Co-Delivery of Probe and Orbiter via Aerocapture for Interplanetary Missions

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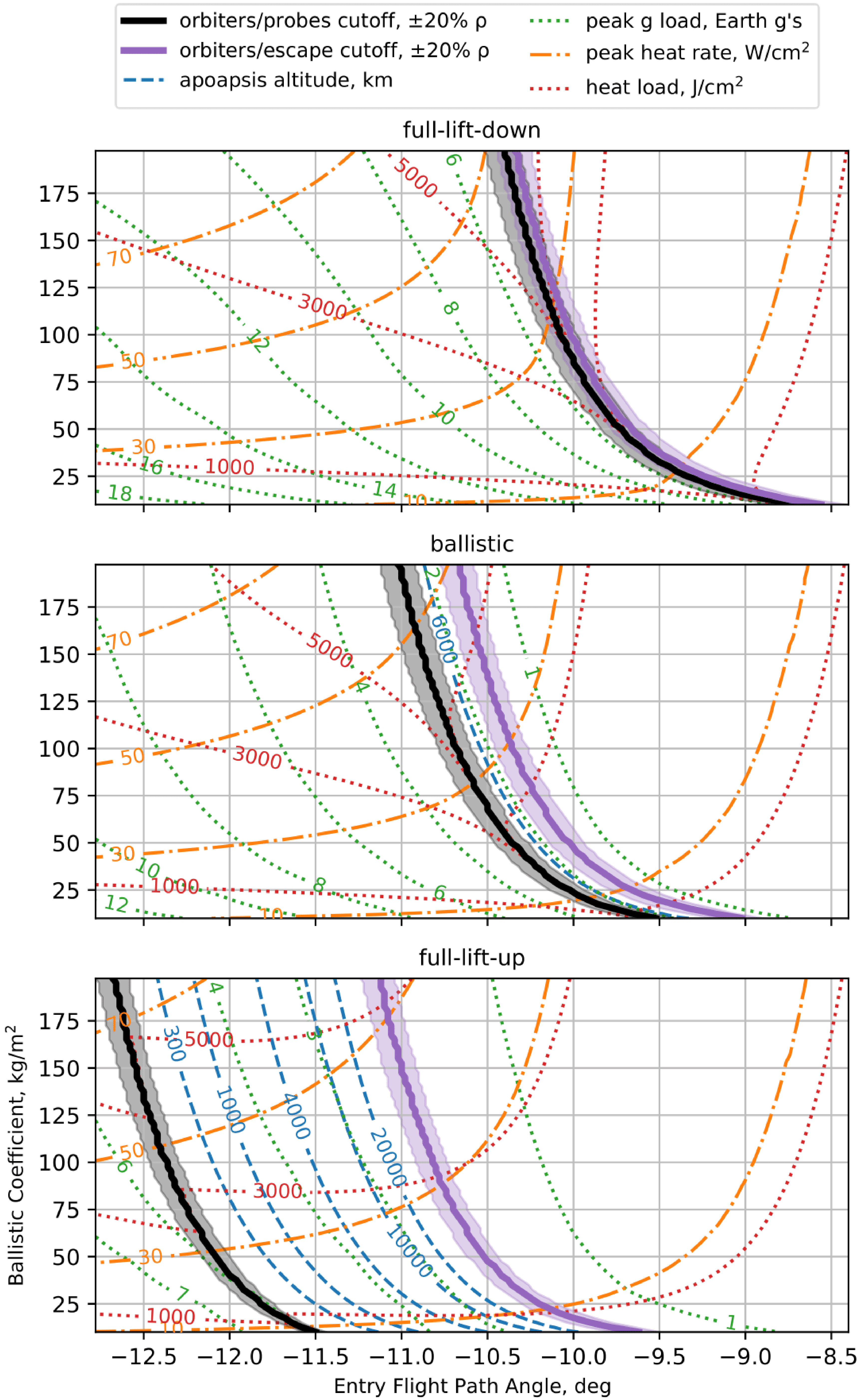
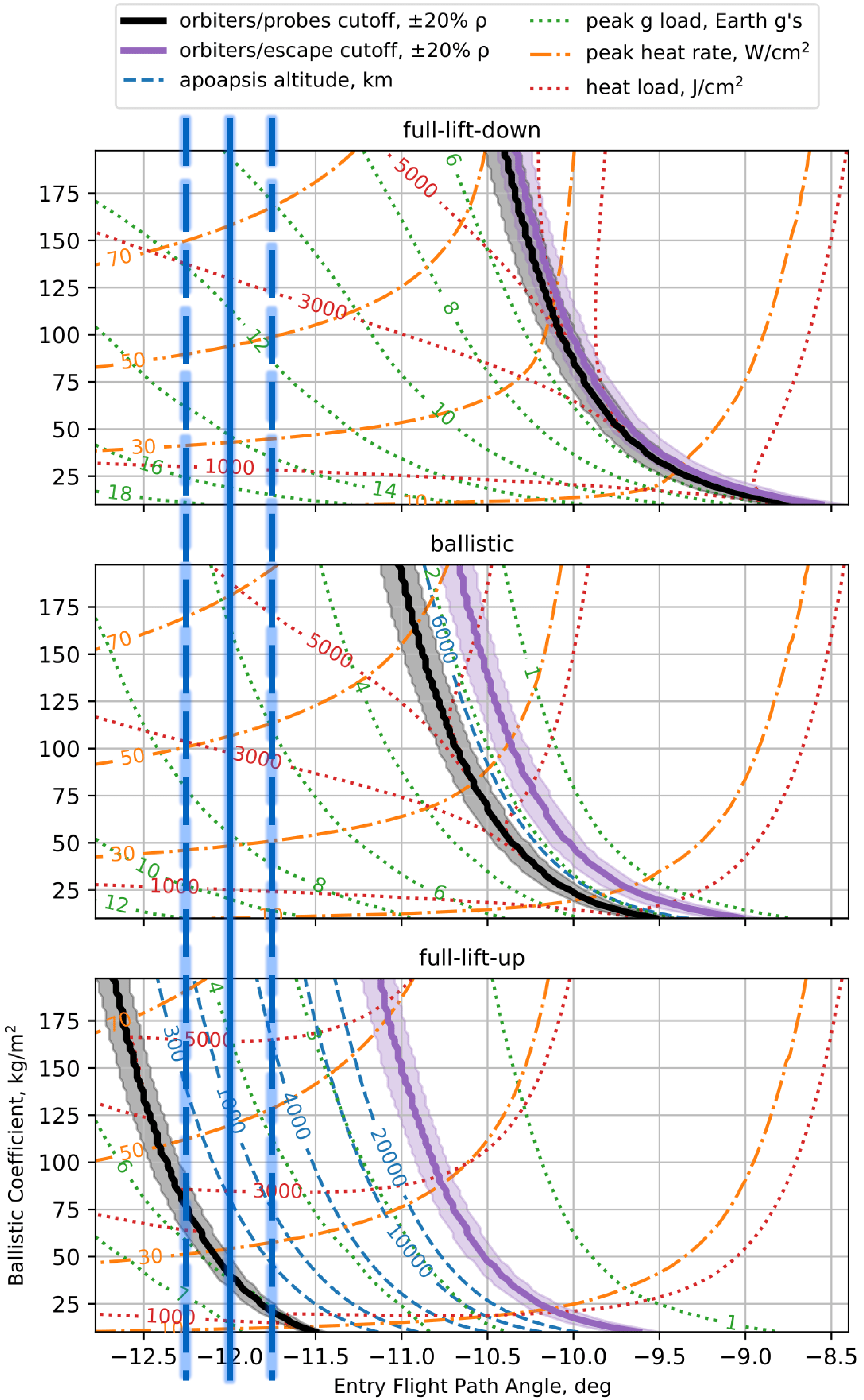
Co-Delivery Concept

Aerocapture and Direct-Entry Co-Delivery



- Mars entry
- 6 km/s planet-relative entry velocity
- L/D = 0.25

$$\beta = \frac{m}{C_D A} = \frac{inertial}{aerodynamic}$$



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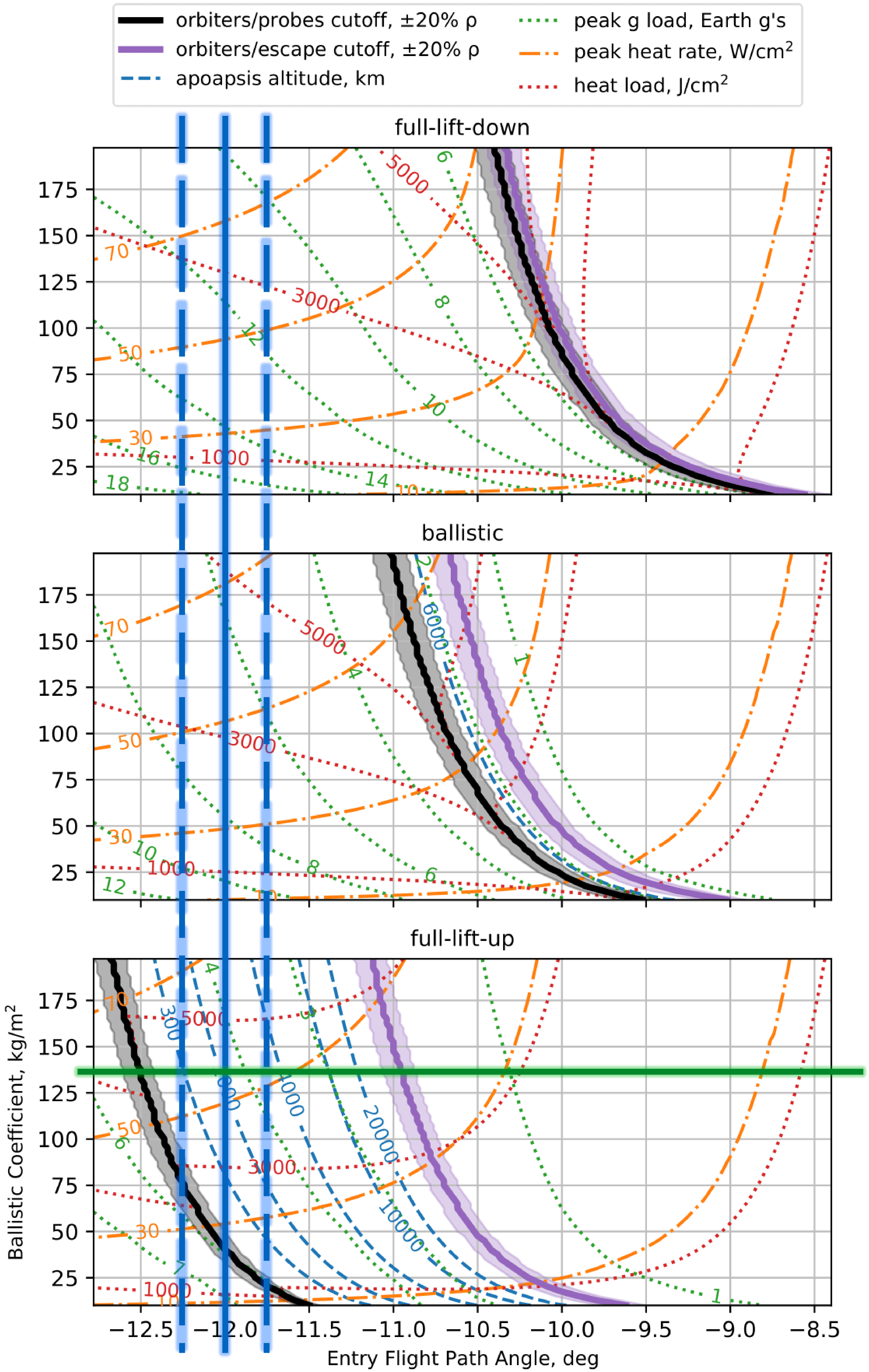
- L/D = 0.25
- -12 deg entry flight path angle
- +/- 0.25 deg entry corridor



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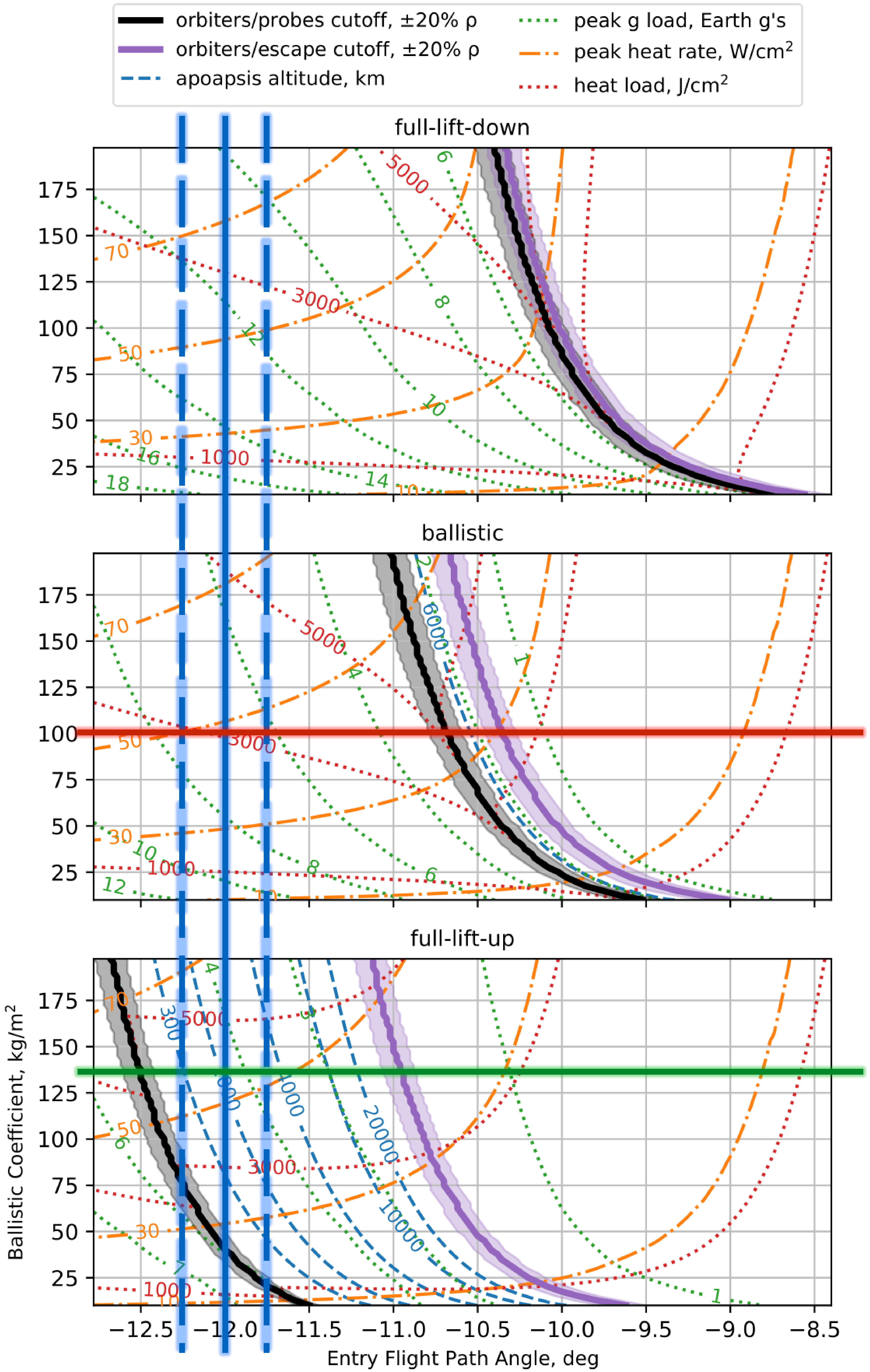
- Apoapsis altitude >= 300 km



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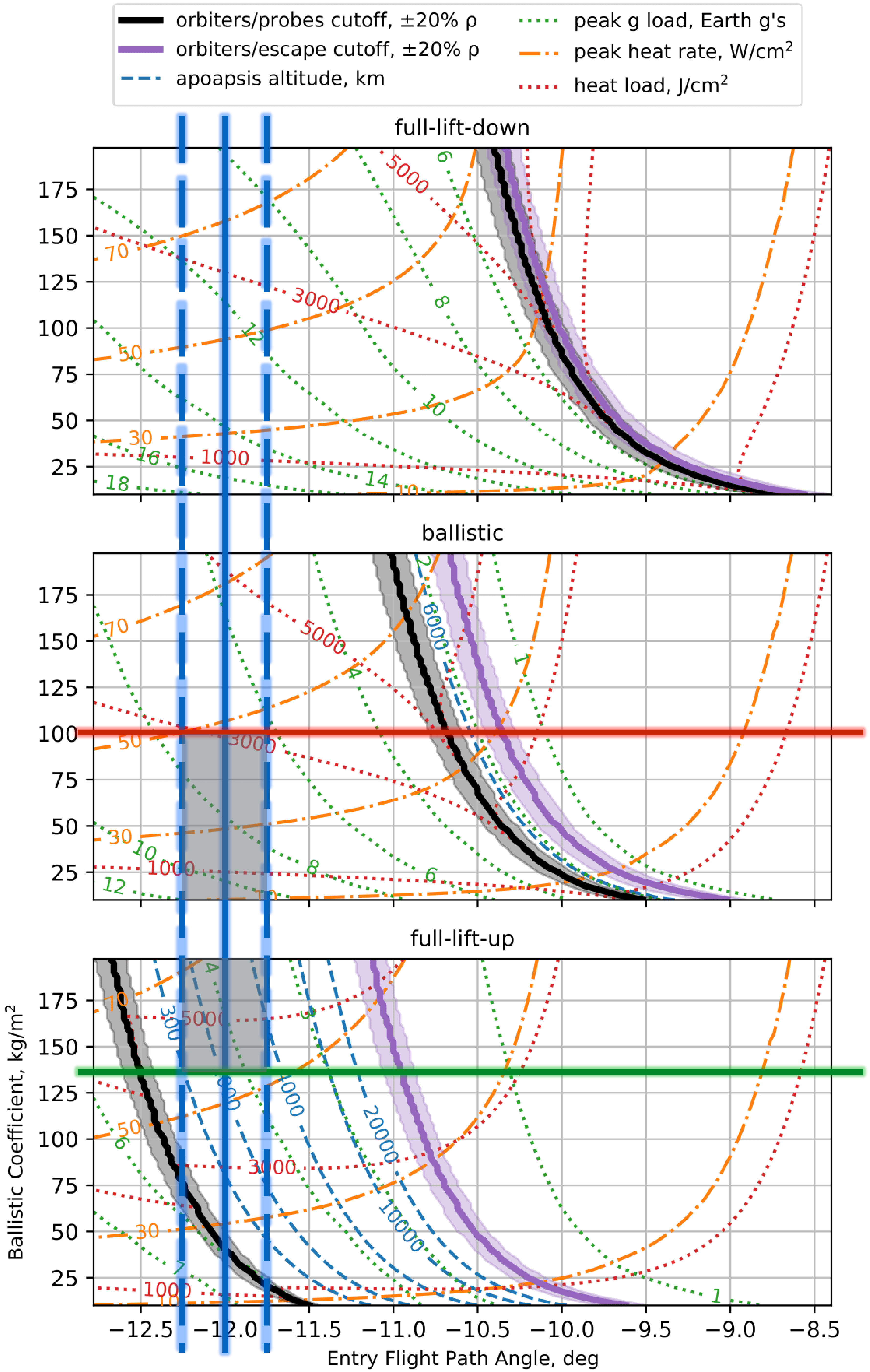

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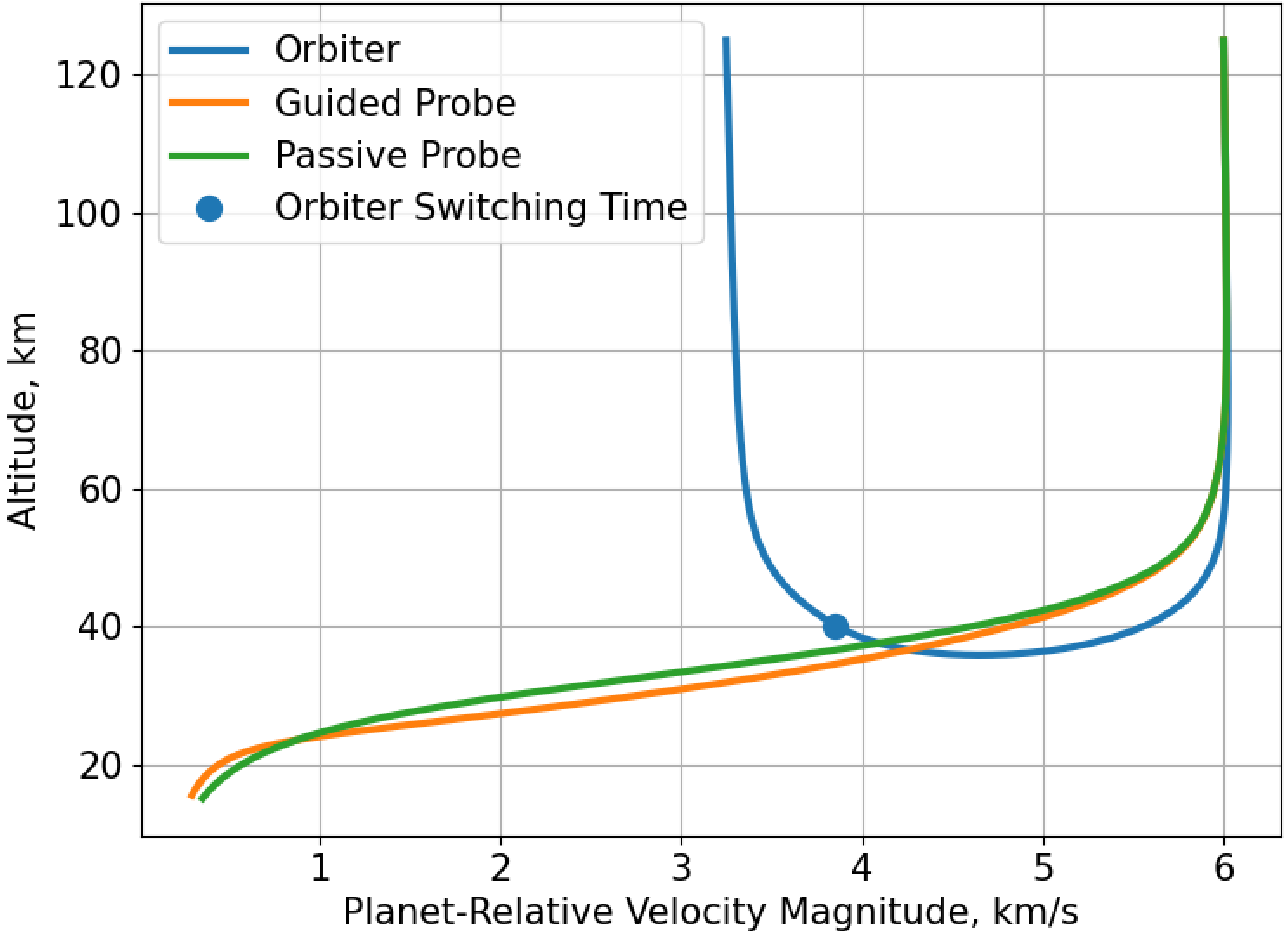
Orbiter: $\beta \geq 130\ kg/m^2$
Probe: $\beta \leq 100\ kg/m^2$

$$\beta = \frac{m}{C_D A} = \frac{inertial}{aerodynamic}$$

Bank Modulation Guidance

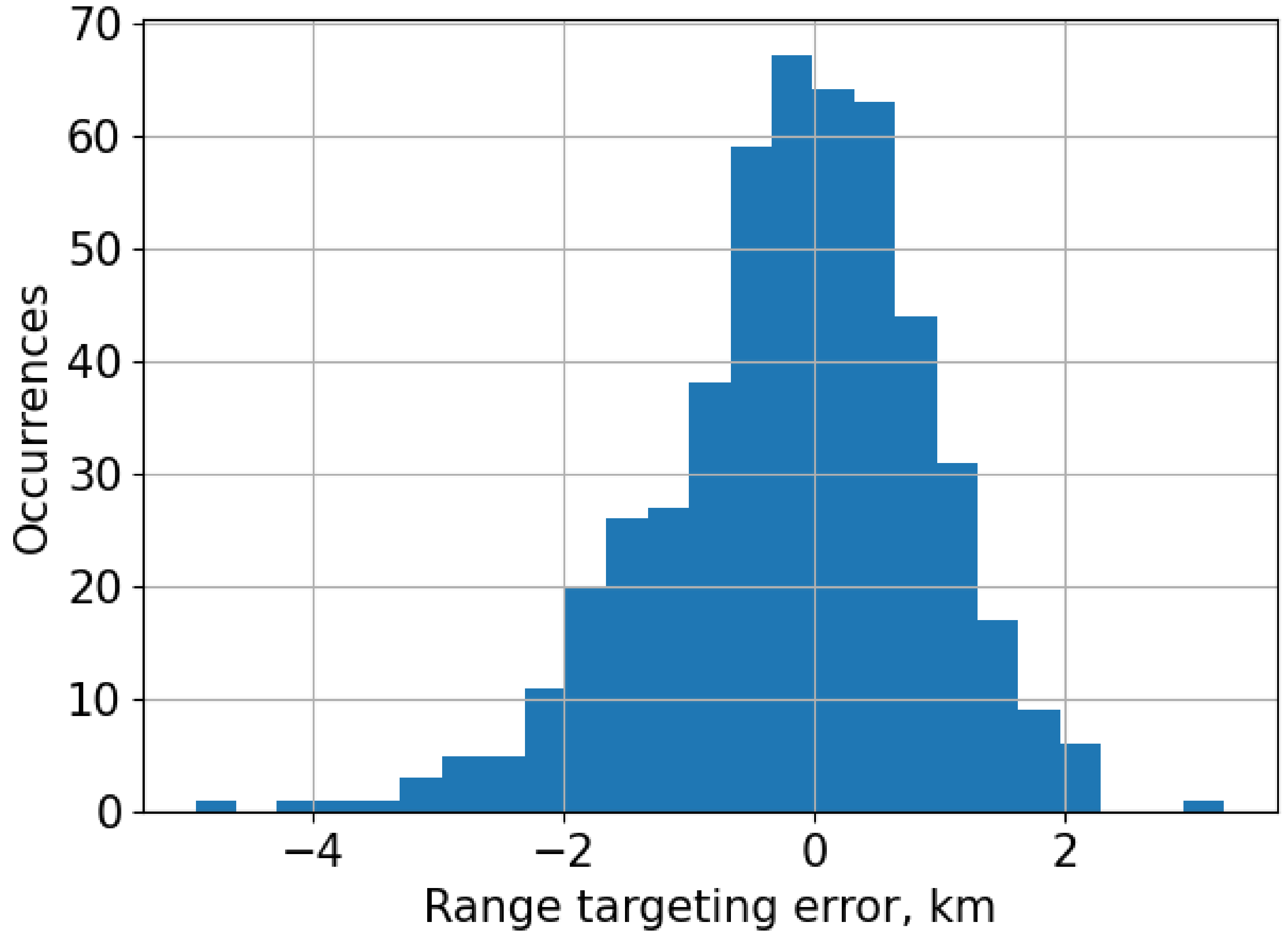
- Mars, 6 km/s, -12 deg
- Orbiter:
  - L/D = 0.25
  - BC = 130 kg/m^2
  - Bank angle modulation
- Guided Probe:
  - L/D = 0.25
  - BC = 35 kg/m^2
  - Bank angle modulation
- Passive probe:
  - L/D = 0
  - BC = 35 kg/m^2



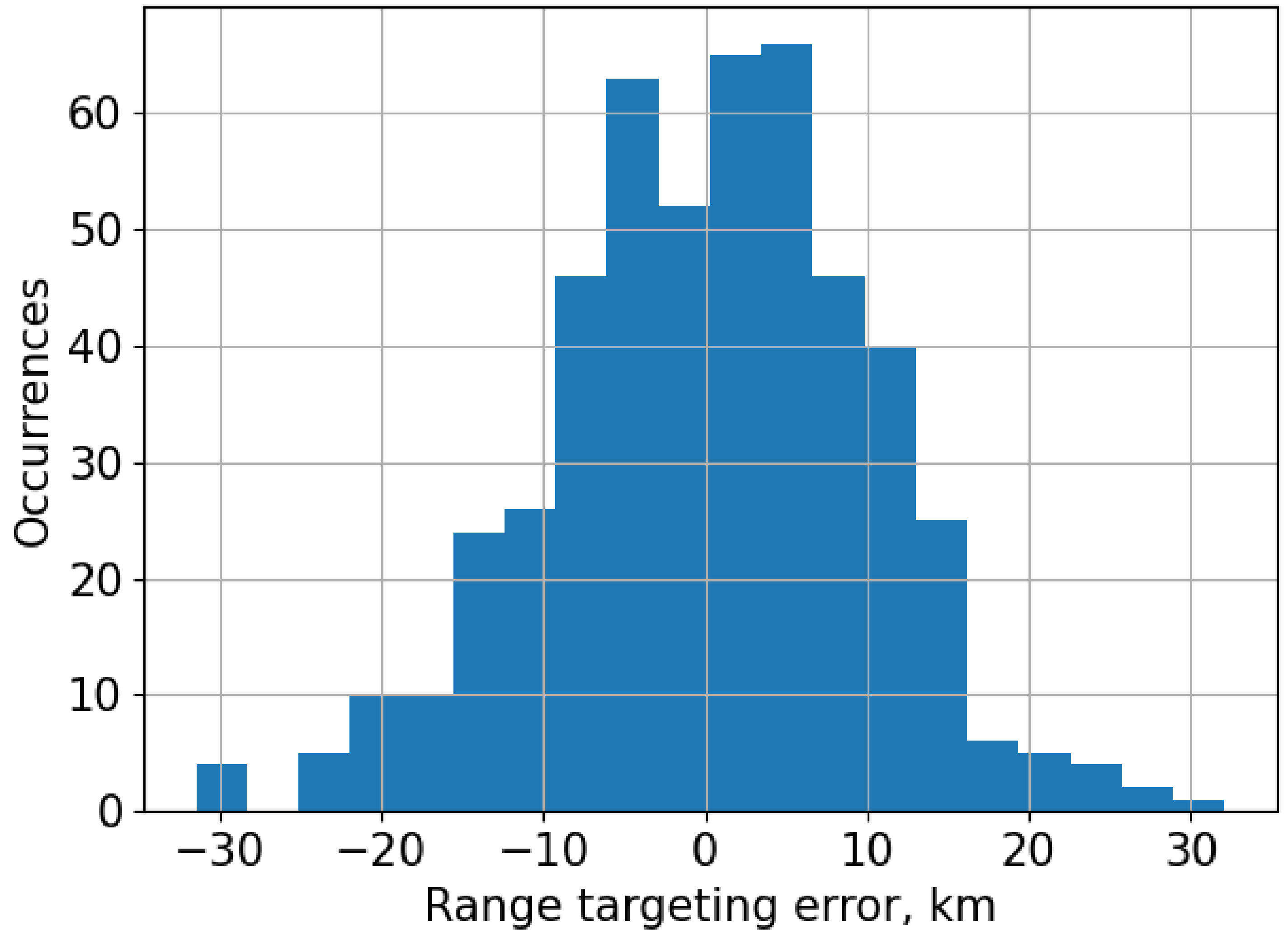
Guidance Performance Under Uncertainty

- Orbiter targets 250 km circular orbit
- Probe targets 300 m/s at 15 km (M = 1.3)

Guided Probe



Passive Probe



Input Dispersions

Parameter	Mean	Dispersions
EFPA	$-12°$	$3\sigma = 0.2°$
Entry Velocity	$6\,\mathrm{km\,s^{-1}}$	$3\sigma = 10\,\mathrm{m\,s^{-1}}$
Orbiter β	$130\,\mathrm{kg\,m^{-2}}$	±5 %
Probe β	$35\,\mathrm{kg\,m^{-2}}$	±5 %
Orbiter L/D	0.25	±5 %
Guided Probe L/D	0.25	±5 %
Density	Mars-GRAM 2010	Mars-GRAM 2010

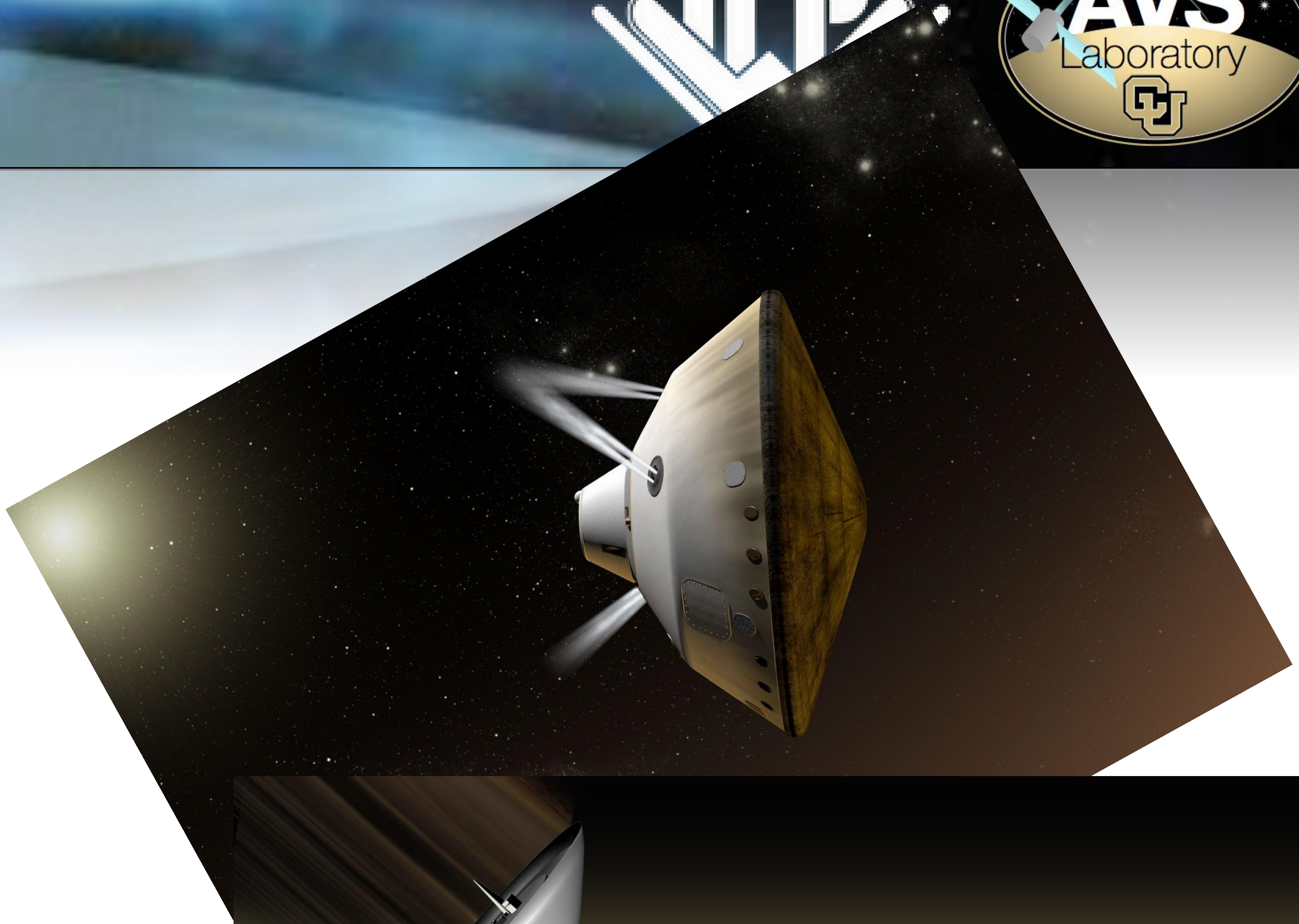
Performance Under Uncertainty

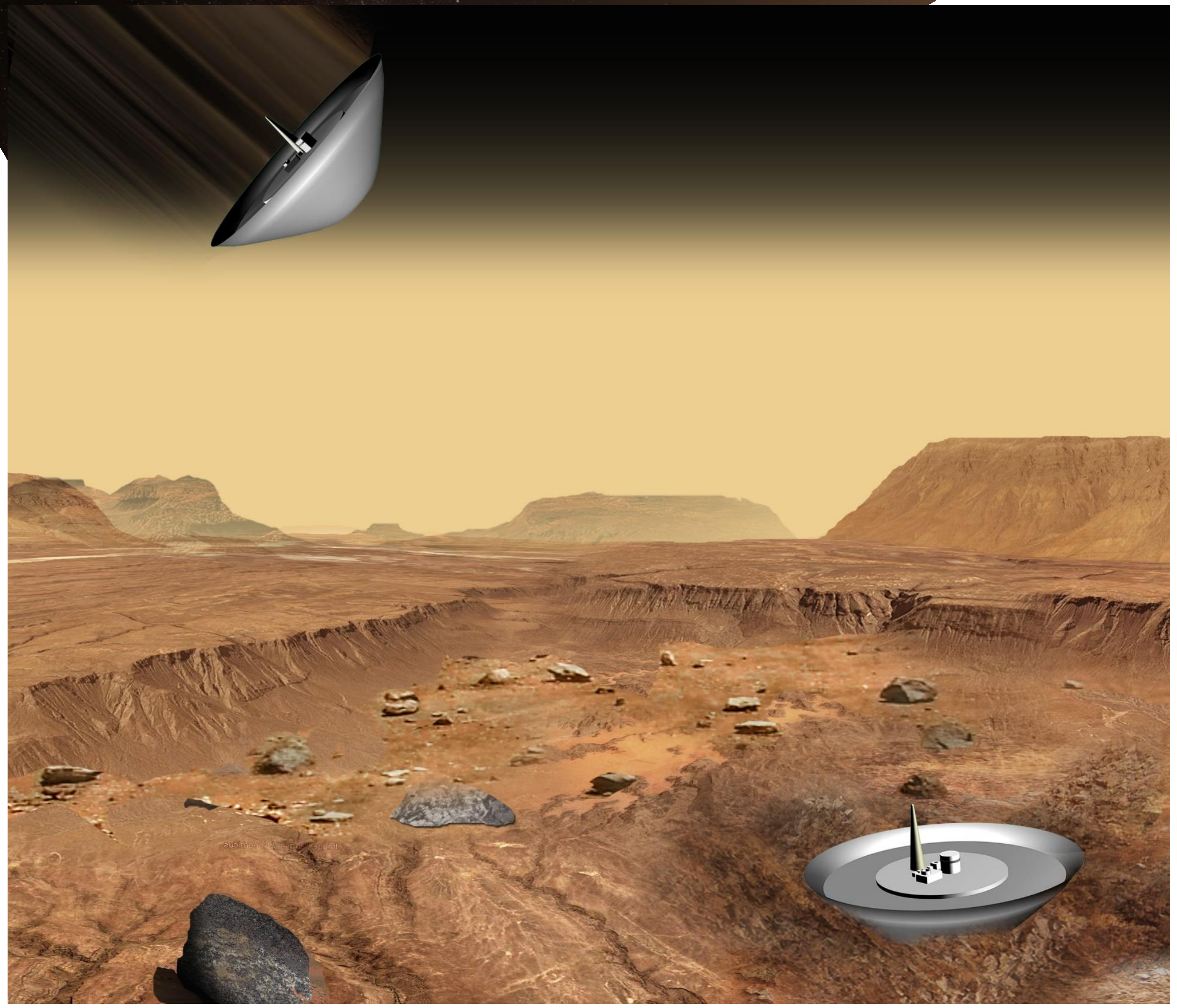
Parameter	Nominal	Mean	STD
Orbiter Apoapsis Error	0 km	30.15 km	63.77 km
Orbiter Total ΔV Cost	$73.73\,\mathrm{m\,s^{-1}}$	$86.93\,\mathrm{m\,s^{-1}}$	$16.92\,\mathrm{m\,s^{-1}}$
Guided Probe Altitude Error	441.1 m	466.3 m	340.7 m
Guided Probe Range Error	0 km	−0.1798 km	1.084 km
Guided Probe Velocity Error	$-5.486\,\mathrm{m\,s^{-1}}$	$-5.834\,\mathrm{m\,s^{-1}}$	$4.278\,\mathrm{m\,s^{-1}}$
Passive Probe Range Error	0 km	0.2480 km	9.975 km
Passive Probe Velocity Error	$0\,\mathrm{m\,s^{-1}}$	$0.086\,03\,\mathrm{m\,s^{-1}}$	$11.55\,\mathrm{m\,s^{-1}}$

Example Mission Scenario

Example Mission Scenario

- Mars, 6 km/s, -12 deg
- MSL-like Orbiter:
  - L/D = 0.25
  - BC = 130 kg/m^2
  - Bank angle modulation
- SHIELD-like rough lander:
  - L/D = 0
  - BC = 35 kg/m^2
  - Crushable material for landing at ~1000 g's
- Multiple (4+) landers form a network
- KISS study tie-in
  - see *Revolutionizing Access to the Mars Surface*, Z. Putnam, IPPW 2021

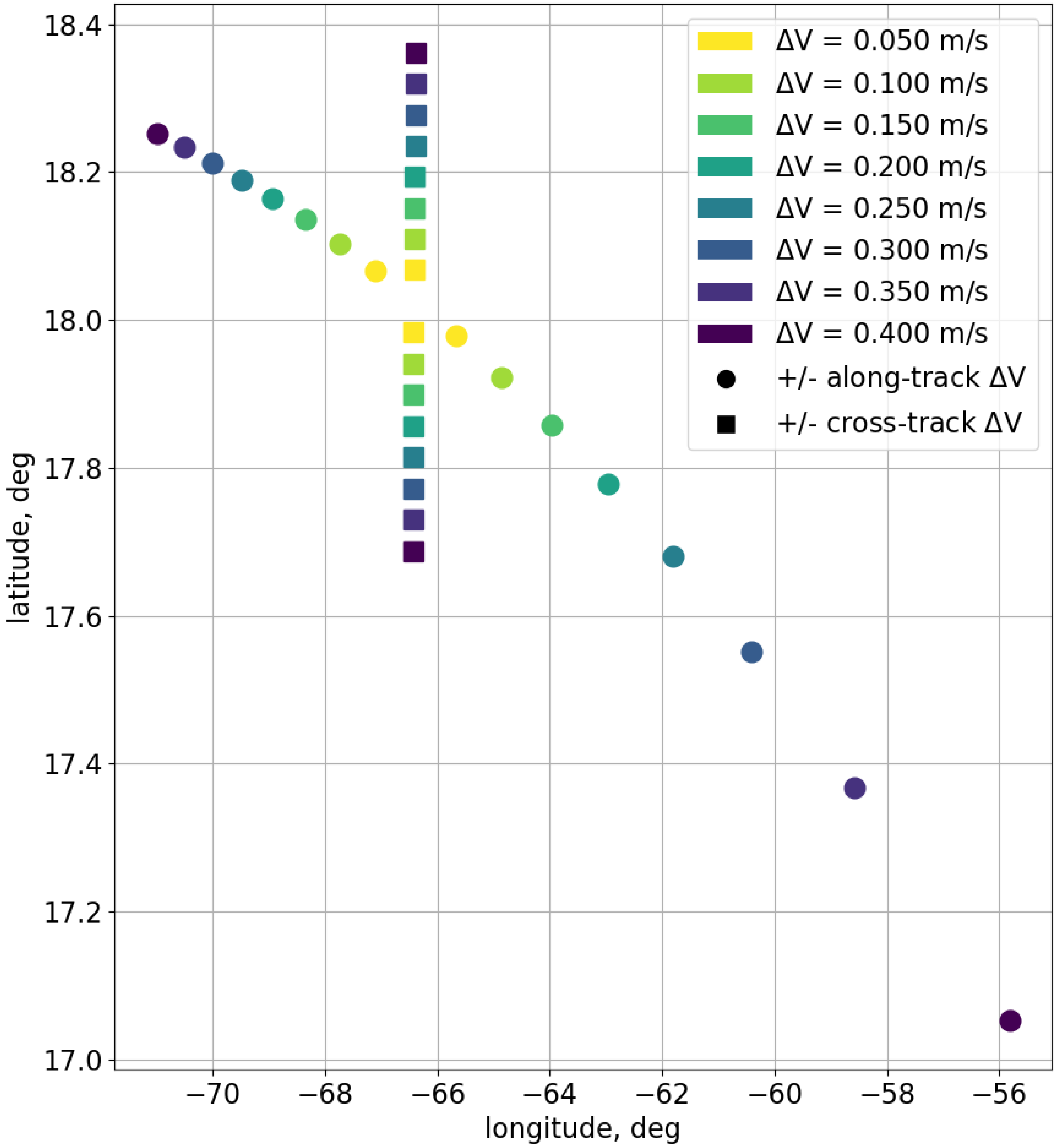


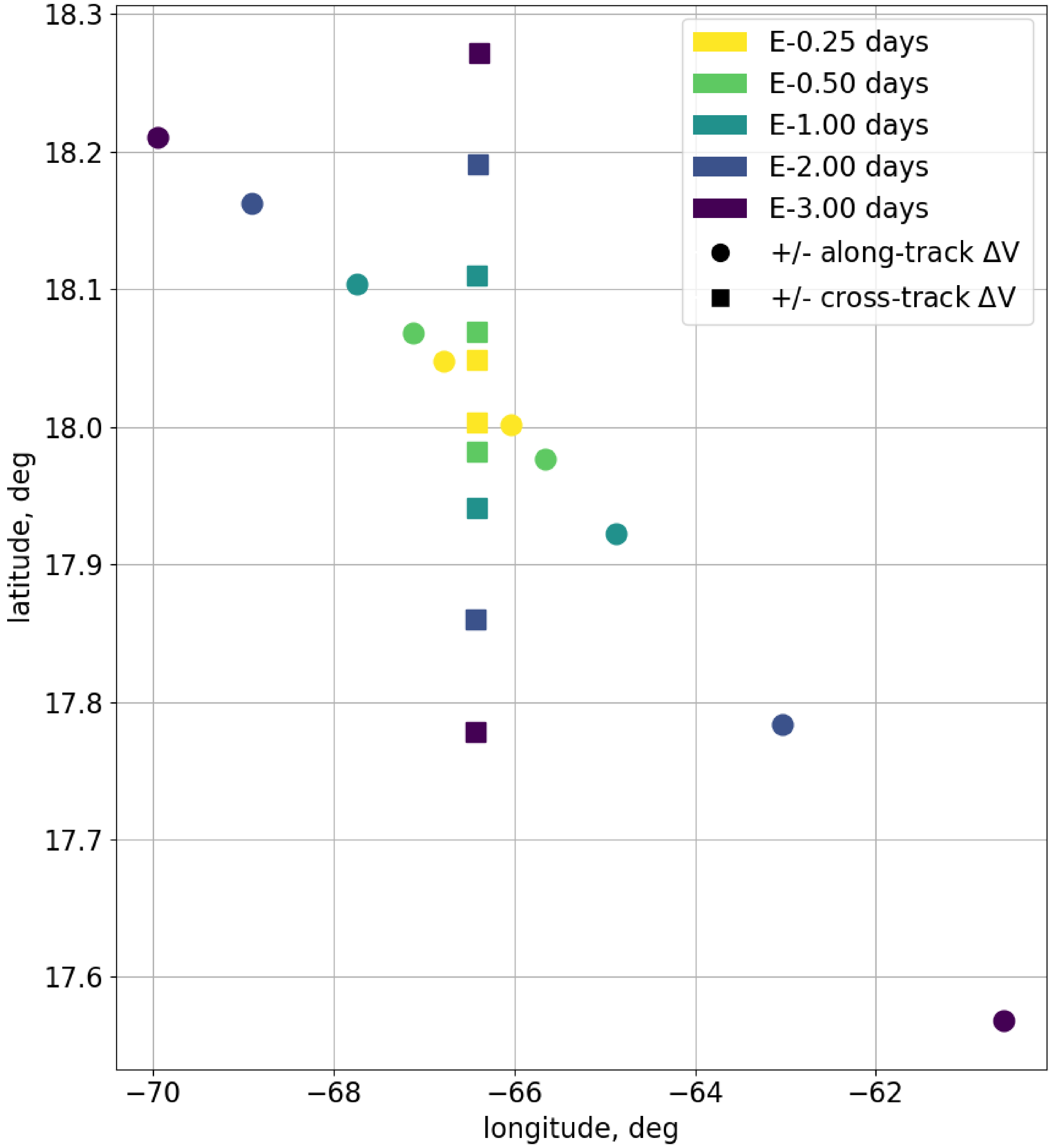


https://www.nasa.gov/mission_pages/msl/multimedia/gallery/pia14834.html
"New Capabilities for Accessing the Martian Surface," Chad Edwards and Larry Matthies, NASA JPL/CalTech

Varying Separation Magnitude and Timing

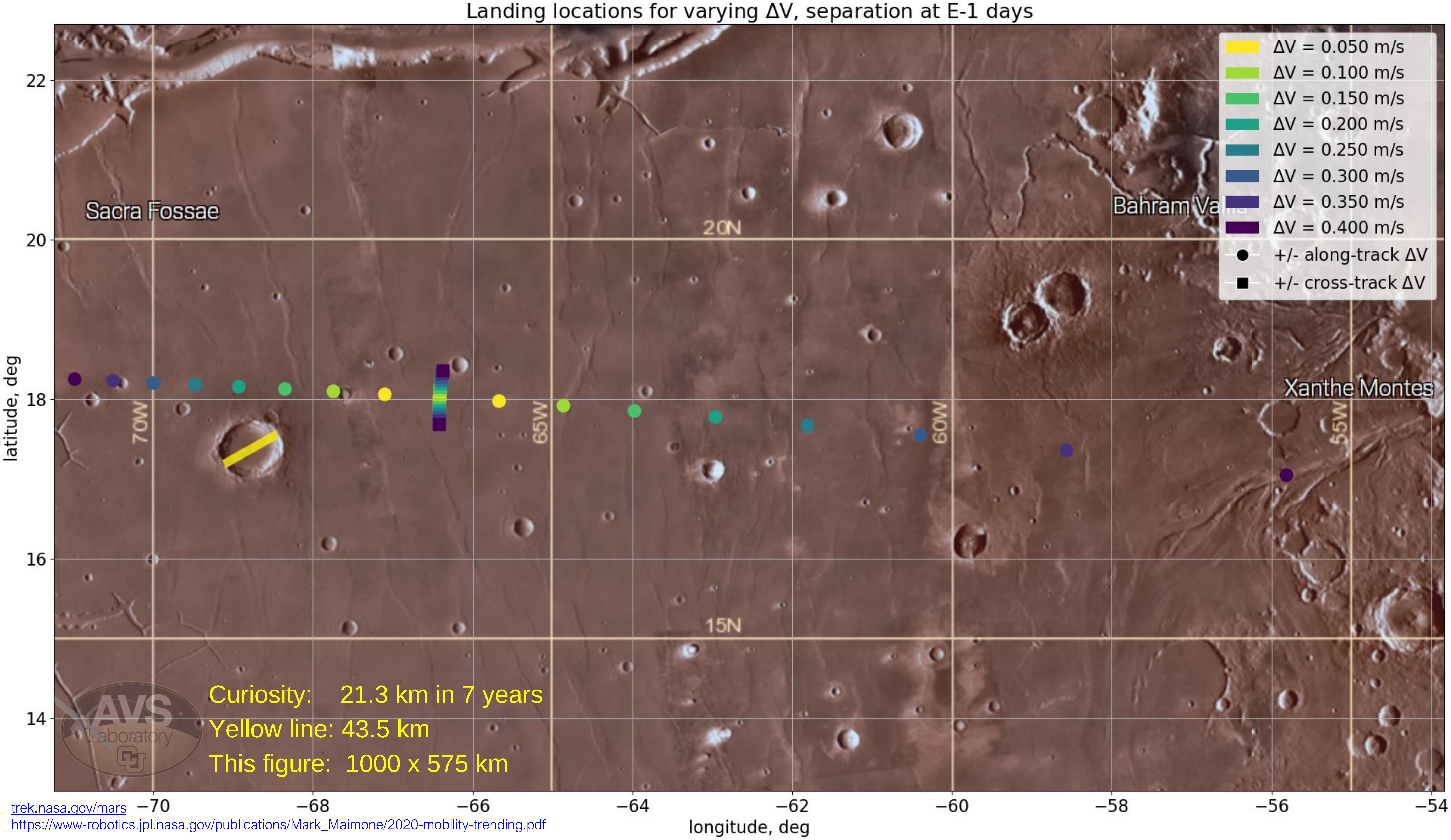
- Nominal separation at E-1 day, 10 cm/s





ΔV, cm/s	Minimum Distance, km	Maximum Distance, km
5	5.006	80.787
10	10.011	162.831
15	15.016	247.581
20	20.021	336.941
25	25.026	433.777
30	30.031	543.062
35	35.035	675.207
40	40.039	859.503

Separation Time, days	Minimum Distance, km	Maximum Distance, km
E-0.25	2.694	42.504
E-0.5	5.151	82.544
E-1	10.011	162.831
E-2	19.674	331.883
E-3	29.311	529.586

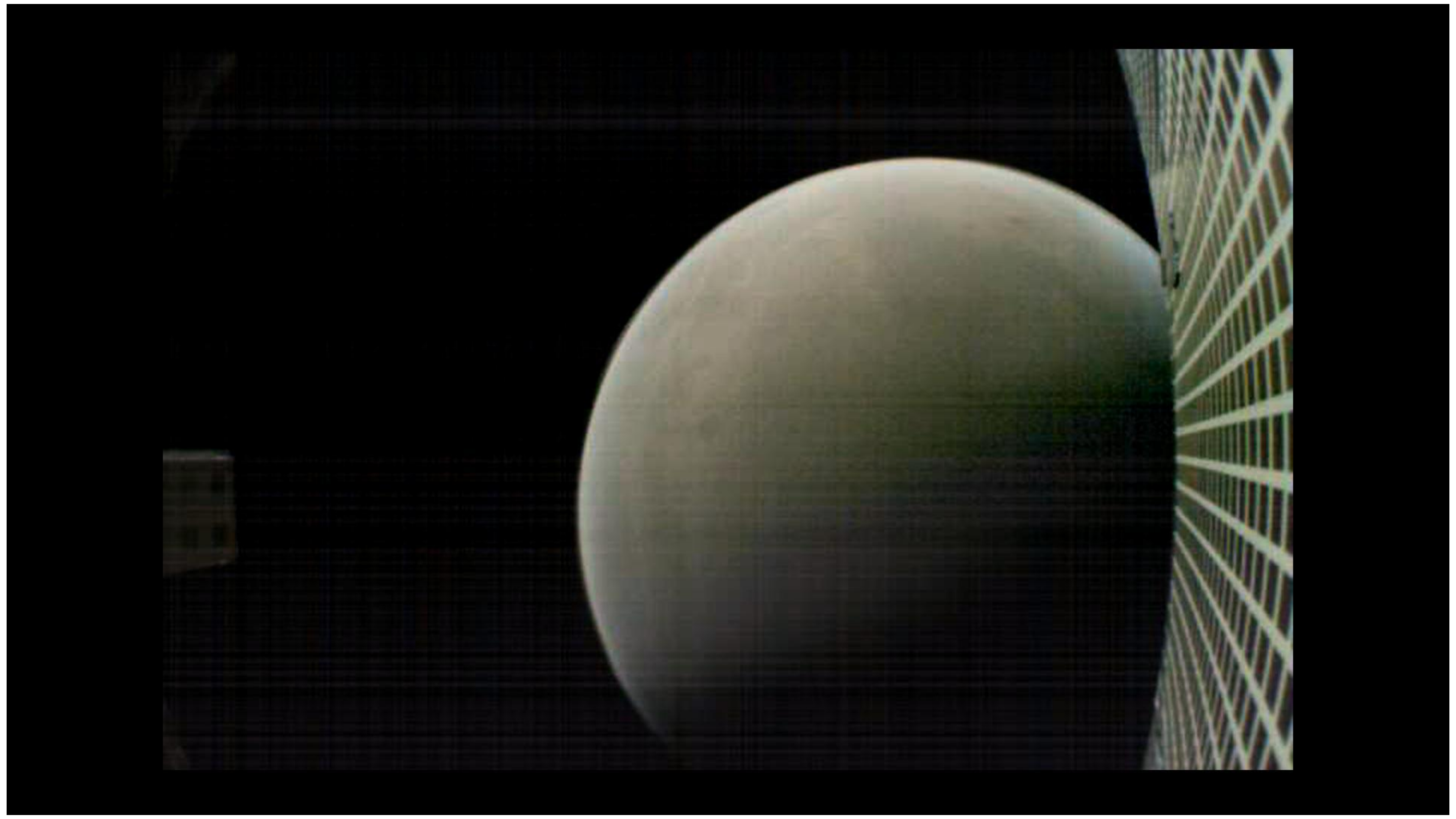


trek.nasa.gov/mars

https://www-robotics.jpl.nasa.gov/publications/Mark_Maimone/2020-mobility-trending.pdf

Conclusions

- The proposed co-delivery method is feasible
- Existing guidance schemes can be applied
- MSL-class orbiter and SHIELD-class rough lander make a nice duo
- May provide a path to low-cost delivery of a network of small landers on the Martian surface



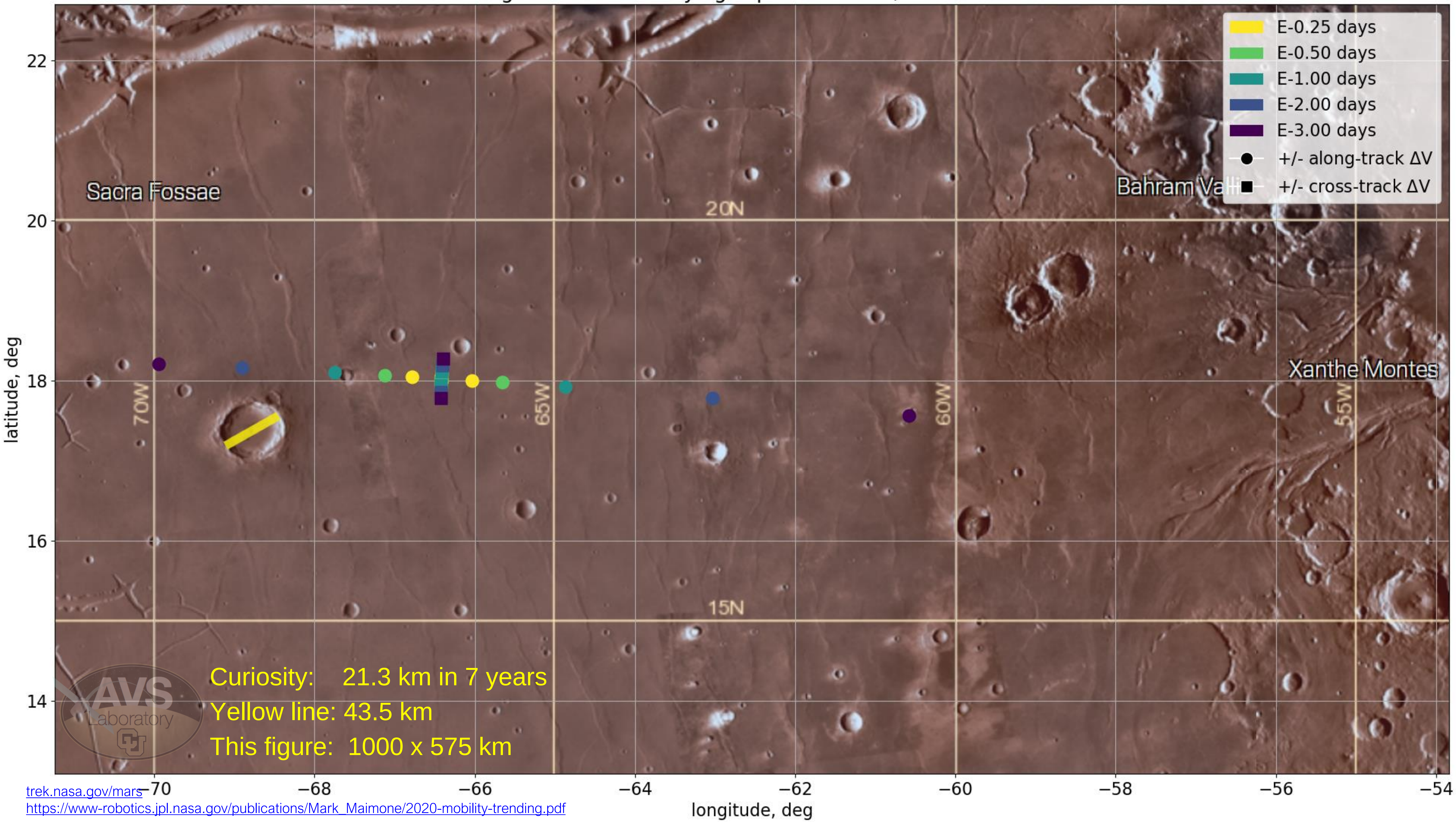
https://www.jpl.nasa.gov/images/farewell-to-mars

https://mars.nasa.gov/resources/25838/mastcam-z-video-of-ingenuity-taking-off-and-landing/

Questions?

Backup

Landing locations for varying separation time, ΔV = 0.100 m/s



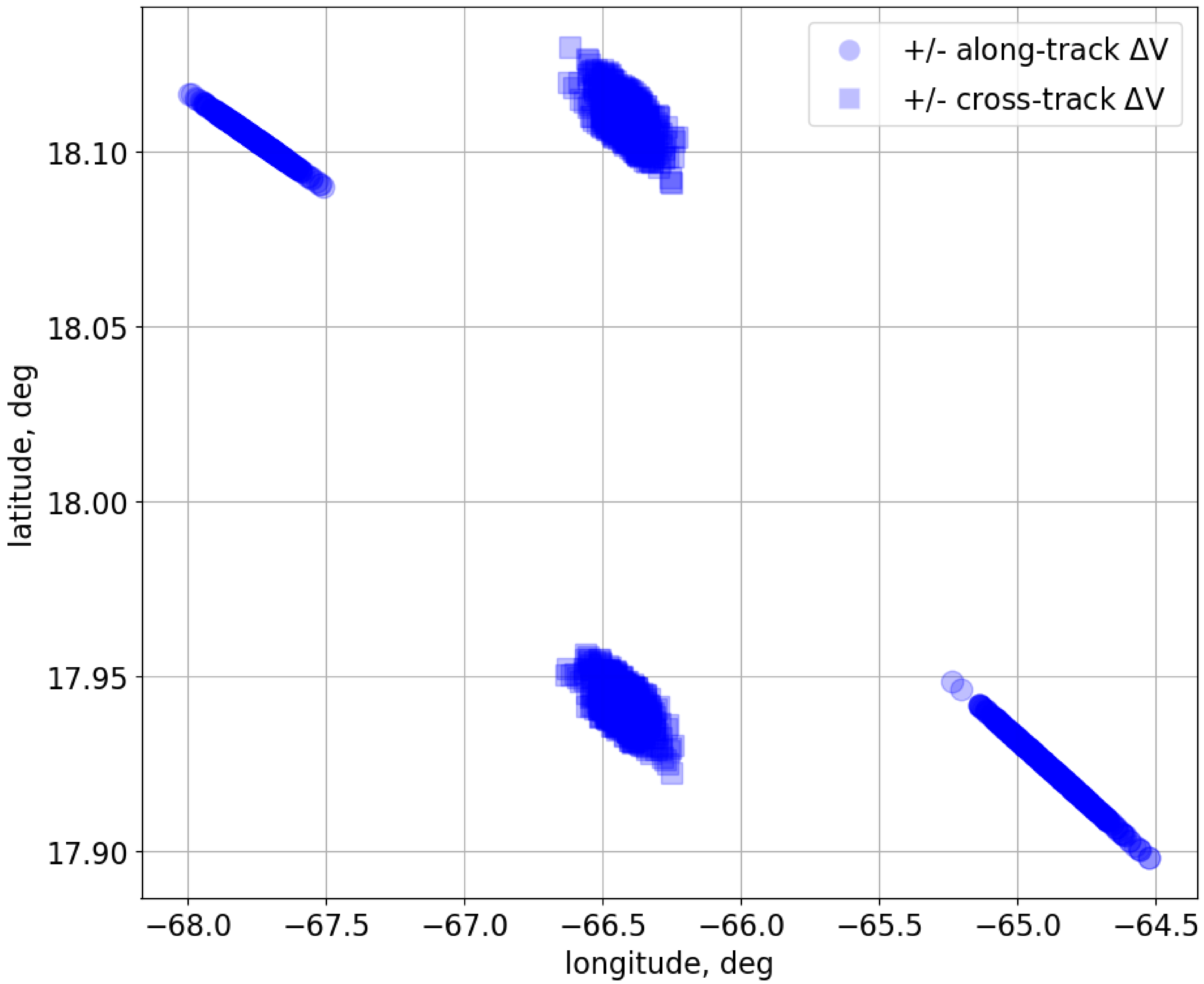
trek.nasa.gov/mars
https://www-robotics.jpl.nasa.gov/publications/Mark_Maimone/2020-mobility-trending.pdf

Separation Uncertainty

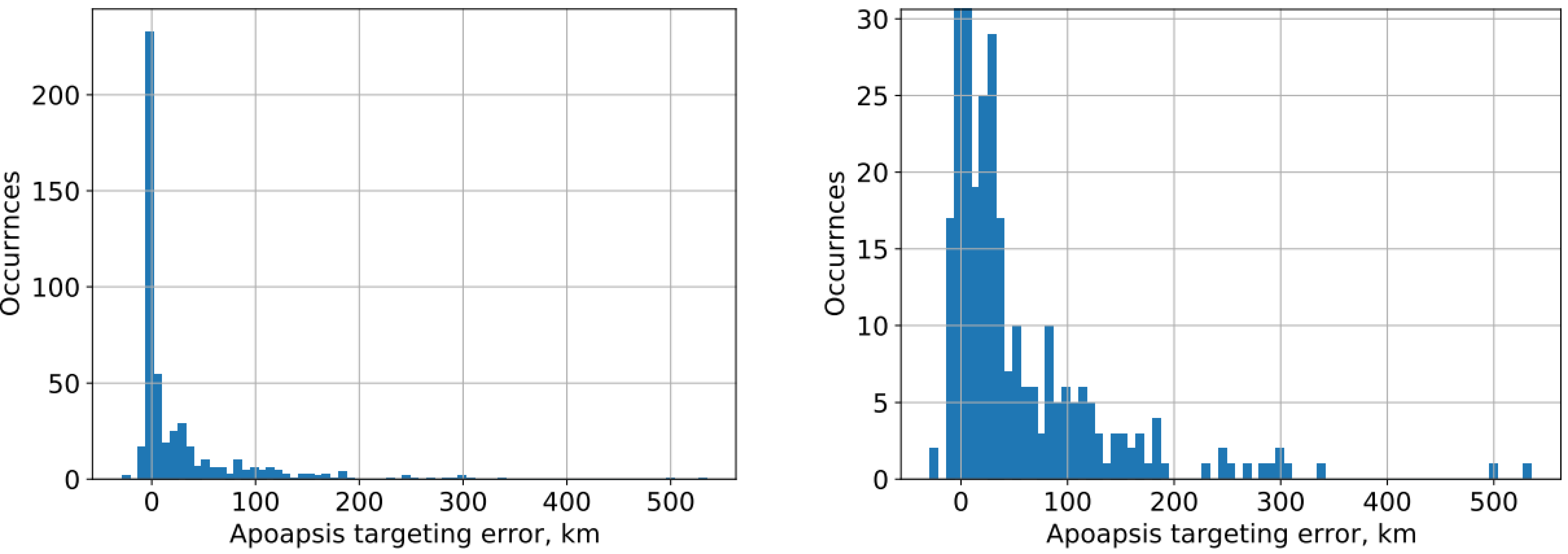
- Dispersed separation magnitude +/- 10%, ballistic coefficients +/- 5%, and atmosphere

- Minimum separation:
  - 9.98 km average
  - 0.407 km STD

- Maximum separation:
  - 163 km average
  - 7.30 km STD



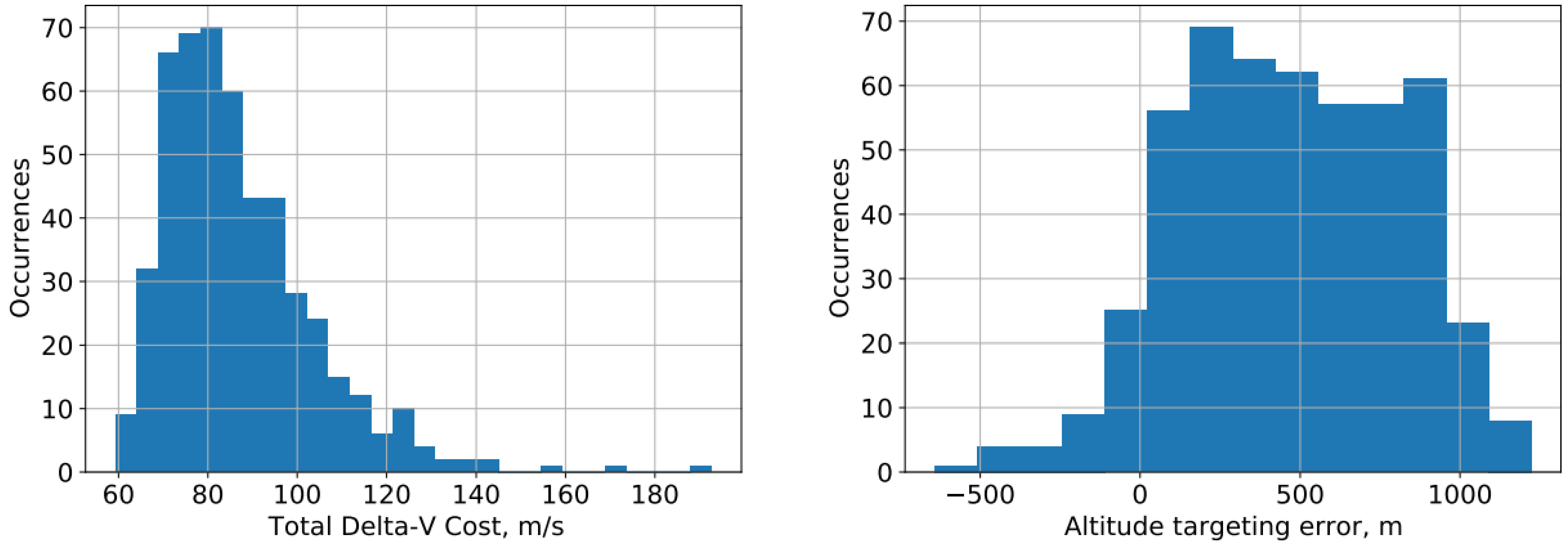
Guidance Performance Results



(a) Histogram of apoapsis error for orbiter

(b) Zoomed-in view of Fig. 9a

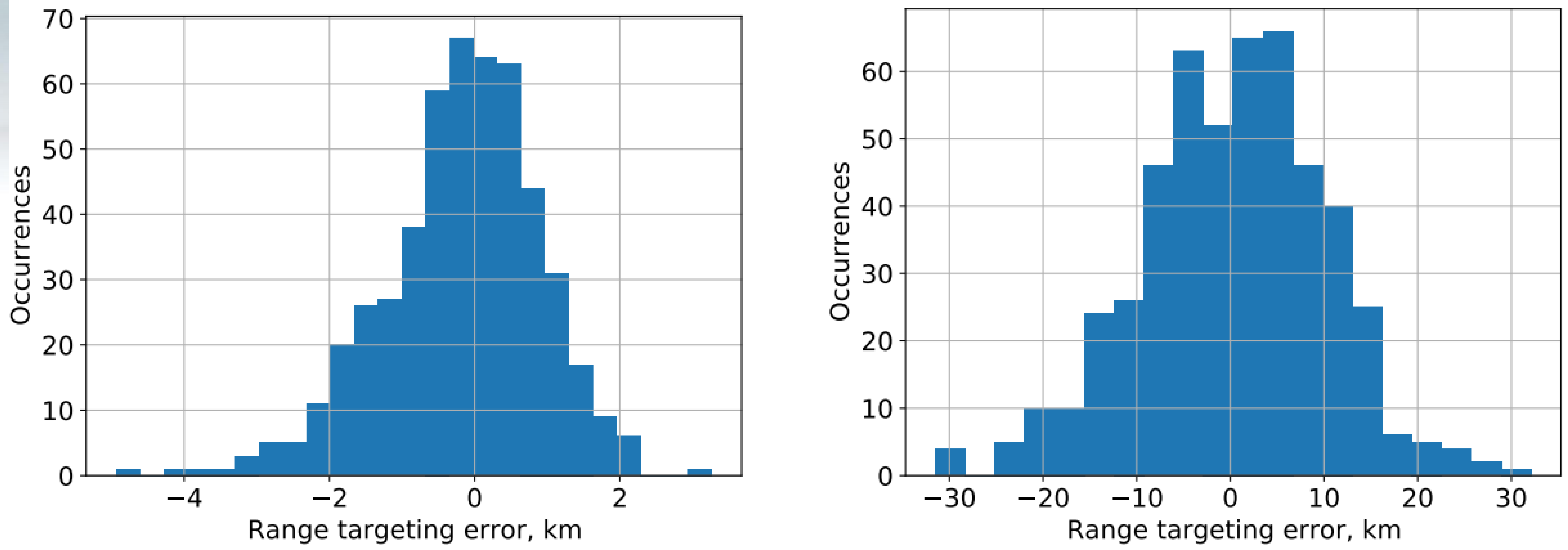
Fig. 9 Apoapsis results for orbiter



(a) Histogram of total ΔV cost for orbiter

(b) Histogram of altitude error for guided probe

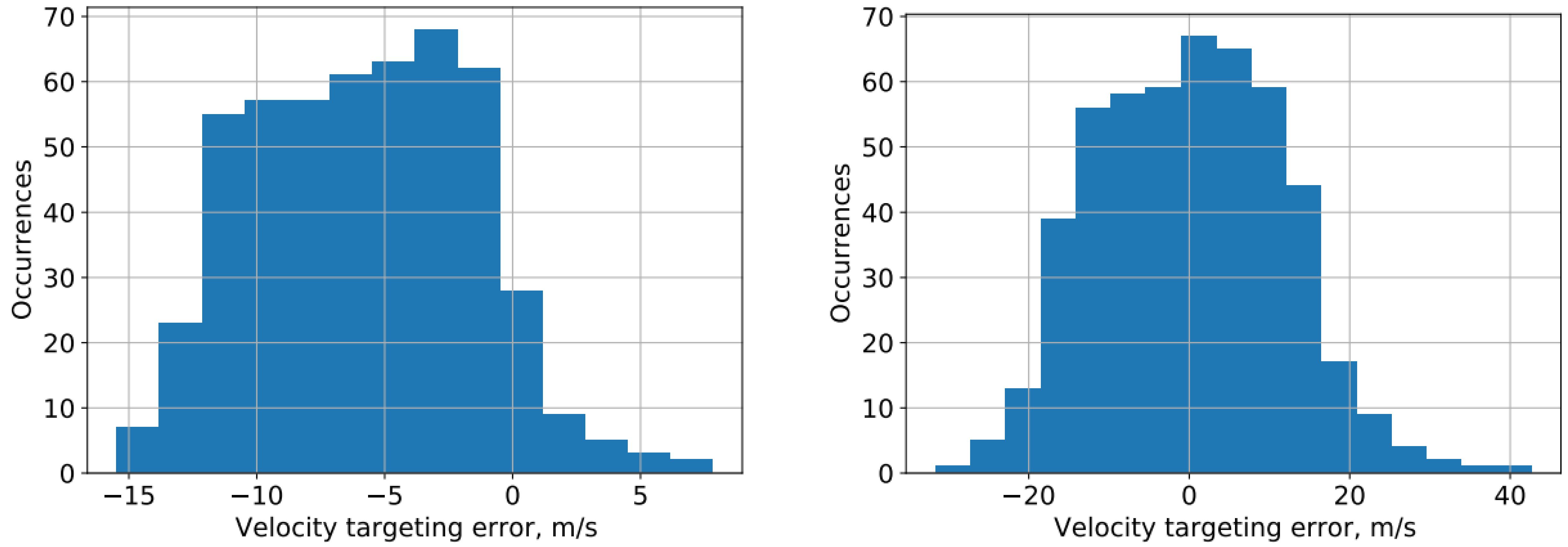
Fig. 10 ΔV cost for orbiter and altitude error for guided probe



(a) Guided probe

(b) Passive probe

Fig. 11 Target range error histograms for guided and passive probes



(a) Guided probe

(b) Passive probe

Fig. 12 Target velocity error histograms for guided and passive probes

SHIELD Drop test (from Chad Edwards, JPL)

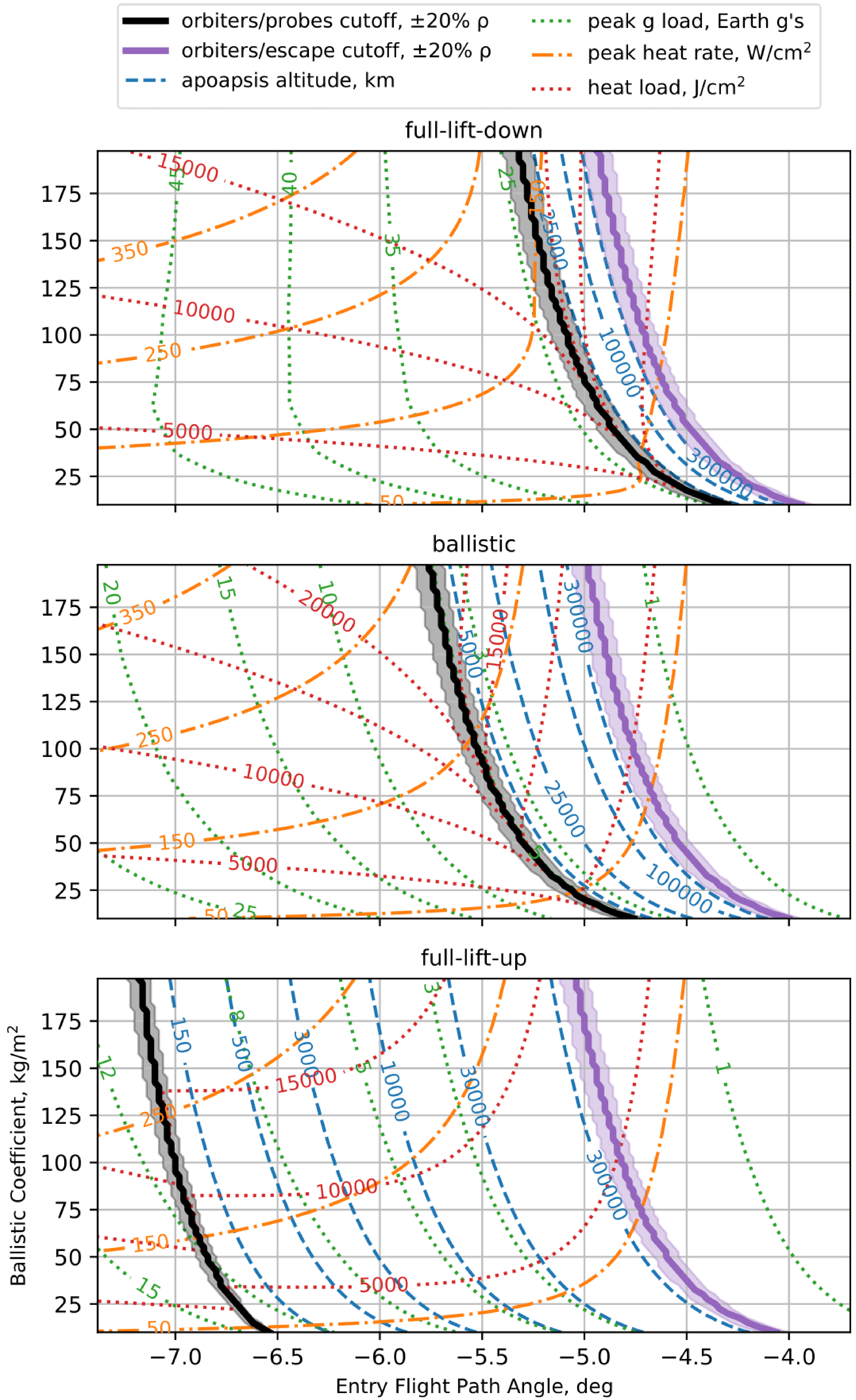
March 5, 2021 SHIELD Drop Test

Mojave playa, covered with sandstones ~35 mm thick

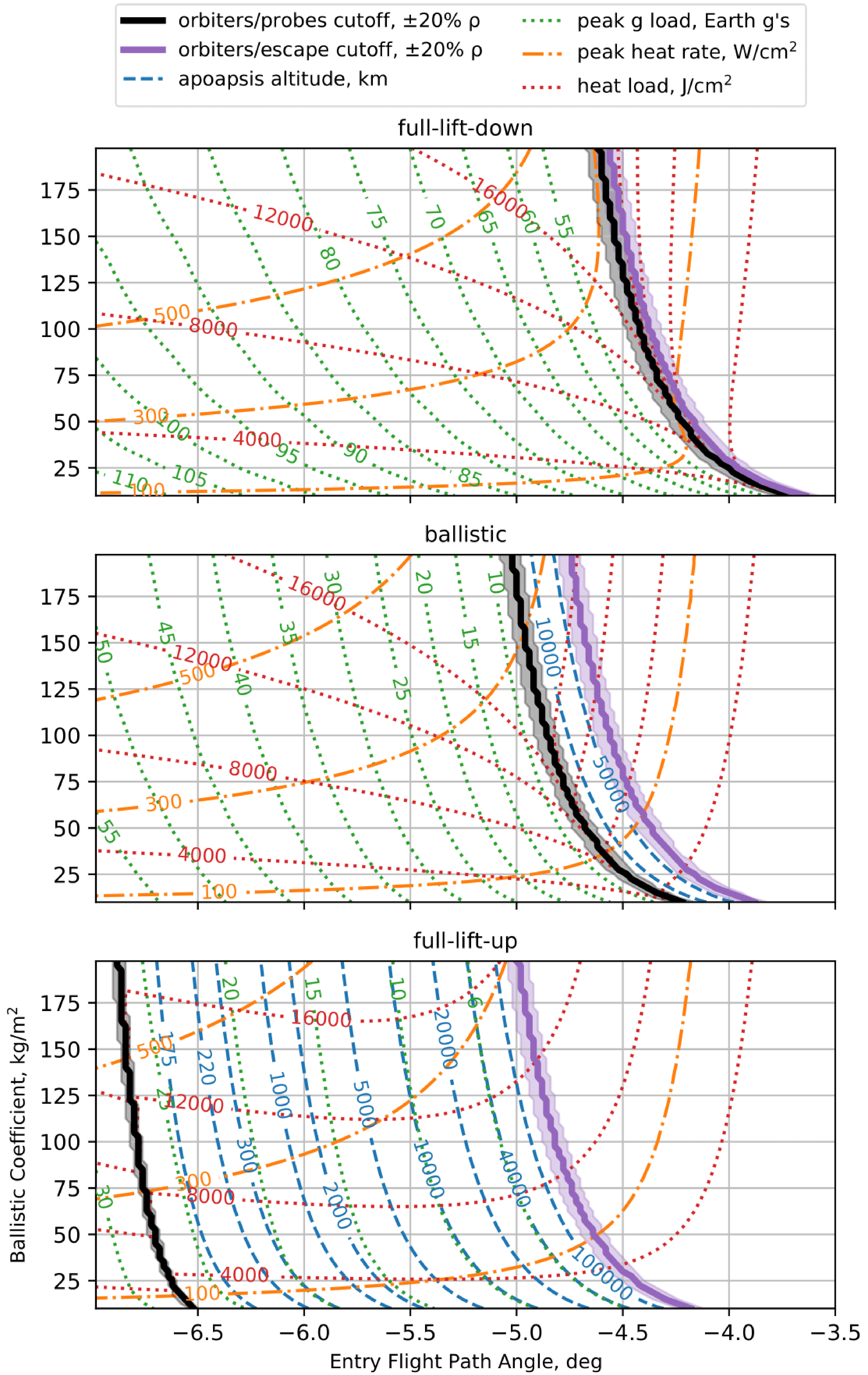
Peak deceleration <1000 g (4 kHz LPF)

Recorded at 10,000 FPS
Playback at 30 FPS

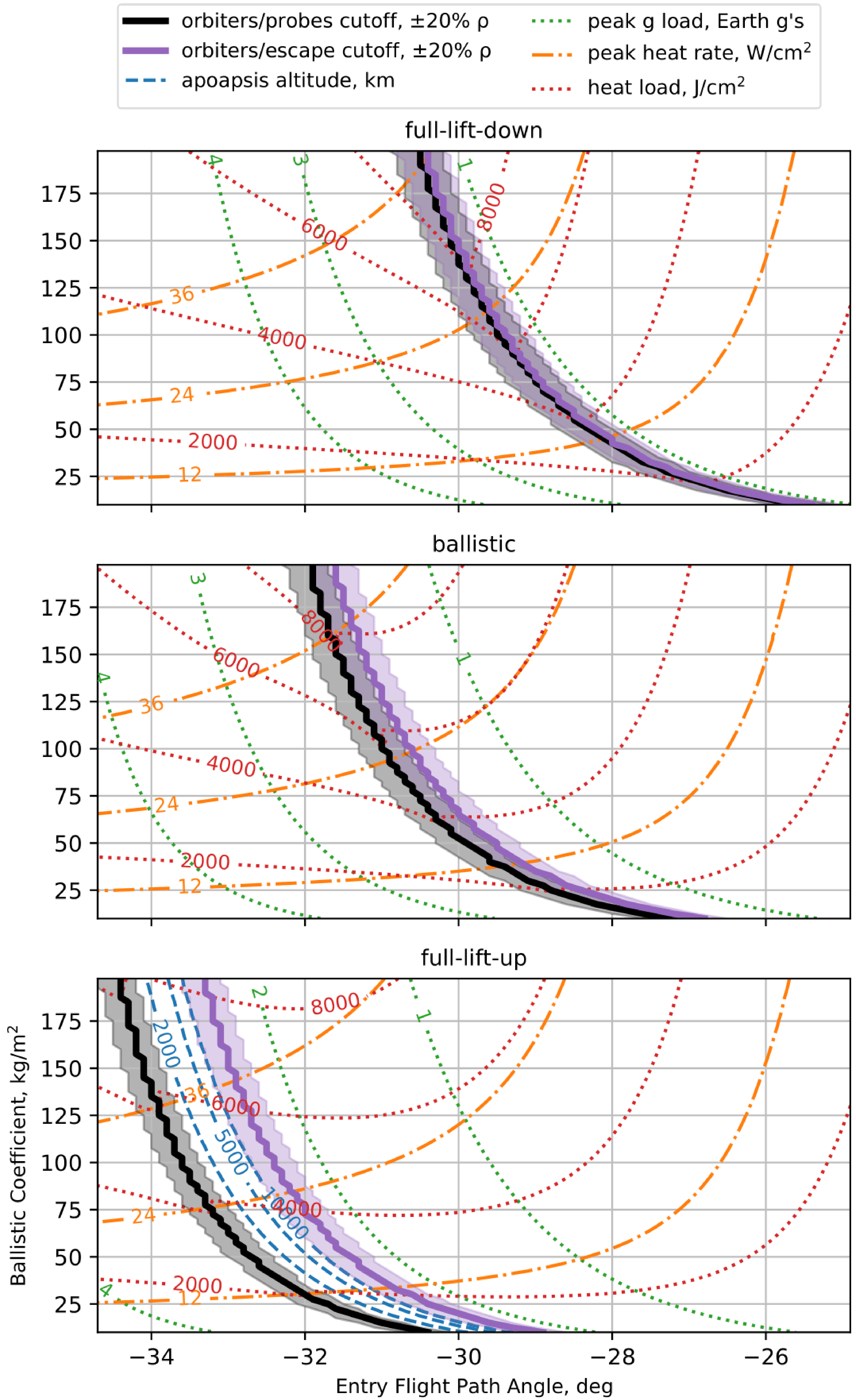
Earth Feasibility Space



Venus Feasibility Space



Titan Feasibility Space



Neptune Feasibility Space