Entry Flight Mechanics Analysis for SHIELD: Small High Impact Energy Landing Device

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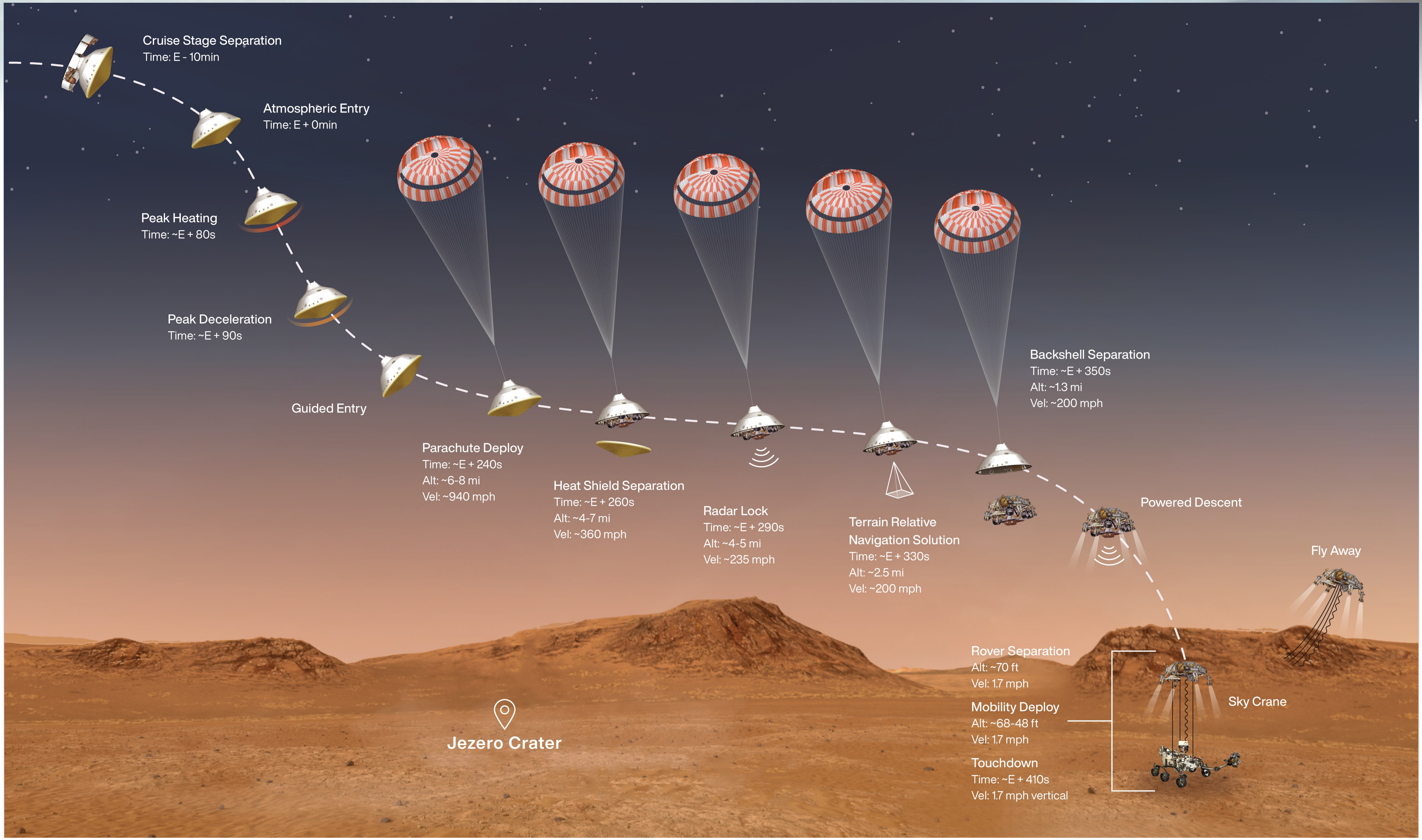
Motivation

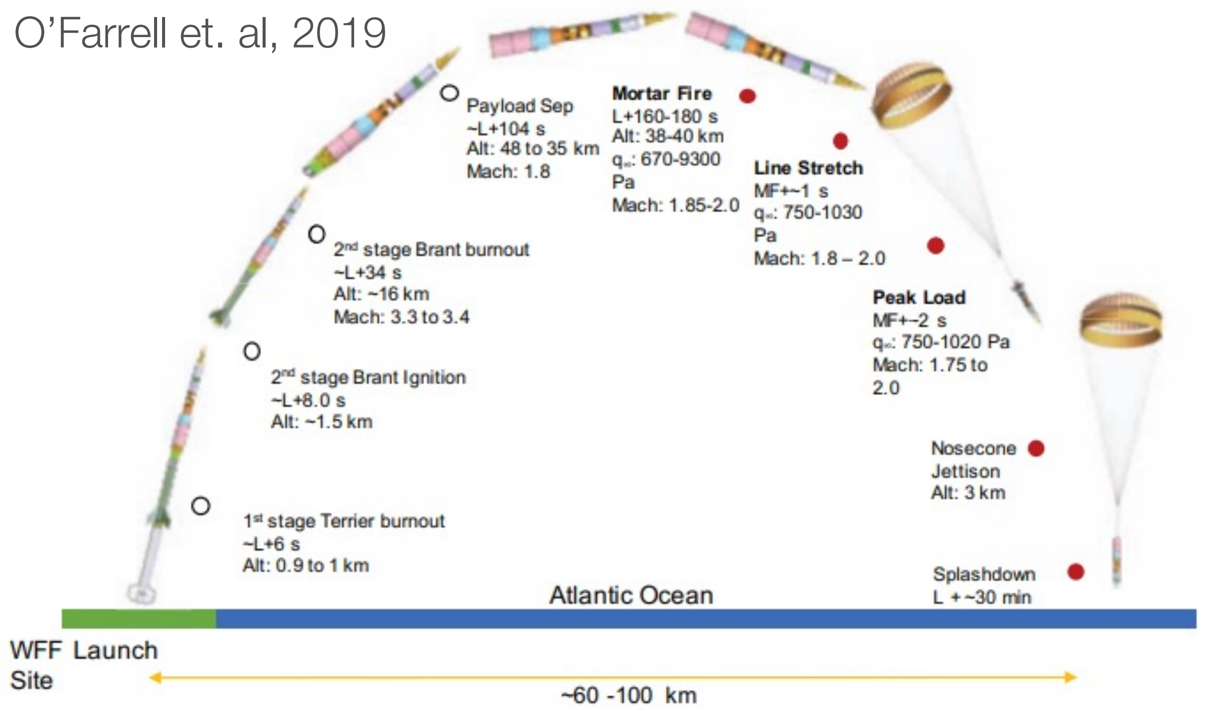
Mars 2020 EDL – "7 Minutes of Terror"

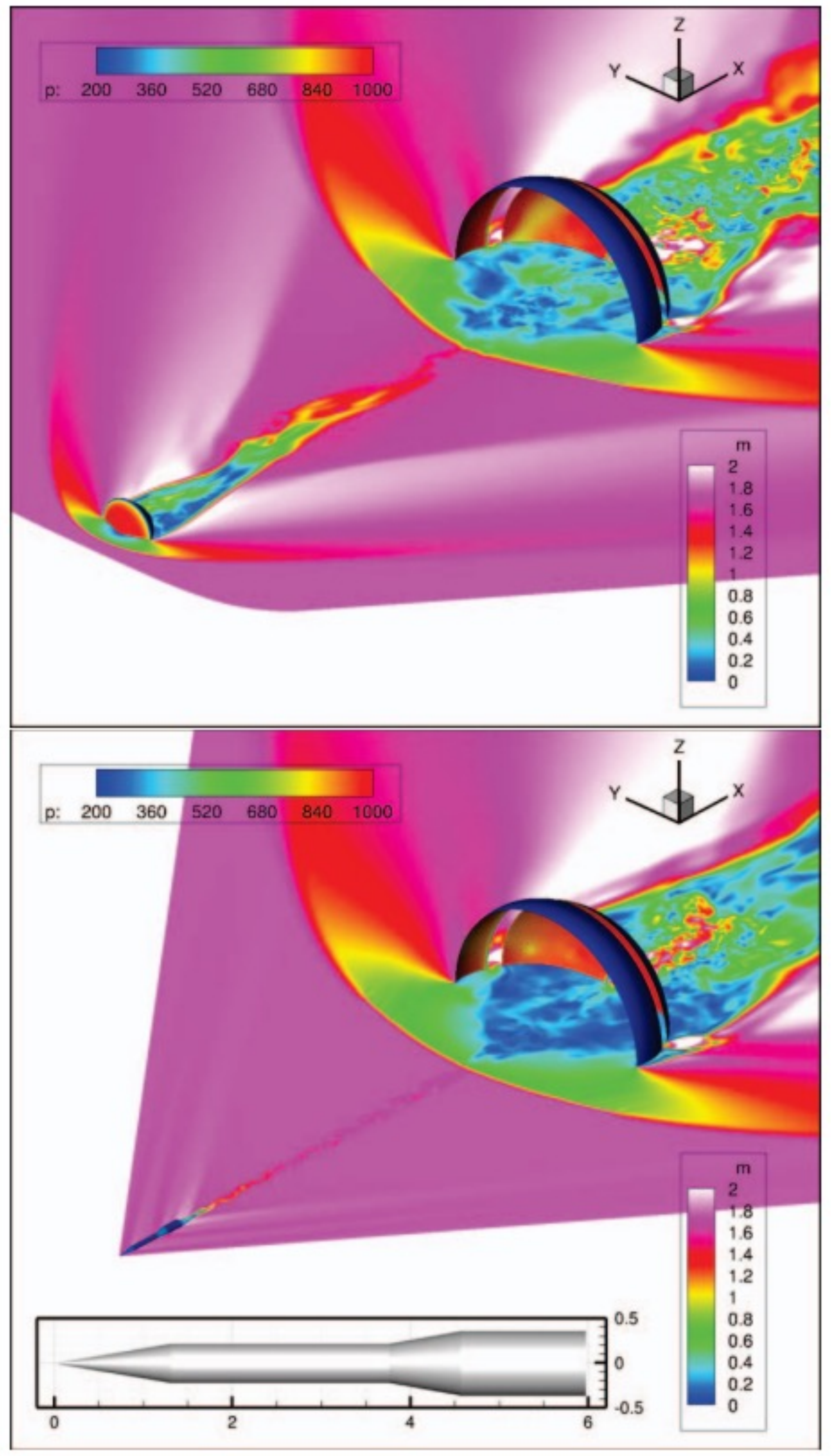


NASA/JPL-Caltech

Mars 2020 Supersonic Parachute – Risk Reduction

O'Farrell et. al, 2019





O'Farrell et. al, 2017

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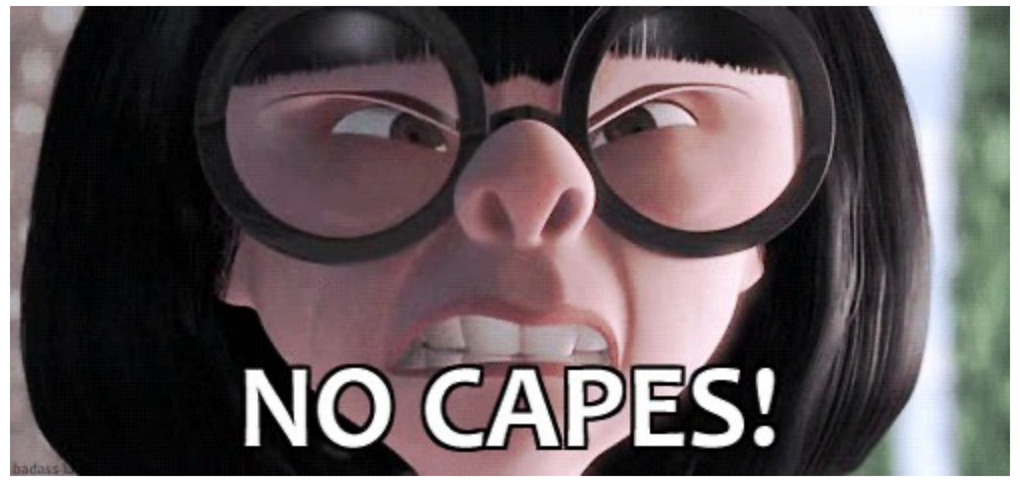
How could we dramatically reduce cost and risk from the parachute subsystem?

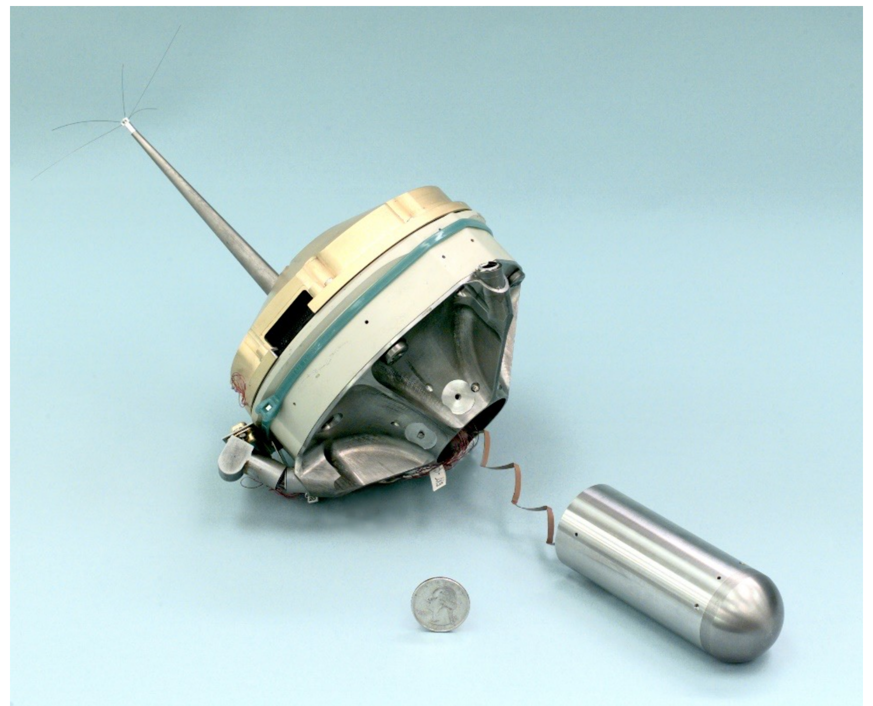
Eliminate the parachute.

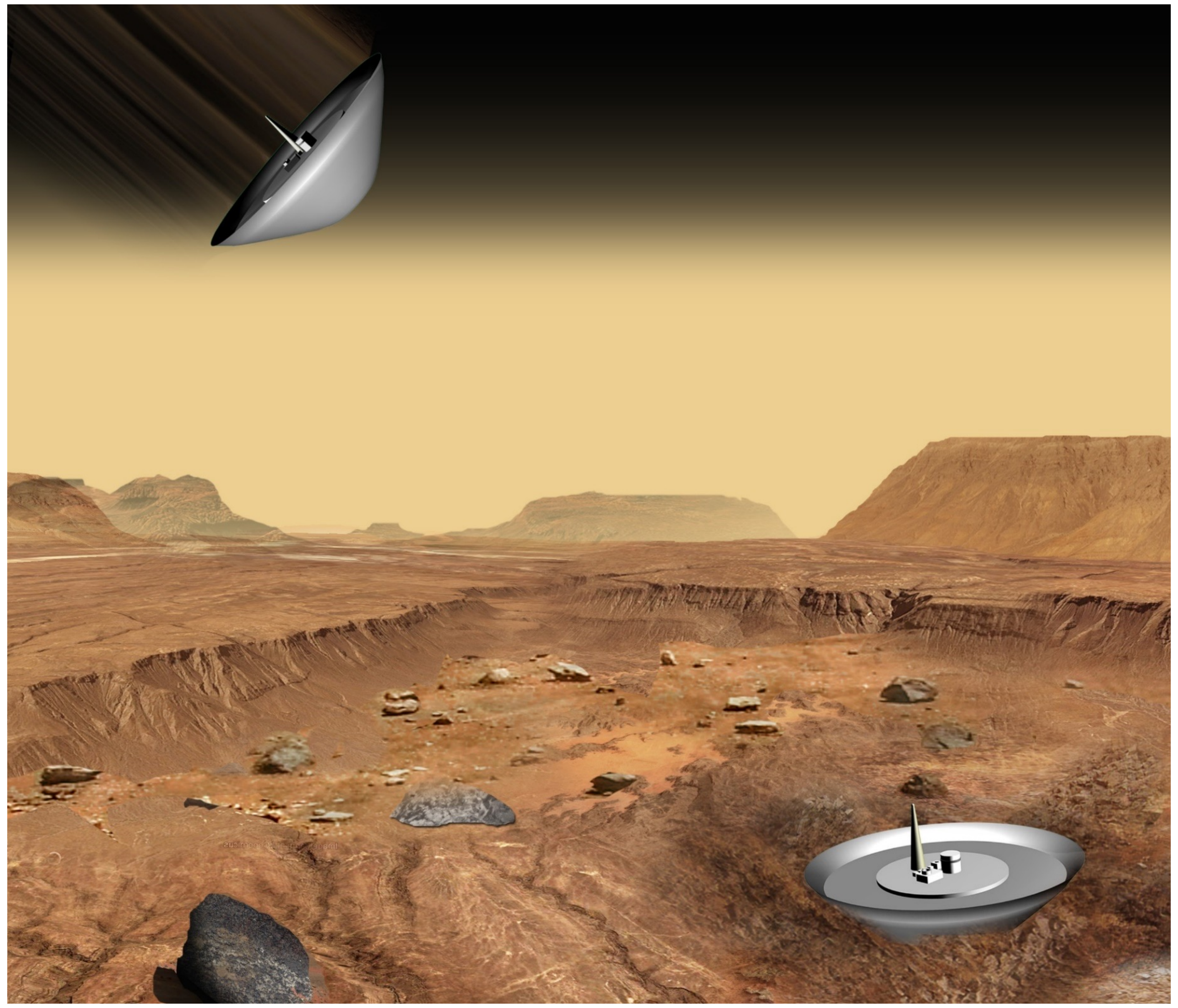


Small High Impact Energy Landing Device (SHIELD)

- Vehicle concept under development at NASA JPL
- **Minimum complexity –** eliminate subsystems wherever possible
- Small, mostly passive ballistic rough lander for Mars
- Only two EDL events:
  - Subsonic drag skirt deployment
  - Heatshield jettison
- Crushable material attenuates final impact deceleration
- ~5 kg payload, ~1,000 Earth g's
- DS2 comparison:
  - 3.6 kg *entry* mass
  - ~30,000 Earth g's

Wikipedia



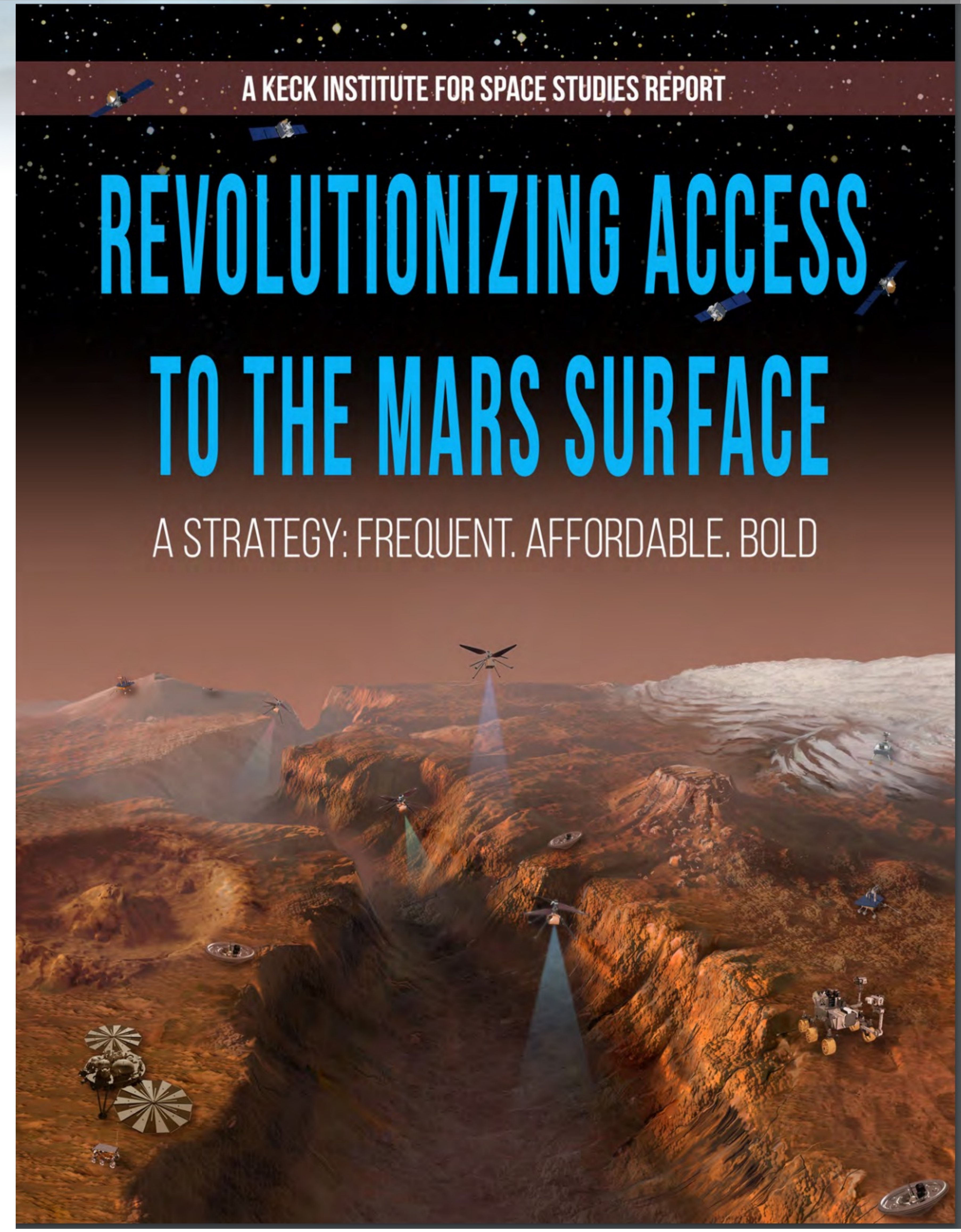


Edwards and Matthies, 2021

Low-Cost Missions to the Martian Surface

- Mars Sample Return:
  - Top priority at Mars for the next decade
  - \$3.8-\$4.4B, multiple missions
- Community interest in low-cost science missions to continue regular mission cadence during & after MSR
  - Keck Institute for Space Studies report, Low-Cost Science Mission Concepts for Mars Exploration Workshop
- Networks of small rough landers are promising mission architecture
  - Atmospheric science, seismology
- Co-deliver passive probes to entry via single carrier spacecraft
  - Further reduce complexity

Maneuver design & uncertainty quantification for co-delivery of network of passive ballistic probes

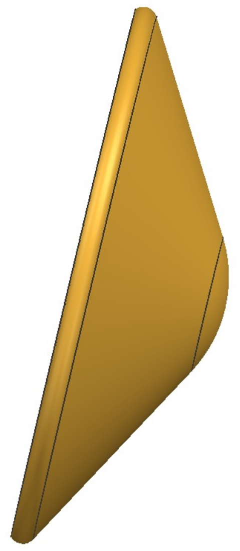


Culbert, Ehlmann, Fraeman, 2022

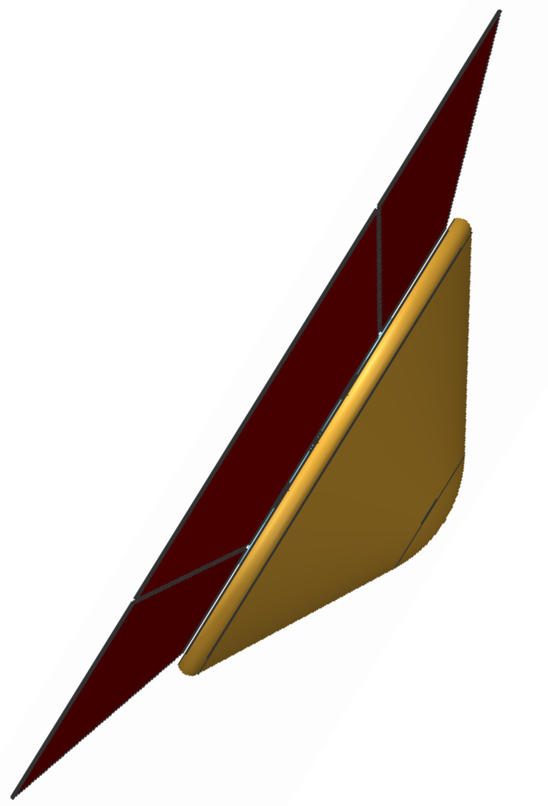
SHIELD Flight Mechanics Analysis

SHIELD EDL Timeline

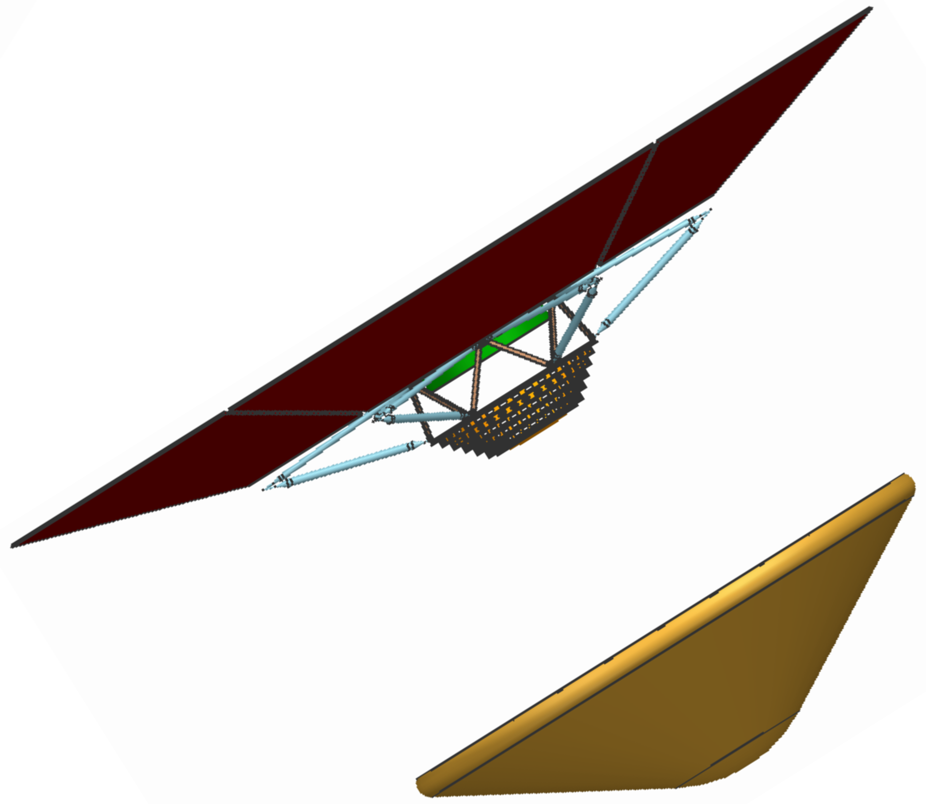
Entry
Stowed in aeroshell
6 km/s at 125 km



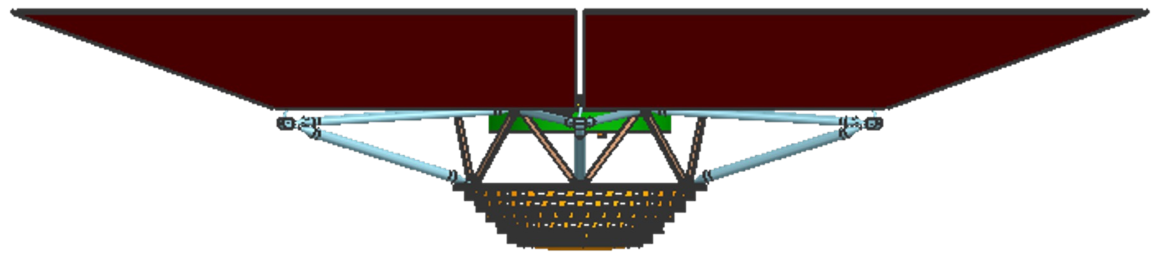
Drag skirt deployment
Mach < 0.9



Heatshield Jettison
> 4 s after drag skirt



Landing
Impact speed < 50 m/s
Assumed spherical Mars



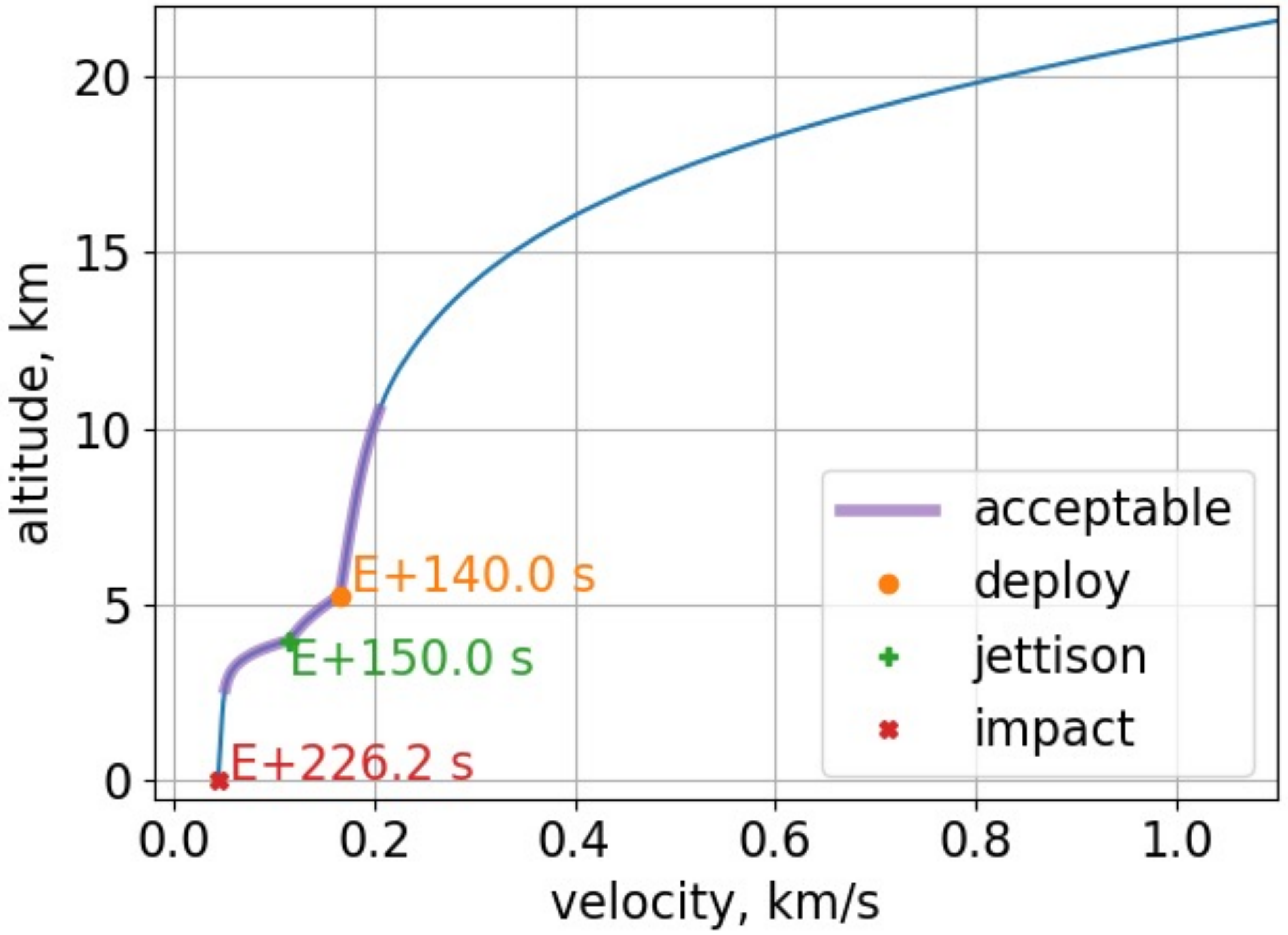
SHIELD images: Giersch et. al, 2022

Nominal Event Timing

- Constraints define range of acceptable event times
- Select nominal values for EFPAs of: $-12°, -18°, -24°$

Table 1: Summary of SHIELD EDL requirements

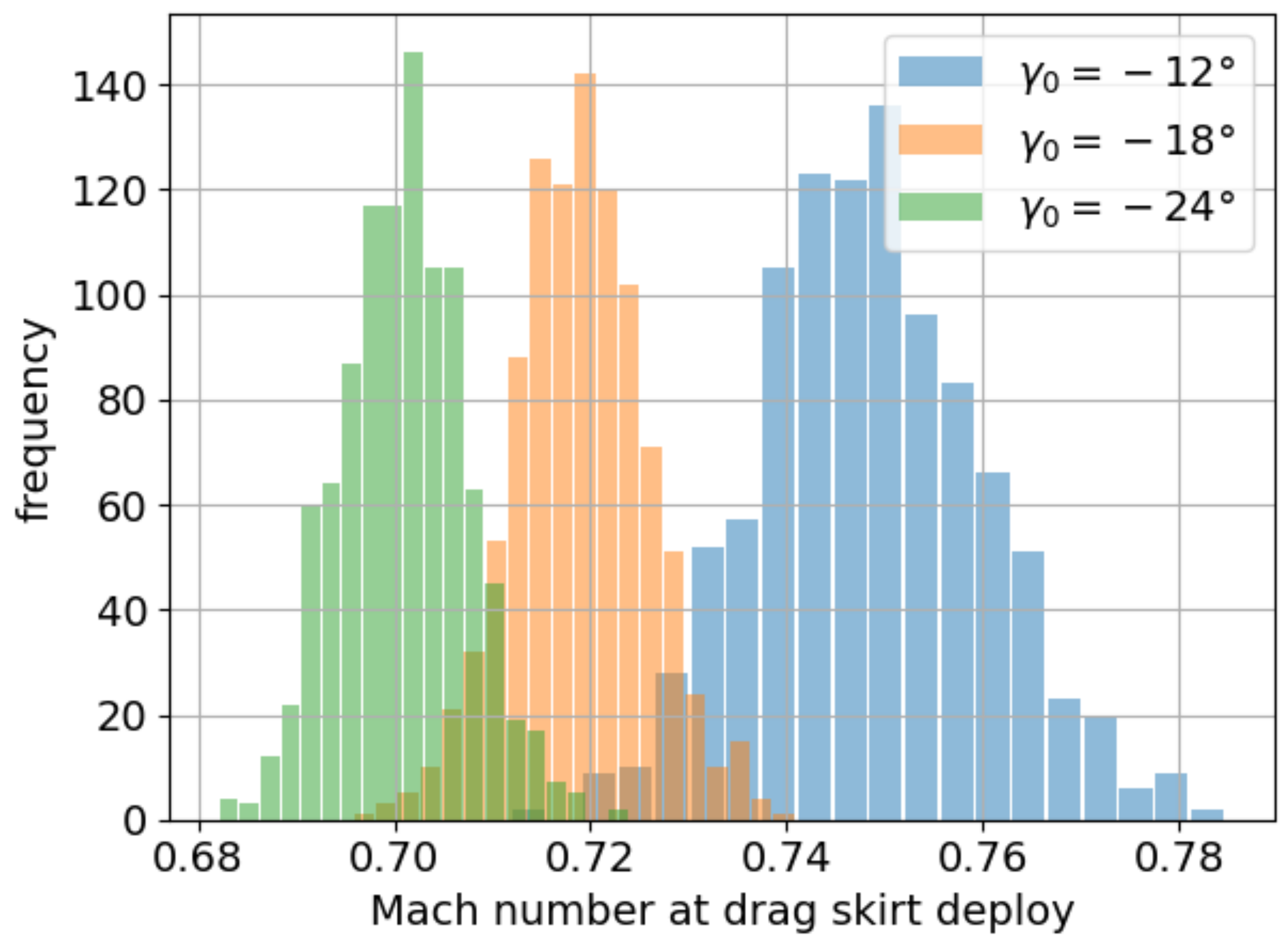
Parameter	Requirement
Mach number at drag skirt deployment	≤ 0.9
Time between drag skirt deployment and heatshield jettison	$\geq 4\,\mathrm{s}$
Impact velocity	$\leq 50\,\mathrm{m/s}$

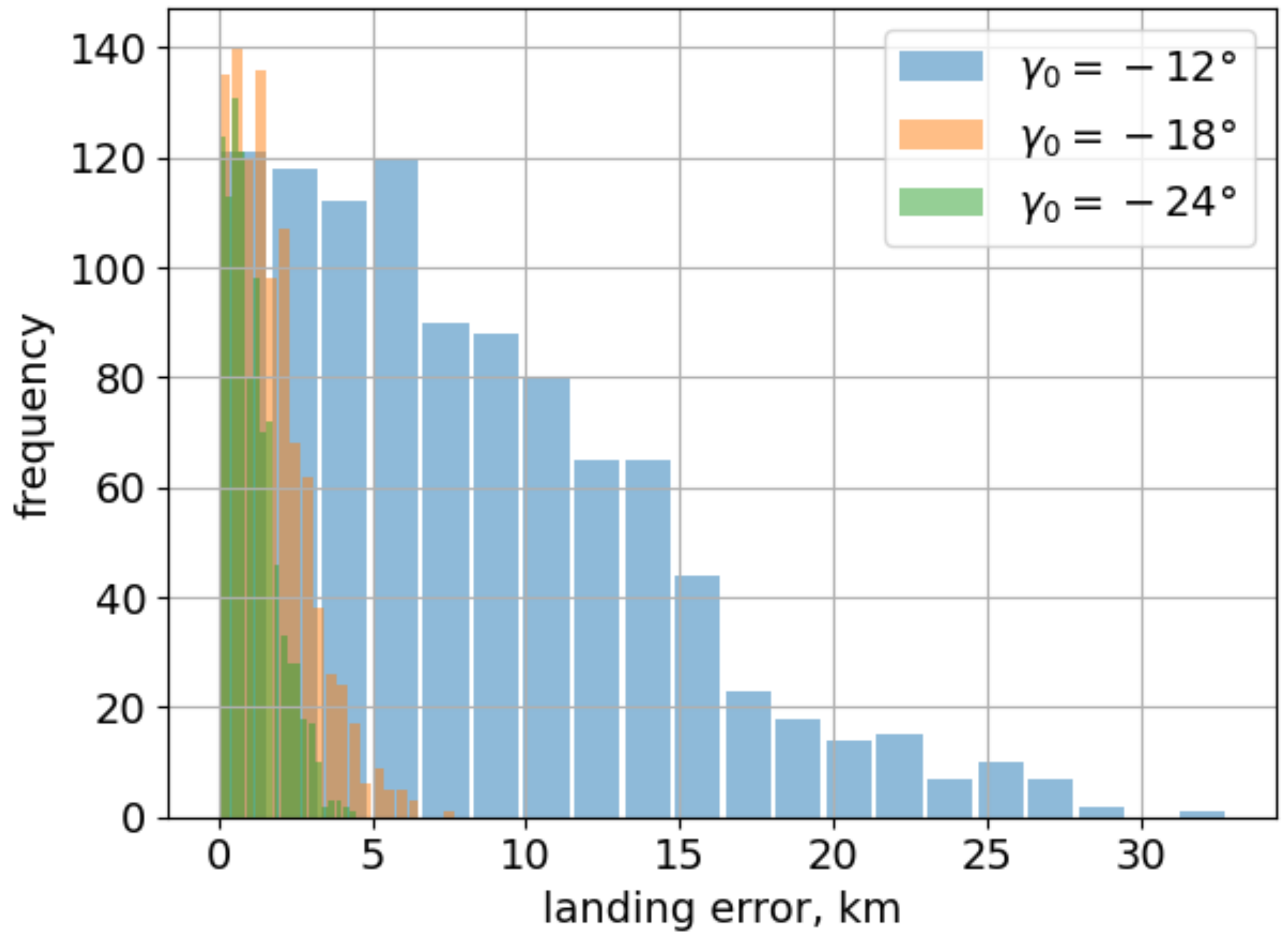


Uncertainty Quantification

- Apply representative uncertainties
  - EFPA: Gaussian, $3\sigma = 0.2°$
  - Velocity: Gaussian, $3\sigma = 2\ \mathrm{m/s}$
  - Density: 2010 Mars Global Reference Atmospheric Model (Mars GRAM)
  - Drag coefficient: Uniform, +/- 5%

A timer, triggered by deceleration threshold, is sufficient to command EDL events within requirements.





Drag skirt deployment only provides about 3 km of control authority, not enough to moderate downrange error*.

Regional Probe Networks

Assumptions

- **Precision landing not required, but network should achieve desired distribution**
- Probes are co-delivered by a single carrier spacecraft on an entry trajectory
- Probes separate from the carrier mechanically within 20 days of entry
- For regional networks, assume EFPA of -12 deg

Parameter	Dispersion
atmospheric density ρ	MarsGRAM
entry velocity magnitude V_0	$3\sigma = 2\text{m/s}$
entry flight-path angle γ_0	$3\sigma = 0.2°$
probe ballistic coefficient β	±5%
jettison speed V_j	±10%

Linearized Targeting

- Linearize relationship between jettison velocity $\boldsymbol{V_j}$ and changes in landing site coordinates $\Delta \boldsymbol{x}_{\boldsymbol{\theta\phi}}$

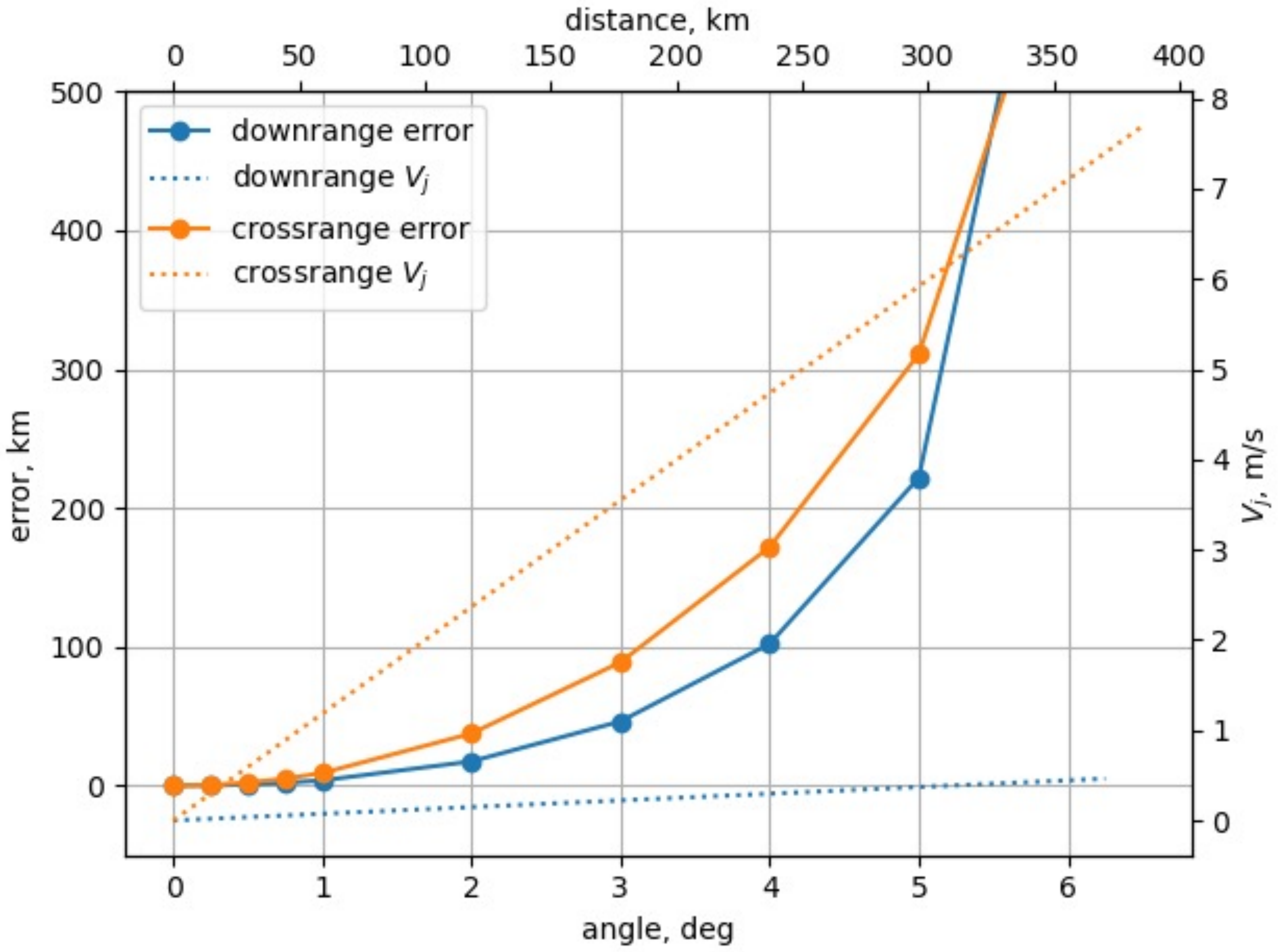
- Numerically evaluate Jacobian

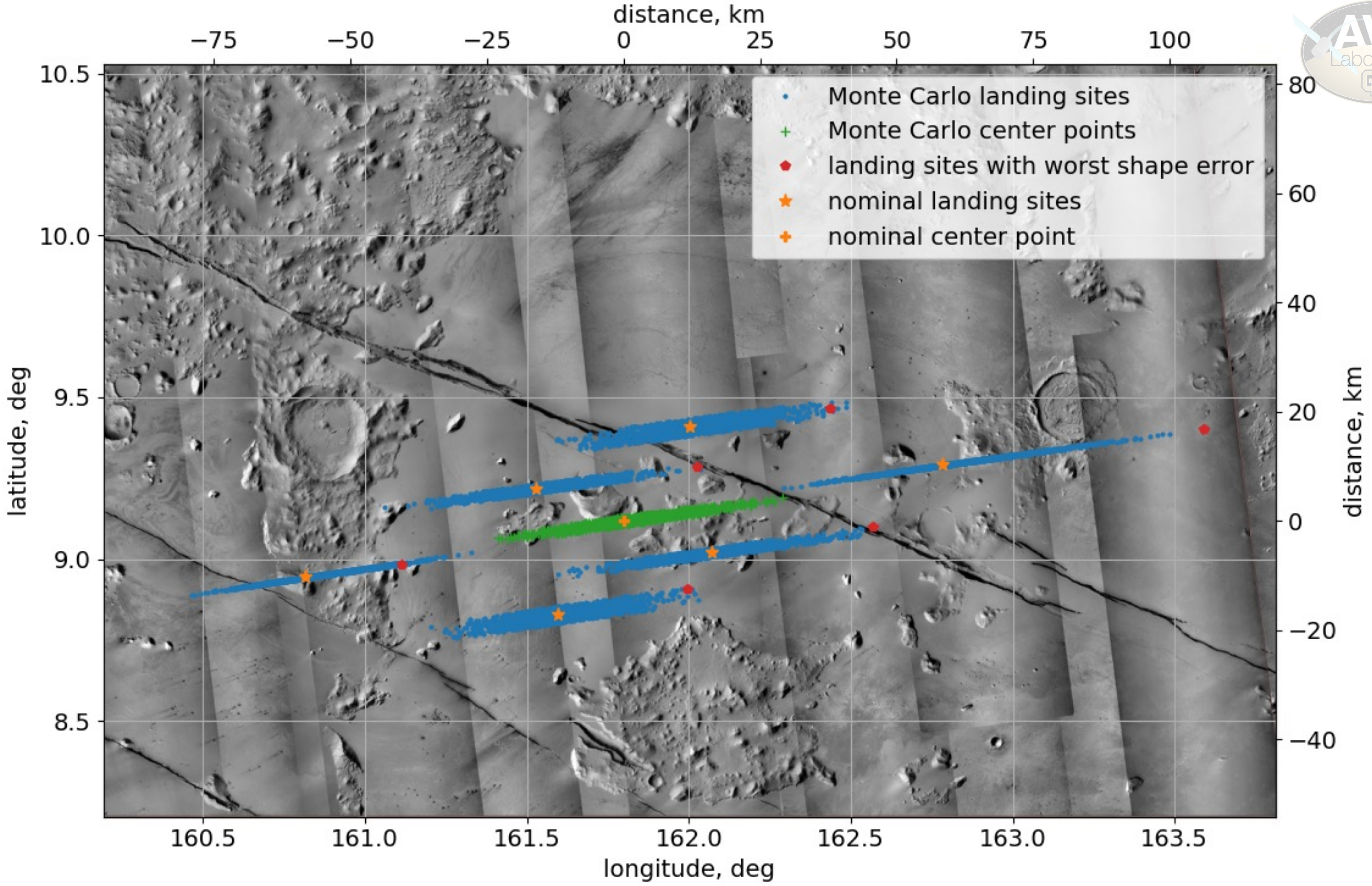
- Take least-norm solution to solve for jettison velocity given desired change in landing site

- Works well for separations < ~100 km, fails for larger separations

$$\Delta \boldsymbol{x}_{\theta\phi} \approx \left.\frac{\partial \boldsymbol{x}_{\theta\phi}}{\partial \boldsymbol{V}}\right|_{*} \boldsymbol{V}_j = [\boldsymbol{J}]\boldsymbol{V}_j \qquad [\boldsymbol{J}] = \begin{bmatrix} \frac{\partial\theta}{\partial V_x} & \frac{\partial\theta}{\partial V_y} & \frac{\partial\theta}{\partial V_z} \\ \frac{\partial\phi}{\partial V_x} & \frac{\partial\phi}{\partial V_y} & \frac{\partial\phi}{\partial V_z} \end{bmatrix}_{*}$$

$$\boldsymbol{V}_j = [\boldsymbol{J}]^T \left([\boldsymbol{J}][\boldsymbol{J}]^T\right)^{-1} \Delta \boldsymbol{x}_{\theta\phi}$$





distance, km
−75
−50
−25
0
25
50
75
100
10.5
10.0
9.5
9.0
8.5
latitude, deg
80
60
40
20
0
−20
−40
distance, km
160.5
161.0
161.5
162.0
162.5
163.0
163.5
longitude, deg
Monte Carlo landing sites
Monte Carlo center points
landing sites with worst shape error
nominal landing sites
nominal center point

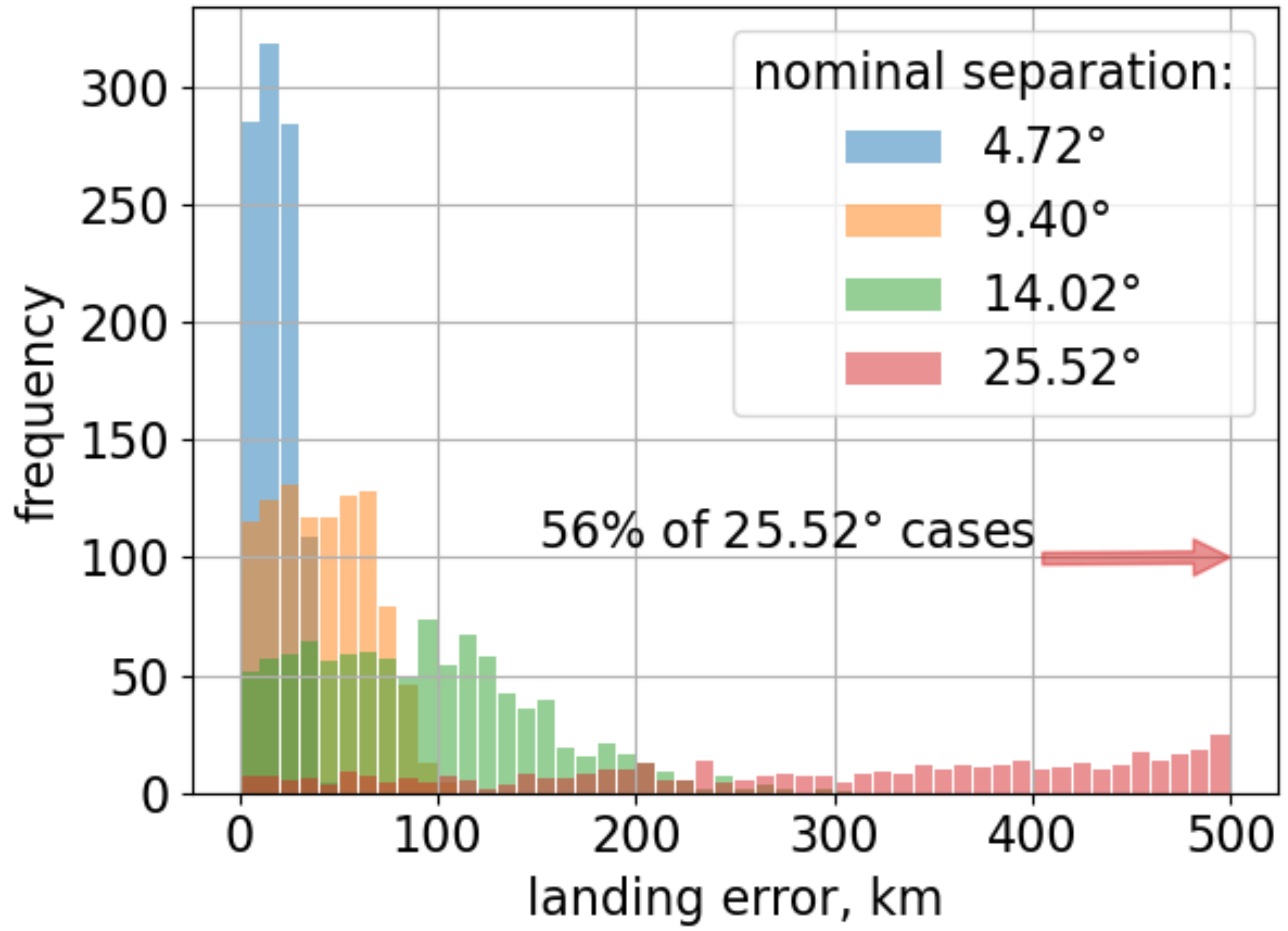
Large-Scale Probe Networks

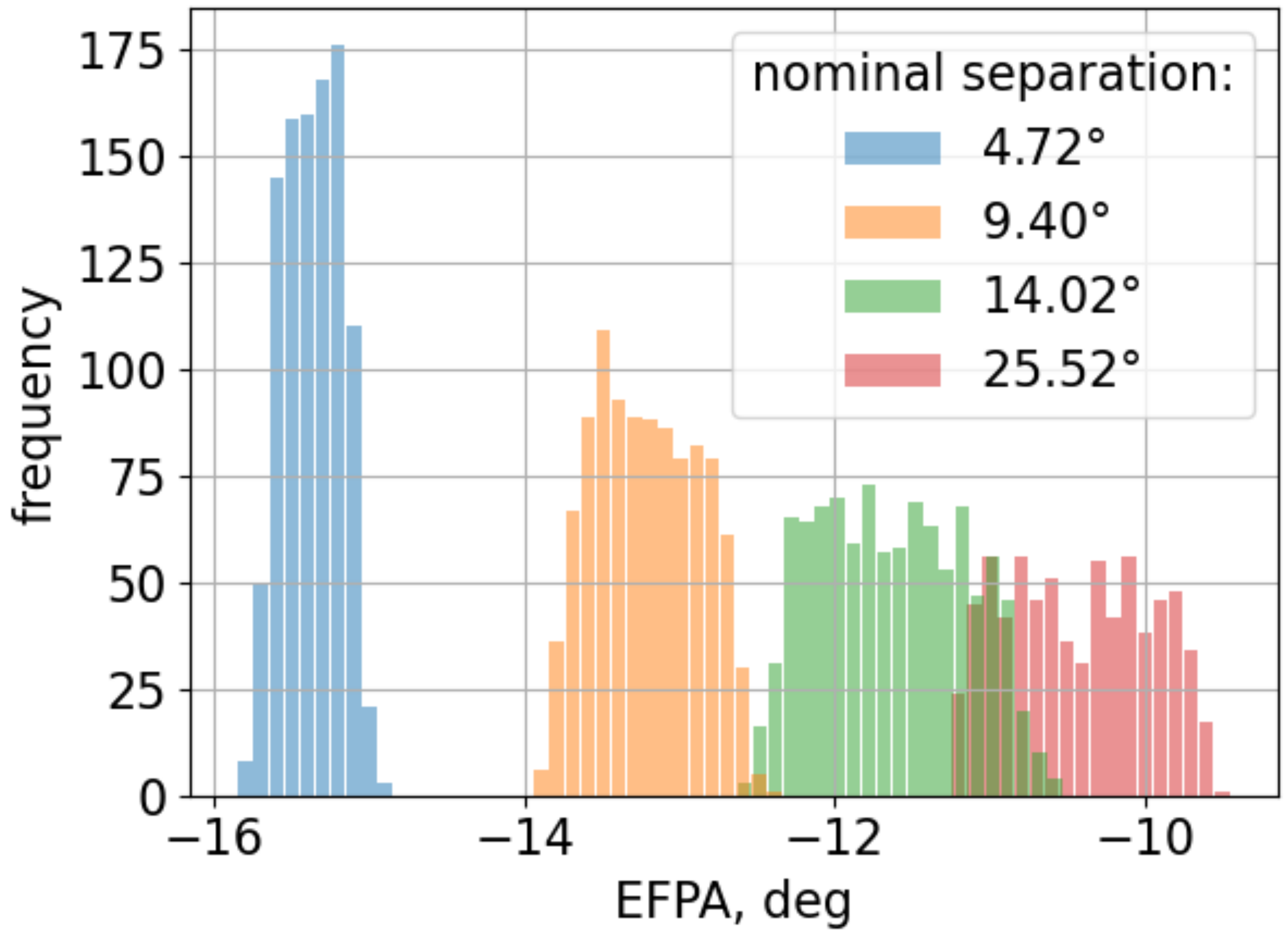
Large-Scale Networks Setup

- Carrier entry flight-path angle of -18 deg
- Target sites with increasing offsets in along-track and cross-track
  - 5, 10, 15, 25 deg along-track
  - 5, 10, 15, 30 deg cross-track
- Numerical nonlinear optimizer generates jettison velocities at fixed times
  - E-3 days for along-track
  - E-18 days for cross-track
- Quantify error when applying maneuver under uncertainty
- Same assumptions as before
- Targeting trade study plots in backup slides

Monte Carlo Analysis: Along-Track Performance

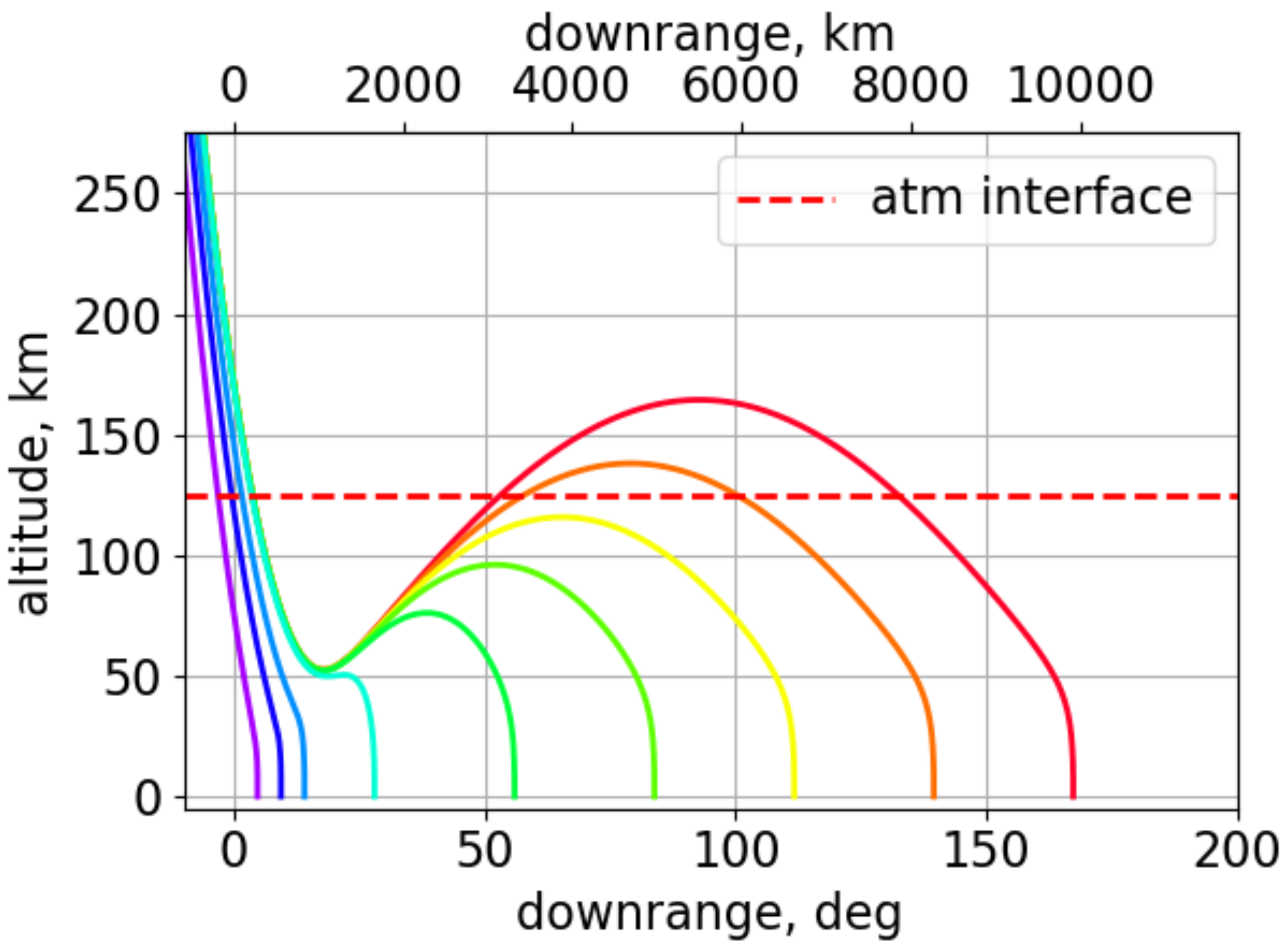
- Separation 3 days before entry, carrier EFPA of -18 deg
- 29% of the 25.52 deg cases miss the planet entirely!
- Shallow EFPA, long coast time → high sensitivity to error



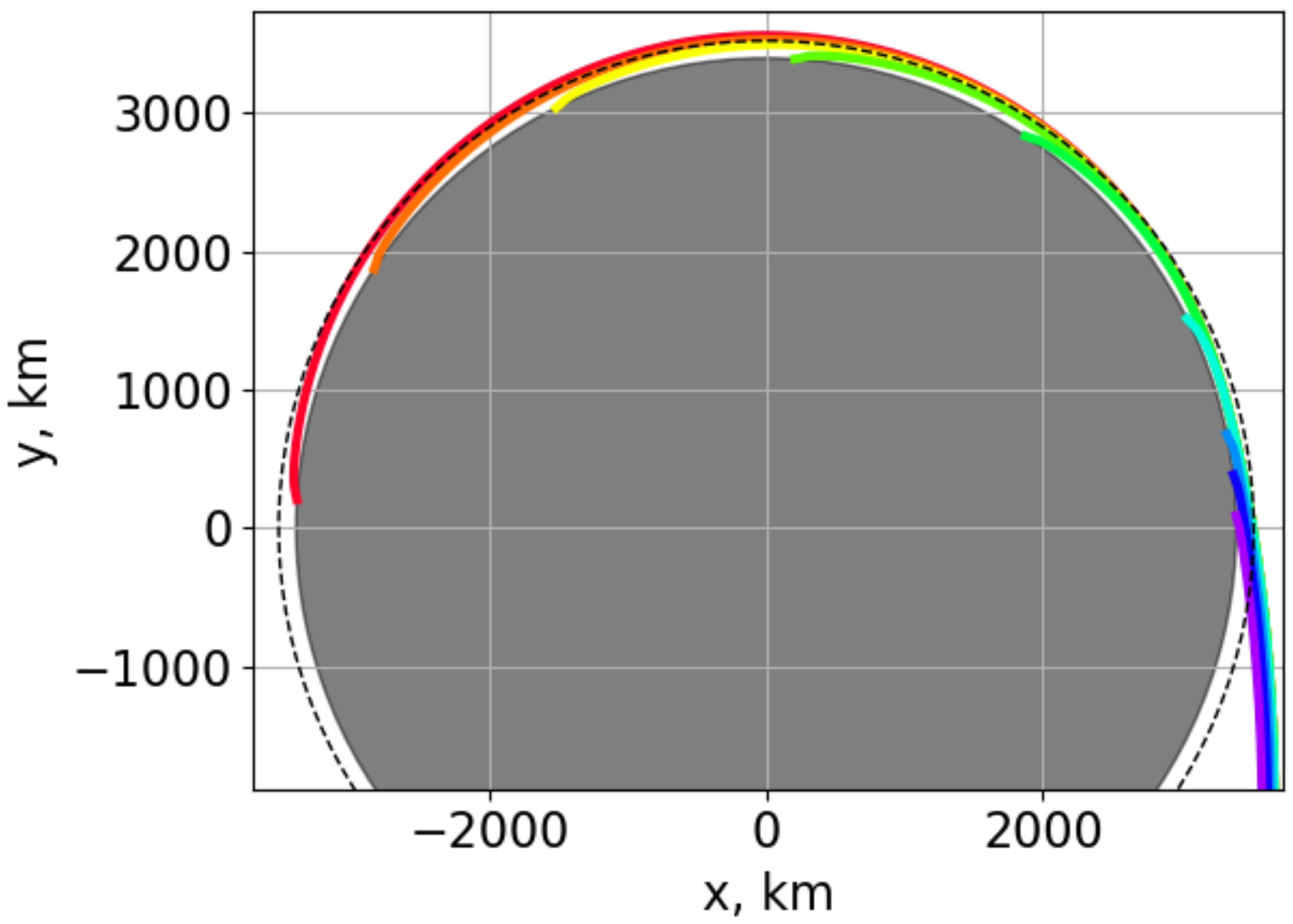


Along-Track Separation Trajectories

- Along-track separation 3 days before entry, -18 deg EFPA



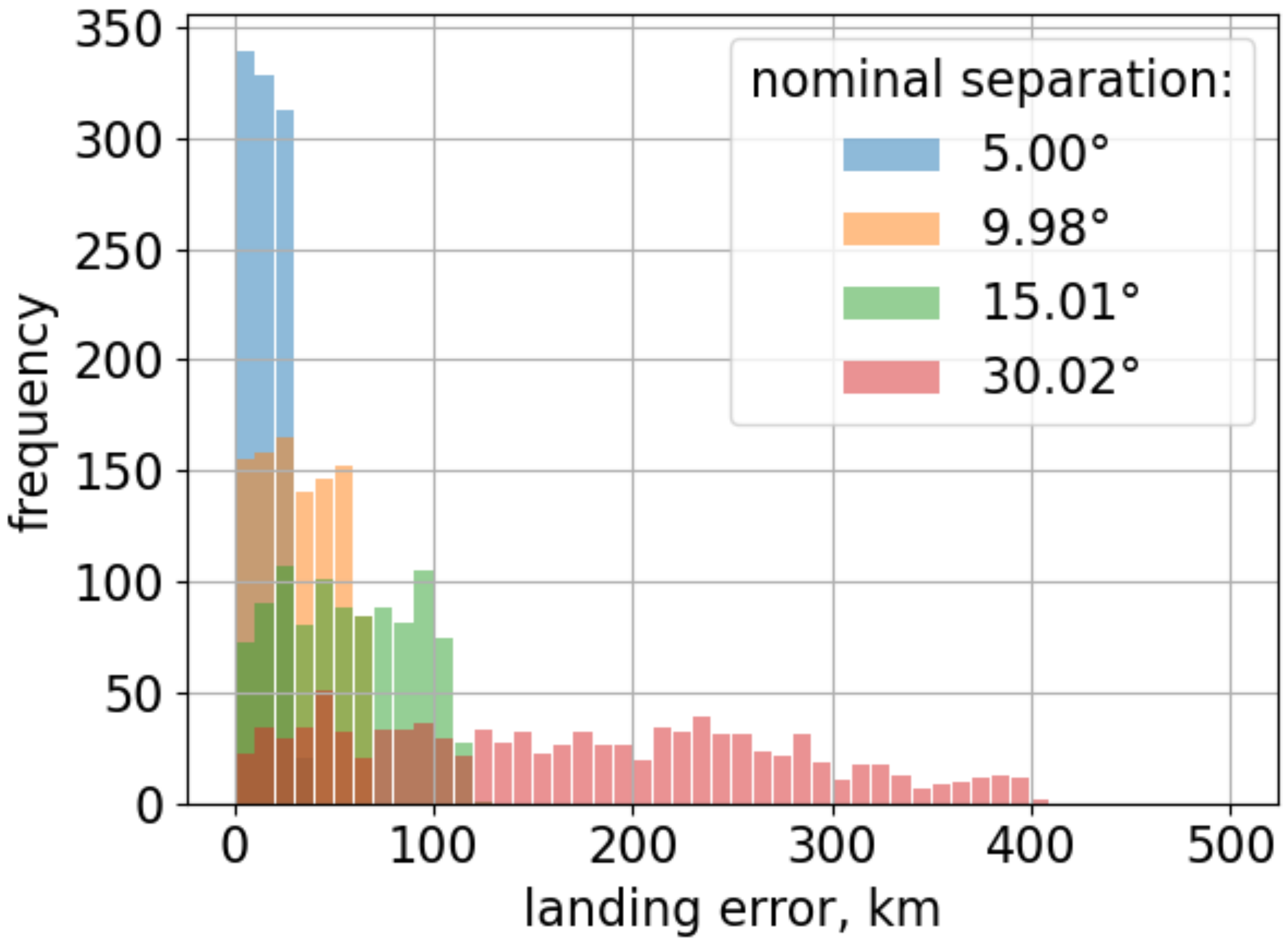
Altitude vs. downrange

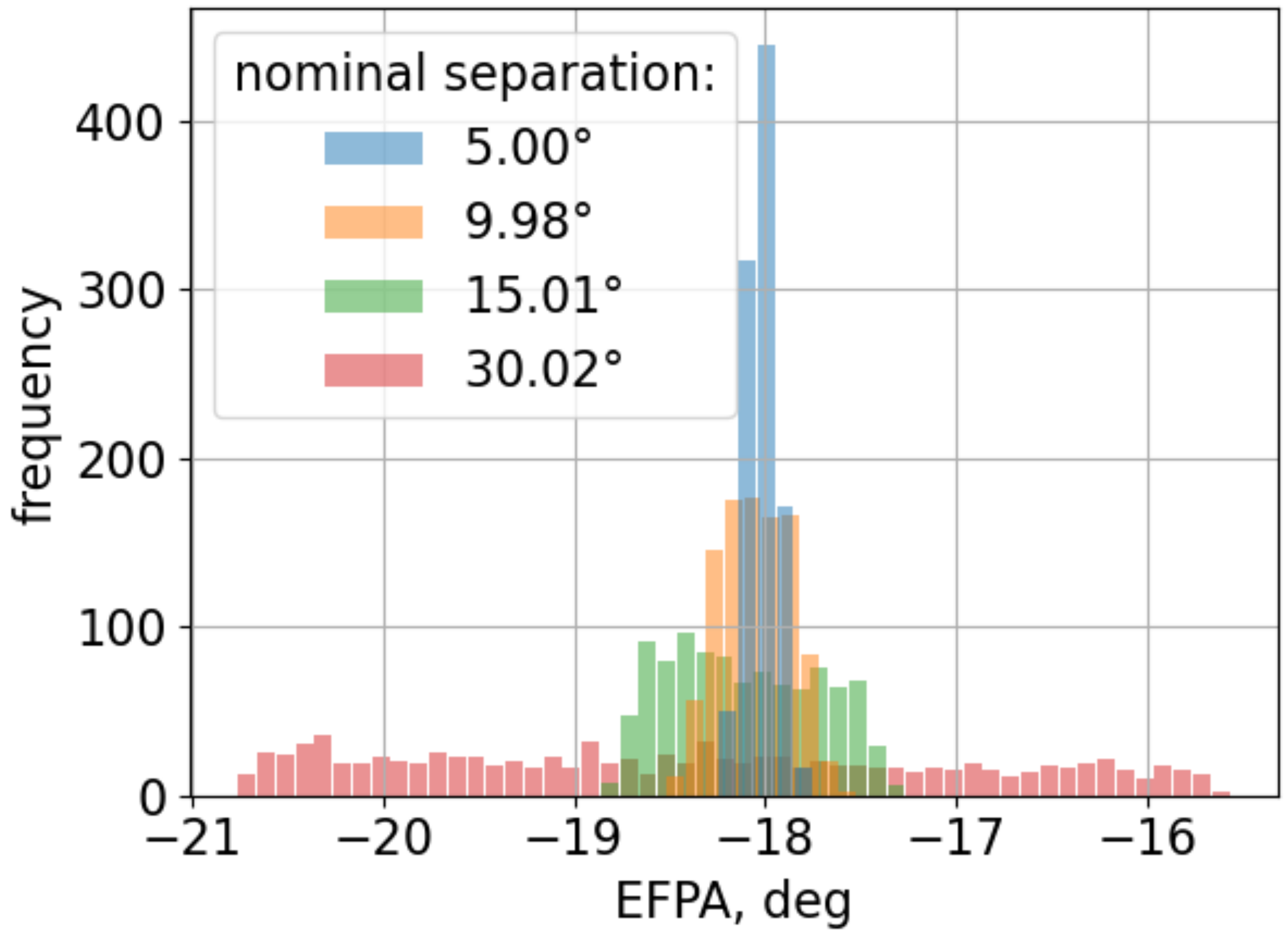


View down from North pole, inertial

Monte Carlo Analysis: Cross-Track Performance

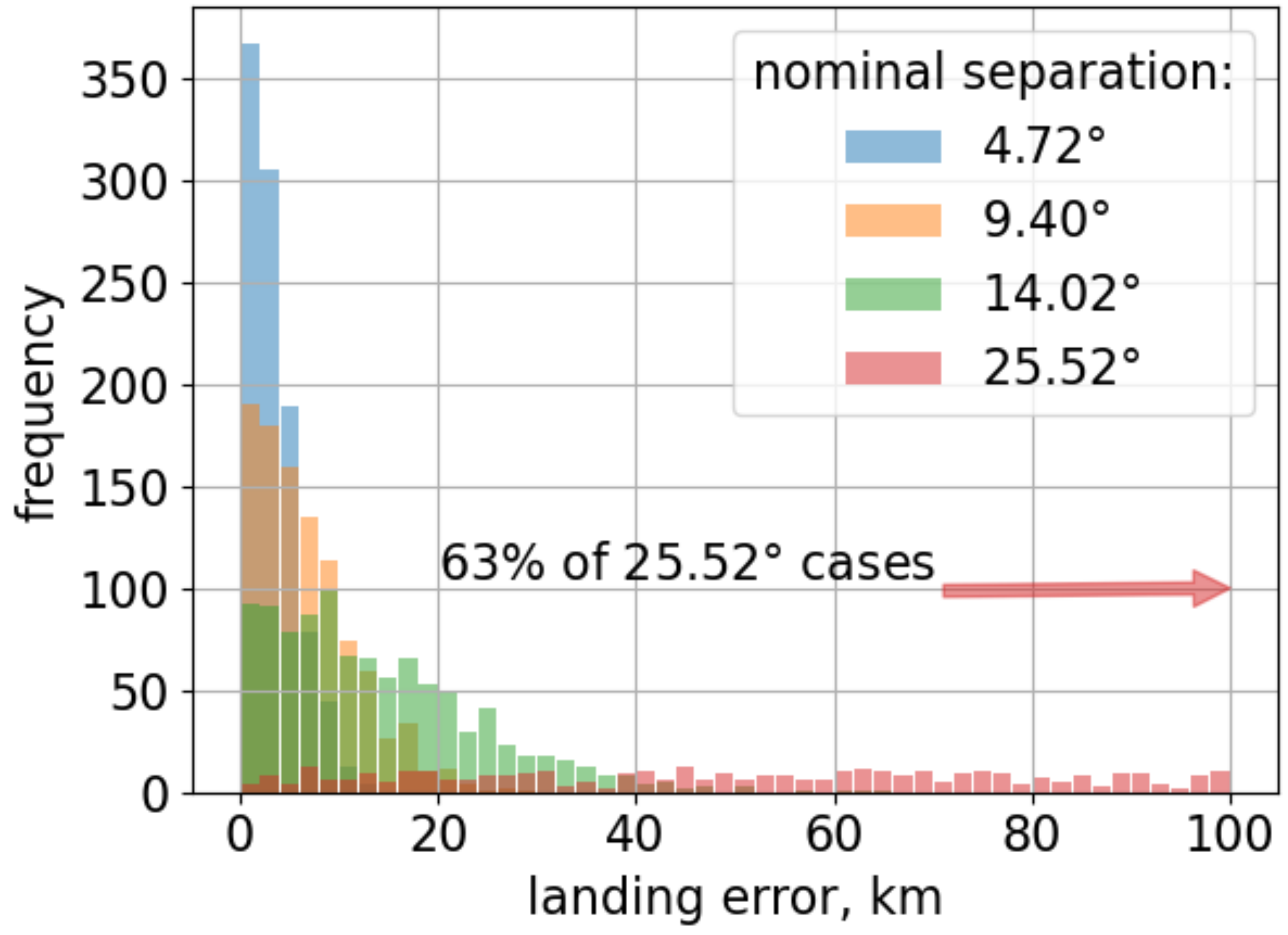
- Separation 18 days before entry, carrier EFPA of -18 deg
- Lower error across the board, no cases miss the planet
- Larger maneuver → large EFPA dispersions → large landing error



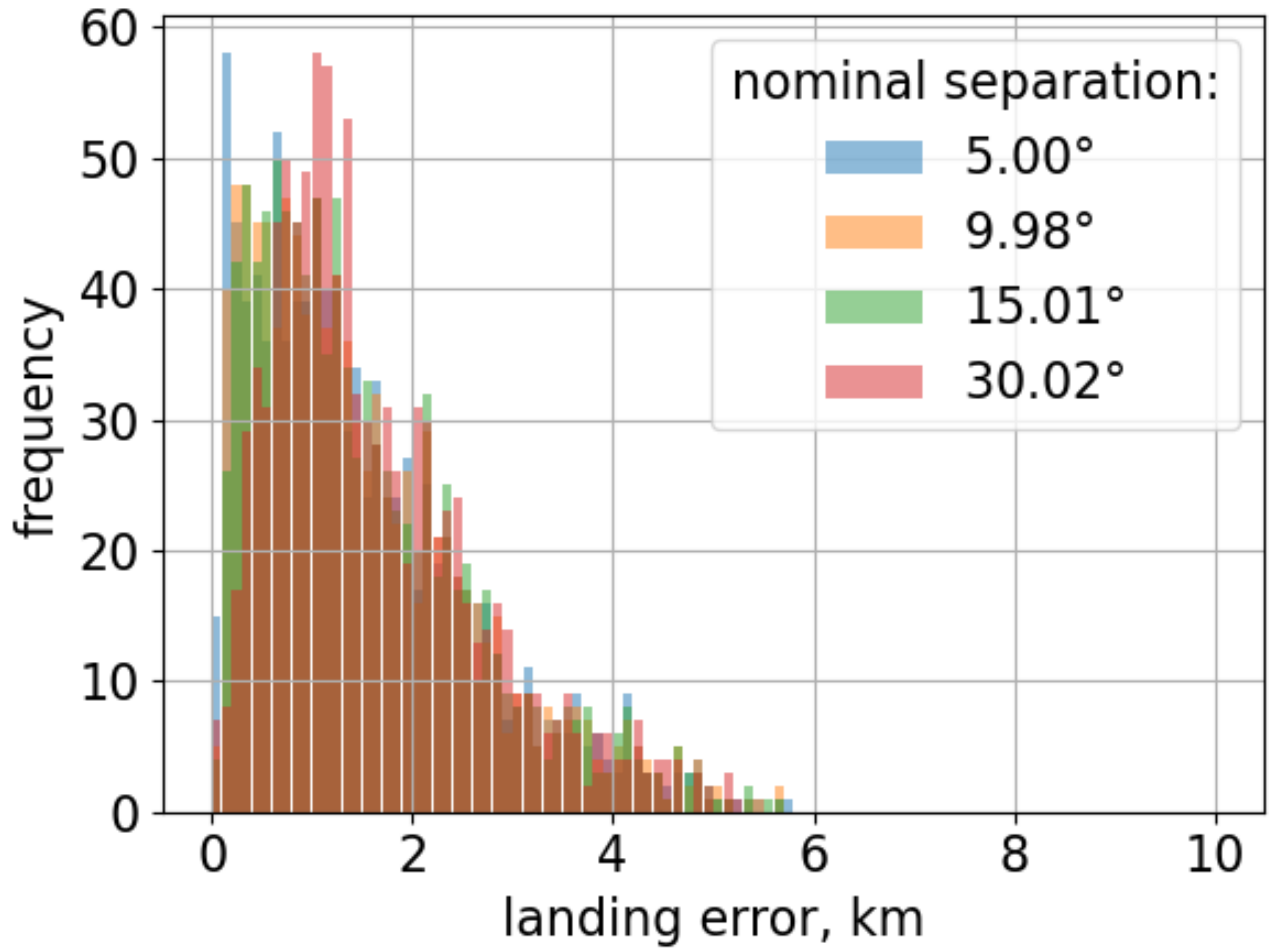


Monte Carlo Analysis: Perfect Maneuver Execution

- Remove maneuver dispersions, all else equal
- Along-track: no cases miss planet, 25.52 deg case still performs terribly, other cases reasonable
- Cross-track: all cases perform well, consistent with nominal single-probe analysis



Along-track performance



Cross-track performance

Conclusions

Conclusions

- Co-delivery of a network of small rough landers is a promising architecture for low-cost Mars missions
- Under current assumptions, SHIELD has ample margin to rely on time-triggered EDL events
- Within about 100 km, maneuver design is approximately linear and probes can be passively co-delivered to a consistent network shape
- In the 100-1000 km range (up to about 15 deg separation), maneuver design is nonlinear but probes can still be passively delivered with rough accuracy
- Above about 1000 km, the generated trajectories become too sensitive for passive targeting
- Other approaches:
  - Significantly reduce expected maneuver (jettison) execution error
  - Allow carrier spacecraft to perform multiple maneuvers during approach, allow separation earlier than 20 days
  - Multiple carrier spacecraft
  - When optimizing, avoid long atmospheric coast phases and constrain range of probe EFPAs

References & Acknowledgements

This work was supported by a NASA Space Technology Research Fellowship. Grateful acknowledgement to: the SHIELD team at JPL including Louis Giersch, Nathan Barba, Ryan Woolley, and Chad Edwards, and other participants in the Revolutionizing Access to the Martian Surface workshop organized by the W. M. Keck Institute for Space Studies and the Low-Cost Science Mission Concepts for Mars Exploration workshop.

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- L. Giersch, N. J. Barba, V. Cormarkovic, M. Delapierre, M. Golombek, N. Williams, R. C. Woolley, M. Lobbia, E. Sklyanskiy, R. Burke, “SHIELD: A New Low-Cost Architecture for Deliverying Science Payloads to the Surface of Mars,” Low-Cost Science Mission Concepts for Mars Exploration Workshop, 2022.


Questions?
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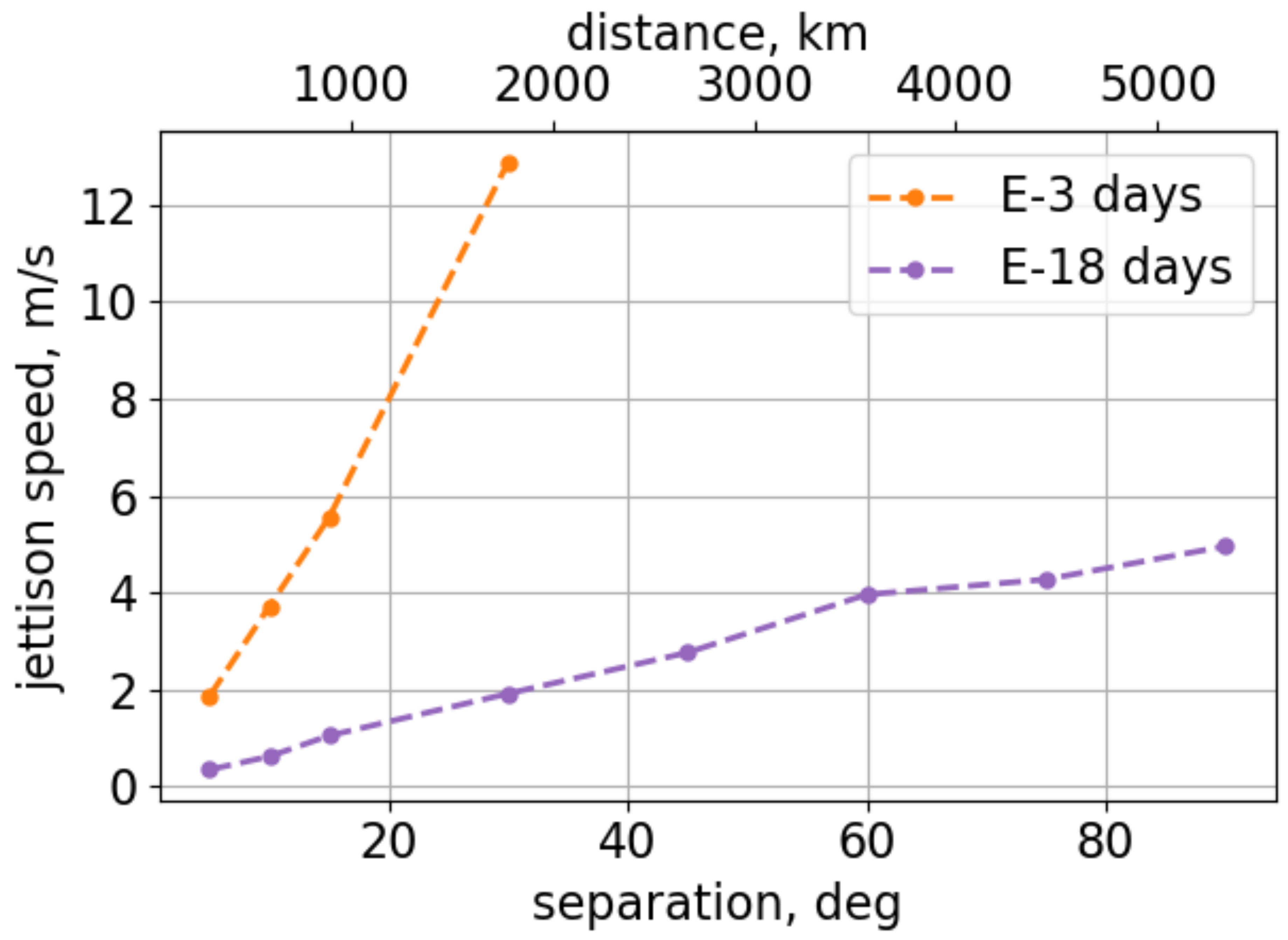
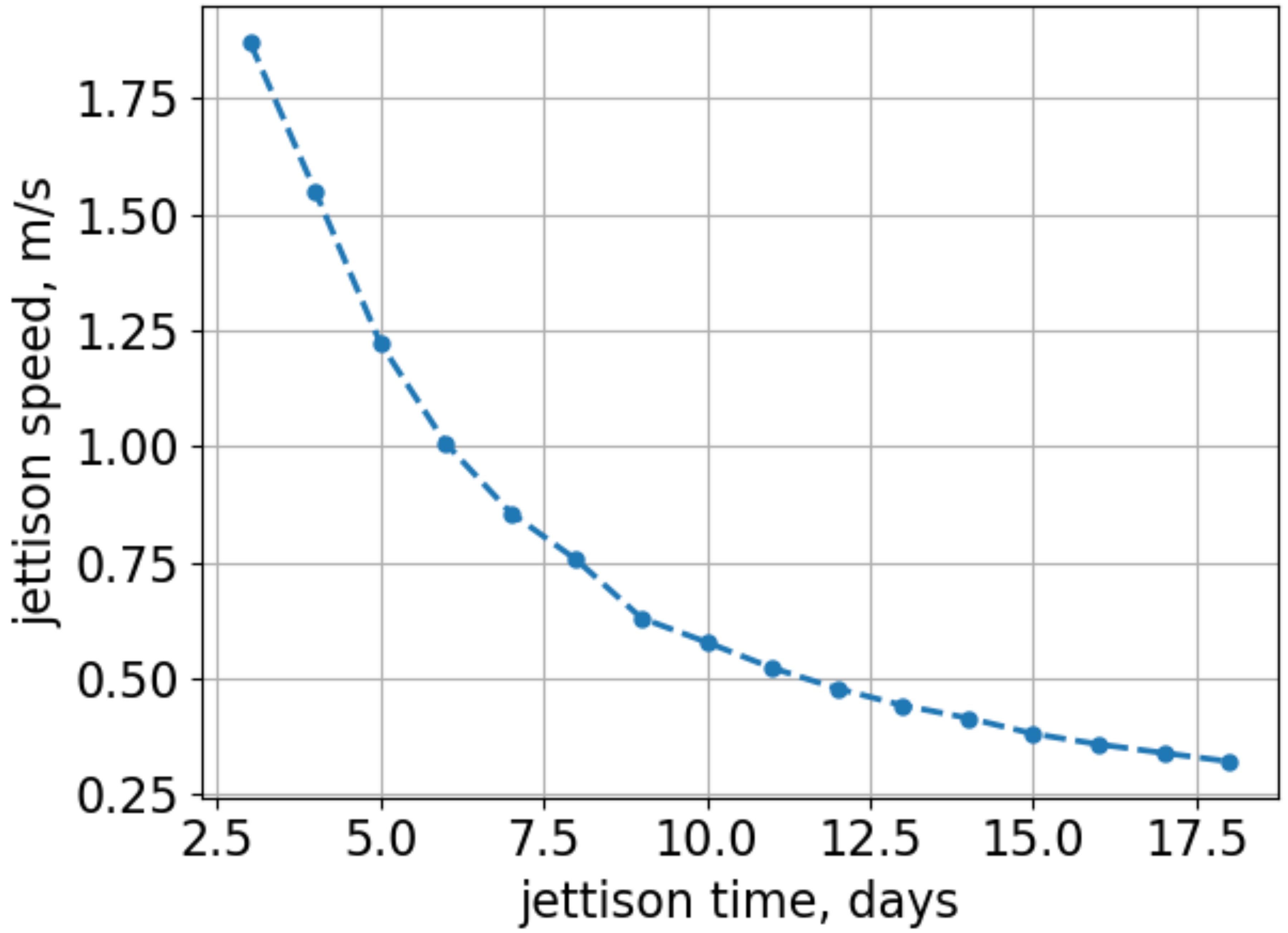
Backup

Varying Separation Timing

- Cross-track separation, EFPA of -18 deg



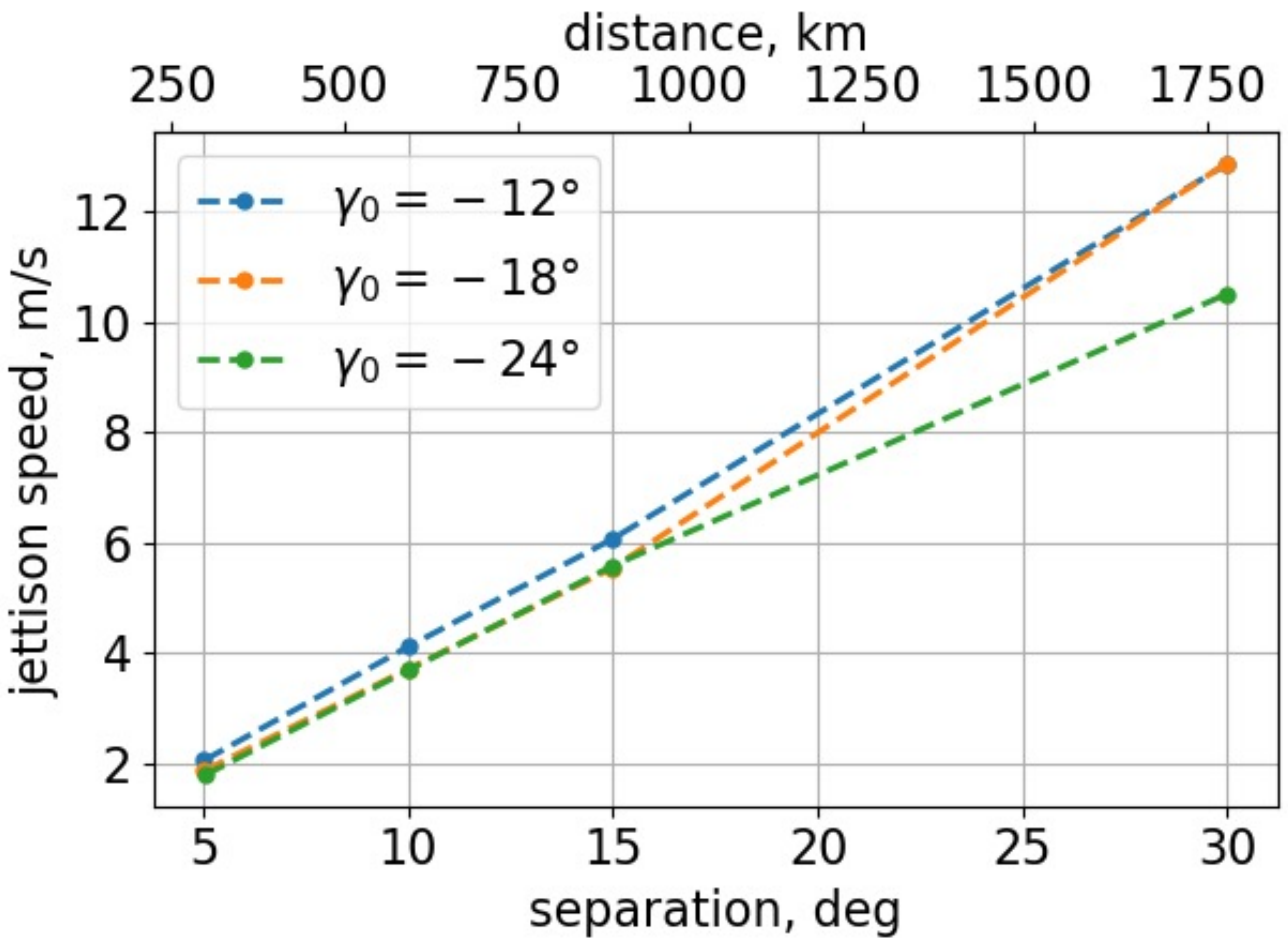
Varying cross-track separation



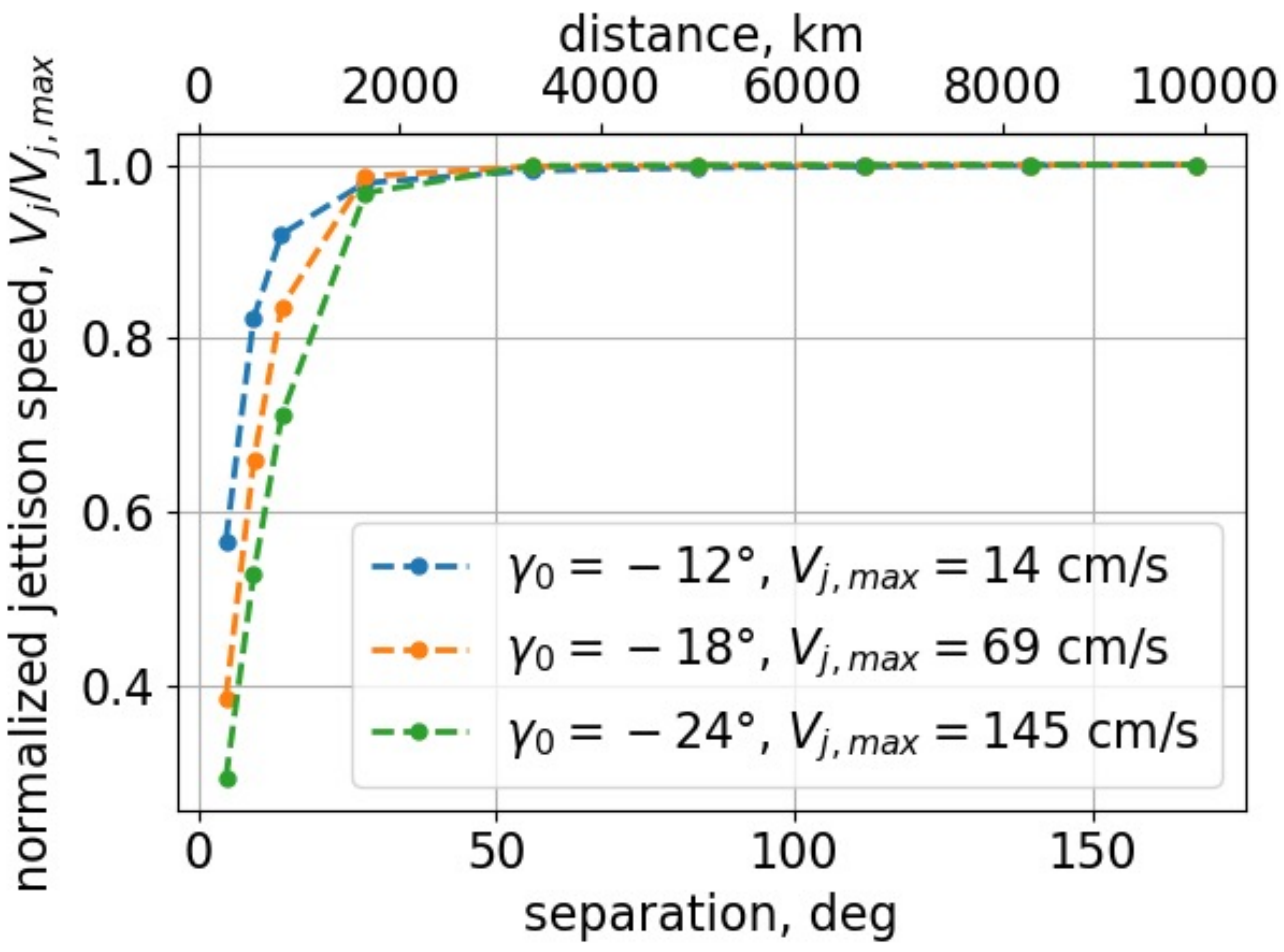
5 deg cross-track separation

Varying Separation Distance

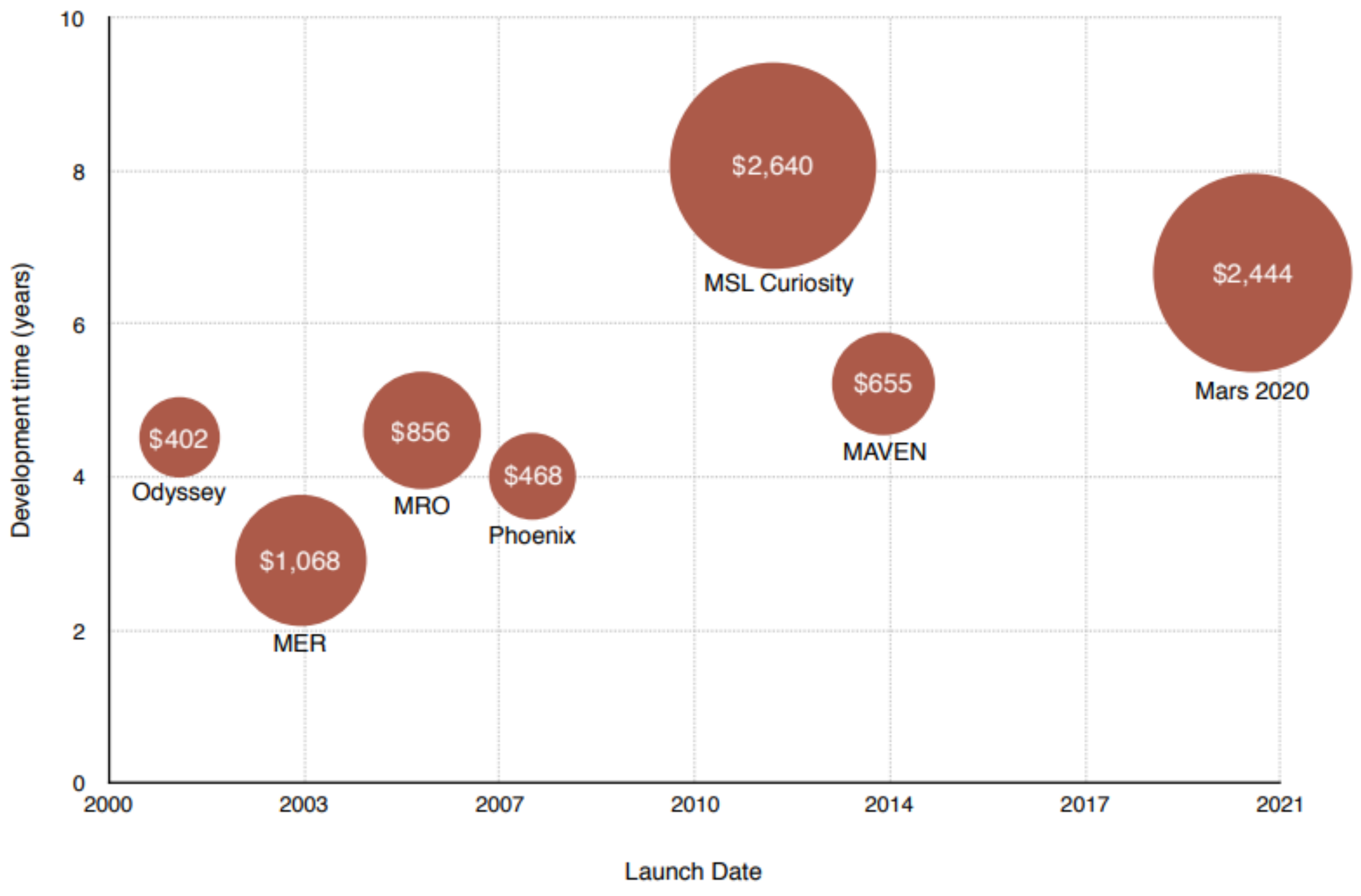
- Separation 3 days before entry



Cross-track separation



Along-track separation

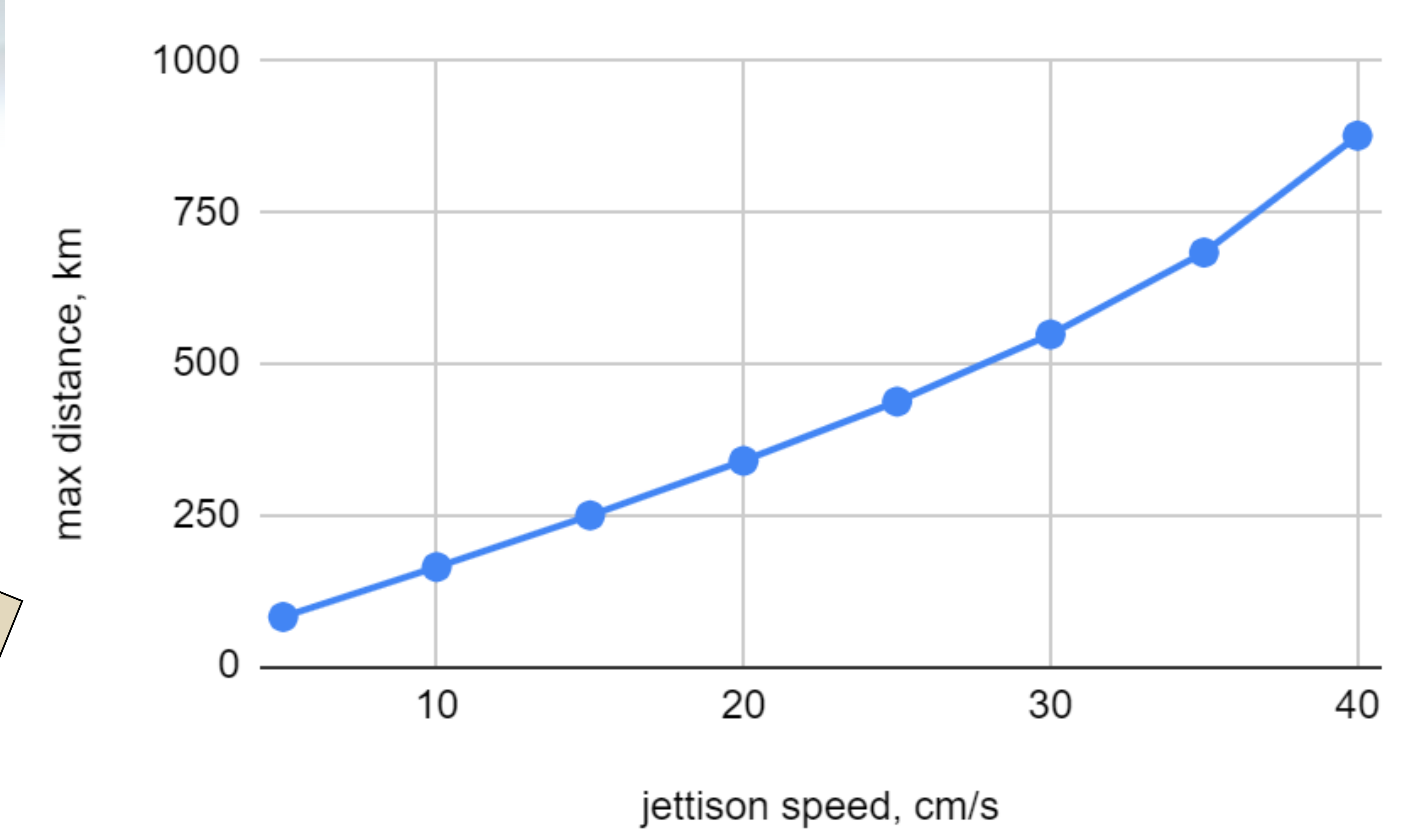


10
8
6
4
2
0
Development time (years)
$2,640
MSL Curiosity
$2,444
Mars 2020
$655
MAVEN
$402
Odyssey
$856
MRO
$468
Phoenix
$1,068
MER
2000
2003
2007
2010
2014
2017
2021
Launch Date

Two-Decade Vision for Mars Exploration
Telecom Infrastructure
Hard Lander Network
Fixed Landers
Mobility
Humans

Linear Relationship → Linearized Targeting

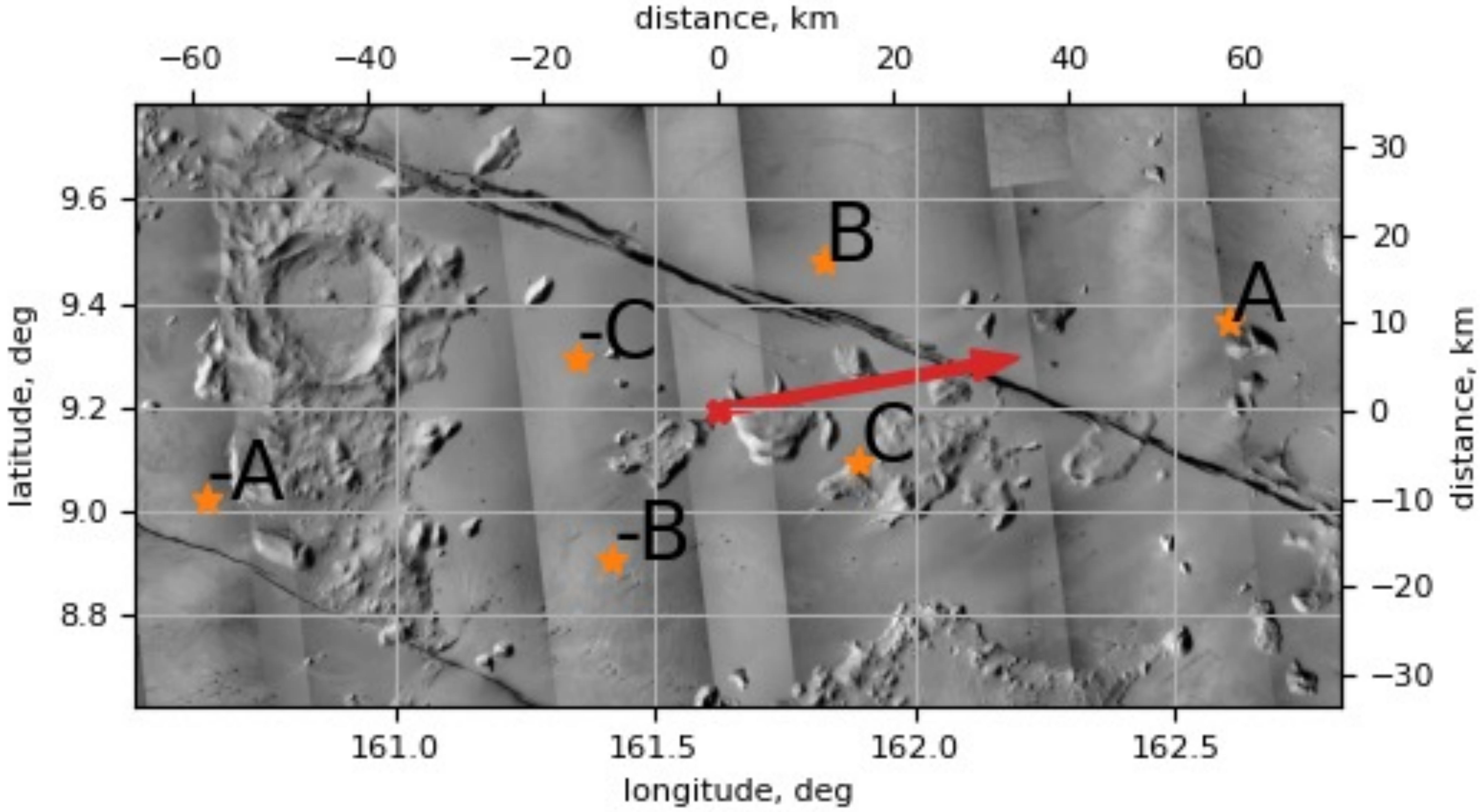
V_j, cm/s	Separation Time, days	Minimum Distance, km	Maximum Distance, km
5	E-1	5.014	81.315
10	E-0.25	2.697	42.767
10	E-0.5	5.159	83.072
10	E-1	10.028	163.926
10	E-2	19.710	334.440
10	E-3	29.366	534.907
15	E-1	15.042	249.332
20	E-1	20.056	339.516
25	E-1	25.070	437.490
30	E-1	30.083	548.555
35	E-1	35.096	684.054
40	E-1	40.108	877.297

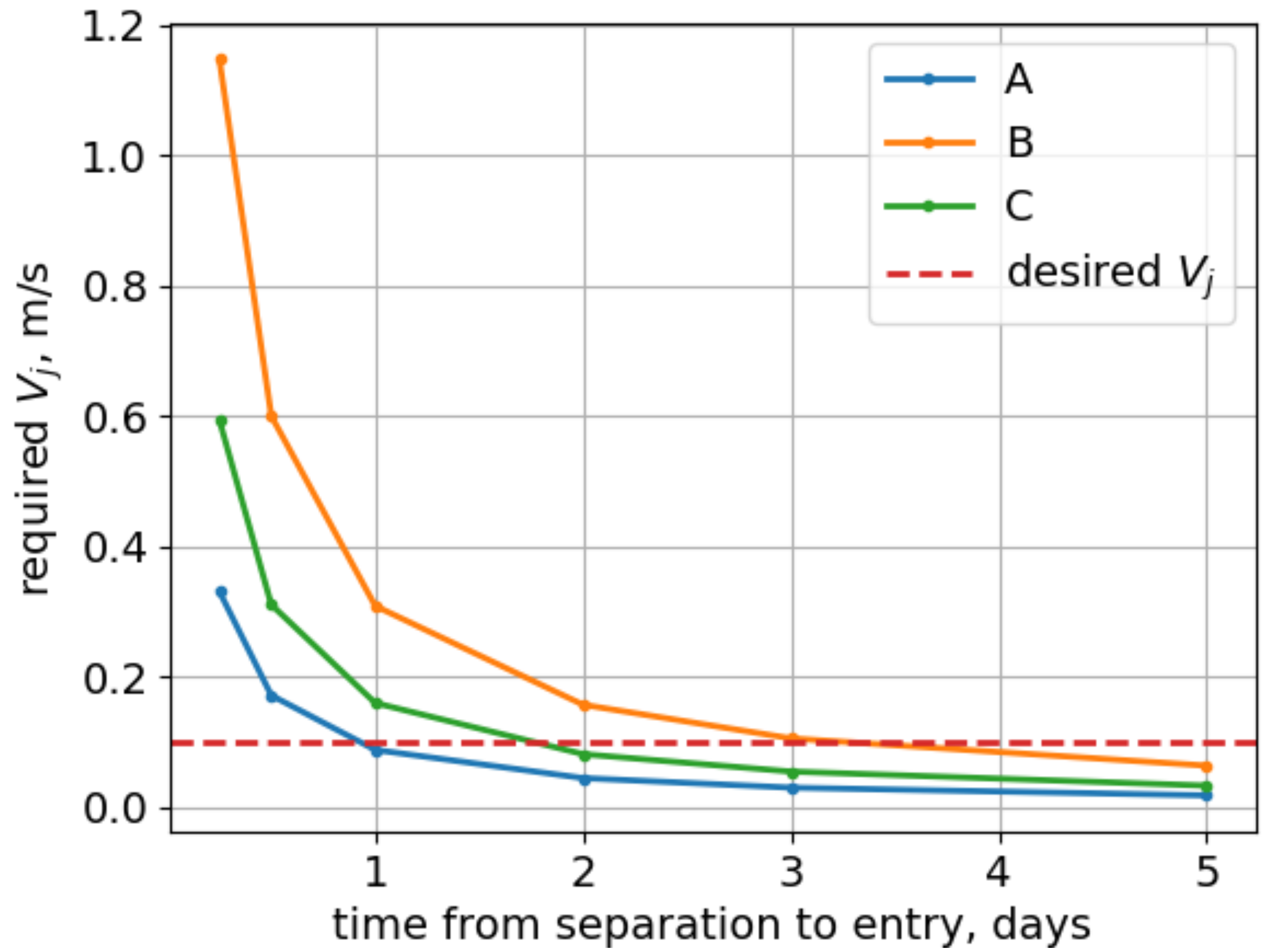


$$\Delta \boldsymbol{x}_{\theta\phi} \approx \left.\frac{\partial \boldsymbol{x}_{\theta\phi}}{\partial \boldsymbol{V}}\right|_{*} \boldsymbol{V}_j = [\boldsymbol{J}]\boldsymbol{V}_j \qquad [\boldsymbol{J}] = \begin{bmatrix} \frac{\partial\theta}{\partial V_x} & \frac{\partial\theta}{\partial V_y} & \frac{\partial\theta}{\partial V_z} \\ \frac{\partial\phi}{\partial V_x} & \frac{\partial\phi}{\partial V_y} & \frac{\partial\phi}{\partial V_z} \end{bmatrix}_{*}$$

$$\boldsymbol{V}_j = [\boldsymbol{J}]^T \left([\boldsymbol{J}][\boldsymbol{J}]^T\right)^{-1} \Delta \boldsymbol{x}_{\theta\phi}$$

Design of Example Network





Nominal Network Parameters and MC Dispersions

Table 2 Properties of nominal network, jettison velocity and timing, and nominal targeting error

pair	downrange, km	crossrange, km	$\hat{V}_j \cdot \hat{r}$, m s^{-1}	$\hat{V}_j \cdot \hat{\theta}$, m s^{-1}	$\hat{V}_j \cdot \hat{h}$, m s^{-1}	t_j, days	nominal errors, km
A	59.292	0	0.00826	0.893	0.450	0.821	3.095, 3.804
B	14.823	14.823	0.0152	0.392	0.920	3.136	0.804, 0.841
C	14.823	-8.558	-0.0153	0.108	-0.994	1.651	0.370, 0.399

Table 3 Monte Carlo analysis input dispersions

Parameter	Dispersion
atmospheric density ρ	MarsGRAM
entry velocity magnitude V_0	$3\sigma = 2$m/s
entry flight-path angle γ_0	$3\sigma = 0.2°$
probe ballistic coefficient β	±5%
jettison speed V_j	±10%

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Shape and Center Error Params Definitions

$$\varepsilon_c = \sqrt{(\bar{\theta}^* - \bar{\theta})^2 + (\bar{\phi}^* - \bar{\phi})^2}$$

$$\varepsilon_s = \frac{\sqrt{(\delta_1^* - \delta_1)^2 + \ldots + (\delta_d^* - \delta_d)^2}}{N}, \qquad d = \frac{N(N-1)}{2}$$

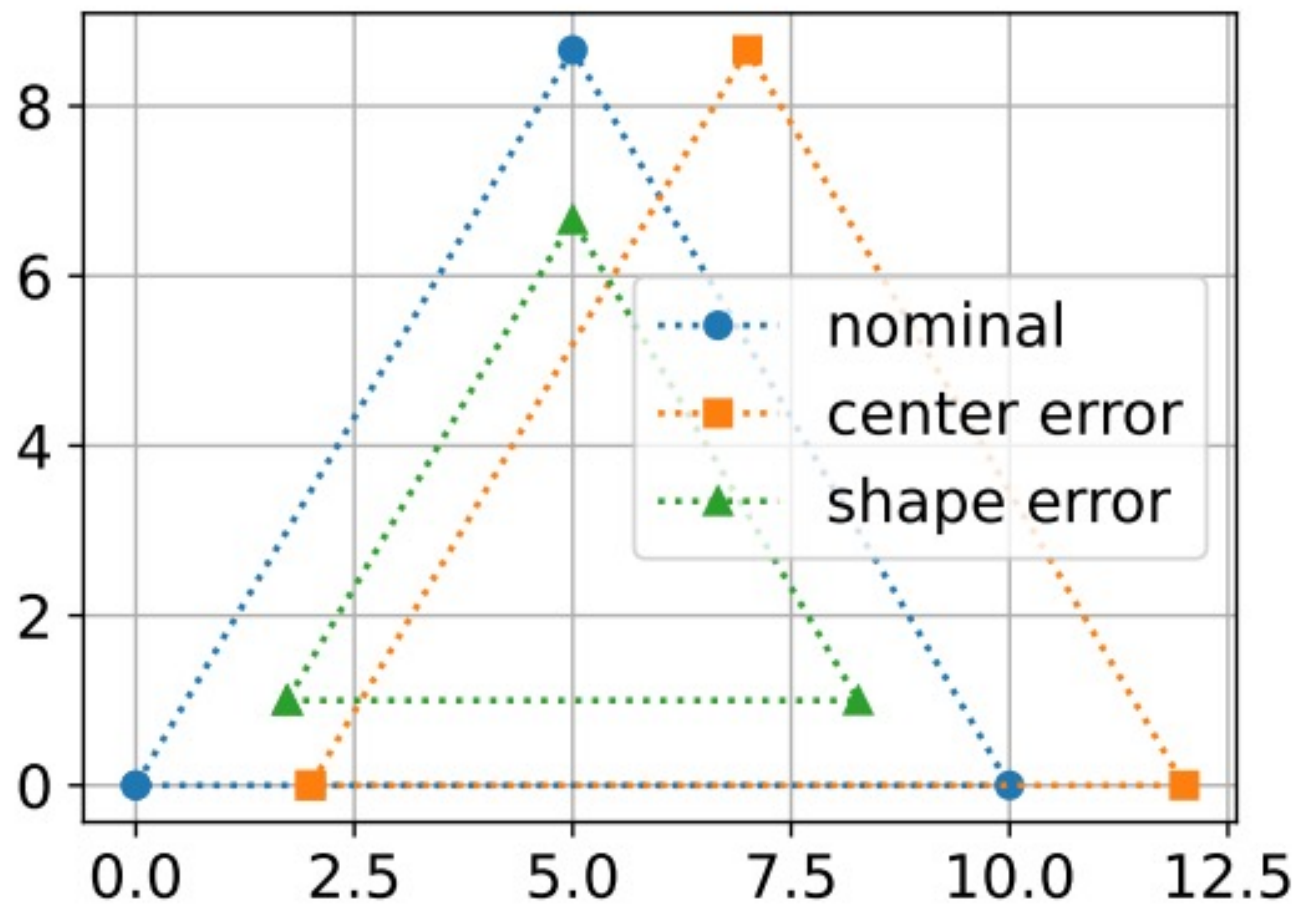


Fig. 7 Three example networks, illustrating center error vs. shape error

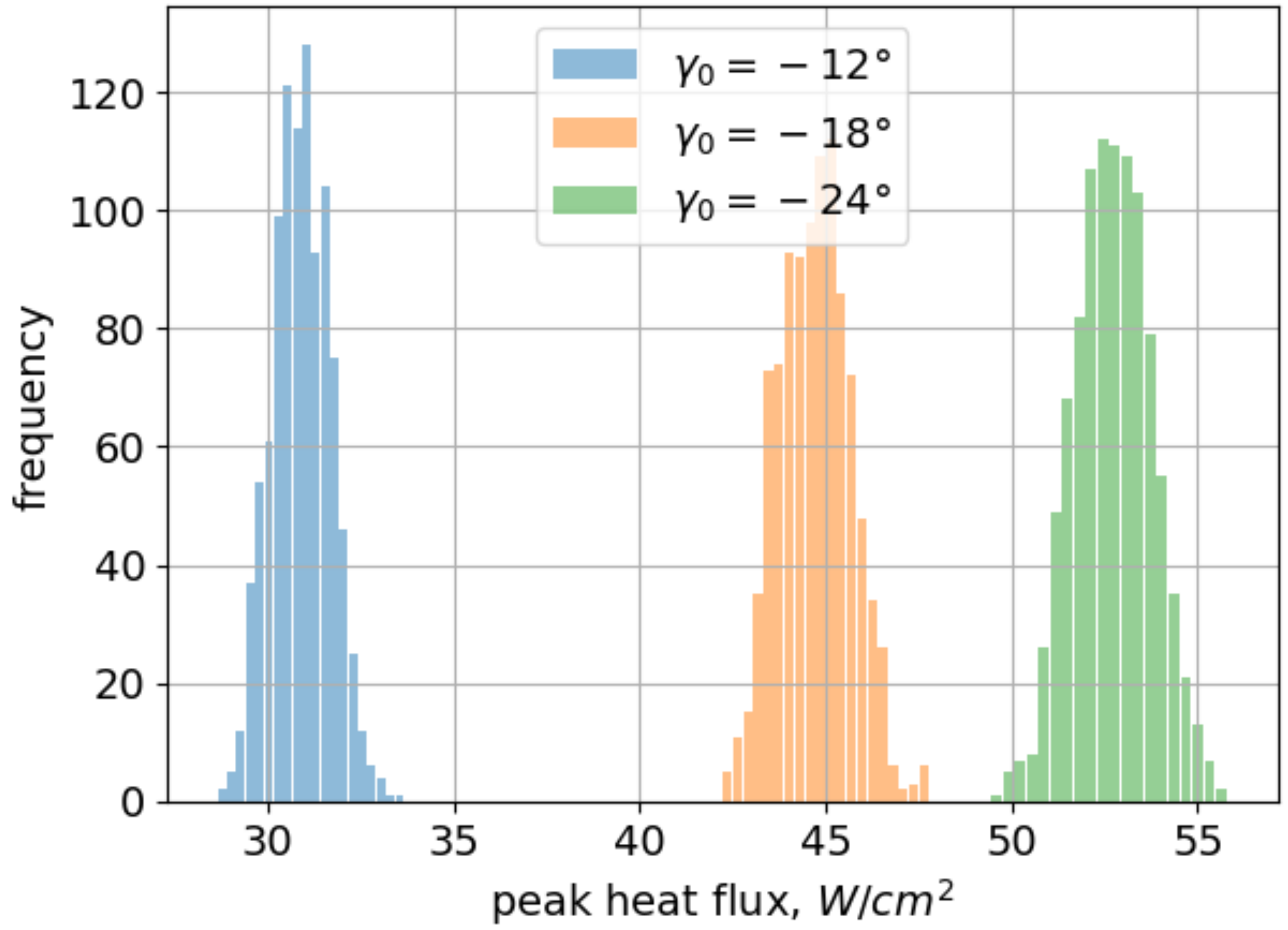
Regional Network Monte Carlo Results

Table 4 Statistics of relative landing site separation distances

Parameter	Mean	Min.	Max.	3σ
center error ε_c, km	5.309	0.012	26.344	12.102
shape error ε_s, km	2.285	0.366	6.055	2.859
min. separation, km	21.741	20.000	24.113	2.363
max. separation, km	118.808	103.312	137.478	17.011
avg. separation, km	52.168	46.583	59.441	5.924

Heat flux

- SHIELD TPS baseline is PICA (Phenolic Impregnated Carbon Ablator)
- Max allowable heat flux in the range of 1200 W/cm^2
- Peak heat flux analysis:
  - Sutton-Graves heating
  - Convective heat flux at the stagnation point for fully-catalytic surface
- Based on this preliminary analysis, SHIELD comes nowhere near this value for any considered EFPA, thanks to its low ballistic coefficient



Equations of Motion

$$\dot{r} = V \sin\gamma$$

$$\dot{\theta} = \frac{V \cos\gamma \sin\psi}{r \cos\phi}$$

$$\dot{\phi} = \frac{V \cos\gamma \cos\psi}{r}$$

$$\begin{aligned}\dot{V} &= -D - g_r \sin\gamma - g_\phi \cos\gamma \cos\psi \\ &\quad + \omega_p^2 r \cos\phi \left(\cos\phi \sin\gamma - \sin\phi \cos\gamma \cos\psi\right)\end{aligned}$$

$$\begin{aligned}\dot{\gamma} &= \frac{1}{V}\Bigg[L \cos\sigma + \cos\gamma \left(\frac{V^2}{r} - g_r\right) + g_\phi \sin\gamma \cos\psi + 2\omega_p V \cos\phi \sin\psi \\ &\quad + \omega_p^2 r \cos\phi \left(\cos\phi \cos\gamma + \sin\phi \sin\gamma \cos\psi\right)\Bigg]\end{aligned}$$

$$\begin{aligned}\dot{\psi} &= \frac{1}{V}\Bigg[\frac{L \sin\sigma}{\cos\gamma} + \frac{V^2}{r} \tan\phi \cos\gamma \sin\psi + g_\phi \frac{\sin\psi}{\cos\gamma} \\ &\quad - 2\omega_p V \left(\cos\phi \tan\gamma \cos\psi - \sin\phi\right) + \frac{\omega_p^2 r}{\cos\gamma} \cos\phi \sin\phi \sin\psi\Bigg]\end{aligned}$$

$$L = \frac{\rho V^2}{2\beta} L/D$$

$$D = \frac{\rho V^2}{2\beta}$$

$$g_r = \frac{\mu}{r^2}\left[1 + \frac{3 J_2 R^2}{2 r^2}\left(1 - 3\sin^2\phi\right)\right]$$

$$g_\phi = \frac{\mu}{r^2}\left[\frac{3 J_2 R^2}{2 r^2} 2 \sin\phi \cos\phi\right]$$