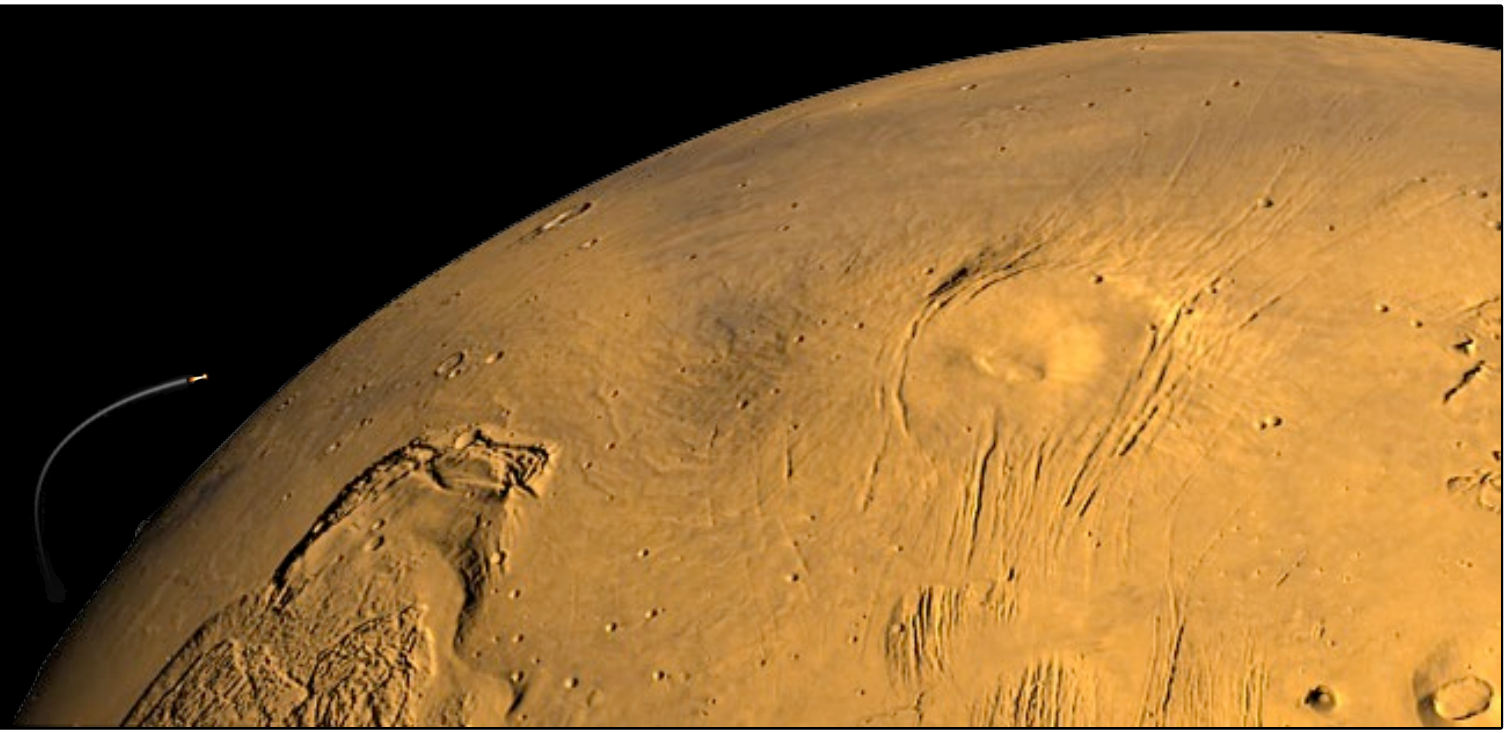
Mars Ascent Vehicle



Jet Propulsion Laboratory
California Institute of Technology

MARSHALL
SPACE FLIGHT CENTER

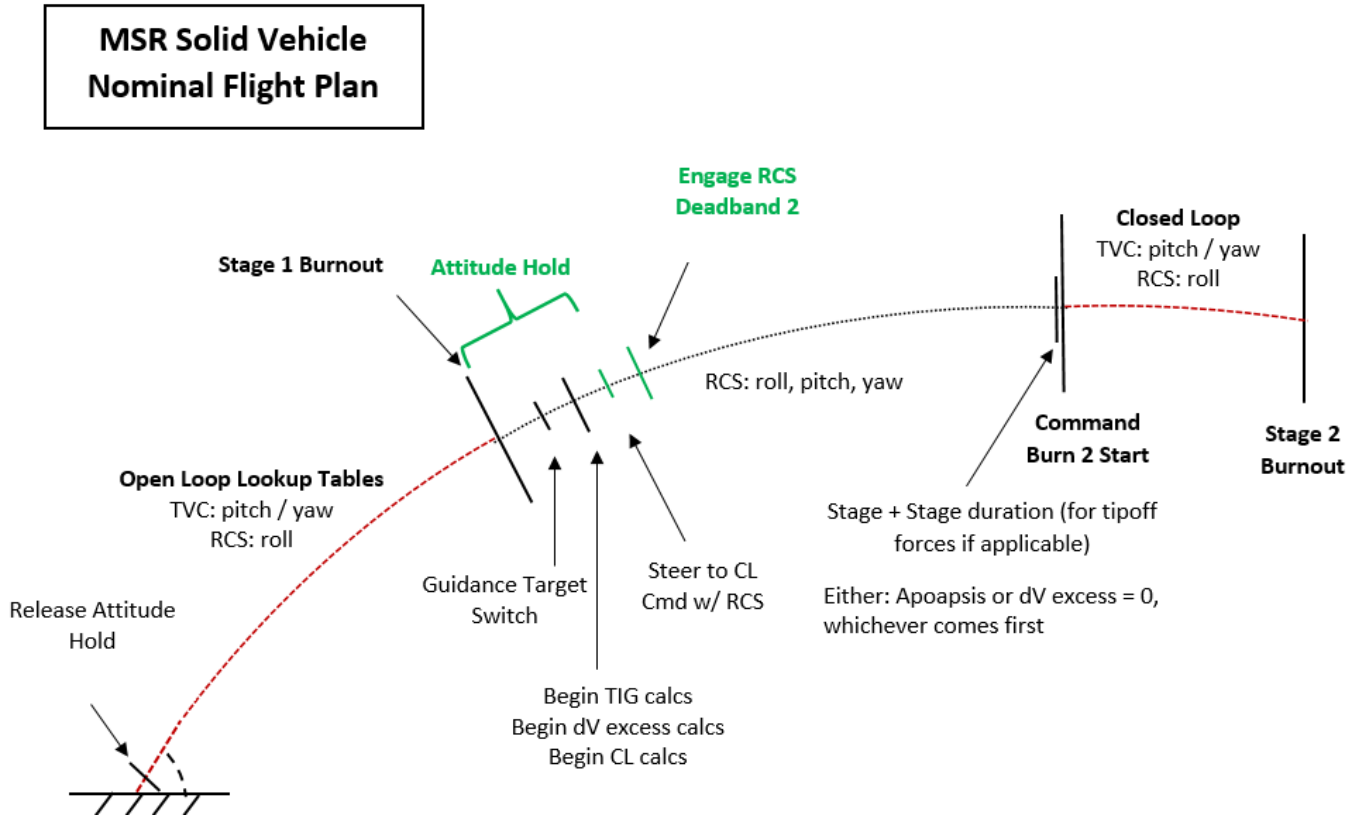
A Generalized Guidance Approach to In-Space Solid-Propellant Vehicle Maneuvers

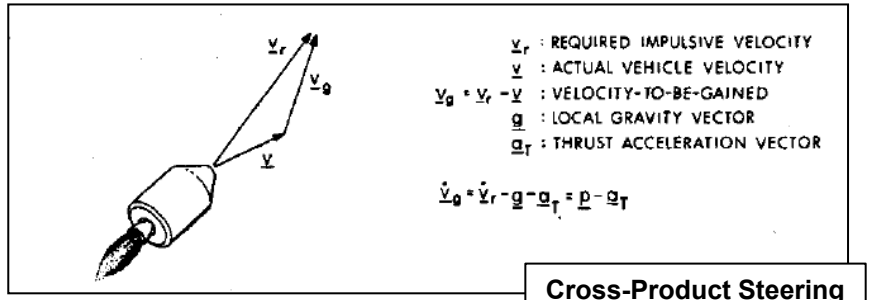
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Introduction

- Closed-Loop second stage guidance developed for Mars Sample Return (MSR) Mars Ascent Vehicle (MAV)
- MAV vehicle sensitivity requires high-precision, closed-loop orbital insertion guidance. Other attempted methods were not providing orbital accuracy.
- Original attempts for closed-loop guidance:
  - Open-loop vs. Time, Open-loop vs. Alt
  - PEG w/ numerically computed thrust integrals
  - General energy management steering and PEG
  - Cross-Product Steering @ Apoapsis
- Resulting guidance algorithm after studies: Open-loop vs. Alt for burn 1, Simple Cross-Product Steering (SxS) for burn 2
- **Simple Cross-Product Steering (SxS)**
  - Modified Cross-Product Steering (different velocity targeting routine)
  - Smart ignition time calculation
    - Based on velocity targeting partial





Cross-Product Steering

$$L = \int_0^{t_{go}} (F/m)\,dt \qquad S = \int_0^{t_{go}} \int_0^{t} (F/m)\,ds\,dt$$

$$J = \int_0^{t_{go}} (F/m)t\,dt \qquad Q = \int_0^{t_{go}} \int_0^{t} (F/m)t\,ds\,dt$$

$$H = \int_0^{t_{go}} (F/m)t^2\,dt \qquad P = \int_0^{t_{go}} \int_0^{t} (F/m)t^2\,ds\,dt$$

(McHenry)

SxS Target Frame Representation

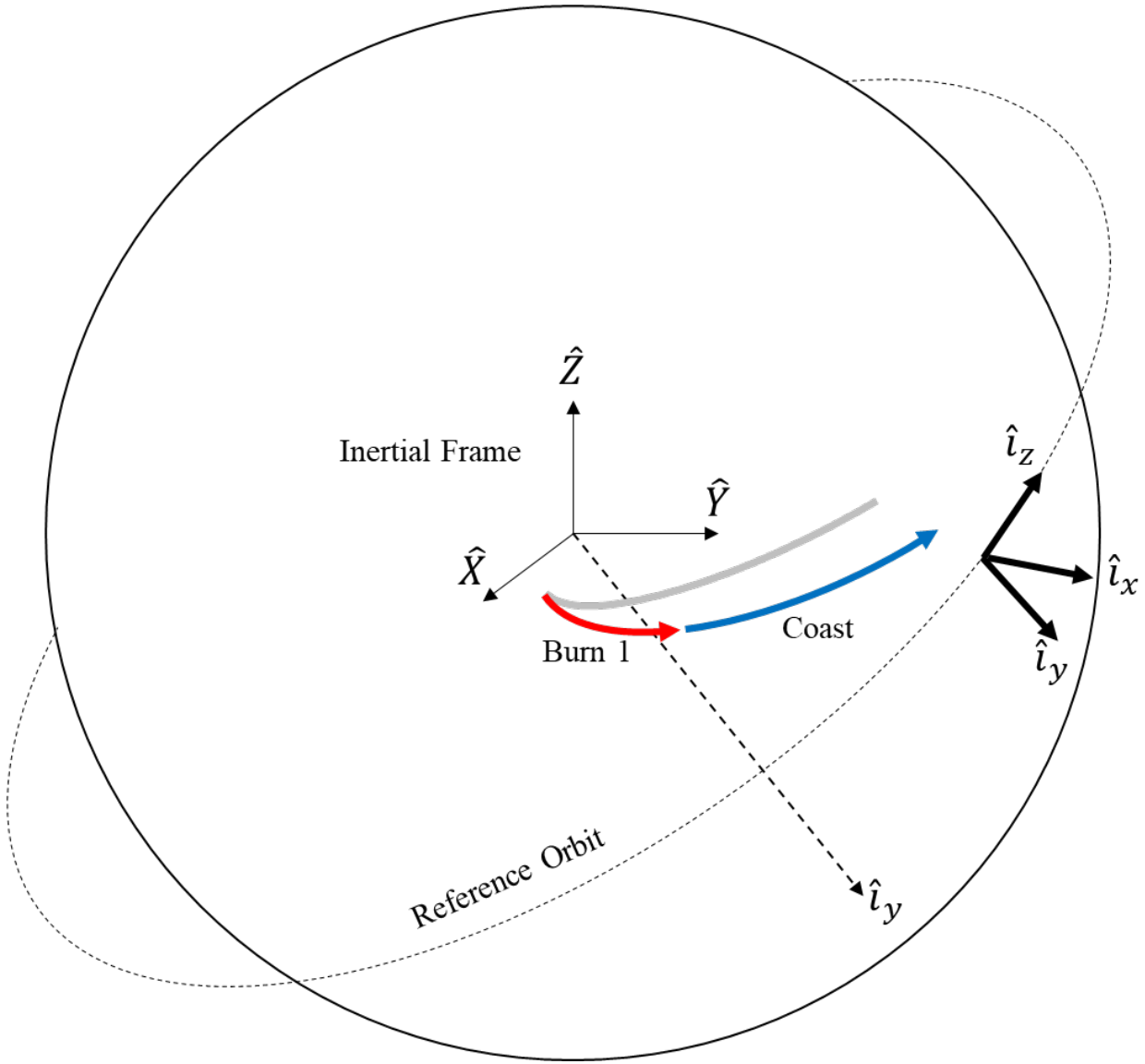
- Target orbit is not fully inertially constrained, in order to avoid algorithm infeasibilities.
  - Constrained orbital plane, but floating argument of periapsis and eccentricity.
- Targeted parameters:
  - $\boldsymbol{a_d}$ – target semi-major axis
  - $\boldsymbol{\Omega_d}$ – target orbital right ascension of the ascending node (RAAN)
  - $\boldsymbol{i_d}$ – target orbital inclination
- Target Frame Construction:

$$\hat{\imath}_y = \begin{bmatrix} -\sin(\Omega_d)\sin(i_d) \\ \cos(\Omega_d)\sin(i_d) \\ -\cos(i_d) \end{bmatrix}$$

$$\hat{\imath}_x = \frac{\vec{r} - (\vec{r}\cdot\hat{\imath}_y)\hat{\imath}_y}{\left|\vec{r} - (\vec{r}\cdot\hat{\imath}_y)\hat{\imath}_y\right|}$$

$$\hat{\imath}_z = \frac{\hat{\imath}_x \times \hat{\imath}_y}{\left|\hat{\imath}_x \times \hat{\imath}_y\right|}$$

- Notes on target frame construction:
  - Similar derivation to PEG
  - Subtraction of out-of-plane component in $\hat{\imath}_x$ does not effect this algorithm (as will be seen)



SxS Velocity Targeting Routine

National Aeronautics and Space Administration
Jet Propulsion Laboratory / Marshall Space Flight Center
Mars Sample Return / Mars Ascent Vehicle

- Velocity targeting assumes:
  - Impulsive maneuver
  - Final state will lie on the apse line of target orbit ($\dot{r}$ nulling)
    - Used to bleed off excess energy of vehicle (energy management)

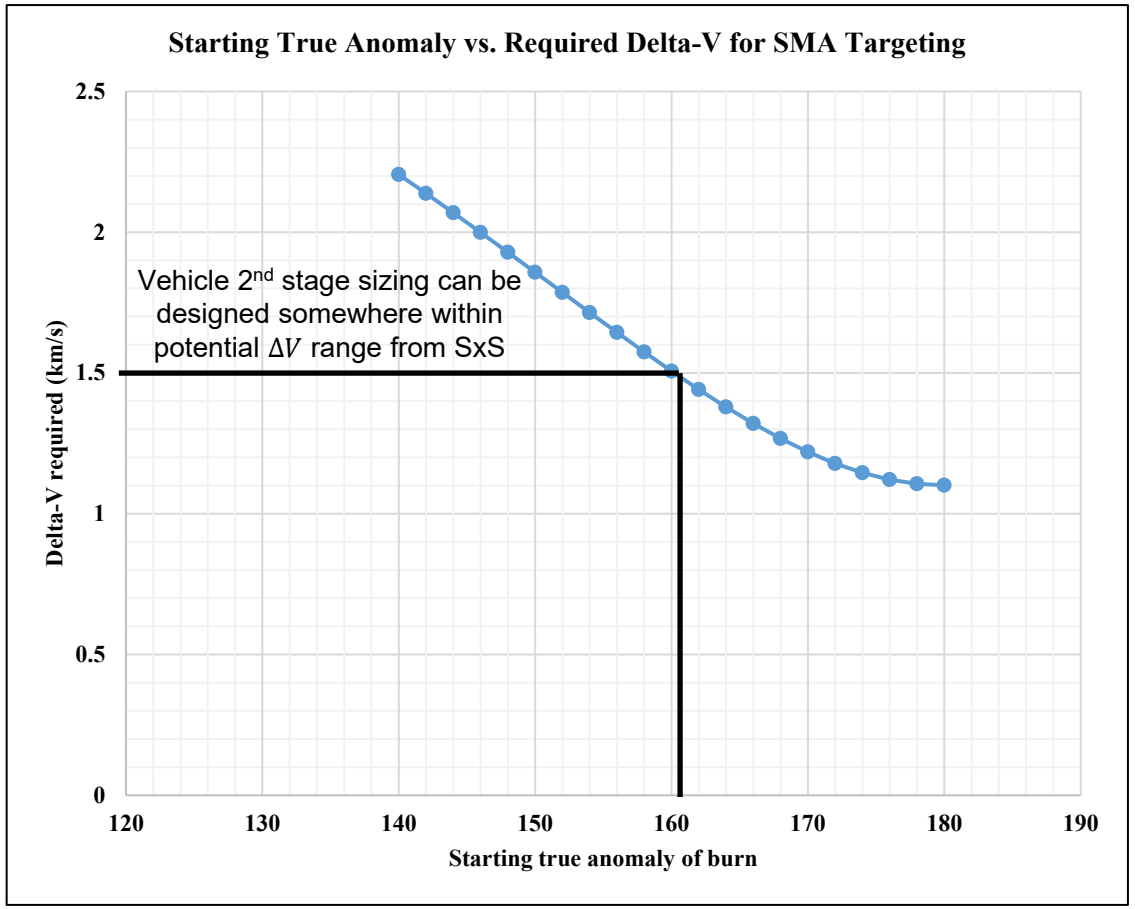
$$v_d = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a_d}\right)}$$

$$\vec{v}_d = v_d \hat{\imath}_z$$

$$\vec{v}_{go} = \vec{v}_d - \vec{v} = v_d \hat{\imath}_z - \vec{v}$$

- Note that only $\hat{\imath}_z$ appears directly in $\vec{v}_{go}$, along with the following simplification:

$$\hat{\imath}_z = \frac{\hat{\imath}_x \times \hat{\imath}_y}{|\hat{\imath}_x \times \hat{\imath}_y|} = \frac{\vec{r} \times \hat{\imath}_y}{|\vec{r} \times \hat{\imath}_y|}$$



Note: not real MAV Data

- 2-dimensional $\dot{r}$ nulling analysis:

$$r_1 = \frac{h_1^2}{\mu}\frac{1}{1 + e_1 \cos\theta_1}$$

$$v_2 = \frac{h_{tgt}}{r_1}$$

$$v_{\perp_1} = \frac{h_1}{r}$$

$$v_{r_1} = \frac{\mu}{h_1} e_1 \sin\theta_1$$

$$v_1 = \sqrt{v_{\perp_1}^2 + v_{r_1}^2}$$

$$\gamma_1 = \operatorname{atan}\frac{v_{r_1}}{v_{\perp_1}}$$

$$\Delta v = \sqrt{v_1^2 + v_2^2 - 2v_1 v_2 \cos(\gamma_1)}$$

- Values that will *not* change during coast to apoapsis:
  - $\mu, \gamma_2, h_1, e_1, a_2$
- Values that will change during coast to apoapsis:
  - $\theta_1, r_1 = r_2, e_2, h_2$

SxS Iterative-Based Ignition Prediction

- At some time during flight, required velocity for burn (v_{go}) will approximately equal vehicle 2nd stage capacity (v_{cap}).
- This time can be predicted forward if the change in v_{go} over time is known.
- A Newton-Raphson iterative scheme can be applied to determine time to ignition, t_{ig}:

$$f(t_{ig}) = v_{go}(t_{ig}) - v_{cap}$$

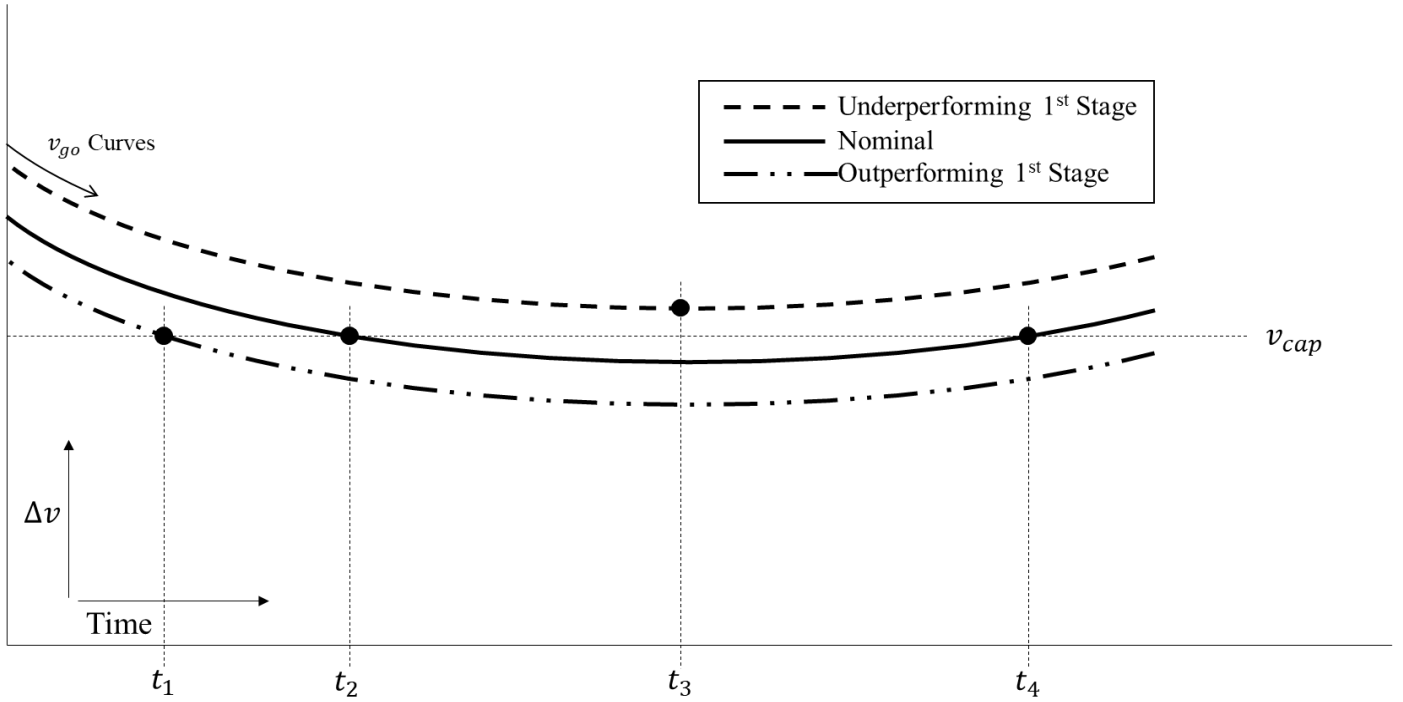
$$t_{ig_{k+1}} = t_{ig_k} - \frac{f(t_{ig})}{f'(t_{ig})} = t_{ig_k} - \frac{v_{go}(t_{ig}) - v_{cap}}{\frac{\delta v_{go}}{\delta t_{ig}}}$$

- Velocity targeting routine is simple enough to provide a stable solution for Newton-Raphson scheme.

$$\frac{\delta v_{go}}{\delta t} = \frac{\delta |\vec{v}_{go}|}{\delta t} = \hat{v}_{go} \cdot \frac{\delta \vec{v}_{go}}{\delta t}$$

- Velocity targeting partial:

$$\frac{\delta \vec{v}_{go}}{\delta t} = -\frac{\mu}{v_d r^2}[\hat{r} \cdot \vec{v}]\hat{\imath}_z - v_d \frac{\vec{v} \cdot \hat{\imath}_z}{\vec{r} \cdot \hat{\imath}_x}\hat{\imath}_x + \frac{\mu}{r^3}\vec{r}$$

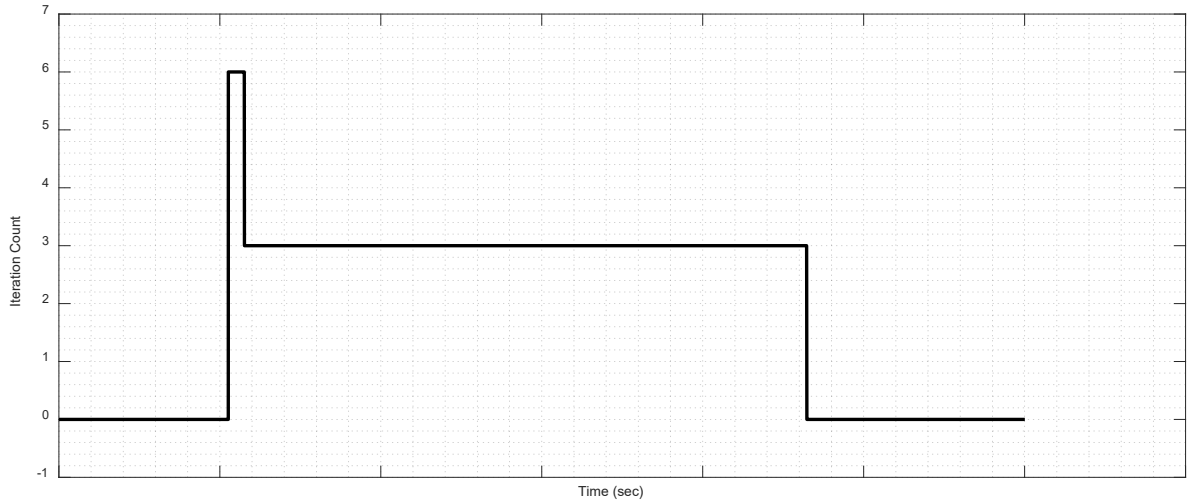


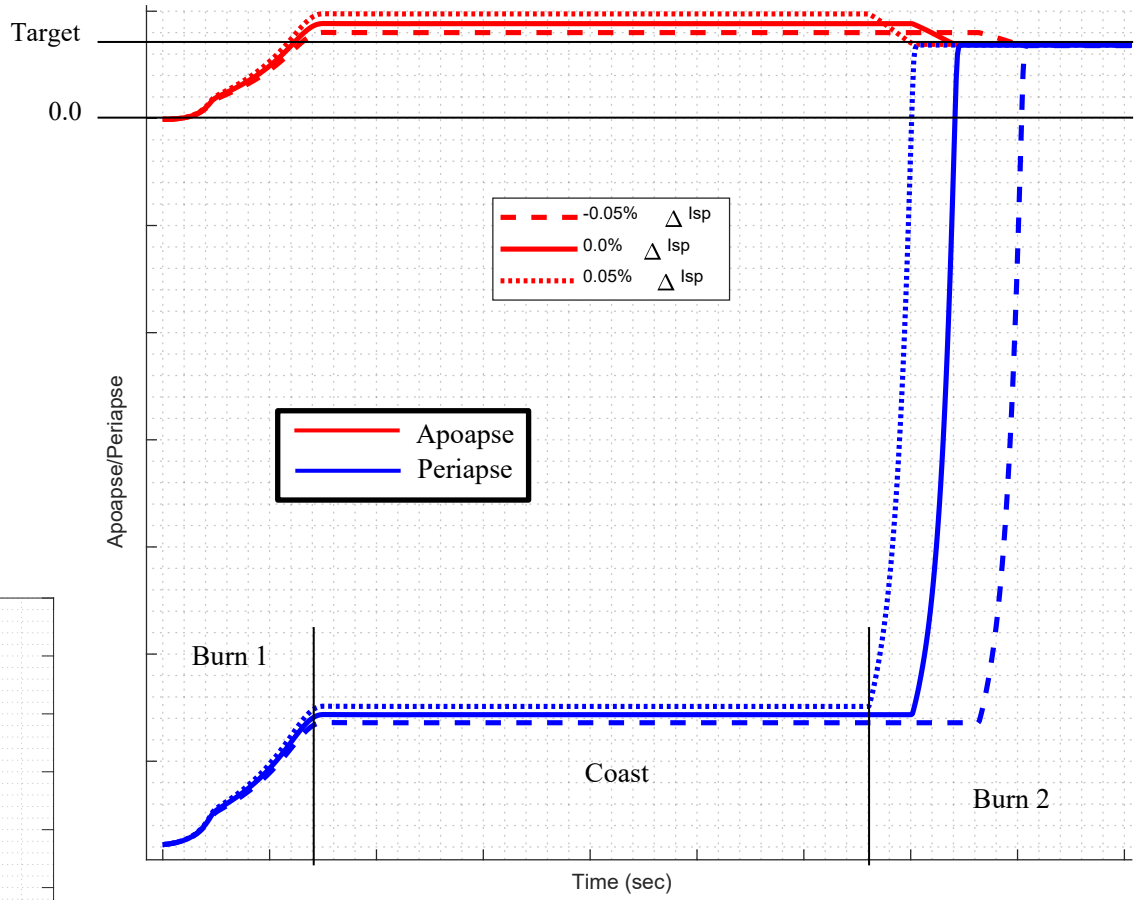
Velocity targeting partial components:

- **Radial Distance Effect** – $\vec{v}_{go}$ will decrease in time as vehicle coasts to apoapsis (in the negative $\hat{\imath}_z$ direction)
- **Target Frame Rotation** – Downrange ($\hat{\imath}_z$) direction of the target frame will change over time in the negative radial direction ($\hat{\imath}_x$)
- **Gravity** – $\vec{v}_{go}$ will change over time proportional to how $\vec{v}$ changes over time (gravity)

Performance in Martian Environment

- In greater excess energy cases, burn 2 (insertion) is pushed earlier by SxS to place more energy into $\dot{r}$ nulling
- In lesser excess energy cases, burn 2 pushed closer to apoapsis for more optimal burn location
- Mechanization notes:
  - Iteration scheme skipped if burn predicted to not have enough energy for successful maneuver
  - Maneuver off of nodal crossing leads to either RAAN or inclination dispersion
  - v_{go} (and vehicle attitude) should be frozen at significantly low values
  - Iterative scheme does not have to be called every minor guidance cycle

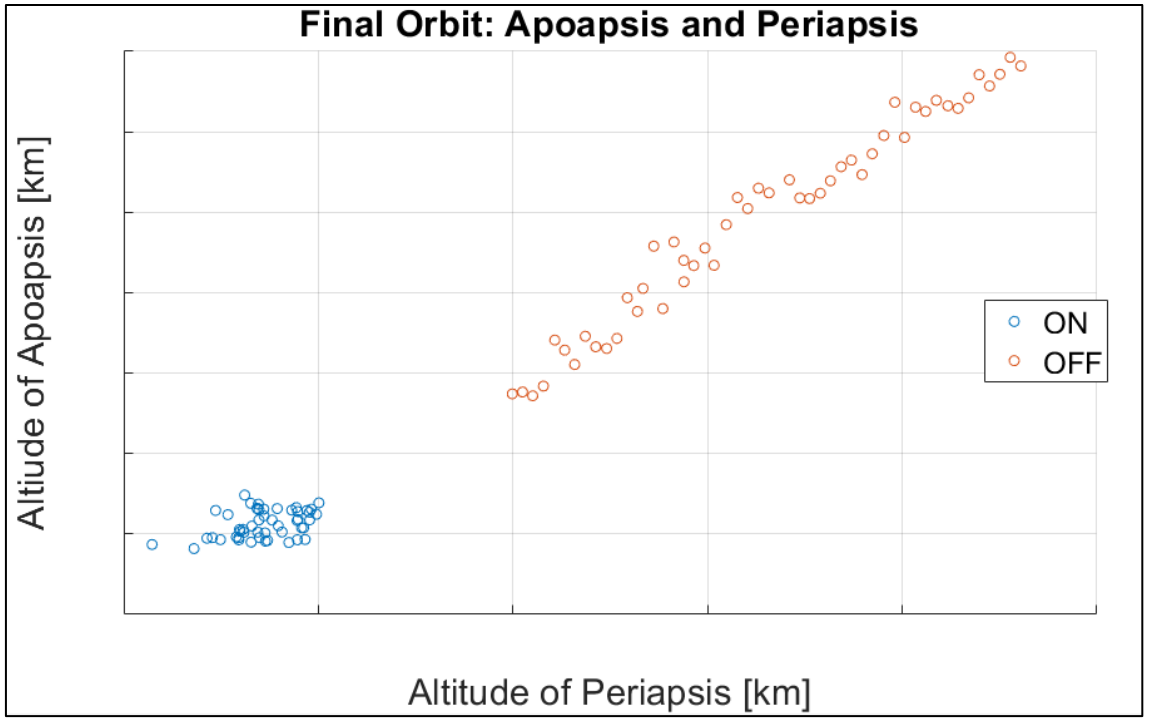




Conclusion

- Dispersion results heavily dependent on upper stage I_{sp} dispersions and accurate guidance estimations of v_{cap}

- Future work:
  - Test different velocity targeting routines (i.e. LTVC), including $\frac{\delta v_{go}}{\delta t}$
  - Develop more dispersion results for further testing
  - Continue development of algorithm for use on MAV MSR mission
  - Test applications to a lunar environment for lunar braking burns



Example of targeting 348 km. circular orbit with and without SxS for varying 1st stage I_{sp}

Any Questions?

