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Transfers Between Near-Rectilinear Halo Orbits and the Moon

Sergey Trofimov
Maksim Shirobokov (speaker)
Anastasia Tselousova
Mikhail Ovchinnikov

Keldysh Institute of Applied Mathematics

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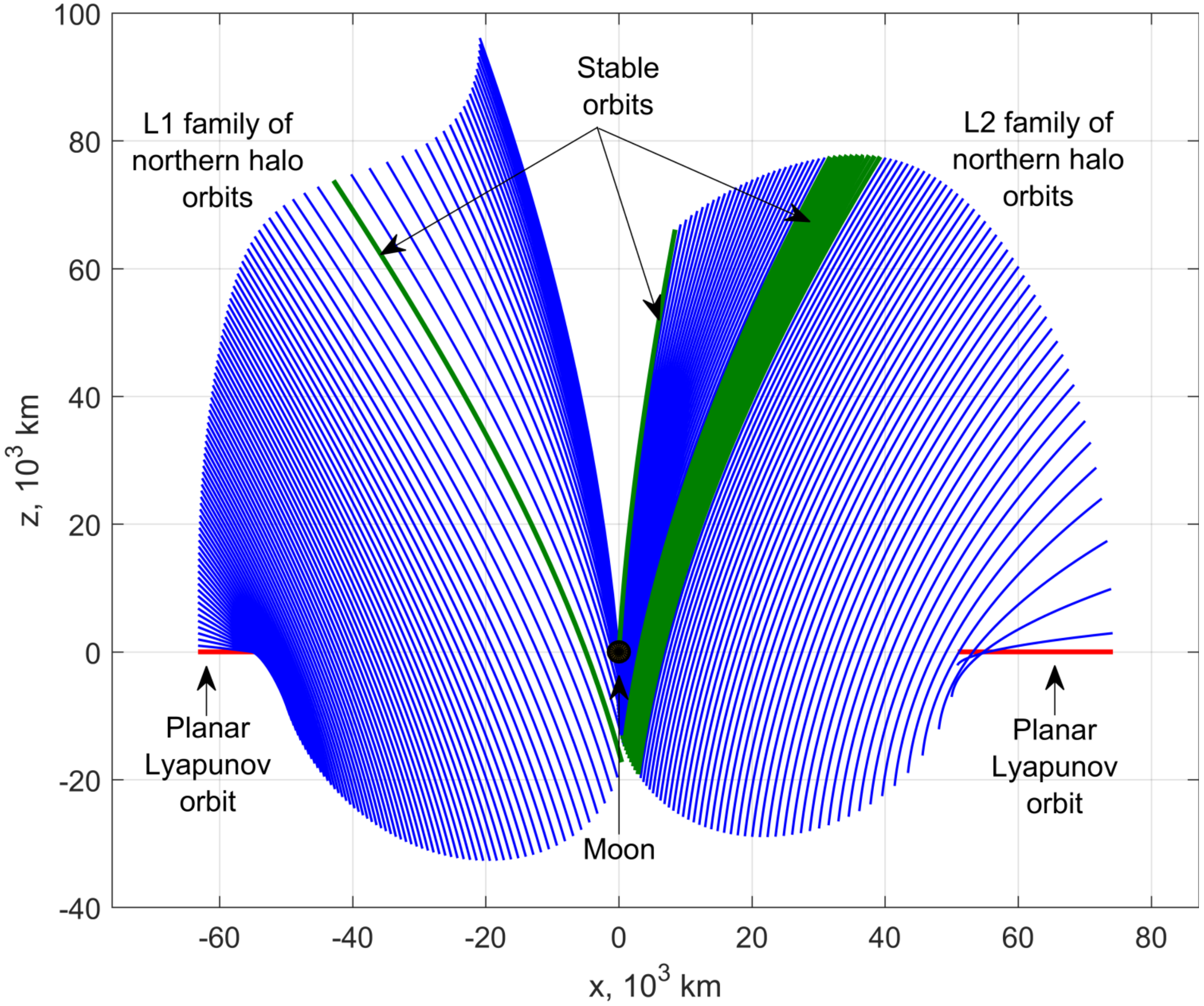
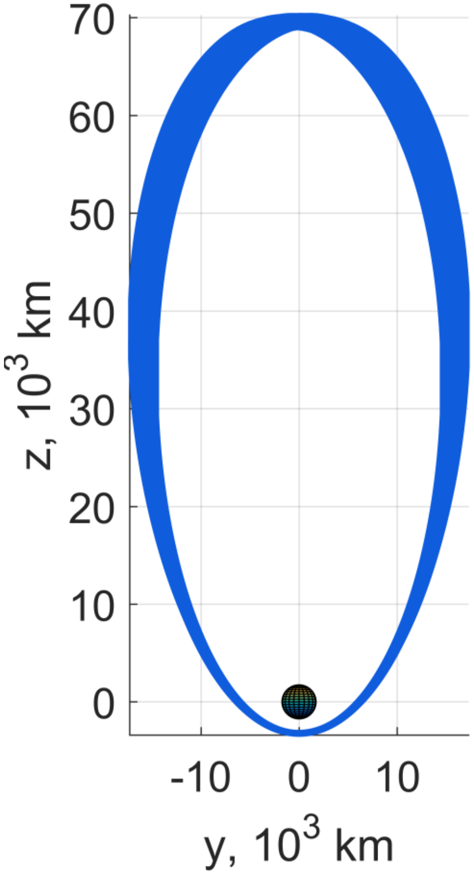
- Near-Rectilinear Halo Orbits
- General scheme of the NRHO-Moon transfer
- Gravity-turn landing technique
- Landing trajectories
- Targeting and stabilizing low-perilune orbits
- Conclusions

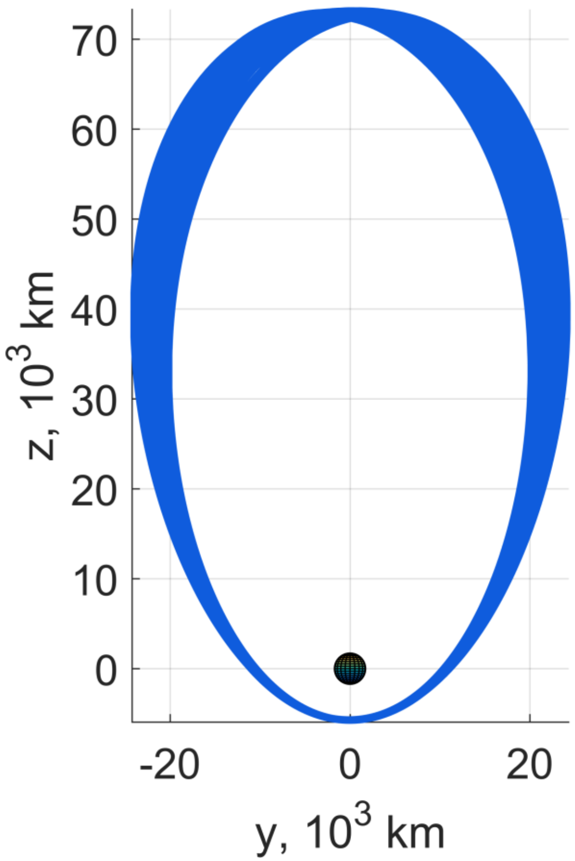
L1 and L2 families of halo orbits



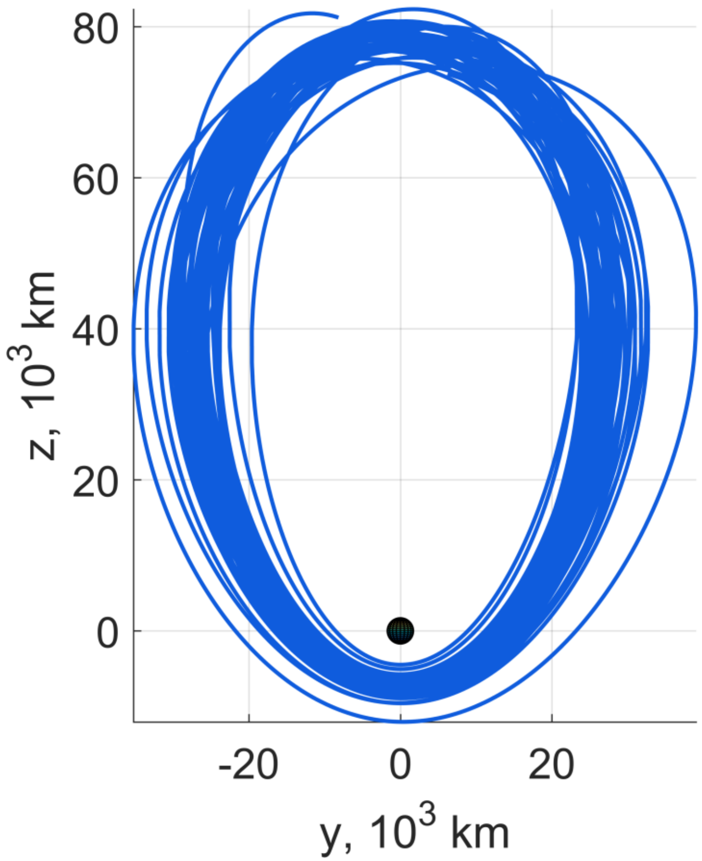
Selected resonant NRHOs from the L1 and L2 northern families adapted to the high-fidelity model



Northern 9:2 L2 NRHO
rp = 3,100 km
P = 6.6 days



Northern 4:1 L2 NRHO
rp = 5,500 km
P = 7.3 days



Northern 11:3 L1 NRHO
rp = 4,500 km
P = 8 days

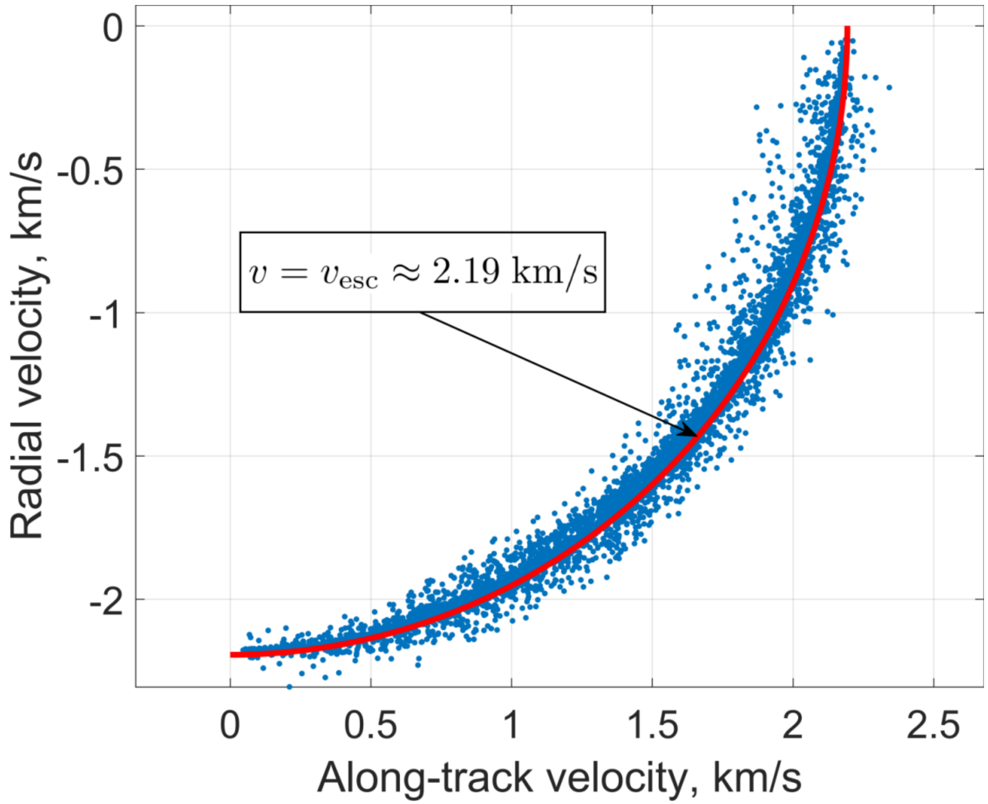
NRHO-Moon transfer

- Two scenarios of delivering a lander to the Moon are considered:
  - the direct landing from the working NRHO orbit
  - the transfer to some intermediate low-perilune orbit
- Outline landing sites and low-perilune orbits accessible from NRHOs
- Estimate landing/transfer costs

Departure from NRHO

- The initial phase of the both scenarios is the departure impulse at some point of the working orbit
- We examined 100 candidate points that are equally distributed across the period of a given NRHO. The magnitude of the impulse was selected from the following discrete set: 50, 100, ..., 450, 500 m/s
- Finally, 92 impulse directions are sampled nearly uniformly on the unit sphere, which gives a set of **92,000 departing trajectories**

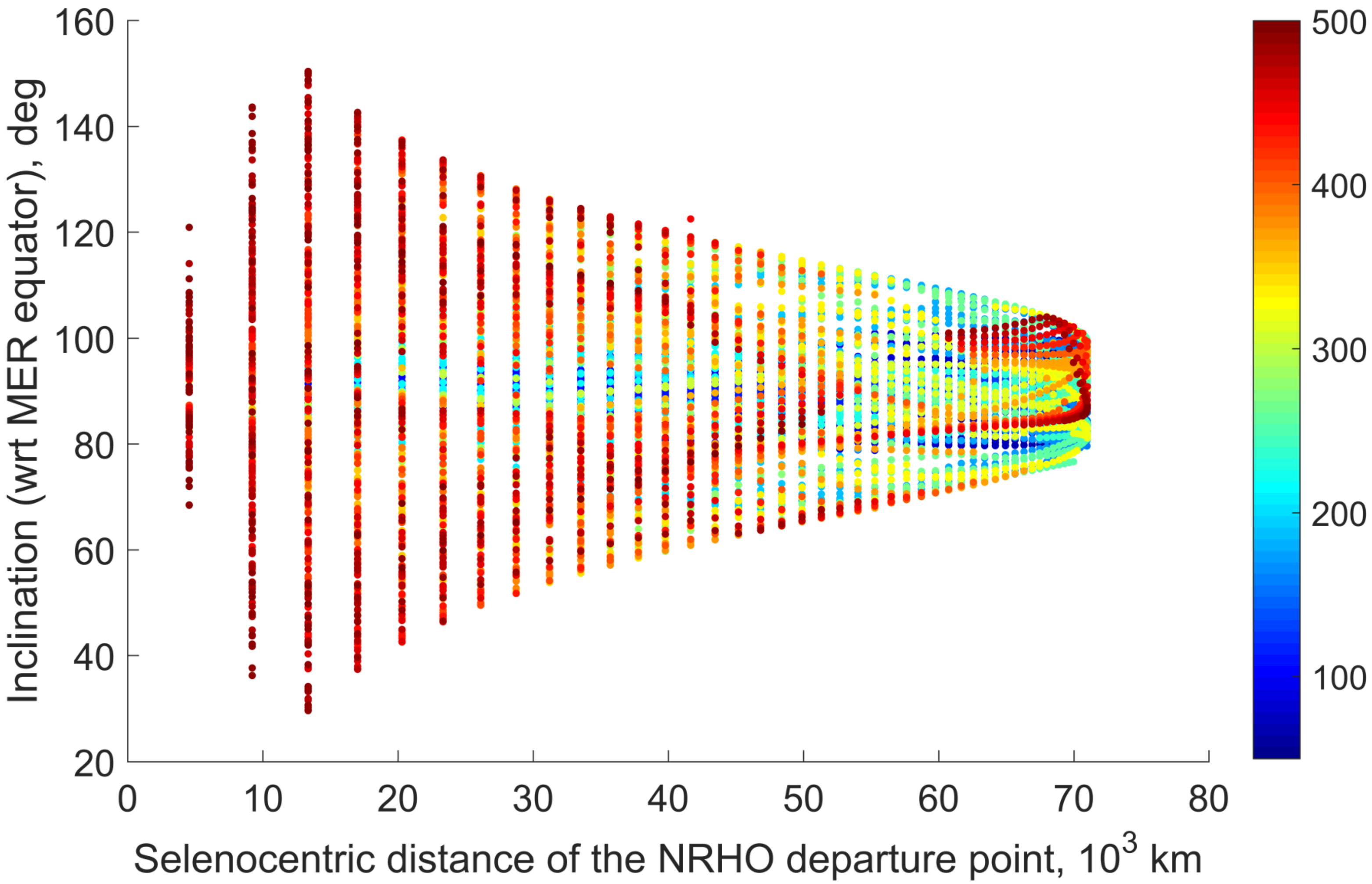
Approaching trajectories are all near-parabolic!



Velocity components (along-track and radial) at the 300 km altitude for the northern 9:2 L2 NRHO

Only 5-10% of the trajectories approach the Moon with **a perilune altitude of 300 km** or less (these trajectories are referred as the approaching trajectories)

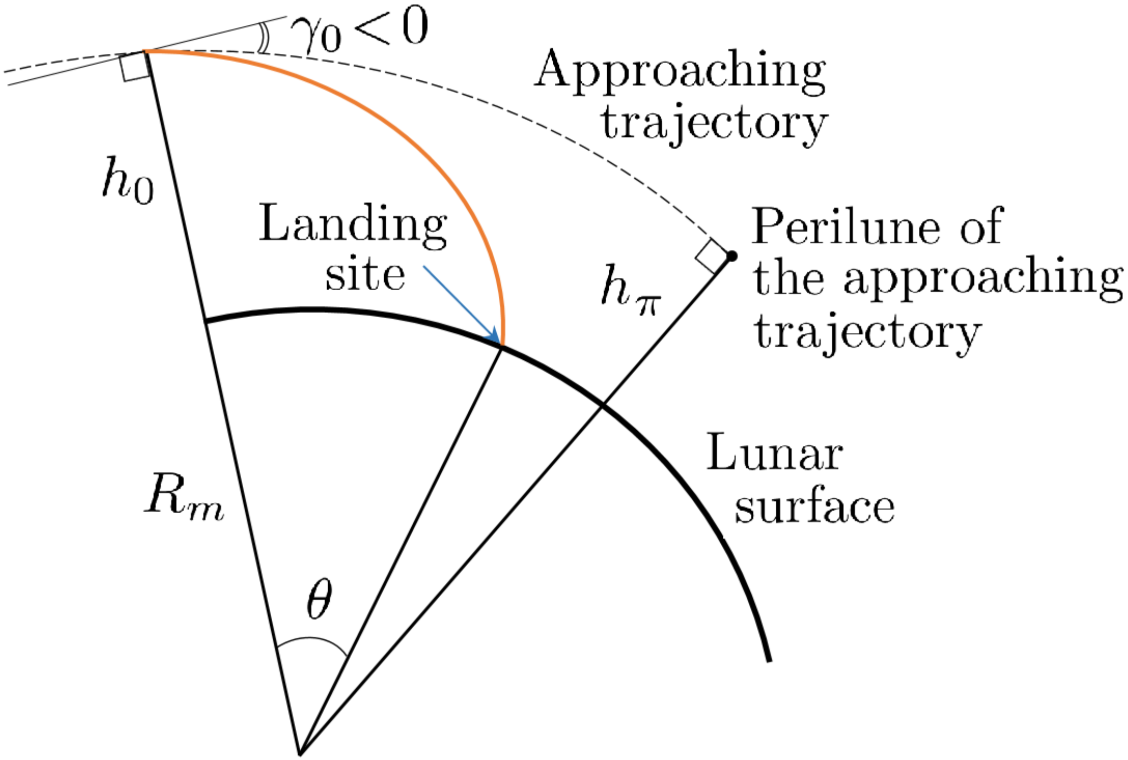
Inclinations accessible from the northern 9:2 L2 NRHO and the associated departure V (in m/s)



Gravity-turn landing technique

Assumptions:

1) Spherical non-rotating Moon
2) Gravity and thrust accelerations are of constant magnitude
   $n = a_t / g_m = \text{const}$
3) Angle of attack is zero



$$n^2 + \left(\frac{v_0^2}{2g_m h_0} + 1\right) n \sin\gamma_0 - \frac{v_0^2 \cos^2\gamma_0}{4 g_m h_0}\left(1 + \frac{2 g_m h_0}{v_0^2}\right)^2 \left(1 - \frac{v_0^2}{2 g_m R_m}\right) = 0$$

Citron, S.J., Dunin, S.E., and Meissinger, H.F., A *Terminal Guidance Technique for Lunar Landing*, AIAA Journal, 1964, Vol. 2, No. 3, pp. 503-509.

Parabolic approaching trajectory assumption

- For parabolic orbits, γ_0 and v_0 can be simply expressed as functions of h_0
- The equation has a unique positive solution

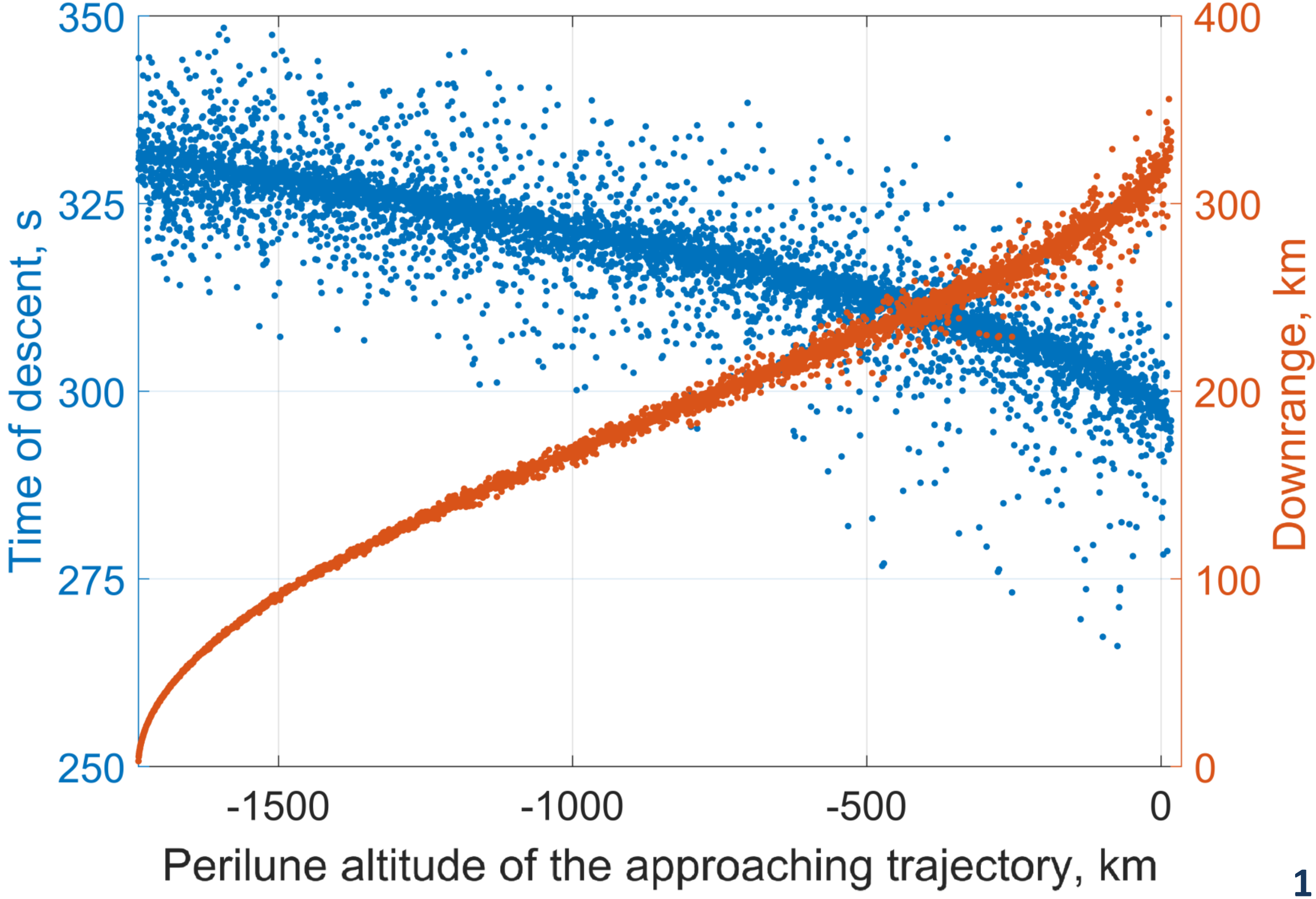
$$\frac{h_0}{R_m} = \frac{1}{2n^2} + \sqrt{\frac{1}{4n^4} - \frac{h_\pi}{n^2 R_m}}$$

if

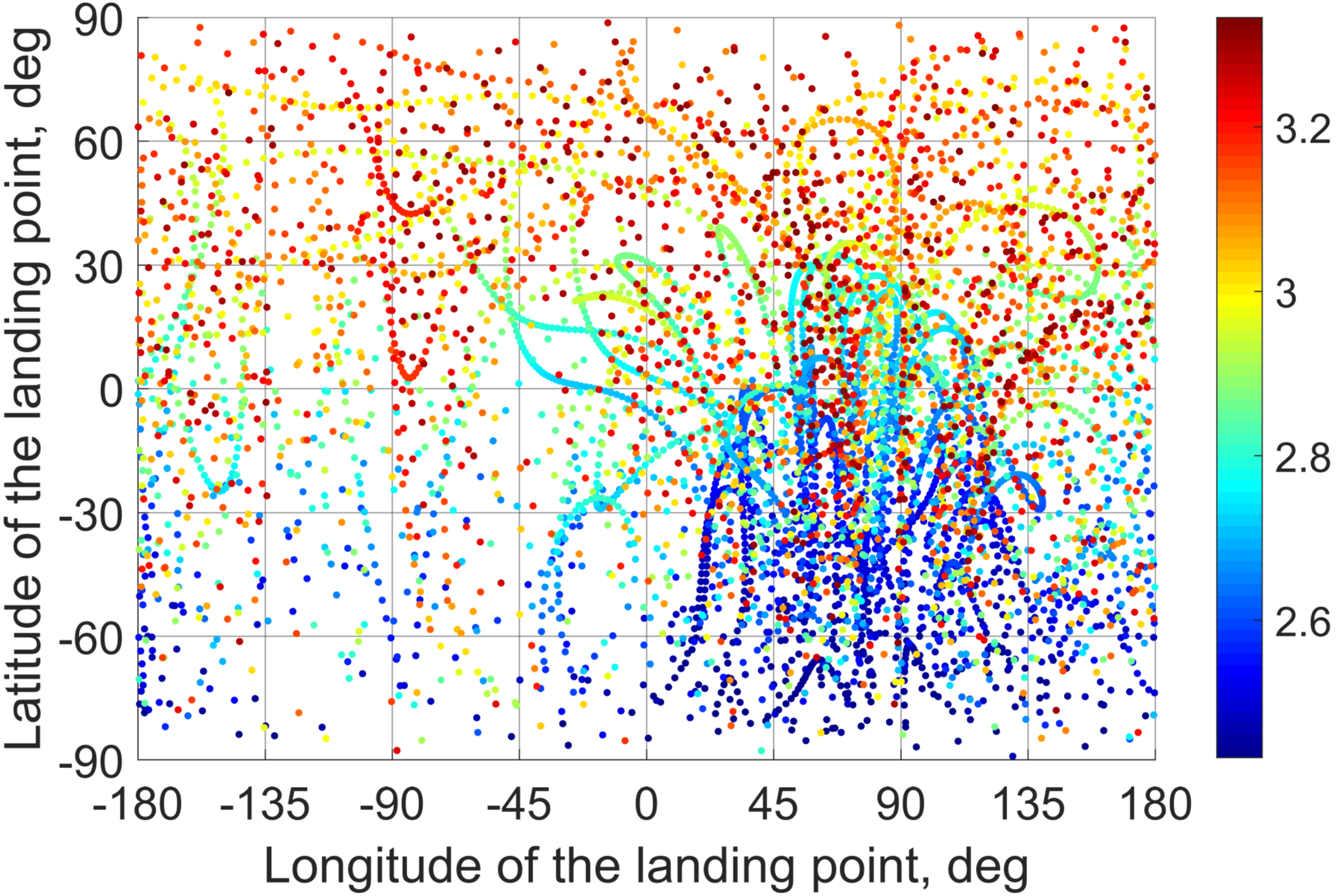
$$\frac{h_\pi}{R_m} \leq \frac{1}{4n^2}$$

For $n = 5$ we get $h_\pi \leq 0.01 R_m \approx 17 \text{ km}$

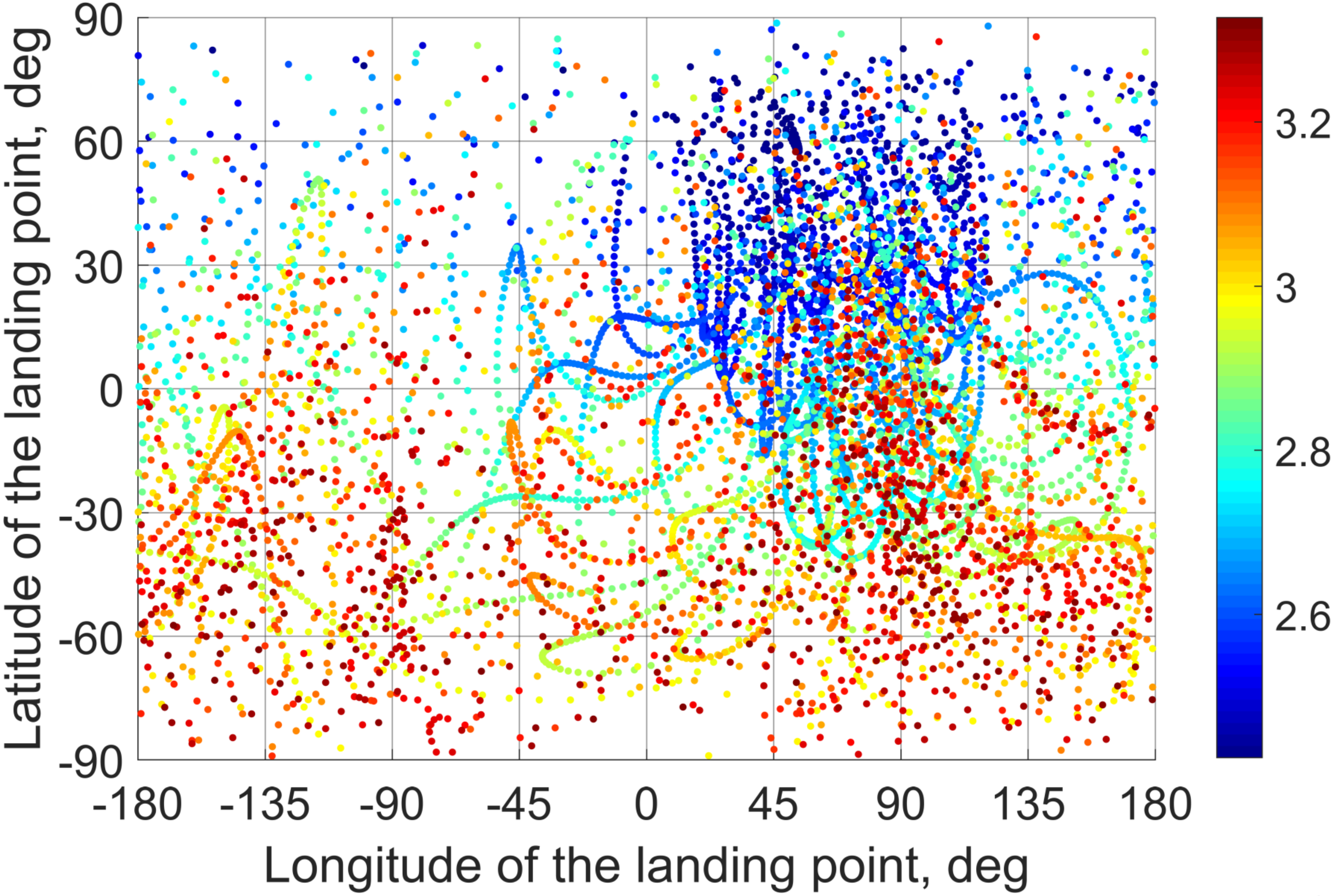
Time of descent and downrange values for landing from the southern 9:2 L2 NRHO



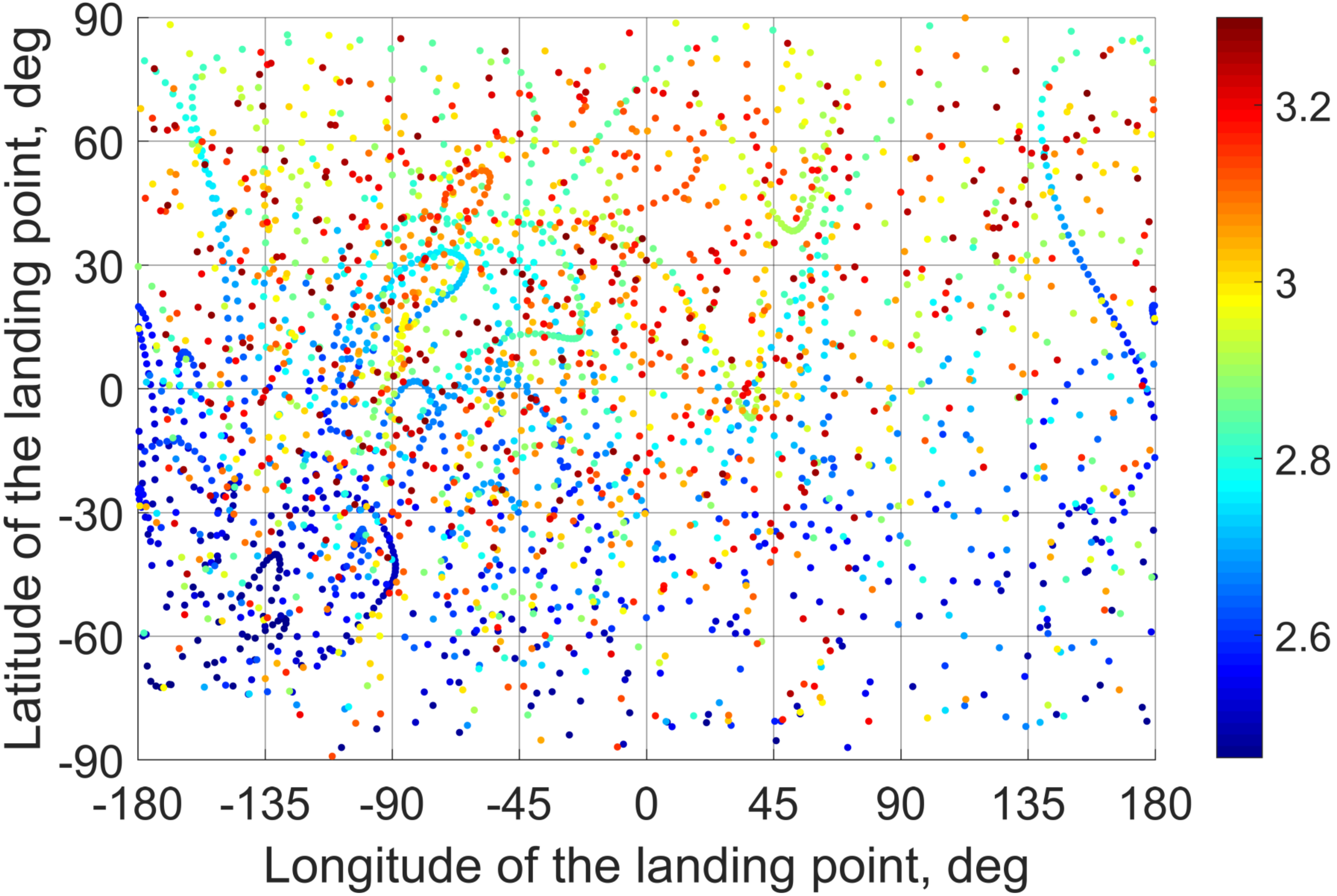
Possible sites of direct landing from the northern 9:2 L2 NRHO and the associated total ΔV (in km/s)



Possible sites of direct landing from the southern 9:2 L2 NRHO and the associated total ΔV (in km/s)



Possible sites of direct landing from the northern 11:3 L1 NRHO and the associated total ΔV (in km/s)



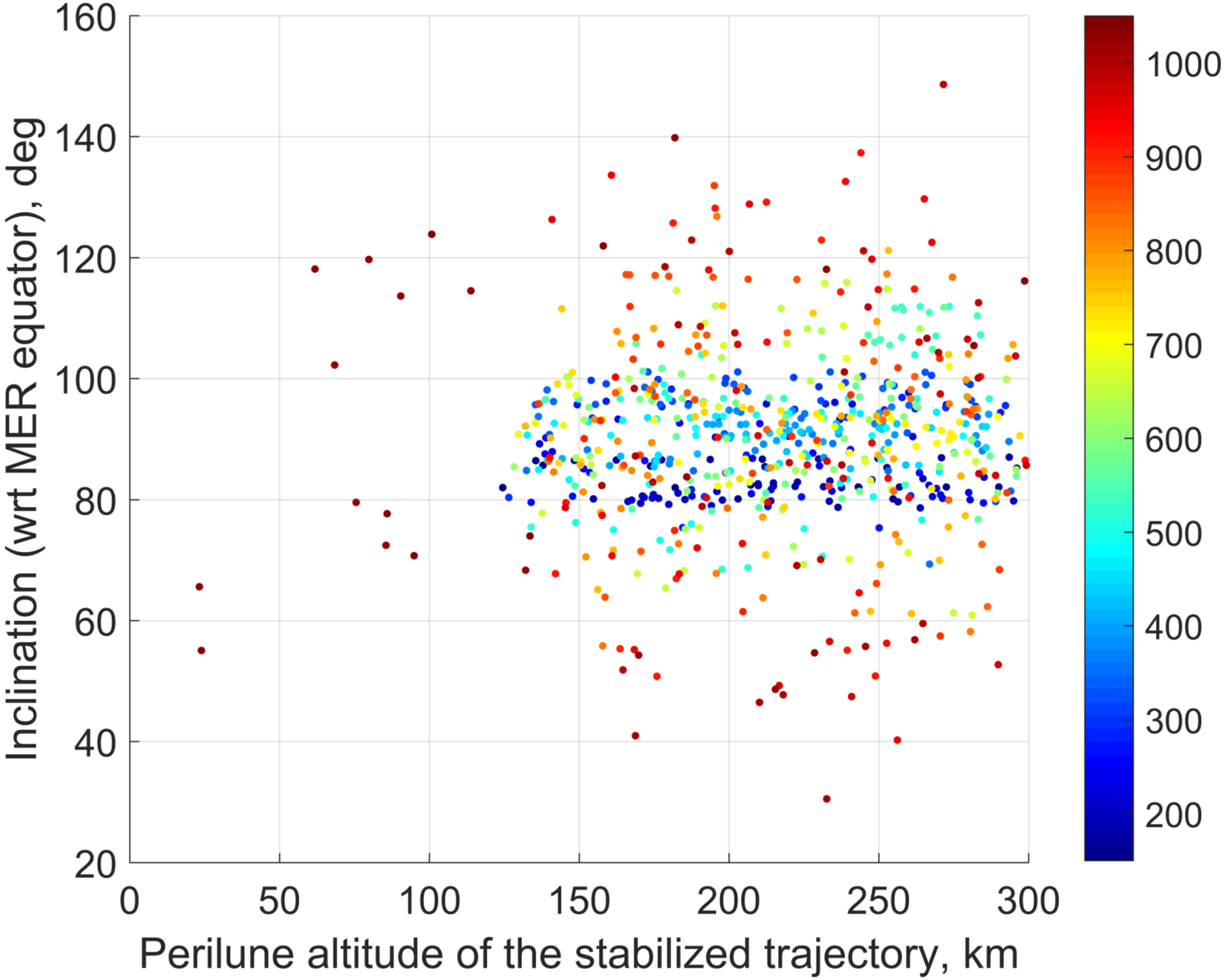
Cheapest-to-get lunar regions

	L1 halo orbit	L2 halo orbit
Perilune above the south pole	South-West	South-East
Perilune above the north pole	North-West	North-East

Targeting and stabilizing low-perilune orbits

- In another scenario, involving a transfer to some low-perilune orbit, the minimum stabilizing impulse at the perilune of approaching trajectories is sought
- Upon applying the braking impulse, an approaching trajectory should be transformed in a stable elliptic orbit
- By stable we imply the orbit whose perilune altitude and inclination variations throughout three consecutive revolutions around the Moon do not exceed 10% and 0.1 deg, respectively

Inclination and perilune altitude of stable low-perilune orbits accessible from the northern 9:2 L2 NRHO and the associated total ΔV (in m/s).

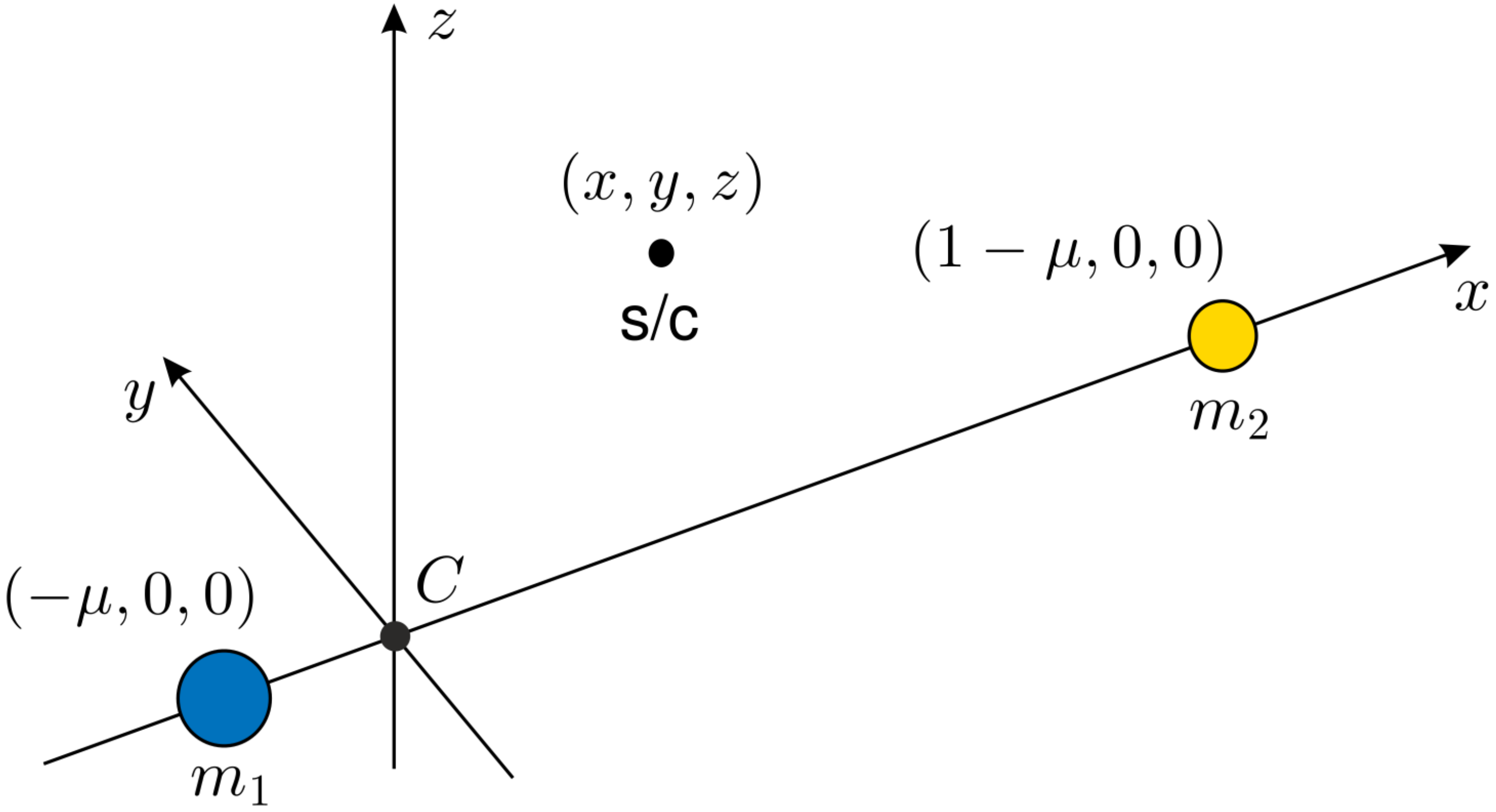


Conclusions

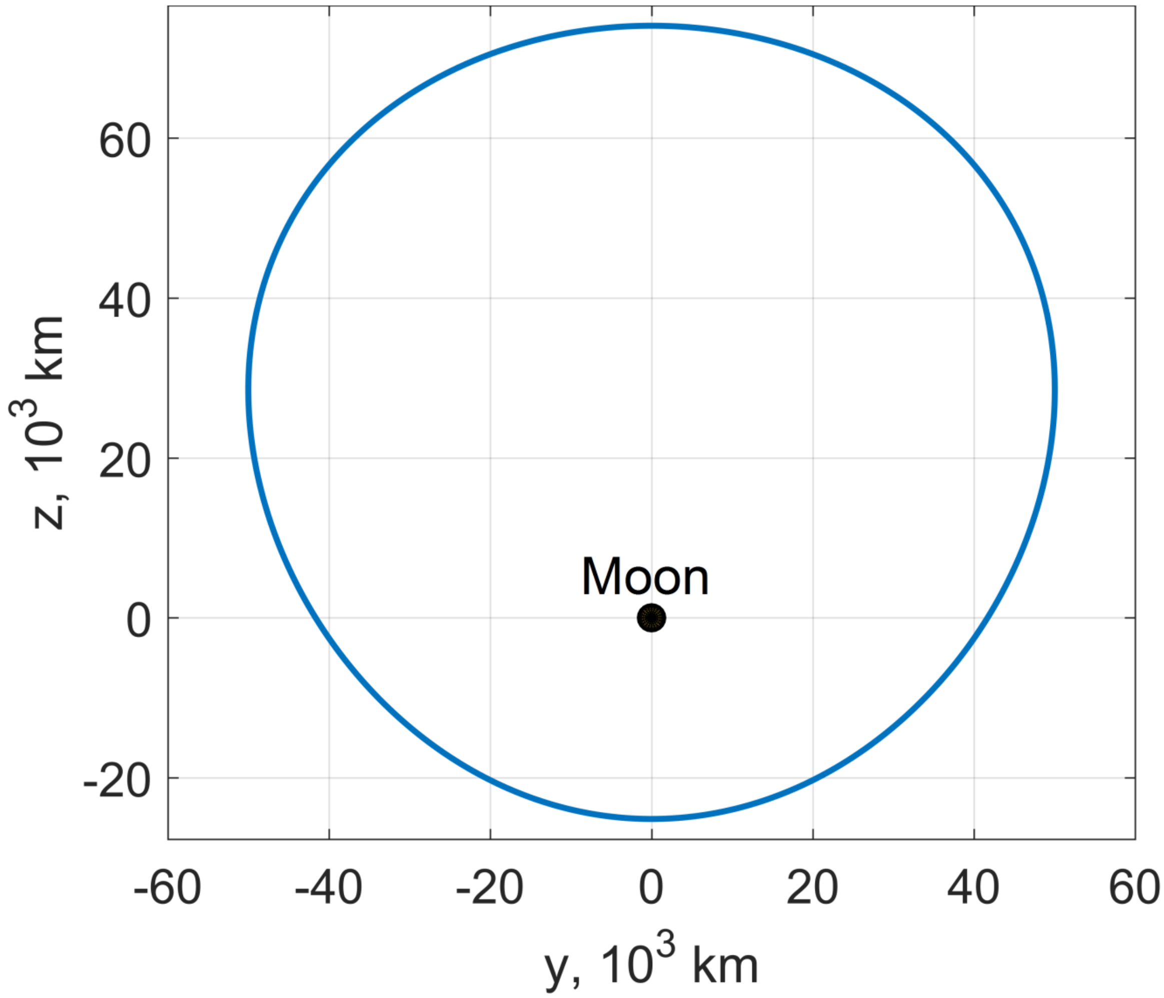
- The problem of delivering a lander from the working near-rectilinear halo orbit around the Moon directly to the lunar surface (soft landing) or to some intermediate low-perilune orbit has been examined
- Although any landing site is in principle feasible, there exist areas of least-cost landing
- The former asymmetry has appeared to be related to the NRHO subtype (northern/southern), while the latter is connected to what libration point is considered
- The landing characteristics have been estimated using the relationships of the gravity-turn landing strategy
- Among low-perilune orbits, a wide range of inclinations is accessible, with (near-)polar orbits being stabilizable at lowest cost
- The perilune of stabilizable orbits cannot be too low to avoid the influence of the highly irregular lunar gravity field

Backups

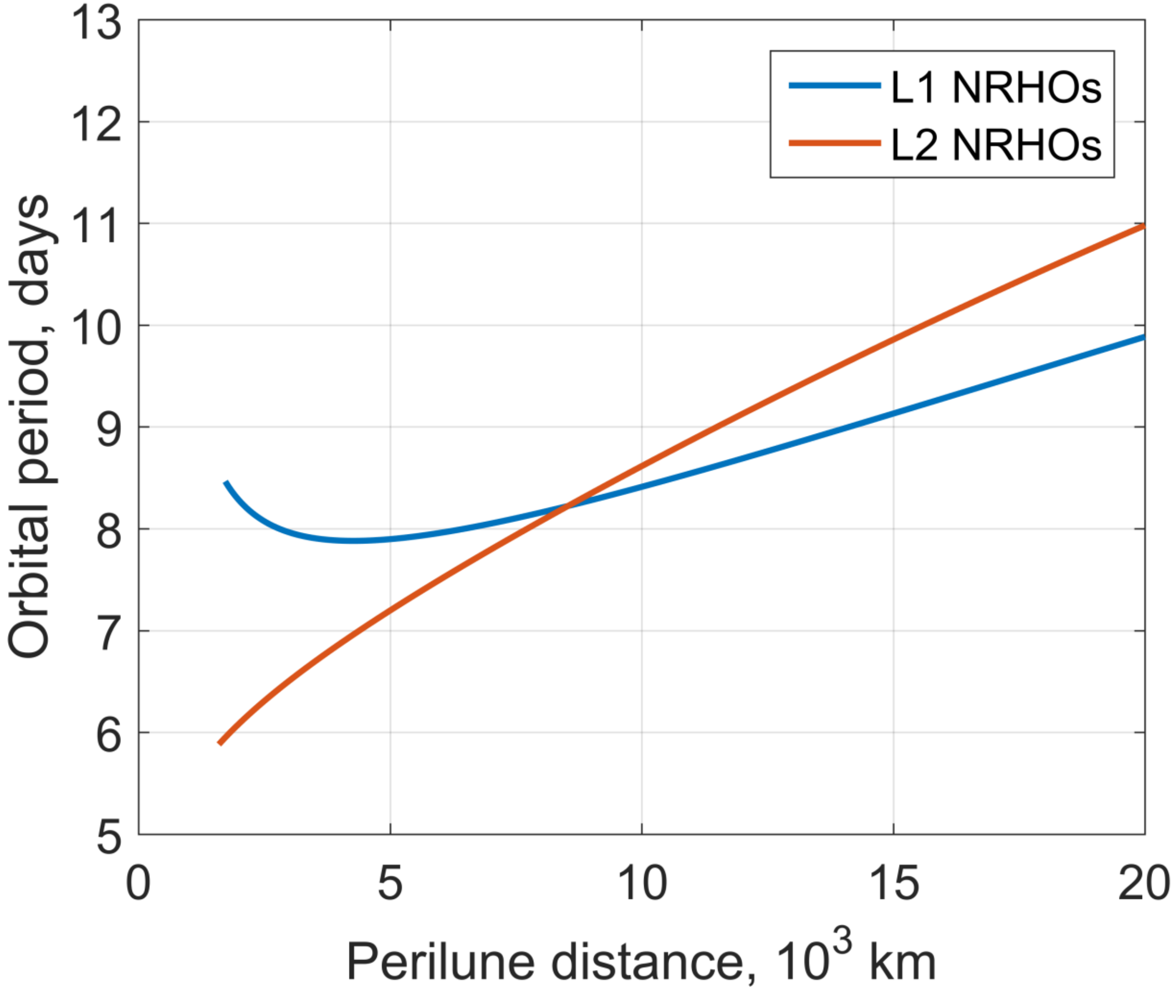
Rotating frame in the circular restricted three-body problem



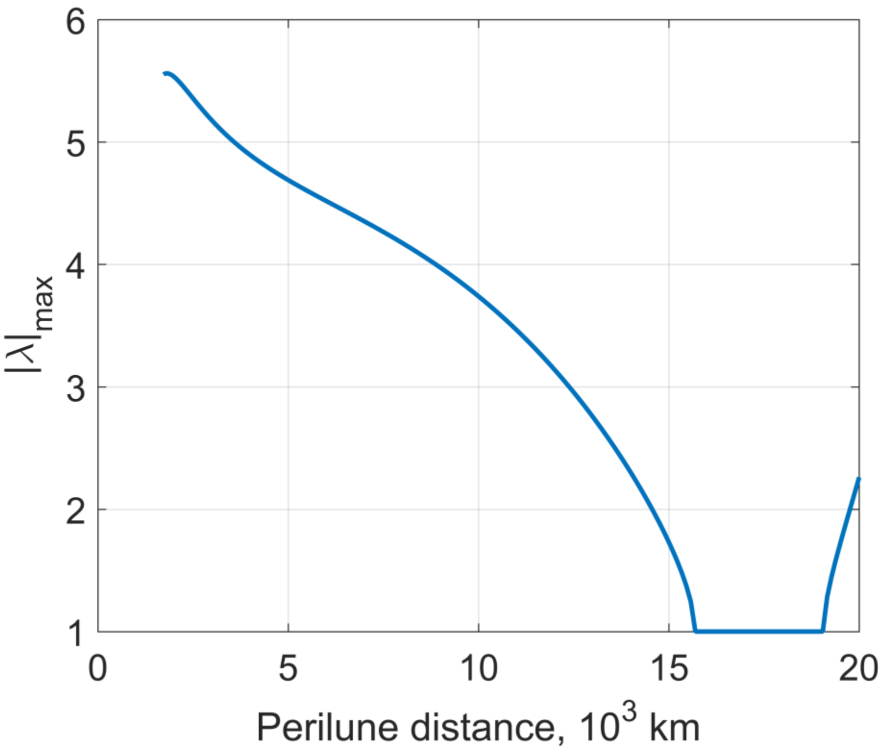
The frontal view (as seen from the Earth) of a sample lunar L2 halo orbit



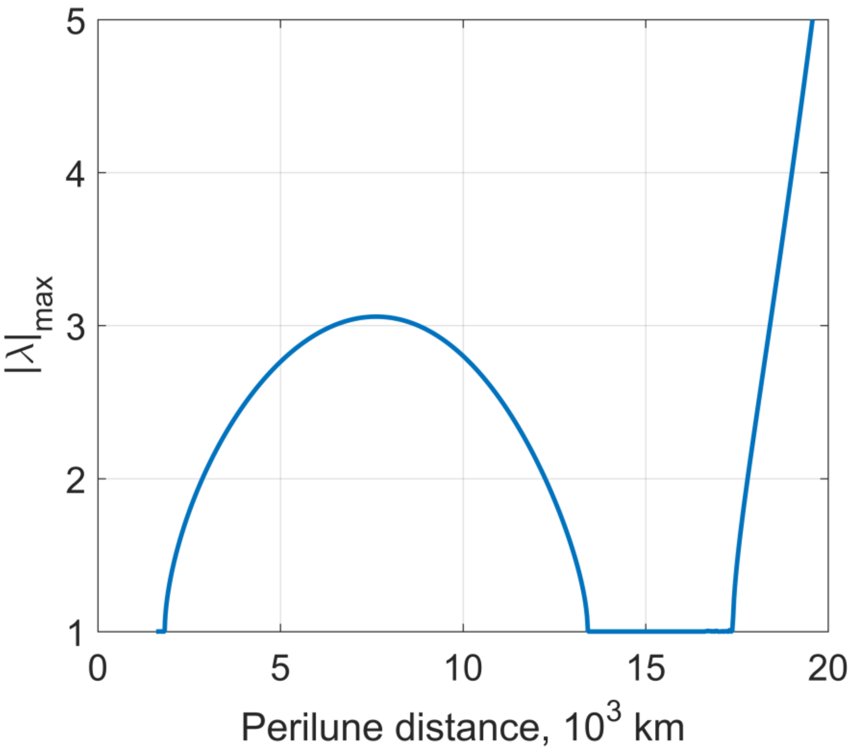
The perilune distance and the orbital period of the lunar L1 and L2 NRHOs



Variation of the largest eigenvalue modulus with the perilune distance for the L1 and L2 NRHOs

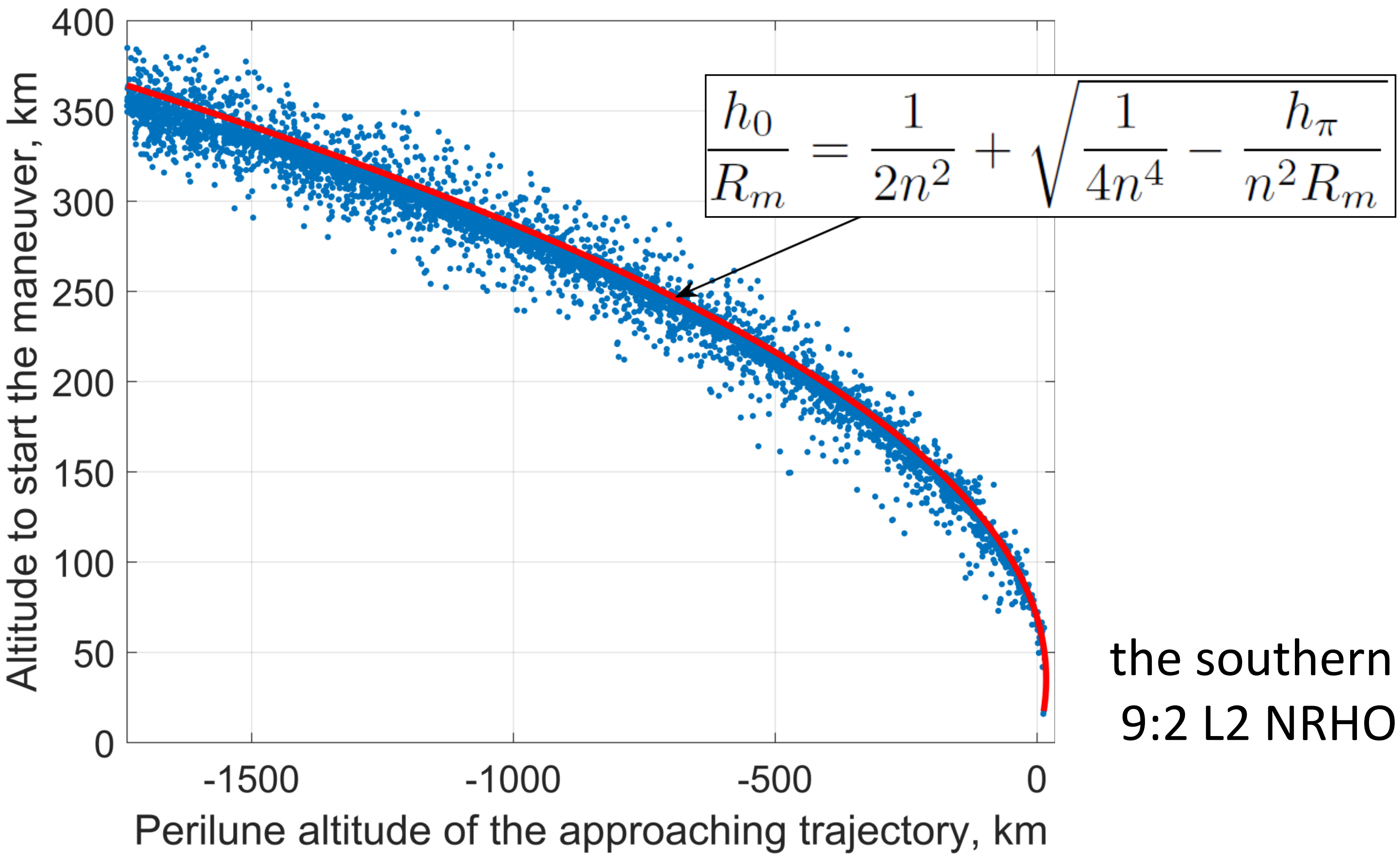


L1 NRHOs



L2 NRHOs

Altitude of initiating the gravity-turn maneuver for approaching trajectories with different h_π



$$\frac{h_0}{R_m} = \frac{1}{2n^2} + \sqrt{\frac{1}{4n^4} - \frac{h_\pi}{n^2 R_m}}$$

the southern
9:2 L2 NRHO