Orion Powered Flight Guidance Burn Options for near term exploration

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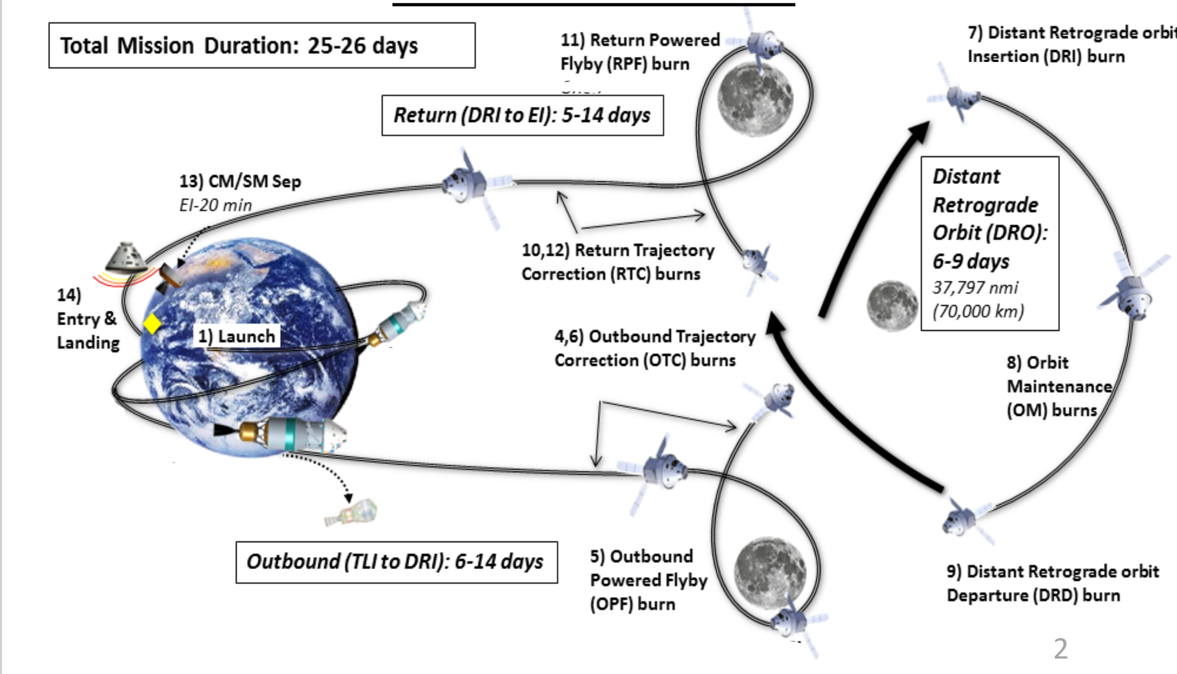
Powered Flight Guidance to support MPCV Mandate

"…missions beyond low-Earth orbit …conduct regular in-space operations…alternative means for delivery of crew and cargo to the ISS…capacity for efficient and timely evolution…"

- NASA Authorization Act of 2010

- Provide Burn Guidance for Range of Missions
  - LEO & Beyond
- Flexibility
  - Nominal
  - Abort
- Evolutionary
  - EM-1 and Beyond

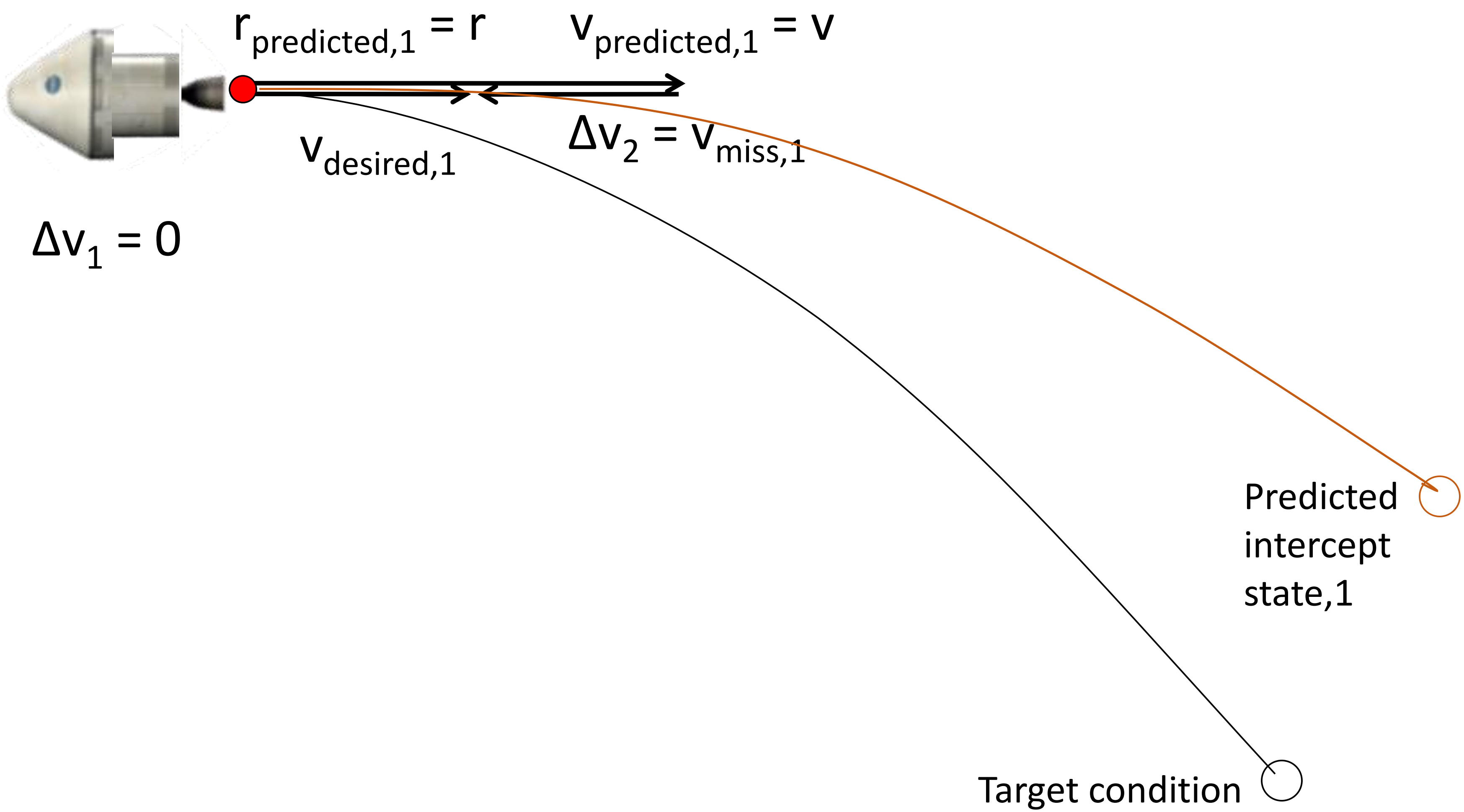
EM-1 Mission Profile



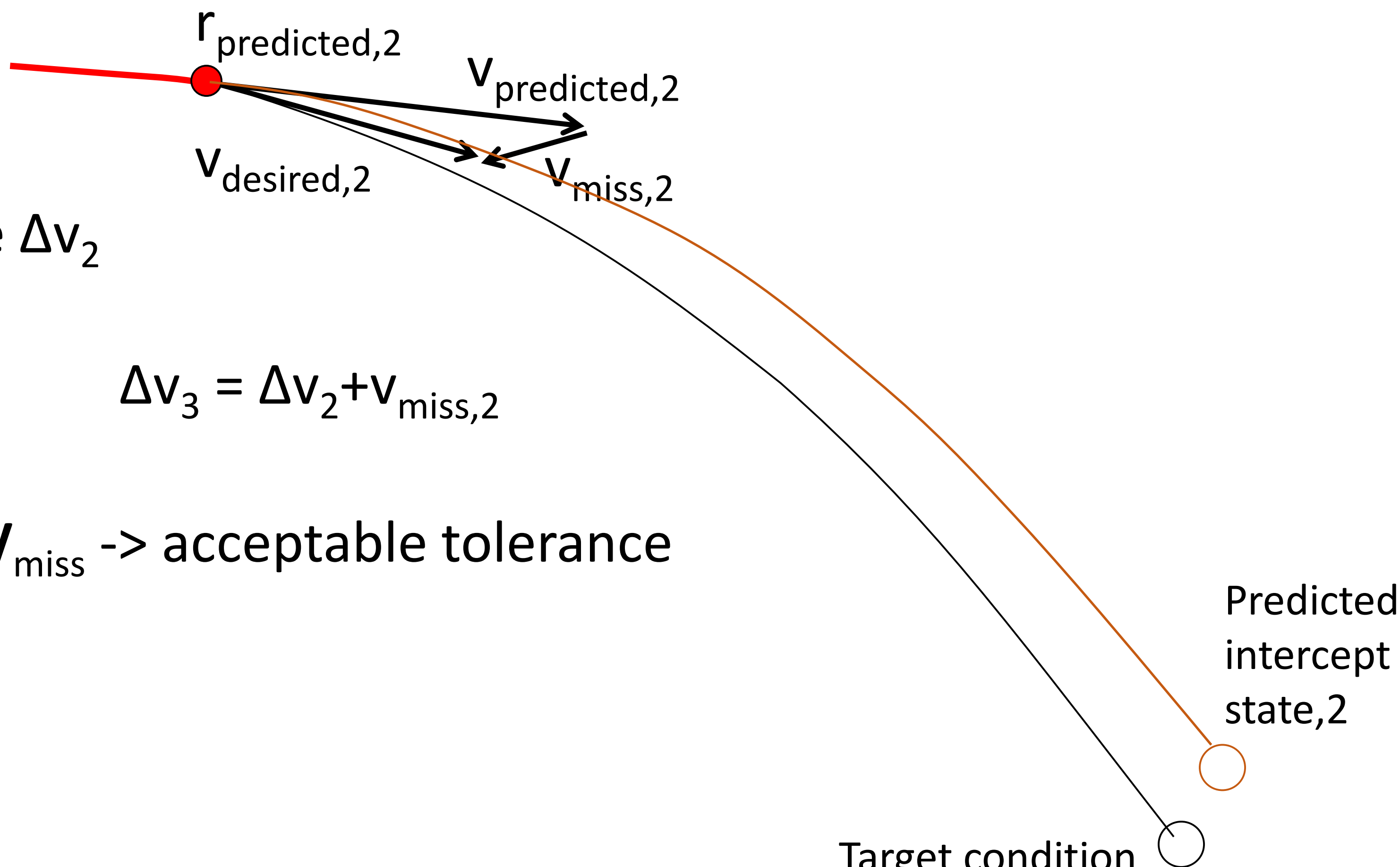
OrbGuid: Executive Summary

- Primary Function: Guide the vehicle through a burn such that, vehicle achieves a desired trajectory at burn cutoff.
- Uses the Powered Explicit Guidance (PEG) algorithm.
  - Shuttle heritage with numerous extensions and added capability.
  - Explicit – no reliance on an a reference trajectory.
- OrbGuid acts as a wrapper executive to call the PEG algorithm.
- Architecture supports a menu of desired (burn cutoff) velocity options.
  - Current suite of five options
  - New desired velocity options can be added as necessitated by the mission.

Powered Explicit Guidance



Powered Explicit Guidance



Propagate Δv_2

$\Delta v_3 = \Delta v_2 + v_{miss,2}$

Etc. until $\mathbf{V}_{miss}$ -> acceptable tolerance

OrbGuid Executive

OrbGuid runs in two execution modes, shown in brown boxes:
- Pre-burn computations:
- Active burn guidance:

Exec:

Controls execution initializations, resets, transitions

[t > (TIG – tGuidPreTIG) && burnEnable == TRUE]

[runPreBurnCompsFlag ==TRUE]

Pre-burn Computations:

Calls PEG to Converge steering solution from scratch to achieve targets.

Sets burnEnable to TRUE if converged, FALSE otherwise.

Active Burn Guidance:

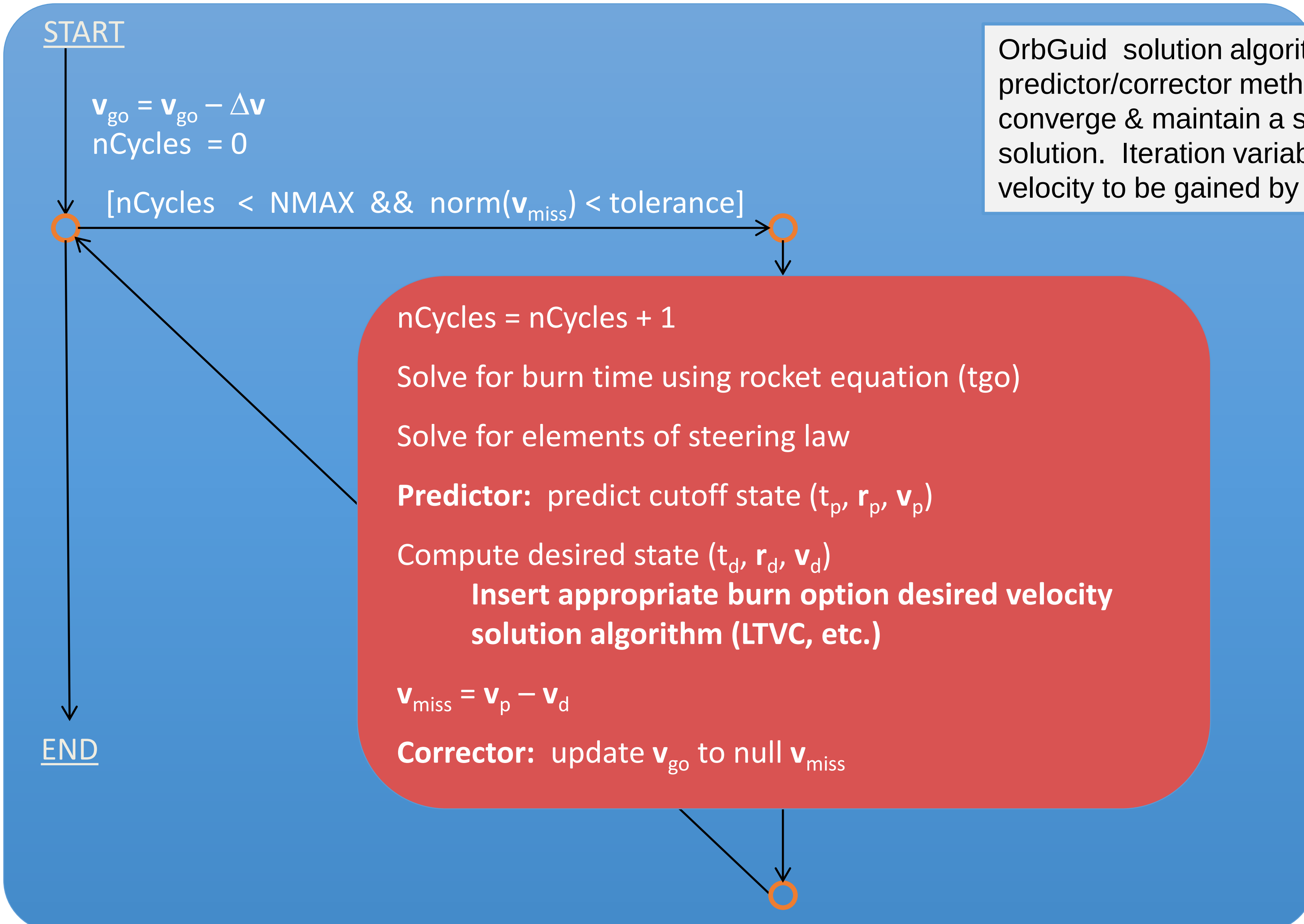
Maintains solution (via call to PEG) in the presence of dispersions.

Output Processing:

Burn cutoff time, Steering outputs

OrbGuid (PEG)

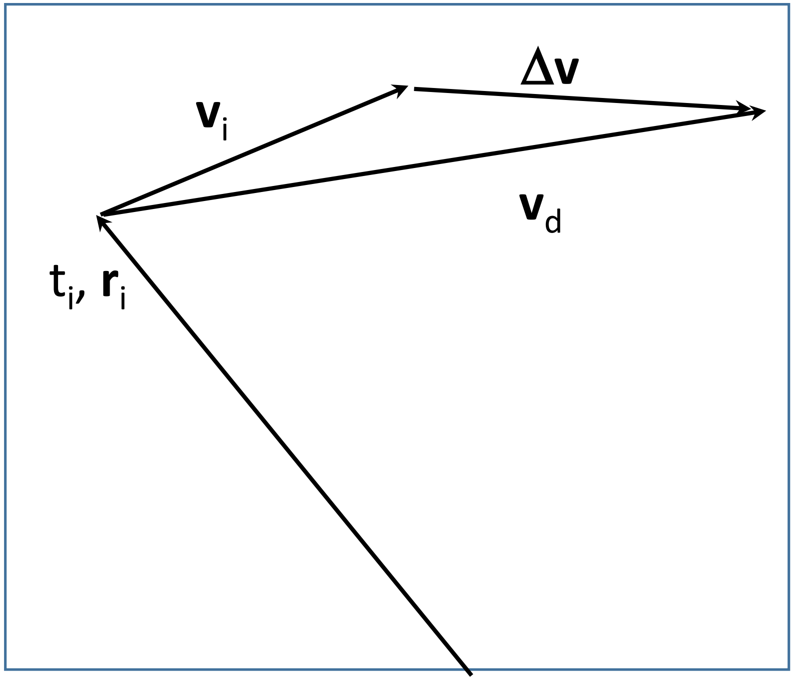
OrbGuid solution algorithm uses a predictor/corrector methodology to converge & maintain a stable guidan solution. Iteration variable is v_{go} (the velocity to be gained by thrust)



External DV

- Spec: Ext-$\Delta\mathbf{V}$
  - in either TIG LVLH or inertial Frame
- Typical Usage
  - Trajectory Correction Burns
  - Orbit maintenance

- PEG yields $\mathbf{V}_{go}$ = Ext-$\Delta\mathbf{V}$

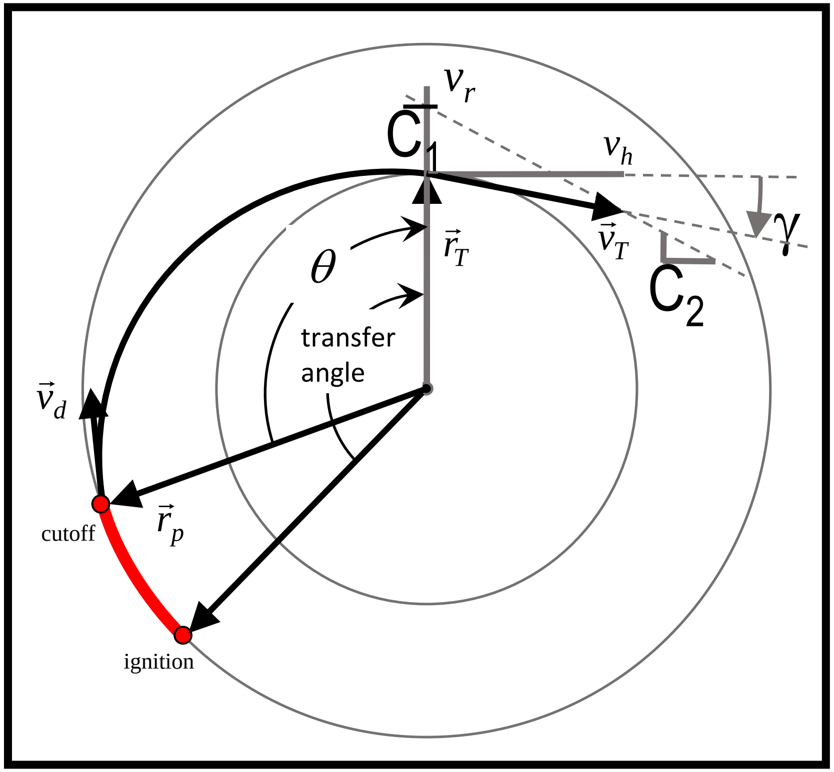


Linear Terminal Velocity Constraint (LTVC)

- Space Shuttle heritage transfer problem
  - Result of a search for a generalized targeting algorithm.
- Linear Velocity Constraint imposed at Intercept

$$v_r = C_1 + C_2 v_h$$

- Spec $\mathbf{r}_T$, c_1 , c_2 (& TIG)
  - $\mathbf{r}_T$: sometime as a spec altitude a spec transfer angle from TIG
- Used on Shuttle Orbit insertion & Deorbit
- Common Transfers
  - Line-of-Apsides Control / Hohmann-like transfers
    - Target defines desired Apsis altitude and location
    - $C_1 = C_2 = 0$
  - Deorbit
    - Target defined Entry Interface
    - $C1 = 0$; $C2 = \tan(\gamma_{EI})$



- Solution is a quadratic in the unknown $v_{T,h}$

$$[k(1+w^2)+2(1-wc_2)](v_{T,h})^2 - 2wc_1 v_{T,h} - \frac{2\mu}{r_T} = 0$$

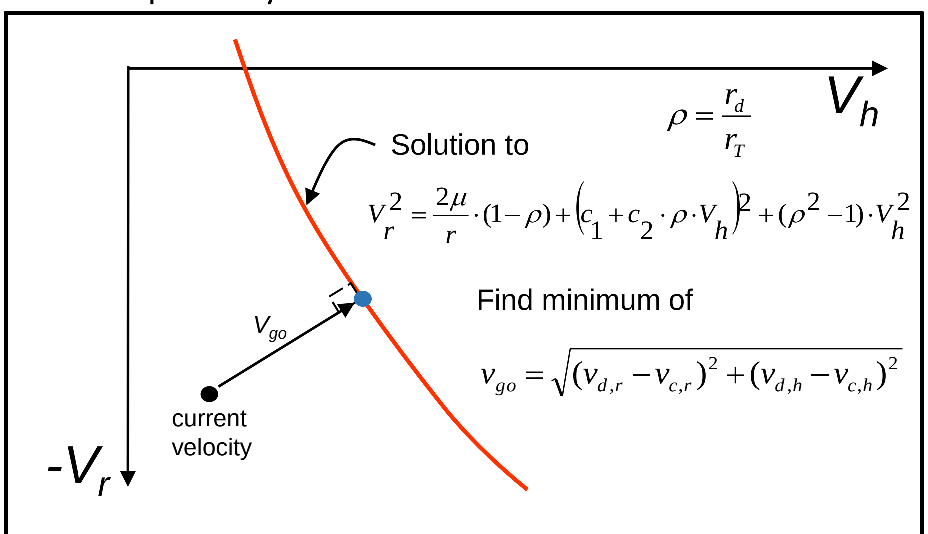
$$k = \frac{r_T - r_d}{r_d}$$

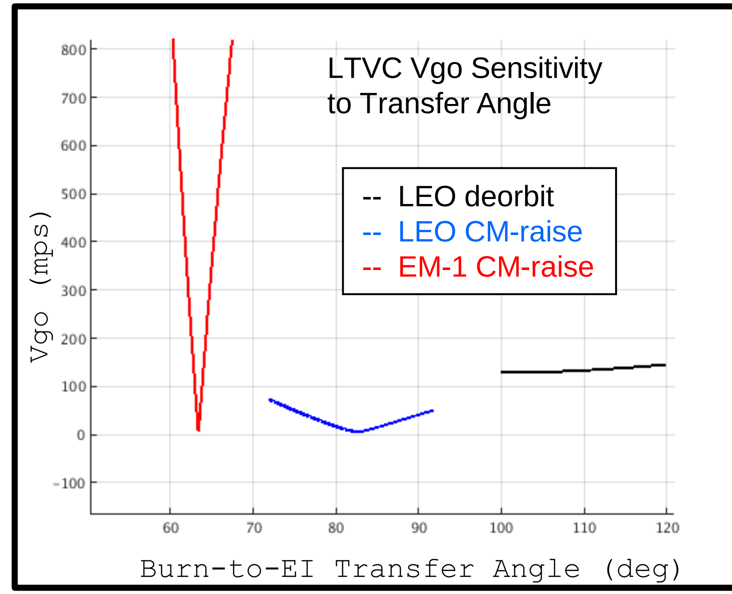
$$w = \cot\frac{\theta}{2} = \frac{\sin\theta}{1-\cos\theta}$$

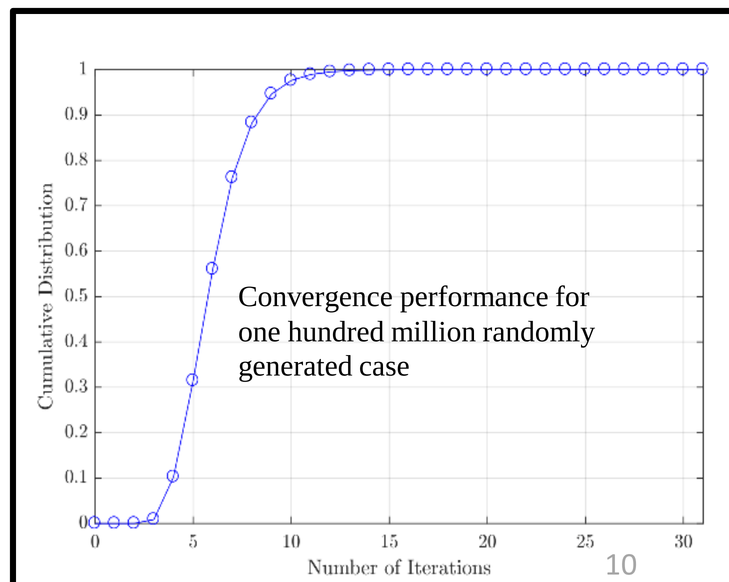
- $v_{T,r}$ From constraint; Map $\vec{v}_T$ back to $\vec{r}_p$ to obtain $\vec{V}_d$

Free-Range LTVC (FRLTVC)

- Orion CM executes short burn to separate from the SM prior to Entry
  - Via Shallower flight-path angle at EI
- FRLTC created to address extreme sensitivity of LTVC ΔV on return-from-moon Trajectory
  - CM-raise is a mini-deorbit adjustment burn
  - But Vehicle is close to EI
  - Eccentricity is near parabolic
- Resolution: relax transfer angle specification
- Spec $\mathbf{r}_T$ (magnitude only) , c_1 , c_2 (& TIG)
  - Optionally altitude

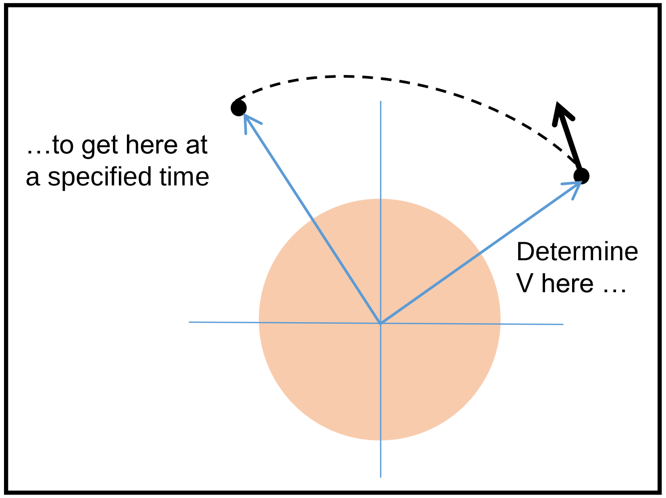


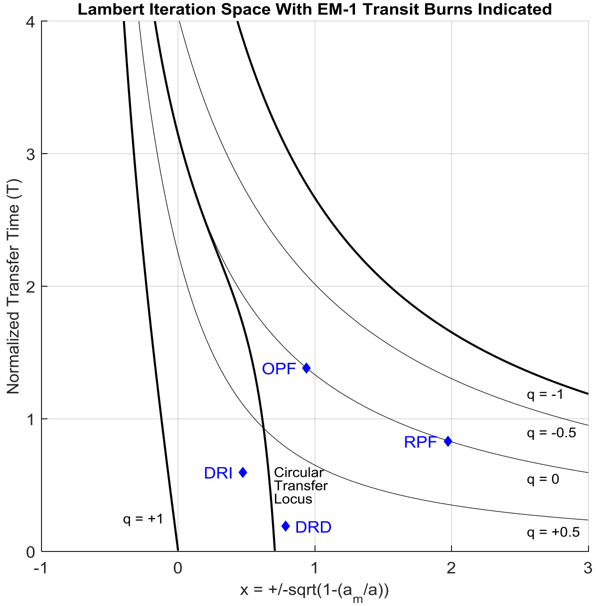


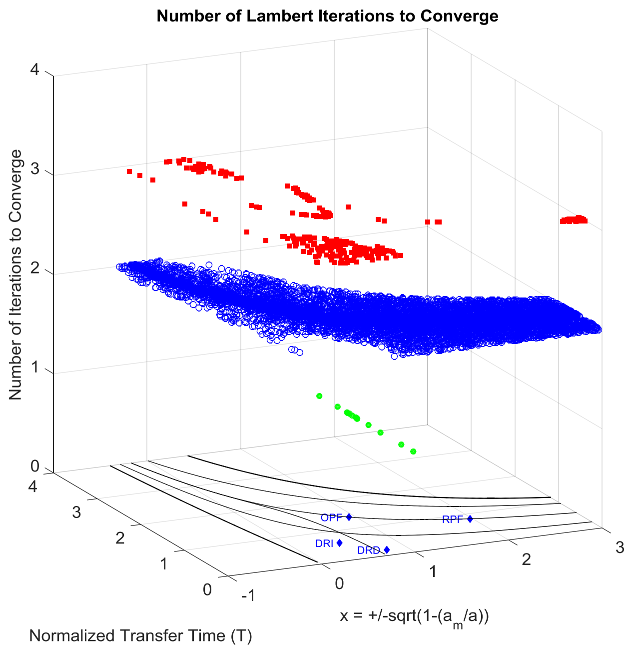


Transit / Lambert Desired Velocity

- Lambert guidance solves the two-point boundary value problem constrained by time-of-flight (TOF)
  - Adds a new parameter to define time-of-flight by specifying the time-of-intercept (i.e., transit time from ignition to intercept)
- Spec $\mathbf{r}_T$, Transfer Time (& TIG)
- Algorithm based on work by Lancaster, Blanchard and Devaney (1966), but enhanced by Gooding.
  - Lancaster, Blanchard and Devany based algorithm used on Shuttle
  - Gooding algorithm using for Constellation and is basis for Orion algorithm.
  - Gooding's new developments achieve a desired level of solution accuracy throughout the iteration space in a fixed number of iterations

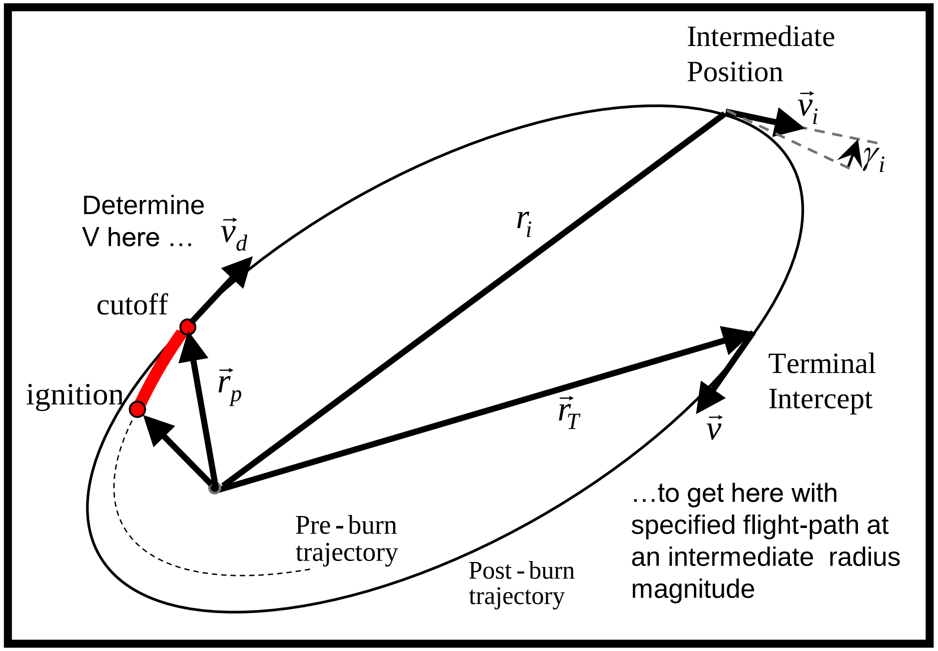






Constrained Intermediate Terminal Intercept (CITI)

- Determines velocity required to intercept a specified target position vector ($\mathbf{r_T}$) while attaining a specified flight-path angle at an intermediate radius (r_γ).
- Flight-path angle at the intercept target is not specified.
- Intermediate radius location is unimportant
- Spec $\mathbf{r}_T$, r_i , γ_i (& TIG)
- An analytic solution exists:
  - Robertson (1972): "Closed Form Solution of a Certain Common Conic De-orbit Problem".
  - Genesis is Return-to-Earth Targeting during Apollo.

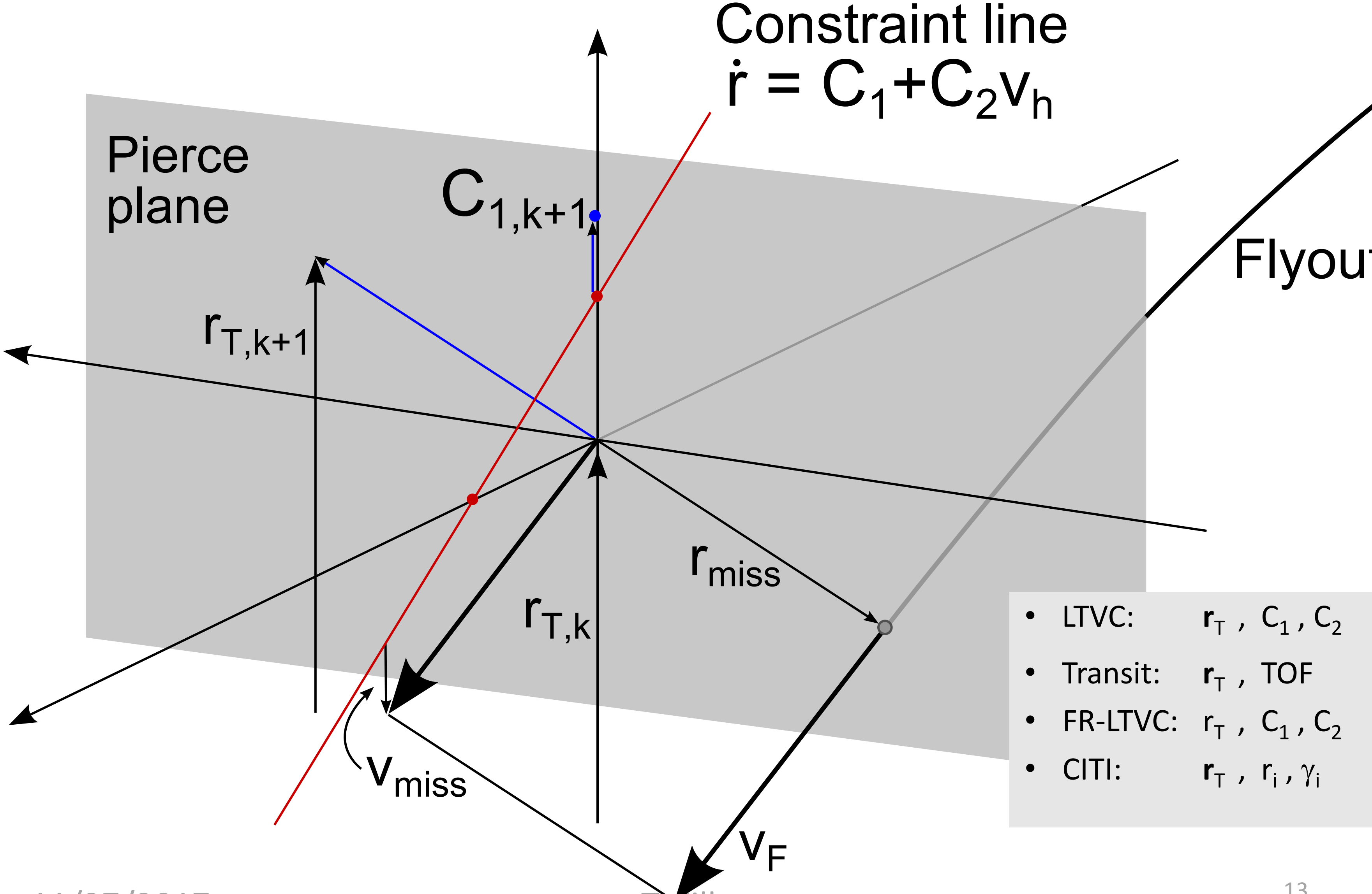


- Solution is a quadratic in the unknown Tangent of Flightpath angle at burn cutoff ($\Gamma_d = \tan(\gamma_d)$)

$$\Gamma_d^{\,2} + 2\left(\frac{r_d}{r_i} - 1\right)\cot\left(\frac{\theta}{2}\right)\Gamma_d + \left[1 - \left(\frac{r_d}{r_i}\right)^2 (1 + \Gamma_i^{\,2}) + \frac{2}{1-\cos\theta}\left(\frac{r_d}{r_i} - 1\right)\left(\frac{r_d}{r_T} - \cos\theta\right)\right] = 0$$

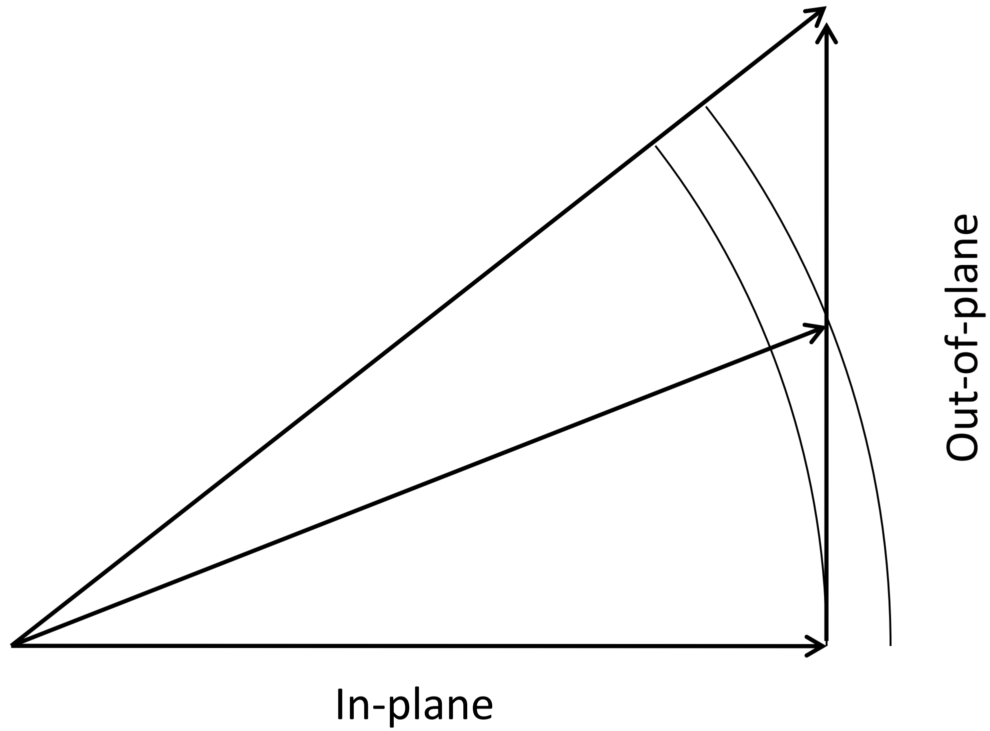
- Roots dependent on relationship between r_d, r_i & r_T (6 regions in all)
- Scenarios of current interest are $r_i > r_d > r_T$ (lunar and Earth orbit maintenance burns), and $r_d > r_i > r_T$ (direct return aborts during the outbound leg to the Moon and deorbit burns from LEO).

Target Biasing (LTVC example)



- LTVC: $\mathbf{r}_T$, C_1 , C_2
- Transit: $\mathbf{r}_T$, TOF
- FR-LTVC: r_T , C_1 , C_2
- CITI: $\mathbf{r}_T$, r_i , γ_i

Out-of-Plane Constraints



$$\Delta v_{max,mass} = v_{ex} \ln \left(mass/mass_{min} \right)$$ (preserve propellant reserves)

$$\Delta v_{max,tti} = -v_{ex} \ln\left(1 - (t_{go} + tti + tti_{min})/\tau_A\right)$$ (preserve coast time-to-intercept (

Questions?