

Path-Adaptive Guidance Algorithm Trades for a Two- Stage Lunar Descent Vehicle

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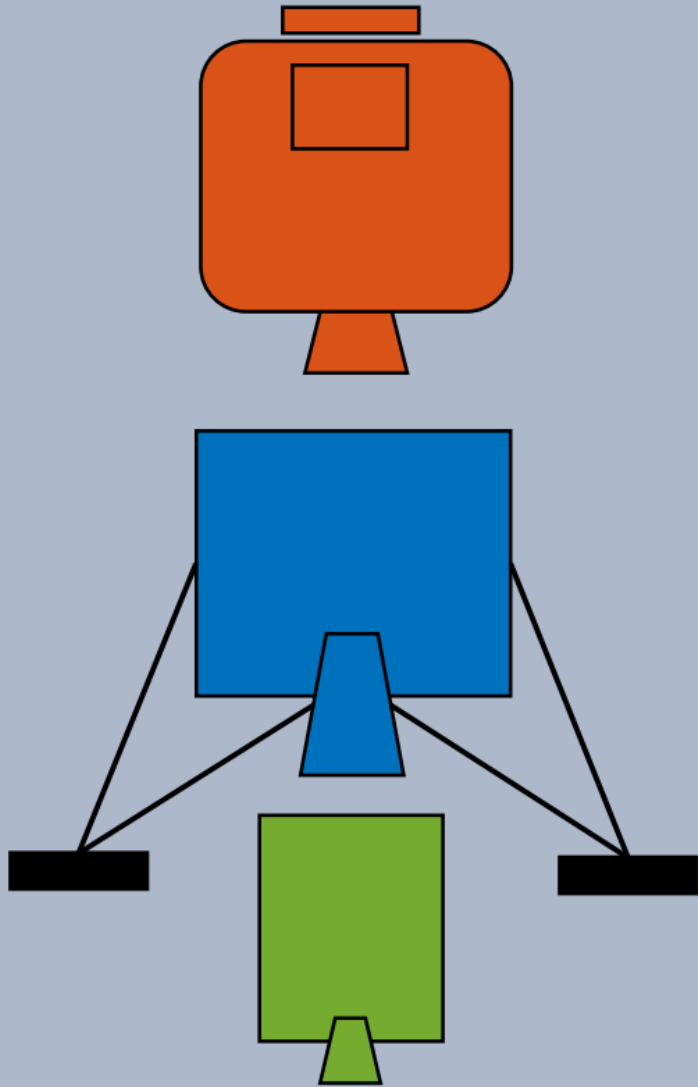
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The Need for Two-Stage Descent Guidance



- Two-stage descent vehicle architecture part of NASA's Artemis reference design
 - Lower stage (green) provides assist burn to initiate braking maneuver
 - Intermediate coast phase window for staging, separation, and jettison
 - Upper stage (blue) continues burn through terminal descent and landing
 - Payload stage (crew capsule – orange) used for lunar ascent only
- Many single-stage guidance algorithms developed over past five decades
- *Objective: determine if single-stage algorithms are still applicable and near-optimal for a two-stage architecture*

Summary of Common Heritage Guidance Algorithms

- System Dynamics:

$$\dot{\vec{r}} = \vec{v}$$

$$\dot{\vec{v}} = \vec{a}_c + \vec{g} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\vec{a}_c = \vec{a}_T - \vec{g}$$

- Linear Acceleration Law:

$$\vec{a}_T(t) = \vec{c}_0 + \vec{c}_1 t$$

$$\vec{a}_T(0) = \frac{6}{t_{go}^2} (\vec{r}_0 - \vec{r}_f - \vec{v}_0 t_{go}) + \frac{2}{t_{go}} (\vec{v}_0 - \vec{v}_f)$$

- Quadratic Acceleration Law:

$$\vec{a}_T(t) = \vec{c}_0 + \vec{c}_1 t + \vec{c}_2 t^2$$

$$\vec{a}_T = \frac{12}{t_{go}^2} (\vec{r}_0 - \vec{r}_f - \vec{v}_0 t_{go}) - \frac{6}{t_{go}} (\vec{v}_0 - \vec{v}_f) + \vec{a}_{T_f}$$

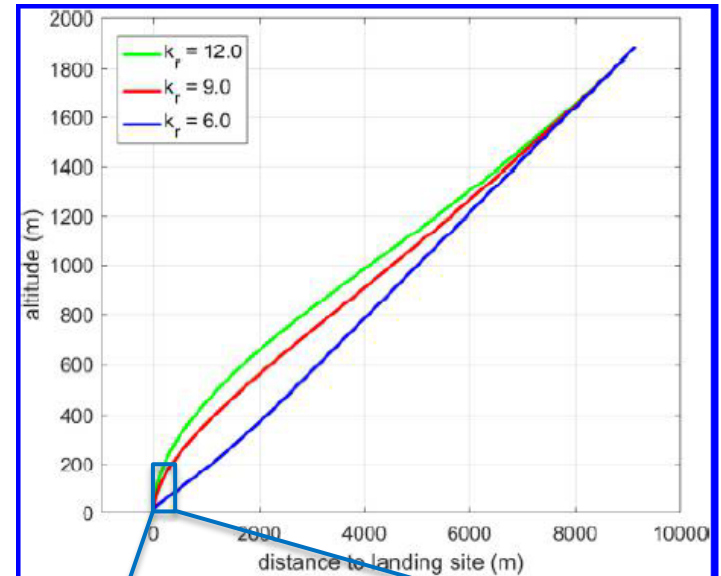
- Tunable Quadratic Acceleration Law (right):

$$\vec{a}_T(t) = \frac{2}{t_{go}} \left(1 - \frac{1}{3} k_r \right) [\vec{v}_f - \vec{v}(t)] +$$

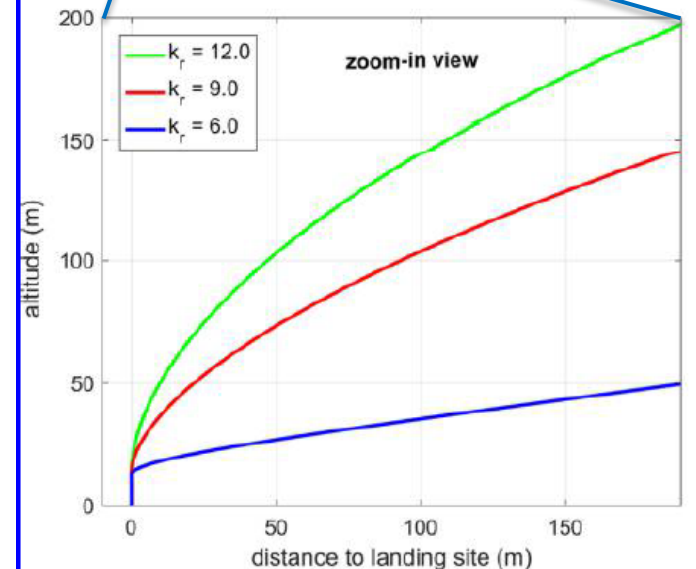
$$\frac{k_r}{t_{go}^2} [\vec{r}_f - \vec{r}(t) - \vec{v}(t) t_{go}] +$$

$$\left(\frac{1}{6} k_r - 1 \right) \vec{a}_{T_f} + \left(\frac{1}{6} k_r - 2 \right) \vec{g}$$

- Universal Powered Guidance (UPG)

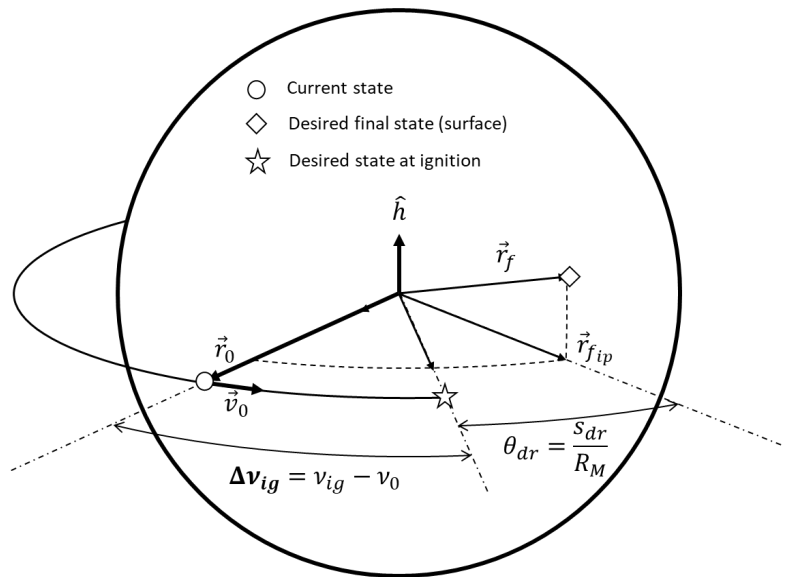


a) Descent trajectories under tunable powered descent guidance law



b) Zoom-in view of the descent trajectories under tunable powered descent guidance law

Time-to-go, Ignition, Staging



- Time-to-go computational options:
 - Load to vehicle based on simulated optimal solution
 - UPG soft-landing solution
 - Analytical calculations:

$$t_{go}^4 + at_{go}^2 + bt_{go} + c = 0$$

$$a, b, c = f(\vec{r}, \vec{v}, \vec{r}_t, \vec{v}_t, \Gamma, \vec{g})$$

- Ignition timing options:
 - Downrange distance
 - Fixed time epoch from ground
- Staging methods for a two-stage vehicle:
 - Mass limit by specified threshold
 - Δv tracker and threshold
 - Altitude or altitude rate threshold

$$t_{go}^4 + at_{go}^2 + bt_{go} + c = 0$$

$$a = -\frac{2[\mathbf{v}^T \mathbf{v} + \mathbf{v}_f^T (\mathbf{v} + \mathbf{v}_f)]}{\left(\Gamma + \frac{\mathbf{g}^T \mathbf{g}}{2}\right)}$$

$$b = -\frac{12(\mathbf{r} - \mathbf{r}_f)^T (\mathbf{v} + \mathbf{v}_f)}{\left(\Gamma + \frac{\mathbf{g}^T \mathbf{g}}{2}\right)}$$

$$c = -\frac{18(\mathbf{r} - \mathbf{r}_f)^T (\mathbf{r} - \mathbf{r}_f)}{\left(\Gamma + \frac{\mathbf{g}^T \mathbf{g}}{2}\right)}$$

Two-Stage Vehicle Analysis Configuration

Parameter	Value
Initial Orbit Altitude (MSL)	100 x 15 km
Initial Orbit True Anomaly	-20°
Stage 1 Propellant Mass	8 Mg
Stage 1 Inert Mass	10 Mg
Stage 1 Thrust	100 kN
Stage 1 Specific Impulse	450 sec
Stage 1 Minimum Burn Time	50 sec
Coast Time	Variable
Stage 2 Propellant Mass	8 Mg
Stage 2 Inert Mass	15 Mg
Stage 2 Thrust	100 kN
Stage 2 Specific Impulse	450 sec
Stage 3 (Crew Capsule) Mass	5 Mg
Target Altitude (AGL)	200 m
Target Vertical Velocity	-15 m/s
Landing Site	-90° S, 0° W

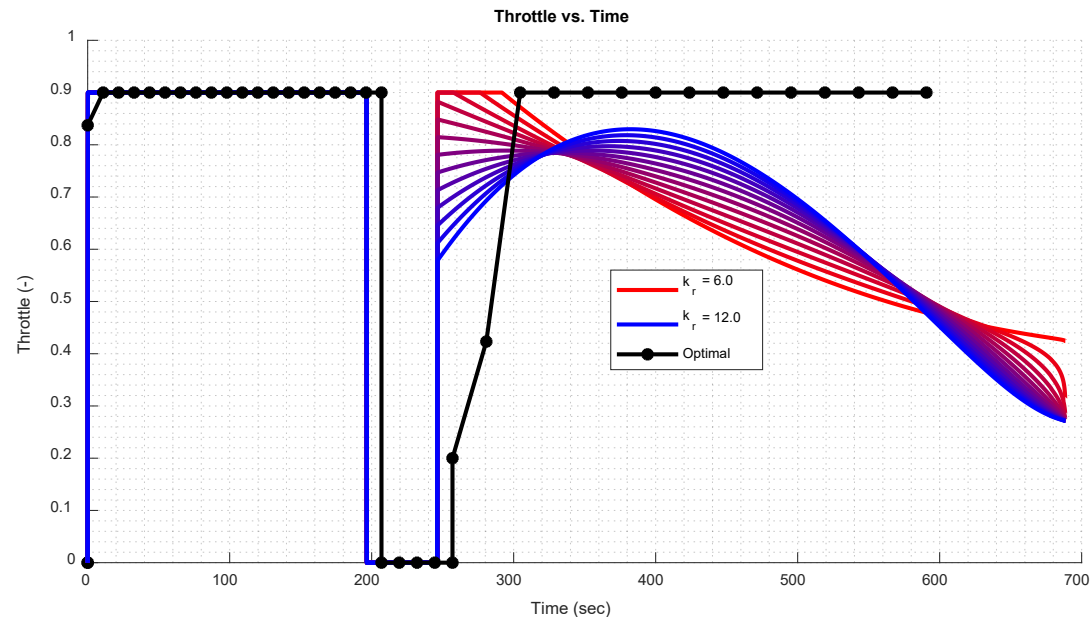
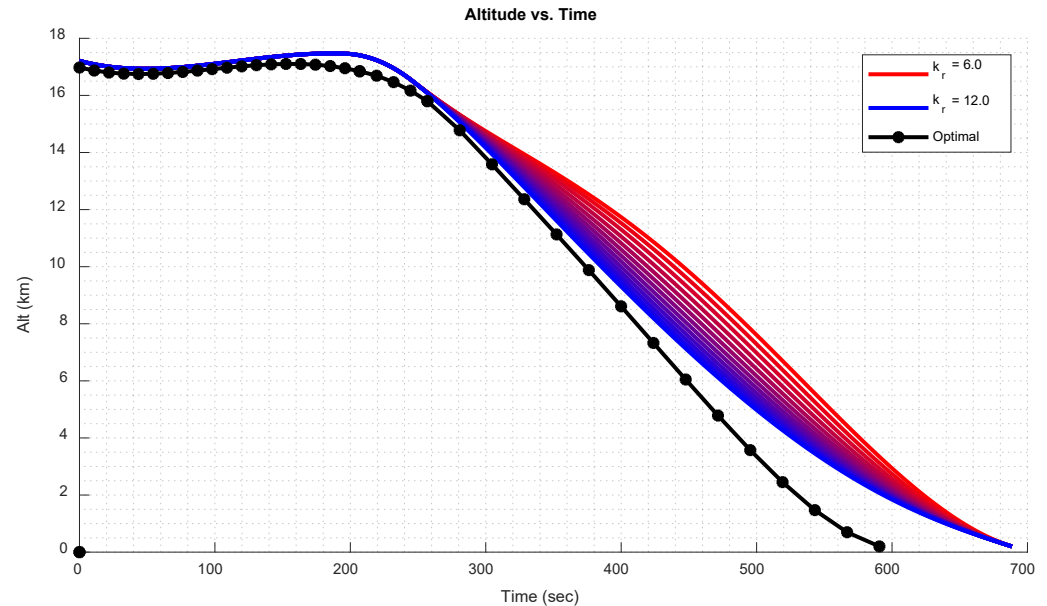
- Vehicle:
 - Approximate masses for light crewed vehicle
 - Loosely based on govt. reference design
- Simulation (MATLAB 3DOF):
 - Spherical gravity model
 - Rotating planet
 - Truth nav
 - Perfect controller
- Optimization:
 - Multi-phase Hermite-Simpson collocation method
 - Throttling constraints, staging constraints
 - Fitness options available for minimum-control and minimum fuel (for each stage)
- Workflow:
 - Configure vehicle in both simulation and optimizer
 - Optimize given vehicle and starting state with specified constraints
 - Use staging and time-to-go outputs from optimizer to feed into simulation
 - Test results for different coast times, mass constraints, throttling constraints, etc.

Comparison #1: 50-Second Coast, Minimum-Fuel Optimization

Thrust saturation occurs at the start of the second stage for lower gains

Altitude lofting due to uniform gravity field assumptions

Trajectory profiles relatively consistent if staged at consistent mass

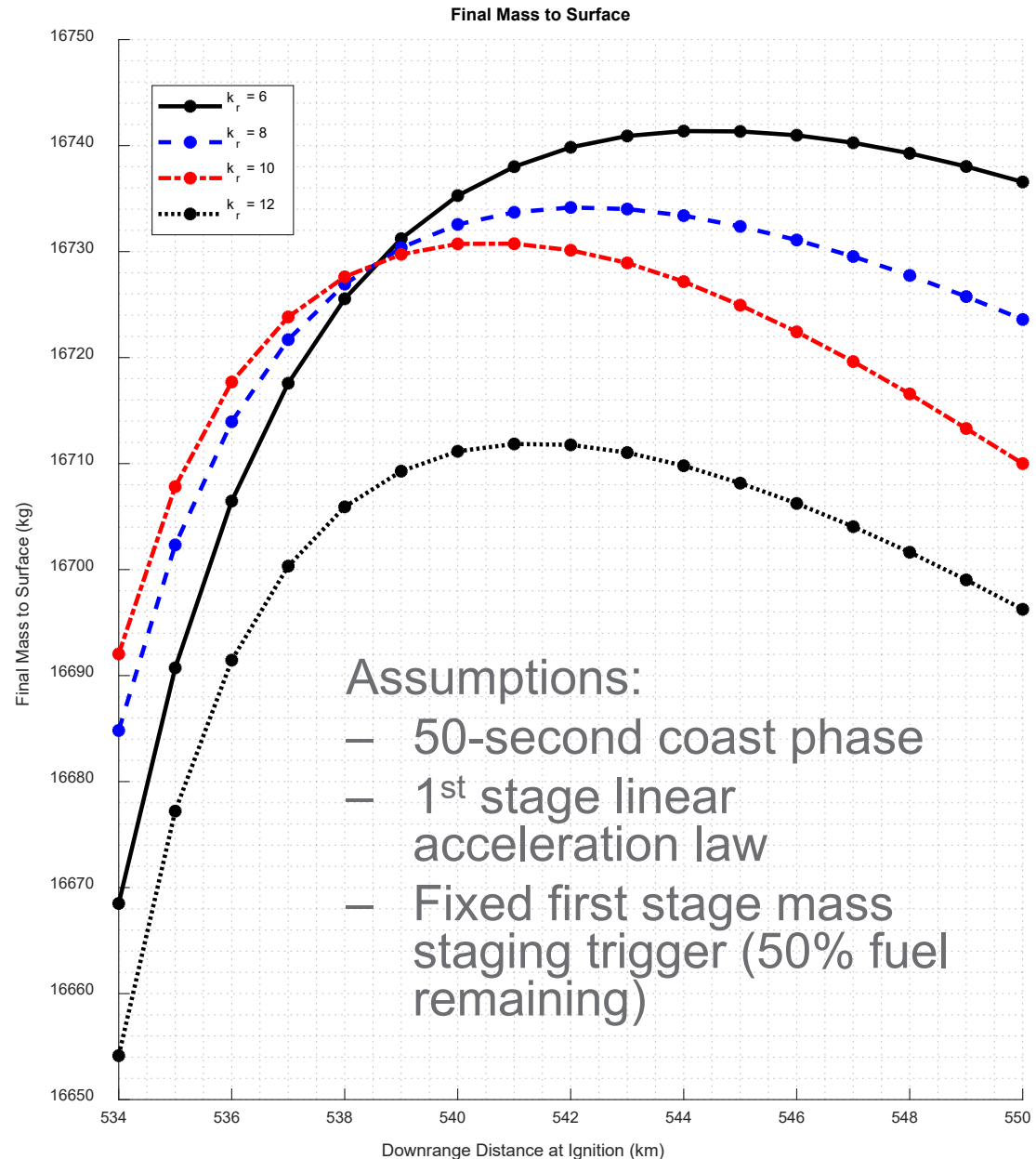


Effects of Downrange Distance & Tunable Gain

Each tunable gain parameter has deterministic “peak” mass-to-surface

Downrange ignition slope more sensitive on close range side

Small mass deltas between range of tunable guidance gains



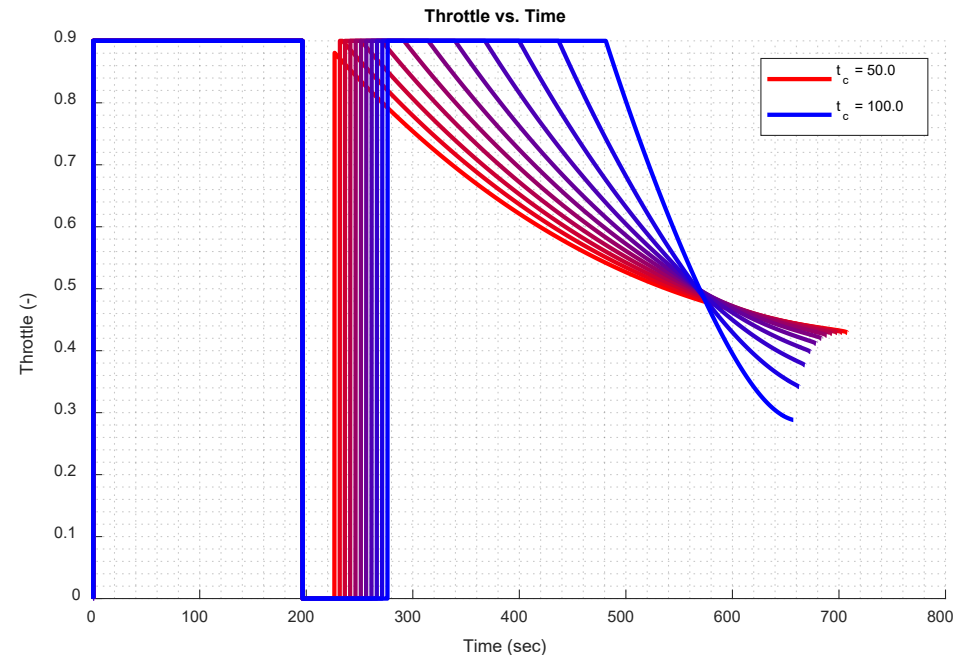
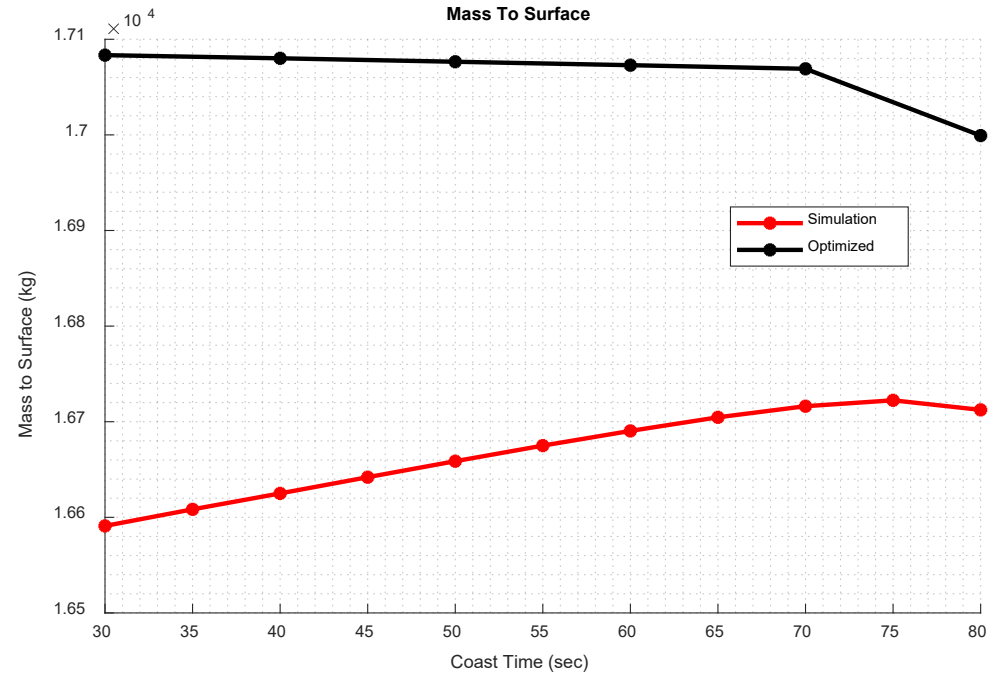
Vehicle Considerations

Effect of coast time:

- Increase in coast time affects mass to surface
- Leads to throttle saturation in second stage
- Insight: set acceptable threshold for mass delta from simulation to optimizer for range of coast durations

Other vehicle considerations:

- Constant stage 1 burn, saturated at 100%
- Alternate MECO triggers (Δv , altitude, vertical speed, etc.)
- Impact of coast time clocking on optimality of guidance targets

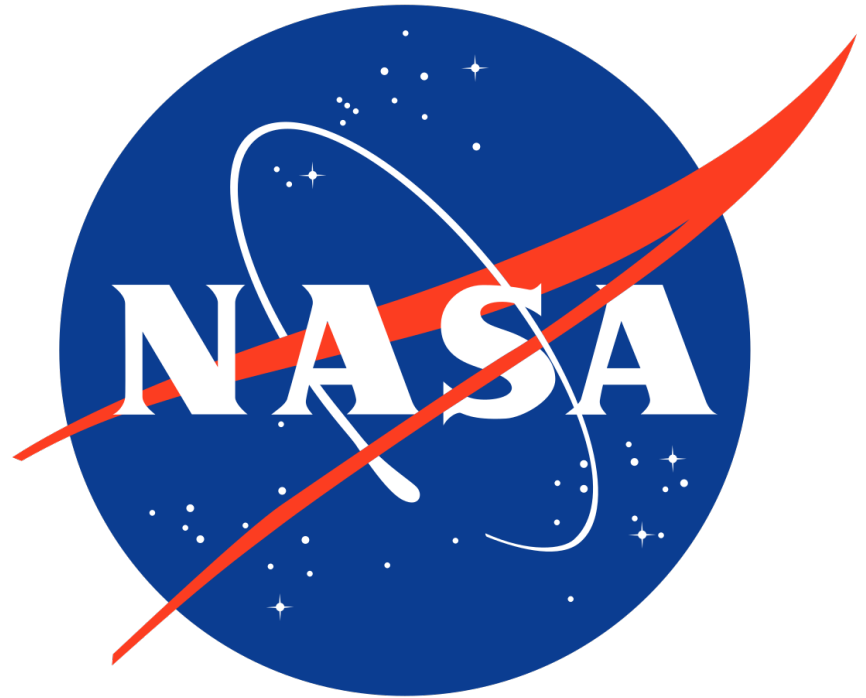


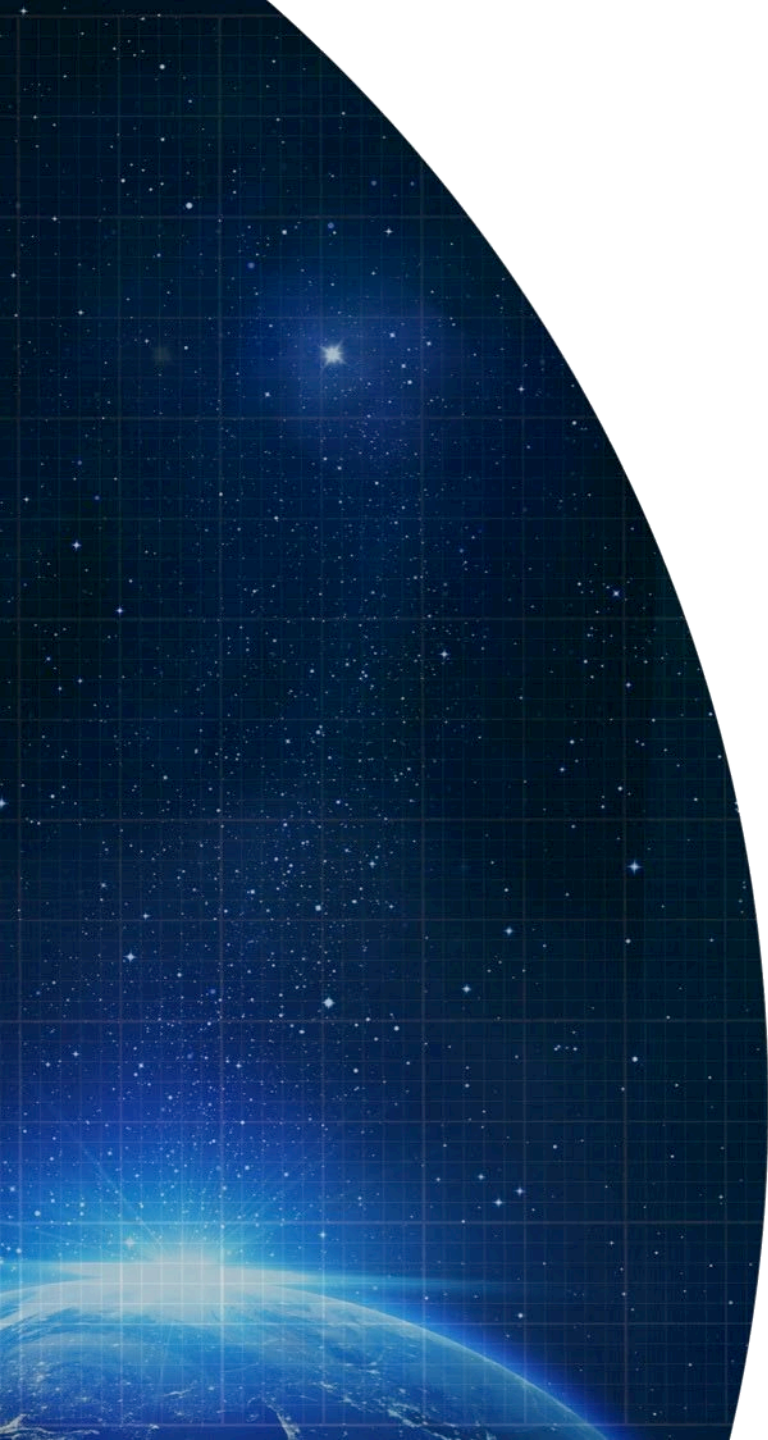
Conclusions

- Single-stage guidance algorithms feasible, within specific tolerances:
 - Heavily dependent on coast time, and thus on vehicle architecture
 - Heavily dependent on staging time and initial vehicle state
- Development progress:
 - Simulation and optimization suite for testing guidance algorithms
 - Performance metrics that prove useful for optimization/simulation standards
- Future work:
 - Continue testing with different guidance algorithms on either stage
 - Test wider range of scenarios (vehicle configurations, starting states, etc.)
 - Monte Carlos, dispersions, abort modes, sensitivities, and perturbations



**Thank you for your time.
Questions?**





References

- Ping Lu, “Augmented Apollo Powered Descent Guidance”, *Journal of Guidance, Control, and Dynamics*, Vol. 42, No. 3, 2019
- Christopher N. D’Souza, “An Optimal Guidance Law for Planetary Landing”, AIAA-97-3709, Charles Stark Draper Laboratory, 1997