Feasible Mission Designs for Solar Probe Plus to Launch in 2015, 2016, 2017, or 2018

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APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

2007 Solar Probe Study & Mission Requirements

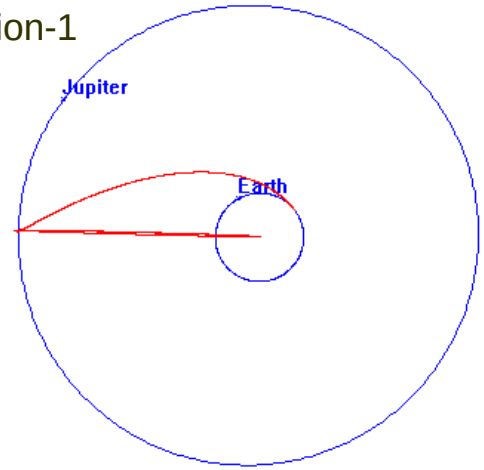
Trajectory study and mission design trades were conducted in the fall of 2007 aimed to develop a feasible mission design for Solar Probe under NASA's new direction and guidelines. The new program constraints and mission requirements include:

- **No nuclear power source**
- **Perihelion distance less than 10 Rs***
- **Three flybys with perihelion less than 10 Rs**
- **Mission duration less than 10 years**
- **Launch time around 2015**
- **Total mission cost under $750 Million**

*Rs = Solar radius

Various Trajectory Designs Representing Different Mission Concepts Developed

Option-1



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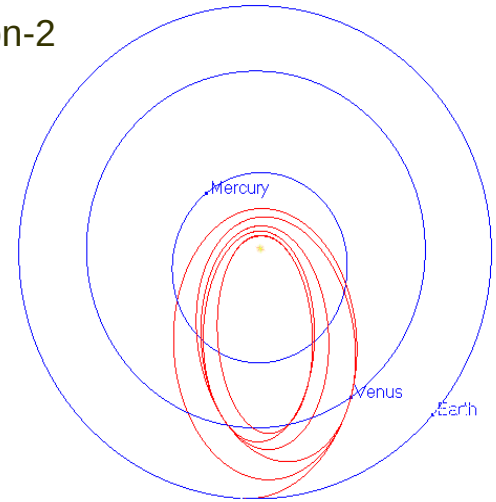

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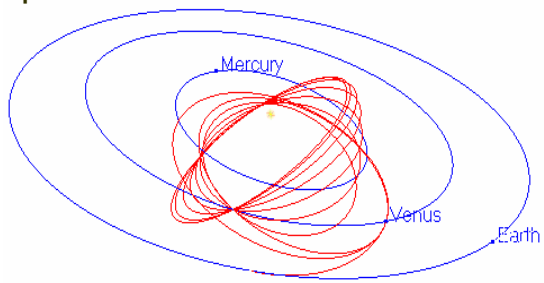

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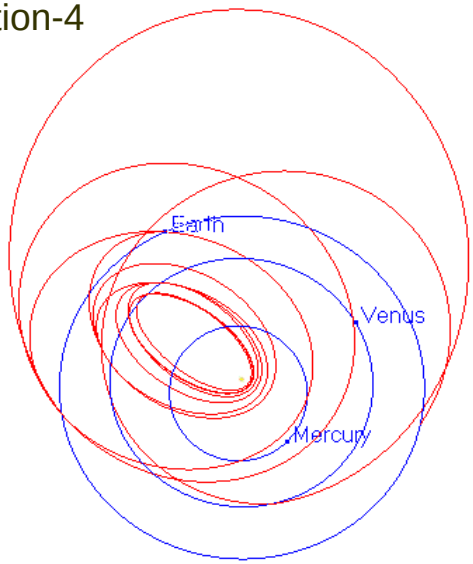
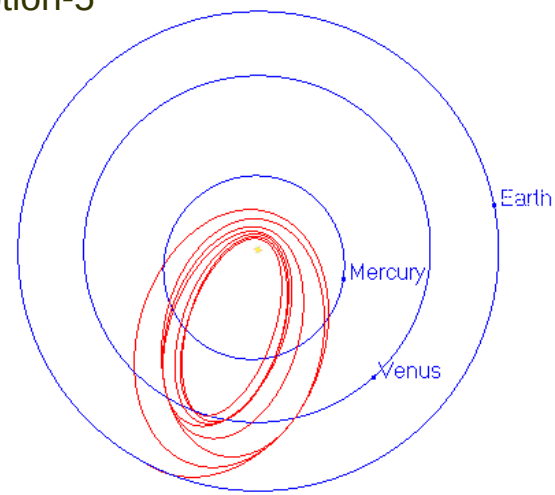
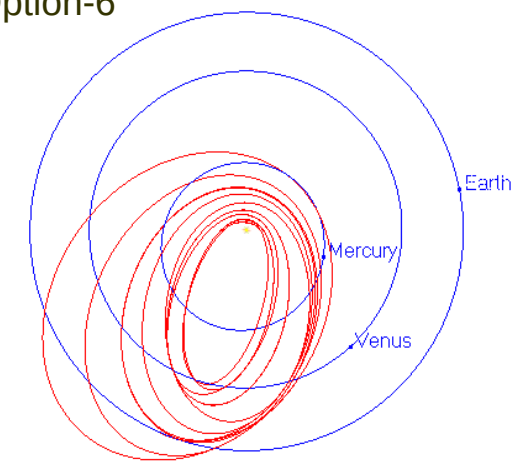


Option-5



Option-6



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Characteristics of The Various Trajectory Types

Trajectory Option		Option-1	Option-2	Option-3	Option-4	Option5	Option-6
Launch	Date	11/20/2015	5/30/2015	5/30/2015	9/6/2014	5/21/2015	5/24/2015
	C3 (km^2/s^2)	114	156	156	108	158	128
Trajectory	Flybys	1 Jupiter	5 Venus	9 Venus	3 Earth, 7 Venus	7 Venus	1 Earth, 9 Venus
	Deep Space Maneuver (ΔV)	None	None	None	1 (232 m/s)	None	1 (397 m/s)
	Max Aphelion (AU)	5.56	1	1	2.29	1	1.19
Final orbit	Perihelion (Rs)	4	11.8	39.8	9.5	9.5	9
	Aphelion (AU)	5.56	0.75	0.725	0.73	0.73	0.73
	Inclination from ecliptic (deg)	90	3.4	37.9	2.9	3.4	3.4
	Orbital period	4.6 yr	94 d	112 d	88 d	88 d	88 d
Timeline	launch to min. peri.	4.1 yr	3.3 yr	2.1 yr	10 yr	6.4 yr	9.5 yr
	Mission duration	4.5 yr	3.8 yr	5.8 yr	10.5 yr	6.9 yr	9.95 yr
Near Sun Pass	Total # of solar passes (< 0.2 AU)	1	12	18	16	24	21
Pros		Pole-to-pole solar flyby at 4 Rs	Short mission duration; multiple, frequent solar flybys; aphelion < 1 AU	Short mission duration; multiple, frequent solar flybys; aphelion< 1 AU	Good perihelion distance; multiple, frequent Solar flybys; moderate C3	Good perihelion distance; multiple frequent solar flybys; short mission duration; no deep space maneuver; aphelion < 1 AU	Good perihelion distance; multiple, frequent solar flybys; moderate C3
Cons		Single solar flyby; great aphelion distance; long cruise; long orbit Period	Low inclination ; high C3	Large perihelion distance; high C3	Long mission duration; requiring deep space maneuver	low inclination; high C3	Long mission duration; requiring deep space maneuver

V^7GA Launch Opportunity (occurring every 19 months)

Launch Opportunity		2013	2015	2017	2018
Launch	Date	10/25/2013	5/31/2015	1/10/2017	8/9/2018
	Optimum C3 (km^2/s^2)	170.0	155.6	177.2	157.0
Trajectory	Flybys	7 Venus	7 Venus	7 Venus	7 Venus
	Deep Space Maneuver (ΔV)	None	None	None	None
	Max aphelion (AU)	1	1	1	1
Final orbit	Perihelion (Rs)	9.5	9.5	9.5	9.5
	Aphelion (AU)	0.73	0.73	0.72	0.73
	Inclination from ecliptic (deg)	3.4	3.4	3.4	3.4
	Orbital period (day)	88	88	87	88
Near Sun Pass	Total # of solar passes (< 0.2 AU)	24	24	24	24
Timeline	Launch to min perihelion (yr)	6.4	6.4	6.4	6.4
	Mission duration (including three 9.5-Rs passes) (yr)	6.9	6.9	6.8	6.9

New EV^7GA (Earth plus 7 Venus flyby-Gravity Assist) Design Strategy

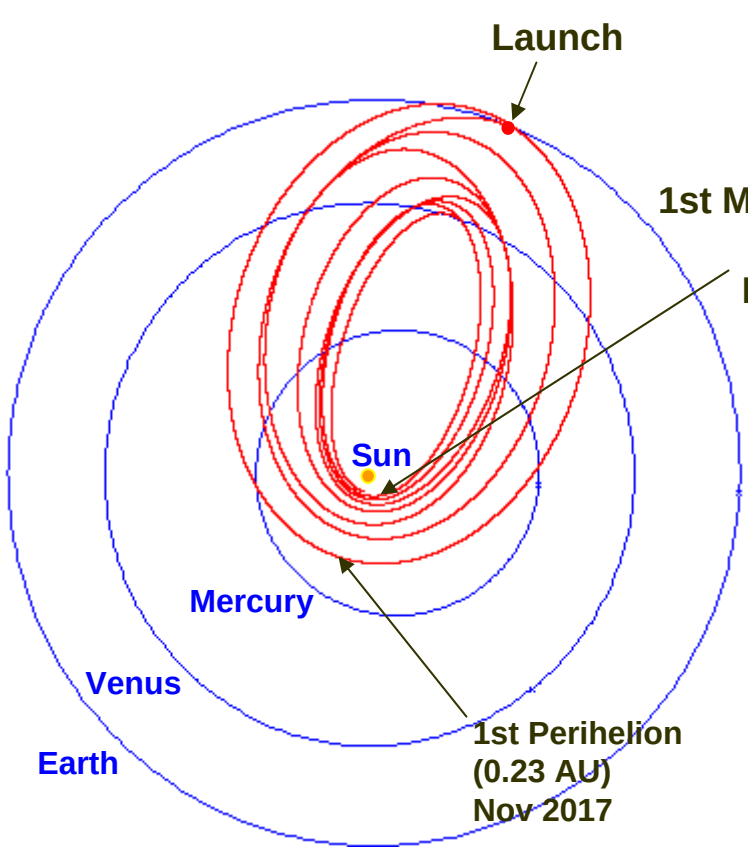
- Maintained a mission concept similar to the 2015 baseline mission and kept all favorable trajectory features
- Utilized two different trajectory designs to lower launch C3 requirement, keeping the maximum launch C3 to no more than 158 km^2/s^2 (same as with 2015 launch)
- Designed the launch with two separate launch periods to increase the total number of launch dates under limited launch C3, a total of launch dates being increased to 4 weeks (1 week more than 2015 launch)
- Constrained to no deep space maneuvers as required
- Constrained maximum aphelion to 1 AU (same as with 2015 launch)
- Requiring no new changes to the spacecraft design to be developed for the 2015 launch

New EV^{7}GA Mission Design for 2017 Launch Preliminary Design

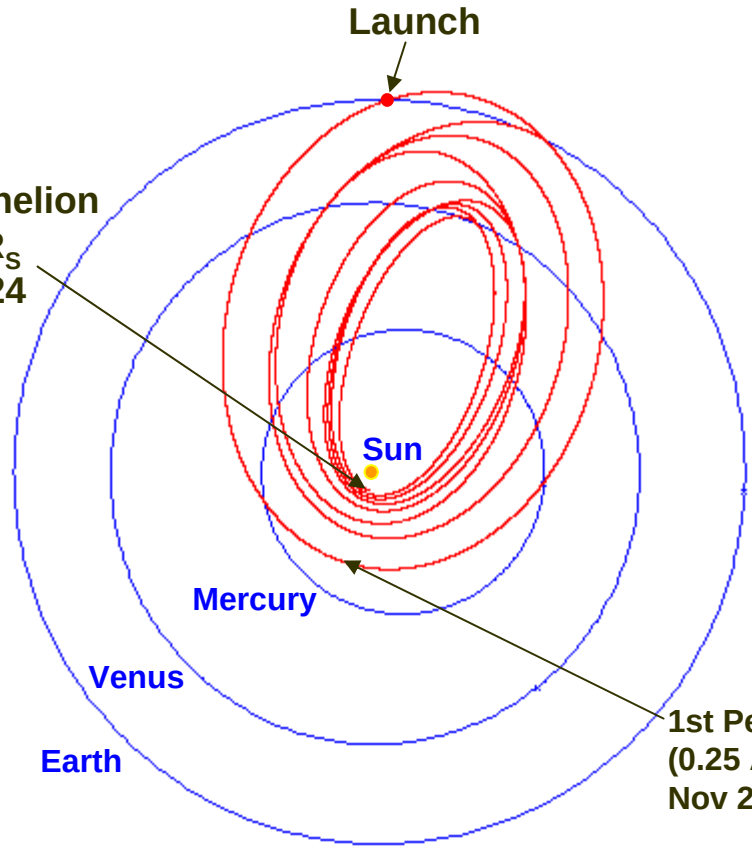
- Launch
  - Dates: Aug 3 -15, Aug 24 - Sept 7, 2017 (28 days) (1 week longer than 2015 launch)
  - Max. Launch C3: 158 km^2/s^2 (*same as 2015 launch*)
- Trajectory Design
  - Earth-Venus-Venus-Venus-Venus-Venus-Venus-Venus Gravity Assists (EV^{7}GA) *(one extra Earth flyby than V^{7}GA)*
  - No deep space maneuver
  - 26 perihelion passes (2 passes more than *V^{7}GA*)
  - Aphelion < 1.05 AU
  - Perihelion gradually decreases to 9.5 R_S
- Final Solar Orbit (*same as V^{7}GA*)
  - Perihelion: 9.5 R_S (8.5 Rs from Sun's surface)
  - Aphelion: 0.73 AU
  - Inclination: 3.4 deg from ecliptic
  - Orbit period: 88 days
- Timeline
  - Launch to 1st min perihelion (9.5 Rs): 7.3 to 7.4 years (*one year longer than V^{7}GA*)
  - Mission duration (3 passes @ 9.5 Rs): 7.8 to 7.9 years (*one year longer than V^{7}GA*)

EV^{7}GA Mission Trajectory (Preliminary Design)

Trajectory I: for launch from August 3 through 15, 2017



Trajectory II: for launch from August 24 through September 7, 2017

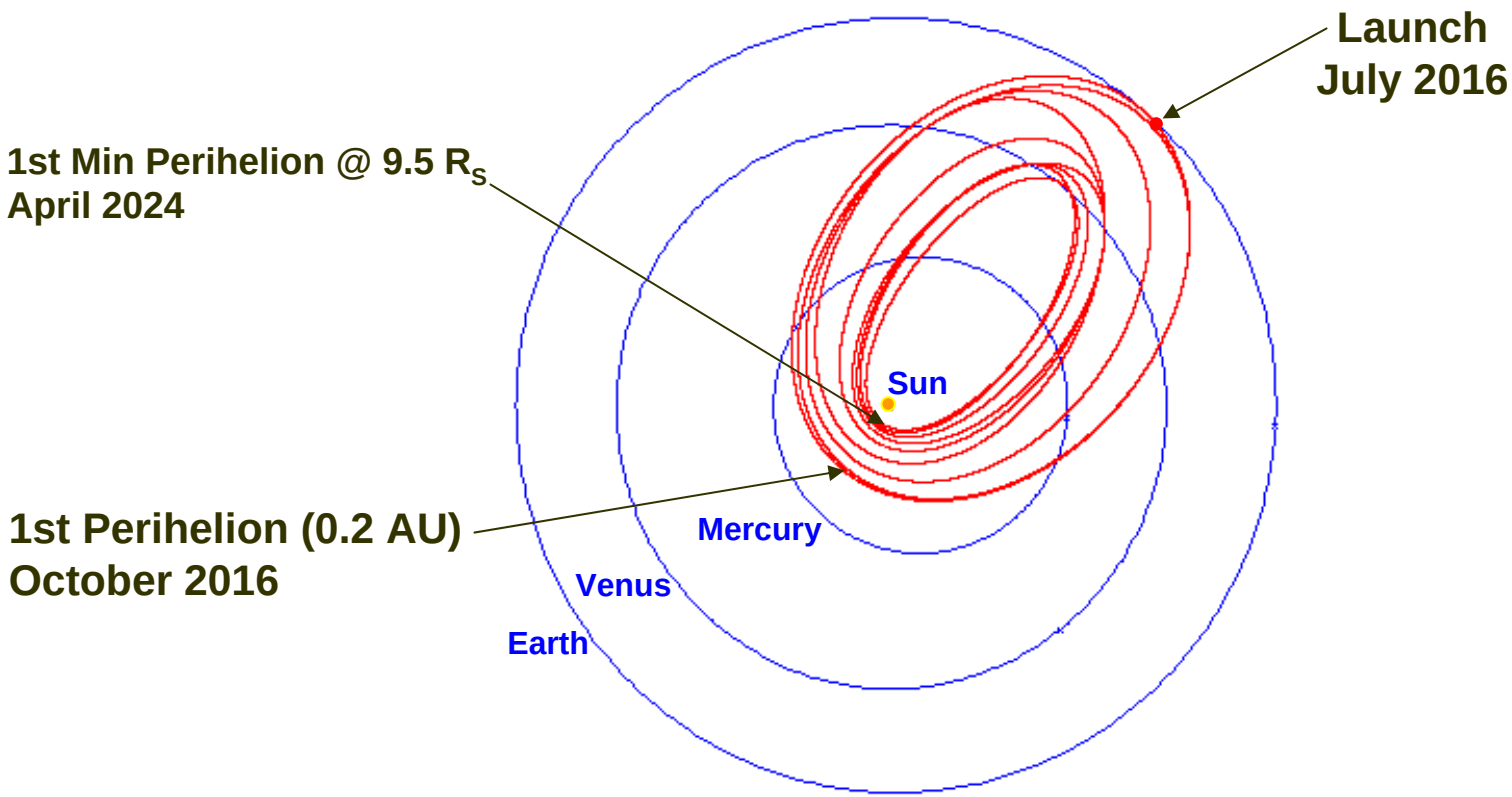


1st Min Perihelion @ 9.5 R_S Dec 2024

New V^8GA (8 Venus Flyby-Gravity Assist) Mission Design for 2016 Launch Preliminary Design

- Launch
  - Dates: July 2016 (20 days or more) (*can be longer than 2015 launch*)
  - Max. Launch C3: ~154 km^2/s^2 (*less than 2015 launch*)
- Trajectory Design
  - Eight Venus Gravity Assists (V^8GA) *(one more Venus flyby than V^7GA)*
  - No deep space maneuver
  - 27 perihelion passes (3 passes more than *V^7GA*)
  - Aphelion < 1.02 AU
  - Perihelion gradually decreases to 9.5 R_S
- Final Solar Orbit (*same as V^7GA*)
  - Perihelion: 9.5 R_S (8.5 Rs from Sun's surface)
  - Aphelion: 0.73 AU
  - Inclination: 3.4 deg from ecliptic
  - Orbit period: 88 days
- Timeline
  - Launch to 1st min perihelion (9.5 R_S): 7.7 years (1.3 *years longer than V^7GA*)
  - Mission duration (3 passes @ 9.5 Rs): 8.3 years (1.4 *years longer than V^7GA*)

V^8GA Mission Trajectory Preliminary Design



Feasible Mission Designs Enabling Solar Probe Plus to Launch Yearly: 2015-2018

Launch Year	2015	2016	2017	2018
Mission Design	**V^7GA**	**EV^7GA**	**V^8GA**	**V^7GA**
Launch C3 (km2/s2)	158	154	158	159
Launch Period (days)	20	20	28	20
Number of Flybys	7	8	8	7
Minimum Perihelion	9.5 Rs	9.5 Rs	9.5 Rs	9.5 Rs
Total # of Passes	24	27	26	26
# of 9.5-Rs Passes	3	3	3	3
Mission Duration (years)	6.9	8.3	7.9	6.9
Date of 1st Min. Perihelion	Oct 2021	Apr 2024	Dec 2024	Dec 2024

Summary and Future Work

- Feasible mission designs for 2015-2018 launch have been developed. The baseline spacecraft design should work for each mission design.
- This is a work in progress. While the 2016 and 2017 opportunities are feasible, more work needs to be done to
  - Analyze the details of each trajectory, such as solar conjunctions, Sun-Probe-Earth angles, etc.
  - Determine if there is any impact on spacecraft design and concept of operations for each new design, such as data downlink strategy, power management, etc.
  - Assess the added cost and risk associated with longer mission with more planetary fly-bys.