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MEMO

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Subject: Solar Orbiter: launch opportunity in 2018 April

Introduction and scope

This document describes in detail a trajectory candidate for Solar Orbiter with launch in April 2018 on an Atlas V 411 from KSC. This is a modified trajectory of the May 2018 presented in Memo SOL-ESC-ME-50008 (RD2) that successfully mitigates the issue of the long eclipse during GAM V2. This has been achieved by modifying the resonance of the orbit between the first and second Venus GAMs from 3:3 to 2:3 (2 S/C revolutions in 3 Venus revolutions).

A 30-days launch window has been identified for this mission opportunity that extends from April 3rd to May 2nd. This window closes more than 80 days before the opening of the NASA's Solar Probe Plus (SPP) launch window on July 30th. This is well over the 60-day turnaround period between consecutive launches required by ULA. Therefore there shall be no interference between this launch window and SPP launch.

This trajectory is considered an attractive option to allow launching Solar Orbiter in the first half of 2018 and it is thus brought to the attention of the project. Further analysis is recommended to understand all the implications of the trajectory in terms of science return and engineering constraints.

References

1. J.M.Sánchez Pérez, "Solar Orbiter: Consolidated Report on Mission Analysis", SOL-ESC-RP-05500, 2012-10-12, Issue 3, Rev. 1.
2. J.M.Sánchez Pérez, "Solar Orbiter: launch opportunity in 2019", SOL-ESC-ME-50008, 2014-08-07.
3. Arianespace, "Feasibility mission analysis, Trajectory & performance study, ExoMars mission on A5-ECA", A5-NT-1-H-018-AE, Issue 1 rev 0, 2007-01-18.

Launch opportunity details & trajectory description

The identified trajectory opportunity responds to the following mission profile:

- **Transfer to Venus**: after launch the sequence of GAMs is Venus-Venus-Earth-Venus (E+2V23VEV). The first arc from Earth to Venus takes 2 complete revolutions around the Sun in 1.6 years. The arc between the 2 consecutive Venus GAMs is in a 2:3 resonance with the planet, that is the spacecraft will describe 2 full revolutions while Venus describes 3. The maximum distance to the Sun of 1.293 AU occurs during this arc and it is reached twice. This is not believed to be a big issue since the distance to the Sun is lower than the current maximum allowed by the Solar Orbiter spacecraft, but the fact that such a maximum Sun range is reached 2 times is a new feature for the mission. After the second Venus GAM there is a fast transfer to the Earth of about 85 days and the next Earth GAM turns the orbit for the next Venus encounter, reduces the aphelion to an acceptable level and reduces the perihelion just below 0.4 AU to allow starting the science operations. For the sequence of resonances of the science mission the Venus GAMs are encountered when increasing the Sun distance after perihelion in a similar way to the 2017 July trajectory.

- **Science phase with sequence of Venus resonant orbits**: the sequences of resonances that has been found the most suitable for the SolO mission is 1:1-4:3-3:2-3:2-3:2.

Overall the trajectory involves 8 GAMs: 1 with Earth and 7 with Venus and it is thus within the maximum of the current trajectories and within the navigation Delta-V allocation .

The mission summary in Table 1 and all the following trajectory plots and results are based on a reference trajectory for the first day of the launch window (April 3rd). The aphelion radius of 1.587 AU appears in parenthesis and grey colour to highlight that it will never be reached by the spacecraft.

It has been decided to end the cruise phase at the time during the second Earth-Venus arc when the spacecraft comes inside Venus orbit after having passed by the farthest aphelion. In this way the next perihelion at 0.39 AU is considered to be part of the Nominal Science Phase (NMP). The transition between NMP and Extended Mission Phase (EMP) is as usual the Venus GAM immediately before the last 2 science resonant orbits.

It is remarkable that the final solar inclination in this trajectory is over 34.5 deg. In addition this final solar inclination experiences only a small variation across the launch window as will be shown later.

Event	Date	Flight time (days)	Flight time (years)	Ra (AU)	Rp (AU)	i_{ecl} (deg)	i_s (deg)	Lat. Sol. Perih. (deg)	ω (deg/day)
LAUNCH	2018-04-03	0	0.00	1.013	0.524	1.75	6.64	5.89	2.991
GAM-V1	2019-11-13	589	1.61	1.293	0.603	3.66	3.61	3.50	2.465
GAM-V2	2021-09-17	1263	3.46	(1.587)	0.641	3.82	3.45	3.45	2.295
GAM-E1	2021-12-12	1349	3.69	1.154	0.384	3.03	4.24	2.83	5.080
Cruise end / EMP start	2022-05-02	1490	4.08	Cruise Duration : 1490 days / 4.08 years					
GAM-V3	2022-07-15	1564	4.28	1.076	0.371	6.22	12.56	9.99	5.356
GAM-V4	2023-02-25	1789	4.90	0.903	0.292	11.41	17.82	10.02	7.552
GAM-V5	2024-12-30	2463	6.74	0.823	0.281	18.81	25.24	11.19	7.616
NMP end / EMP start	2026-03-24	2912	7.97	NMP Duration : 1422 days / 3.89 years					
GAM-V6	2026-03-24	2912	7.97	0.777	0.327	24.81	31.24	12.03	5.593
GAM-V7	2027-06-17	3362	9.20	0.736	0.368	28.19	34.62	7.03	4.255
EMP end	2028-09-08	3811	10.43	EMP Duration : 899 days / 2.46 years					
Possible Venus encounter	2028-09-08	3811	10.43						

Table 1 2018 April launch: Mission Summary

Table 2 presents a summary of the most relevant trajectory characteristics in comparison with the limits of all 5 selected trajectories from the SolO CReMA Issue 3 Rev. 1 (RD1). It is understood that those values represent on one hand the capabilities and design limits of the spacecraft and on the other the minimums in terms of science return that a trajectory suitable for SolO must achieve. In addition the characteristics for the 2018 May trajectory from RD2 are also provided for comparison. The major changes affect only the maximum Sun distance and eclipse duration, because the trajectory modification affects only the Venus-Venus resonant arc and the two GAMs involved, GAM-V1 and GAM-V2.

The 2018 April mission is slightly longer than the current longest trajectory in the CReMA, mainly because of the longer cruise phase. In addition it also takes longer to reach a close perihelion for the science at a Sun distance < 0.3 AU and to reach the final science orbit with the highest inclination is also slightly delayed as well. These time penalties are not dramatic and it can be worth to accept them in order to have a launch possibility 6 months earlier than the current 2018 October backup.

It must be noticed that the designation of the launch opportunity has been changed to 2018 April after realising that the launch window actually occupies this month almost entirely. In fact, the reference trajectory shown is for the first launch day, while the reference trajectory for the 2018 May is at the end of the window.

Case	CReMA v3.1 Limits	**2018 April**	2018 May
Cruise sequence		**E+2V23VEV**	E+2V33VEV
Venus resonances sequence		**1:1 4:3 3:2 3:2 3:2**	1:1 4:3 3:2 3:2 3:2
Launch		**2018-04-03**	2018-05-01
Vinf (km/s)	3.373 – 5.445	**5.528**	5.332
Declination (deg)	-42.6 -26.1	**11.0**	11.7
Duration (y)	8.87 – 10.24	**10.43**	10.36
Max Earth distance (AU)	1.879 – 2.017	**1.809**	1.880
Min Sun distance (AU)	≥ 0.280	**0.281**	0.281
Max Sun distance (AU)	1.186 – 1.478	**1.293 (x2)**	1.152
Cruise duration (y)	2.94 – 3.40	**4.08**	4.08
1st perih. < 0.3 AU (y)	3.50 – 4.67	**5.25**	5.18
# Perih < 0.3 AU	7 – 12	**7**	7
Time spent < 0.3 AU (d)	46.5 – 101.6	**53**	53
# Below 0.4 AU	12 - 16	**15**	15
Time spent < 0.4 AU (d)	292.8 – 421.4	**345**	346
Time to max. solar i (y)	7.86 – 9.20	**9.37**	9.42
Max. solar i (deg)	32.38 - 36.36	**34.62**	34.87
Max. angular rate (deg/d)	7.76 – 8.31	**7.806**	7.821
SM Blackouts: #	4 – 7	**5**	6
SM Blackouts*: longest (d)	≤ 61.0	**14.8**	17.3
SM Blackouts: accum. (d)		**32.7**	50.5
Conjunctions: #	7 - 9	**7**	8
Conjunctions*: longest (d)	≤ 44.0	**8.8**	9.4
Conjunctions: accum. (d)		**28.0**	37.9
Longest eclipse (min)	≤ 37.1	**25.7**	**103.1**
Longest occultation (min)	≤ 35.1	**15.4**	14.8

Table 2 2018 April & May Mission Opportunities: Summary of trajectory properties

Trajectory plots

The following figures present the projections of both trajectories in the inertial ecliptic frame as well as in the Sun-Earth rotating frame.

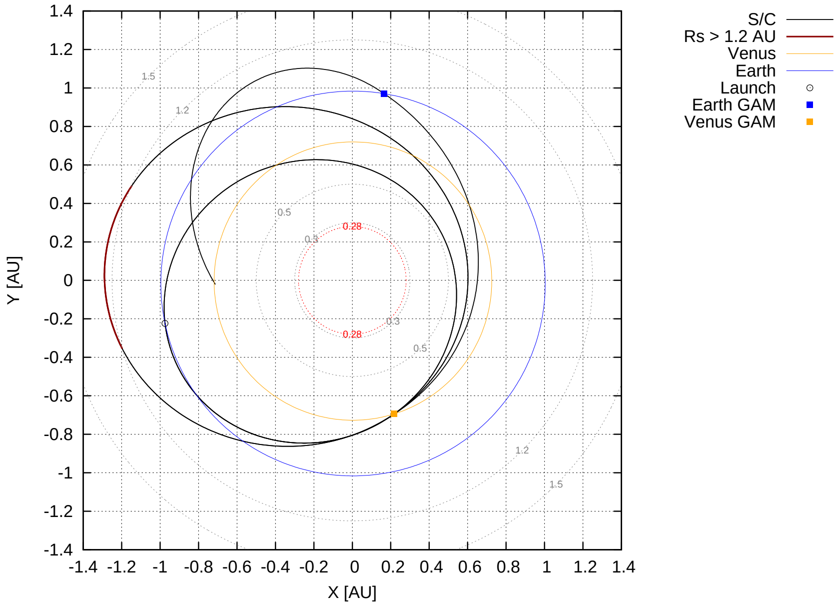

Figure 1 2018 April launch –trajectory projection onto ecliptic X-Y plane – Cruise phase

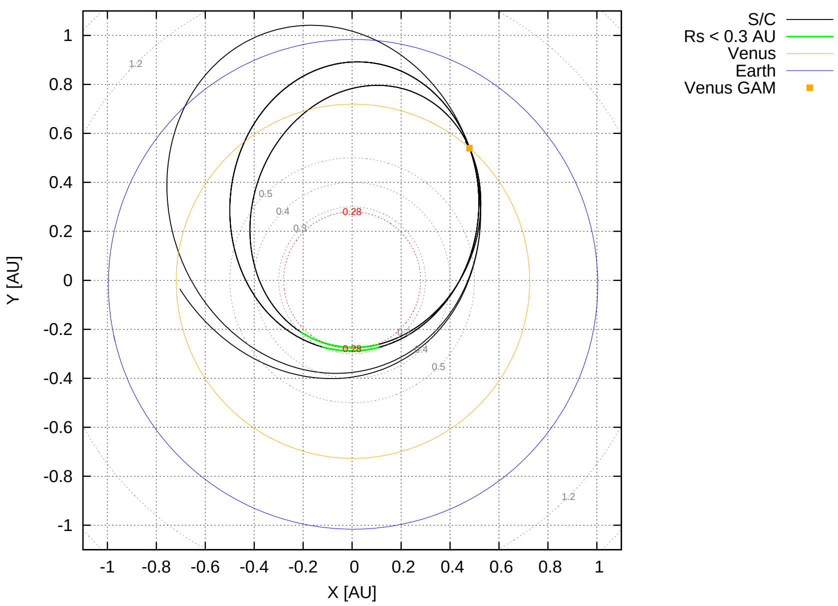

Figure 2 2018 April launch: trajectory projection onto ecliptic X-Y plane – NMP

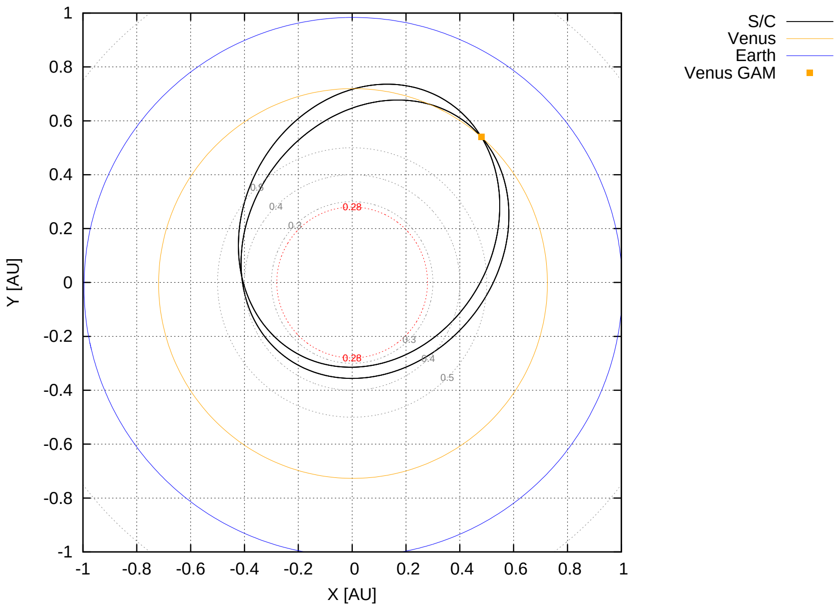

Figure 3 2018 April launch: trajectory projection onto ecliptic X-Y plane – EMP

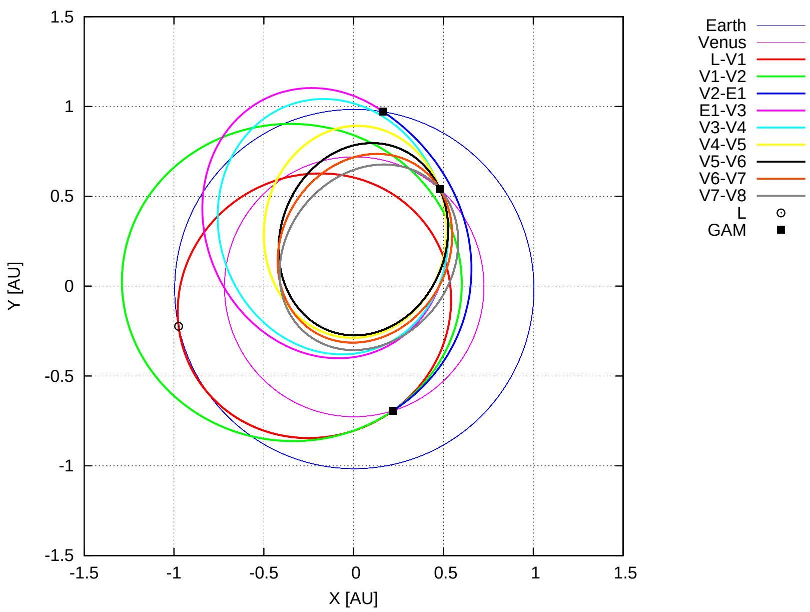

Figure 4 2018 April launch: trajectory projection onto ecliptic X-Y plane

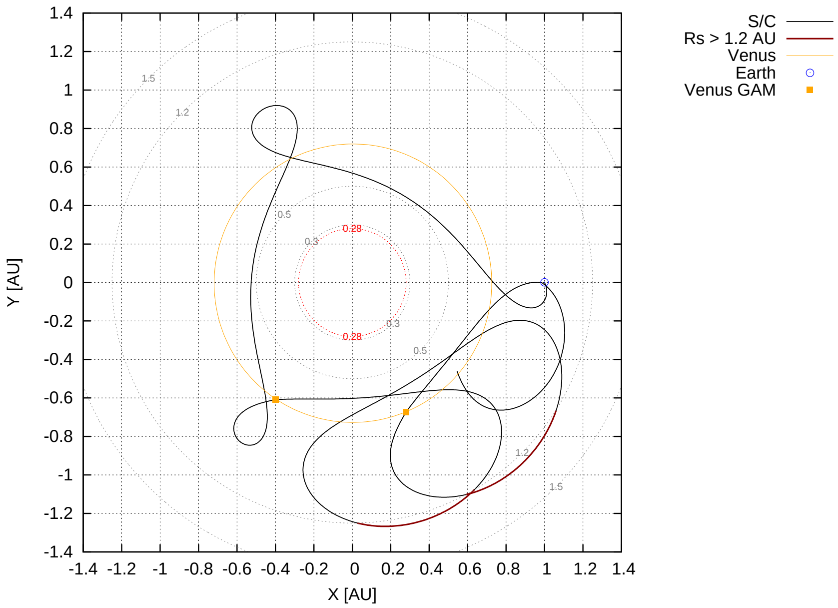

Figure 5 2018 April launch: trajectory projection onto rotating ecliptic X-Y plane – Cruise phase

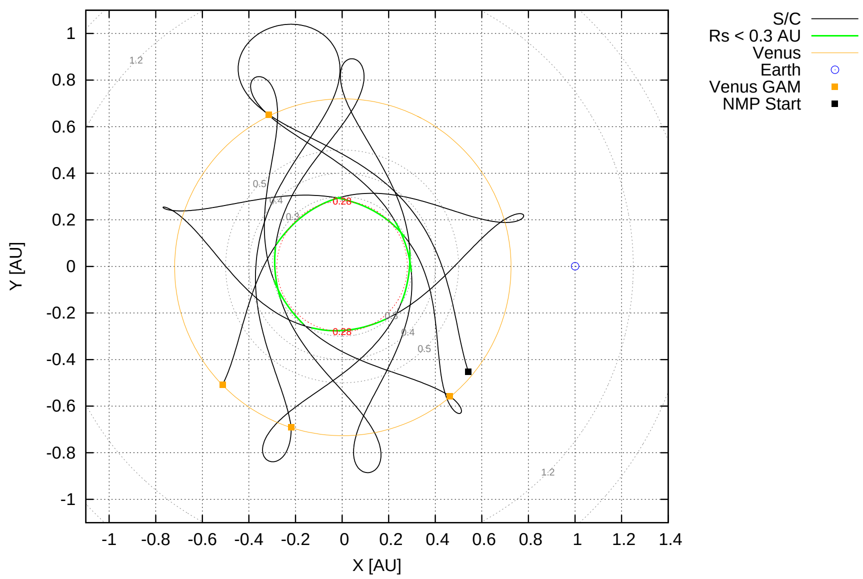

Figure 6 2018 April launch: trajectory projection onto rotating ecliptic X-Y plane – NMP

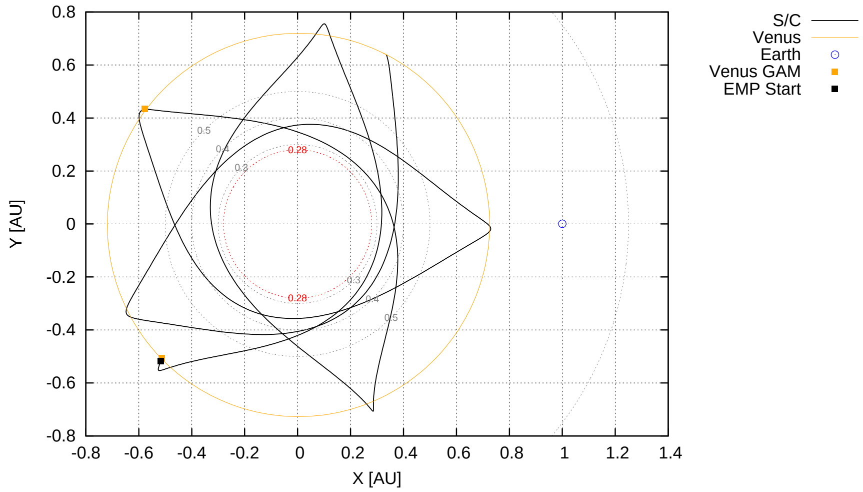

Figure 7 2018 April launch: trajectory projection onto rotating ecliptic X-Y plane – EMP

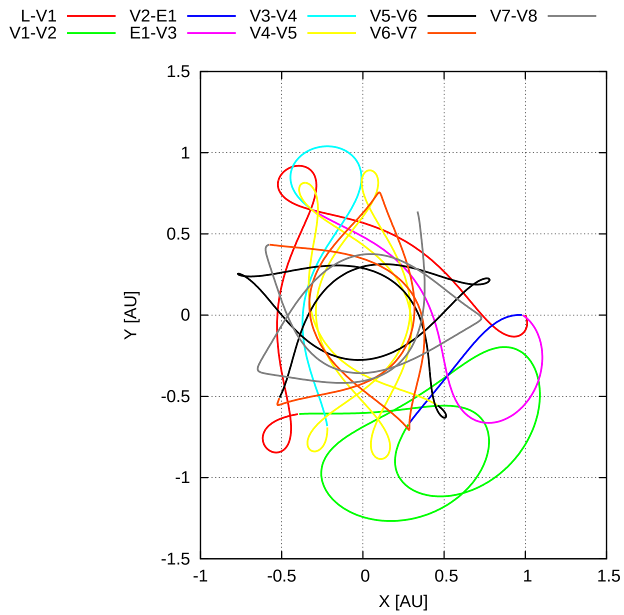

Figure 8 2018 April launch: trajectory projection onto rotating ecliptic X-Y plane

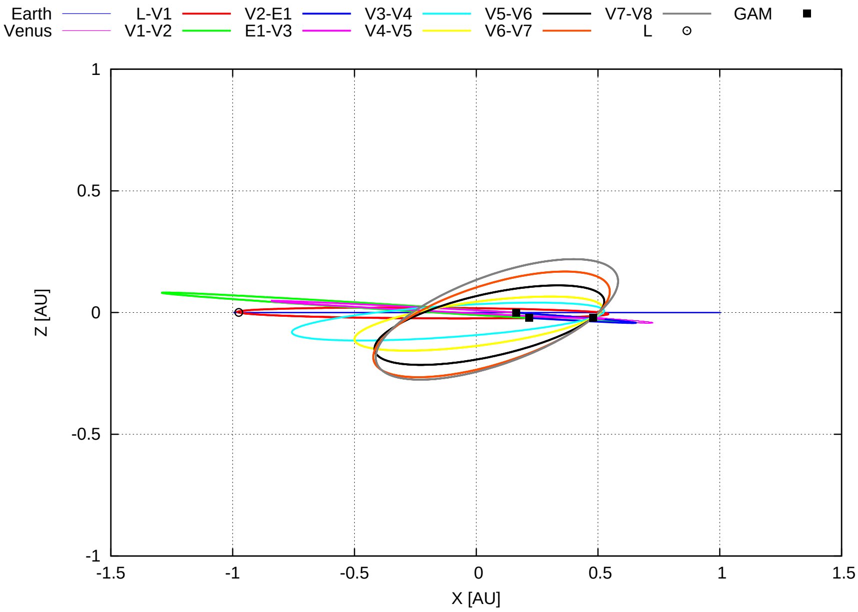

Figure 9 2018 April launch: trajectory projection onto ecliptic X-Z plane

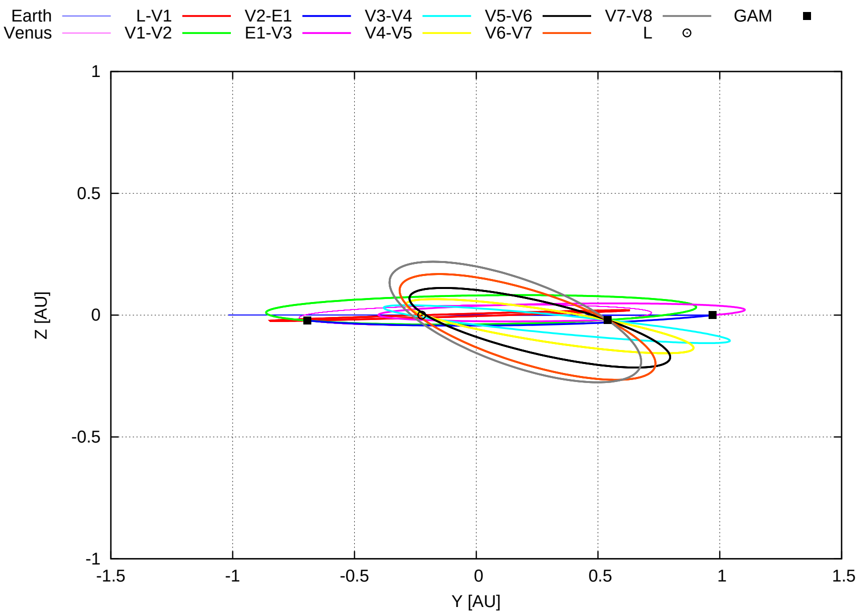

Figure 10 2018 April launch: trajectory projection onto ecliptic Y-Z plane

Evolution of orbit parameters

The following figures provide the evolution of distances, the solar latitude and the communication angles: Sun-Earth-Spacecraft (SES) and Sun-Spacecraft-Earth (SSE) for both options. In the plots, the NMP is highlighted with a yellow background, while the EMP is highlighted with a violet background. Additional tables detail the solar conjunction and the safe mode blackout periods.

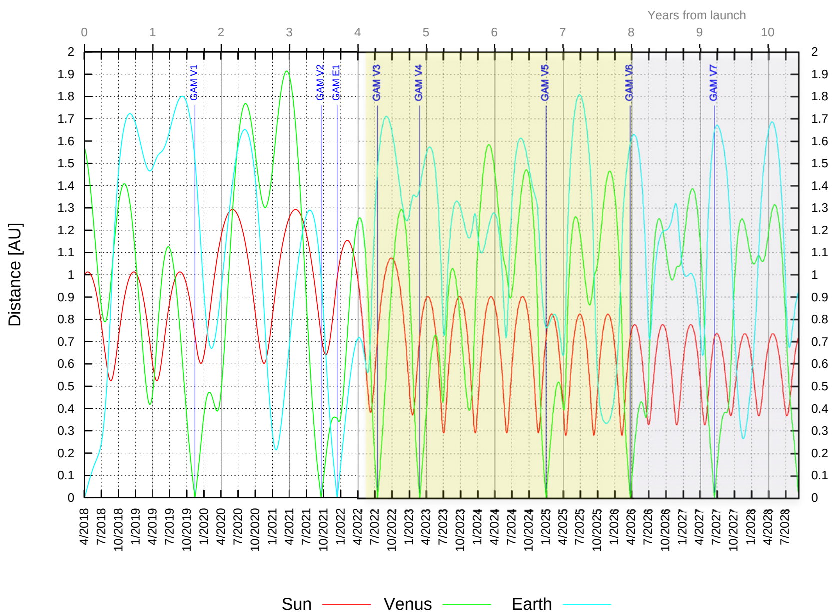

Figure 11 2018 April launch: evolution of distances to Sun, Venus and Earth

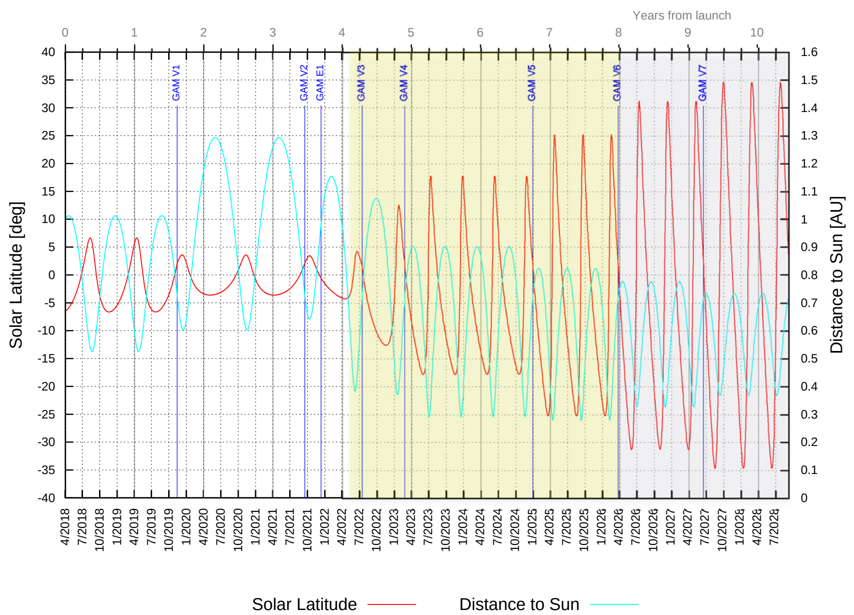

Figure 12 2018 April launch :evolution of solar latitude and Sun distance

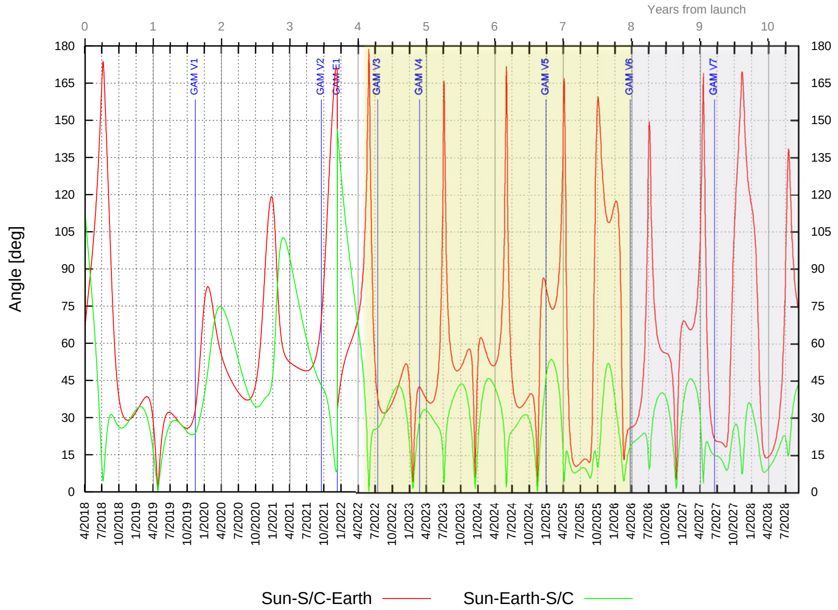

Figure 13 2018 April launch: evolution of comms angles SSE and SES

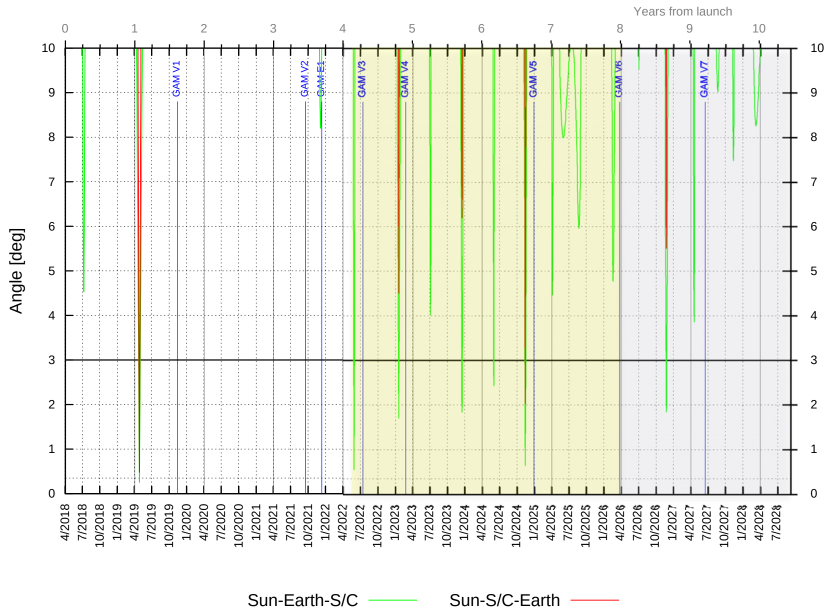

Figure 14 2018 April launch: evolution of comms angles SSE and SES (zoom)

	Type	Start	End	Duration [days]	Min SES [deg]
1	Superior	2019-04-23	2019-05-01	8.8	0.25
2	Inferior	2022-05-27	2022-05-30	2.6	0.56
3	Superior	2023-01-17	2023-01-21	4.2	1.70
4	Superior	2023-12-16	2023-12-19	3.1	1.84
5	Inferior	2024-05-31	2024-06-01	1.3	2.43
6	Superior	2024-11-12	2024-11-16	4.3	0.65
7	Superior	2026-11-23	2026-11-26	3.6	1.84

Table 3 2018 April launch: Solar Conjunction Periods (SES<3 deg)

	Start	End	Duration [days]
1	2019-04-20	2019-05-05	14.8
2	2023-01-16	2023-01-22	5.9
3	2023-12-16	2023-12-19	3.1
4	2024-11-11	2024-11-16	4.6
5	2026-11-22	2026-11-27	4.3

Table 4 2018 April launch: Safe Mode Blackout Periods (SES<3 deg & SSE<10 deg)

GAMs

The following table summarizes the characteristics of the Earth and Venus GAMs during the trajectory. There is a total of 8 GAMs, which is within the allocation for navigation in the Delta-V budget.

As can be seen the trajectories have been made compatible with the currently accepted constraint of a minimum altitude of 350 km during GAMs.

	Date	Re [AU]	V_∞ [km/s]	Hmin [km]	Eclipse [min]	Occultation [min]
GAM-V1	2019-11-13	1.516	11.509	6659	0.0	13.8
GAM-V2	2021-09-17	0.987	11.508	18413	0.0	15.4
GAM-E1	2021-12-12	0	13.446	828	25.7	0.0
GAM-V3	2022-07-15	1.481	18.599	350	23.6	1.4
GAM-V4	2023-02-25	1.391	18.599	350	17.9	0.0
GAM-V5	2024-12-30	0.763	18.597	350	13.2	0.0
GAM-V6	2026-03-24	1.594	18.599	350	10.3	13.3
GAM-V7	2027-06-17	1.651	18.598	350	9.9	8.3

Table 5 2018 April launch: GAMs Characteristics

Evolution of Sun distance and latitude during science phase

The following figures show the evolution of the solar latitude with respect to the distance to the Sun during the orbits of the science mission NMP + EMP. The first plot shows directly both parameters, while the second plot shows the components of the position vector in the Sun Equator plane (Rxy) and perpendicular to it Z. This plot respects the ratio of dimensions so that it allows showing as well the distance to the Sun (grey circles) and the solar latitudes (orange lines).

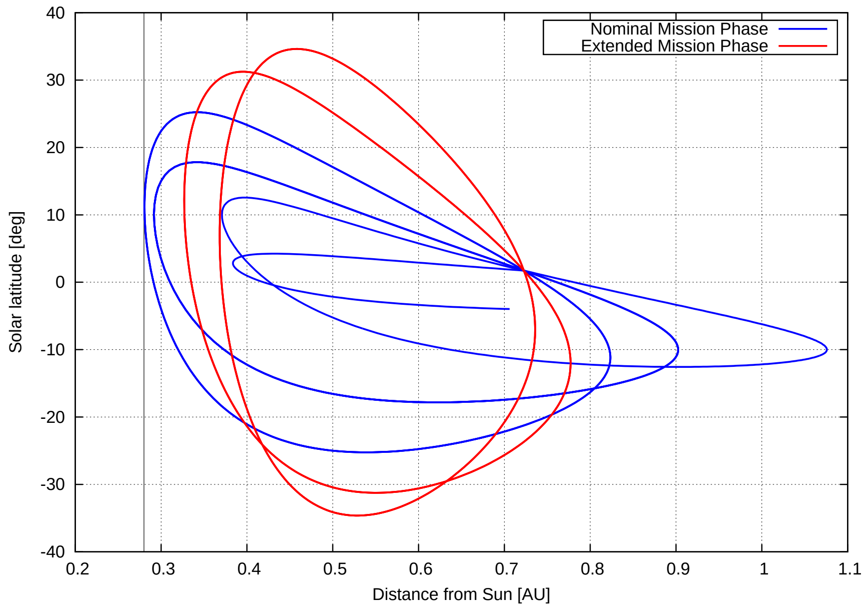

Figure 15 2018 April launch: solar latitude vs. Sun distance during science phase

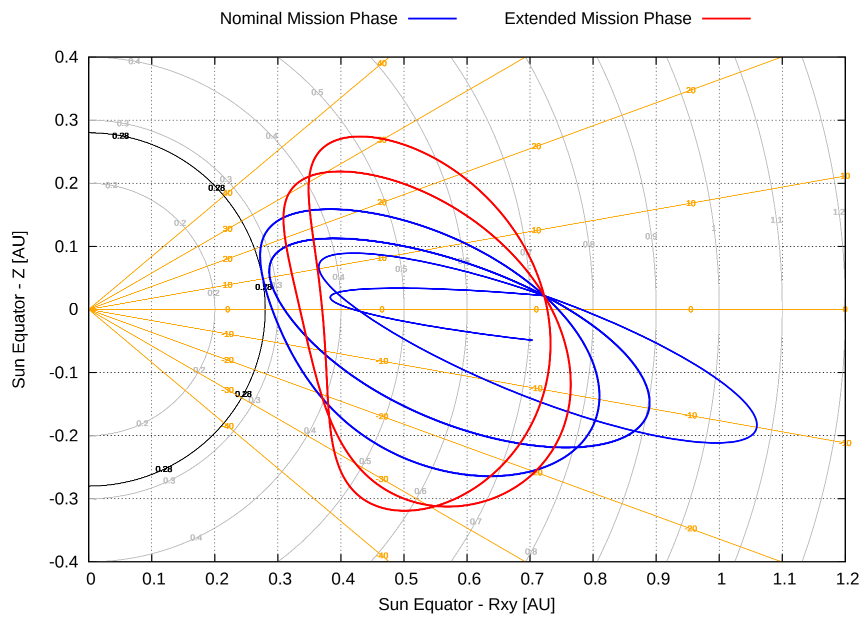

Figure 16 2018 April launch: projection in Sun Equator cylindrical RZ

Launch Windows Analysis

The proposed trajectory requires a relatively low and positive declination of the launch asymptote (DLA) and quite large infinite velocities above 5 km/s. These launch conditions are compatible with the mission baseline launch vehicle – Atlas V 411.

The full analysis of the launch window with Atlas V 411 launch has been performed assuming no constraint on the escape DLA and a maximum capability of the launcher to deliver 5.6 km/s to the 1800 kg SolO spacecraft. The following launch period has been identified:

Launch vehicle	Baseline Launcher Atlas V 411
Launch period (days)	30
Launch dates	Apr-03 – May-02
Escape velocity [km/s]	5.031 – 5.533
DLA [deg]	8.5 – 13
Final solar inclination [deg]	34.62 – 34.90

Table 6 2018 April Atlas V 411 launch window: Summary

Regarding the backup launch vehicle, Ariane 5 ECA, a preliminary assessment based on the escape performance map (Vinf vs DLA) as provided by Arianespace in the frame the ExoMars (RD3) shows that such a launch is not possible. For the declinations involved the launcher seems to be capable of reaching only infinite velocities that are lower than the required ones. Since the mentioned analysis is 7 years old and some of the main assumptions involved could have changed, it might be worth requesting Arianespace to investigate the feasibility of an Ariane 5 ECA launch into the required escape conditions.

The plots in the next pages provide a summary of the variation of the most relevant parameters with the launch day across the launch window. The highlighted region with the yellow background shows the limits of the selected launch period.

For a launch with Atlas V 411 no issue across the proposed launch windows has been identified with respect to the spacecraft engineering constraints or the science goals. In fact most of the parameters present small variations with the launch day.

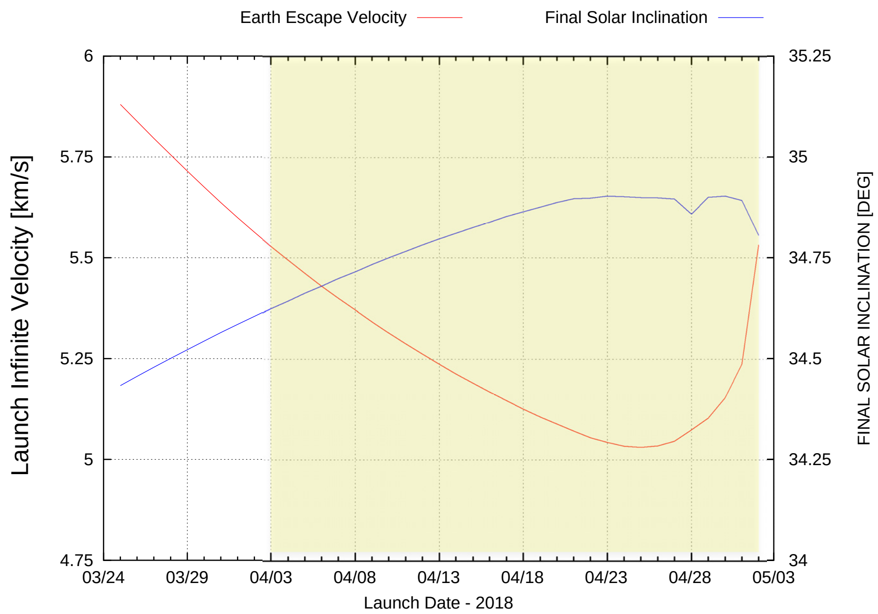

Figure 17 2018 April Atlas V411 launch window: infinite velocity and solar inclination

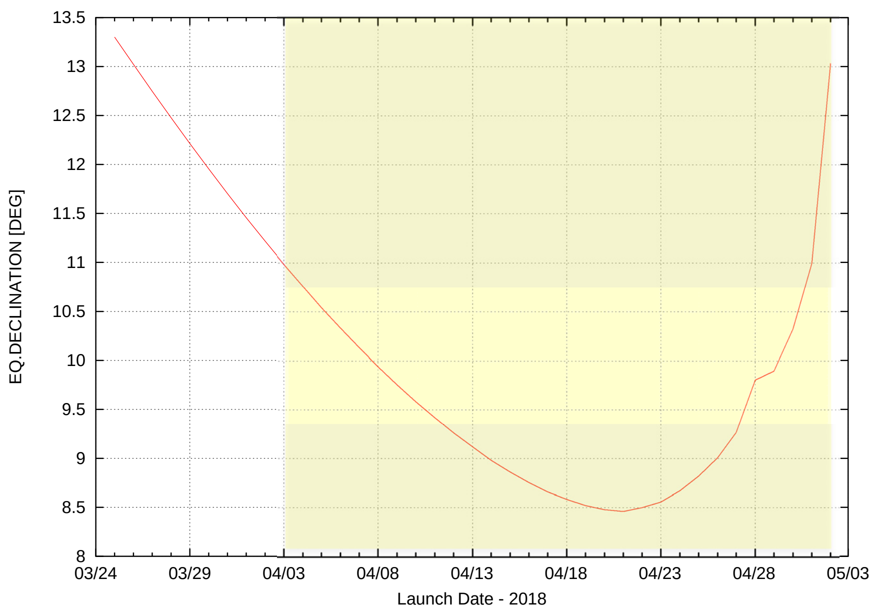

Figure 18 2018 April Atlas V411 launch window: launch DLA

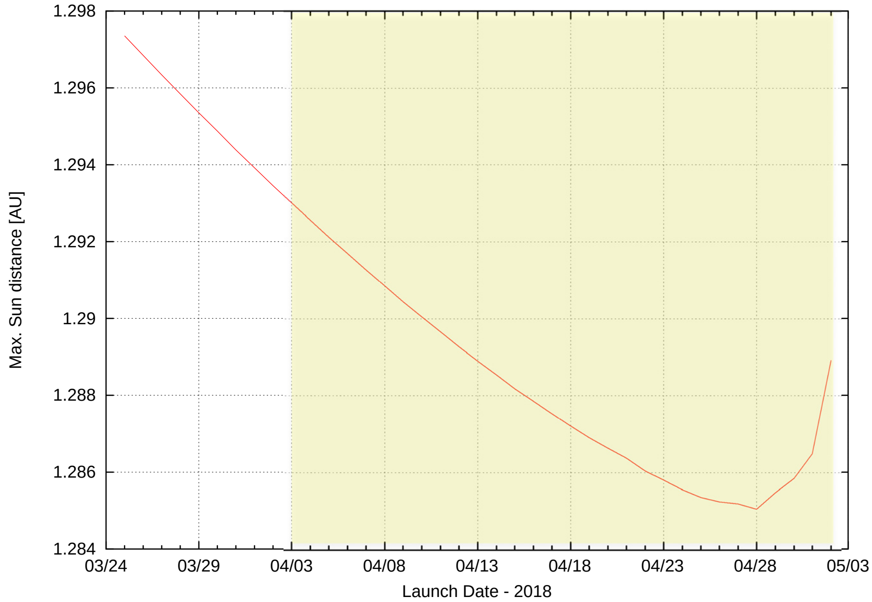

Figure 19 2018 April launch window: infinite velocity and solar inclination

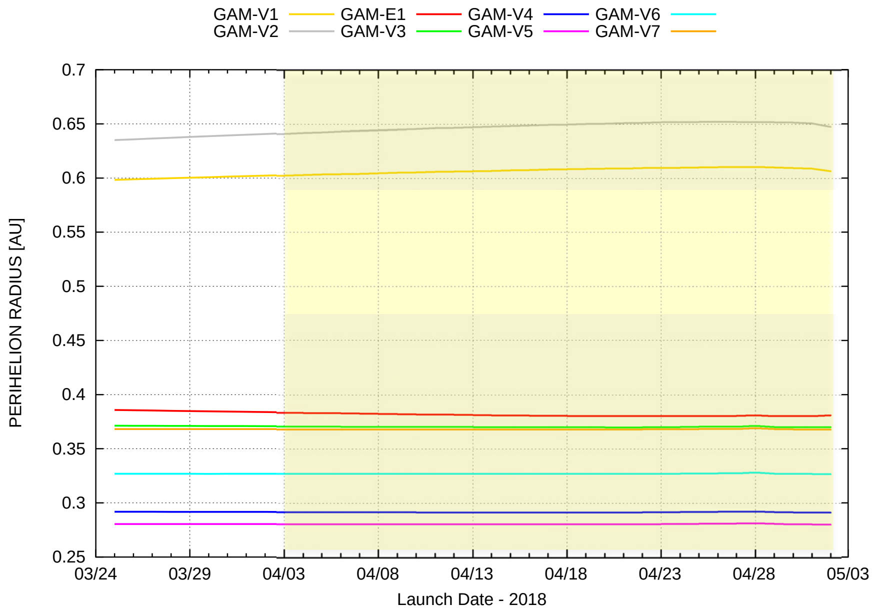

Figure 20 2018 April launch window : Perihelion radius

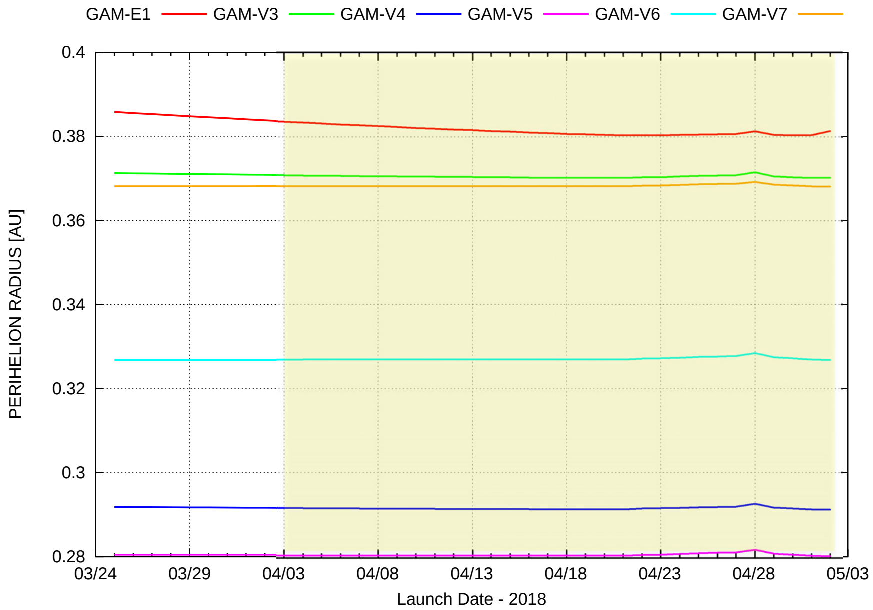

Figure 21 2018 April launch window: Perihelion radius – Science phase

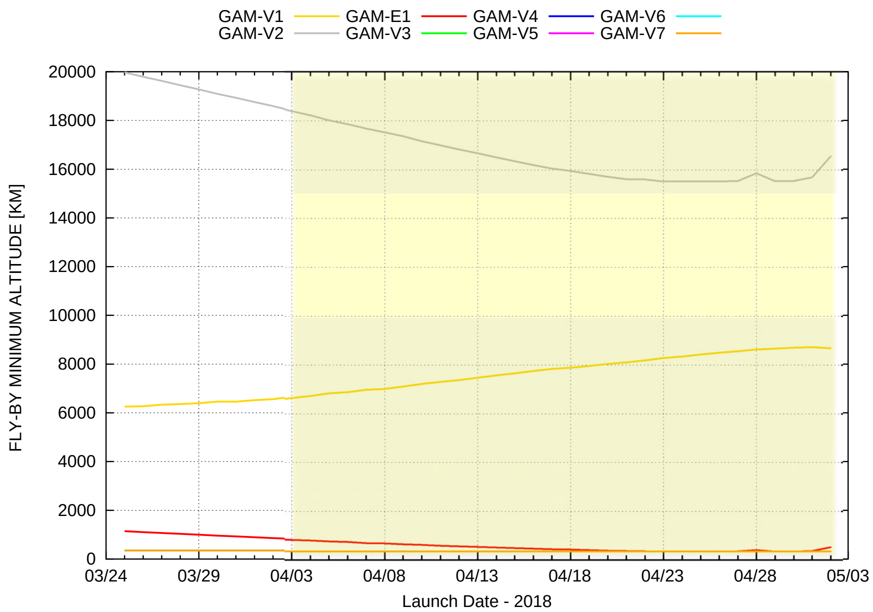

Figure 22 2018 April launch window: GAM altitudes

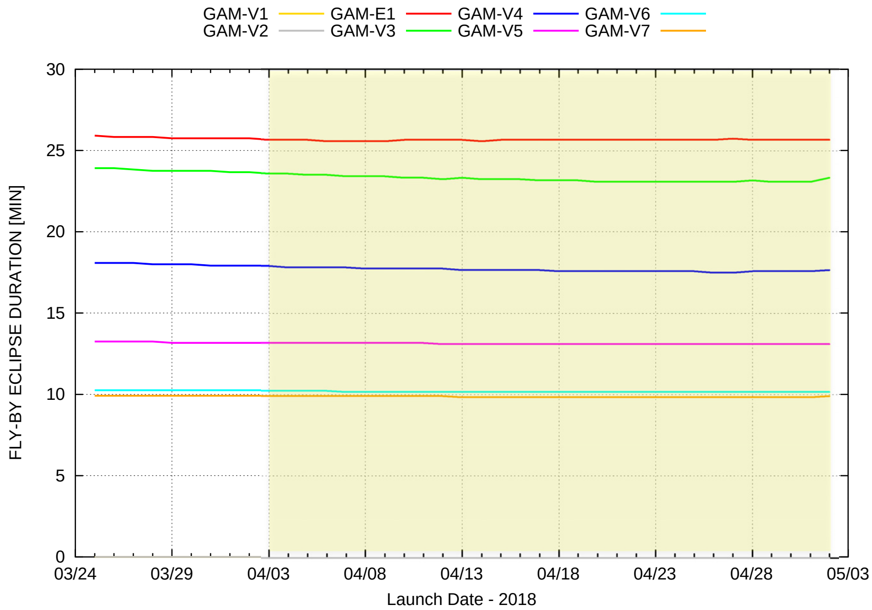

Figure 23 2018 April launch window: GAM eclipses

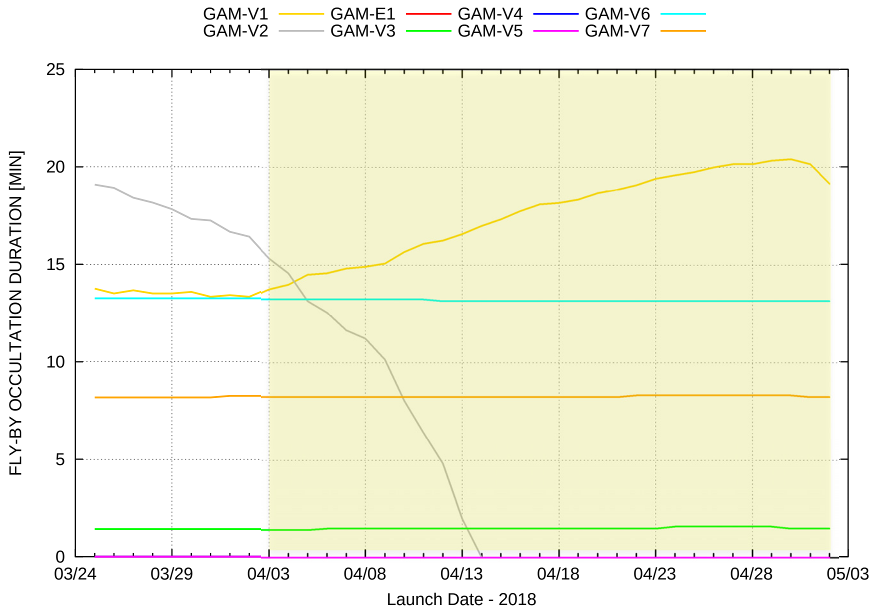

Figure 24 2018 April launch window: GAM Occultations

Conclusions

A launch opportunity for Solar Orbiter on 2018 April has been identified that:

- Is compatible with the mission baseline launch vehicle Atlas V 411 from KSC providing a 30-day launch window

  It is in principle not compatible with an Ariane 5 ECA launch. This statement should be confirmed by Arianespace.

- Allows launching 6 months earlier than the current 2018 October backup and does not present any conflict with the Solar Probe Plus launch window starting end of July

- Is compliant with most of the global mission and spacecraft engineering constraints

  The main drawback in this sense is the slightly longer duration than the currently longest accepted trajectory and the spacecraft lifetime requirement in the SSRD. Additionally the occurrence of 2 aphelion passages at maximum Sun distance instead of one is not in any of the previous mission profiles. Given the moderate 1.3 AU maximum distance this is not believed to create big issues.

  The overall number of GAMs for the trajectory is 8. The Delta-V that is required for the navigation of this number of GAMs is already contained in the mission Delta-V budget. Thus this trajectory does not impact the Delta-V or propellant allocation.

- Achieves the mission science goals with small delays with respect to the current trajectories

  This is produced by the longer cruise phase that delays a bit the first science perihelion passage below 0.3 AU and the final science orbit with the maximum solar inclination

An extensive analysis of the proposed trajectory opportunity has been carried out already and is provided in this document for the consideration of the Solar Orbiter project. In a preliminary assessment at mission analysis level the drawbacks of adopting this trajectory are not found to significantly impact the mission, but it is recommended that this is confirmed by further analysis by the experts in each field.