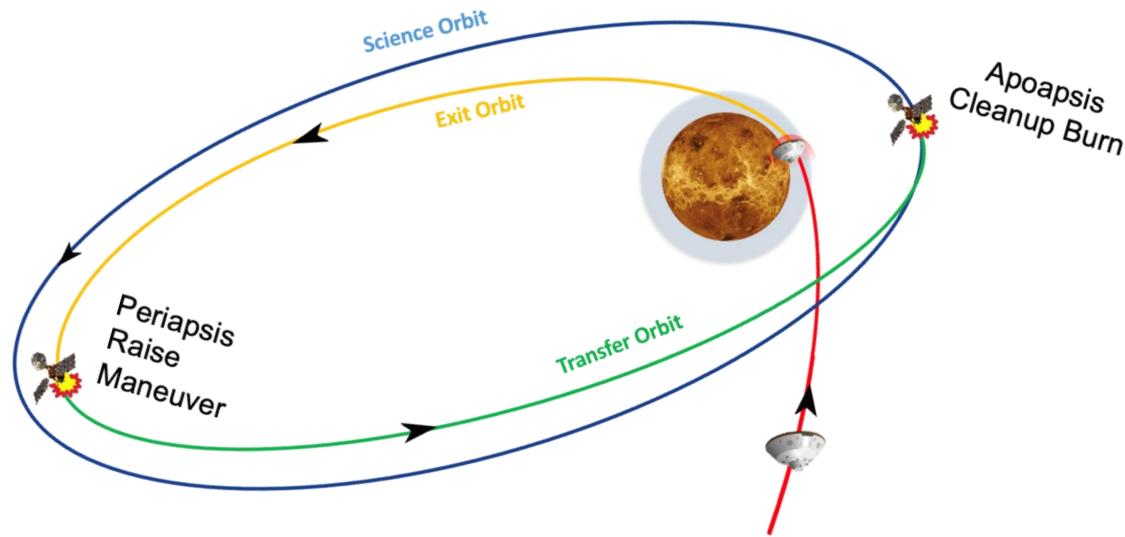
LaRC: Langley Research Center

JSC: Johnson Space Center

DAVINCI: Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging

VERITAS: Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy

Application: Venus Aerocapture



- **Develop an aerocapture problem**
 - Smallsat at Venus
- **LaRC and JSC teams use same:**
 - Vehicle configuration
 - Planet & atmosphere parameters
 - Initial conditions
 - Monte Carlo dispersions (using DAVINCI data for states)
- **Use CSV files that both simulations can directly ingest**
 - Maintain CSV files on Teams channel file area

Vehicle & Environment Parameters

| Category | Parameter | Units | Value |
|----------------|--|----------------------|---------------|
| Vehicle | Diameter | m | 1 |
| Vehicle | Nose radius | fraction of diameter | 0.25 |
| Vehicle | Mass | kg | 150 |
| Vehicle | Sideslip max angular rate | deg/s | 5 |
| Vehicle | Sideslip max angular acceleration | deg/s ² | 5 |
| Vehicle | Angle of attack max angular rate | deg/s | 5 |
| Vehicle | Angle of attack max angular acceleration | deg/s ² | 5 |
| Vehicle | Bank angle max angular rate | deg/s | 15 |
| Vehicle | Bank angle max angular acceleration | deg/s ² | 5 |
| Vehicle | Trim angle of attack | deg | -10 |
| Initial states | Velocity | km/s | 11 |
| Initial states | Azimuth | deg | -90 |
| Initial states | Flight path angle | deg | -5 |
| Initial states | Altitude | km | 150 |
| Initial states | Latitude | deg | 0 |
| Initial states | Longitude | deg | 0 |
| Initial states | Julian date | days | 2455504 |
| GN&C | Target apoapsis | km | 500 |
| GN&C | Target apoapsis tolerance | km | 10 |
| Aerothermal | Model | | Sutton Graves |
| Aerothermal | Constant | | 0.00019 |

| Category | Parameter | Units | Value |
|--------------|----------------------------|---------------------------------|-----------------|
| Simulation | dt | s | 0.1 |
| Environment | Gravitational acceleration | m/s ² | 9.80665 |
| Planet | Equatorial radius | km | 6051.8 |
| Planet | Polar radius | km | 6051.8 |
| Planet | mu | km ³ /s ² | 324860 |
| Planet | J2 | | 4.46E-06 |
| Planet | Rotation rate | hours | -5832.6 |
| Planet | EI Altitude | m | 1.50E+05 |
| Atmosphere | Model | | VenusGRAM 2005C |
| Aerodynamics | Model | | Genesis ADB |

14

Monte Carlo Dispersions

| Parameter | Units | Dispersion | Distribution |
|----------------------|---------|-----------------|--------------|
| Mass | percent | 0.5 | 3 sigma |
| Atmosphere | -- | VenusGRAM 2005C | |
| Velocity | m/s | 0.05045 | 3 sigma |
| Azimuth | deg | 0.022001 | 3 sigma |
| Flight path angle | deg | 0.117877 | 3 sigma |
| Latitude | deg | 0.223376 | 3 sigma |
| Longitude | deg | 0.038872 | 3 sigma |
| Number of MC Samples | N/A | 8000 | |

15

Simulation Environments

➤ Program to Optimize Simulated Trajectories II (POST2)

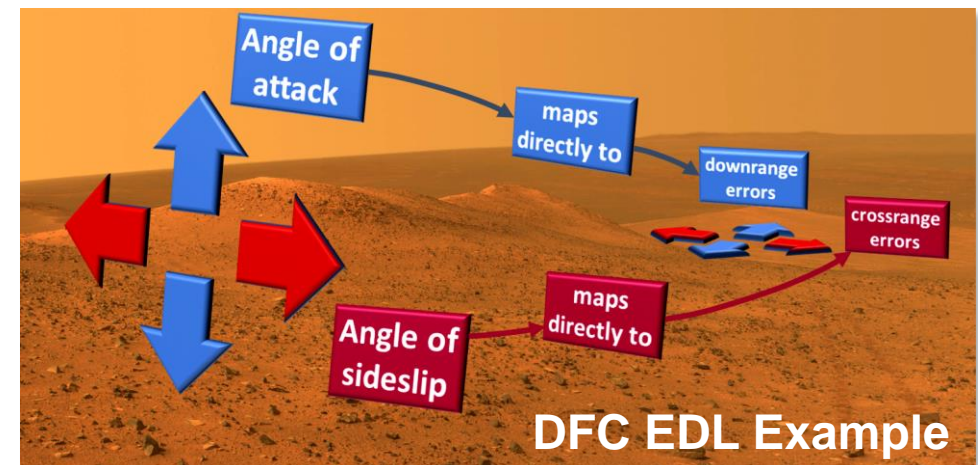
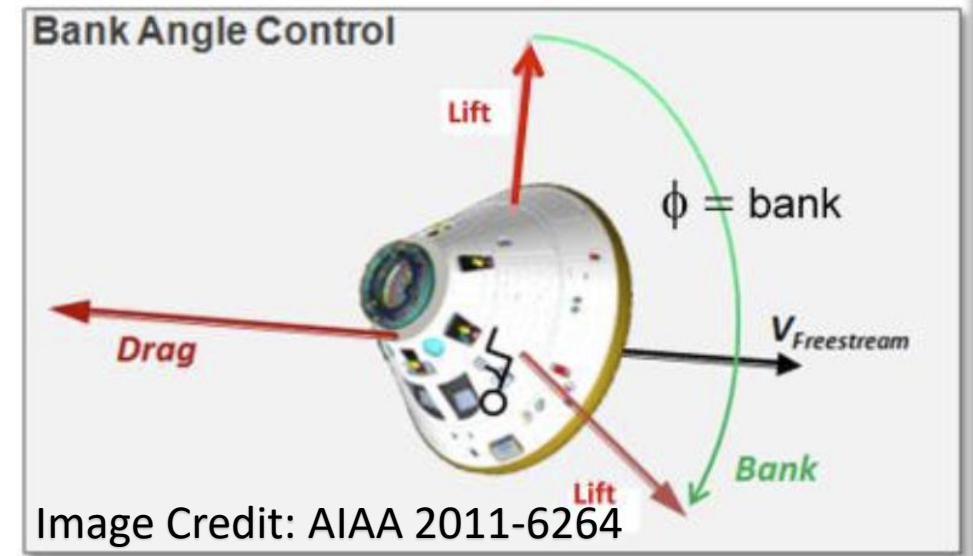
- 3/6/Multi-degree-of-freedom flight-validated simulation and assessment of:
 - endo- and exo-atmospheric flight about a planetary body
 - launch, orbital, and entry phases of flight
 - vehicle design, development, and flight operations
 - single or multiple vehicles working independently or in tandem
- Solves a variety of flight mechanics and orbital transfer problems
 - During preliminary design, can be completely input driven
 - Supports flight vehicle design and operations with detailed vehicle models and flight software code (C, C++, Fortran, Simulink...)
 - GN&C algorithm development and assessment
- Continuously developed and maintained at LaRC (C/C++)
- Recent updates to enable thread safety
 - AIAA SciTech 2023, Session MST-02

➤ Genesis

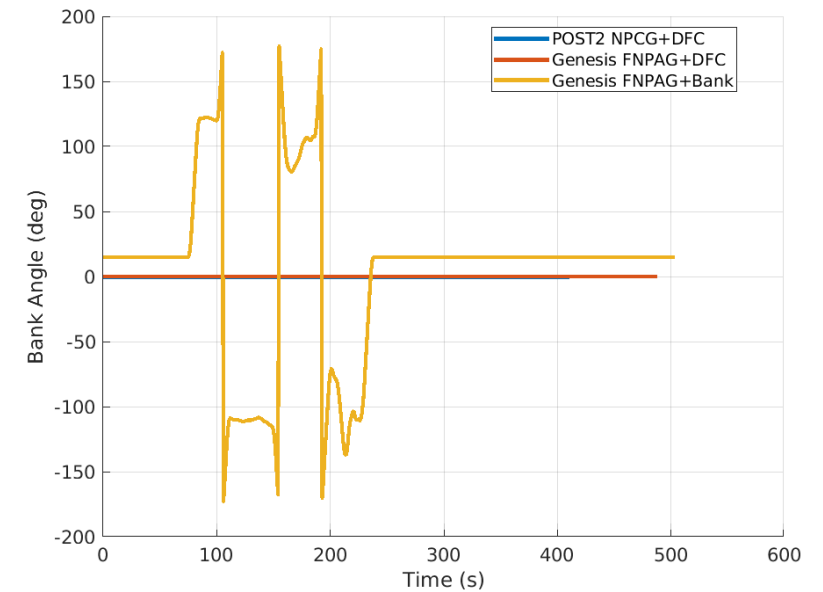
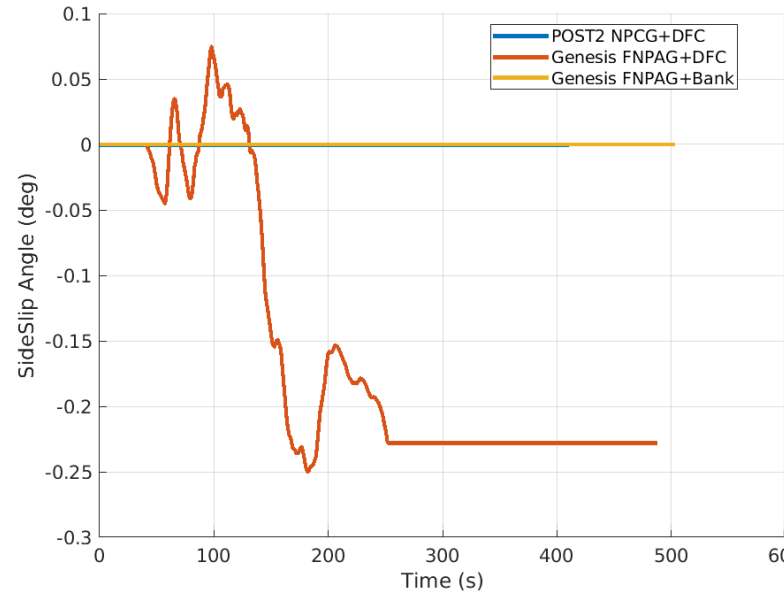
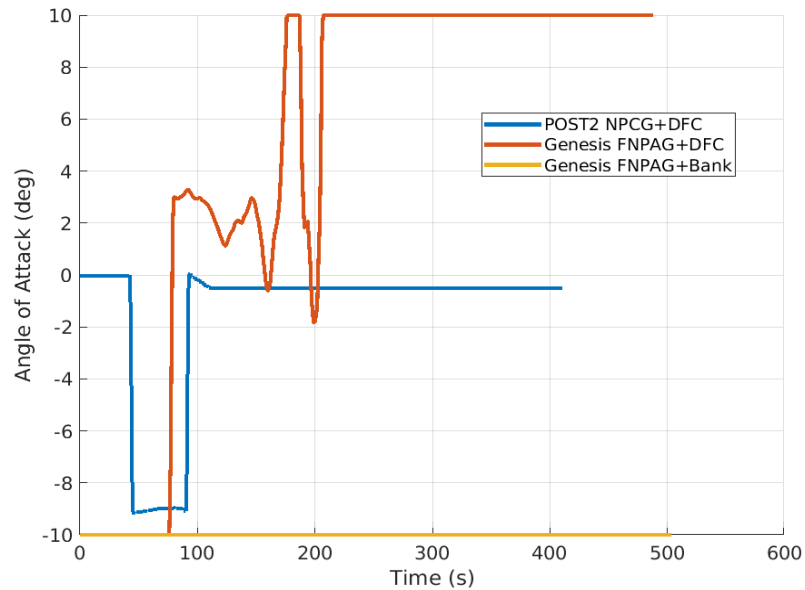
- Generic, variable-degree-of-freedom, multi-vehicle flight mechanics simulation
- Consolidates and modernizes several JSC tools (SORT, DSS, GEMASS, FAST)
- Developed over the last 3+ years by JSC with NASA Engineering & Safety Center (NESC) support
- Architected to better leverage modern high-performance computing (HPC) environments
- Standalone optimization or interoperability with Copernicus for end-to-end trajectory optimization
- Implemented in Julia

Guidance & Steering Algorithms

- **Generalized Numerical Predictor-Corrector Targeting Guidance (NPCG)**
 - Essentially, a framework that provides EOM integrator and targeting algorithms
 - User provides vehicle/environment models and control strategies (DFC, bank reversals, gravity turn, etc.)
 - User also provides control and constraint vectors – number of variables constrained only by compute power
- **Fully Numeric Predictor-corrector Aerocapture Guidance (FNPAG)**
 - Approximates the optimal aerocapture solution
 - Two-phase guidance that flies a lift-up, lift-down profile
 - Lateral channel for bank control commands a user-specified number of bank reversals to geometrically reduce the final wedge angle
 - Lateral channel for DFC uses a PD controller to command sideslip angle to null wedge angle



Results: Nominal Trajectory



➤ Clear differences in steering

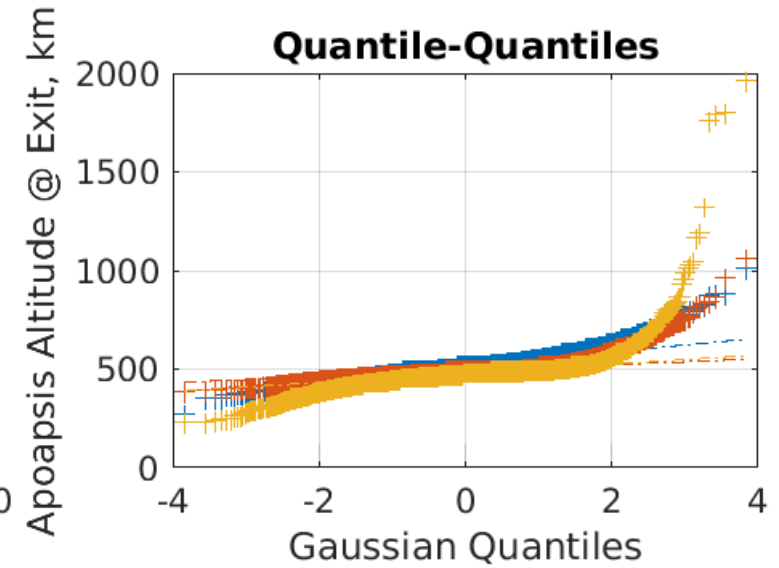
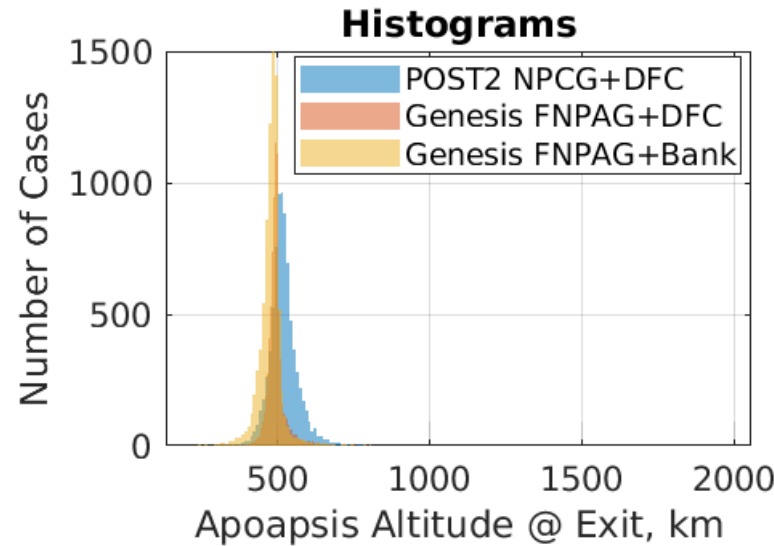
- FNPAG+DFC uses bang-bang steering, NPCG currently uses nominal 0/0 alpha/beta with steeper entry flight path angle to maximize margins
- FNPEG+DFC uses sideslip to control out-of-plane errors, NPCG leaves this channel constant 0

➤ However, overall performance is generally comparable (next slides)

Results: Exit Altitude of Apoapsis

- Key performance parameter
- Target: 500 km
- In-family performance across sims/guidances

— Genesis DFC shows tightest spread, Genesis Bank shows largest



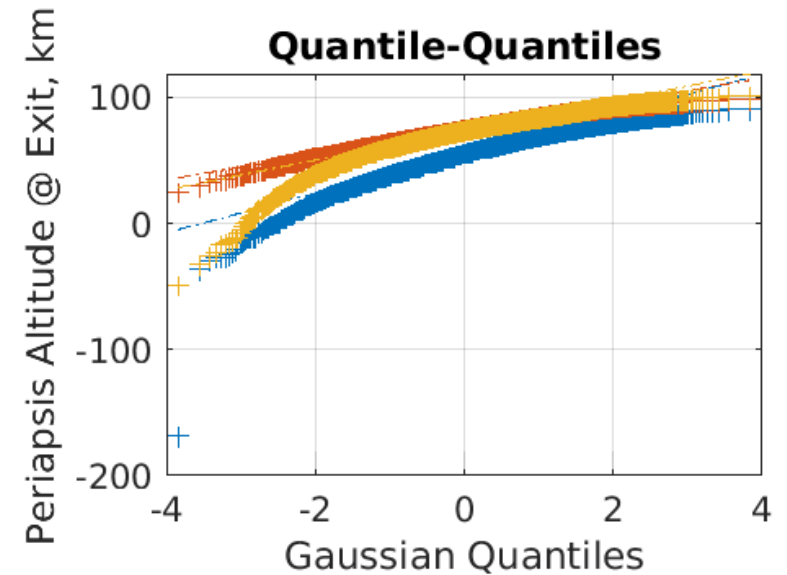
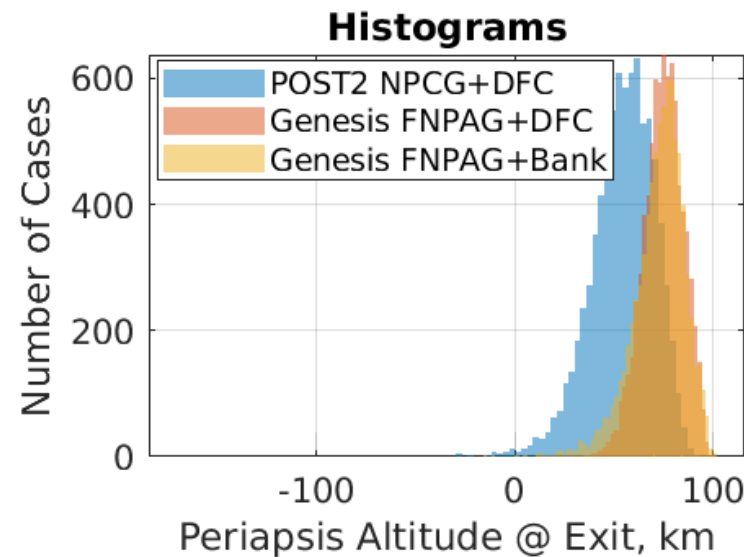
| | POST2 NPCG+DFC | Genesis FNPAG+DFC | Genesis FNPAG+Bank |
|--------------|----------------|-------------------|--------------------|
| Mean | 520.89 | 496.6 | 478.94 |
| 3-sigma | 142.89 | 104.77 | 165.63 |
| 1.00 %-tile | 416.57 | 435.35 | 356.02 |
| 99.00 %-tile | 674.83 | 637.14 | 635.64 |
| Max Value | 1012.3 | 1062 | 1960.6 |
| Min Value | 274.21 | 389.4 | 228.43 |

Results: Exit Altitude of Periapsis

➤ Impacts required clean-up ΔV

- NPCG+DFC shows higher spread (with one outlier)

➤ All approaches would likely benefit from additional tuning

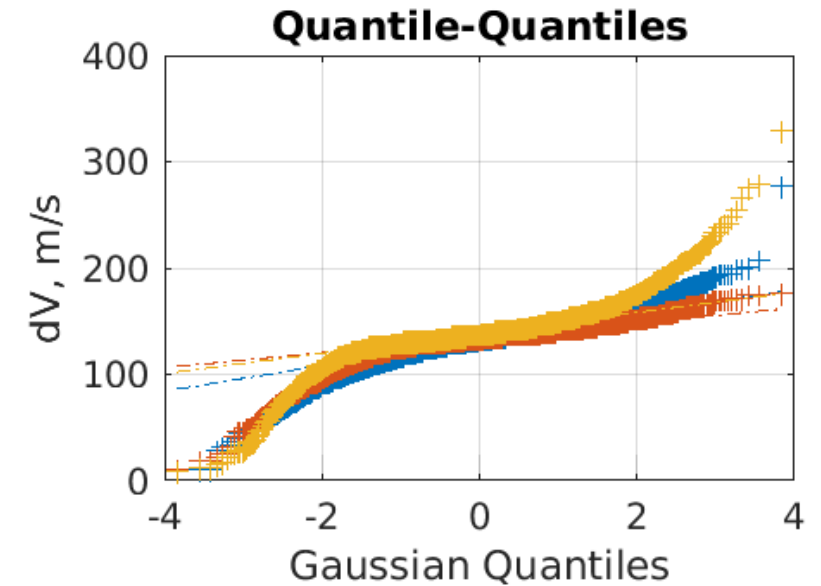
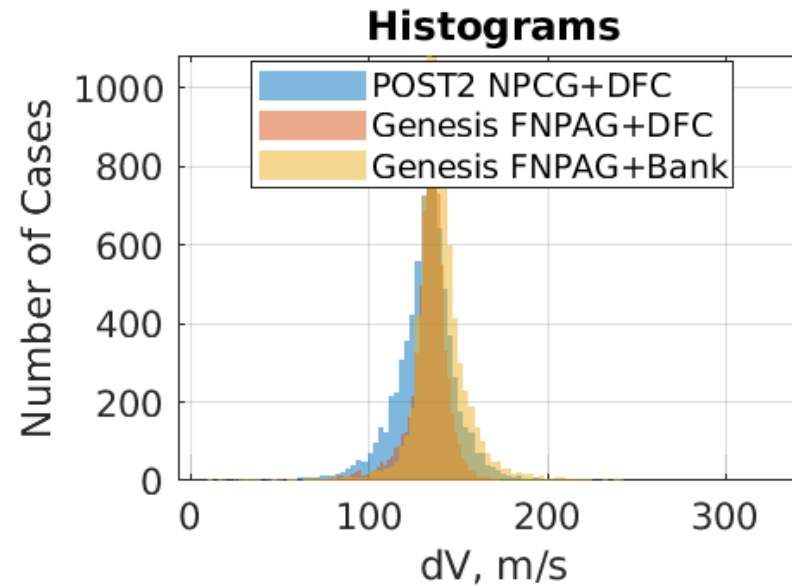


| | POST2 NPCG+DFC | Genesis FNPAG+DFC | Genesis FNPAG+Bank |
|--------------|----------------|-------------------|--------------------|
| Mean | 54.28 | 74.6 | 72.44 |
| 3-sigma | 48.69 | 30.41 | 40.96 |
| 1.00 %-tile | 7.31 | 48.4 | 28.61 |
| 99.00 %-tile | 83.17 | 94.35 | 96.08 |
| Max Value | 91.03 | 98.87 | 101.01 |
| Min Value | -168.21 | 25.3 | -49.02 |

Results: Clean-up ΔV

- Key performance parameter
- In-family performance across sims/guidances

— Genesis DFC shows tightest spread, Genesis Bank shows largest

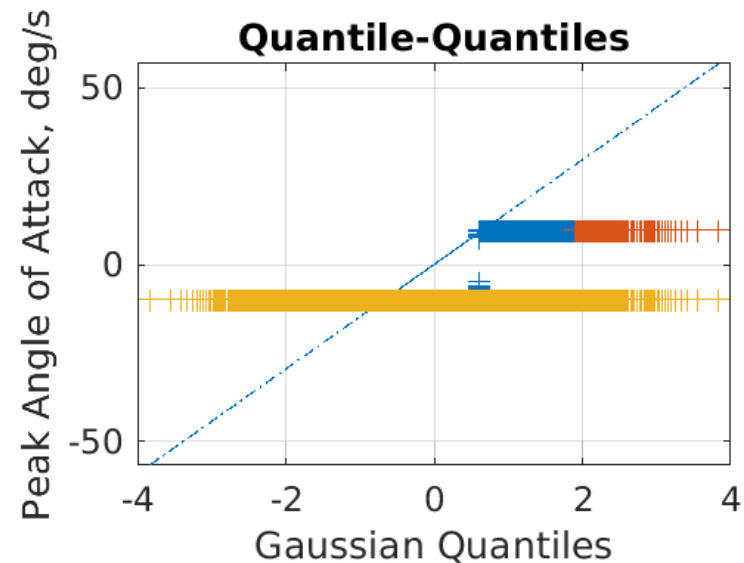
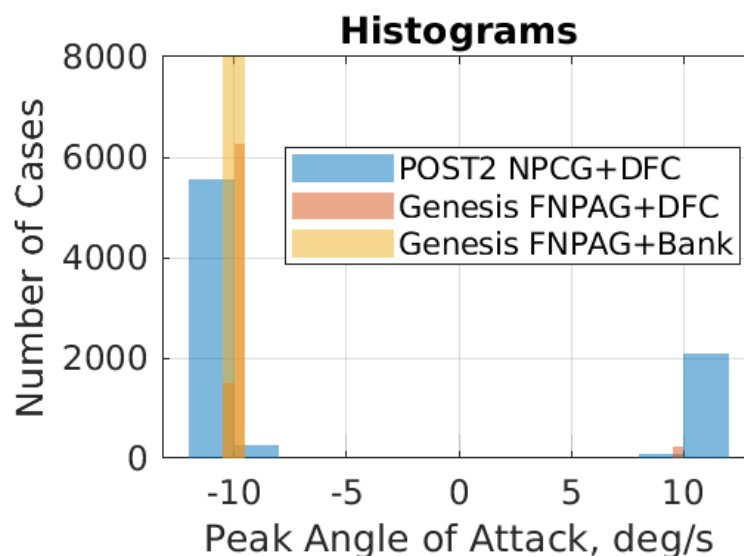


| | POST2 NPCG+DFC | Genesis FNPAG+DFC | Genesis FNPAG+Bank |
|--------------|----------------|-------------------|--------------------|
| Mean | 131.64 | 132.87 | 139.41 |
| 3-sigma | 51.42 | 38.08 | 50.22 |
| 1.00 %-tile | 76.28 | 83.93 | 86.92 |
| 99.00 %-tile | 172.34 | 157.08 | 190.85 |
| Max Value | 277 | 176.49 | 328.8 |
| Min Value | 9.68 | 10.49 | 9.75 |

Results: Peak Angle of Attack

- Bank approach flies constant angle of attack
- Both DFC implementations saturate at ± 10 degrees

— Great control authority possible with more angle of attack



| | POST2 NPCG+DFC | Genesis FNPAG+DFC | Genesis FNPAG+Bank |
|--------------|----------------|-------------------|--------------------|
| Mean | -4.55 | -9.42 | -10 |
| 3-sigma | 26.64 | 10.07 | 0 |
| 1.00 %-tile | -10 | -10 | -10 |
| 99.00 %-tile | 10 | 10 | -10 |
| Max Value | 10 | 10 | -10 |
| Min Value | -10 | -10 | -10 |

Summary and Forward Work

- **100% capture rate in all three Monte Carlo analyses**
- **First round of statistical comparisons between POST2 and Genesis shows differences, but in general are favorable**
 - Need to close the loop on initial condition dispersions and some GR&As
- **List of comparison parameters established**
 - E.g., peak G load, time of atmospheric flight, maximum bank angle, etc.
- **Deliverable/Portable Matlab-based tool suite used to compare trajectories and statistics**
- **ESM has continued funding for FY23**
 - Close out Venus aerocapture work
 - Begin new effort with EDL application

Team

➤ Langley Research Center

- Rafael Lugo
- Soumyo Dutta
- Alejandro Pensado
- Evan Roelke
- John Aguirre
- Richard Powell (retired)

➤ Johnson Space Center

- Daniel Matz
- Breanna Johnson



Backup

Vehicle & Environment Parameters

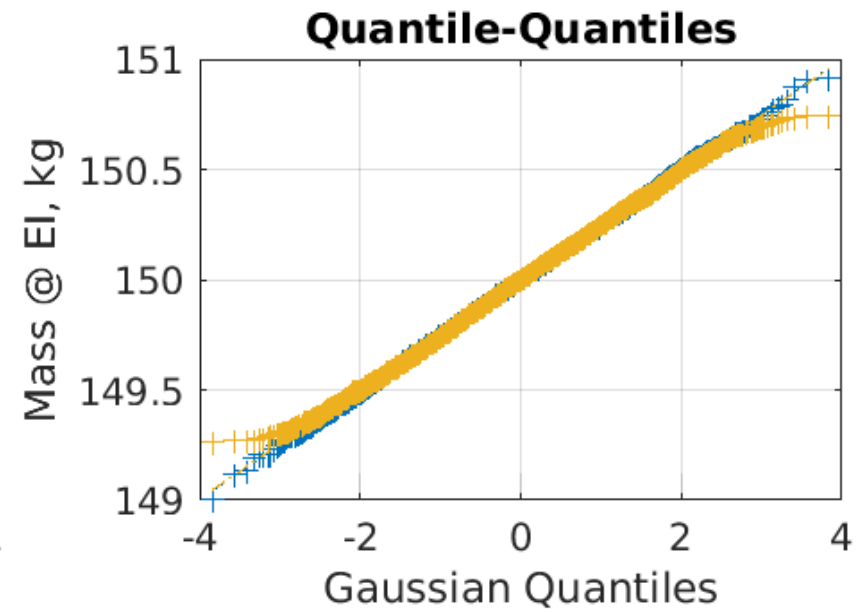
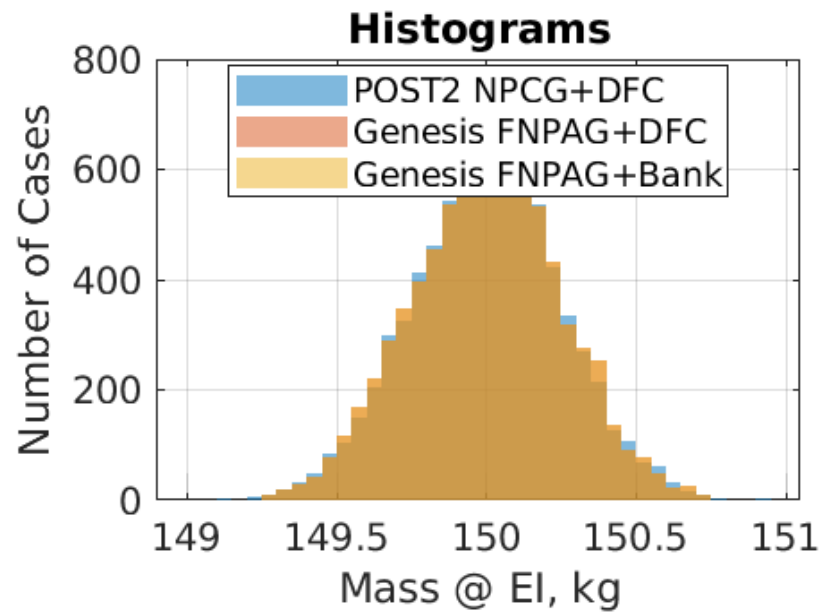
| Category | Parameter | Units | Value |
|----------------|--|----------------------|---------------|
| Vehicle | Diameter | m | 1 |
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| Vehicle | Sideslip max angular acceleration | deg/s ² | 5 |
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| Initial states | Julian date | days | 2455504 |
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| Aerothermal | Constant | | 0.00019 |

| Category | Parameter | Units | Value |
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| Planet | mu | km ³ /s ² | 324860 |
| Planet | J2 | | 4.46E-06 |
| Planet | Rotation rate | hours | -5832.6 |
| Planet | El Altitude | m | 1.50E+05 |
| Atmosphere | Model | | VenusGRAM 2005C |
| Aerodynamics | Model | | Genesis ADB |

Monte Carlo Dispersions

| Parameter | Units | Dispersion | Distribution |
|----------------------|---------|-----------------|--------------|
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| Atmosphere | -- | VenusGRAM 2005C | |
| Velocity | m/s | 0.05045 | 3 sigma |
| Azimuth | deg | 0.022001 | 3 sigma |
| Flight path angle | deg | 0.117877 | 3 sigma |
| Latitude | deg | 0.223376 | 3 sigma |
| Longitude | deg | 0.038872 | 3 sigma |
| Number of MC Samples | N/A | 8000 | |

Results: Mass at Entry Interface



POST2 NPCG+DFC

Genesis FNPAG+DFC

Genesis FNPAG+Bank

| | | | |
|---------------------|--------|--------|--------|
| Mean | 150 | 150 | 150 |
| 3-sigma | 0.75 | 0.75 | 0.75 |
| 1.00 %-tile | 149.41 | 149.43 | 149.43 |
| 99.00 %-tile | 150.59 | 150.57 | 150.57 |
| Max Value | 150.91 | 150.75 | 150.75 |
| Min Value | 149 | 149.27 | 149.27 |