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Enhancements to Space Shuttle Powered Explicit Guidance for Planetary Ascent and Descent

Bharat Mahajan

Gerald Condon

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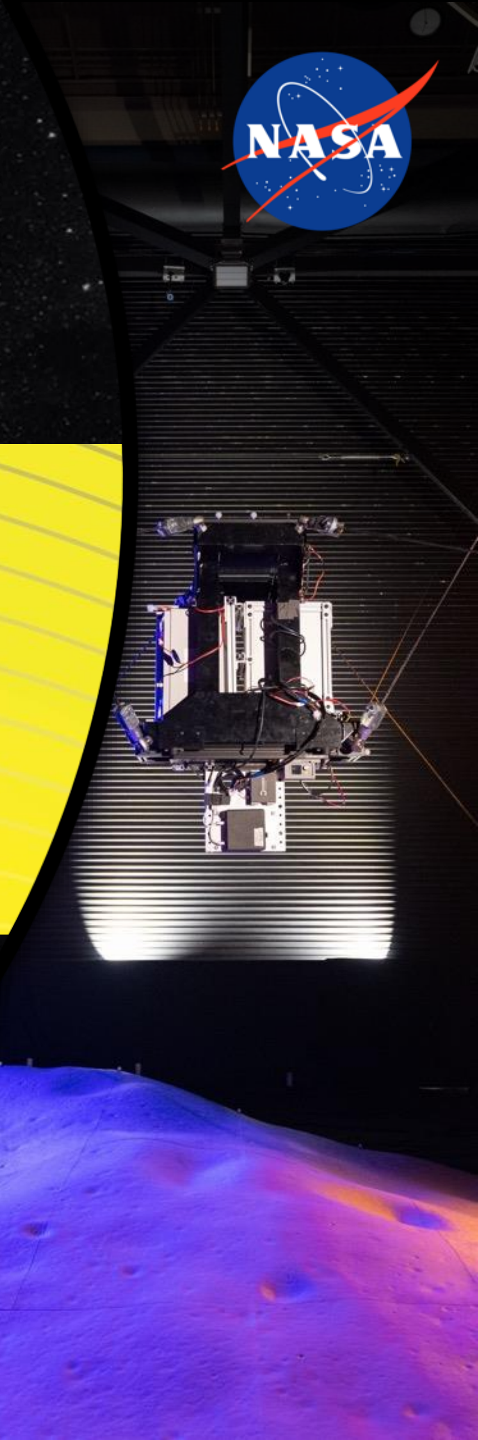


Agenda

- Motivation and Problem Statements
- PEG Introduction
- Elliptical Orbit Insertion using PEG
- Range Control in PEG for Planetary Descent
- Drag Compensation in PEG for Mars Ascent
- Conclusions

Preliminaries

- Motivation
  - Powered Explicit Guidance (PEG) was developed in 1970s for Space Shuttle’s exo-atmospheric nominal and abort trajectories
  - It is a fuel-optimal explicit 3-DOF guidance algorithm that generates thrust pointing vector and for return to launch site (RTLS) abort mode, also computes throttling commands
  - Due to its versatility, PEG has been adopted for use in modern vehicles such as SLS and Orion with some modifications
  - Literature has many references on PEG, however, many have minimal explanations on all the assumptions and approximations utilized for simplifying PEG equations for onboard implementation
  - Since the original development, many PEG modifications has also been developed internally at NASA for various projects that are not well documented, hence this paper

- Problem Statements
  - How to derive PEG in the most general form from first principles and then obtain the conventional PEG equations by introducing simplifying assumptions
  - How to use PEG for insertion into an elliptical orbit with fixed in-plane orientation?
  - How to use PEG for planetary descent with precise landing?
  - How to determine PEG time of ignition for precise landing?
  - How to modify PEG for drag compensation during ascent for Mars applications?
  - How to include more complicated force models like third-body gravity in PEG?

Introduction to PEG

- PEG was originally developed by Roland Jaggers in 1970s and was adapted by McHenry, Brand, Long, Tom Fill and many others for use as Space Shuttle primary on orbit guidance algorithm
- It is an improvement over Apollo guidance routines as it explicitly solves for the optimal trajectory for various target conditions in an efficient manner using the indirect method
- Its development is inspired by Saturn's IGM guidance and provides a vector formulation of linear tangent guidance law unlike the latter
- It uses the indirect method to formulate the necessary conditions for optimality and solves the resulting two-point boundary value problem (TPBVP) using a predictor-corrector approach for computationally efficient implementation

	TPBVP with r_d and v_d specified
Unknowns	$[t_f, \boldsymbol{\lambda}_r, \boldsymbol{\lambda}_v(t_f)]^T$
Constraints	$H(t_f) = 0, \boldsymbol{\theta} = 0$

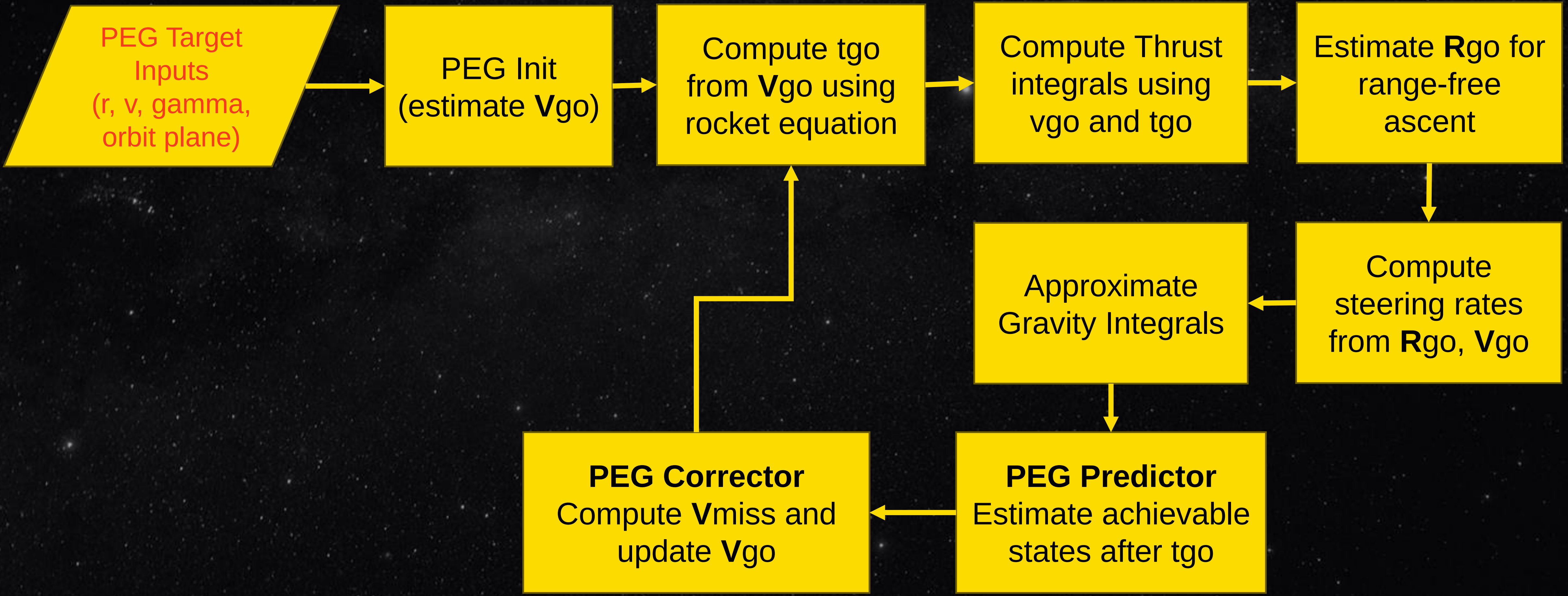
$$\boldsymbol{\theta} = \begin{bmatrix} \boldsymbol{r}(t_f) - \boldsymbol{r}_d \\ \boldsymbol{v}(t_f) - \boldsymbol{v}_d \end{bmatrix}$$

- It assumes flat-planet gravity model to simplify expressions for the costates and thrust direction

$$\boldsymbol{u}(t) = -\frac{\boldsymbol{\lambda}_v(t_0) - \boldsymbol{\lambda}_r t_{go}}{||\boldsymbol{\lambda}_v(t_0) - \boldsymbol{\lambda}_r t_{go}||}$$

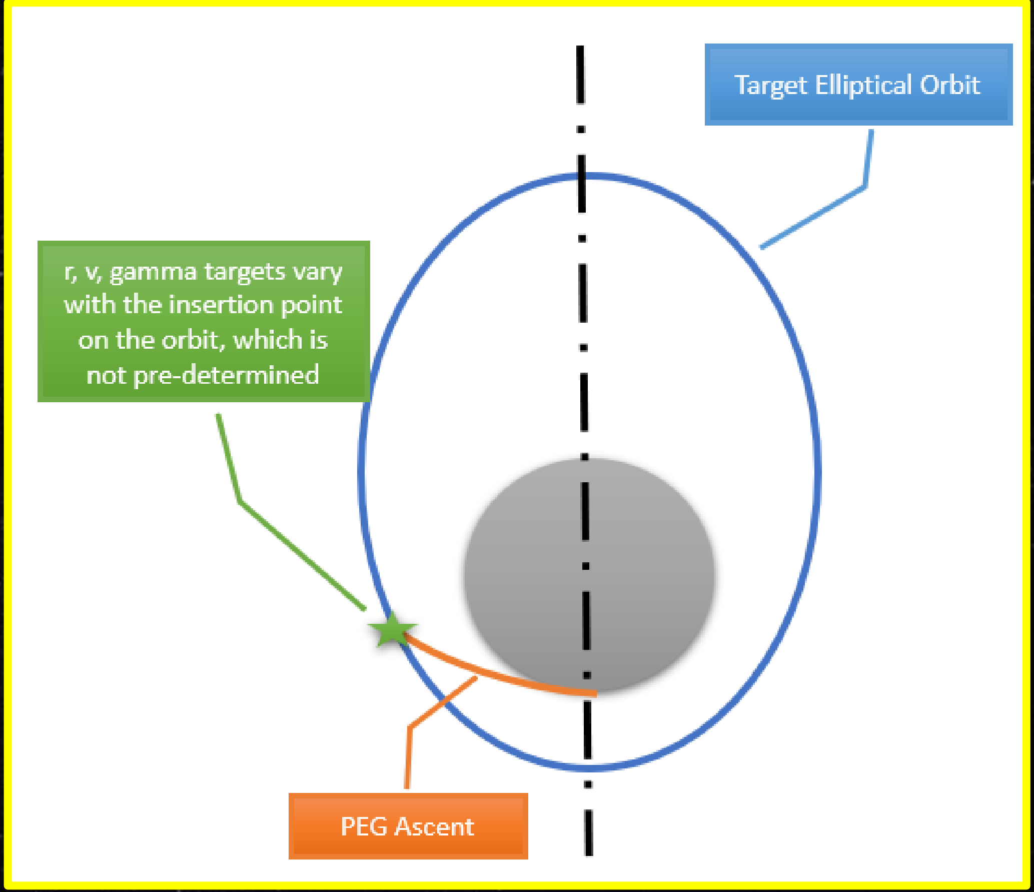
PEG Flowchart

PEG predictor-corrector algorithm enables analytic solution of the TPBVP in an iterative manner by carrying out analytic integration of the EOMs using thrust and gravity integrals



Elliptical Orbit Insertion using PEG

- Conventional PEG targets include
  - Radius (r)
  - Velocity magnitude (v)
  - Flight-path angle (gamma)
  - Orbit plane normal
- For insertion into elliptical orbits, these targets (r, v, gamma) fixes the true anomaly of the burnout state
- Downrange in PEG ascent is free, which results in line of apsides orientation a function of the initial conditions and thrust magnitude
- For achieving desired elliptical orbit in-plane orientation, a different way to specify PEG targets is needed that fixes the argument of periapsis of the burnout state



PEG Modifications for Elliptical Orbit Insertion

- A new set of PEG target or end conditions are needed for fixing the line of apsides:
  - Apoapsis radius (ra)
  - Periapsis radius (rp)
  - Argument of Periapsis angle (ω)
- Desired true anomaly (ν_t) is computed first from the argument of latitude

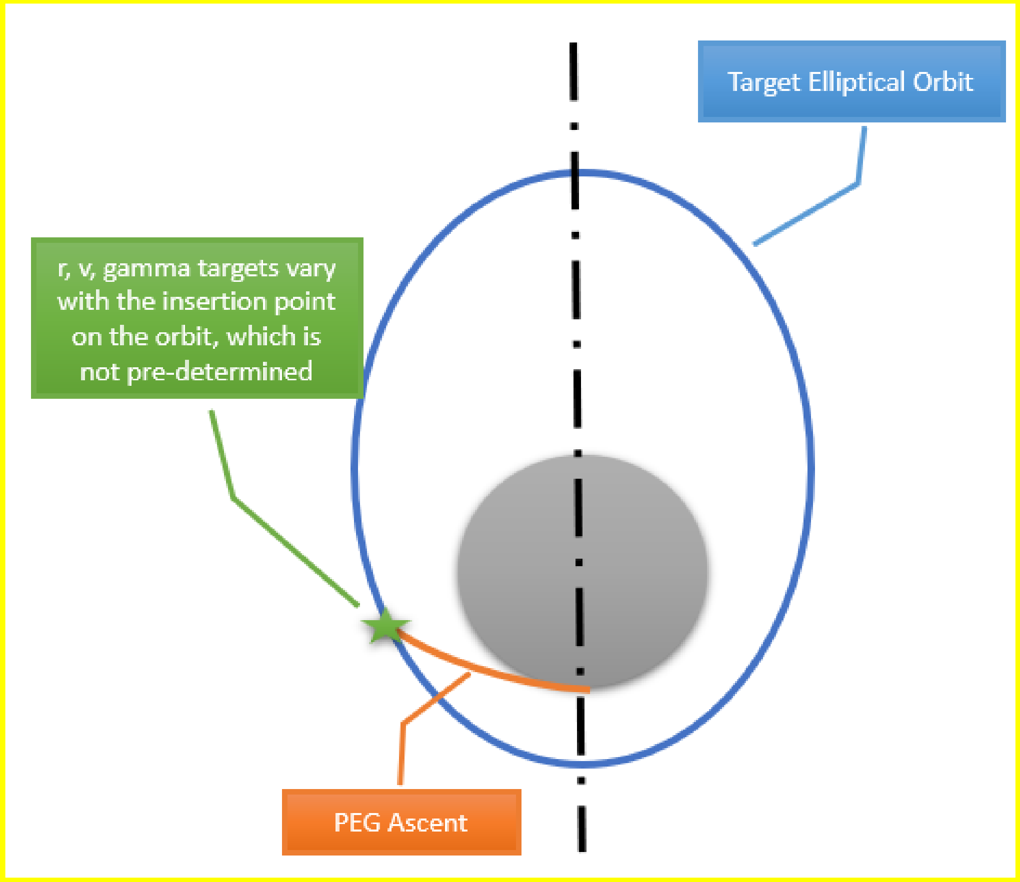
$$\theta = \cos^{-1}(\hat{n}.\hat{\boldsymbol{R}}_t),$$
$$\nu_t = \theta - \omega,$$

- Target radius is computed using the standard two-body formulae:

$$a_t = \frac{r_p + r_a}{2},$$
$$p_t = \frac{r_p r_a}{a_t},$$
$$h_t = \sqrt{\mu p_t},$$
$$r_t = \sqrt{\frac{h_t}{n_t}},$$

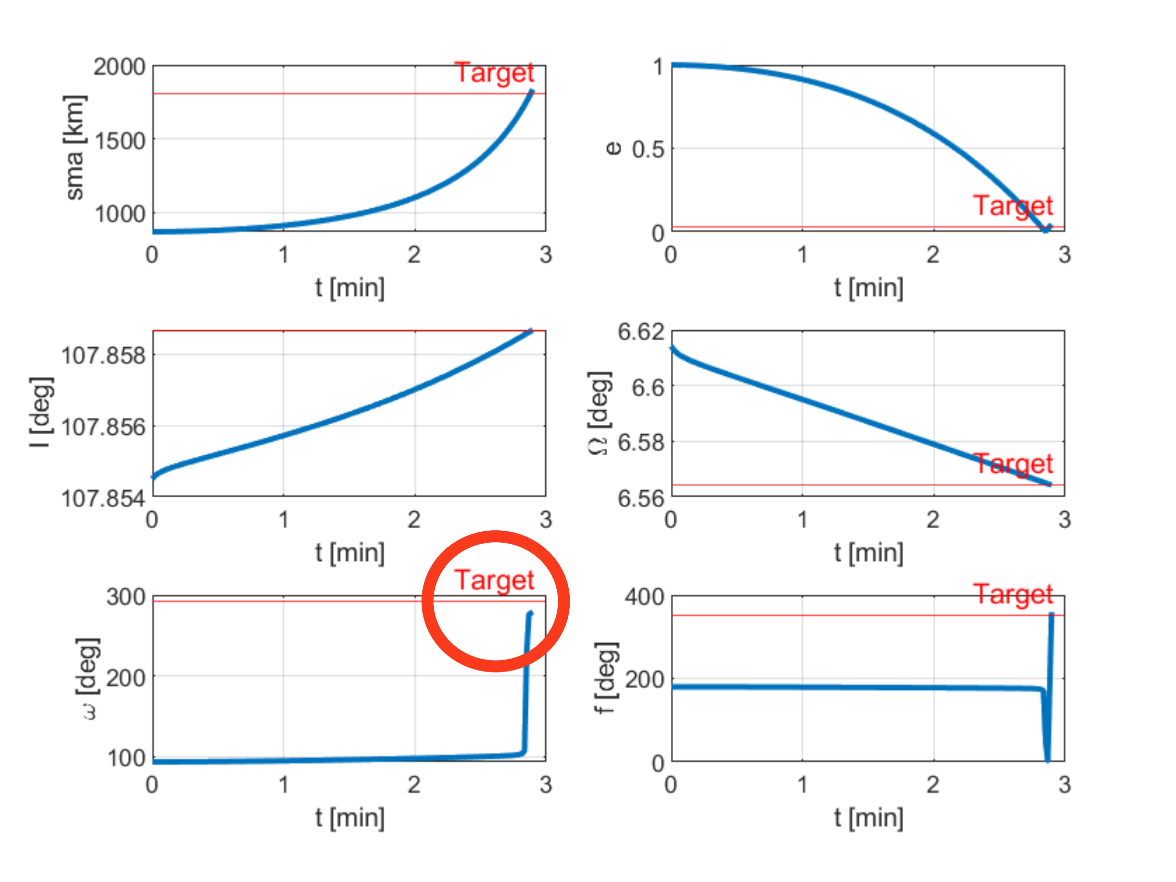
- Finally

$$\boldsymbol{R}_t = r_t \hat{R}_t,$$
$$\boldsymbol{V}_t = \frac{\mu e_t}{h_t}\sin(\nu_t)\hat{\boldsymbol{R}}_t + \frac{h_t}{r_t}(\hat{h} \times \hat{\boldsymbol{R}}_t),$$

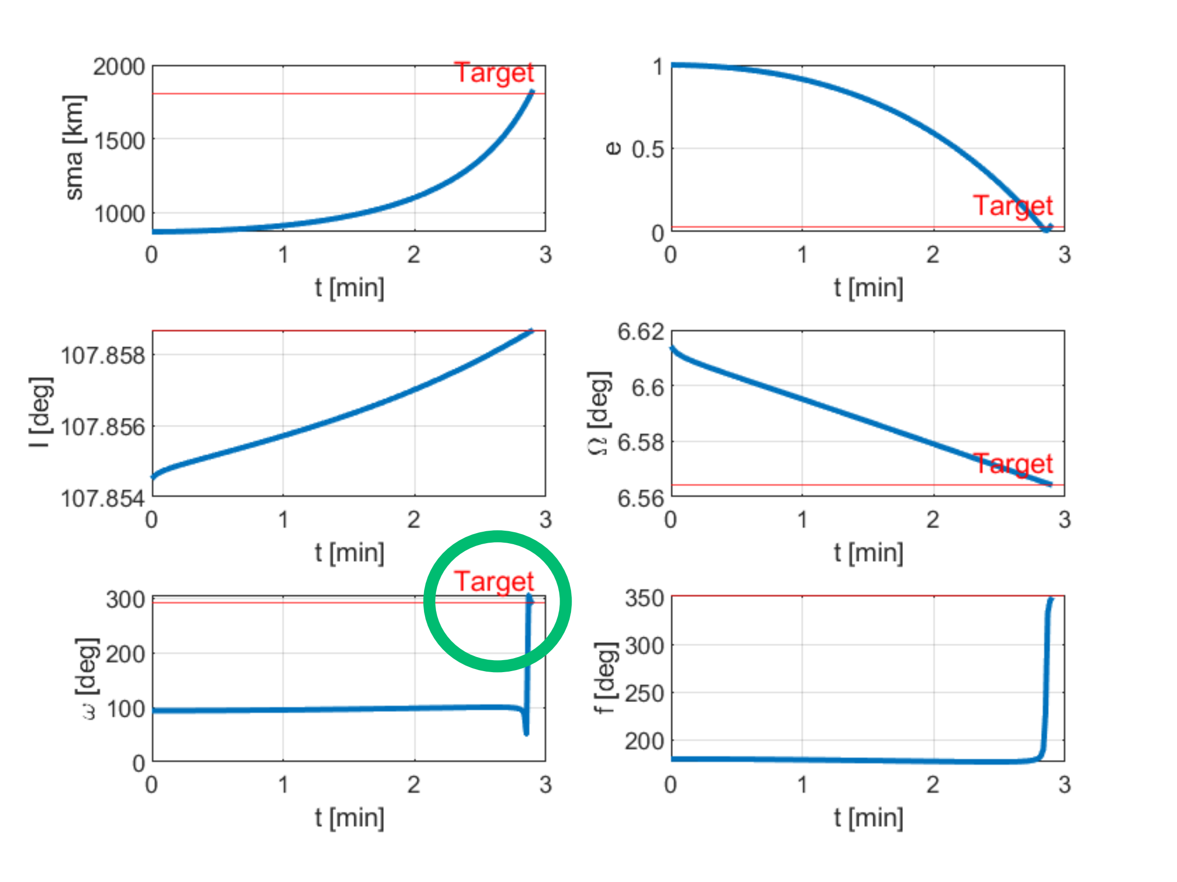


Simulation Results for Elliptical Lunar Orbit Insertion

Conventional PEG Results

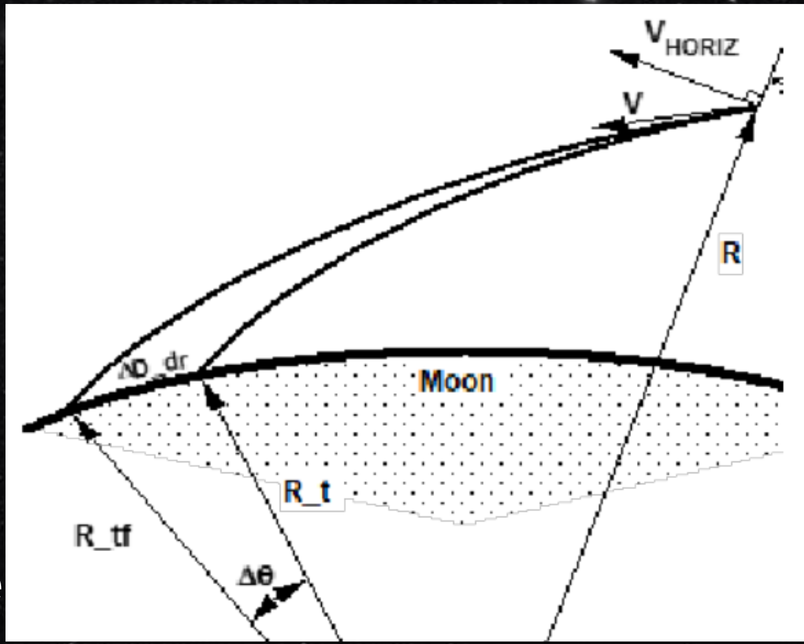


Modified PEG Results



PEG with Range Control for Powered Descent

- For planetary ascent, the burnout state downrange is free but for descent, the range to landing site must be controlled by guidance
- Space Shuttle PEG had a unique RTLS abort capability that was available from liftoff until ~270 sec (first and part of the second stage) to immediately return to the primary launch site if needed
- RTLS guidance required precise range control to the launch site using closed-loop steering and main engine throttling to achieve desired burnout conditions
- Thomas Fill (Draper Labs) adapted RTLS guidance mode to use it for lunar powered descent in NASA's ALHAT project
- Another method for range control in PEG (referred to as Vernier range control here) is developed in this work and the performance of the two are compared



Two Approaches for PEG Range Control

Vernier Range Control Equation

$$\Delta T = \frac{-T^2}{mc(1-\exp(\frac{-V_{go}}{c}))}\frac{R}{V_{HORIZ}}\Delta\Theta$$

- This method uses two-level optimization technique:
  - Outer loop computes sensitivity of PEG downrange distance to thrust magnitude and uses it to compute thrust magnitude change that corrects for the range error
  - PEG Inner loop with thrust magnitude decided in the outer loop

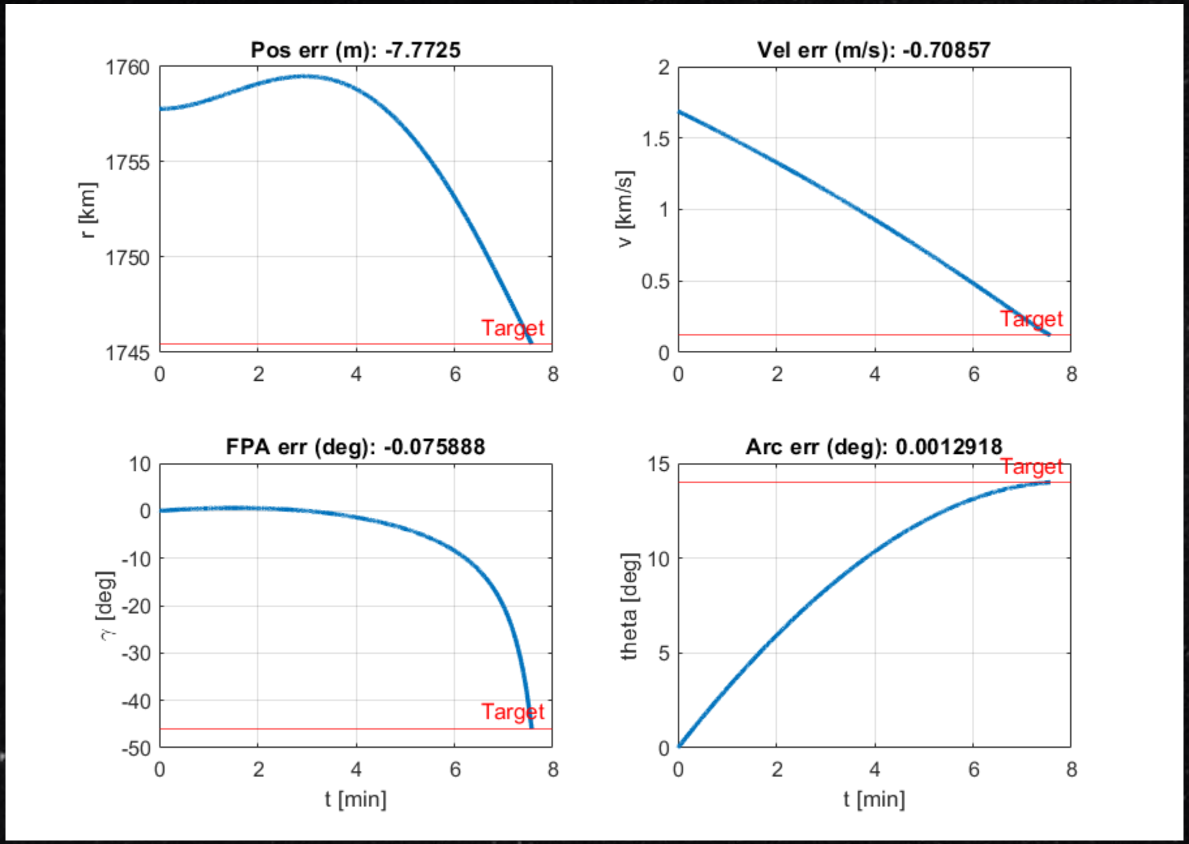
RTLS-inspired Range Control

$$\begin{bmatrix}\Delta \mathbf{V}_{go} \\ \Delta T\end{bmatrix} = \begin{bmatrix}\frac{\partial \mathbf{V}_{\text{miss}}}{\partial \mathbf{V}_{go}} & \frac{\partial \mathbf{V}_{\text{miss}}}{\partial T} \\ \frac{\partial \Theta}{\partial \mathbf{V}_{go}} & \frac{\partial \Theta}{\partial T}\end{bmatrix}^{-1}\begin{bmatrix}-\mathbf{V}_{\text{miss}} \\ -\Delta\Theta\end{bmatrix}$$

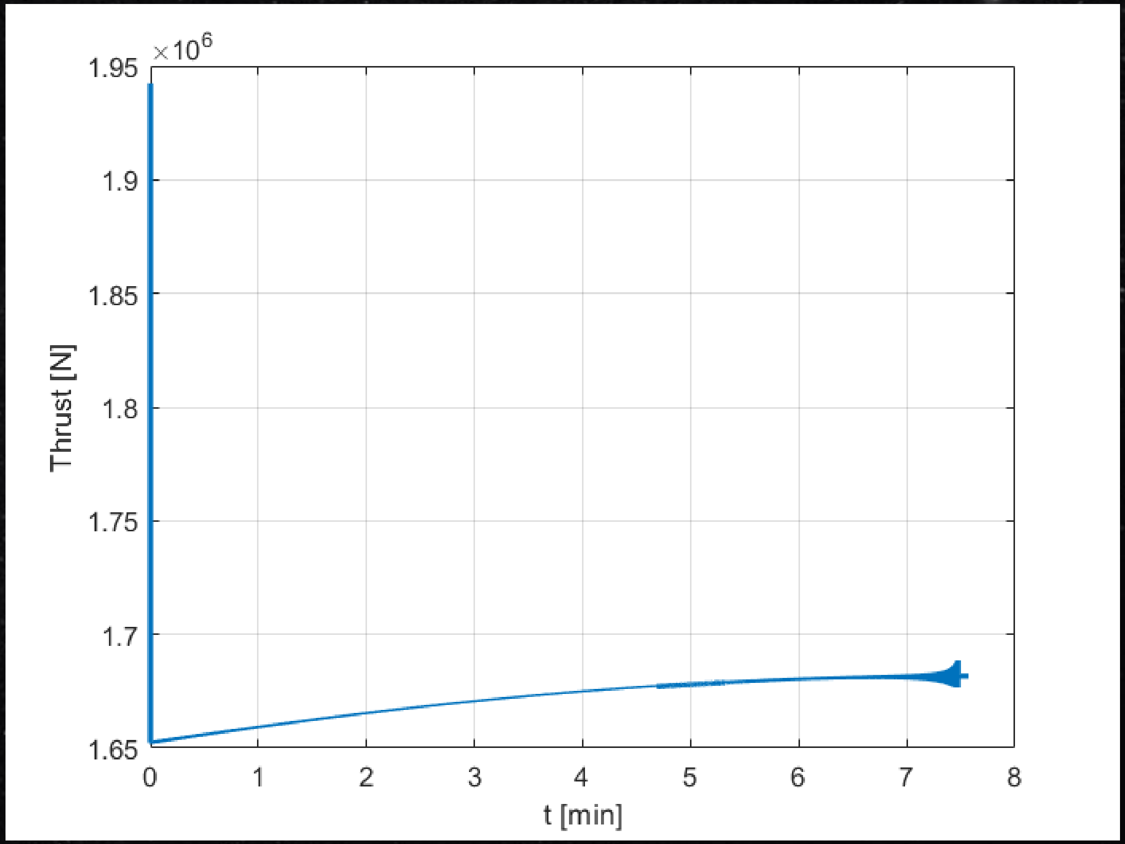
- This method uses a single PEG loop but a different PEG corrector algorithm that computes sensitivity of target velocity and downrange distance simultaneously to **V**go and thrust magnitude
- Each call to PEG updates steering commands and thrust magnitude

Lunar Powered Descent Simulation using PEG

Lunar Lander Trajectory

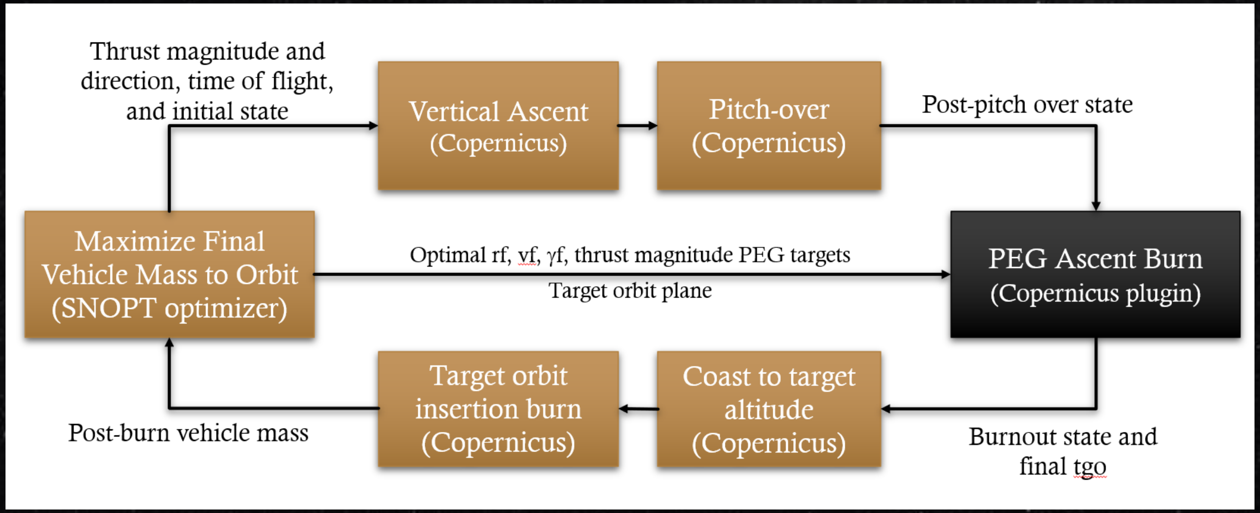


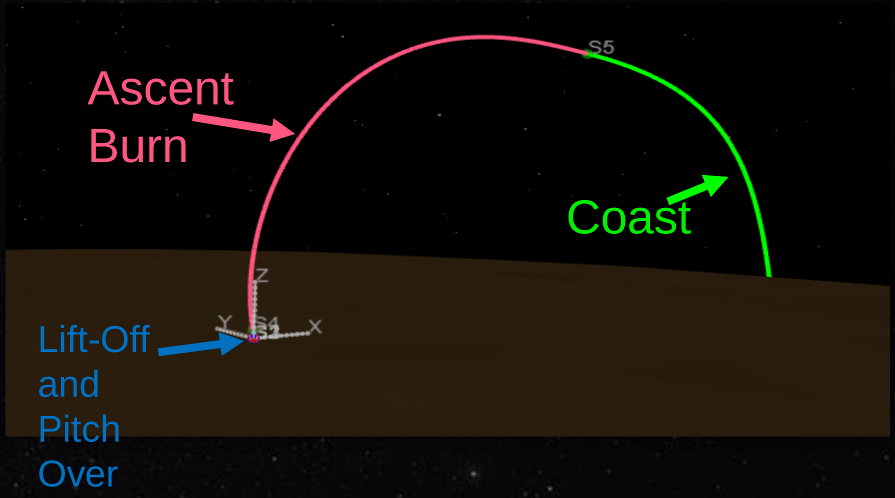
Throttling by PEG



Mars Ascent using PEG

- Compensation for atmospheric drag effects in PEG is necessary for Mars ascent trajectories for efficient propellant usage
- In this work, a drag compensation model was developed for PEG predictor equations to compute endo-atmospheric ascent trajectories
- A Mars ascent simulation was developed by integrating PEG with NASA's Copernicus tool
- Copernicus' optimizer was used as an outer loop for optimizing PEG targets for maximum performance





Conclusions

- PEG is a versatile guidance algorithm that can be adapted to different vehicles and trajectory requirements
- Enhancements to PEG presented in this work improves the versatility of PEG further by adding capabilities for
  - targeting elliptical orbits for ascent guidance
  - powered descent guidance with thrust modulation for precise landing
  - compensation for drag effects for endo-atmospheric ascent trajectories (e.g. Mars ascent)

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Thank You!