

National Aeronautics and
Space Administration



Onboard Autonomous Trajectory Planning for Mars Power Descent

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Onboard Autonomous Trajectory Planning

➤ Motivation:

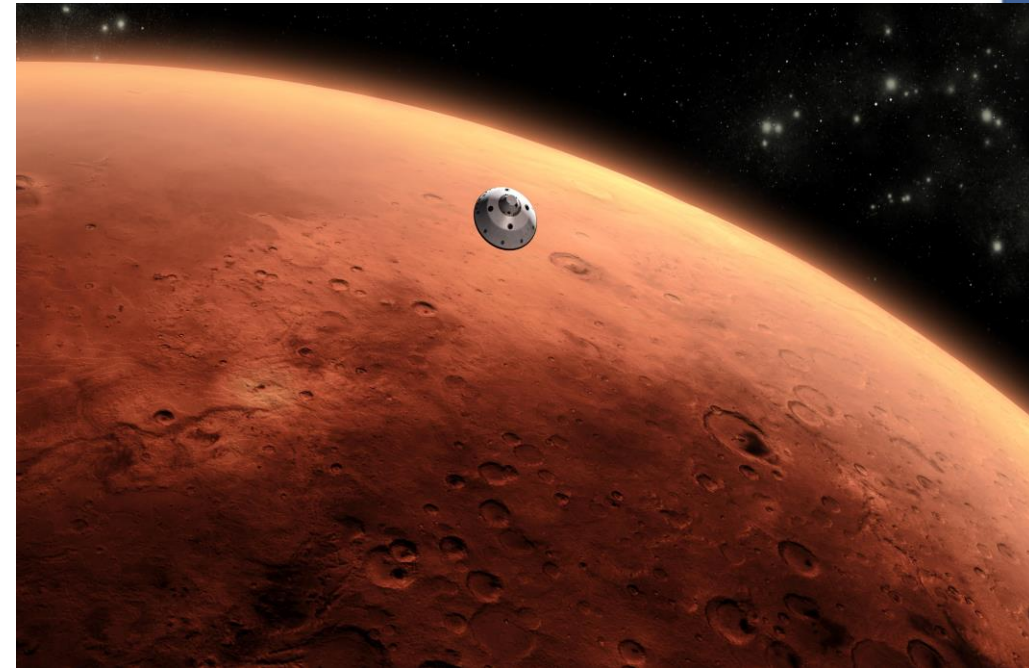
- Current landing precision for Moon and Mars is on the order of kilometers
- Future human and robotic missions require landing precision on the order of 10's m
- Onboard real-time guidance routine is required for missions landing payloads near the already existing ground assets

➤ Past Work:

- This work started with PhD work of Justin S. Green and evolved over the years with the support of center innovation funds and the Entry Systems Modelling (ESM)

➤ Objective of Current Work:

- Integrate onboard real-time powered descent guidance system into POST2 simulation that uses onboard sensor data to provide a robust trajectory optimization under uncertainty framework to achieve precision landing.



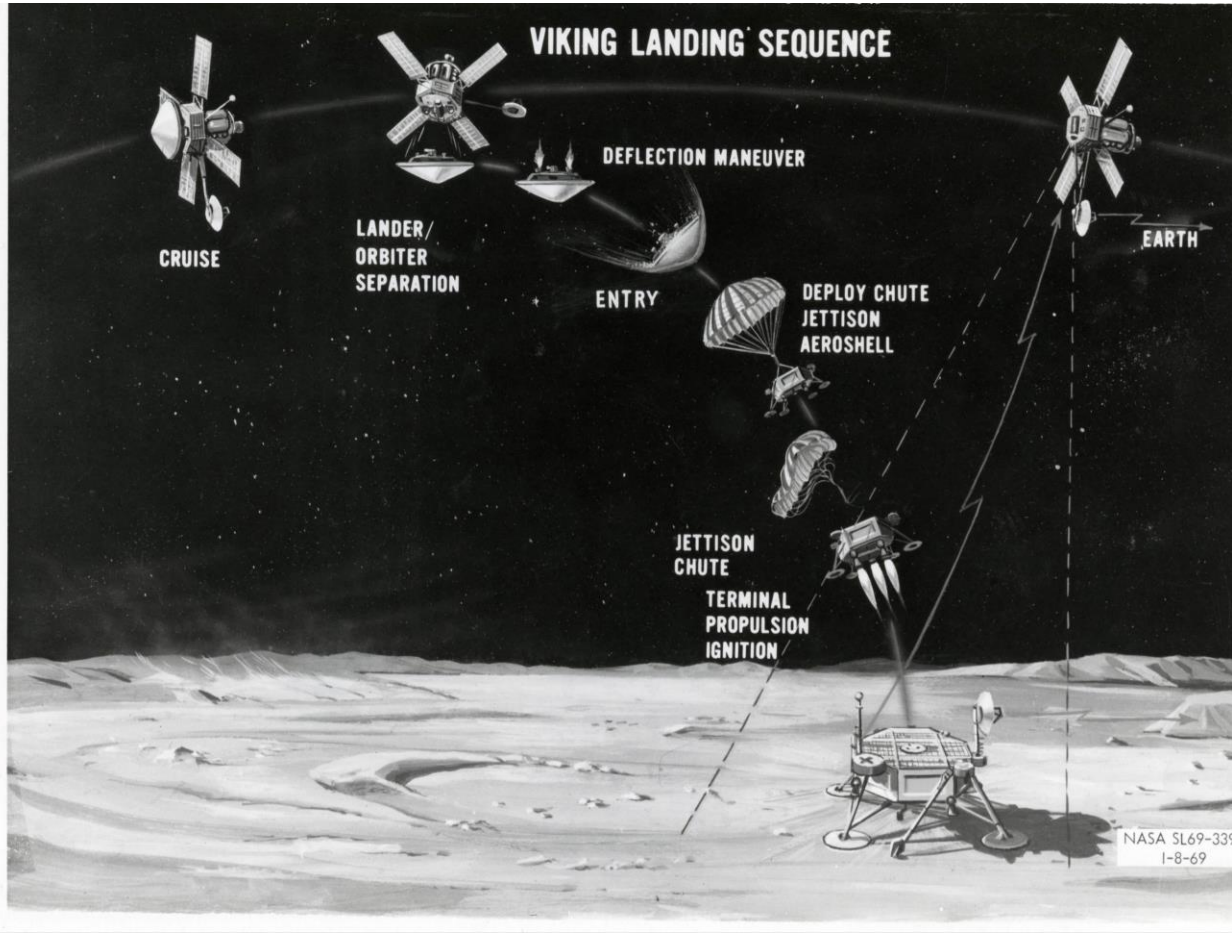


Outline

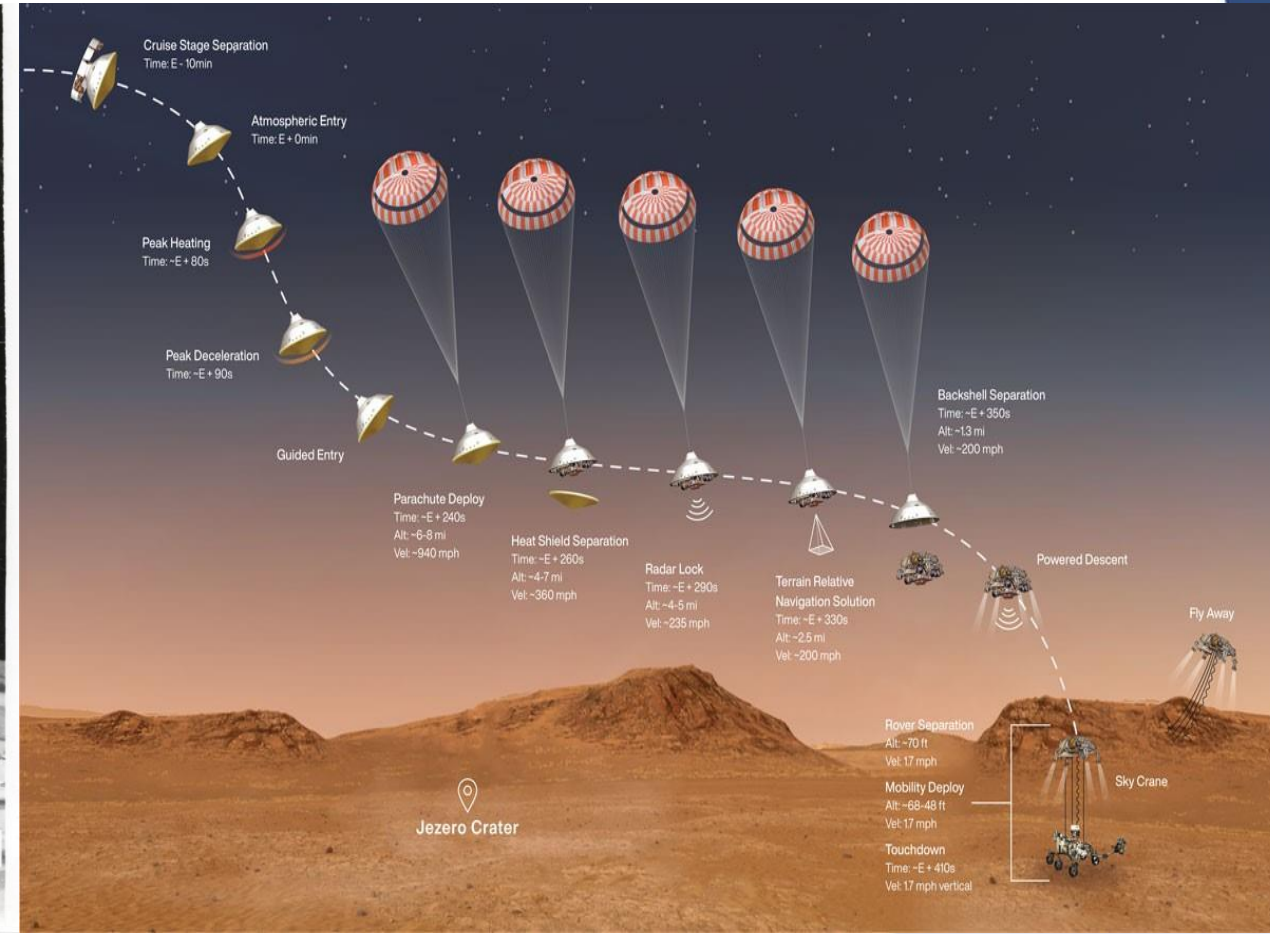


- **Powered divert guidance**
- **SMART guidance**
- **SMART guidance configuration**
- **SMART Guidance - POST2 interface**
- **Powered divert performance using SMART guidance**

Entry, Descent, and Landing (EDL) Mission Evolution

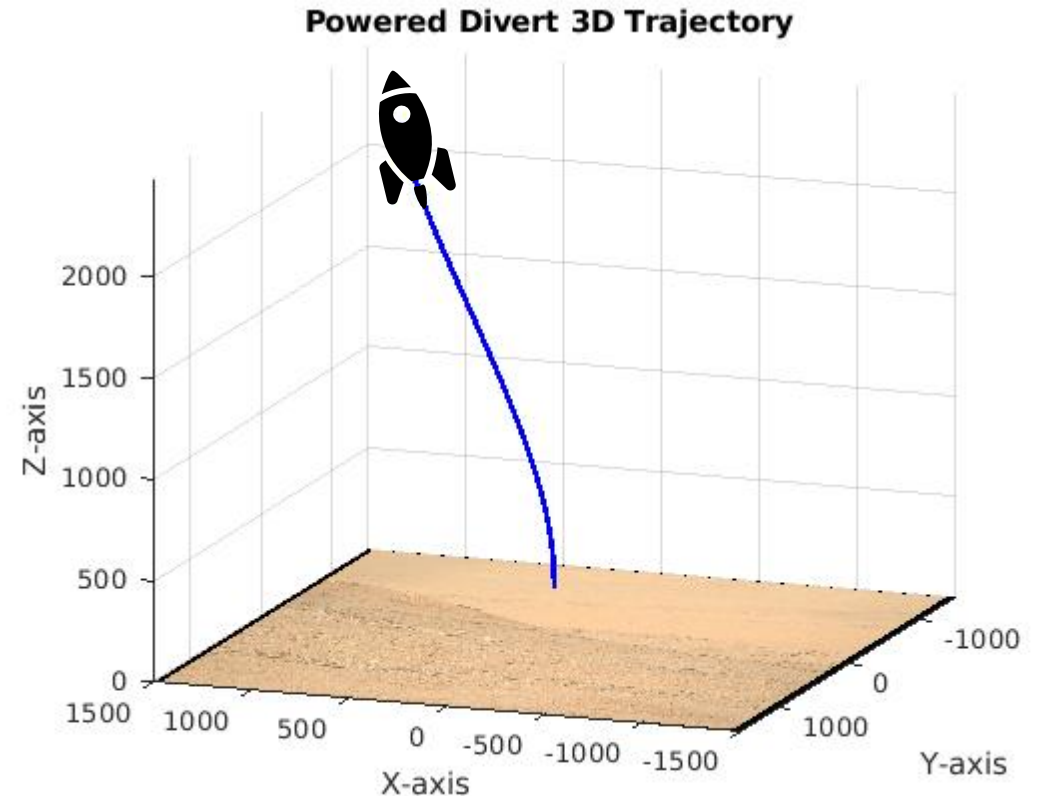


EDL Sequence for Viking in 1976 [1]



Perseverance Rover's EDL Sequence [1]

- **Human exploration and sample return missions will require pinpoint landing capability**
- **Several guidance schemes are available for powered divert**
 - Polynomial guidance
 - Predictor-corrector guidance
 - Guidance for Fuel Optimal Large Divert (G-FOLD)
- **Extensive offline trajectory analysis is required to determine the nominal guidance for the EDL missions**
 - To account for different uncertainties



➤ **Software for Multi-model Autonomous Real-time Trajectories (SMART) Guidance**

➤ **Measured conditions with smaller uncertainties can be obtained using the aggregated onboard sensor data.**

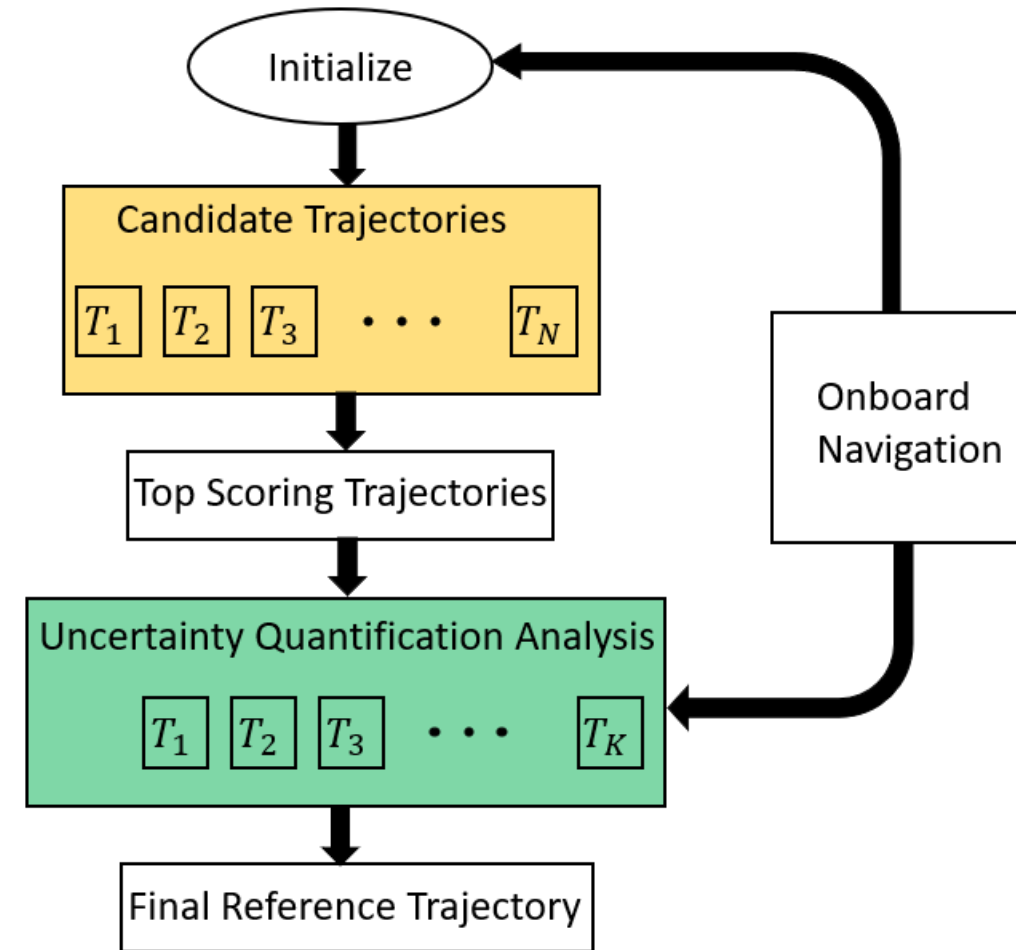
- Unavailable during the offline trajectory analysis

➤ **SMART guidance can determine the guidance on the fly by using the onboard sensor data**

- This is computational expensive

➤ **Several radiation-hardened processors are currently under development for space missions**

- Hewlett Packard Enterprise (HPE) Spaceborne Computer
- High Performance Spaceflight Computing (HPSC)
- These processors allows onboard parallel processing



SMART Guidance Commands

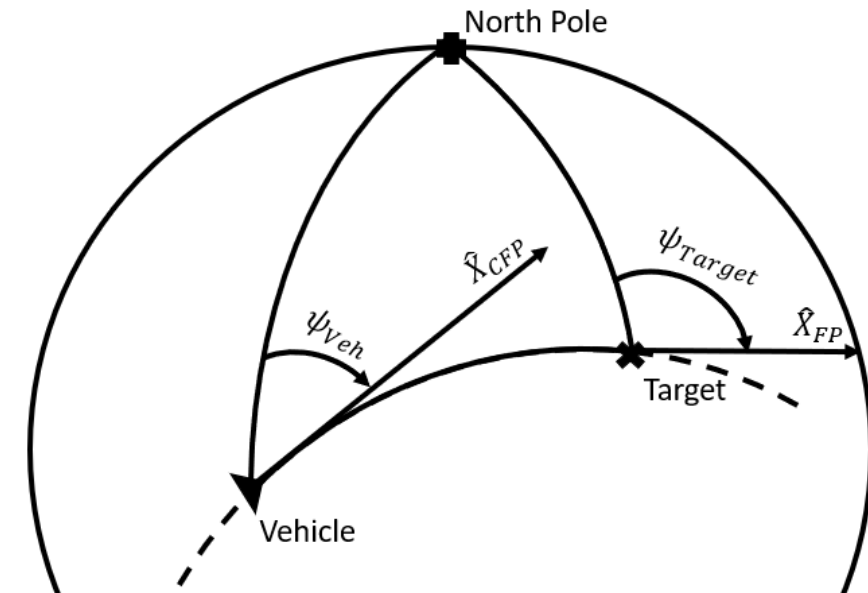
➤ The Flat Planet (FP) frame

- origin : At target location
- positive x-direction : Tangent to the arc joining the vehicle and the target along the shortest path at the origin
- Positive z-direction : Towards the planet's center
- Positive y-direction completes the right-hand rule

➤ The Carried Flat Planet (CFP) frame

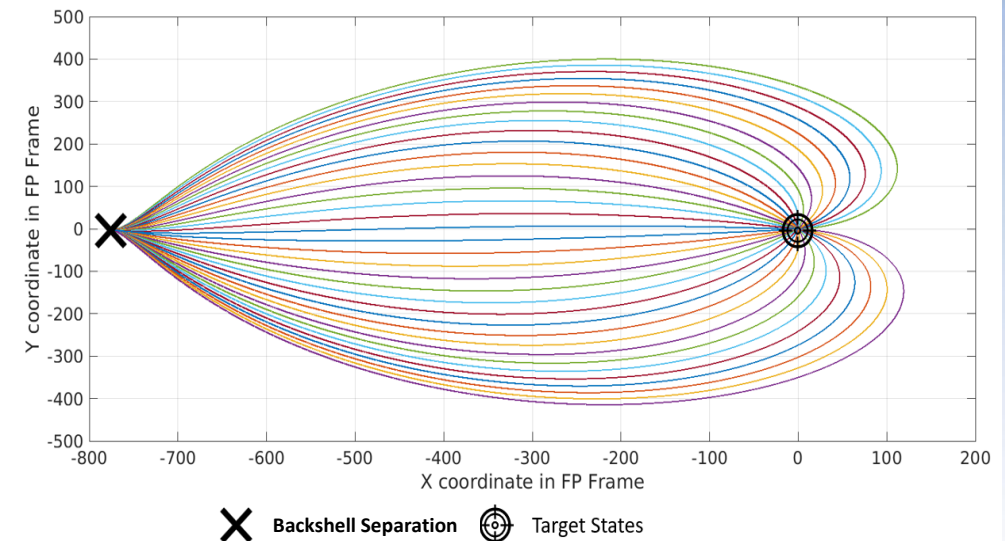
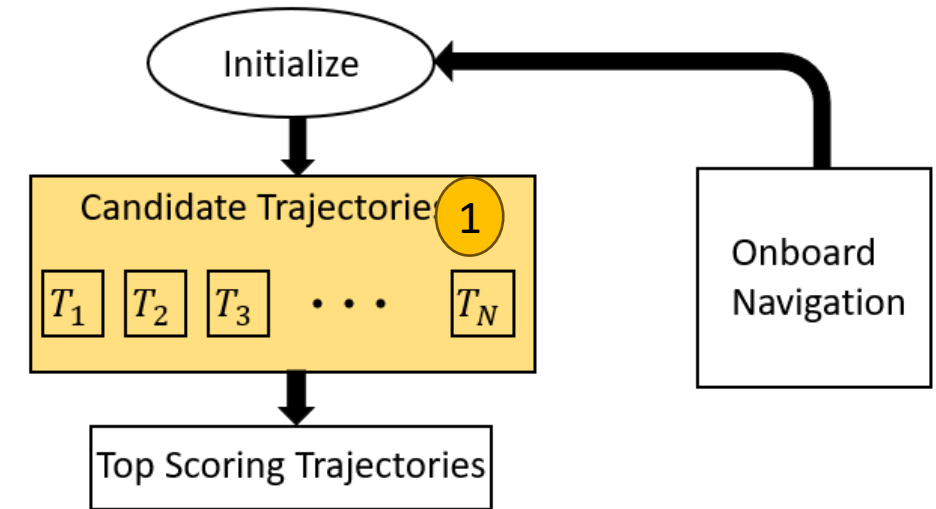
- origin : At vehicle CG location
- positive x-direction : Tangent to the arc joining the vehicle and the target along the shortest path at the origin
- Positive z-direction : Towards the planet's center
- Positive y-direction completes the right-hand rule

➤ The SMART guidance computes the reference commands in FP frame and issues commands in CFP frame for vehicle to track.

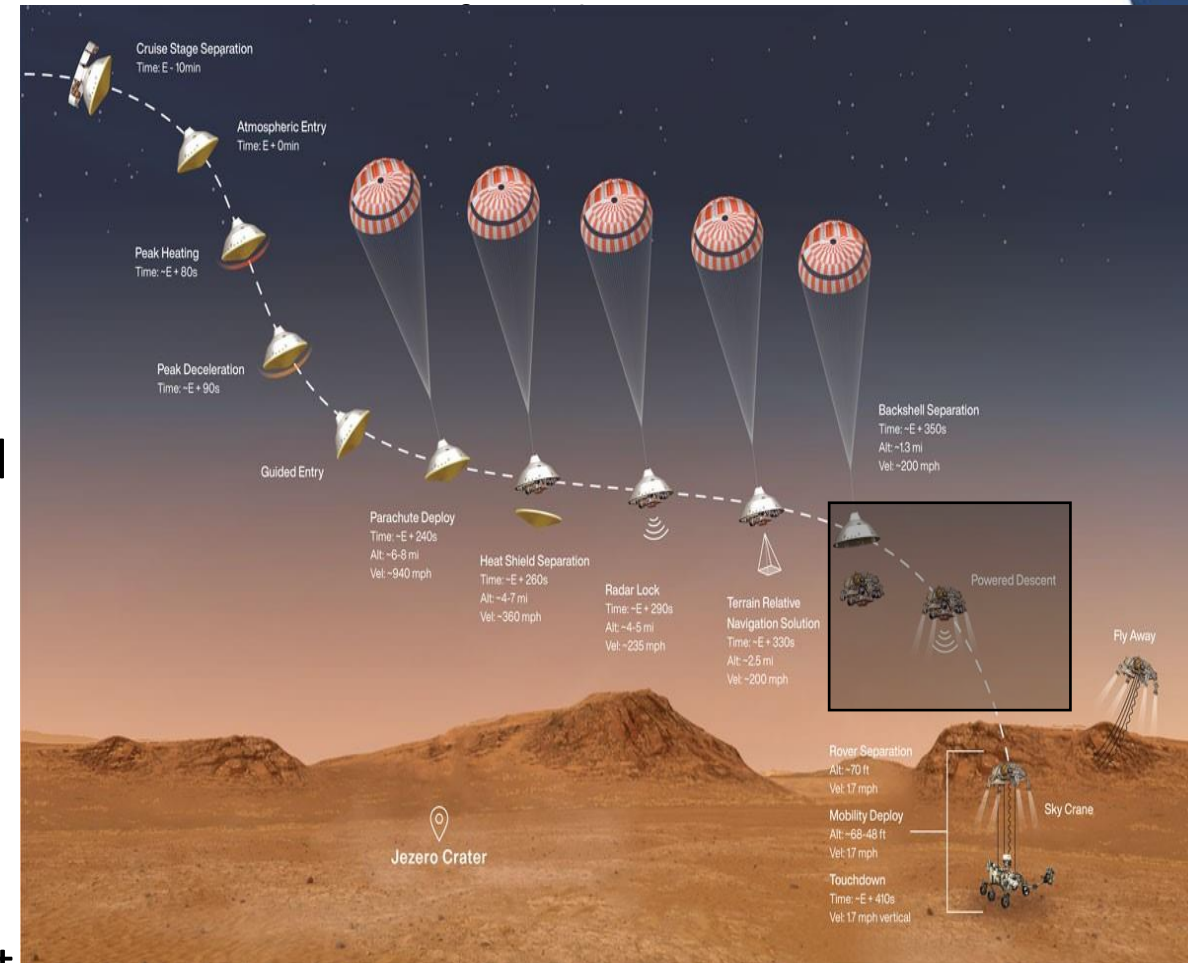


SMART Guidance Candidate Trajectories

- SMART guidance considers candidate trajectories with same initial and final states
- Each candidate trajectory's reference profile within the SMART guidance is computed such that it has different target approach azimuth angle
 - Allows to consider a wide trajectory design space
 - This is a way to discretizing the trajectories and is not the main innovation of the SMART guidance
- Each trajectory is flown within SMART guidance using the multiple modules such as controller, allocator, atmosphere and gravity.
- Each trajectory is scored based on a user defined pruning and scoring metrics



- This work did not model the onboard navigation filter
- In a recent study [1], Mars 2020 trajectory and atmospheric reconstruction were done using onboard IMU and navigation sensor data.
 - Considers the data from Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2)
- This work initializes the SMART guidance candidate trajectories and the Monte Carlo analysis using the Mars 2020 reconstruction data
 - This is synergistic with initializing the SMART guidance using the onboard navigation filter that ingests data from several sensors



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Initial states from the M2020 Reconstruction

	Parameter	Mean	Standard-deviation
Position	X-J2000	2625260.7681 (m)	1.2677 (m)
	Y-J2000	1864901.4022 (m)	1.6451 (m)
	Z-J2000	-1072439.2998 (m)	1.9436 (m)
Velocity	VX-J2000	80.7774 (m/sec)	0.0286 (m/sec)
	VY-J2000	236.6885 (m/sec)	0.0268 (m/sec)
	VZ-J2000	40.2203 (m/sec)	0.0353 (m/sec)
Attitude	Q_I2B_0	0.54313	0.00037
	Q_I2B_1	-0.22003	0.00050
	Q_I2B_2	0.37693	0.00042
	Q_I2B_3	-0.71729	0.00031
Rates	Roll Rate	1.6748 (deg/sec)	0.0576 (deg/sec)
	Pitch Rate	3.4322 (deg/sec)	0.0574 (deg/sec)
	Yaw Rate	-5.7897 (deg/sec)	0.0575 (deg/sec)
	Density	0.01411 (kg/m ³)	2.1924e-5 (kg/m ³)

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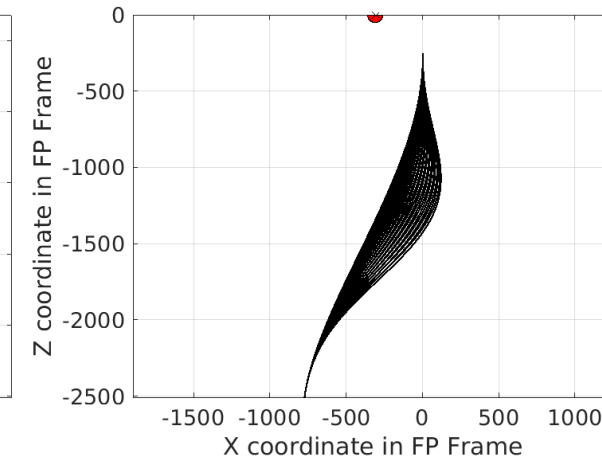
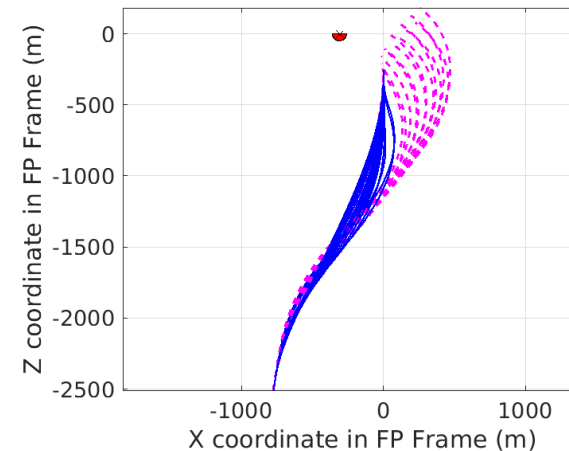
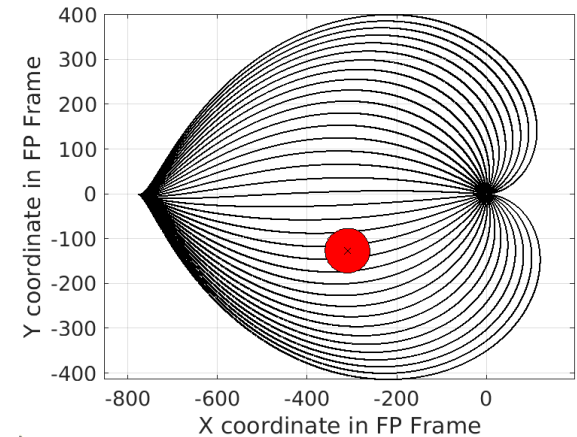
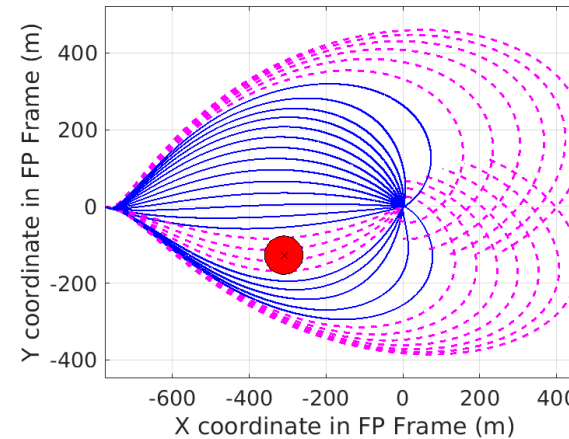
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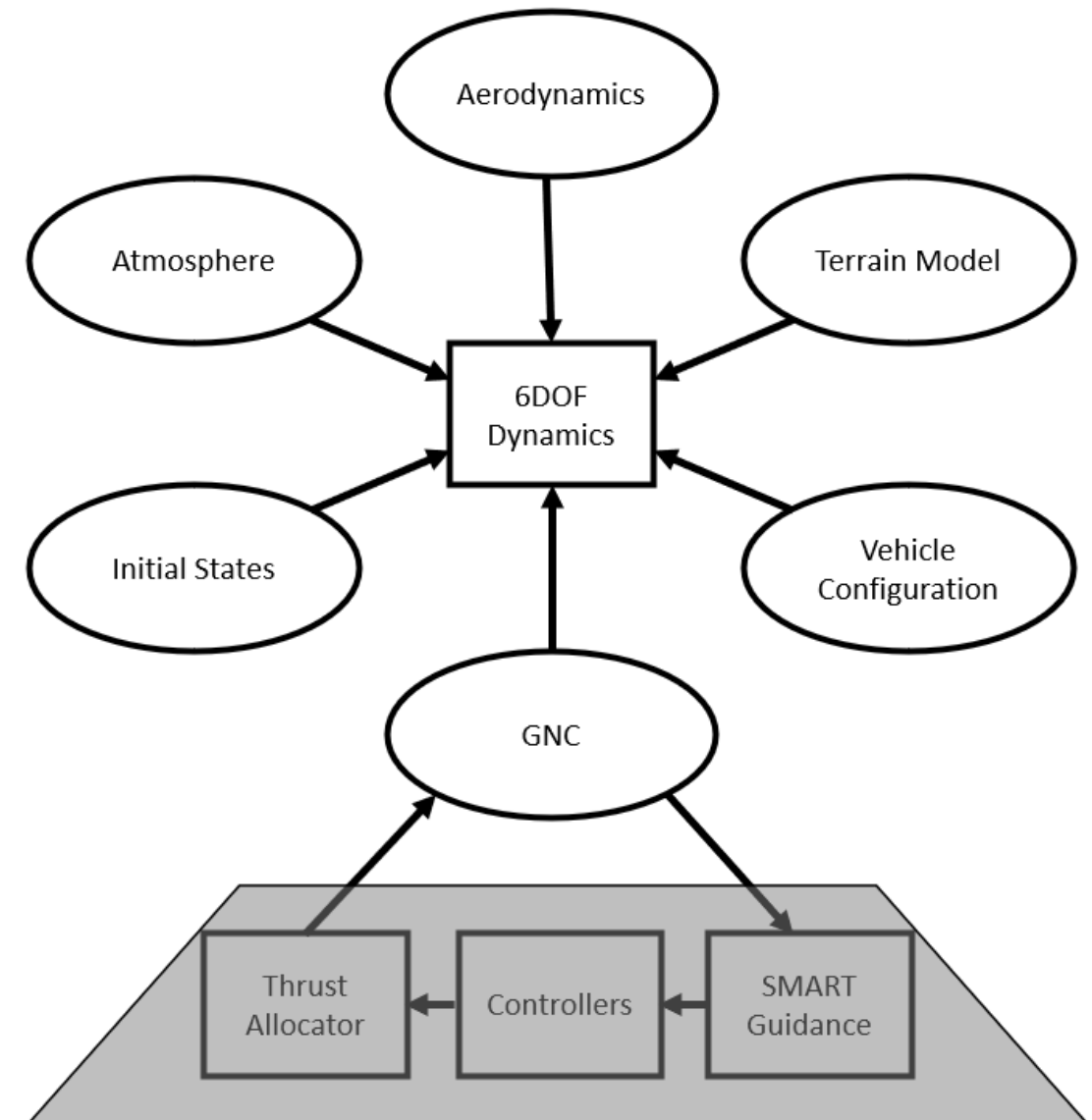
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SMART Guidance Analysis

- **360 reference trajectories in black are generated within the SMART guidance using the polynomial guidance.**
 - The target altitude is 250 m above the ground
- **The blue and magenta trajectories are the simulated trajectories within SMART guidance**
 - Controllers, thrusters, atmosphere, and gravity
 - Magenta trajectories are the infeasible trajectories
- **The trajectories shown in magenta color are eliminated by the SMART guidance**
- **The top three scored feasible trajectories in blue are used for the Monte Carlo analysis**
 - Top scored trajectory within Monte Carlo analysis is considered as the nominal trajectory

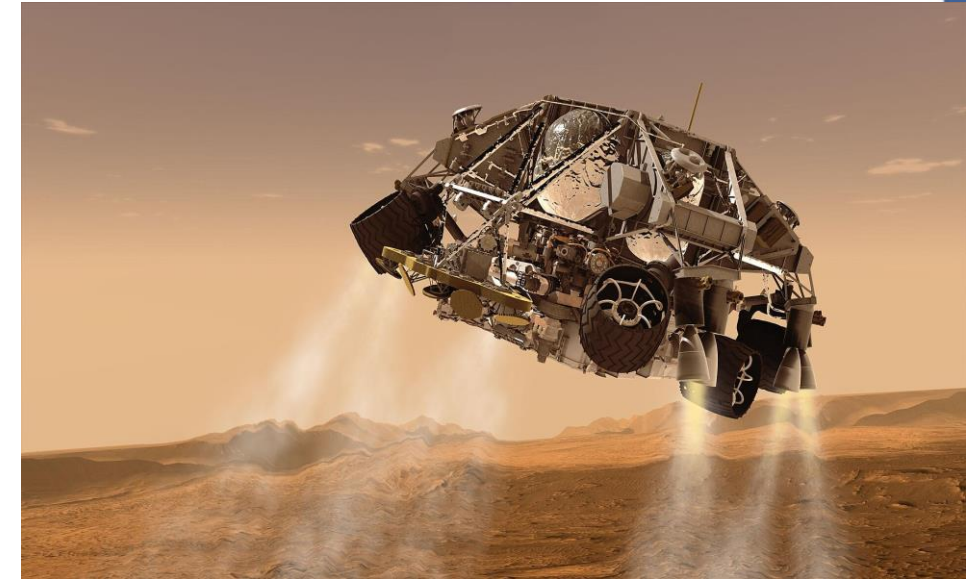


- **This work implemented SMART guidance in Program to Optimize and Simulated Trajectories- II (POST2)**
- **After the SMART guidance computes its nominal trajectory, it issues commands to POST2 outer loop simulation**
 - SMART Guidance can be called once or at regular intervals within the POST2
- **POST2 simulates the trajectory with much higher fidelity**
 - MarsGRAM
 - M2020 like vehicle configuration, aero database and GNC subsystems

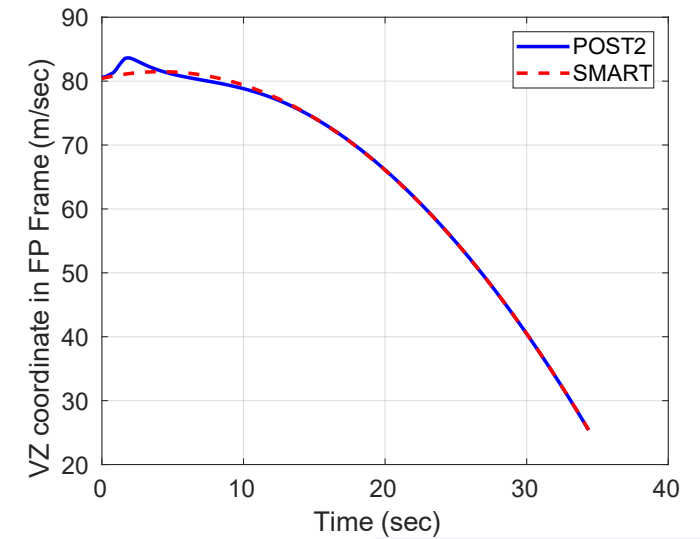
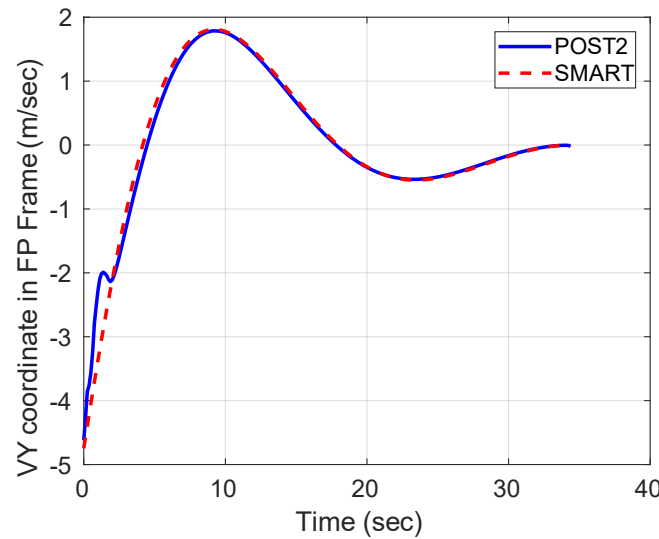
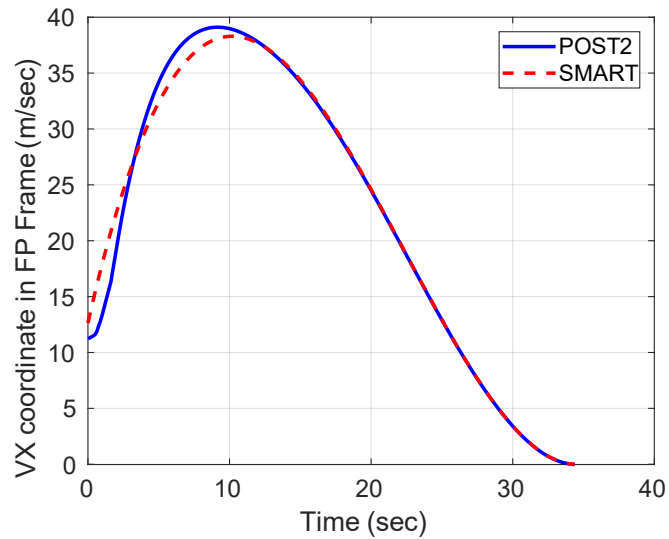
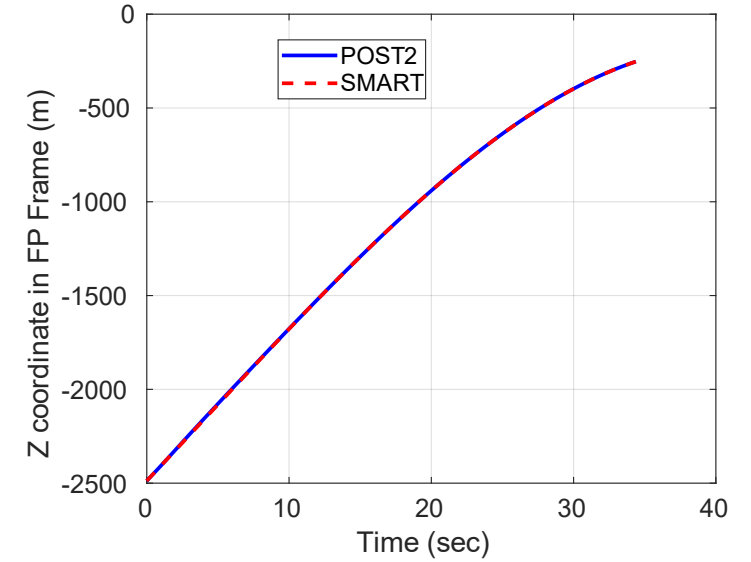
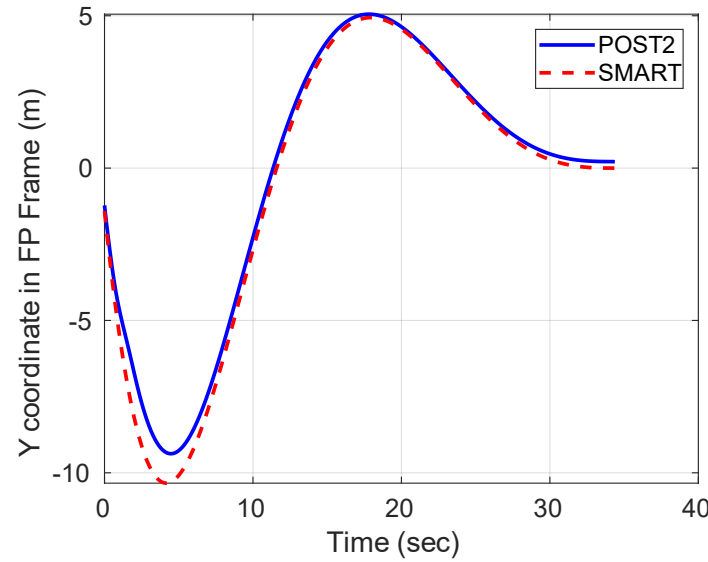
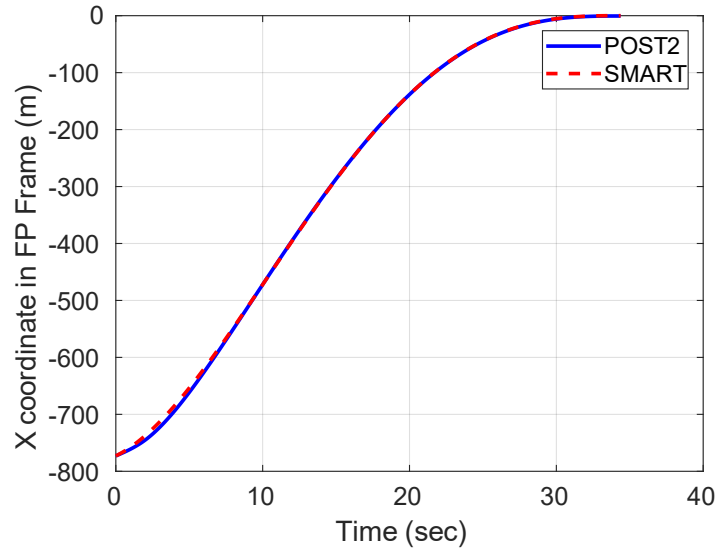


POST2 Controller and Thrust Allocator Setup

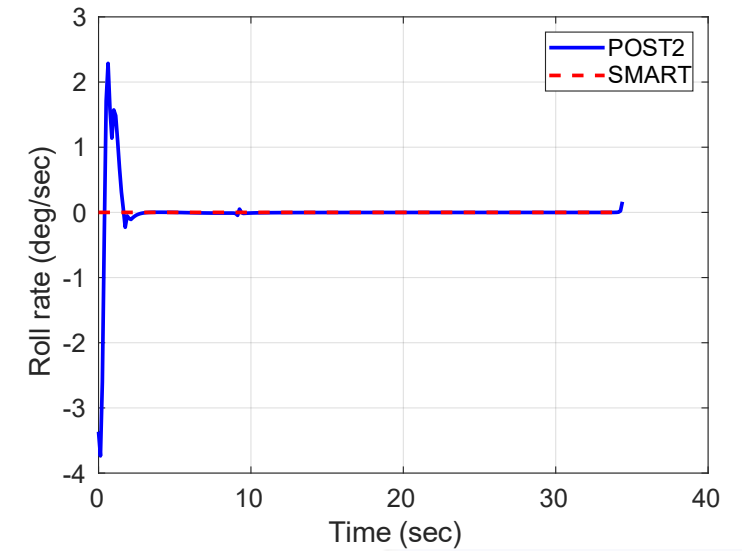
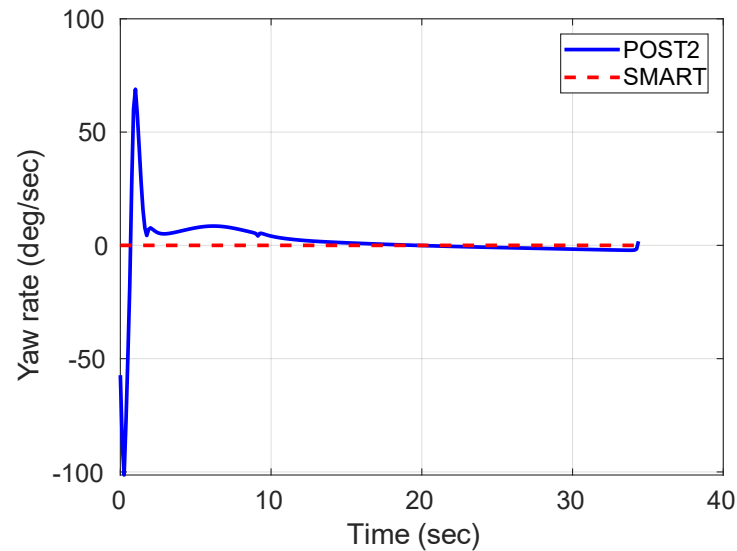
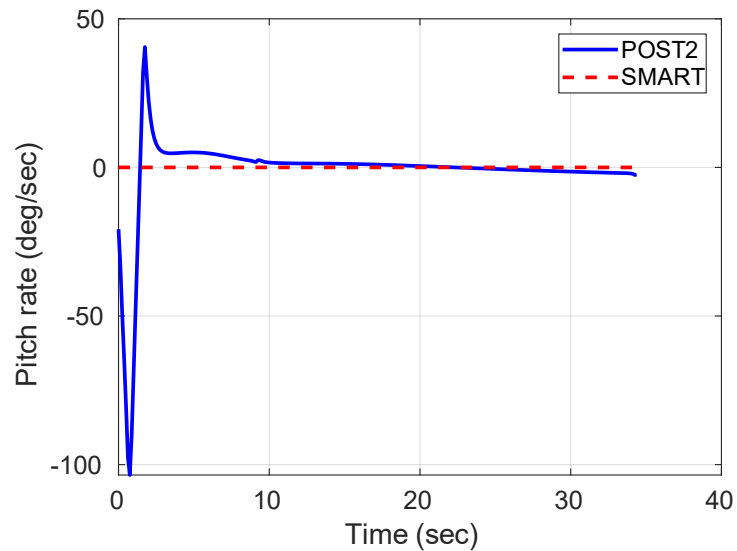
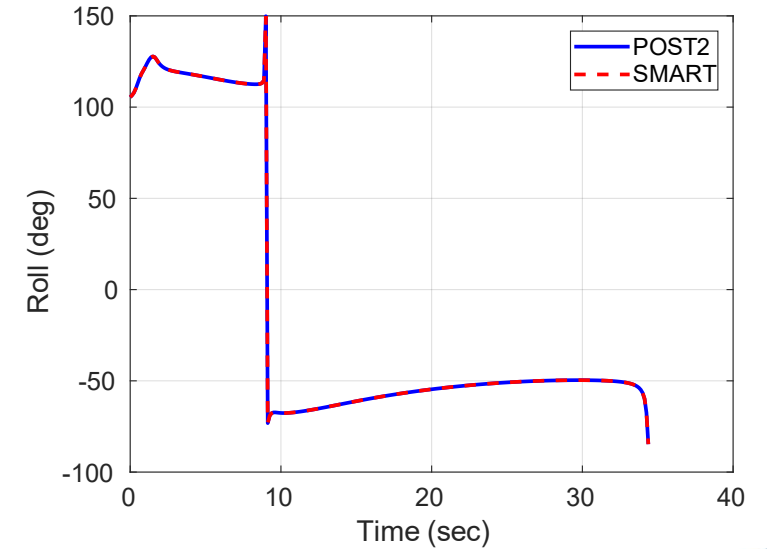
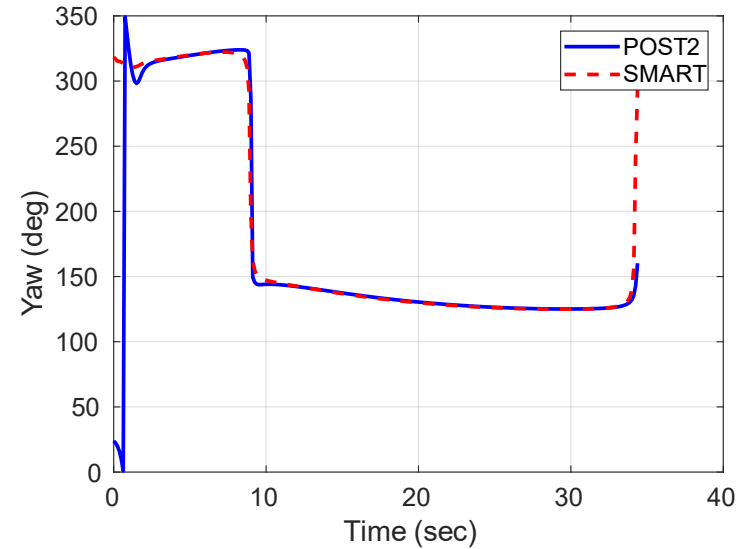
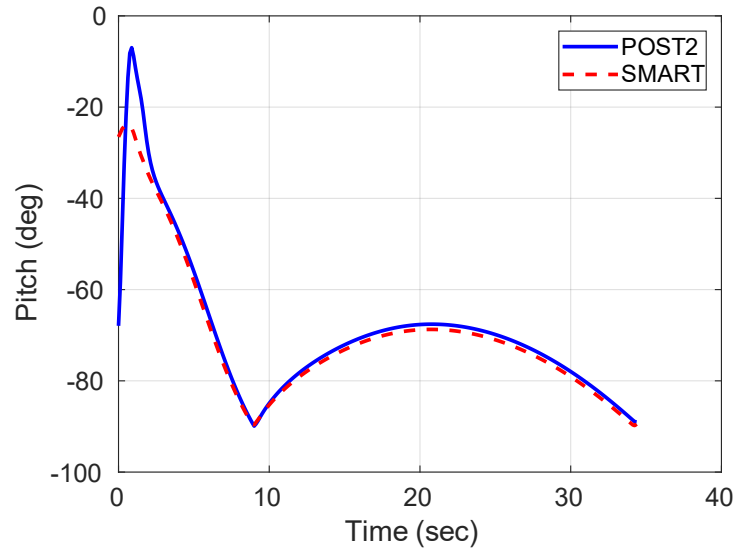
- A proportional-integrator-derivative (PID) controller is used to track the positions and velocity commands from the SMART guidance
- A quaternion based PID controller is used to track the attitude and attitude rate commands
- **Throttle commands are obtained through a pseudo-inverse solution of the $A=Bx$ problem**
 - A = Total axial thrust along with roll, pitch, and yaw moment
 - B = Vehicle plant model (mass and inertia)
 - x = Throttle commands



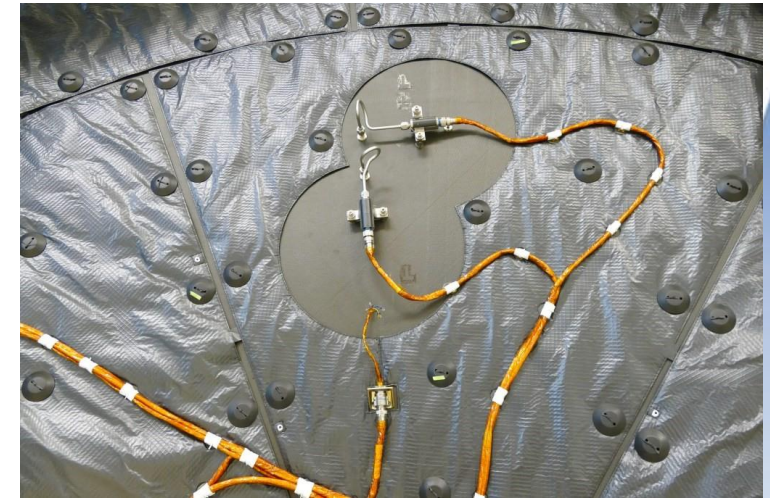
Vehicle Position and Velocity Profiles



Vehicle Attitude and Attitude Rates Profiles



- **SMART guidance is discussed in detail and applied to a real-world application**
- **The simulation is initialized using the states and uncertainties at the back shell separation from the M2020 trajectory reconstruction**
 - Initializing using the M2020 reconstruction data is synergistic to initializing with onboard navigation filter that ingests data from several on-board sensors, such as MEDLI2
- **SMART guidance determined nominal reference trajectory using 360 candidate trajectories and running Monte Carlo analysis for top three candidates**
- **The POST2 outer loop simulations tracks the SMART guidance commands effectively.**
- **Future Work:**
 - Extend the current POST2 interface to the SMART guidance version that uses Multi Fidelity Monte Carlo analysis for uncertainty quantification to achieve computational efficiency



MEDLI2 pressure transducers [2]



Thank You



Desired Target States



➤ Target States:

- 250 m above the landing site
- 25 m/s vertical velocity and no horizontal velocity
- -90 deg pitch angle and zero attitude rates

➤ Scoring metrics

- Fuel used
- Distance from target
- Time on maximum thrust

Initial and Target States

➤ Initial States:

X	-770 m	Pitch	-65 deg
Y	-3 m	Yaw	25 deg
Z	-2500 m	Roll	110 deg
VX	11 m/s	Pitch Rate	20 deg/s
VY	-4.75 m/s	Yaw Rate	-60 deg/s
VZ	80 m/s	Roll Rate	-3.5 deg/s

➤ Target States:

- 250 m above the landing site
- 25 m/s vertical velocity and no horizontal velocity
- -90 deg pitch angle and zero attitude rates



Pruning and Scoring Metrics



Nominal Stage:

➤ Pruning Metrics:

- Violating the Keep Out zone
- Final Attitude: $< 20^\circ$
- Final Attitude Rate: $< 100^\circ/\text{s}$
- Final Horizontal Velocity: $< 3 \text{ m/s}$
- Vertical Descent Violation: Analytic calc checking if vertical descent is capable of landing vehicle with touchdown velocity $< 1 \text{ m/s}$
- Fuel Remaining: $\leq 0 \text{ kg}$

➤ Scoring Metrics:

- Fuel used: Non-dimensionalized by total available propellant
- Distance from target: Non-dimensionalized by 50 m
- Time on maximum thrust: Non-dimensionalized by the profiled flight time

Uncertainty Quantification Stage:

➤ Scoring Metrics:

- Number of successful trajectories
 - Identical to the pruning metrics in the Nominal Stage
- Number of trajectories within 50 m of the landing site
- Percentile of cases with high control saturation

Fuel Used for Powered Divert

- The total fuel used is less than 350 kg and each fuel tank have more than 40 kg fuel left at the end of the powered divert maneuver
- The SMART guidance ensures that the remaining fuel is enough for vertical descent to the ground

