Solar Orbiter alternative trajectories with launch in late 2018

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Introduction

1. Trajectories previously identified
    - 2018 October as described in CReMA
    - 2018 October options A & A1 by Dr. Langevin
    - 2018 October option D (ESOC modification of option A)
    - 2018 November short by Dr. Langevin

2. New trajectory proposed:
    - 2018 October EVVEV short

Other trajectory possibilities have been identified and analysed, but have been found not superior

Trajectory evaluation – 2018 Oct EVVEV

1. Atlas V 411 launch possible from late September to October 20th
   - 30-day LW requires $V_\infty \in (5.07,5.53)$ km/s, DLA$\in$(-12.5,-0.6) deg
   - 20-day LW using Ariane 5 ECA is challenging and requires further detailed analysis and confirmation from Arianespace
2. New trajectory uses a fast EVVEV cruise phase → Very early science
   - Cruise phase until Earth GAM takes 2.26 years
   - **Distance to the Sun < 1.15 AU, no hibernation phase**
   - 2 perihelions at 0.346 AU to start remote sensing in the Earth-Venus arc
3. Core 4:3 science orbit reached only 3.15 years after launch
   - Perihelion just < 0.3 AU and **extremely good performance for data return**
4. Solar **inclination > 31 deg in only 7.5 years** after launch
5. An additional GAM and 3:2 resonant orbit can raise inclination to 33 deg

Full description of trajectory and launch window attached in the extract of the update of SOL-ESC-TN-50007 in preparation

Trajectory Summary

Case	CReMA	2018 Oct CReMA	2018 Option A1	2018 Option D	2018 Nov short	New 2018 EVVEV short	2020 Feb (2019)	2020 Jun (2019)
Venus resonances sequence		1:1 1:1 4:3 3:2 3:2	1:1 4:3 4:3 3:2 5:3	5:4 4:3 3:2 3:2	1:1 4:3 3:2 5:3 NR	**4:3 3:2 3:2 5:3 (3:2)**	1:1 4:3 3:2 5:3 NR	1:1 4:3 3:2 5:3 NR
Launch		2018-10-10	2018-11-07	2018-11-07	2018-11-01	**2018-09-30**	2020-02-27	2020-06-10
Vinf (km/s)	3.373 – 5.445	4.952	5.600	5.618	4.611	**5.221**	4.816	4.771
Declination (deg)	-42.6 -26.1	-6.6	-17.4	-17.5	-5.3	**-8.9**	22.4	-6.9
Duration (y)	8.87 – 10.24	9.46	11.20	10.59	9.47	**9.30 (10.53)**	9.84 (10.84)	9.48 (10.48)
Min Sun distance (AU)	≥ 0.280	0.282	0.281	0.290	0.282	**0.280**	0.280	0.281
Max Sun distance (AU)	1.186 – 1.478	1.471	1.444	1.444	1.484	**1.124**	1.102	1.501
Cruise duration (y)	2.94 – 3.40	3.17	3.05	3.05	2.73	**2.26**	2.46	2.10
1st perih. < 0.3 AU (y)	3.50 – 4.67	3.49	4.54	3.92	5.96	**3.50**	5.20	5.94
# Perih < 0.3 AU	7 – 12	8	9	15	10	**12**	13	10
Time spent < 0.3 AU (d)	46.5 – 101.6	62	70	52	84	**71**	113	96
# Below 0.4 AU	12 - 16	15	18	16	18	**20**	18	18
Time spent < 0.4 AU (d)	292.8 – 421.4	321	462	404	458	**490**	492	470
Time to max. solar i (y)	7.86 – 9.20	8.44	9.56	9.58	7.79	**7.46 (9.30)**	8.22	7.86
Max. solar i (deg)	32.38 - 36.36	32.87	33.43	32.41	30.44	**31.31 (32.92)**	34.30	32.69
Max. angular rate (deg/d)	7.76 – 8.31	8.137	8.018	7.728	7.106	**7.820**	7.484	7.323
SM Blackouts*: longest (d)	≤ 61.0	46.8	37.9	43.5	20.3	**45.4**	52.2	37.5
Conjunctions*: longest (d)	≤ 44.0	14.4	22.2	21.3	4.0	**25.2**	30.9	3.9
Longest eclipse (min)	≤ 37.1	27.4	30.8	30.8	30.0	**26.6**	25.8	33.3
Longest occultation (min)	≤ 35.1	8.8	6.4	4.8	0.0	**10.8**	22.1	0.0

Other comparisons

Comparison of the first 4:3 science orbit

	2018 Oct CReMA	2018 A1	2018 D (5:4 orbit)	2018 Nov	New 2018 EVVEV	2020 Feb	2020 Jun
Start date	2023-12-03	2023-04-14	2022-09-02	2021-07-26	**2021-11-24**	2023-03-24	2023-02-27
After launch	5.15*	4.44	3.82	2.73	**3.15***	3.07 (4.07)	2.72 (3.72)
Rp (AU)	0.290	0.281	0.290	0.333	**0.295**	0.313	0.313
R at max. lat. (AU)	0.600	0.585	0.611	0.359	**0.357**	0.347	0.697
R at min. lat. (AU)	0.347	0.340	0.349	0.726	**0.589**	0.692	0.346
Perihelion latitude (deg)	-11.08	-8.37	-6.46	15.06	**6.30**	15.08	-14.20
w at perih. (deg/day)	7.492	7.983	7.717	6.213	**7.445**	6.806	6.825
Solar inclination (deg)	21.68	16.88	12.71	19.84	**13.07**	21.88	20.28
Downlink index (1/AU²)	0.73	1.60	2.43	0.90	**2.09**	0.81	0.92

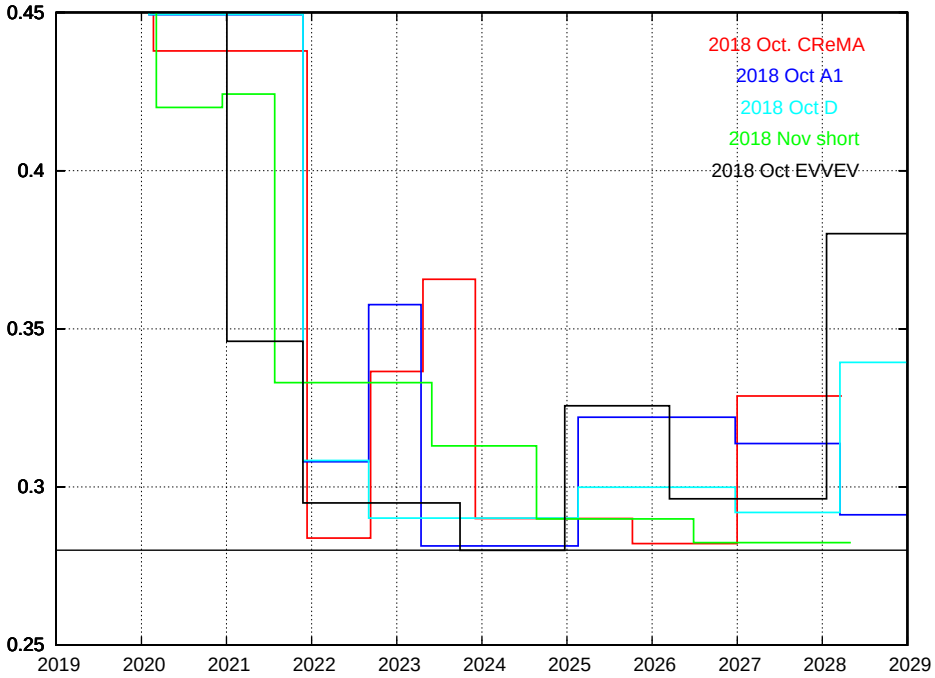
* In 2018 CReMA already 2 science orbits with Rp at 0.284 AU and 0.337 AU.
In 2018 EVVEV already 2 science orbits with Rp 0.346 AU

Comparison of downlink index

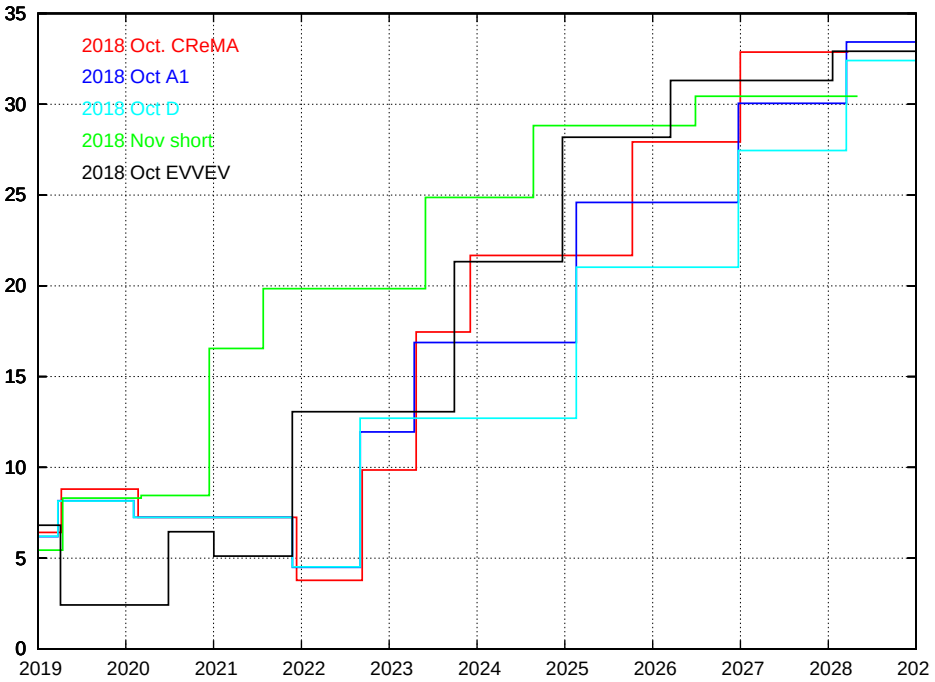
	2018 Oct CReMA	2018 A1	2018 D	2018 Nov	New 2018 EVVEV (10.5 y)	New 2018 EVVEV (9.3 y)	2020 Feb	2020 Jun
From V2/3 to end NMP	0.88	1.64	2.18	1.10	**1.74**	**1.74**	1.04	1.11
Entire EMP	1.36	1.14	1.28	1.29	**1.41**	**1.34**	1.29	1.29
From V2/3 to end EMP	1.09	1.43	1.89	1.20	**1.55**	**1.54**	1.17	1.20

Evolution of parameters

Perihelion Radius (AU)



Solar inclination (deg)



Conclusions

1. New EVVEV October short trajectory is fully compatible with all mission and spacecraft constraints and presents superior science performance

2. Of all the late 2018 trajectories currently regarded:
   - Fastest perihelion decrease
     - First trajectory to get < 0.35 AU and < 0.3 AU
     - Majority of NMP has perihelion < 0.3 AU (7 out of 9 perihelia)
   - 2nd fastest inclination increase
     - Only 2018 November is better, but final inclination gets only to 30 deg and perihelion < 0.3 AU achieved only during the EMP
   - 2nd best performance for data return
     - Only 2018 Oct D is better thanks to the 3 aphelia close to inferior conjunction of the 5:4 orbit instead of 2 aphelia of the 4:3

2018 October EVVEV

TRAJECTORY DETAILS

5.1 2018 October Short Cruise

5.1.1 Trajectory description

This trajectory is based on a short EVVEV transfer. The arc from launch to Venus is direct taking about half a year, the 2:2 resonance with Venus (1.2 years) is inserted basically to provide an adequate phasing for the next Venus-Earth arc of about half year as well. The maximum distance to the Sun of only 1.12 AU is achieved during the Venus-Earth arc, therefore no hibernation phase should be needed. The perihelion gets down to 0.346 AU after GAM-E1 marking the entry into the NMP after a very short cruise phase of 2.2 years. The Earth-Venus arc will offer 2 perihelion passages at this Sun range and low solar inclination before encountering Venus in the outbound leg. This is the fastest cruise phase that has been found in the analyzed launch timeframe leading to a solar inclination above 33 deg in less than 10 years.

The sequence of resonances 4:3 3:2 3:2 5:3 has been selected to provide close perihelions below 0.3 AU for the rest of the NMP and a gradual increase of the solar inclination to 21 deg. The first 3:2 resonance of the EMP raises the perihelion to 0.326 AU with solar inclination over 28 deg and then the 5:3 resonance provides another 5 perihelion passes below 0.3 AU with an inclination over 31 deg. A final 3:2 resonance has been added after a hypothetical GAM-V7 that shows that a final inclination of 33 deg can be achieved.

The 4:3 science orbit is reached 3.15 years after launch with a very good phasing at an Earth-Sun-Venus angle of -27 deg that provides one of the aphelia in an almost inferior conjunction configuration. The downlink capability of this orbit is very large providing an index of 2.09 $1/AU^2$. The following orbits provide a rather acceptable overall downlink capability.

The overall trajectory duration as presented is 10.53 years including the last 3:2 resonance and 9.3 years up to the end of the 5:3 resonance.

It must be pointed out that there is some flexibility for the end of the trajectory. If a shorter trajectory is preferred, the EMP can be declared finished at the end of the 5:3 resonant orbit. The final solar inclination of 31.3 deg is so reached in only 7.5 years from launch and the trajectory up to this point includes 12 perihelions below 0.3 AU and 17 below 0.35 AU in 9.3 years. For the presentation of the trajectory an additional 3:2 resonance has been added to the EMP. This implies a raise of the perihelion to 0.38 AU and of the solar inclination by additional 1.6 deg with respect to the previous 5:3 orbit. An alternative to the final 3:2 resonance can be the selection of a 5:3 resonance with perihelion at 0.305 AU and solar inclination of 32.3 deg, or the selection of a non-resonant orbit at the closest perihelion of 0.28 AU and solar inclination of 31.9 deg. Thus, the penalty in final solar inclination with respect to the 3:2 option is 0.6 deg for the 5:3 and 1 deg for the non-resonant.

Another alternative for the end of the mission is to select a 3:2 resonance after GAM V6 raising the perihelion to about 0.363 AU and the inclination to 31.7 deg. The advantage of doing this is that the final maximum solar inclination after GAM V7 can be reached 1 Venus revolution faster, that is 0.6 years before or from launch in only 8.7 years. It will then be natural to go for a lower perihelion for the last science orbits of the mission, either in the 5:3 resonance or in a non-resonant orbit. However, in this case the inclination increase produced by GAM V7 is rather limited. These alternatives are illustrated in the V-infinity diagram (Figure 73).

This trajectory has been also analyzed preliminarily from the point of view of navigation. One of the possible issues might be related to the 2:2 resonance with Venus in the cruise phase. Actually this

means that the spacecraft and Venus have the same period and encounter each other after every revolution. During the first encounter after one revolution the spacecraft must fly-by Venus at large distance such as to avoid modifying the heliocentric orbit. This will probably require a small trajectory correction manoeuvre to ensure that the spacecraft stays far away from the planet. At the second encounter the spacecraft will have to perform the GAM-V2 for which accurate navigation is needed. The geometry is such that there is a superior conjunction ending 40 days before the first Venus encounter (for SES < 3 deg). Thus a comfortable time margin is available for any navigation activity before the encounter with Venus. There is also an inferior conjunction ending 16 days before GAM-V2. This later is rather short: the SES stays below 3 deg for only 3 days and the minimum SES is 1.6 deg. Based on ESOC's operational experience, communication disruptions can be expected for SES angle below 1.5 deg. Therefore, it is not expected that the mentioned solar conjunctions pose any issue or added risk to the navigation of this trajectory.

Phase	Cruise			NMP			EMP		
Trajectory arc	L-V1	V1-V2	V2-E1	E1-V3	V3-V4	V4-V5	V5-V6	V6-V7	V7-End
Start	2018-09-30	2019-04-04	2020-06-26	2021-01-01	2021-11-24	2023-09-29	2024-12-21	2026-03-15	2028-01-19
Flight time at start (years)	0.00	0.51	1.74	2.26	3.15	5.00	6.23	7.46	9.30
Duration (days)	186	449	189	326	674	449	449	674	449
Number of revolutions Venus Resonance	0	2 2:2	0	1	4 4:3	3 3:2	3 3:2	5 5:3	3 3:2
Period (days)	257.0	224.7	304.7	203.2	168.5	149.8	149.8	134.8	149.8
R at aphelion (AU)	1.012	0.927	1.124	1.007	0.899	0.824	0.778	0.733	0.724
R at max. latitude (AU)	0.991	0.823	0.649	0.429	0.357	0.348	0.399	0.405	0.514
R at min. latitude (AU)	0.577	0.560	1.120	0.645	0.589	0.523	0.541	0.440	0.484
R at perihelion (AU)	0.570	0.520	0.648	0.346	0.295	0.280	0.326	0.296	0.380
Perihelion latitude (deg)	-6.43	-1.64	6.38	2.11	6.30	8.51	10.00	2.94	-3.02
ω at perih. (deg/day)	2.606	2.974	2.142	5.892	7.445	7.741	5.723	6.249	4.055
Ecliptic inclination (deg)	1.90	5.32	12.23	2.48	7.73	15.91	22.75	25.87	27.48
Solar inclination (deg)	6.81	2.43	6.45	5.12	13.07	21.33	28.19	31.31	32.92
Downlink index ($1/AU^2$)	3.87	0.82	4.45	1.56	2.09	1.23	1.79	1.05	1.56

Table 32: 2018 October short – Trajectory Summary

GAM	Date	Re (AU)	Vinf (km/s)	Hmin (km)	Eclipse (min)	Occult. (min)	Ls (deg)	SSE (deg)	SES (deg)	ESV (deg)
V1	2019-04-04	1.294	9.871	9000	0.0	0.0	289.7	50.3	34.0	95.7
V2	2020-06-26	0.362	9.870	1459	26.6	0.0	289.7	135.1	30.4	14.5
E1	2021-01-01	0.000	9.722	351	0.0	0.0	101.1	-	-	-
V3	2021-11-24	0.479	17.492	350	18.7	0.0	34.4	108.6	44.0	-27.4
V4	2023-09-29	0.510	17.492	350	14.1	0.0	34.4	107.4	43.6	29.0
V5	2024-12-21	0.827	17.492	350	10.7	0.0	34.4	78.4	46.1	-55.5
V6	2026-03-15	1.620	17.493	350	10.6	10.1	34.4	22.9	16.5	-140.6
V7	2028-01-19	1.156	17.493	1158	8.0	10.8	34.4	57.8	38.5	-83.7

Table 33: 2018 October short – GAM Properties

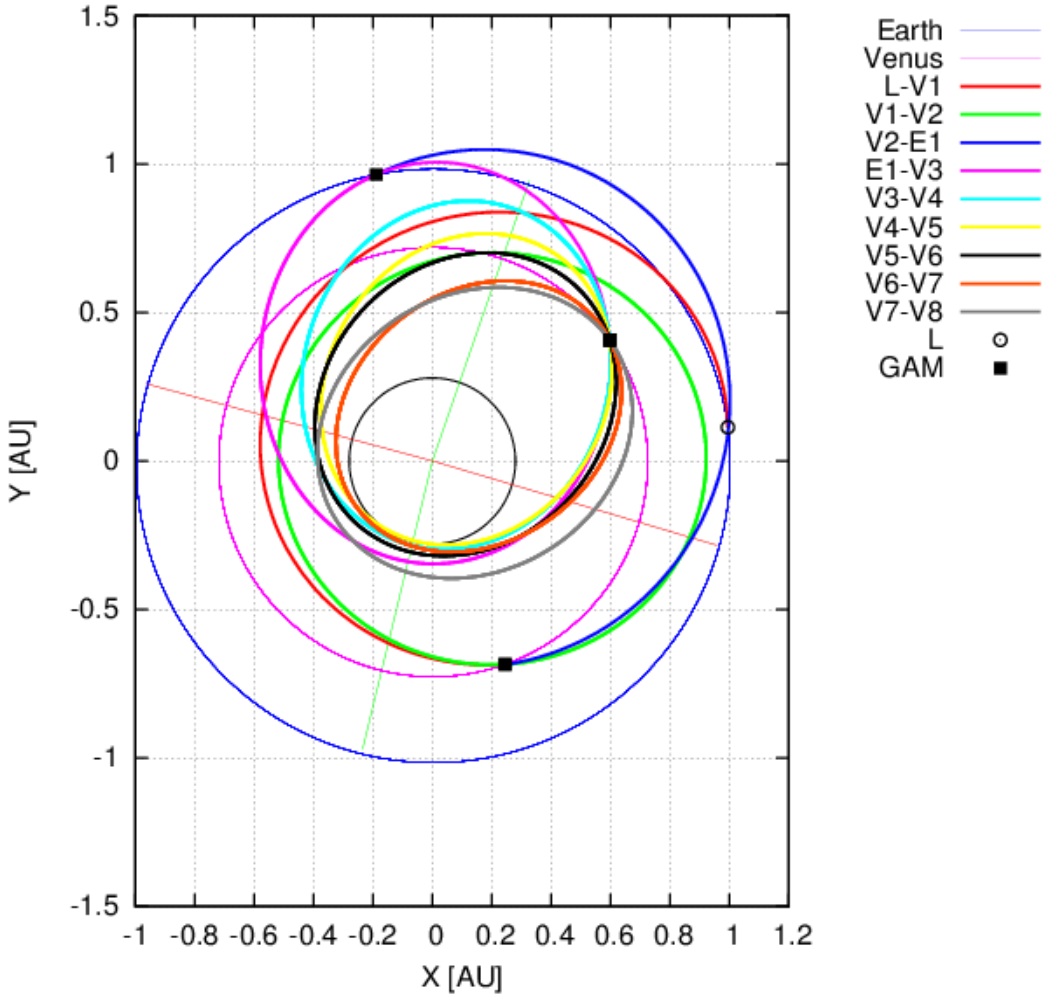


Figure 70: 2018 October short – Trajectory Projection in the Ecliptic Plane

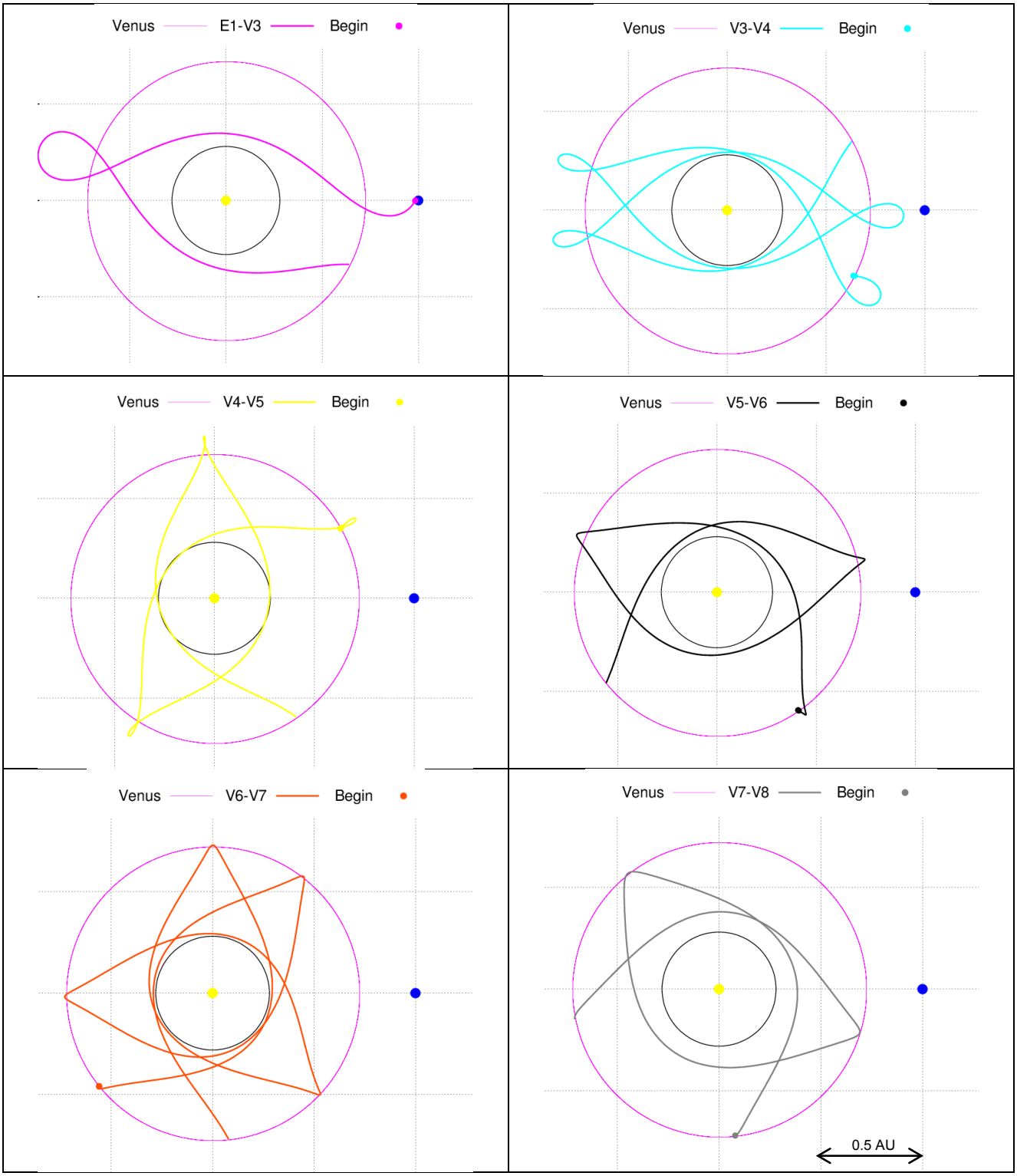
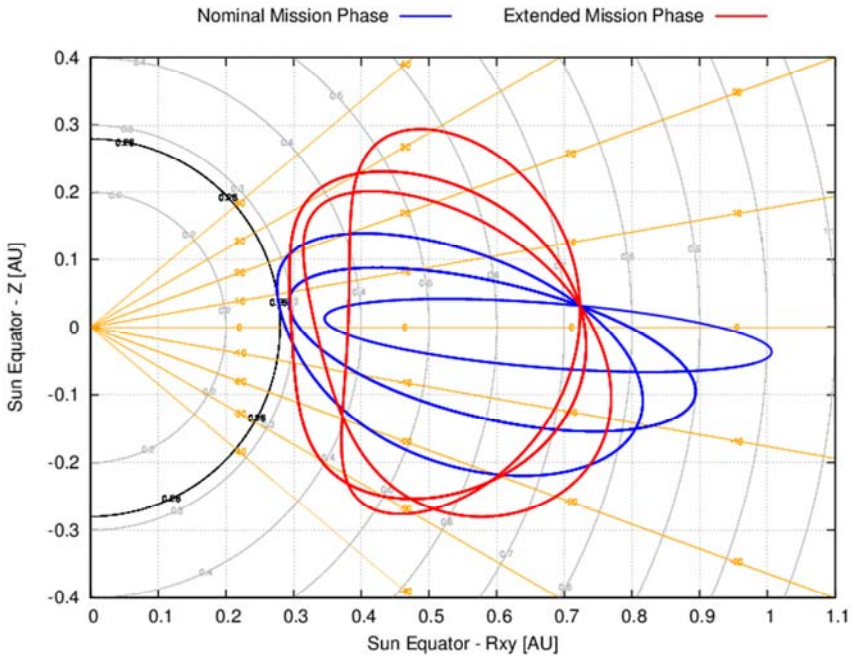


Figure 71: 2018 October short – Trajectory Projection in the Ecliptic Plane



Note: plot includes the last 3:2 orbit of the after GAM V7 in the EMP

Figure 72: 2018 October short – Trajectory projection of science orbits wrt Sun Equator and North Pole

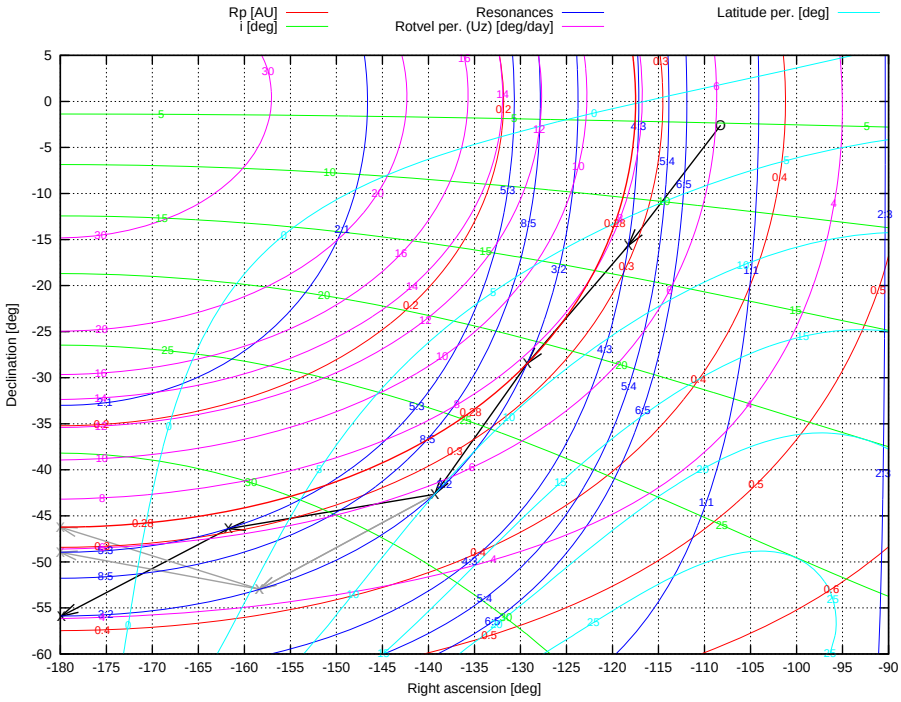


Figure 73: 2018 October short – V-infinity diagram

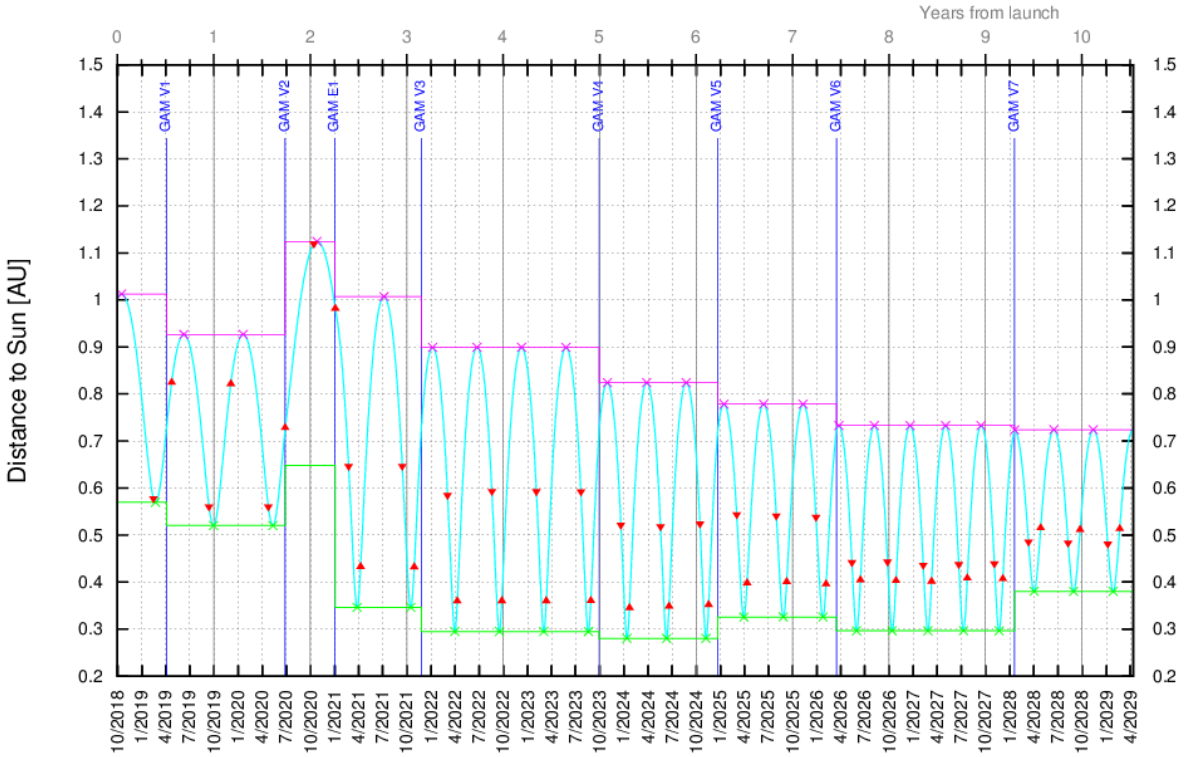


Figure 74: 2018 October short – Distance to Sun

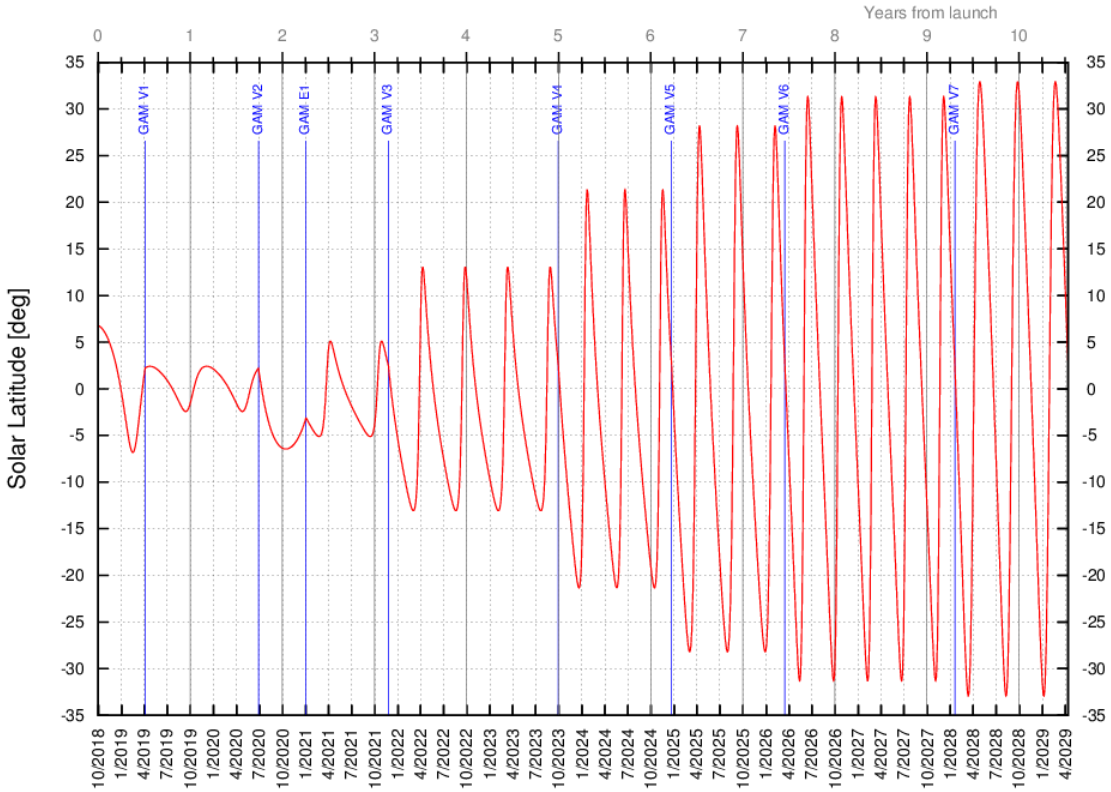


Figure 75: 2018 October short –Solar latitude

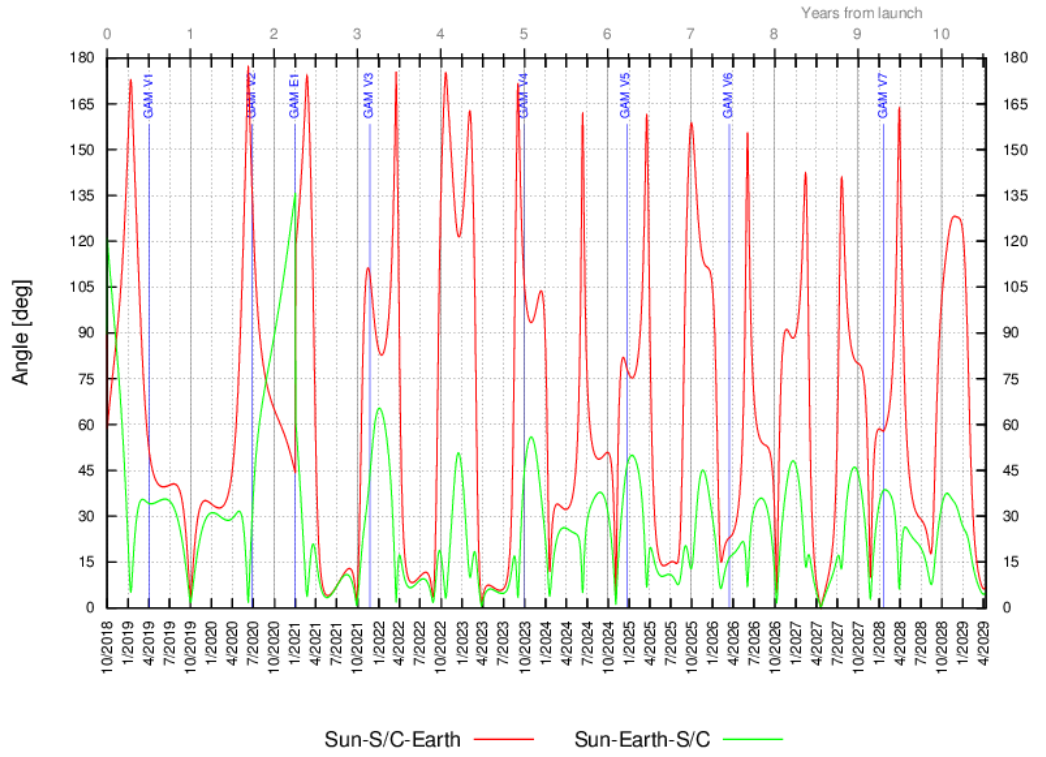


Figure 76: 2018 October short – Communication angles SES and SSE

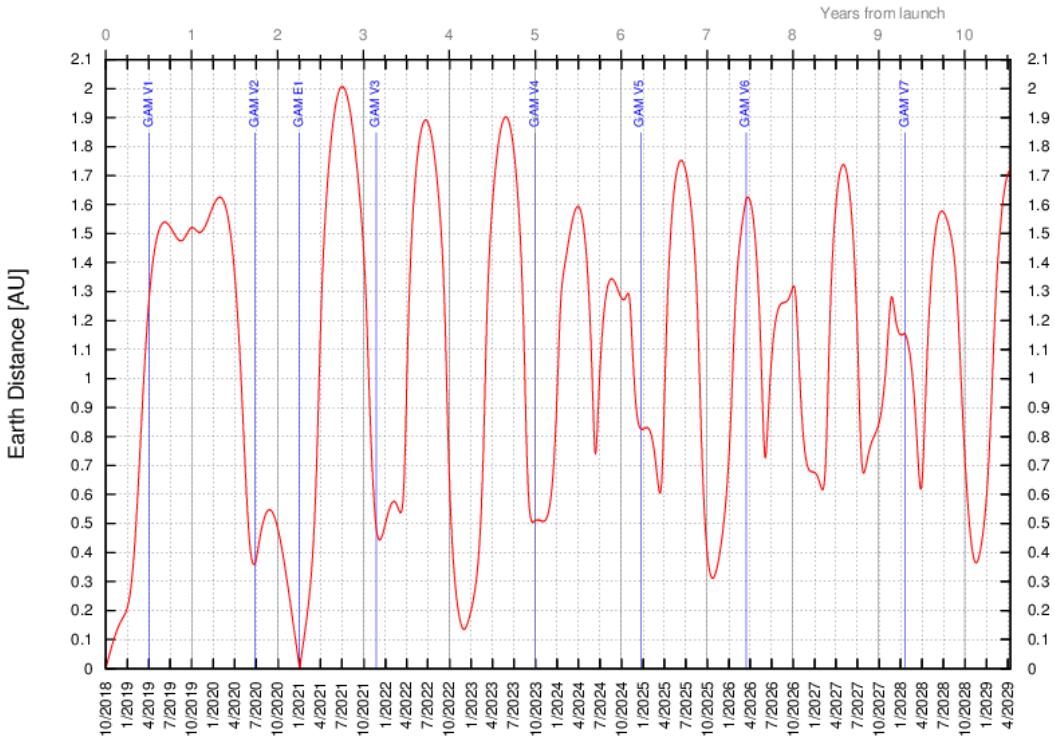


Figure 77: 2018 October short – Distance to Earth

Solar Conjunction Periods
SES<3 deg

	Type	Start	End	Duration [days]	Min SES [deg]
1	Superior	2019-09-27	2019-10-04	7.1	1.80
2	Inferior	2020-06-07	2020-06-10	2.8	1.62
3	Superior	2021-09-21	2021-09-30	9.2	0.83
4	Inferior	2022-03-17	2022-03-19	2.3	1.79
5	Superior	2022-08-22	2022-08-30	8.5	1.75
6	Superior	2023-03-21	2023-04-04	14.4	0.53
7	Superior	2024-11-01	2024-11-05	3.8	0.97
8	Superior	2026-10-07	2026-10-10	3.8	1.48
9	Superior	2027-04-08	2027-05-03	25.2	0.07
10	Superior	2027-11-22	2027-11-23	0.4	2.95

Safe Mode Blackout Periods
SES<5 deg & SSE<10 deg

	Start	End	Duration [days]
1	2019-09-23	2019-10-07	13.9
2	2021-04-29	2021-06-14	45.4
3	2021-09-17	2021-10-02	15.3
4	2022-08-16	2022-09-01	15.7
5	2023-03-19	2023-04-14	26.7
6	2023-06-09	2023-07-07	27.6
7	2024-11-01	2024-11-05	3.7
8	2026-10-06	2026-10-10	3.9
9	2027-03-31	2027-05-12	41.9
10	2027-11-22	2027-11-23	0.4
11	2029-03-24	2029-04-11	18.5

Table 34: 2018 October short - Solar Conjunctions

5.1.2 Launch window analysis

The analysis of the launch window for this trajectory shows an interesting variation of the required infinite velocity and the achieved final inclination (see Figure 78). The infinite velocity is always rather large, at least 5.074 km/s on October 15th. From September 15th onwards it decreases slowly with the launch day until reaching this minimum, but then increases sharply exceeding 5.6 km/s by October 21st. On the other hand, the solar inclination after GAM-V6 and consequently after GAM-V7 increase steadily with the launch day, smoothly during the period from September 30th to October 15th and sharply beyond this launch day. This means that launching on the launch window open day will lead to the overall lowest solar inclination.

The following table proposes a 30-day and a 20-day launch period for Atlas V 411. By reducing the launch window it is possible to increase the final solar inclination by 0.6 deg with no impact to any other major trajectory parameter. As shown by the figures, the perihelion radii during the science phase remain stable across the launch window. Only the perihelion after GAM-E1 shows a smooth decrease with the launch day, meaning also that late launch dates will also provide slightly better conditions for the science observations at this point. After October 21st it becomes difficult to meet the 0.28 AU minimum perihelion constraint, but the required infinite velocity is already too large for these late launch days.

All the trajectories were constrained in order to maintain an acceptable eclipse duration at GAM-V2. This has been achieved by trying to fix the minimum altitude at GAM-V1 to 9000 km, which is possible for all launch dates after September 19th. This leads to a comfortable longest eclipse of 26.8 minutes at GAM-V2.

The DLA for this trajectory is negative and increasing with the launch day from -12.5 and -0.6 deg for the 30-day launch window. The launch conditions are not far away from targets that can be achieved with an Ariane 5 ECA launch, but achieving a window of at least 20 consecutive launch days is quite challenging. Such a launch window is preliminarily proposed based on the use of 6

launch programs and a 45 m/s allocation for the adjustment of the infinite velocity vector with respect to the launch program target. This assumes that DLA and hyperbolic velocity must be corrected, while the correct RLA is provided by adjustment of the lift-off time.

Figure 79 shows the grouping of Earth escape targets with the launch programs. Two of the launch programs might be optimistic as they assume that DLA of -9.7 and -8.6 deg are feasible for an infinite velocity of 5.22 km/s. This needs confirmation from the launcher authority. The other launch programs have target infinite velocity between 5.1 and 5.19 km/s and DLA between -7.6 and -4.2 deg, which are deemed not so challenging for the launcher. Dedicated launch programs per launch day would be needed from October 17th to October 20th with increasing infinite velocity and the infinite asymptote approaching the Equator. Those might be considered as well if necessary to extend the launch window with Ariane 5 ECA.

A possible issue to further investigate in this trajectory is the variation of the longest safe mode blackout period with the launch day. For the reference trajectory described in the previous section with launch on September 30th this is 45.4 days. However, this parameter increases with the launch day so that for launch on October 20th a maximum duration of 63.7 days has been found. This value is marginally exceeding the current spacecraft constraint (61 days). This is not expected to have a major impact on the results provided in this document.

Launch vehicle	Atlas V 411	Atlas V 411	Ariane 5 ECA
Launch period (days)	30	20	20
Launch dates	2018 Sep-21 – Oct-20	2018 Oct-01 – Oct-20	2018 Sep-27 – Oct-16
Escape velocity (km/s)	5.074 – 5.529	5.074 – 5.529	5.101 – 5.216
DLA (deg)	-12.5 – -0.6	-8.6 – -0.6	-9.73 - -4.25
RLA (deg)	-55.4 – -37.8	-50.4 – -37.8	-52.3 – -34.7
Solar inclination GAM-V6 (deg)	30.73 – 32.32	31.36 – 32.32	31.11 – 31.64
Solar inclination GAM-V7 (deg)	32.34 – 33.93	32.96 – 33.93	32.73 – 33.29
Max. Sun distance (AU)	1.149	1.149	1.139
Longest eclipse (min)	26.8 (V2)	26.8 (V2)	26.8 (V2)

Table 35: 2018 October short launch windows summary

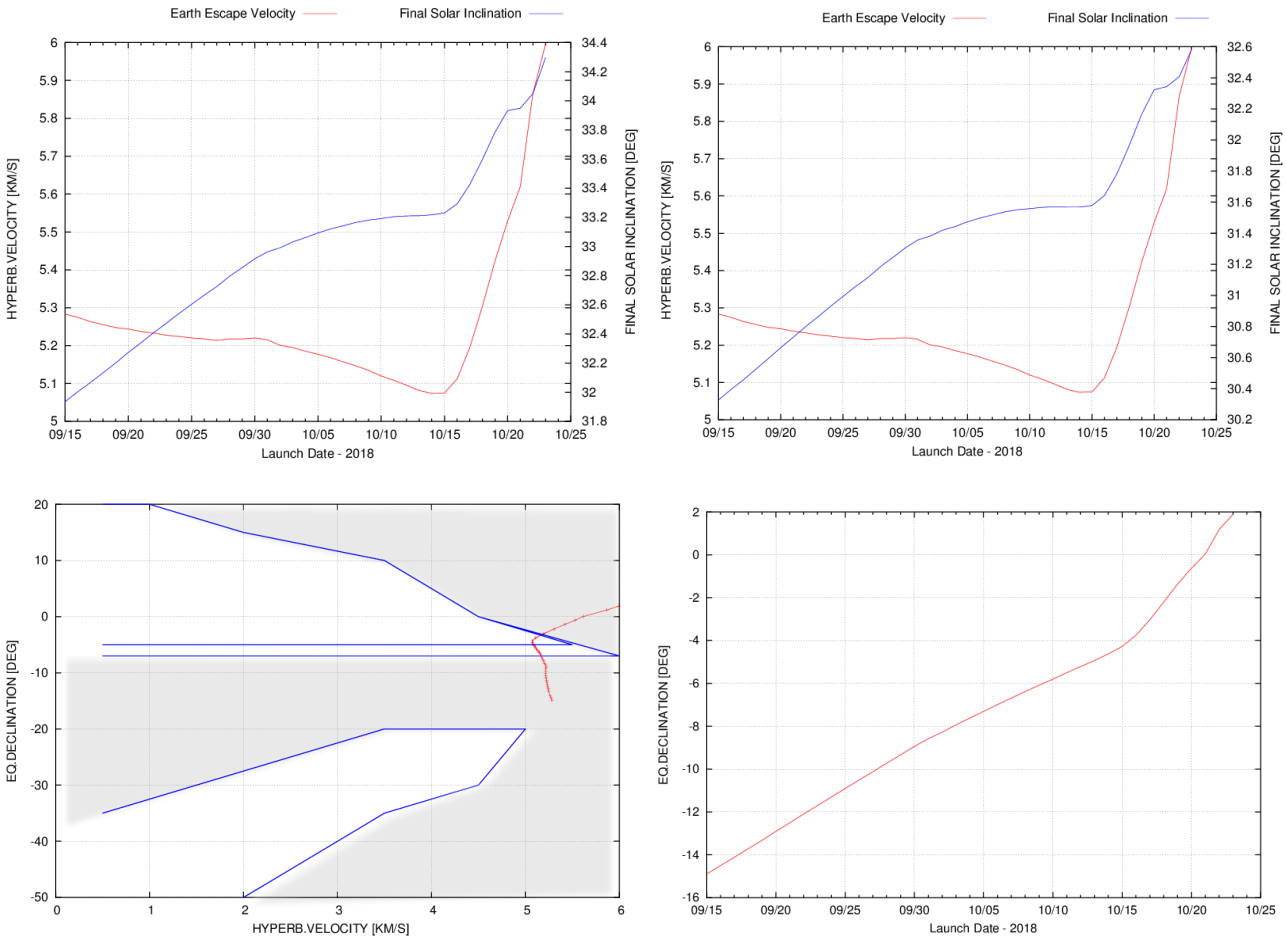


Figure 78: 2018 October short launch window – Launch targets and solar inclination

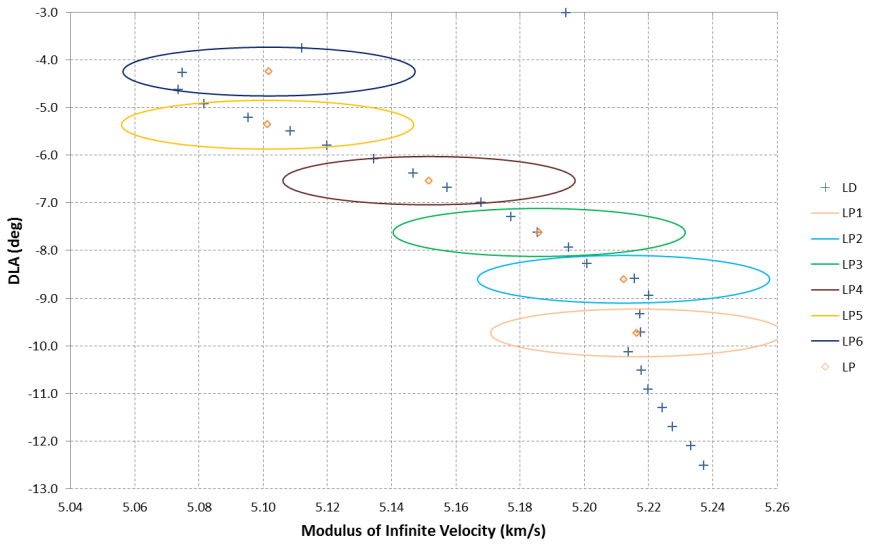


Figure 79: 2018 October short launch window – Ariane 5 ECA preliminary analysis of launch programs

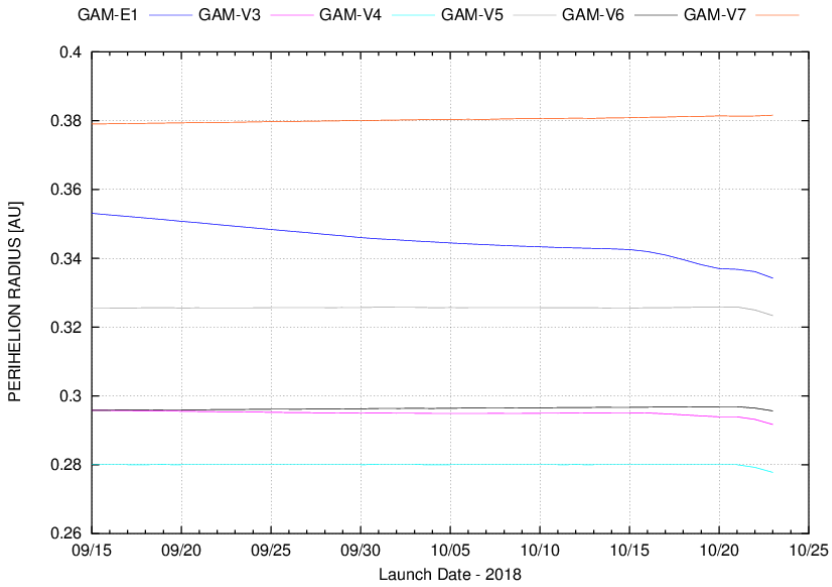


Figure 80: 2018 October short launch window – Perihelion of science orbits

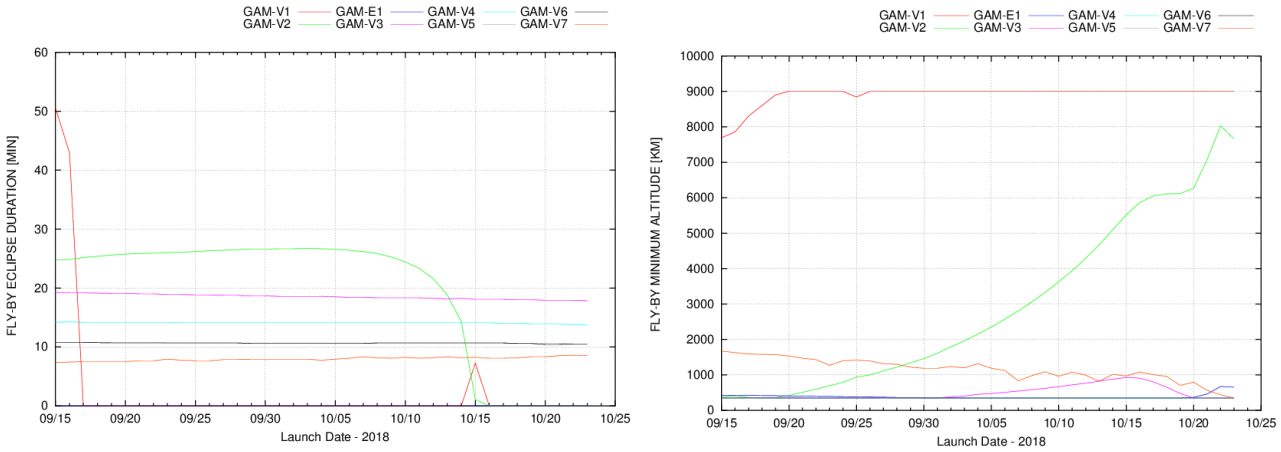


Figure 81: 2018 October short launch window – GAM eclipse duration and minimum altitude