Interplanetary Trajectory Design for NASA's Common Probe Study

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WHAT'S THE COMMON PROBE STUDY?

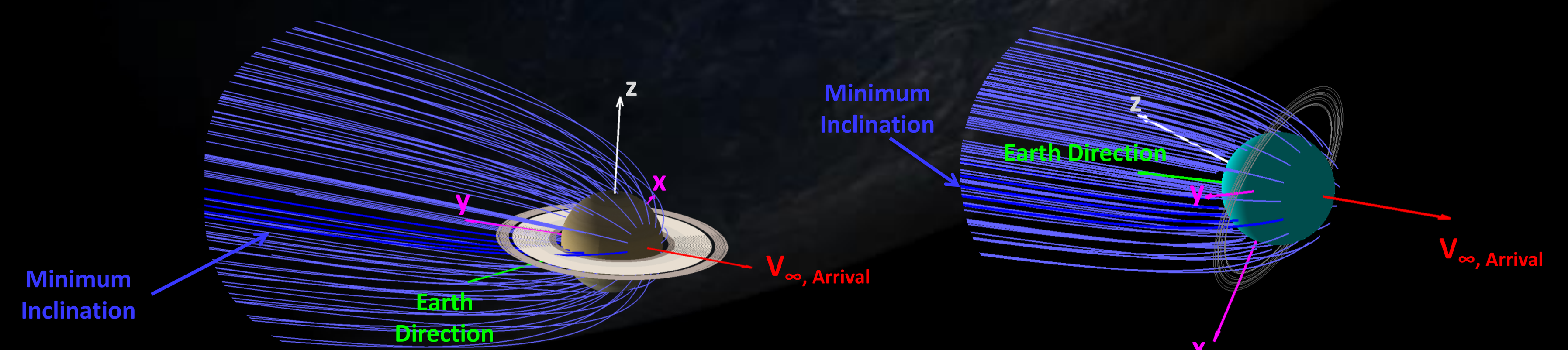
- NASA study to determine if probe designs can be standardized, to what extent, with what compromises, and with what cost savings
- Atmospheric probe designs share many similar attributes:
  - Aeroshell design and probe geometry
  - Instruments: mass spectrometers, atmosphere structure sensors
- Study scope:
  - NASA Centers: Ames, Goddard, Langley, and JPL
  - Targets: Venus, Jupiter, Saturn, Uranus, and Neptune
  - No sample-return (separate study)
  - Draws from recent probe studies and current/new technology advancements
  - Addresses common aeroshell and descent vehicle design, size, and instrument suite
- Questions to answer:
  - Can a single common probe be designed for all targets? (E.g. extreme heating and g-load at Jupiter and high pressure at Venus?)
  - If not, how many designs are needed to accommodate all targets? Can many of the components be made common?
  - What are the cost savings for any such commonality?
  - What is the compromise/penalty to standardize? Does it limit mission science? What volume and mass constraints are imposed on mission?

OBJECTIVES OF THE INTERPLANETARY TRAJECTORY DESIGN

- Design interplanetary trajectories for plausible future probe mission scenarios to Venus, Jupiter, Saturn, Uranus, and Neptune
- Multiple design objectives:
  - Low ΔV
  - Low flight time
  - Low arrival velocity (to reduce probe entry speed)
  - Low arrival declination (to match desired probe entry latitude)
- Provide atmospheric entry conditions for a variety of entry flight path angles
- Design a flyby trajectory for the carrier spacecraft that accommodates the carrier-probe communications link

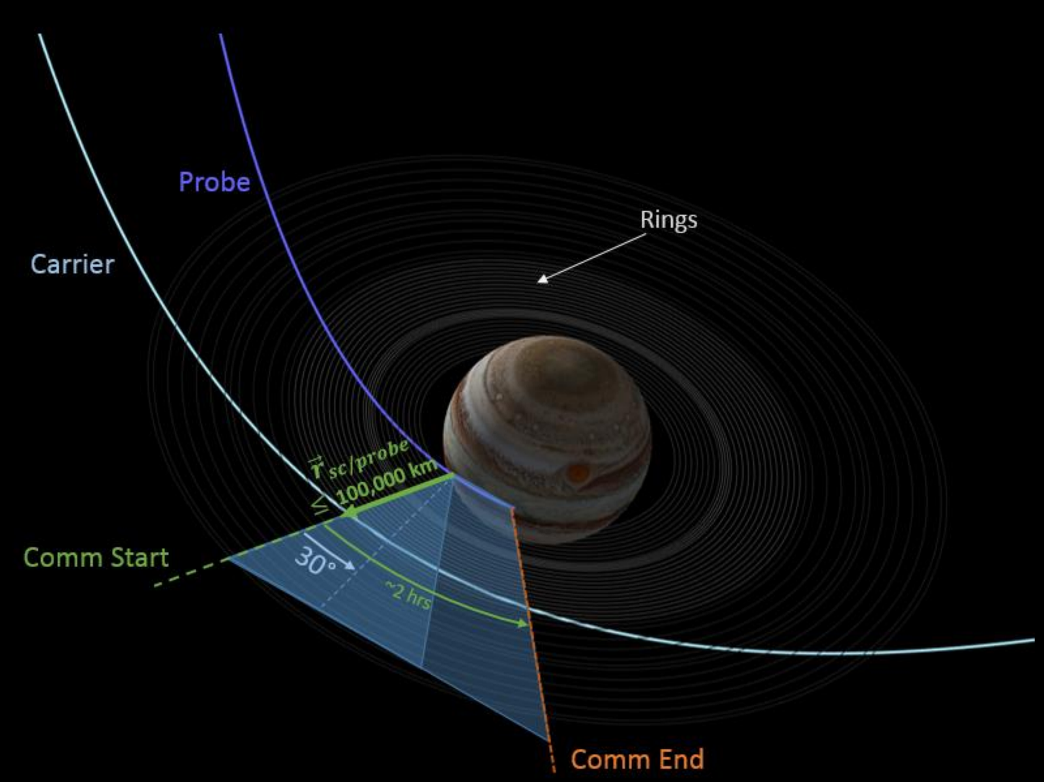
HYPERBOLIC APPROACH

- An single interplanetary trajectory may provide a wide variety of entry conditions
- Available hyperbolic approach solutions gets narrowed down by entry conditions (e.g. entry flight path angle, altitude, latitude, etc.)—possibly to a unique solution



CARRIER-PROBE COMMUNICATION LINK

- Distance within:
  - Giant planets: ~100,000 km
  - Venus: ~14,000 km
- Probe to carrier aspect angle:
  - Giant planets: 30°
  - Venus: ~50°
- Maintain link for:
  - Giant planets: ~2 hr
  - Venus: ~0.5 hr
- Probe oriented nadir
- Probe fixed at entry point and moves with rotation of atmosphere
- Probe release prior to atmospheric entry
  - Giant planets: 60 days
  - Venus: 4 days



JUPITER TRAJECTORY DESIGN

- Entry altitude of 450 km
- Entry at equator
  - Different from Galileo's 6°N entry
  - Slower relative velocity if heading eastward
- Scenarios:
  - FPA: -4.10°, -4.47°, -5.31°, -6.50°
  - Peak g-load: 70, 100, 150, 200 (respectively)
- Key challenge: High entry speeds
  - Due to Jupiter's immense gravity
  - Insensitive to arrival V_∞ (for V_∞ < ~10 km/s)

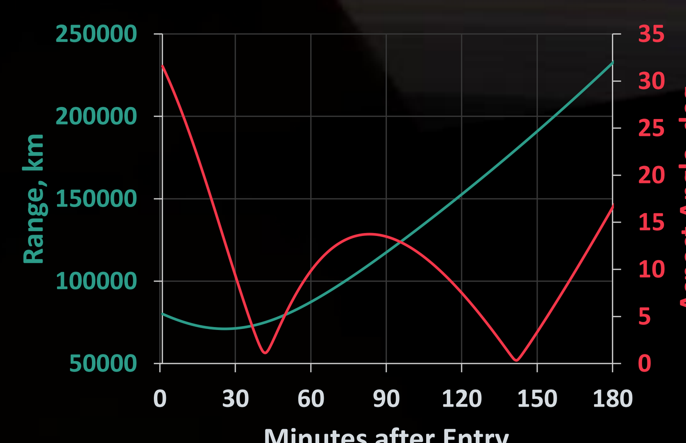
Venus-Earth Gravity-Assist Trajectory

Trajectory Events

Event	Epoch	Parameters
Launch	27 Sept 2029	C_3 = 17.0 km²/s²
Closest Approach to Sun	27 Jan 2030	0.6 AU
Venus Gravity Assist	23 Nov 2030	Alt = 959 km, V_∞ = 9.0 km/s
Earth Gravity Assist	16 Feb 2032	Alt = 300 km, V_∞ = 13.5 km/s
DSM	17 Mar 2032	ΔV = 203 m/s
Carrier Divert ΔV	30 Aug 2034	ΔV = 46 m/s
Probe Entry at Jupiter	29 Oct 2034	V_∞ = 6.4 km/s, V_{Entry} = 47.1 km/s
Total Deterministic ΔV	--	249 m/s

Values shown for 70-g solution

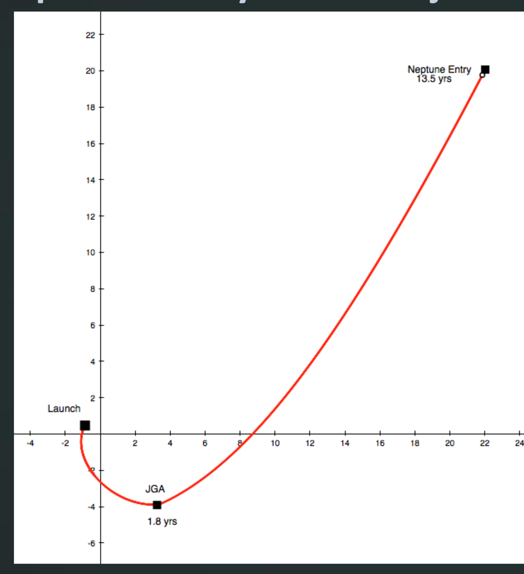
Probe-Carrier Comm Link: 70-g



NEPTUNE TRAJECTORY DESIGN

- Entry altitude of 1500 km
- Entry at 10°S latitude
- Scenarios:
  - FPA: -16.00°, -23.03°
  - Peak g-load: 50, 150 (respectively)
- Key challenge: Distance from Earth and Sun
  - Long flight times

Jupiter Gravity-Assist Trajectory

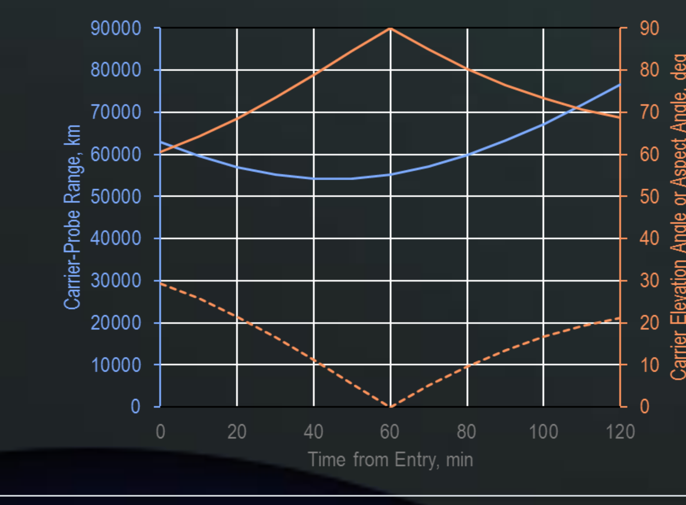


Trajectory Events

Event	Epoch	Parameters
Launch	21 Feb 2031	C_3 = 81.8 km²/s²
Jupiter Gravity Assist	17 Dec 2032	Alt = 11.8 RJ, V_∞ = 8.2 km/s
Carrier Divert ΔV	22 June 2044	ΔV = 14 m/s
Probe Entry at Neptune	21 Aug 2044	V_{Entry} = 21.1 km/s
Total Deterministic ΔV	--	14 m/s

Values shown for 50-g solution

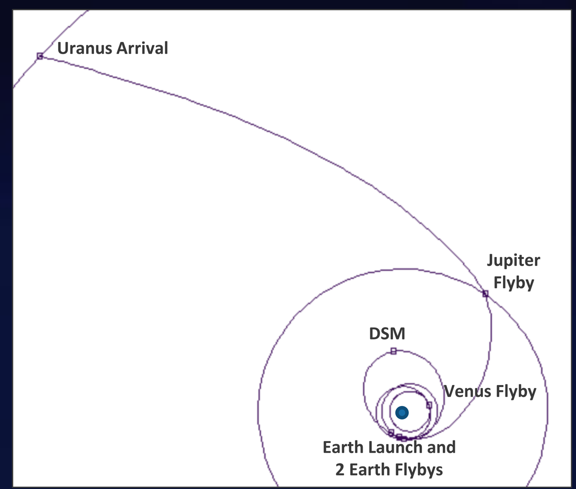
Probe-Carrier Comm Link: 50-g



URANUS TRAJECTORY DESIGN

- Entry altitude of 1500 km
- Entry at equator
- Scenarios:
  - FPA: -16.5°, -35.0°
  - Peak g-load: 50, 200 (respectively)
- Key challenges: Distance from Earth and Sun, 98° axial tilt
  - Long flight times
  - Higher entry speeds (heading transverse to atmosphere)
  - Probe in atmosphere moves transverse to carrier spacecraft—presents comm-link challenge

Venus-Earth-Earth-Jupiter Gravity-Assist Trajectory

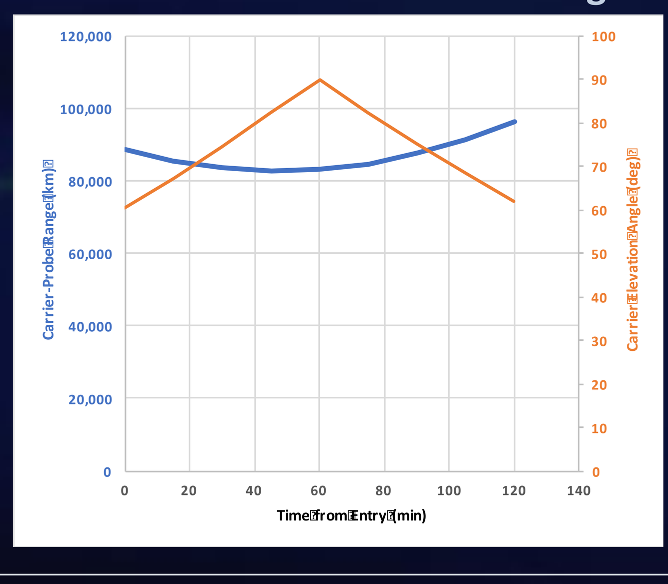


Trajectory Events

Event	Epoch	Parameters
Launch	15 Apr 2030	C_3 = 13.0 km²/s²
Venus Gravity Assist	18 Sept 2031	Alt = 6138 km, V_∞ = 4.4 km/s
Closest Approach to Sun	18 Sept 2031	0.7 AU
Earth Gravity Assist	8 June 2032	Alt = 2804 km, V_∞ = 7.8 km/s
DSM	9 June 2033	ΔV = 757 m/s
Earth Gravity Assist	9 May 2034	Alt = 300 km, V_∞ = 11.9 km/s
Jupiter Gravity Assist	23 Mar 2036	Alt = 18.5 RJ, V_∞ = 7.5 km/s
Carrier Divert ΔV	21 Mar 2043	ΔV = 23 m/s
Probe Entry at Uranus	18 May 2043	V_∞ = 8.4 km/s, V_{Entry} = 20.9 km/s
Total Deterministic ΔV	--	780 m/s

Values shown for 50-g solution

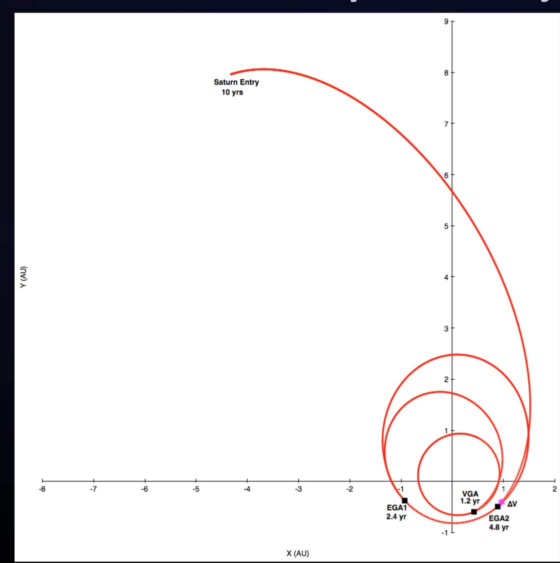
Probe-Carrier Comm Link: 50-g



SATURN TRAJECTORY DESIGN

- Entry altitude of 1500 km
- Entry at equator
  - Slower entry with eastward heading
- Scenarios:
  - FPA: -11.88°, -24.98°
  - Peak g-load: 50, 150 (respectively)
- Key challenges: Ring avoidance and entry speed
  - Carrier flies through F-G ring gap for these solutions

Venus-Earth-Earth Gravity-Assist Trajectory

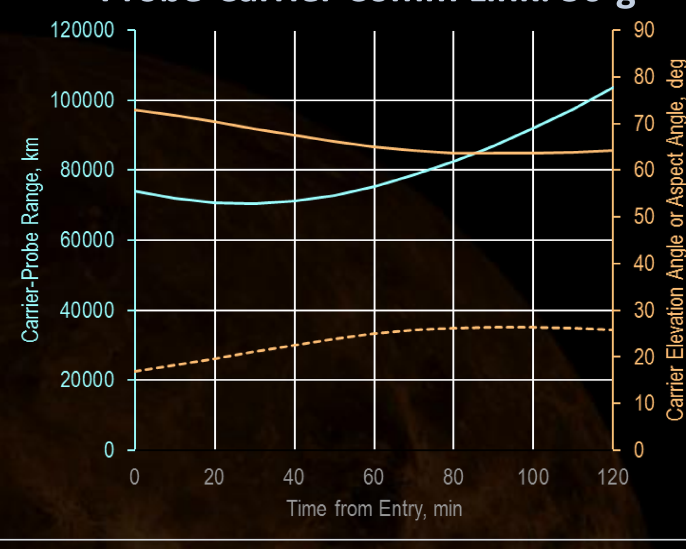


Trajectory Events

Event	Epoch	Parameters
Launch	24 Nov 2024	C_3 = 18.7 km²/s²
Closest Approach to Sun	6 Apr 2025	0.6 AU
Venus Gravity Assist	18 Jan 2026	Alt = 321 km, V_∞ = 7.8 km/s
Earth Gravity Assist	12 Apr 2027	Alt = 10531 km, V_∞ = 13.1 km/s
Earth Gravity Assist	24 Aug 2029	Alt = 500 km, V_∞ = 13.1 km/s
DSM	29 Aug 2029	ΔV = 214 m/s
Carrier Divert ΔV	30 Aug 2034	ΔV = 37 m/s
Probe Entry at Saturn	3 Nov 2034	V_{Entry} = 26.9 km/s
Total Deterministic ΔV	--	251 m/s

Values shown for 50-g solution

Probe-Carrier Comm Link: 50-g



VENUS TRAJECTORY DESIGN

- Entry altitude of 175 km
- Entry at 3.53°N latitude, 64.70°W longitude
- Scenarios:
  - FPA: -9.00°, -16.12°
  - Peak g-load: 50, 150 (respectively)
- Key challenges:
  - Nearly zero planet rotation with super-rotating atmosphere
  - Targeting longitude has large impact on trajectory due to slow rotation

Direct-to-Venus Transfer

Trajectory Events

Event	Epoch	Parameters
Launch	20 Dec 2024	C_3 = 7.3 km²/s²
Carrier Divert ΔV	5 May 2025	ΔV = 36 m/s
Probe Entry at Venus	9 May 2025	V_∞ = 3.9 km/s, V_{Entry} = 10.9 km/s
Total Deterministic ΔV	--	36 m/s

Values shown for 50-g solution

Probe-Carrier Comm Link: 50-g

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