INVESTIGATION OF ALTERNATIVE RETURN STRATEGIES FOR ORION TRANS-EARTH INJECTION DESIGN OPTIONS

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Autonomous Targeting Goals

- LLO → EEI via 3 Deterministic ΔV's
  - EEI Targets: ALT, FPA & AZ, LAT & LON
  - Controls: Up to 3 Deterministic ΔV's
  - Feasible Total ΔV < 1.5 km/sec
  - Turn-key return capability required
- Targeting in Sun perturbed Earth-Moon 3BP
  - N-body regimes (for N > 2) → Iterative Solution Process
  - Feasible or Optimal Algorithms Require Startup Arc
  - Quality of startup arc is crucial for onboard determination
    - 2BP vs 3BP Startup Arcs

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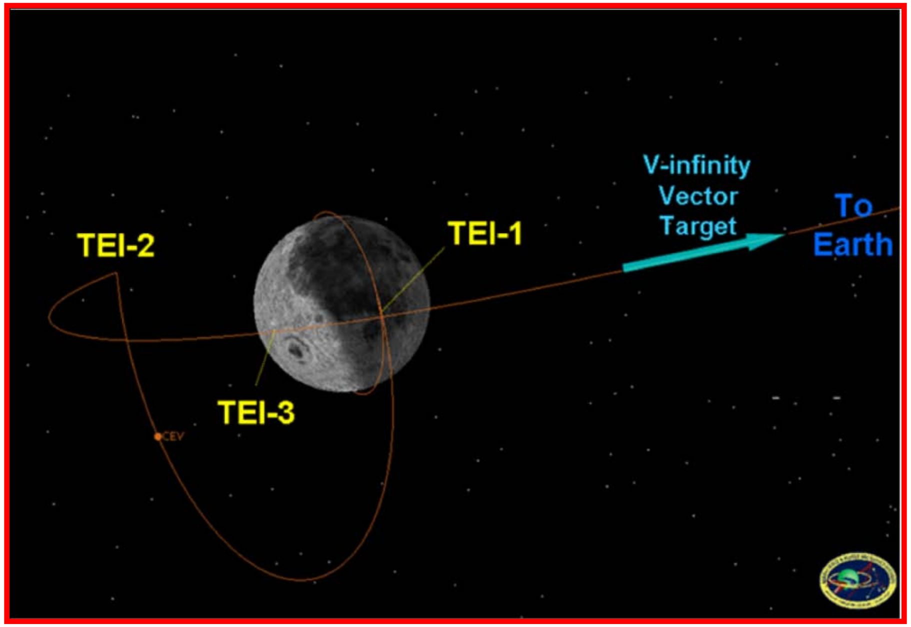
Precision Earth Entry from Polar LLO



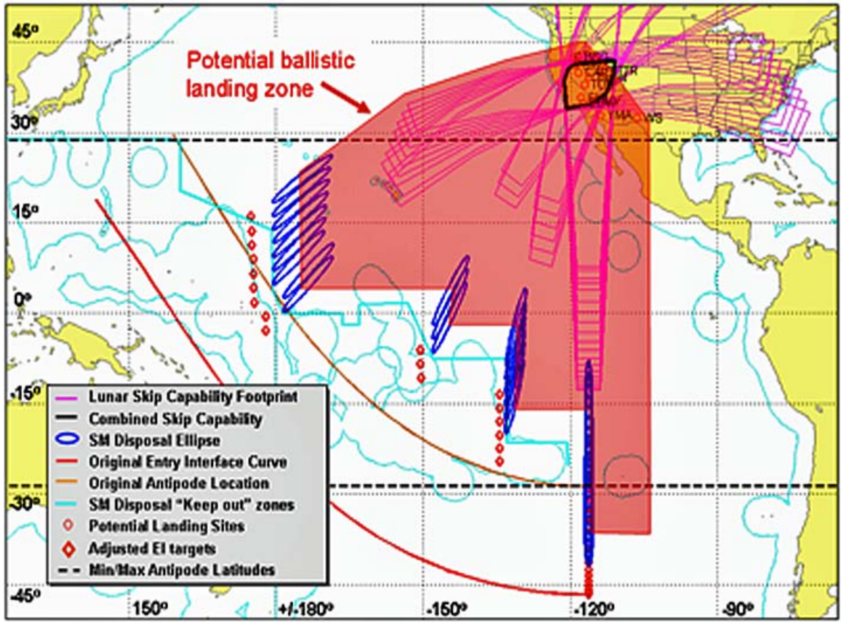


Table 1. Entry Interface Parameters

Entry Parameter	EEI-1	EEI-2	EEI-3	EEI-4	EEI-5	EEI-6
Longitude	-115.5°	-121.00°	-134.5456°	-151.4038°	173.5216°	175.6365°
Latitude	-46.66992°	-8.8522°	-19.20410°	-7.14720°	15.36700°	15.36700°
Flight Path Azimuth	0.0°	0.0°	13.9960°	34.1065°	62.3311°	49.3291°
Flight Path Angle	-5.81°	-5.99°	-6.03°	-6.16°	-6.16°	-5.86°

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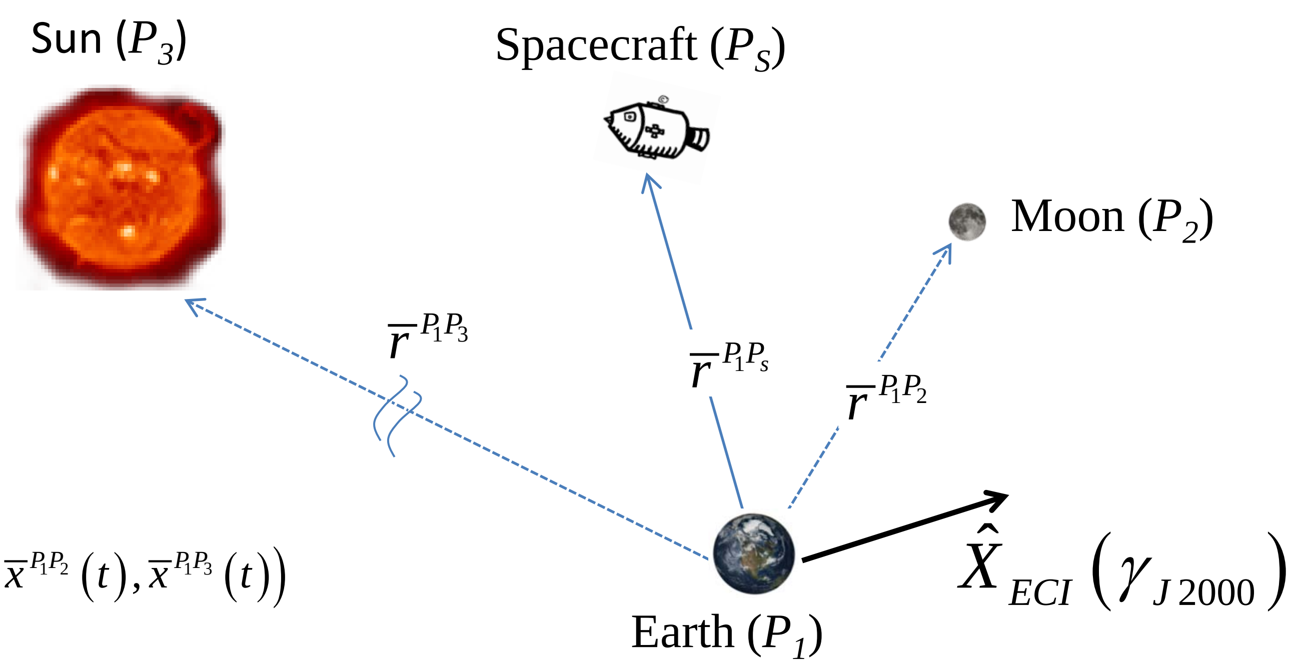
Ephemeris (EPHEM) Model: Sun Perturbed Earth-Moon System



$$\bar{x}^{P_1P_s} = \begin{bmatrix} \bar{r}^{P_1P_s} \\ {}^{ECI}\dot{\bar{r}}^{P_1P_s} \end{bmatrix}$$

$${}^{ECI}\dot{\bar{x}}^{P_1P_s} = \begin{bmatrix} {}^{ECI}\dot{\bar{r}}^{P_1P_s} \\ {}^{ECI}\ddot{\bar{r}}^{P_1P_s} \end{bmatrix} = \bar{f}\left(t, \bar{x}^{P_1P_s}(t), \bar{x}^{P_1P_2}(t), \bar{x}^{P_1P_3}(t)\right)$$

$$\bar{f}\left(t, \bar{x}^{P_1P_s}(t), \bar{x}^{P_1P_2}(t), \bar{x}^{P_1P_3}(t)\right) = -\frac{\mu_{P_1}}{\left\|\bar{r}^{P_1P_s}(t)\right\|^3} - \sum_{j=2}^{3} \mu_{P_j}\left(\frac{\bar{r}^{P_1P_s}(t) - \bar{r}^{P_1P_j}(t)}{\left\|\bar{r}^{P_1P_s}(t) - \bar{r}^{P_1P_j}(t)\right\|^3} + \frac{\bar{r}^{P_1P_j}(t)}{\left\|\bar{r}^{P_1P_j}(t)\right\|^3}\right)$$

$\bar{r}^{P_1P_2}(t), \bar{r}^{P_1P_3}(t) \Rightarrow$ From JPL DE405 Ephemerides

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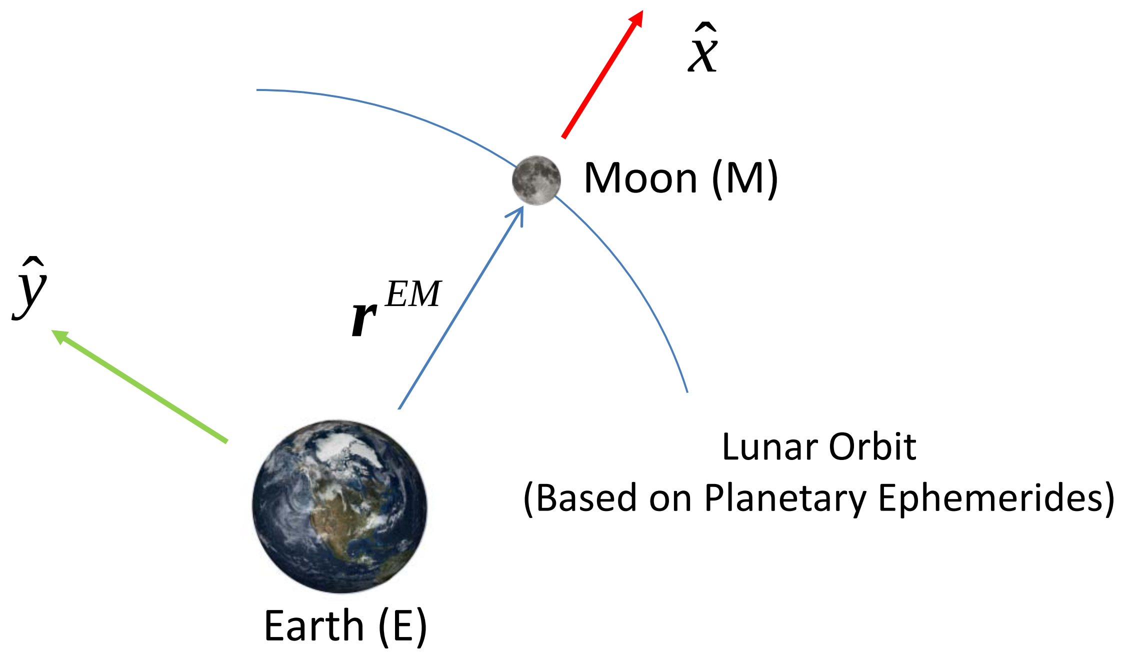
The Synodic Rotating Frame (SRF)



$$\hat{x} = \frac{r_{ECI}^{EM}}{||r_{ECI}^{EM}||}$$

$$\hat{z} = \frac{r_{ECI}^{EM} \times v_{ECI}^{EM}}{||r_{ECI}^{EM} \times v_{ECI}^{EM}||}$$

$$\hat{y} = \hat{z} \times \hat{x}$$

ECI = Earth Centered Inertial Frame (EME J2000)
SRF = Synodic Rotating Frame

$${}^{ECI}C^{SRF} = \begin{bmatrix} \hat{x} & \hat{y} & \hat{z} \end{bmatrix} \Rightarrow r_{SRF}^{ES} = \left[{}^{ECI}C^{SRF}\right]^T r_{ECI}^{ES}$$

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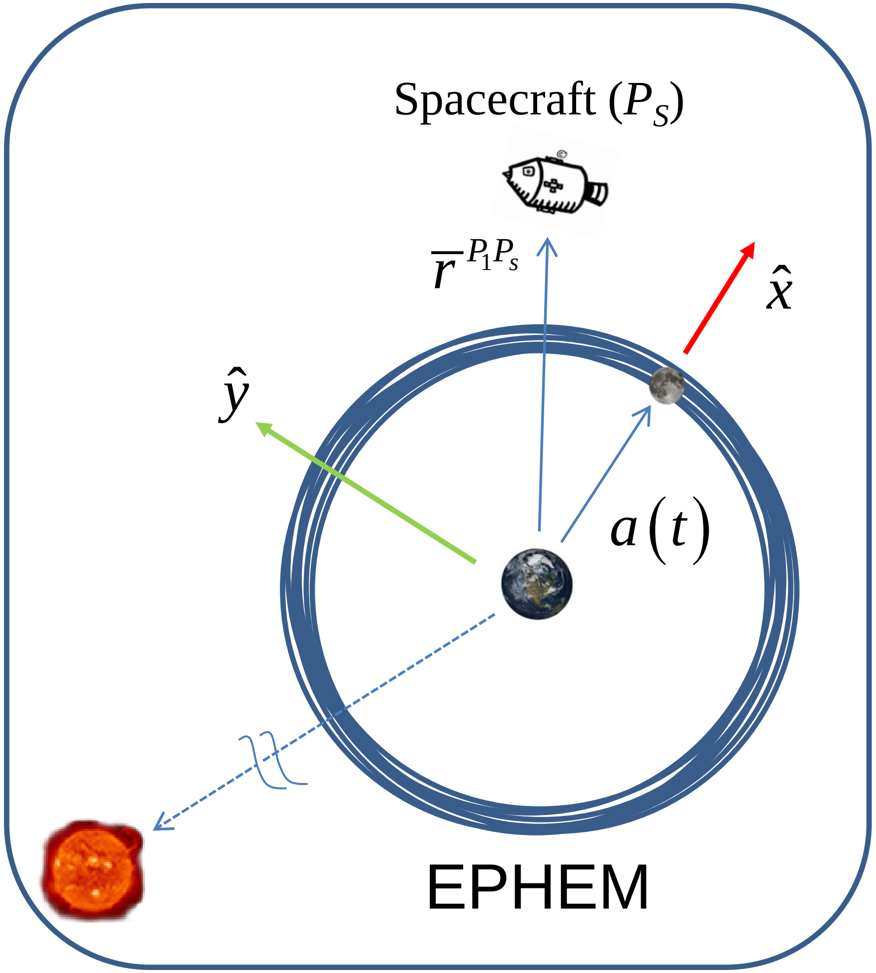
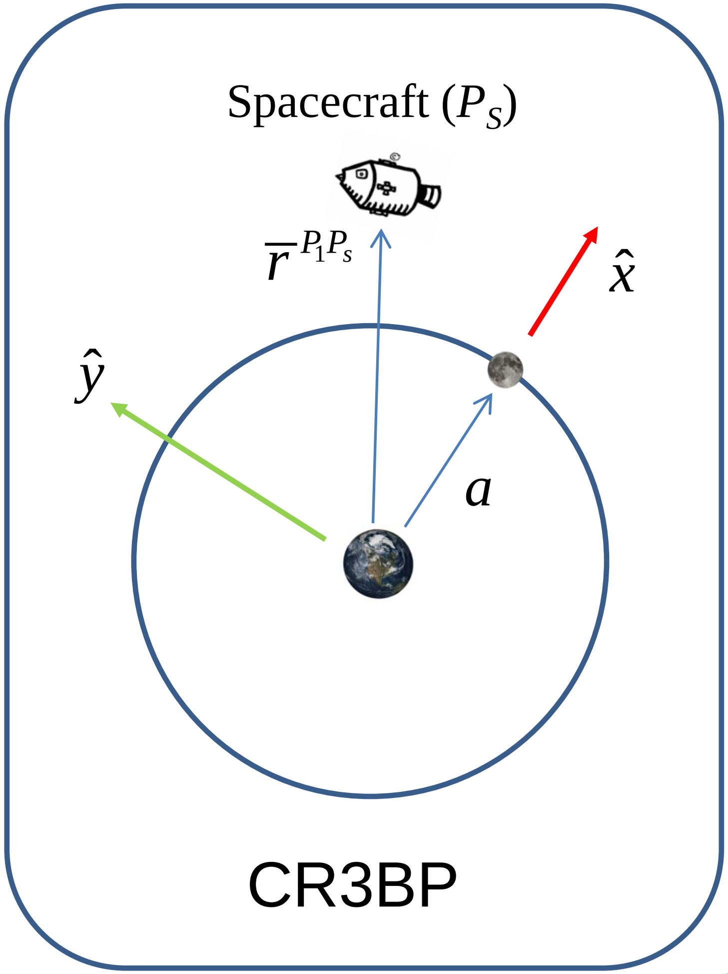
Ephemeris Model vs. The Circular Restricted 3-Body Problem





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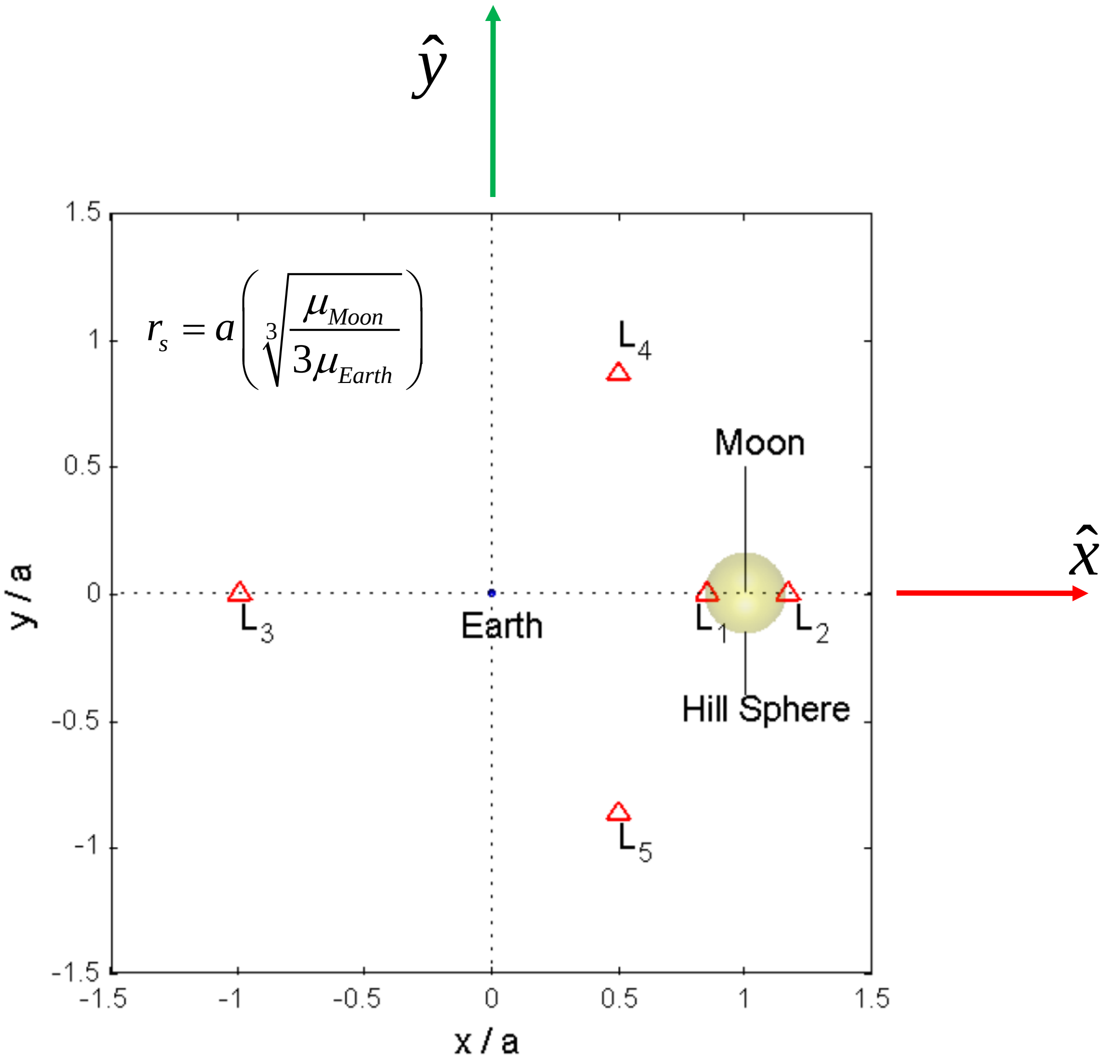
The Hill Sphere in the Earth-Moon CR3BP



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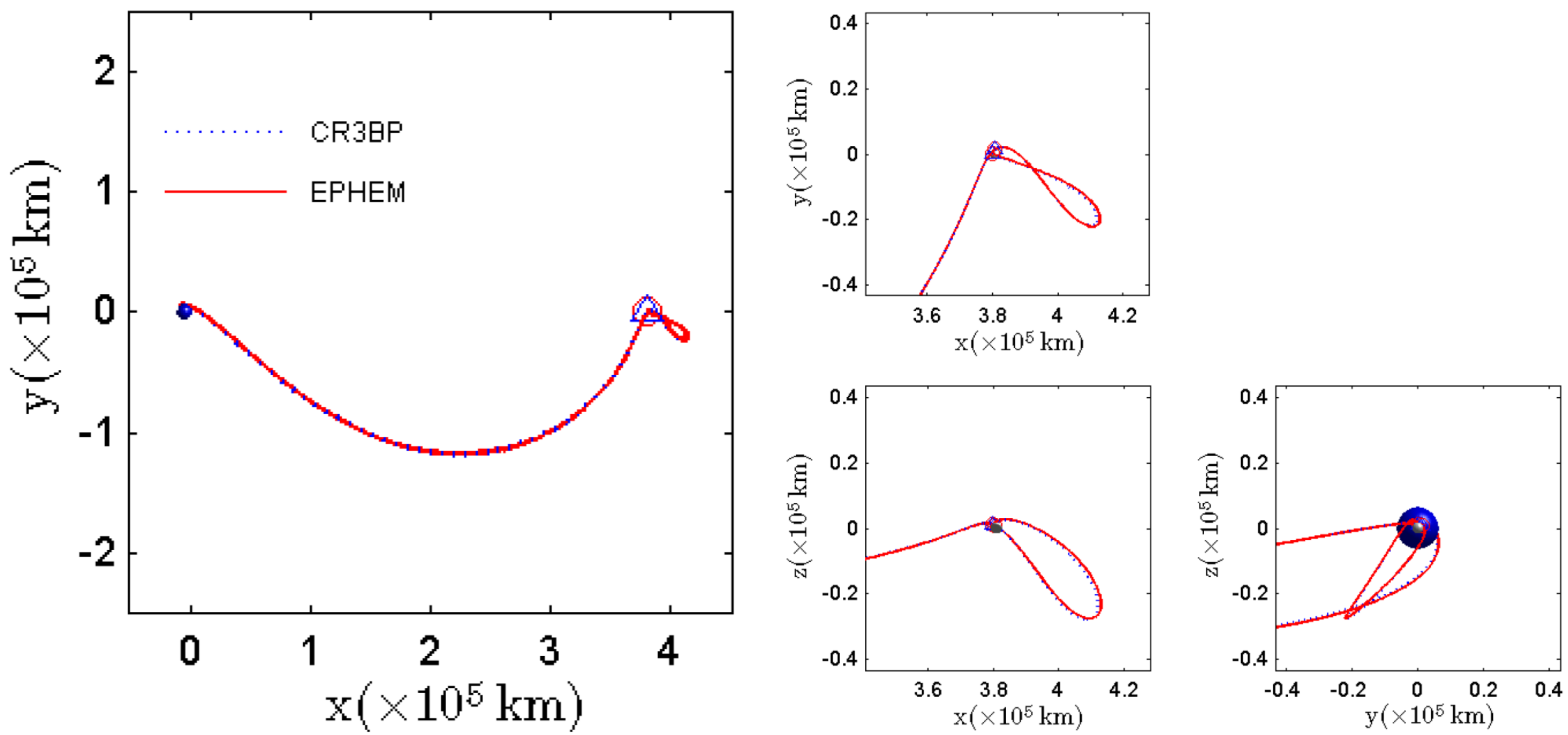
Comparison of Moon-to-Earth Transfers: CR3BP vs. EPHEM Models

Targets: Altitude = 121.912 km, FPA = -5.86 deg, ΔV = 1.0 kps



Close-up View Near the Moon:
(SRF View)

Assessing Entry Constraint Coupling and it's Impact on Startup Arc Selection

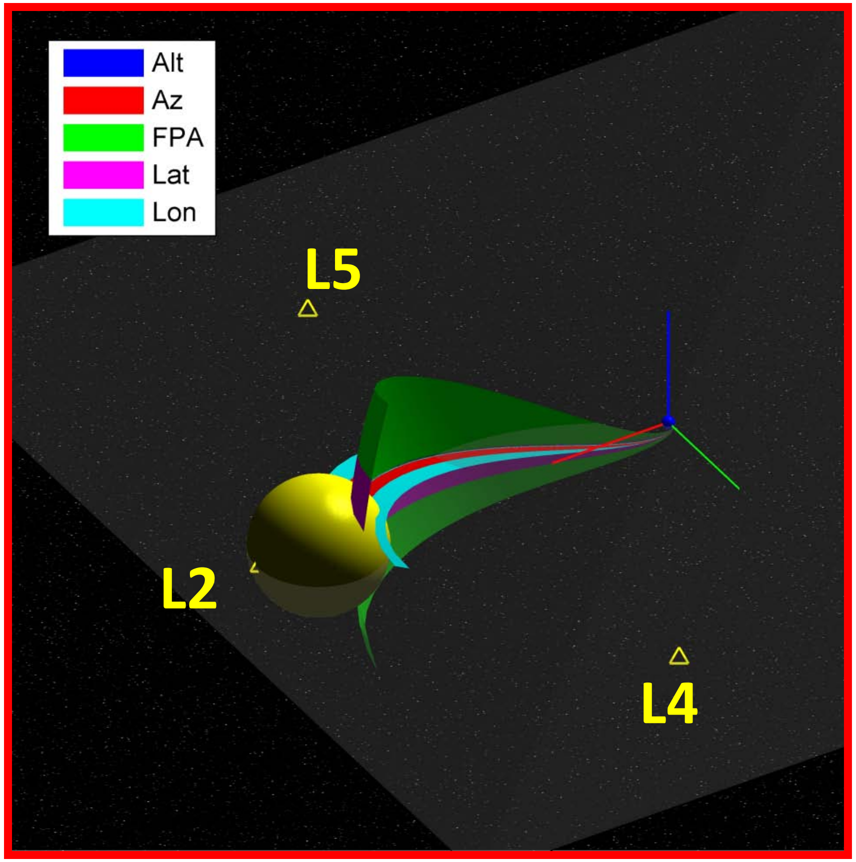
- For each **E**arth **E**ntry **I**nterface (EEI-k, for k=1,…,6) State
  1. U_k = set of sample perturbed states relative to EEI-k
  2. W_k = set of trajectories generated by

$$\overline{x}^{P_1P_s}(t) = \overline{x}^{P_1P_s}(t_{EEI}) + \int_{t_{EEI}}^{t} \overline{f}\left(\tau, \overline{x}^{P_1P_s}(\tau), \overline{x}^{P_1P_2}(\tau), \overline{x}^{P_1P_3}(\tau)\right) d\tau$$

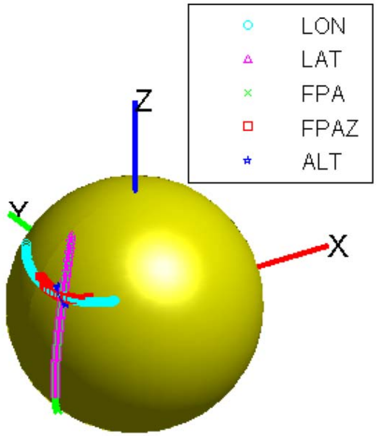
     W_k forms the **dispersion manifold** for EEI-k.

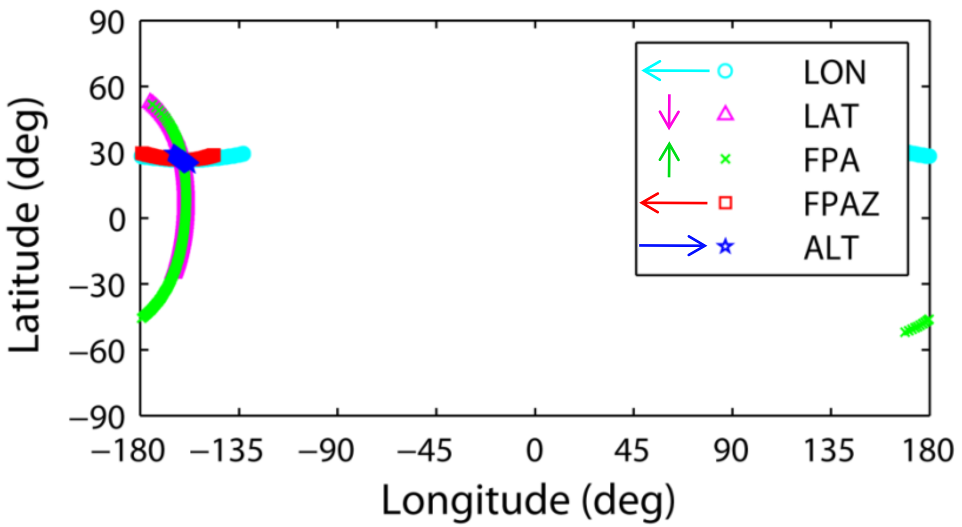
  3. $\Omega_k = [{}^{SRF}C^{ECI}]\, W_k$
  4. $\Omega_k' = \Omega_k * a / a(t)$
  5. H = surface defined by **Hill Sphere** in the SRF of the CR3BP
  6. Identify $\Omega_k' \cap H$

EEI-1 Dispersion Manifolds: Intersections w/ Hill Sphere (SRF View)



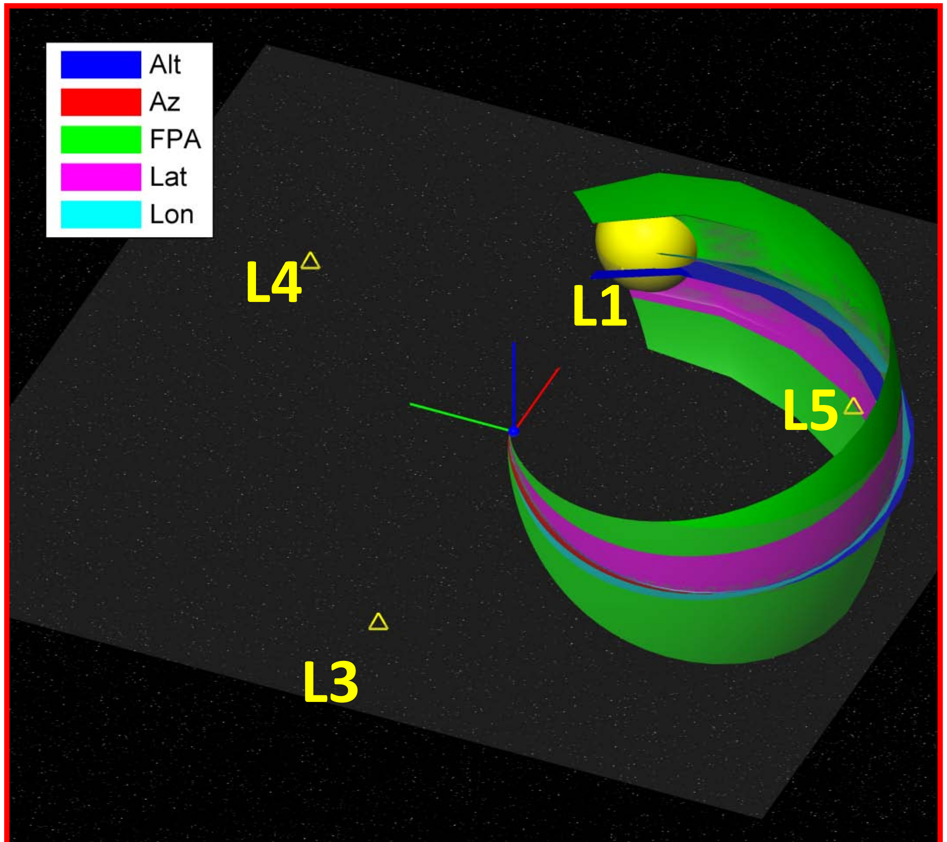
Intersections with Hill Sphere

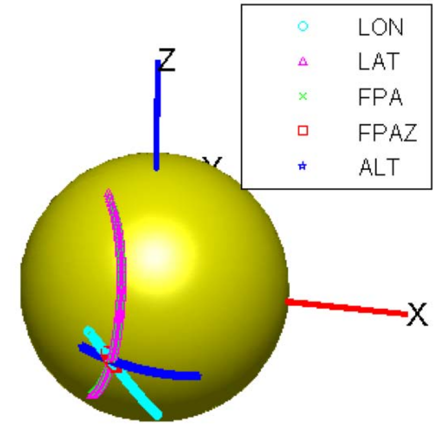


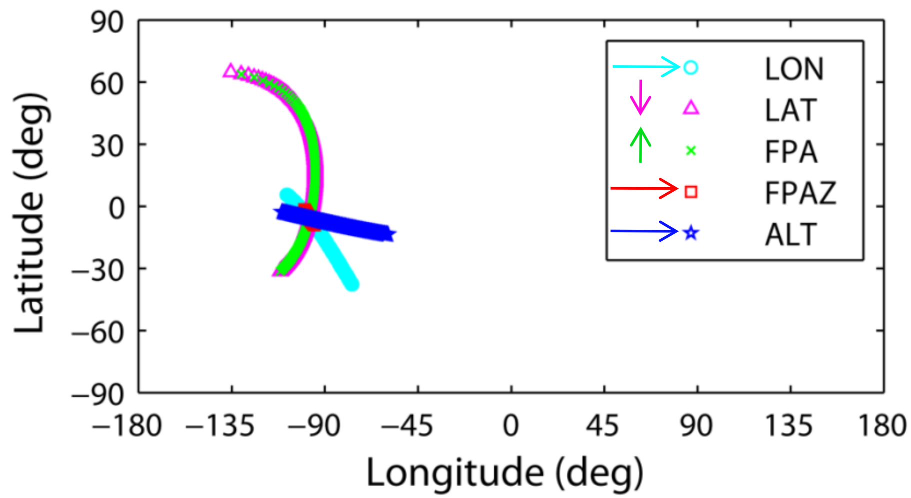


Lat/Lon of Intersections Along Hill Sphere

EEI-2 Dispersion Manifolds: Intersections w/ Hill Sphere (SRF View)







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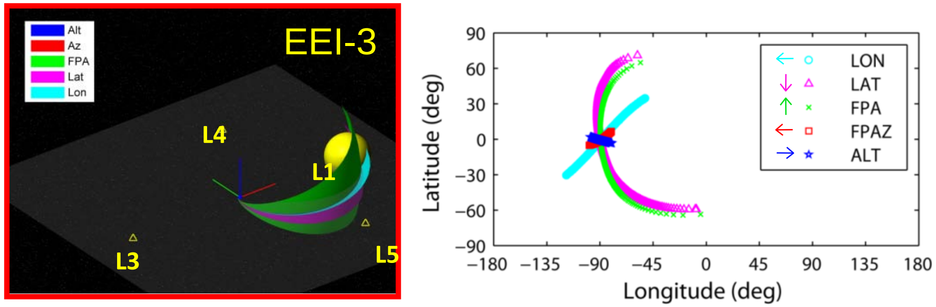
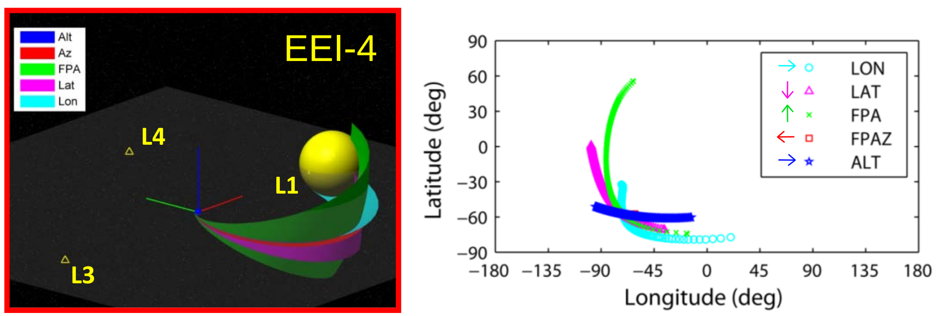
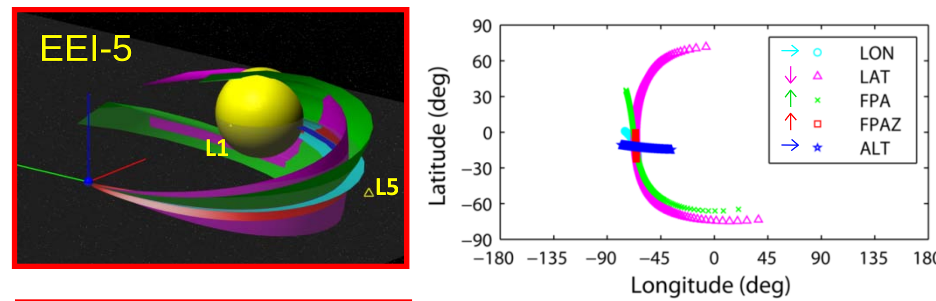
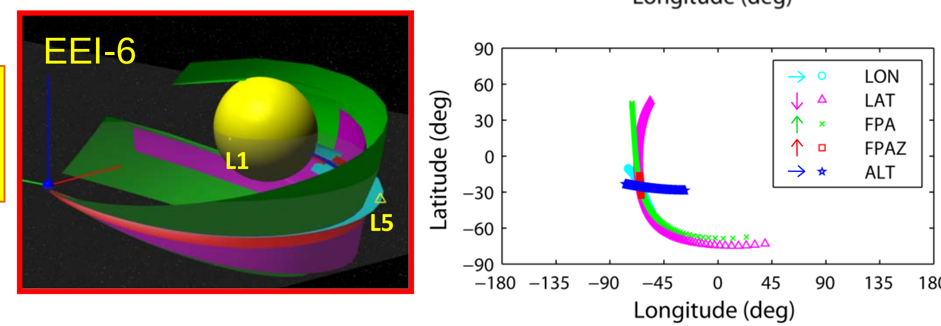
EEI-k (k=3,4,5,6) Dispersion Manifolds: Intersections w/ Hill Sphere (SRF View)









EEI Constraint Coupling Can
Be Deduced From Hill Sphere Projections

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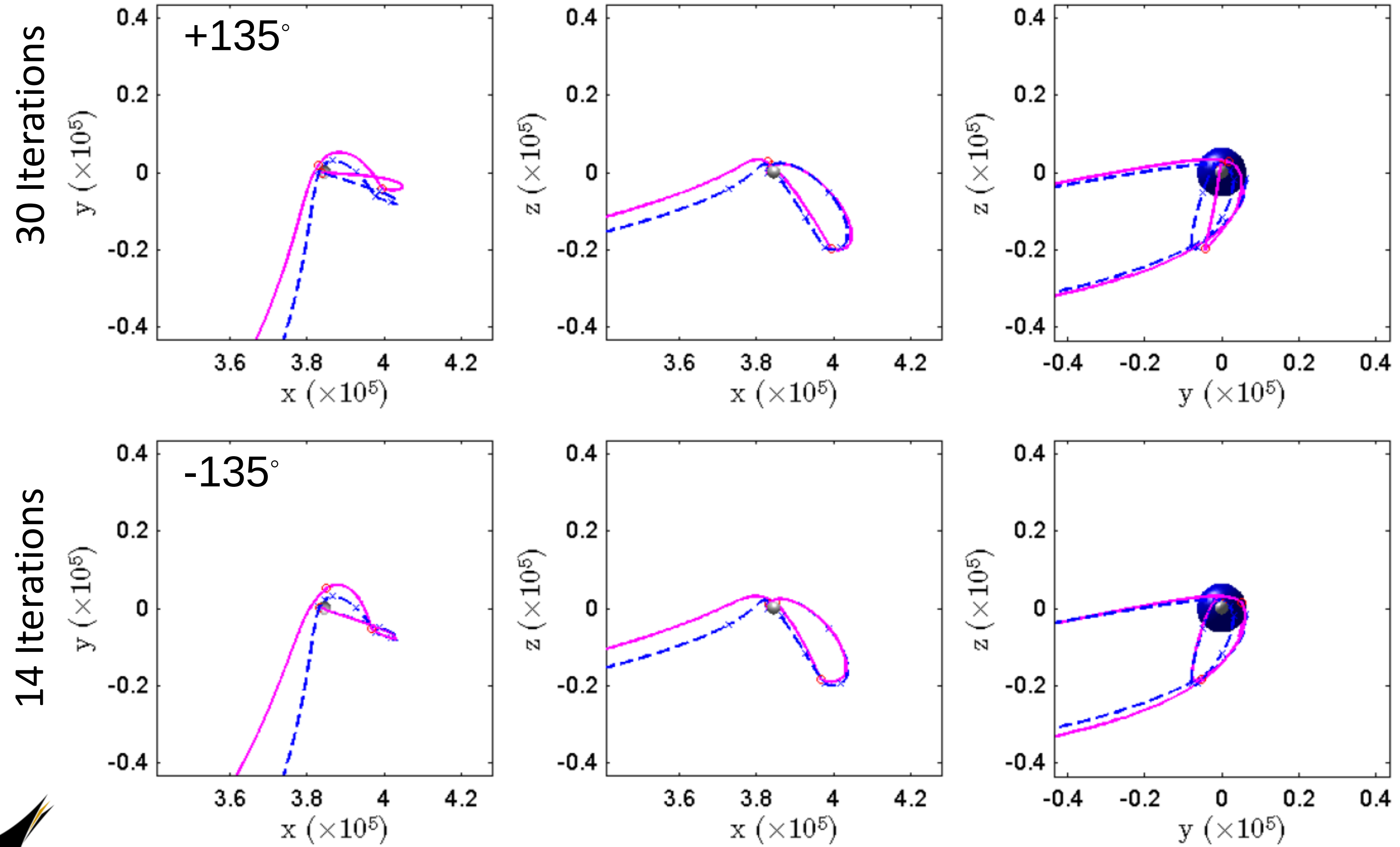
Impact of Entry Longitude Errors

Targets: Altitude = 121.912 km, FPA = -5.86 deg, ΔV = 1.5 kps

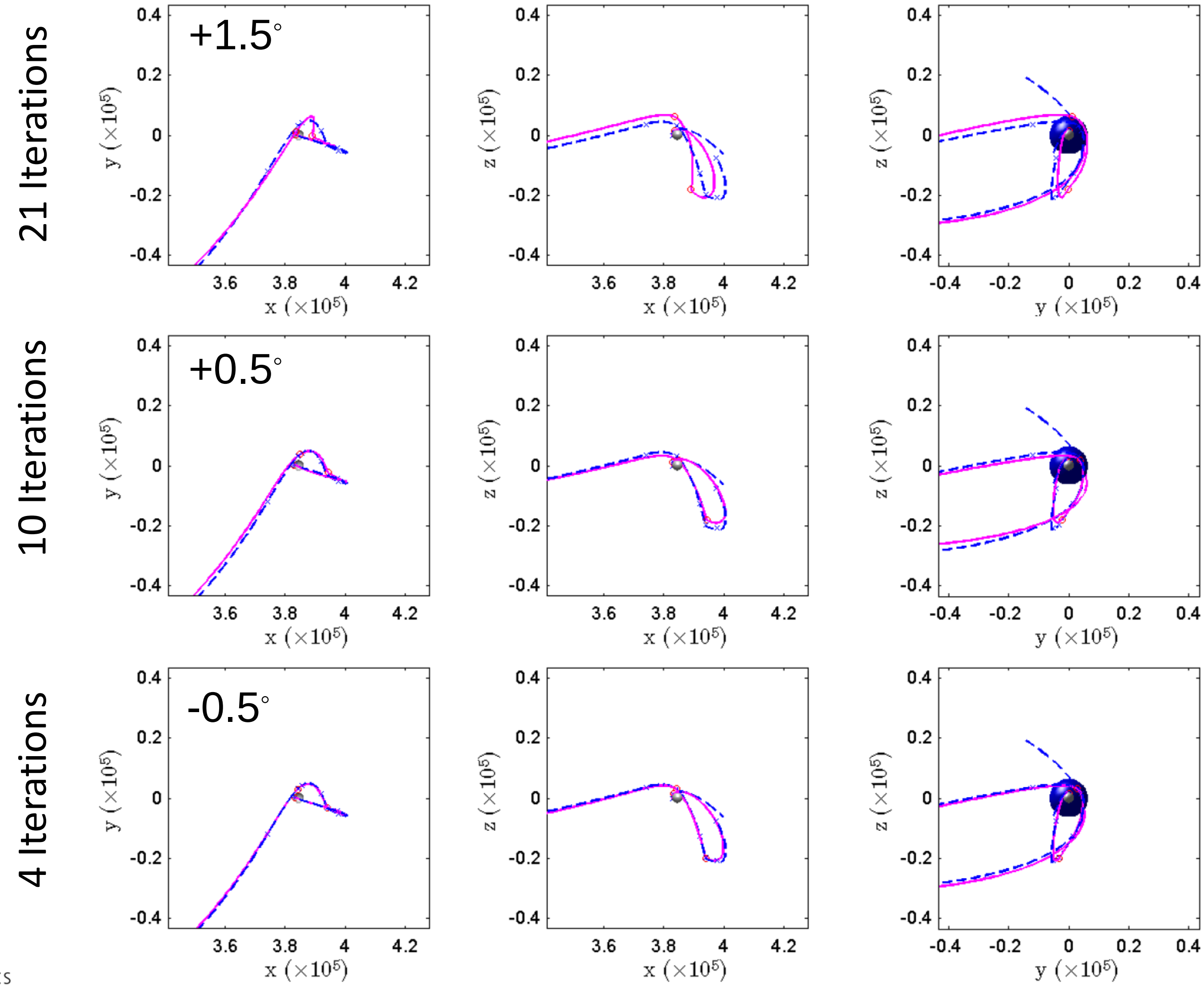
Initial Longitude: 76.01 deg



Impact of Entry Latitude Errors

Targets: Altitude = 121.912 km, FPA = -5.86 deg, ΔV = 1.5 kps

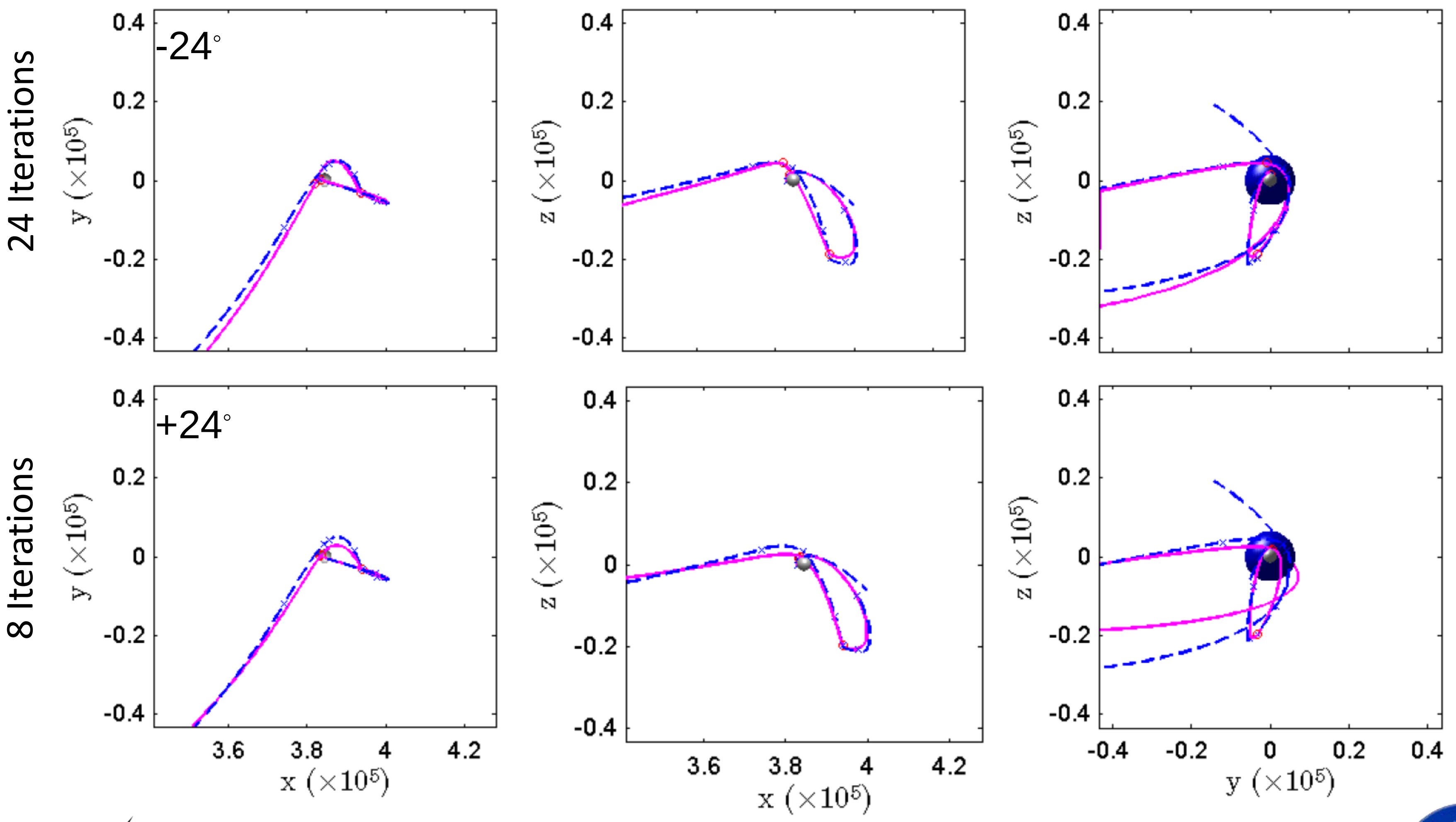
Initial Latitude: -1.29 deg



Impact of Entry Azimuth Errors

Targets: Altitude = 121.912 km, FPA = -5.86 deg, ΔV = 1.5 kps

Initial Azimuth = 8.41 deg



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Conclusions

- Without loss of generality, the precision entry problem can be studied within the context of the CR3BP and the results are easily transitioned and nearly identical to those in the EPHEM model.
- Intersections of EEI dispersion manifolds with Hill Sphere, in SRF, yields useful information regarding entry constraint coupling. This knowledge can be used in future studies to enhance startup arcs and, subsequently, targeting performance.
- Validated constraint coupling conjectures, from Hill sphere analysis, for FPA & LON, FPA & LAT, and FPA & AZ, by analyzing targeter performance in the presence of EEI errors in LON, LAT, and AZ, respectively.
- A multi-body analysis in the SRF of the Earth-Moon system offers a more representative set of startup arcs than those obtained from 2BP approximations. The resulting improved startup arcs facilitate an efficient onboard targeting process.

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