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TECHNICAL NOTE

Solar Orbiter: Backup Launch Options in 2020

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Table of contents:

1 INTRODUCTION

The Solar Orbiter mission is currently set for baseline launch on February 2020. All the details of this baseline are thoroughly described in the last issue of the CReMA (RD 1). The launch window has been recently refined and latest launch targets are reported in RD 2. The 2020 February trajectory exhibits a fast cruise phase that allows an early start of the remote sensing observations, a large number of perihelion passages at close Sun distance (below 0.3 AU) and an excellent capability for the science data downlink.

For programmatic reasons it is desirable to identify possible launch options later in 2020. Under the current well advanced spacecraft development (at post-CDR stage), any credible launch option must respect all the engineering constraints, based not only on the requirements, but also on the expected spacecraft performance.

ESOC mission analysis has investigated the full search space of possible trajectories in order to identify viable launch options in 2020 compatible with the spacecraft and mission constraints. This document summarises the method used and its results, and describes the most promising launch options.

3 candidate trajectories have been identified and are reported hereafter:

- 2020 July A: launch period open from June 28 to July 16
- 2020 July A: launch period open from June 28 to July 16
- 2020 September: launch period open from August 20 to September 21

Notice that the name given to the trajectories and the actual start month of the launch window might be different.

1.1 Reference Documents

RD 1 J.M.Sánchez Pérez, "Solar Orbiter: Consolidated Report on Mission Analysis", SOL-ESC-RP-05500, Issue 4, Rev. 1, 2017-06-01.

RD 2 J.M. Sánchez Pérez, "Solar Orbiter: Launch Targets for 2020 February Launch Window", SOL-ESC-ME-50016, 2017-12-18.

RD 3 J.M. Sánchez Pérez, "Solar Orbiter: 2018-2020 Launch Options Favouring Data Return", SOL-ESC-TN-50007, Issue 2, Rev. 2, 2016-03-04.

RD 4 A. Boutonnet, W. Martens and J. Schoenmaekers, "SOURCE: A Matlab-Oriented Tool For Interplanetary Trajectory Global Optimization. Fundamentals", AAS 13-300, 23rd AAS/AIAA Space Flight Mechanics Meeting, Kauai, Hawaii, February 2013.

2 COMPREHENSIVE SEARCH OF TRAJECTORY OPTIONS

The search method and first-guess solution database used for the current analysis is the same as the one detailed in steps 1 and 2 of RD 3, section 5.1. Only the post-processing/filtering was tailored to the needs of the new analysis. For convenience, however, the procedure of the search and selection are summarized in the following.

2.1 Search Procedure, Assumptions and Constraints

The search for trajectories was carried out using the in-house software, SOURCE (RD 4), using a three-step procedure:

1. Identification of promising transfer structures: By "structures" a sequence of trajectory parameters like full revolutions around the Sun, Lambert parameters and transfer type for each trajectory arc is meant. From the large amount of considered structures only a limited amount give rise to interesting transfer options. This limits the search space for the next step in the procedure which would otherwise become overwhelmingly large.
2. Global search for end-to-end trajectories: For each of the structures identified in step 1 a global optimization of trajectories is conducted which includes both the transfer and the science phase. Since each transfer opportunity typically allows for several possible science phases, the resulting amount of trajectories after this step is in the order of several thousands. For technical reasons the final solar inclination (and also the final spacecraft orbit) for a trajectory search has to be fixed a-priori. In order to find the highest possible solar inclination for a given trajectory, the search has to be carried out for a series of solar inclinations, like 31°,32°, 33°, 34° and 35°.
3. Post-processing: There is a redundancy in the pool of trajectories that resulted from step 2 (i.e. the same trajectory might be present in the pool with several different final solar inclinations). To retain only the ones with the highest solar inclination, an additional, post-processing step is needed. In this step also more strict filtering criteria are applied to further reduce the amount of trajectories.

Only the assumptions of step 3 have changed with respect to RD 3. The overall set of assumptions resulting from the combination of all three steps is summarized in the following:

- The following transfer sequences have been considered: EVEV, EVVEV and EVEEV. Note that transfer phases like VV or EE may also contain more than two planet encounters, i.e. VVV or EEE are also included in the search.
- The launch is assumed to be between December 1st 2019 and January 31st 2022. The possibility of an initial 1-year Earth–Earth arc instead of launching directly towards Venus is considered.
- The launch infinite velocity is constrained to be lower than 5.6 km/s.
- The fly-by altitude was constrained to values above 300 km for both Earth and Venus.
- The maximum number of full revolutions around the Sun is constrained to be less or equal than 3 for each arc during the transfer phase.
- The maximum distance to the Sun during cruise is constrained to be lower than 1.5 AU.
- The minimum Sun distance is constrained to be higher than 0.27 AU.
- During science phase the perihelion is constrained to values below 0.4 AU.
- The final arc is always assumed to be a 3:2 resonance. However, usually it can simply be replaced by a 5:3 resonance a-posteriori. Technically speaking, the final arc shall be viewed

as artificial, because the flyby altitude leading to that arc is set to -1000 km for the search procedure which is in order to guarantee that the final (fixed) spacecraft orbit can be reached. In many cases this procedure still results in a feasible trajectory even if the final GAM altitude is raised to 300 km a-posteriori. Otherwise the final arc is omitted in the post-processing phase at the cost of a lower final solar inclination.

- For the science phase maximum number of spacecraft revolutions around the Sun is ≤ 5, the maximum number of Venus revolutions ≤ 4.
- The maximum number of resonant arcs during the science phase is ≤ 5 (EVEV) or ≤ 4 (EVVEV and EVEEV). Thus the maximum total number of GAMs is 8.
- The total number of Venus revolutions during the science phase is ≤ 16 (EVEV and EVVEV) or ≤ 15 (EVEEV).
- The duration between launch and the first Venus GAM in the science phase is below 4.6 years.
- The total mission duration is below 10.7 years. For solutions that don't satisfy this constraint a-priori, the final (artificial) 3:2 resonant arc with Venus is omitted.
- The minimum final solar inclination is 31°.
- The duration until the distance to the Sun drops below 0.35 AU must be less than 4.5 years (that interval is defined as the cruise phase).
- Only trajectories that go below 0.315 AU Sun distance are retained.
- The average data return must be above 1.5 Tbit/year. The average data return is calculated starting from the Venus encounter that marks the beginning of the science phase. The following simple model has been used for the calculation of the data return:

$$DR = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} \frac{8}{24} b(D)\, dt$$

$$b(D) = \begin{cases} \dfrac{201.53 \frac{kb}{s} AU^2}{D^2} & if\ D \geq 0.4494\, AU \\ 998 \frac{kb}{s} if\ D & < 0.4494\, AU \end{cases}$$

  Here b(D) is the bitrate in kb/s as a function of the distance to the Earth, D. The fraction 8/24 represents the duty cycle since a maximum ground station contact of 8 hours per day is assumed. The cut-off represents the maximum available data rate that can be handled by the communications system. Figure 1 shows the function b(D).

- No superior conjunctions are allowed during 20 days before a fly-by. This criterion is considered violated if for more than 14 days during that period the Sun-Earth-Spacecraft angle is below 3° and the Sun-Spacecraft-Earth angle is below 10°.
- The duration of superior conjunctions (other than before fly-bys) shall be less than 120 days. Here a stricter threshold on the Sun-Earth-Spacecraft angle of 5° has been used.
- The maximum allowed eclipse duration is assumed to be 45 minutes. If the eclipse duration exceeds that threshold during the science phase, there is some freedom in choosing the inclination during the resonant orbits that can be used in order to reduce it. If it is not successful, the solution is discarded.

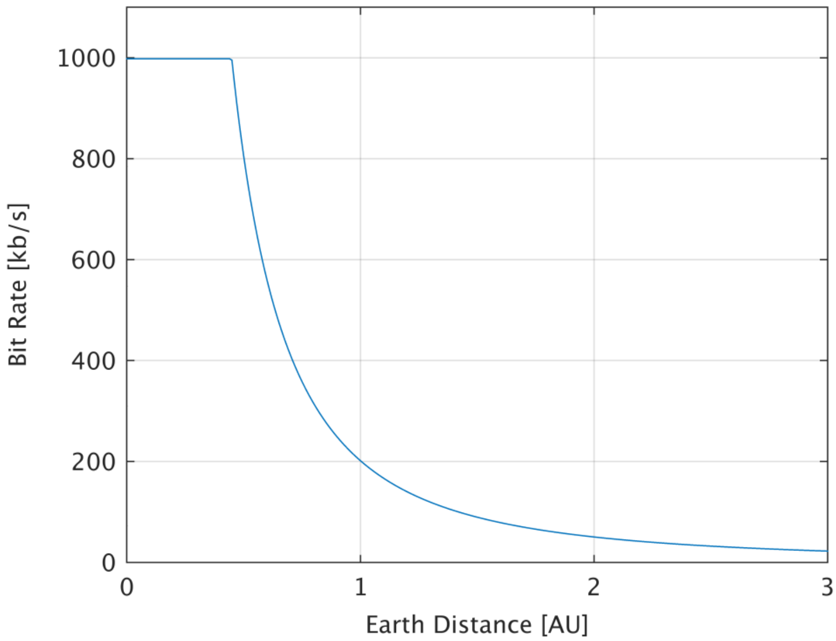


Figure 1: Data rate model used to assess the total data return for candidate trajectories.

Instead of using the total duration in years as a figure of merit, the equivalent Sun hours are introduced which represents more accurately the actual engineering constraint. This time-like quantity is equivalent to normal time at 1 AU distance and scales with one over the Sun distance squared along the spacecraft trajectory. High values mean a high demand on the solar arrays, which have a limited lifetime in equivalent Sun hours.

2.2 Global Trajectory Analysis

The search procedure described in the previous section resulted in a total of 308 end-to-end trajectories after post-processing. The number of trajectories for each transfer sequence is shown in Table 1.

Transfer sequence	Number of trajectories
EVEV	157
EEVEV	6
EVEEV	22
EEVEEV	2
EVVEV	90
EEVVEV	10
EVVVEV	20
EEVVVEV	1
TOTAL	**308**

Table 1: Number of end-to-end trajectories resulting from global search.

In the following a statistical analysis of quantities like transfer duration, data return, final inclination of the obtained trajectories will be presented that will help the final selection of interesting options.

Figure 2 shows all the 308 solutions in a scatter plot as mission duration vs. launch date. Also the cruise duration (i.e. the duration until 0.35 AU Sun distance are first reached) and final solar inclination are indicated by colour and symbols respectively. The solutions are clustered around lines with the same arrival date, indicating that only arrival at certain solar longitudes yields high final solar inclinations. Almost continuous launch dates are covered until July 2020. After that date solutions are sparser and between March and September 2021 there are hardly any solutions. Moreover, these solutions require a long cruise phase. Figure 3 shows the same set of solutions, but indicating the data return as a function of the launch date.

In Figure 4 to Figure 6 various correlations between the maximum reached Sun distance and other quantities are shown. All these figures clearly show that the number of available options would strongly decrease if the maximum Sun distance constraint was reduced below 1.2 AU. Finally, Figure 7 is the same as Figure 6, but with a reduced set of trajectories that only includes options with up to 3.5 years cruise duration and up to 1.2 AU maximum Sun distance.

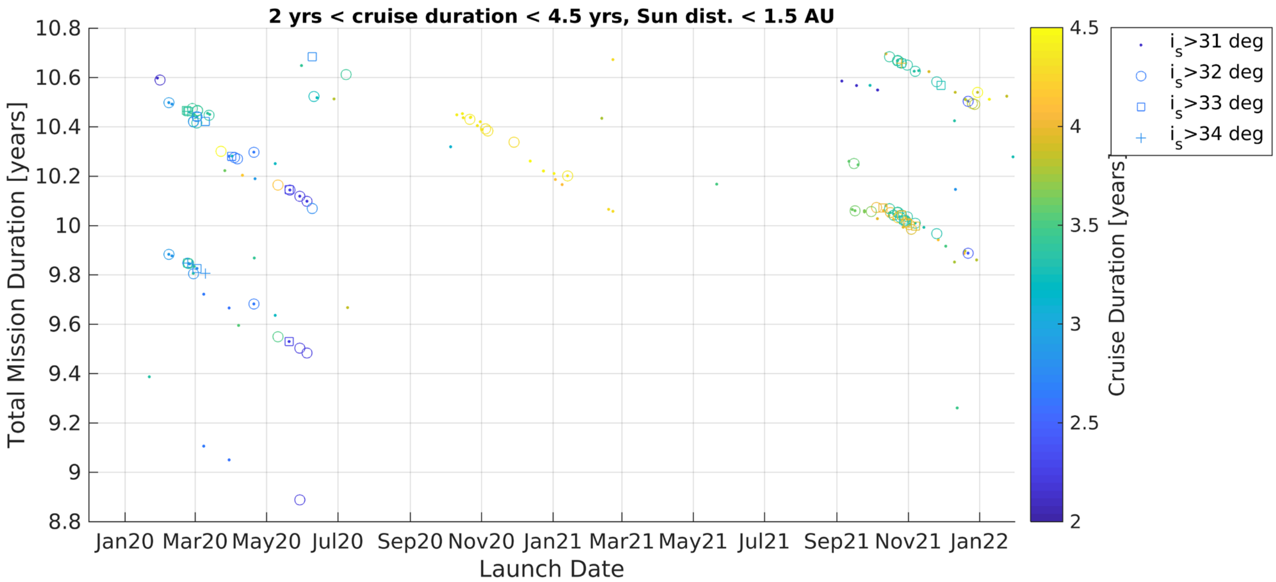


Figure 2: Transfer duration of all end-to-end trajectories vs. launch date with an indication of the cruise duration (color) and final solar inclination (symbols).

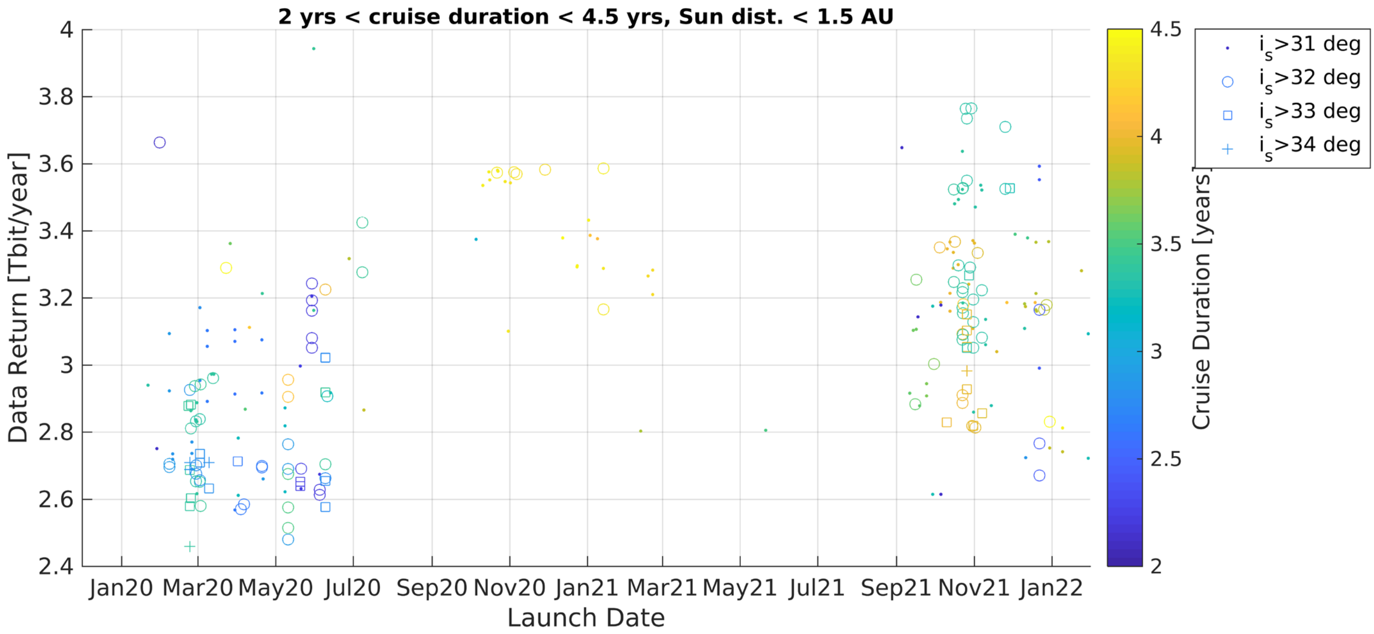


Figure 3: Data return of all end-to-end trajectories vs. launch date with an indication of the cruise duration (color) and final solar inclination (symbols).

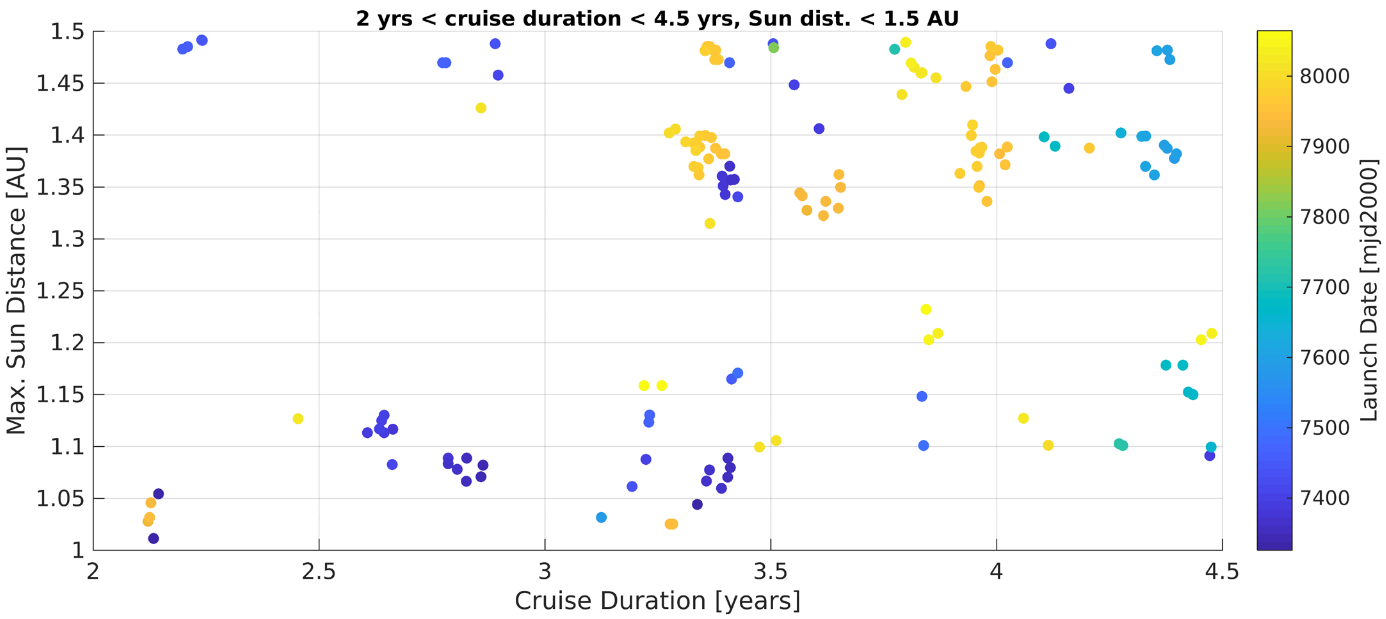


Figure 4: Correlation between cruise duration and max. Sun distance.

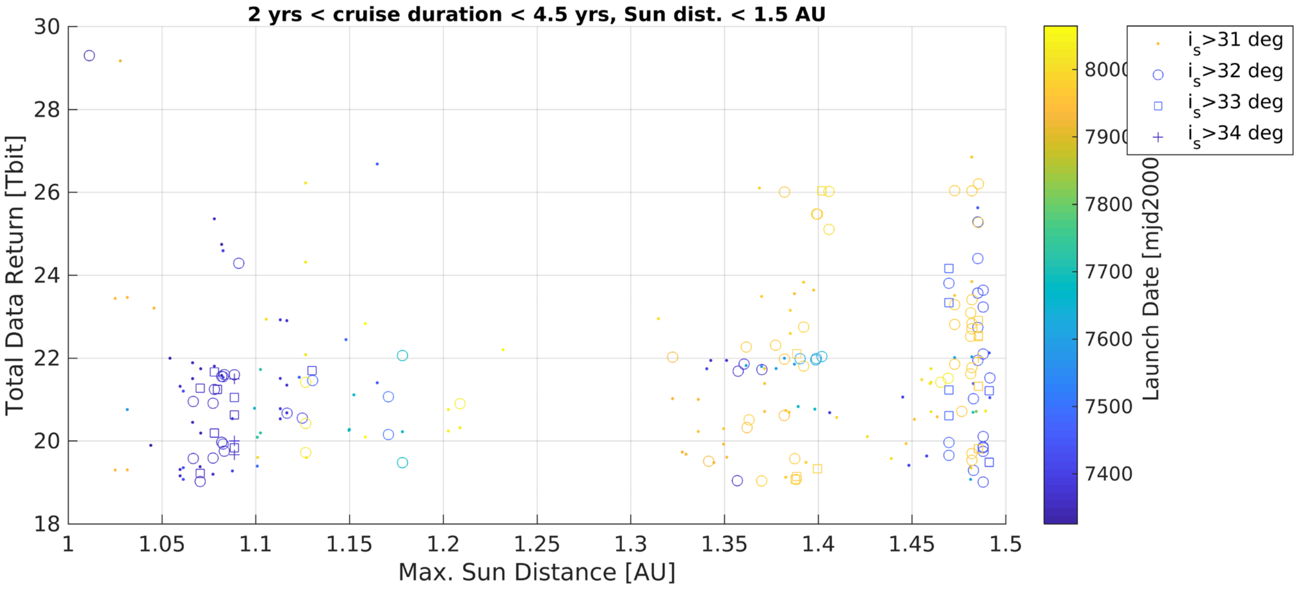


Figure 5: Correlation between max. Sun distance and total data return.

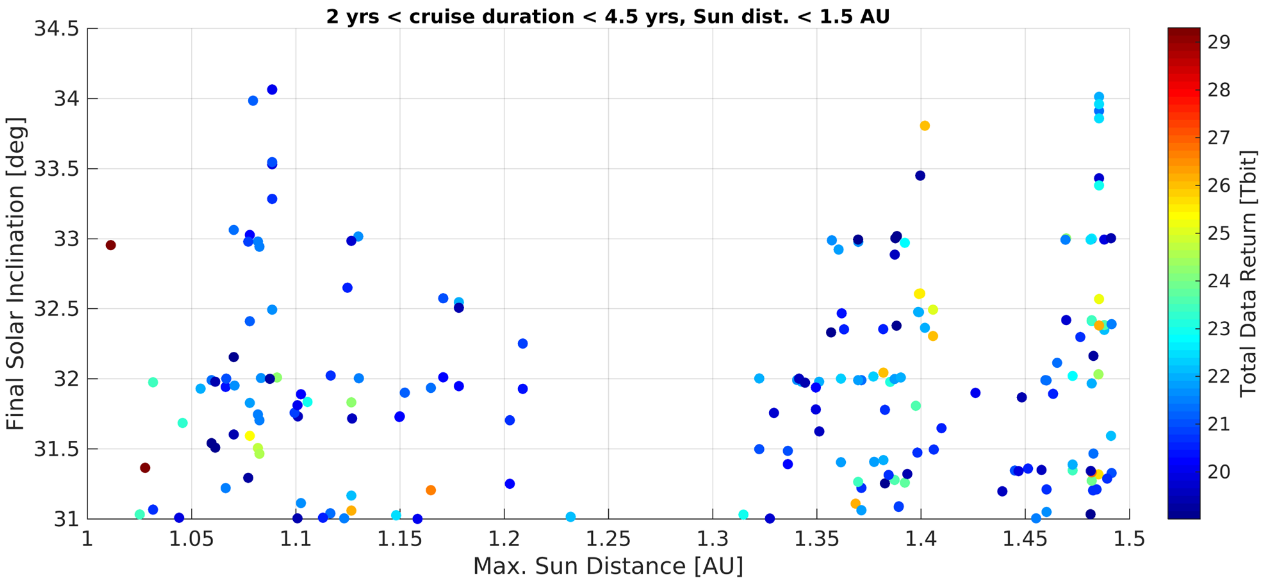


Figure 6: Correlation between max. Sun distance and final solar inclination.

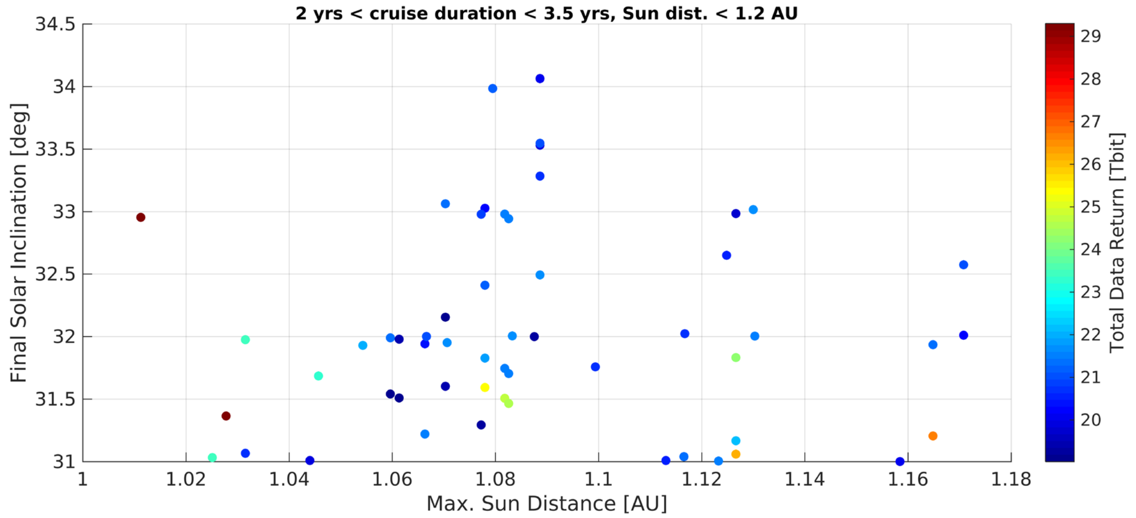


Figure 7: Correlation between max. Sun distance and final solar inclination for trajectories with up to 3.5 years cruise duration.

3 ADDITIONAL LAUNCH OPTIONS IN 2020

This chapter provides an extensive description of the most promising trajectories identified in the analysis carried out by ESOC.

For each of the trajectories a table is provided with the characteristics of the different orbits used during the mission. This table includes the downlink index (DLi) providing a proxy to the capability of data downlink computed as follows (RD 3):

$$DL_{index} = \frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} \frac{1}{D_*^2} dt\,, \quad with\ D_* = \begin{cases} D & if\ SES > 3\ \text{deg}\ and\ D > 0.45\ AU \\ 0.45\ AU & if\ SES > 3\ \text{deg}\ and\ D \le 0.45\ AU \\ \infty & if\ SES \le 3\ deg \end{cases}$$

With this definition the DLi takes into account the absence of communications during solar conjunction and the maximum downlink rate that can be provided by the communications subsystem.

A second table describes the characteristics of the Venus and Earth GAMs. A third table provides the details of superior conjunctions and safe mode blackout periods.

The graphical information provided consists of:

- Ecliptic XY projection of the full trajectory
  This plot presents all the different arcs/orbits with different colour and the location of launch and GAMs. Green straight lines from the Sun indicate the Venus positions for which the maximum increase of solar inclination for a given infinite velocity can be achieved, approximately at solar longitudes 71 deg and -102 deg. The positions that are less favoured for the inclination increase are shown in red.
- XY Projection into the Sun-Earth rotating frame orbit per orbit from the last Earth GAM
  In this representation the Sun and the Earth are fixed at the coordinates (0,0) and (1 AU, 0), respectively. A yellow and a blue circle indicate the Sun and Earth positions. The orbit of Venus is seen as a big circle. In addition, a smaller circle shows the Sun range constraint of 0.28 AU. The location of aphelia with respect to the Earth permits a quick assessment of downlink performance: when close to the Earth long periods with high data rates are provided.
- Projection in Sun equator cylindrical R-Z frame during the science phase only
  This representation shows the components of the position vector in the Sun Equator plane (Rxy) and in the direction of the Sun North Pole Z. The figure respects the ratio between the two coordinates, thus the distance to the Sun has been represented by grey circles and the solar latitude by straight orange lines. The direction in which Solar Orbiter moves along the curves in this plot can vary from case to case.
  In addition, this plot includes tick marks for the location of the TCMs. This assumes the nominal TCM timeline described in RD 1 that considers 4 pre-GAM TCMs (at -30, -14, -7 and -3 days) and 1 post-GAM TCM (at +7 days). In the case of an outbound Venus GAM, the TCM at GAM-30 days is shifted back preliminarily to GAM-100 days in order to avoid implementing manoeuvres too close to the Sun and to interfere with the remote sensing window around perihelion.
- V-infinity diagram for the science phase

Level lines of the relevant heliocentric orbit parameters are shown as a function of the 2 direction angles determining the direction of the V-infinity vector at Venus. The right ascension α is measured in-plane from the direction of the Venus velocity vector and is positive towards the Sun (α=0 along Venus velocity, α=90 deg along radial, α=-90 deg along anti-radial, α=180 against Venus velocity direction). The declination δ is the angle between the infinity velocity vector and Venus orbital plane.
During NMP+EMP Solar Orbiter implements only unpowered GAM between resonances with Venus. Therefore, the modulus of the V-infinity vector and the position of Venus in its orbit are unchanged and the V-infinity diagram remains the same. The effect of a Venus GAM is to change the direction of the V-infinity vector. This is represented in the diagram with an arrow from the incoming to the outgoing V-infinity vector directions. The V-infinity vector direction needs to be on one of the blue lines to be in resonance with Venus orbit. The sequence of GAMs for the trajectory is represented in the diagram.

- Evolution with time of the distance to the Sun, aphelion/perihelion radius, solar latitude, Sun-Earth-Spacecraft and Sun-Spacecraft-Earth angle
- Evolution of distance to the Earth and the estimated downlink volume per day assuming an 8-hour daily ground station contact. In addition, the plot includes markers for the perihelion passes during NMP+EMP and shows the periods in which the maximum data rate is provided (green shadow).

3.1 2020 July A

3.1.1 Trajectory description

This launch opportunity is based on an EVVEV cruise profile. For the reference trajectory shown in this section launch occurs on July 8th, while the launch window is open from June 28 to July 16 2020 (see 3.1.2). Transfer from Earth to Venus is direct and takes less than half-year. The next arc is in 1:1 resonance with Venus. Due to the extra degree of freedom of the resonance, there is flexibility to select the altitude at either V1 or V2. The proposed trajectory fixes the altitude of V1 to 50000 km in order to limit the V1 eclipse duration below 25 minutes.

The V2-E1 and E1-V3 arcs involve each 2 revolutions. In the 24-month V2-E1 arc the highest aphelion at 1.171 AU is reached 3 times. In the E1-V3 arc the perihelion is lowered below 0.35 AU for the first time in the mission. Thus the NMP is considered to start right after E1 and the cruise phase to take 3.19 years. The sequence of Venus resonances used in the science phase is 4:3-3:2-3:2-5:3. The perihelion dips below 0.3 AU in 2 of the resonances and stays very close to 0.3 AU in the final 5:3 resonance. The minimum Sun range is 0.287 AU achieved during the V4-V5 arc. The core of the NMP in the V3-V4 arc is well optimised for the science data return. The final science orbit with a solar inclination of almost 32 deg is reached after V6, 8.8 years after launch. The total trajectory duration as planned is 10.6 years.

Phase	Cruise			NMP			EMP		
Trajectory arc	L-V1	V1-V2	V2-E1	E1-V3	V3-V4	V4-V5	V5-V6	V6-End	
Arc start date	2020-07-08	2020-12-13	2021-07-25	2023-09-16	2024-12-23	2026-10-28	2028-01-20	2029-04-14	
Flight time at arc start (years)	0.00	0.43	1.05	3.19	4.46	6.31	7.54	8.77	
Flight time at arc end (years)	0.43	1.05	3.19	4.46	6.31	7.54	8.77	10.61	
Arc duration (days)	158	225	783	464	674	449	449	674	
Number of revolutions in arc Venus Resonance	0	1 1:1	2	2	4 4:3	3 3:2	3 3:2	5 5:3	
Orbit Period (days)	243.9	224.7	299.9	207.8	168.5	149.8	149.8	134.8	
Rs at aphelion (AU)	1.018	0.964	**1.171**	1.024	0.897	0.817	0.769	0.729	
Rs at max. latitude (AU)	0.874	0.795	1.169	0.978	0.719	0.595	0.582	0.468	
Rs at min. latitude (AU)	0.556	0.540	0.584	0.355	0.324	0.330	0.389	0.390	
Rs at perihelion (AU)	0.510	0.482	0.583	0.349	0.297	**0.287**	0.335	0.300	
Perihelion latitude (deg)	-3.38	-3.02	-9.79	-7.84	-11.93	-13.82	-14.43	-6.63	
$\dot{\theta}$ at perih. (deg/day)	3.12	3.39	2.59	5.89	7.48	7.59	5.56	6.13	
Ecliptic inclination (deg)	2.79	2.78	5.77	3.12	10.29	17.97	24.01	26.30	
Solar inclination (deg)	5.04	5.27	9.82	8.25	15.89	23.62	29.66	**31.96**	Total
Rs < 0.3 AU (days/orbit)					3.5	8.0			38.0
Rs < 0.4 AU (days/orbit)				19.7	25.5	27.0	24.5	28.1	436.4
Heliolatitude > 25 deg (days/orbit)							32.3	26.9	231.3
Heliolatitude < -25 deg (days/orbit)							14.7	18.7	137.8
Downlink index ($1/AU^2$)	3.44	0.40	2.08	1.64	2.14	1.03	1.57	1.27	

Table 1: 2020 July A – Trajectory Summary

GAM	Date	Re (AU)	Vinf (km/s)	Hmin (km)	Eclipse (min)	Occult. (min)	Ls (deg)	SSE (deg)	SES (deg)	ESV (deg)
V1	2020-12-13	1.486	11.698	50000	0.0	21.2	201.8	34.8	24.8	120.4
V2	2021-07-25	1.354	11.698	3731	15.4	10.7	201.8	47.4	31.5	101.1
E1	2023-09-16	0.000	9.066	2138	0.0	0.0	353.2	-	-	-
V3	2024-12-23	0.815	17.483	350	0.0	0.0	37.1	79.2	46.3	54.5
V4	2026-10-28	0.274	17.483	350	0.0	11.4	37.1	167.9	8.8	3.3
V5	2028-01-20	1.145	17.484	350	0.0	0.0	37.1	58.5	38.8	82.7
V6	2029-04-14	1.716	17.483	352	0.0	0.0	37.1	7.7	5.5	166.8

Table 2: 2020 July A – GAM Properties

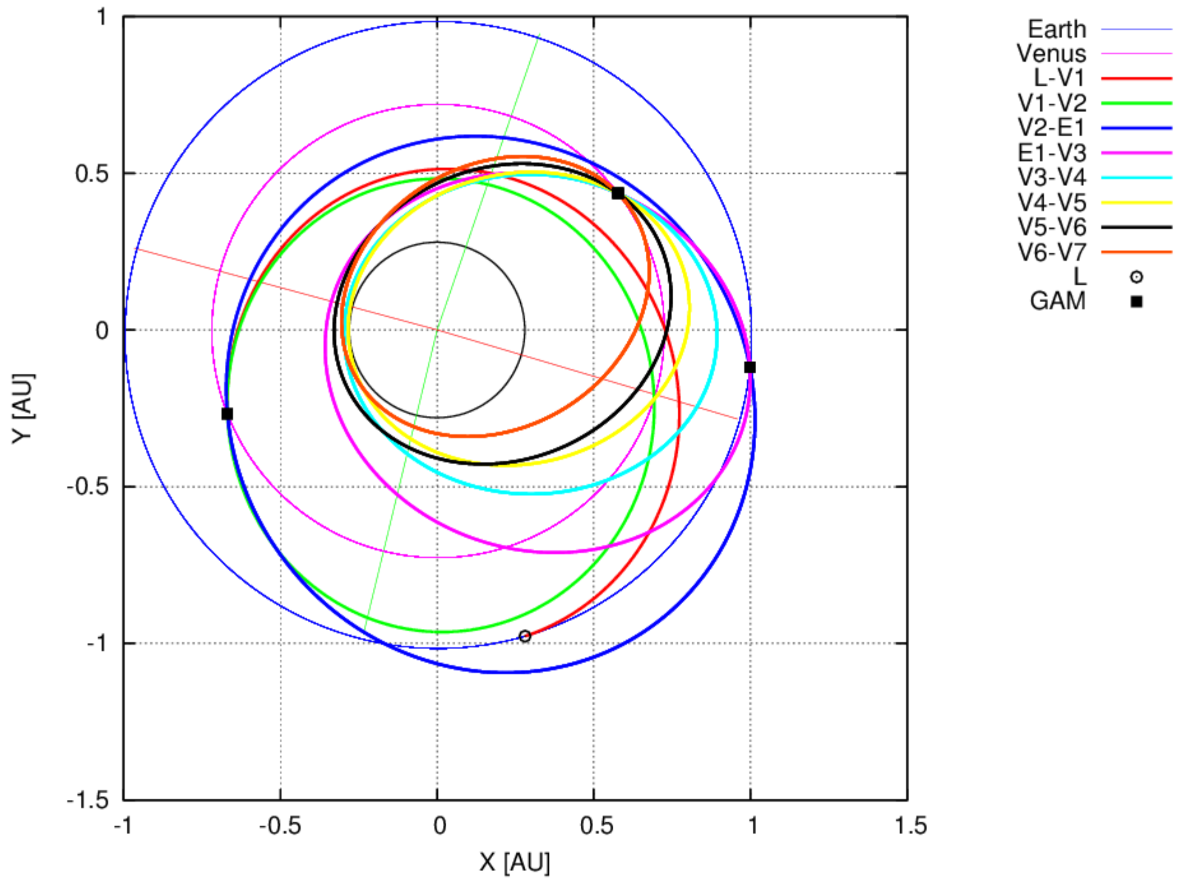


Figure 8: 2020 July A – Trajectory Projection in the Ecliptic Plane

In terms of science data return capability, the second aphelion of the E1-V3 arc is well suited for downlink. The core 4:3 science orbit at the start of NMP is close to a best-case for data downlink with DLi of 2.14 (see Table 1) thanks to the 2nd and 4th aphelions being very close to the Earth . The first of the 3:2 resonances is the arc less suited for data downlink with no aphelion in good phasing with Earth, thus the low DLi of 1.03. This is well recovered by the following 3:2 and 5:3 resonances that have one aphelion close to Earth. The overall downlink capability is at the same level as the 2018 October Option E trajectory (RD 1) and only below that of the best 2 trajectories to current knowledge, 2020 February B and 2018 October Option D.

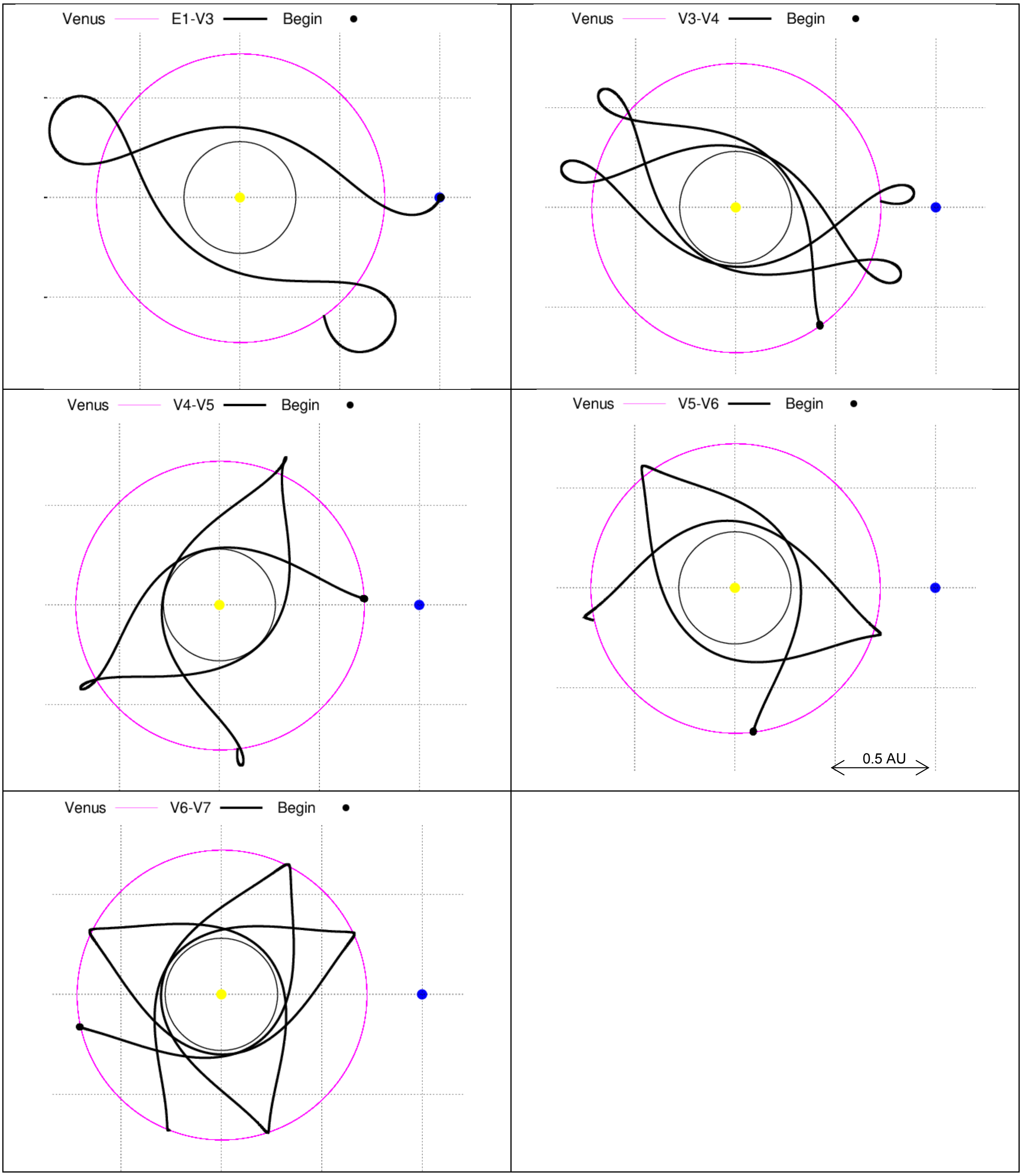
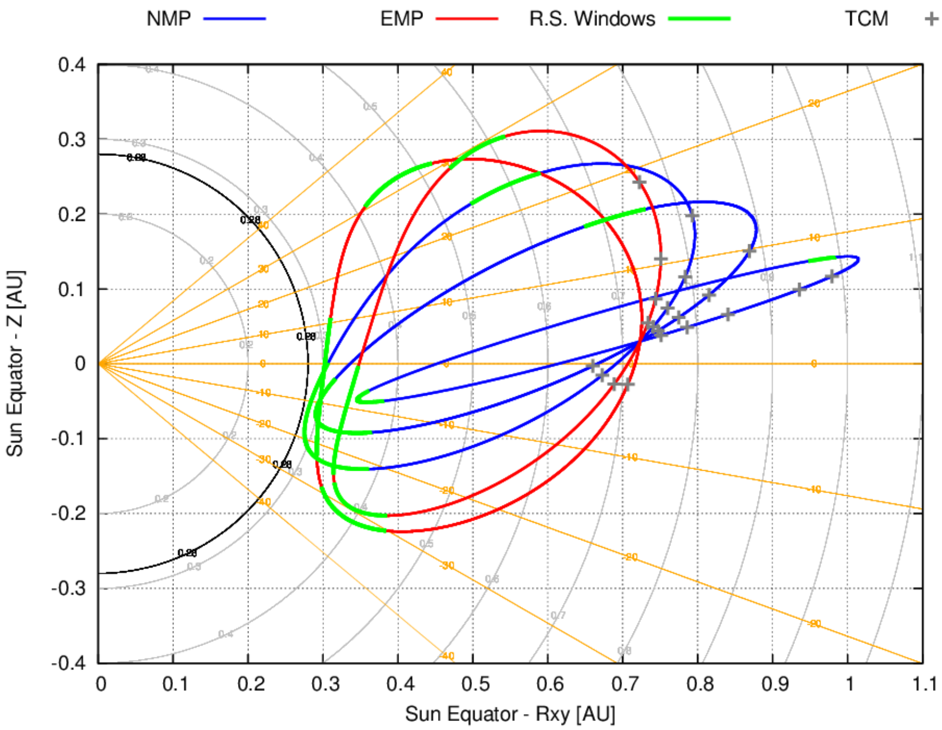


Figure 9: 2020 July A – Trajectory Projection in the Sun-Earth rotating frame



Note: outbound Venus GAMs. TCMs at GAM-100, -14, -7, -3 and + 7 days

Figure 10: 2020 July A – Trajectory projection of science orbits wrt Sun Equator and North Pole

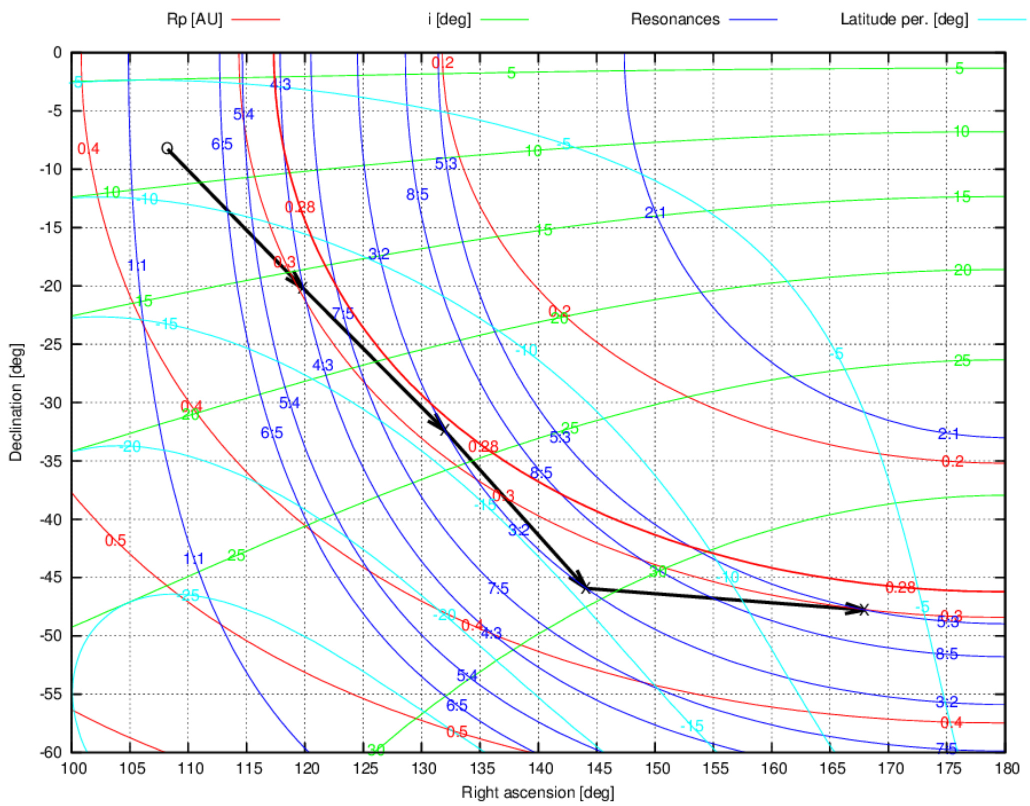


Figure 11: 2020 July A – V-infinity diagram

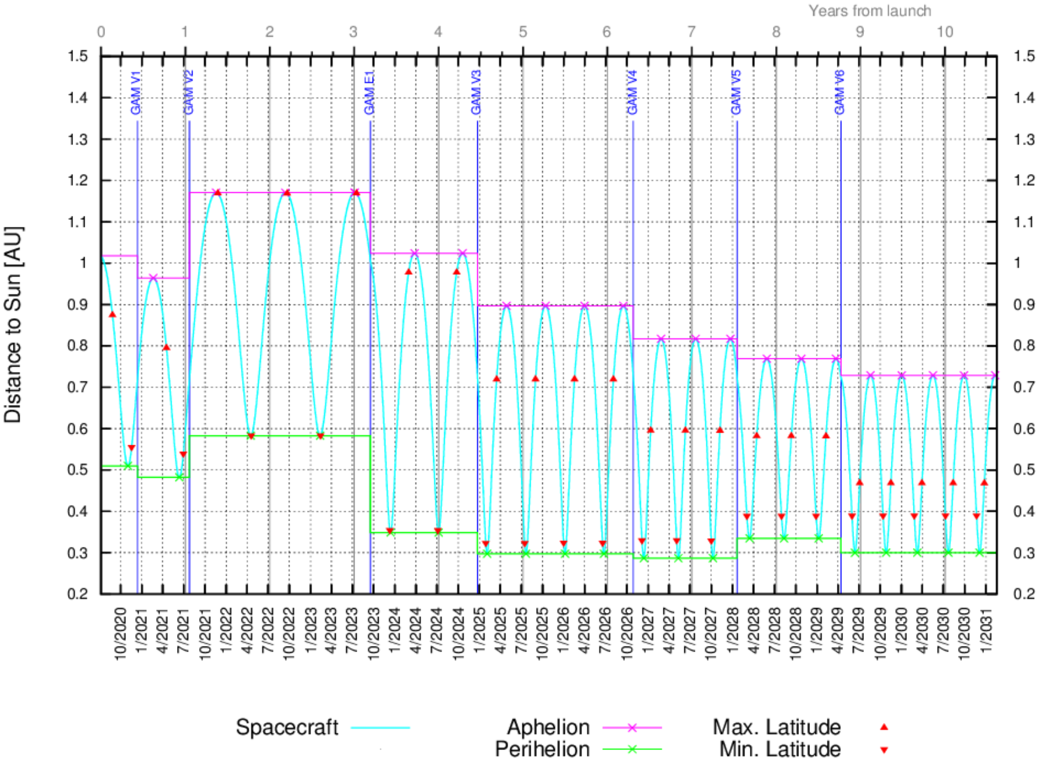


Figure 12: 2020 July A – Distance to Sun

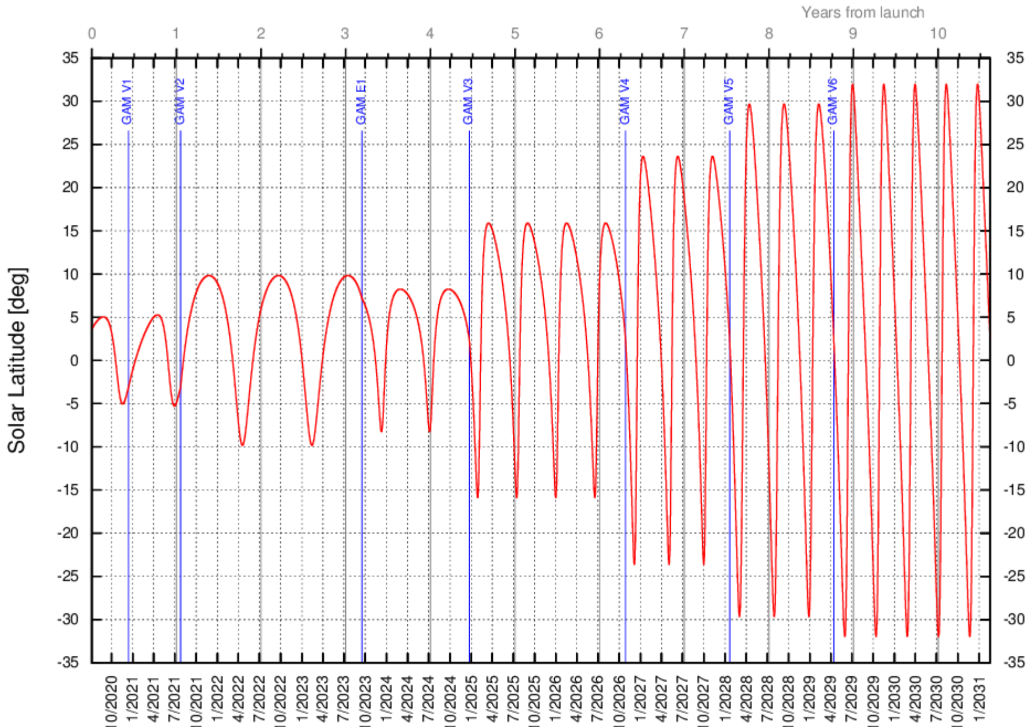


Figure 13: 2020 July A –Solar latitude

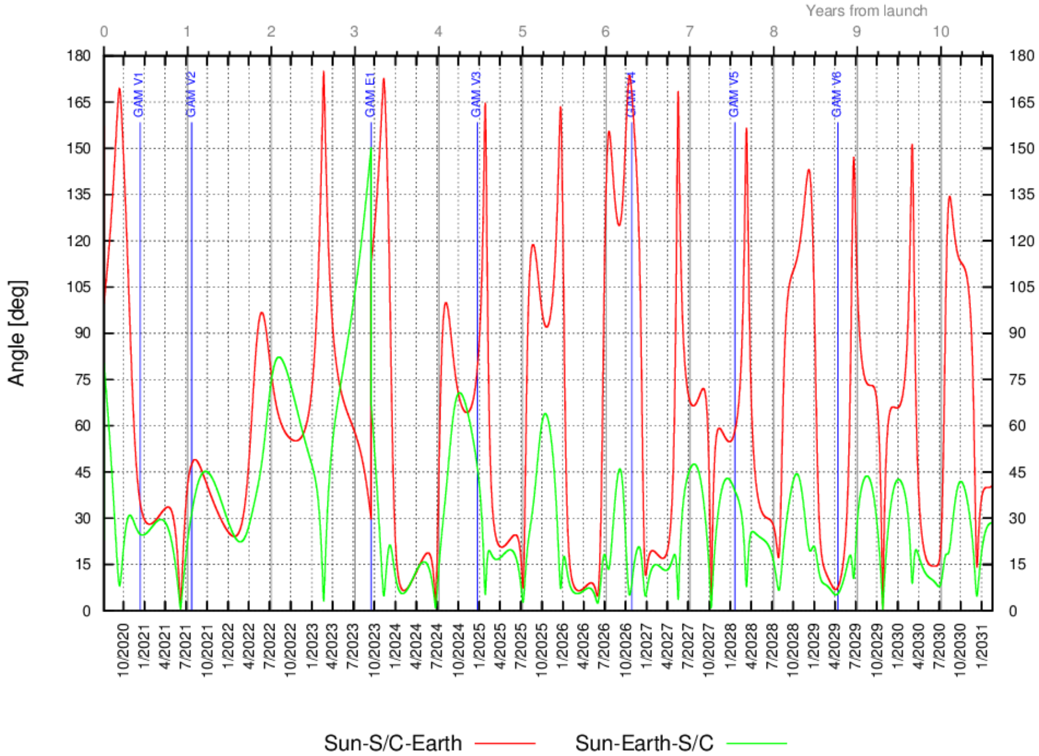


Figure 14: 2020 July A – Communication angles SES and SSE

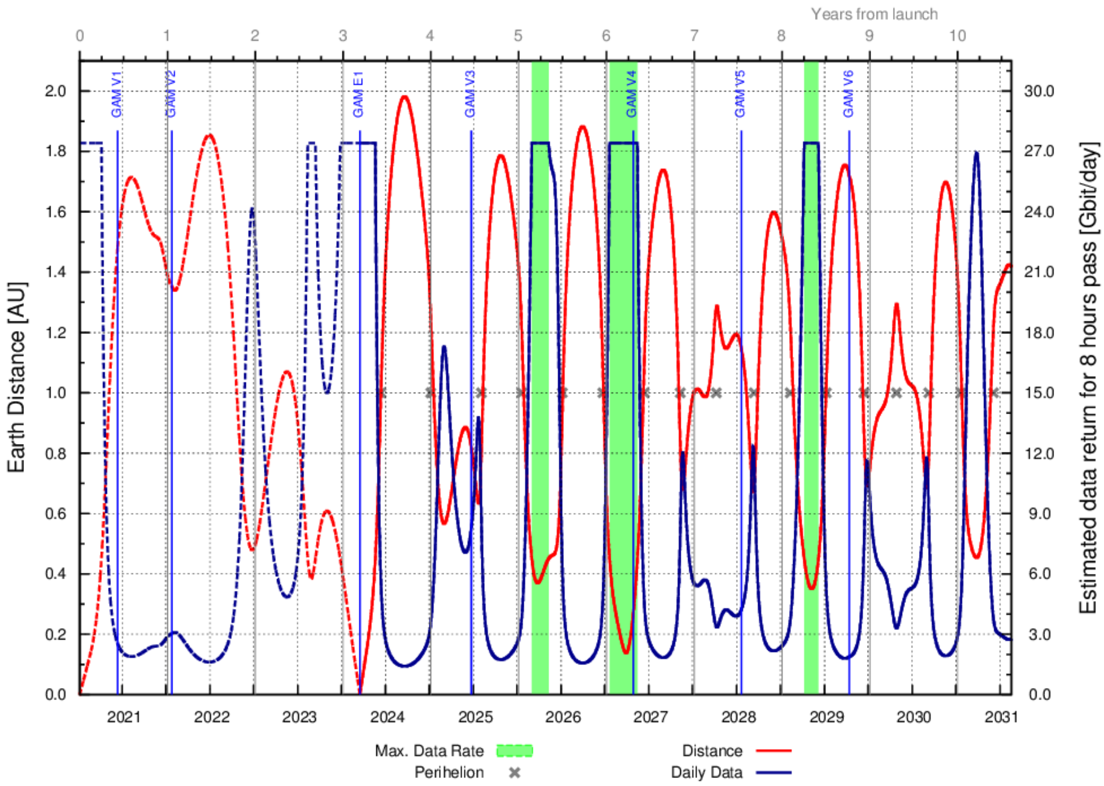


Figure 15: 2020 July A – Distance to Earth and potential daily data downlink

Solar Conjunction Periods
SES<3 deg

	Type	Start	End	Duration [days]	Min SES [deg]
1	Superior	2021-06-03	2021-06-10	7.7	0.5
2	Superior	2024-06-20	2024-06-27	7.1	0.9
3	Superior	2025-07-09	2025-07-11	2.4	2.8
4	Superior	2026-05-27	2026-06-04	7.2	2.5
5	Superior	2027-10-07	2027-10-11	3.7	1.0
6	Superior	2029-10-25	2029-10-29	4.2	0.1

Safe Mode Blackout Periods
SES<=5 deg OR SSE<=3 deg

	Start	End	Duration [days]
1	2021-05-31	2021-06-13	13.0
2	2023-02-19	2023-02-23	3.6
3	2023-11-10	2023-11-12	2.0
4	2024-06-16	2024-06-29	12.4
5	2025-07-05	2025-07-14	8.6
6	2026-05-19	2026-06-08	20.0
7	2026-12-24	2026-12-28	3.8
8	2027-05-16	2027-05-19	2.8
9	2027-10-06	2027-10-13	6.5
10	2029-10-23	2029-10-30	7.0
11	2030-12-10	2030-12-13	2.8

Table 3: 2020 July A - Solar Conjunctions

Figure 16 shows a zoom of the SES and SSE angles around GAM-V2, -V4 and -V6, respectively. GAM-V4 is close to an inferior conjunction with the SES angle remaining always above 5 deg. GAM-V6 is close to a superior conjunction where both angles, SES and SSE, become relatively small, but still always above the 5 deg threshold considered by ESOC for implementation of critical operations. Therefore, navigation of this GAM is not expected to be an issue.

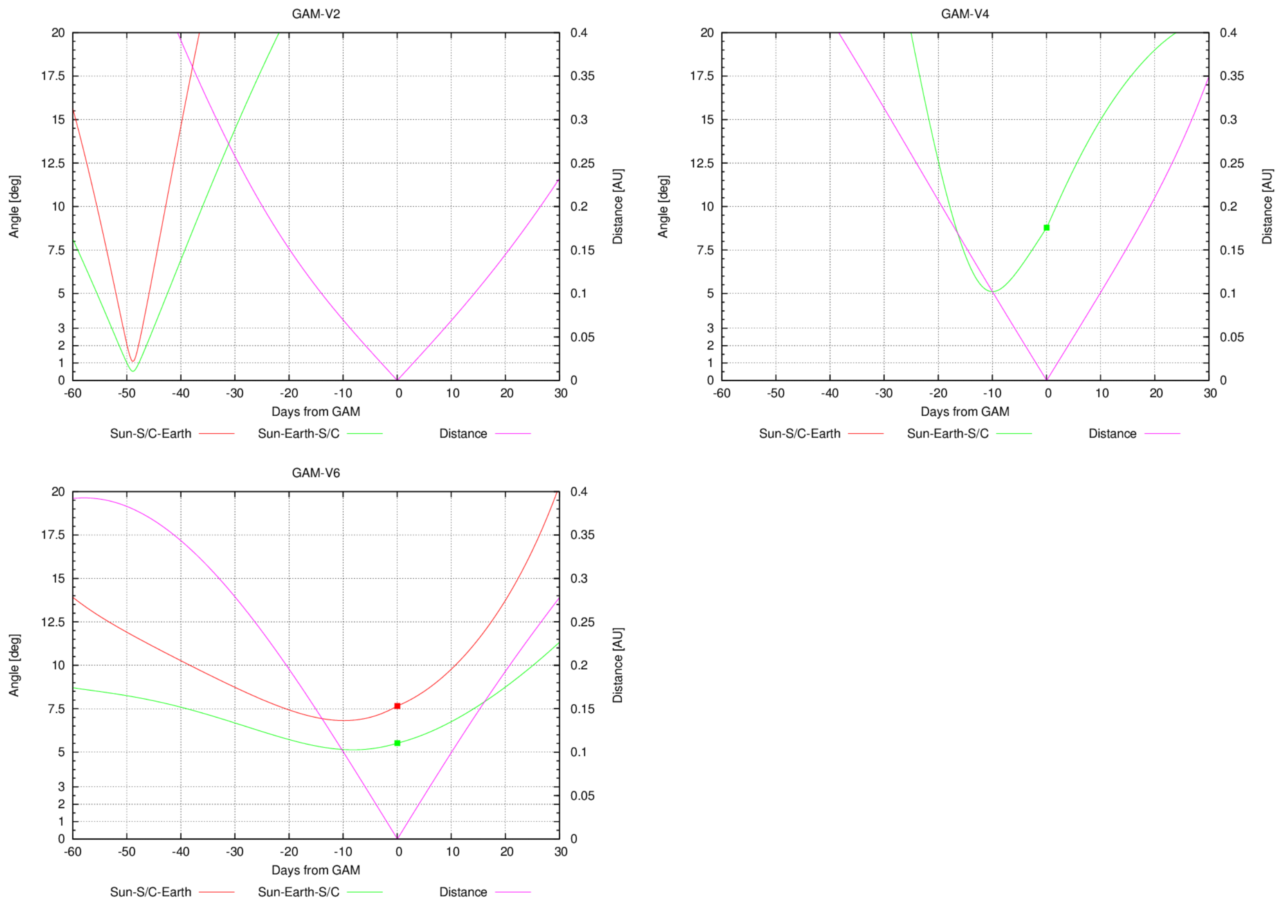


Figure 16: 2020 July A – Communication angles SES and SSE around GAM-V2, -V4 and –V6

3.1.2 Launch window analysis

The launch window has been analysed for the 2020 July A trajectory considering compatibility with an Atlas V 411 launch vehicle. The assumed maximum escape velocity for the 1800 kg Solar Orbiter spacecraft is 5.64 km/s in compliance with CReMA 4.1 (RD 1). A launch period of 19 consecutive days from June 28 to July 16[1] has been identified. The launch period is limited in both extremes by the launcher performance.

The eclipse duration at GAM-V1 has been taking into account for the design of the trajectory and launch period. In the case that GAM-V1 and GAM-V2 are left unconstrained, the trajectory solution leads to an eclipse a 40-min eclipse at GAM-V2. The altitude at GAM-V1 can easily be constrained above 50000 km, with no Delta-V or trajectory performance penalty, in order to have GAM-V2 eclipse durations below 20 minutes. A higher altitude leads to even shorter eclipse, but also leads to a reduction of the launch period by 1 or 2 days at 60000 km. As alternative constraining the altitude at GAM-V2 was investigated. A fixed GAM-V2 altitude above 3500 km also limits the eclipse duration below 20 min. A good compromise is found with the proposed trajectory with GAM-V1 fixed at 50000 km altitude.

Table 4 provides a summary of trajectory properties for this launch window. A maximum escape velocity of 5.612 km/s is required and the absolute value of the DLA is well below the nominal inclination of the parking orbit of Atlas V (~28.7 deg). The final solar inclination remains between 32 and 32.3 deg. This launch window respects all spacecraft, operational and science constraints and goals.

[1] Notice that the trajectory is named July although the launch period is actually open for the last 3 days of June.

Launch vehicle	Atlas V 411
Launch period (days)	19
Launch dates	Jun-28 – Jul-16
Escape velocity (km/s)	5.331 – 5.612
DLA (deg)	-18.6 – -12.7
RLA (deg)	180.1 – 192.2
Final solar inclination (deg)	31.96 – 32.26
Max. Sun distance (AU)	1.178
Longest eclipse (min)	19.3 (V2)
Longest occultation (min)	22.5 (V1)
Longest safe-mode blackout (days)	

Table 4: 2020 July A launch windows summary

The following figures provide the variation of several relevant parameters with the launch day.

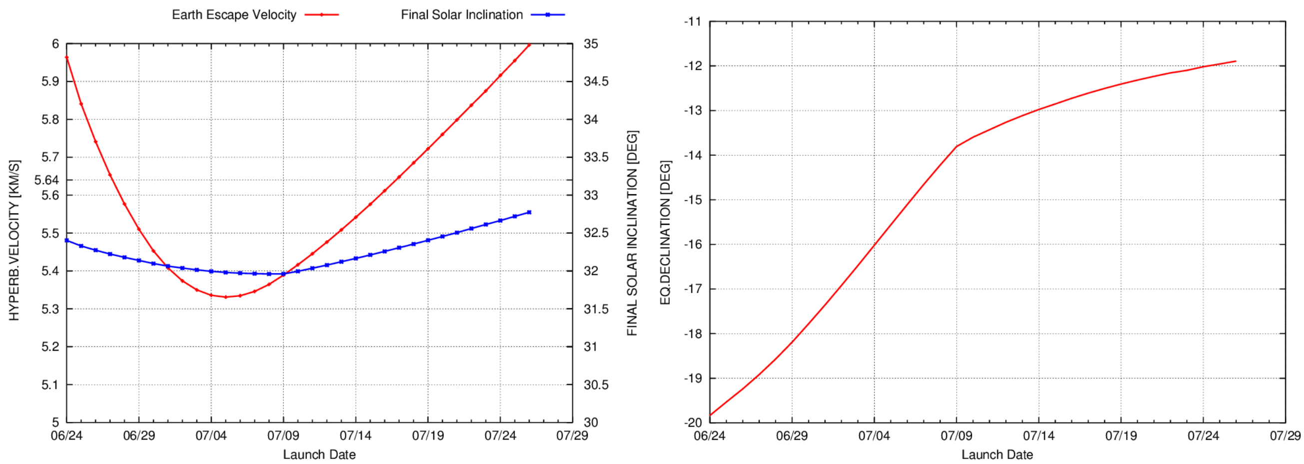


Figure 17: 2020 July A launch window – Launch targets and solar inclination

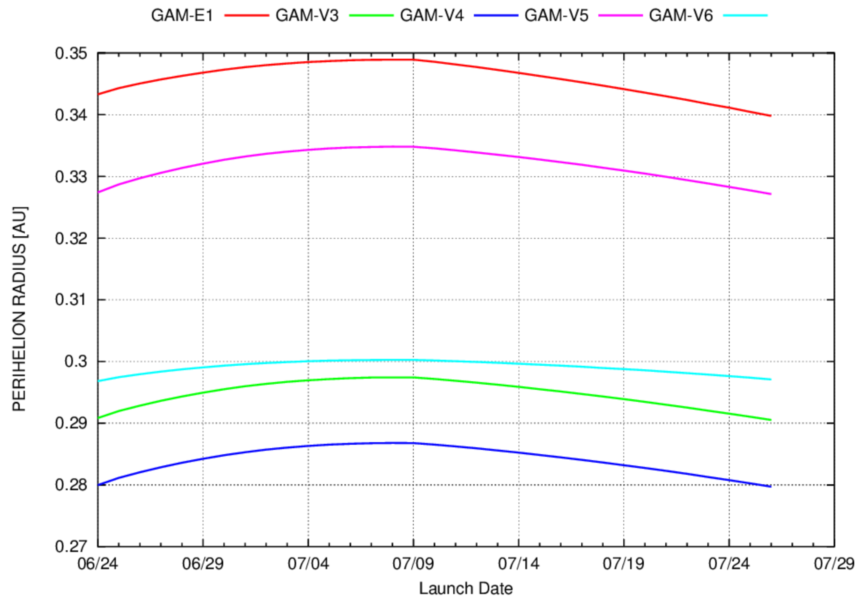


Figure 18: 2020 July A launch window – Perihelion of science orbits

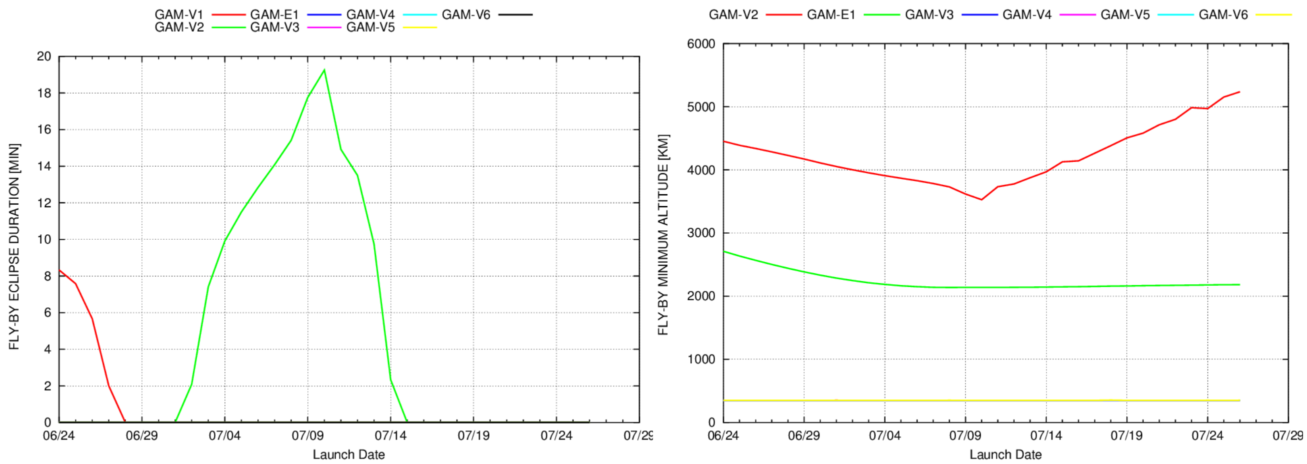


Figure 19: 2020 July A launch window – GAM eclipse duration and minimum altitude

3.2 2020 July B

3.2.1 *Trajectory description*

This trajectory is just a variation of the 2020 July A (see 3.1.1) with exactly the same cruise profile (EVVEV, with a 1:1 Venus resonance) and a different sequence of resonances during the science phase. Indeed the sequence is 4:3-4:3-3:2-3:2 so that until GAM-V4 the trajectory is exactly the same as 2020 July A. The altitude of GAM-V1 has also been fixed in this case to 50000 km in order to limit the duration of GAM-V2.

The duration of the entire mission is maintained at 10.6 years. In this trajectory the perihelion goes below 0.3 AU only for the first 4:3 resonance and stays between 0.33-0.37 AU afterwards. The final solar inclination in the 3:2 resonance is 0.5 deg higher than in the 5:3 resonance of the 2020 July A option.

Phase	Cruise			NMP			EMP		
Trajectory arc	L-V1	V1-V2	V2-E1	E1-V3	V3-V4	V4-V5	V5-V6	V6-End	
Arc start date	2020-07-08	2020-12-13	2021-07-25	2023-09-16	2024-12-23	2026-10-28	2028-09-01	2029-11-24	
Flight time at arc start (years)	0.00	0.43	1.05	3.19	4.46	6.31	8.15	9.38	
Flight time at arc end (years)	0.43	1.05	3.19	4.46	6.31	8.15	9.38	10.61	
Arc duration (days)	158	225	783	464	674	674	449	449	
Number of revolutions in arc Venus Resonance	0	1 1:1	2	2	4 4:3	4 4:3	3 3:2	3 3:2	
Orbit Period (days)	243.9	224.7	299.9	207.8	168.5	168.5	149.8	149.8	
Rs at aphelion (AU)	1.018	0.964	**1.171**	1.024	0.897	0.853	0.773	0.732	
Rs at max. latitude (AU)	0.874	0.795	1.169	0.978	0.719	0.706	0.584	0.545	
Rs at min. latitude (AU)	0.556	0.540	0.584	0.355	0.324	0.373	0.385	0.450	
Rs at perihelion (AU)	0.510	0.482	0.583	0.349	**0.297**	0.342	0.332	0.372	
Perihelion latitude (deg)	-3.38	-3.03	-9.79	-7.84	-11.92	-17.10	-14.57	-9.07	
$\dot{\theta}$ at perih. (deg/day)	3.12	3.39	2.60	5.89	7.48	5.90	5.68	4.33	
Ecliptic inclination (deg)	2.79	2.77	5.77	3.12	10.27	18.39	23.69	26.87	
Solar inclination (deg)	5.04	5.28	9.82	8.25	15.88	24.04	29.35	**32.53**	Total
Rs < 0.3 AU (days/orbit)					3.5				14.2
Rs < 0.4 AU (days/orbit)				19.7	25.5	22.4	24.8	18.7	361.3
Heliolatitude > 25 deg (days/orbit)							31.6	33.9	196.5
Heliolatitude < -25 deg (days/orbit)							14.0	23.4	112.2
Downlink index (1/AU^2)	3.44	0.40	2.08	1.65	2.14	1.49	1.19	1.42	

Table 5: 2020 July B – Trajectory Summary

GAM	Date	Re (AU)	Vinf (km/s)	Hmin (km)	Eclipse (min)	Occult. (min)	Ls (deg)	SSE (deg)	SES (deg)	ESV (deg)
V1	2021-05-04	1.691	9.803	12438	0.0	69.4	68.5	14.3	10.2	155.6
E1	2023-06-07	0.000	9.294	837	20.3	0.0	256.2	-	-	-
V2	2024-03-26	1.606	17.711	350	0.0	0.0	323.1	25.3	18.2	136.5
V3	2024-11-06	1.139	17.711	350	0.0	0.0	323.0	59.4	39.2	81.4
V4	2026-09-11	0.473	17.709	350	0.0	0.0	323.0	112.1	42.1	25.8
V5	2027-12-05	1.406	17.710	350	0.0	0.0	323.0	41.4	29.2	109.3
V6	2029-02-26	1.704	17.709	350	0.0	0.0	323.0	8.7	6.4	164.9
V7	2030-05-22	1.167	17.709	-	-	-	323.0	59.3	38.2	82.5

Table 6: 2020 July B – GAM Properties

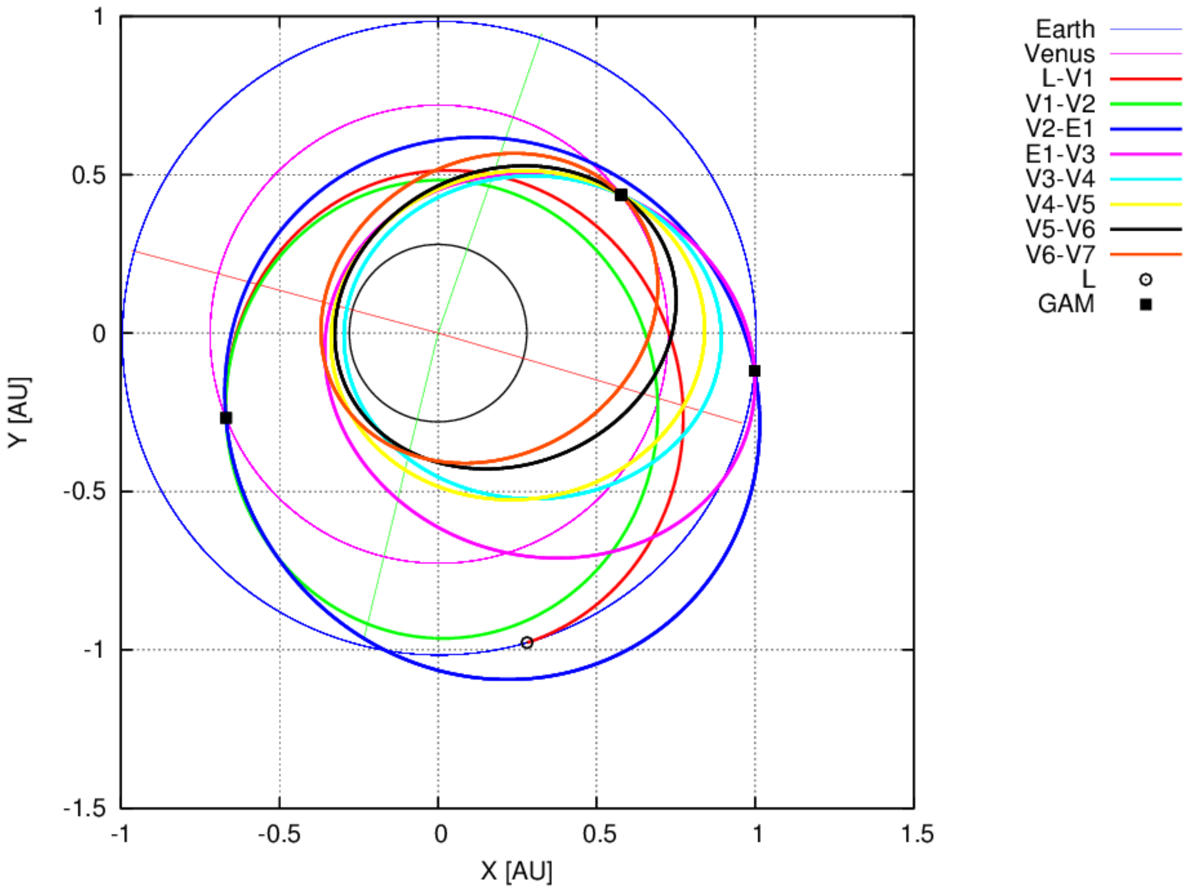


Figure 20: 2019 August – Trajectory Projection in the Ecliptic Plane

In terms of science data return capability, as in the 2020 July A trajectory the E1-V3 and V3-V4 arcs are well suited for data downlink. The first aphelion of the second 4:3 resonance in the V4-V5 arc is also well phased with Earth leading to an overall arc DLi of 1.49. The 3:2 resonances, however, do not favour the data downlink. Thus in comparison with the 2020 July A this trajectory offers slightly increased performance for science data return during the NMP and slightly worse during EMP.

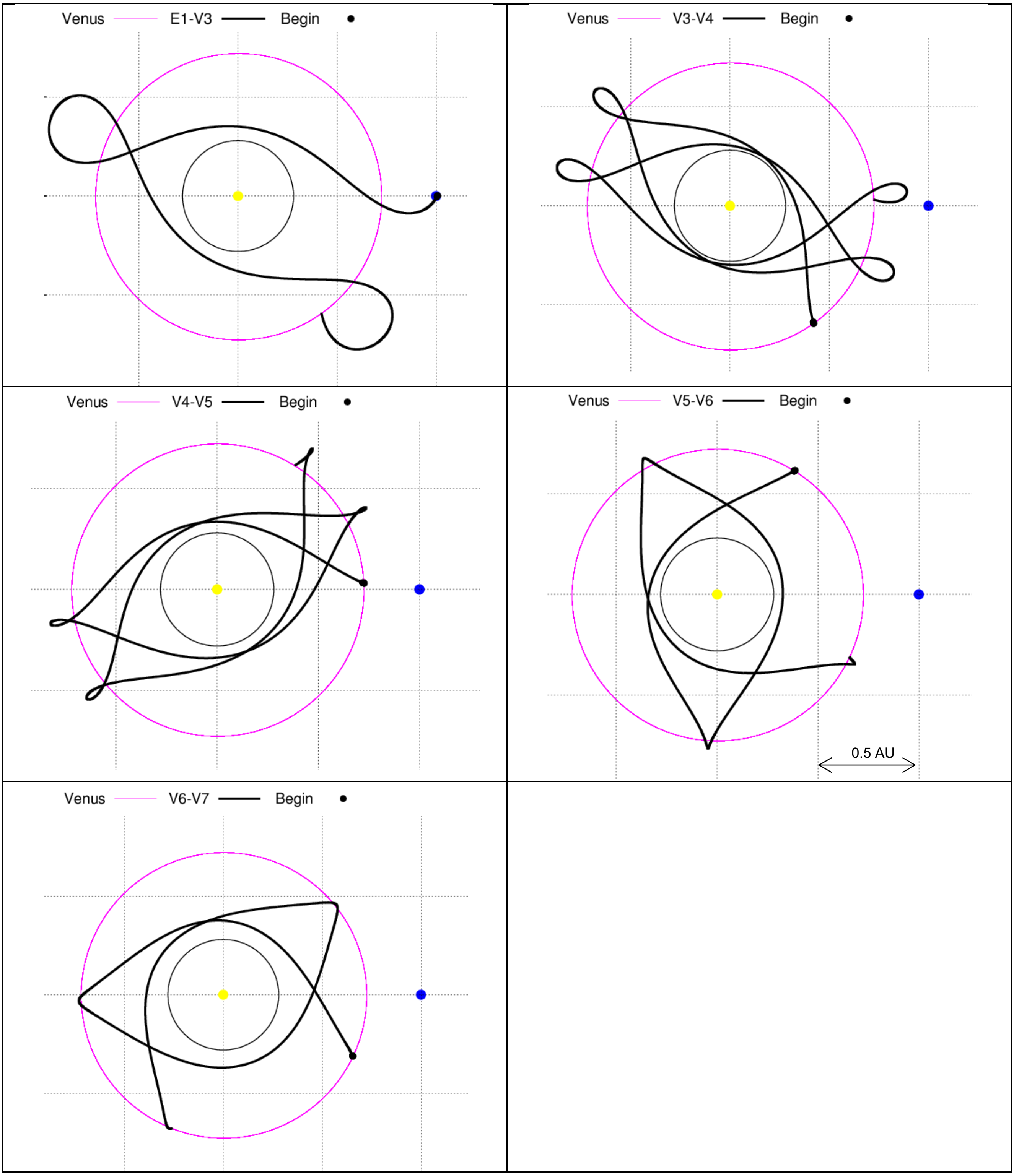


Figure 21: 2020 July B – Trajectory Projection in the Sun-Earth rotating frame

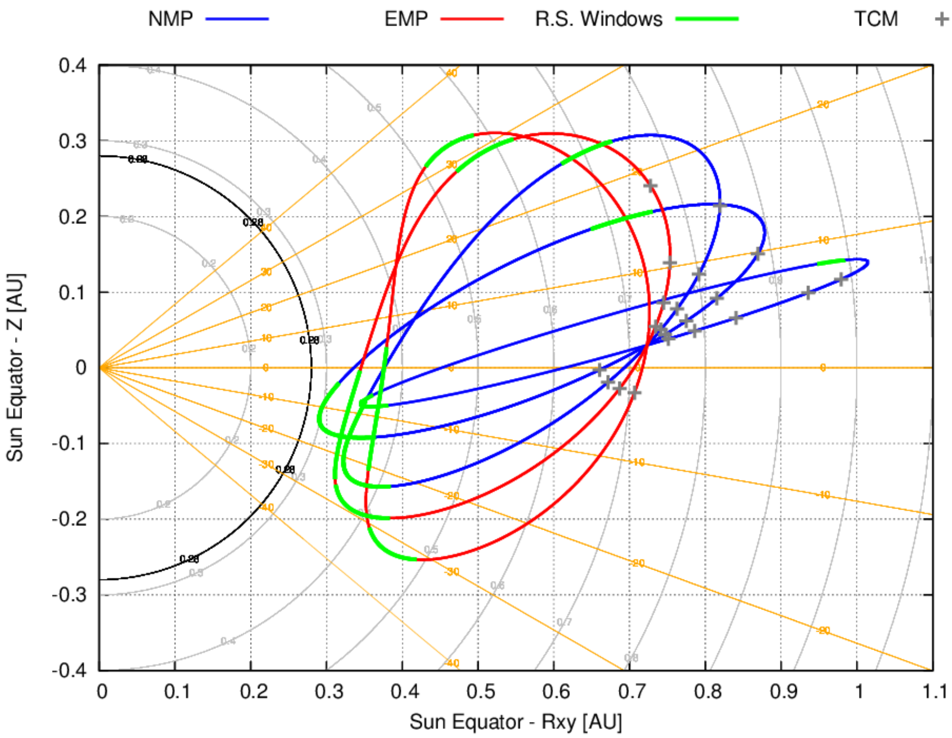


Figure 22: 2020 July B – Trajectory projection of science orbits wrt Sun Equator and North Pole

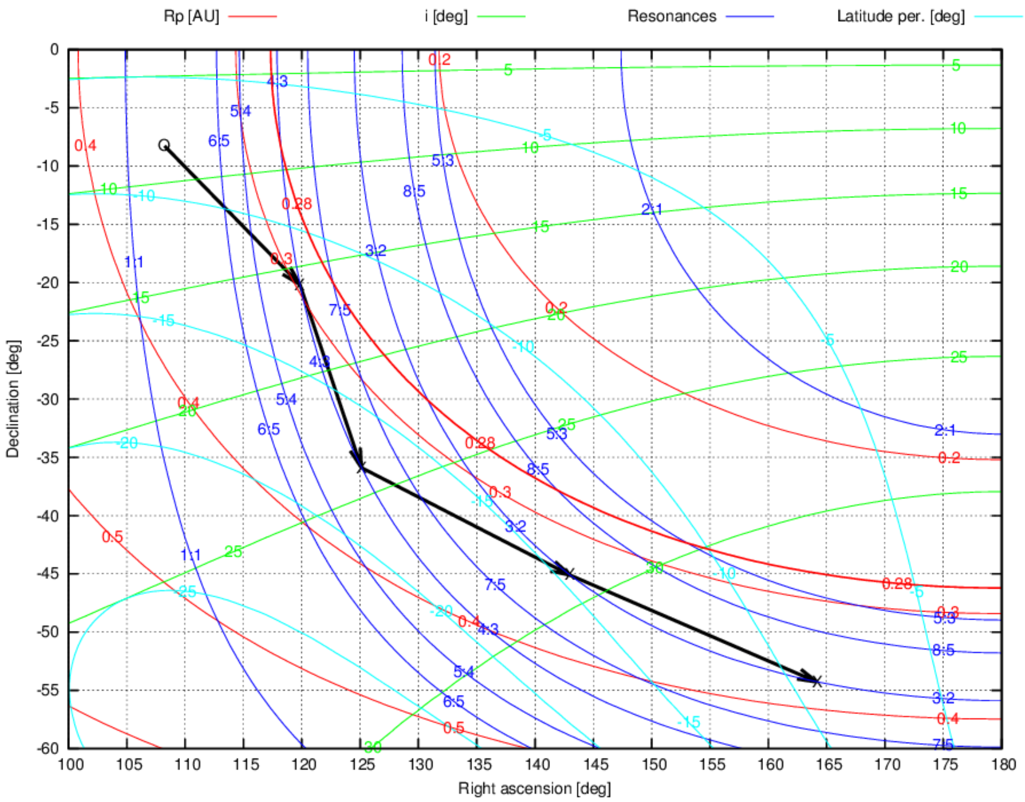


Figure 23: 2020 July B – V-infinity diagram

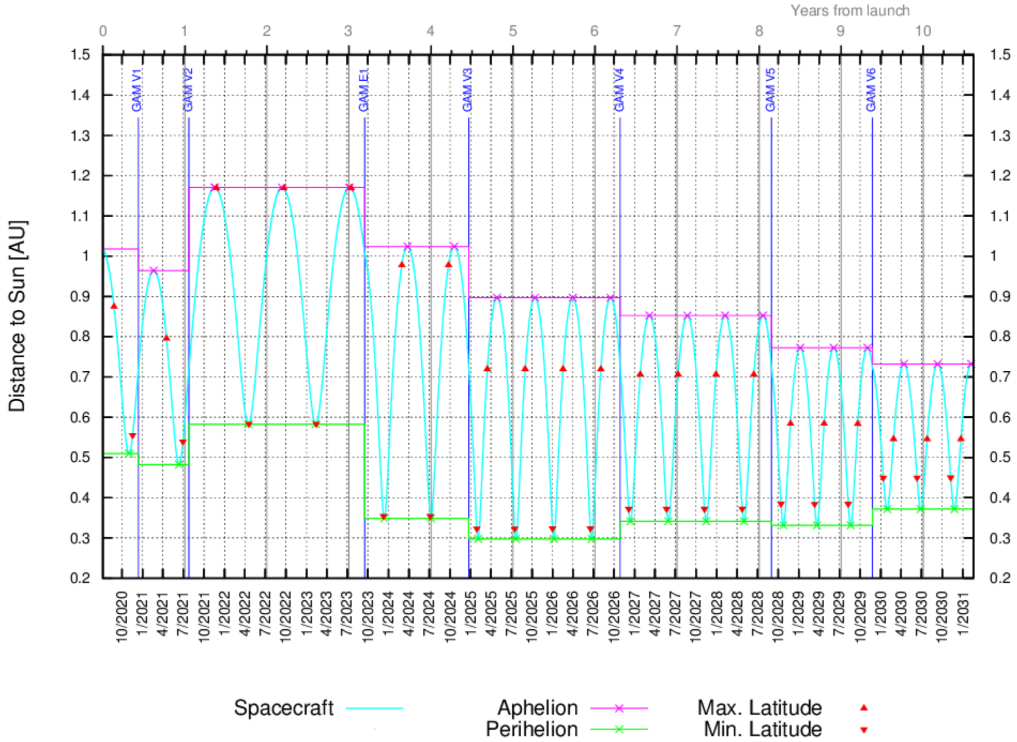


Figure 24: 2020 July B – Distance to Sun

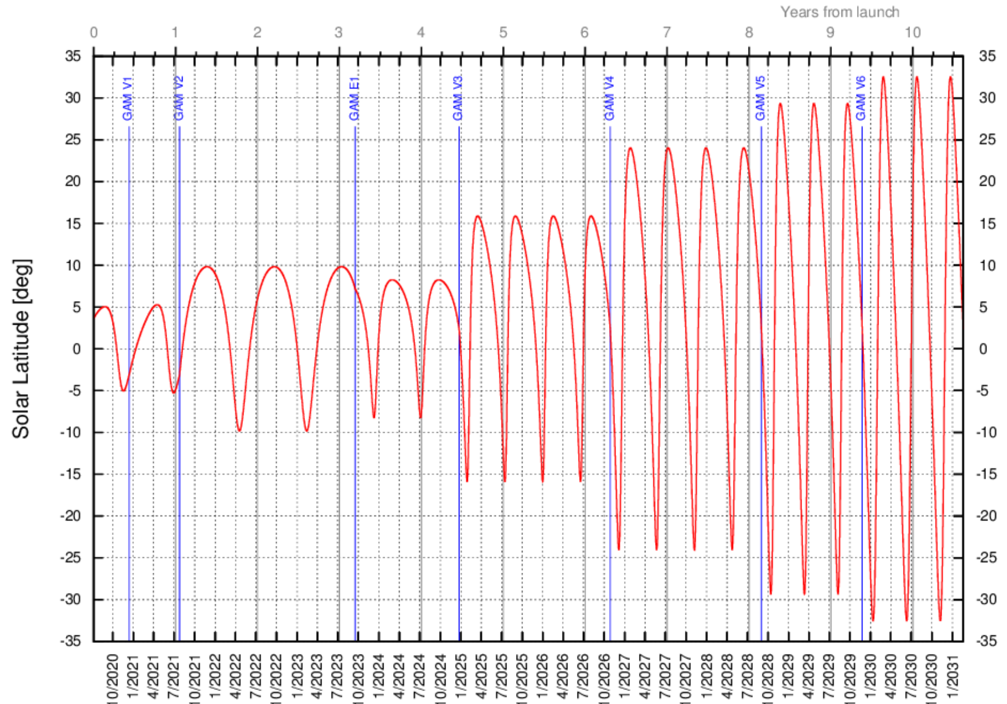


Figure 25: 2020 July B –Solar latitude

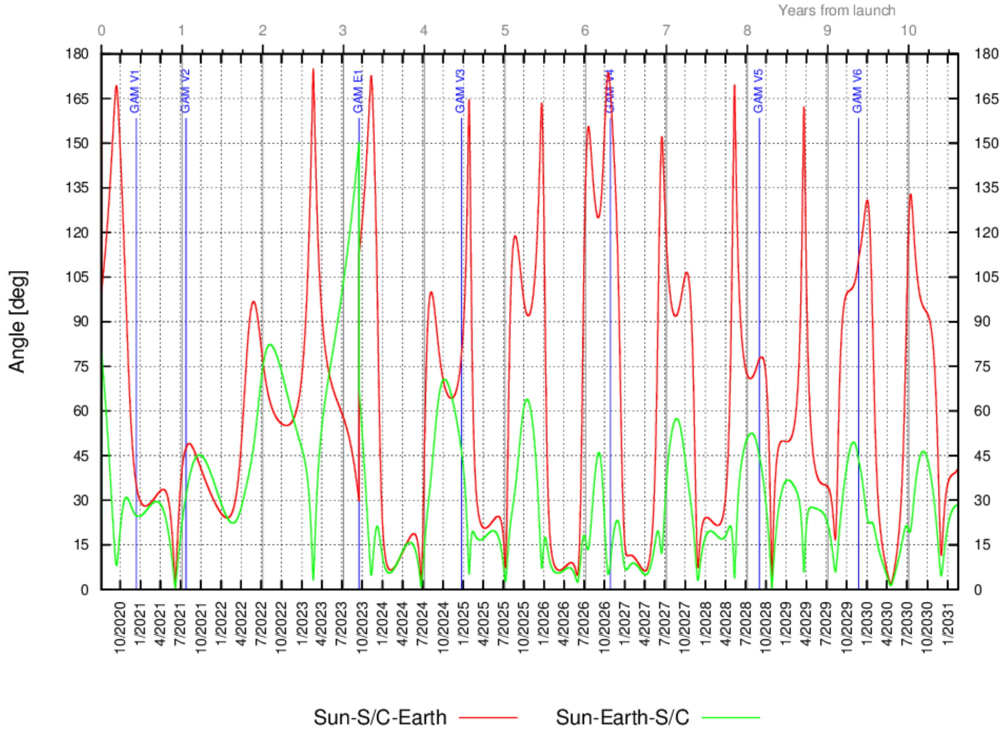


Figure 26: 2020 July B – Communication angles SES and SSE

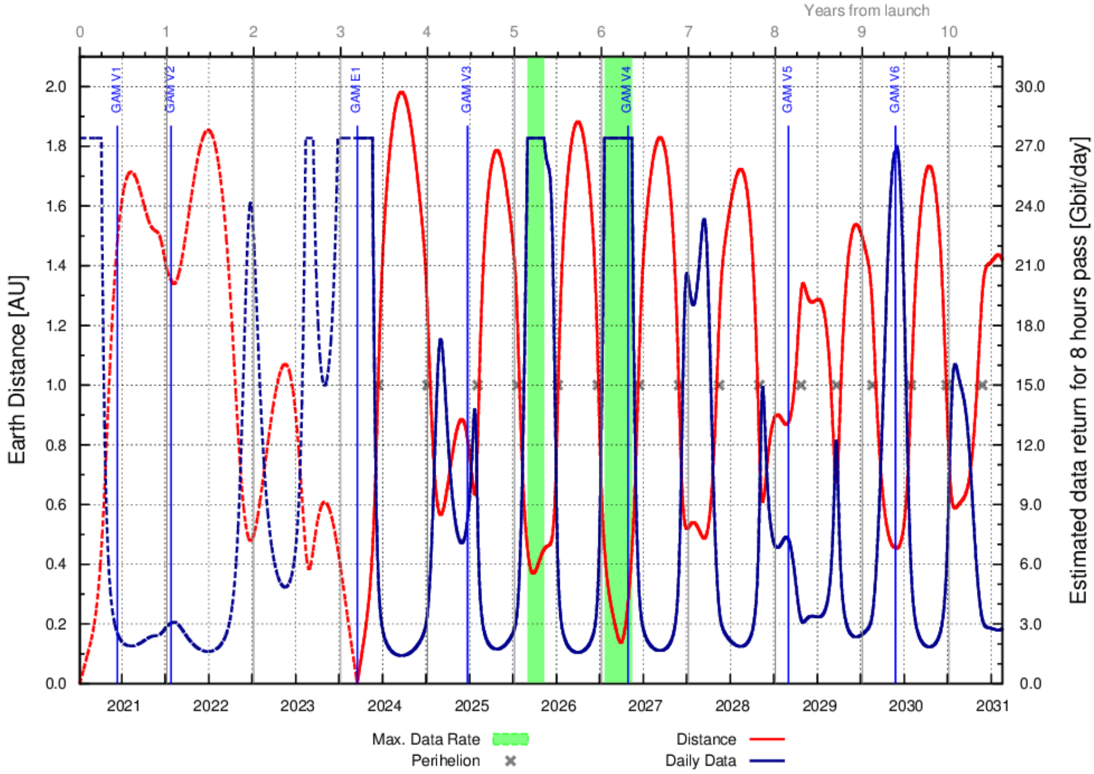


Figure 27: 2020 July B – Distance to Earth and potential daily data downlink

Solar Conjunction Periods
SES<3 deg

	Type	Start	End	Duration [days]	Min SES [deg]
1	Superior	2021-06-03	2021-06-10	7.7	0.5
2	Superior	2024-06-20	2024-06-27	7.1	0.9
3	Superior	2025-07-09	2025-07-11	2.4	2.8
4	Superior	2026-05-27	2026-06-04	7.2	2.5
5	Superior	2027-10-07	2027-10-11	3.7	1.0
6	Superior	2029-10-25	2029-10-29	4.2	0.1

Safe Mode Blackout Periods
SES<=5 deg OR SSE<=3 deg

	Start	End	Duration [days]
1	2021-05-31	2021-06-13	13.0
2	2023-02-19	2023-02-23	3.6
3	2023-11-10	2023-11-12	2.0
4	2024-06-16	2024-06-29	12.4
5	2025-07-05	2025-07-14	8.6
6	2026-05-19	2026-06-08	20.0
7	2026-12-24	2026-12-28	3.8
8	2027-05-16	2027-05-19	2.8
9	2027-10-06	2027-10-13	6.5
10	2029-10-23	2029-10-30	7.0
11	2030-12-10	2030-12-13	2.8

Table 7: 2020 July B - Solar Conjunctions

Figure 28 shows a zoom of the SES and SSE angles around GAM-V6. Both angles become relatively small, but still remain above the 5 deg threshold considered by ESOC for the implementation of critical operations. Therefore, navigation of this GAM is not expected to be an issue.

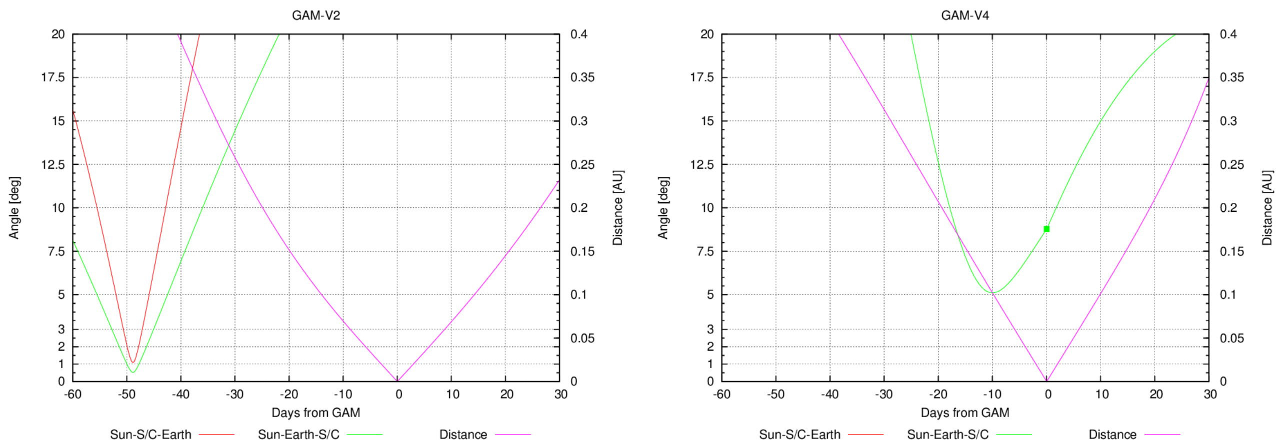


Figure 28: 2020 July B – Communication angles SES and SSE around GAM-V2 and –V4

3.2.2 *Launch window analysis*

Given the common profile of the cruise phase, the launch window is the same as for the 2020 July with launch period open 19 consecutive days from June 28 to July 16. For the launch window computations the altitude at GAM-V1 has been fixed at 50000 km in order to limit the duration of eclipse at GAM-V2.

The following table and figures provide the main results of the launch window analysis. They are consistent with the results provided in 3.1.2.

Launch vehicle	Atlas V 411
Launch period (days)	19
Launch dates	Jun-28 – Jul-16
Escape velocity (km/s)	5.331 – 5.612
DLA (deg) – MEE2000	-18.5 – -12.7
RLA (deg) – MEE2000	180.2– 192.1
Final solar inclination (deg)	32.5 – 32.8
Max. Sun distance (AU)	1.178
Longest eclipse (min)	17.9 (V2)
Longest occultation (min)	22.9 (V1)
Longest safe-mode blackout (days)	

Table 8: 2020 July B launch windows summary

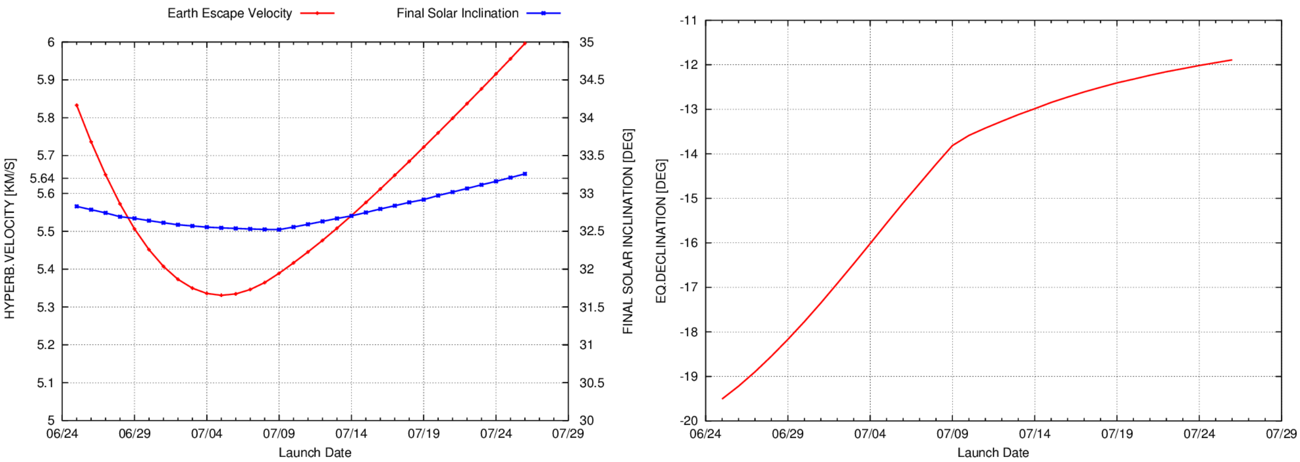


Figure 29: 2020 July B launch window – Launch targets and solar inclination

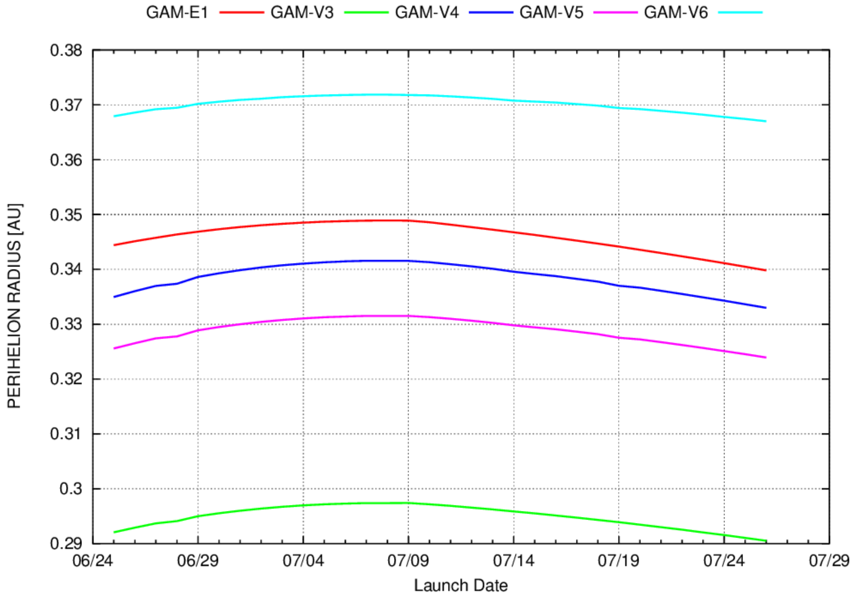
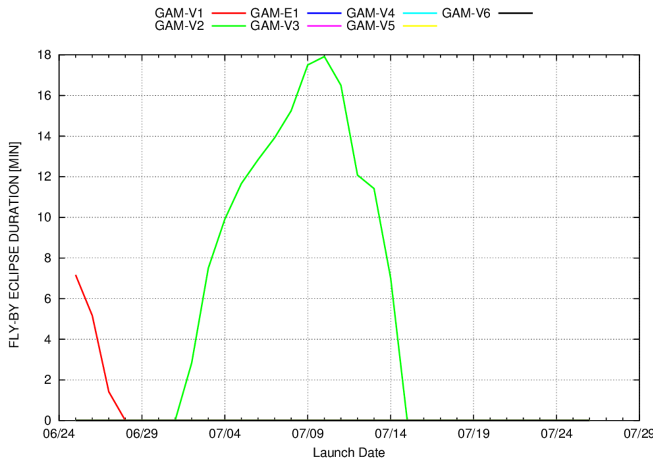


Figure 30: 2020 July B launch window – Perihelion of science orbits



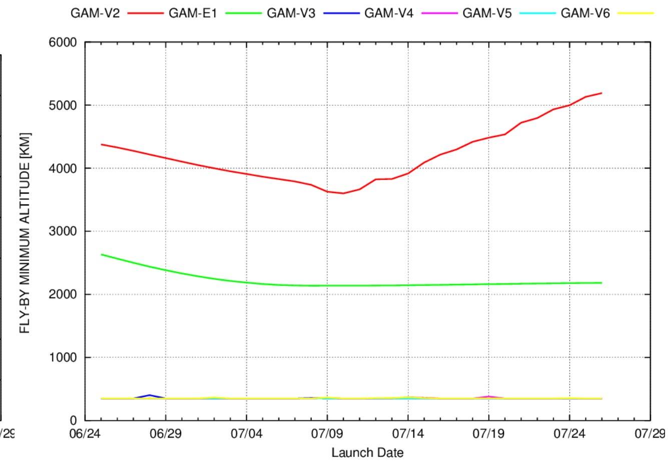


Figure 31: 2020 July B launch window – GAM eclipse duration and minimum altitude

3.3 2020 September

3.3.1 Trajectory description

This trajectory was identified in an attempt to provide a later backup launch in 2020. It requires relaxing 2 mission constraints: namely the overall mission duration is extended to 11.6 years, thus 1 additional year wrt previous trajectories, and the total number of GAMs to 9. During the science phase the trajectory goes below 0.3 AU only in one of the 3:2 resonances and stays close to this value in the core 5:4 and 4:3 resonances of the NMP. It is expected that the value of equivalent Sun hours (or integrated $1/Rs^2$) accumulated by the end of mission will remain within the level of previous baseline trajectories as the 2018 Option E and the current 2020 February baseline. One of the reasons to propose this trajectory is the excellent data return capability during the NMP.

The 2020 September launch option is described here using a reference trajectory with launch on Sep 11. The actual launch period opens actually from Aug 20 to Sep 21 (Section 3.3.2). The trajectory is based on an EEVVEV cruise profile, thus the same trajectory can be used with launch 1 year later in September 2021. The Earth-Earth arc is a 1:1 resonance in which the orbit can either go inwards or outwards. In the rest of this section, the tables and figures present the outwards trajectory only. In general for a given DLA only one of the two possibilities is feasible with no need of Delta-V manoeuvres. For the selected reference launch date of Sep 11, both solutions are feasible. The highest Sun range will be encountered during this first Earth-Earth arc.

The first Earth-Venus arc takes more than one revolution in 10.5 months. The next arc in 1:1 resonance with Venus offers an extra degree of freedom that can be used to select the altitude at either V1 or V2 and have some degree of control over the eclipses encountered at these GAMs. In this document V1 is fixed at 30000 km, which works well for the entire launch period and avoids long eclipses. From Venus to Earth the arc is direct and the Earth is encountered before reaching the aphelion. GAM-E2 sets the perihelion at 0.336 AU so that the NMP can start 2.8 years after launch. The E2-V3 arc involves one such perihelion pass.

The sequence of resonances in the science phase is 5:4-4:3-3:2-3:2-3:2, which includes 2-3 Venus revolutions more than typical Solar Orbiter trajectories. This is needed in order to reach a solar inclination above 30 deg by the end of mission. Otherwise at the second 3:2 resonance barely 28.5 deg are achieved. The 3 first resonances have perihelions close to 0.3 AU, but only dipping below 0.3 AU in the 4:3 resonance. As a result the overall stay below 0.3 AU is short, while below 0.4 AU the stay remains long due to the longer duration. It must be noticed that there is a 3 hour long occultation at GAM-V3 that will have to be considered when planning the operations.

In terms of science data return capability the 5:4 resonance has an excellent performance (DLi 2.41) due to the favourable phasing of 3 of the aphelions. The favourable phasing is also maintained during the 4:3 resonance with DLi 1.91. Thus if the NMP is considered until V5, the data return potential during this phase is excellent. During the EMP, the first and third 3:2 resonances are not well suited for the downlink, while the second 3:2 resonance has the second aphelion close to Earth resulting in a DLi of 1.61 and allowing the maximum data rate for a period of several weeks.

The overall downlink capability is at the same level as the 2020 February baseline trajectory.

It is also worth pointing out that this September launch opportunity repeats in 2021 with direct launch towards Venus. In this case the mission duration is 10.6 years and a total of 8 GAMs (1 Earth + 7 Venus) are needed. Thus 2021 September launch would be respecting the current set of mission and engineering constraints.

Phase	Cruise				NMP			EMP			
Trajectory arc	L-E1	E1-V1	V1-V2	V2-E2	E2-V3	V3-V4	V4-V5	V5-V6	V6-V7	V7-End	
Arc start date	2020-09-11	2021-09-11	2022-07-26	2023-03-08	2023-07-06	2024-04-08	2026-09-24	2028-07-29	2029-10-22	2031-01-14	
Flight time at arc start (y)	0.00	1.00	1.87	2.49	2.82	3.58	6.04	7.88	9.11	10.34	
Flight time at arc end (y)	1.00	1.87	2.49	2.82	3.58	6.04	7.88	9.11	10.34	11.57	
Arc duration (days)	365	319	225	120	277	899	674	449	449	449	
Number of revs. in arc Venus Resonance	1	1	1 1:1	0	1	5 5:4	4 4:3	3 3:2	3 3:2	3 3:2	
Orbit Period (days)	365.3	241.6	224.7	293.4	204.6	179.8	168.5	149.8	149.8	149.8	
Rs at aphelion (AU)	**1.147**	1.007	0.963	(1.164)	1.023	0.947	0.887	0.806	0.758	0.729	
Rs at max. latitude (AU)	1.076	1.004	0.952	(1.145)	0.906	0.396	0.375	0.378	0.436	0.502	
Rs at min. latitude (AU)	0.897	0.512	0.487	0.569	0.350	0.536	0.584	0.515	0.521	0.489	
Rs at perihelion (AU)	0.853	0.512	0.484	0.565	0.336	0.300	0.308	**0.298**	0.346	0.375	
Perihelion latitude (deg)	-5.00	-7.26	-5.21	-6.20	-3.68	2.44	7.60	7.78	6.55	-1.28	
$\dot{\theta}$ at perih. (deg/day)	1.34	3.13	3.39	2.71	6.23	7.32	6.85	6.80	5.04	4.23	
Ecliptic inclination (deg)	4.01	0.62	1.94	0.99	3.94	8.00	16.75	23.51	28.48	30.52	
Solar inclination (deg)	8.13	7.30	5.34	6.40	4.22	8.48	17.14	23.88	28.84	**30.88**	Totals
Rs < 0.3 AU (days/orbit)								2.8			8.4
Rs < 0.4 AU (days/orbit)					21.3	24.8	25.0	26.7	23.3	17.8	448.8
Heliolat.>25 deg (d/orb.)									16.7	26.0	128.3
Heliolat.<-25 deg (d/orb.)									23.7	24.7	145.2
Downlink index ($1/AU^2$)	4.23	1.90	0.45	3.16	2.01	2.41	1.91	0.95	1.61	0.99	

Table 9: 2020 September – Trajectory Summary

GAM	Date	Re (AU)	Vinf (km/s)	Hmin (km)	Eclipse (min)	Occult. (min)	Ls (deg)	SSE (deg)	SES (deg)	ESV (deg)
E1	2021-09-11	0.000	5.233	632	19.8	0.0	348.2	-	-	-
V1	2022-07-26	1.533	11.624	30000	0.0	0.0	66.3	33.8	23.3	123.0
V2	2023-03-08	1.332	11.623	10549	0.0	12.7	66.3	47.0	32.1	100.9
E2	2023-07-06	0.000	8.954	509	19.0	0.0	284.0	-	-	-
V3	2024-04-08	1.647	17.768	350	0.0	179.5	343.4	20.9	15.0	144.1
V4	2026-09-24	0.386	17.767	350	0.0	5.5	343.4	125.8	36.0	18.2
V5	2028-07-29	0.614	17.767	350	0.0	5.7	343.4	98.0	45.2	36.8
V6	2029-10-22	0.708	17.767	350	0.0	0.0	343.4	87.8	46.9	45.3
V7	2031-01-14	1.556	17.767	350	0.0	0.0	343.4	28.8	20.9	130.3
V8	2032-04-07	1.651	17.767	-	-	-	343.4	20.4	14.6	145.0

Table 10: 2020 September – GAM Properties

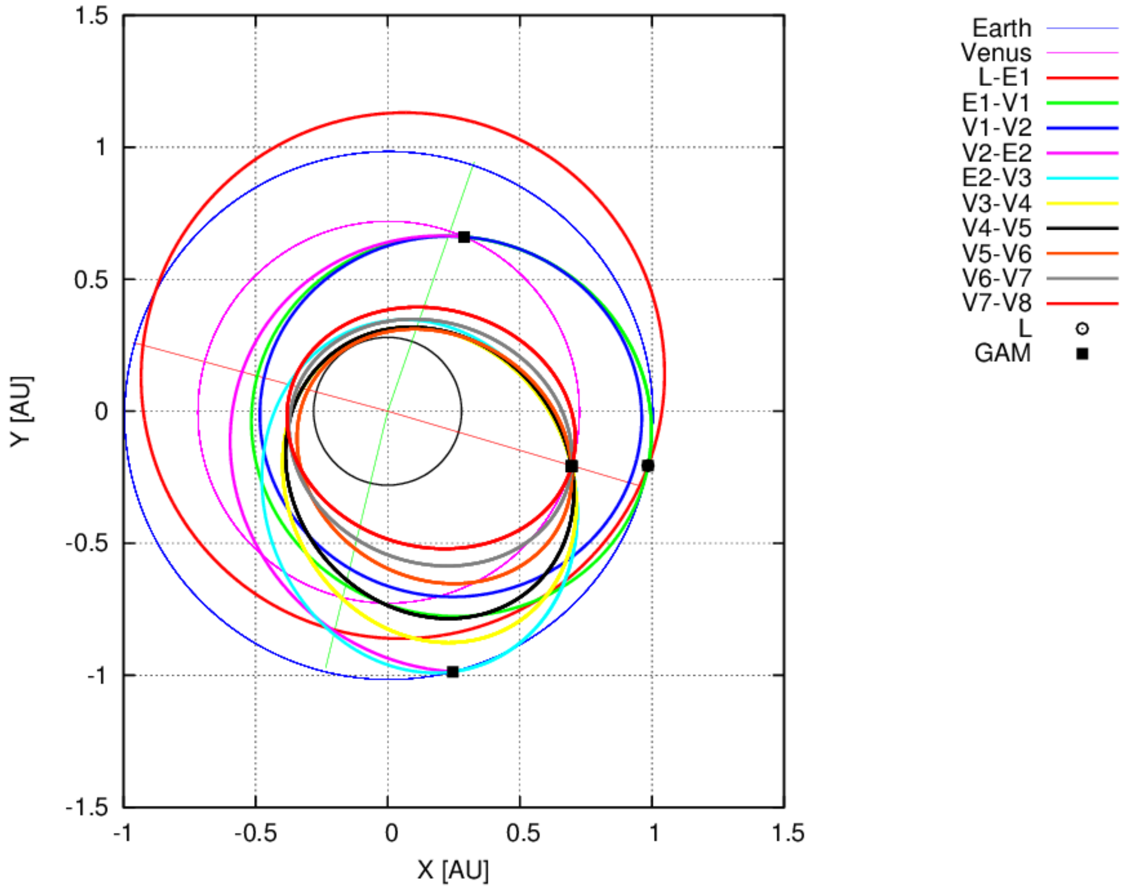


Figure 32: 2020 September – Trajectory Projection in the Ecliptic Plane

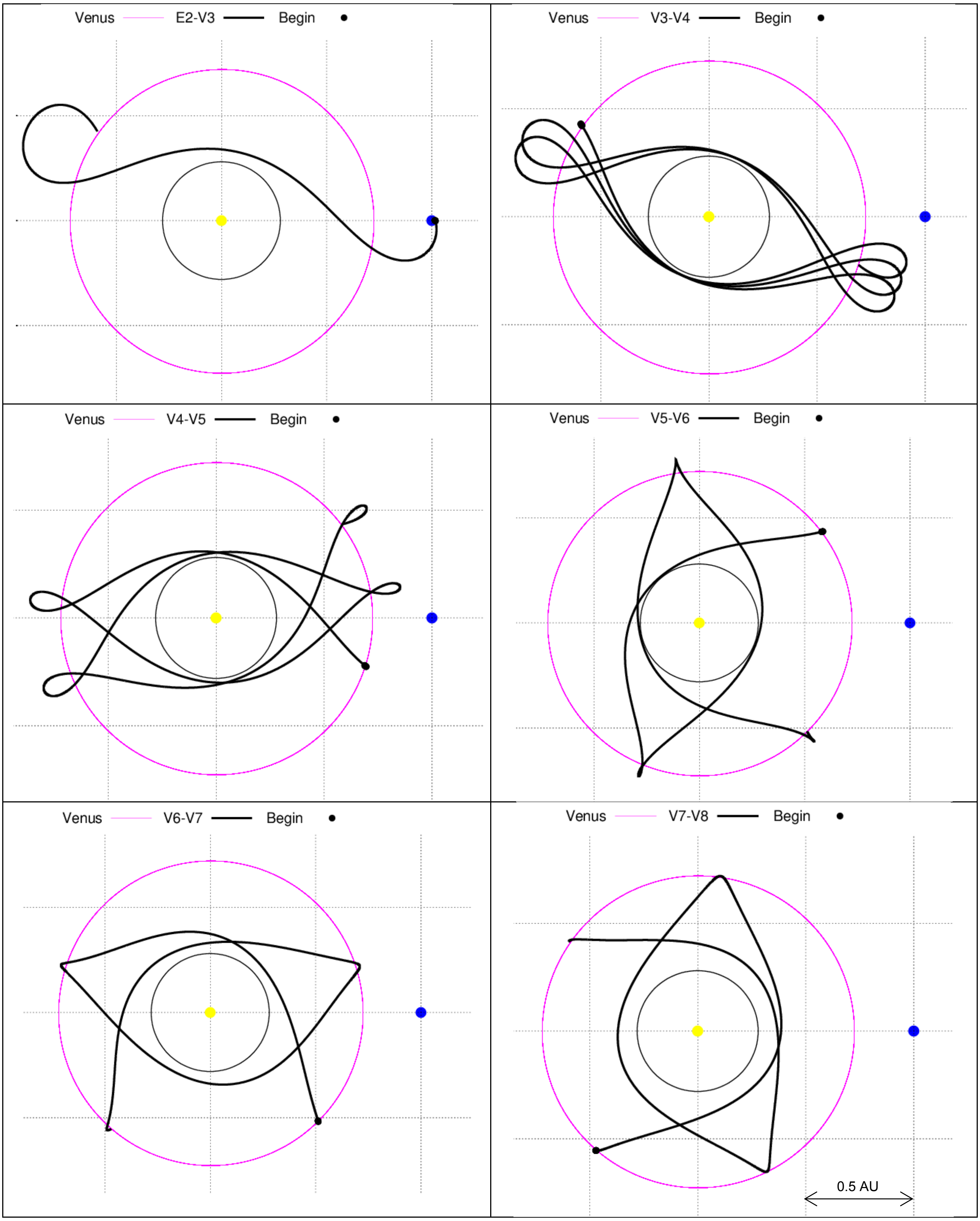


Figure 33: 2020 September – Trajectory Projection in the Ecliptic Plane

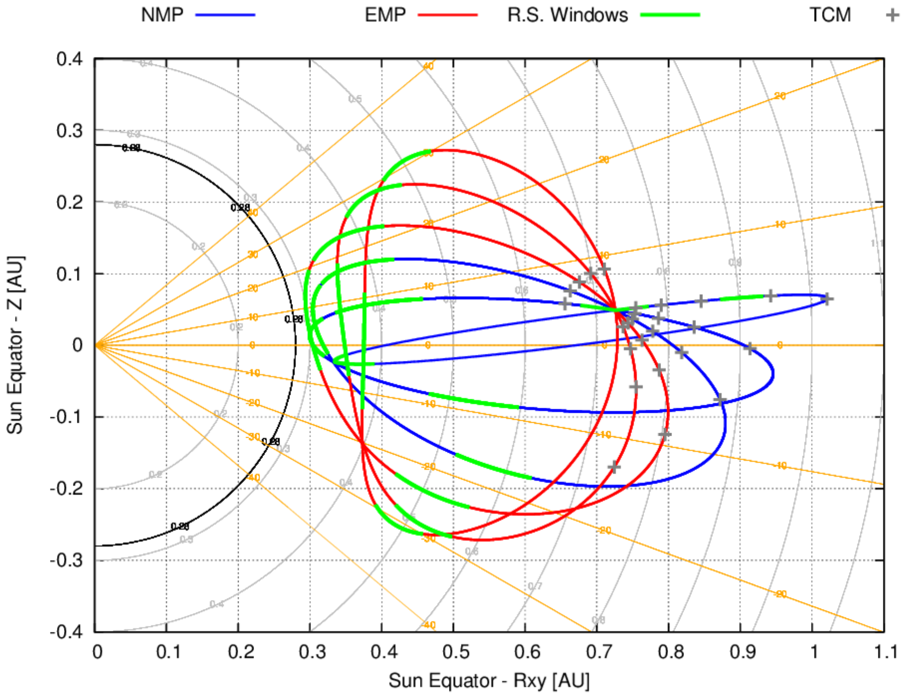


Figure 34: 2020 September – Trajectory projection of science orbits wrt Sun Equator and North Pole

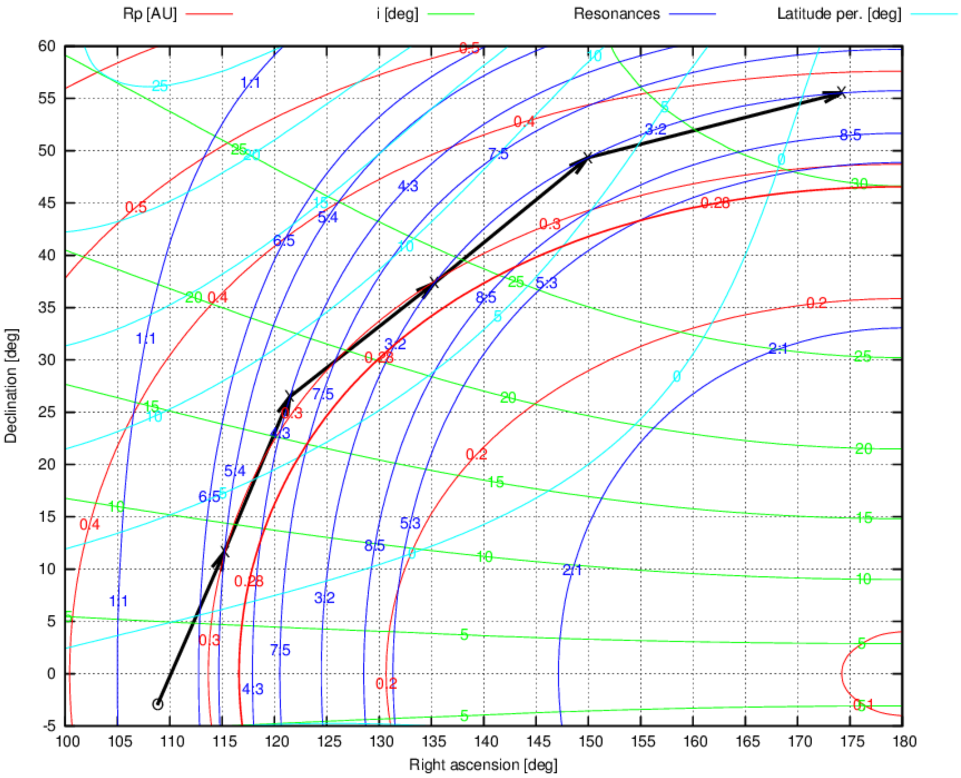


Figure 35: 2020 September – V-infinity diagram

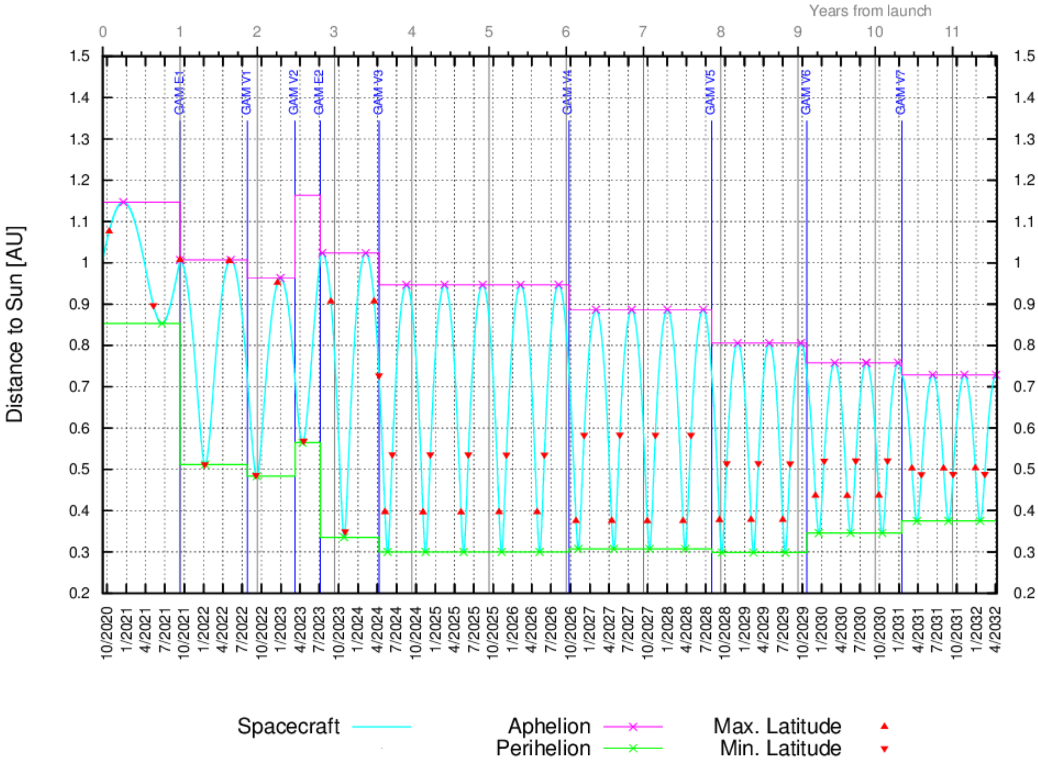


Figure 36: 2020 September – Distance to Sun

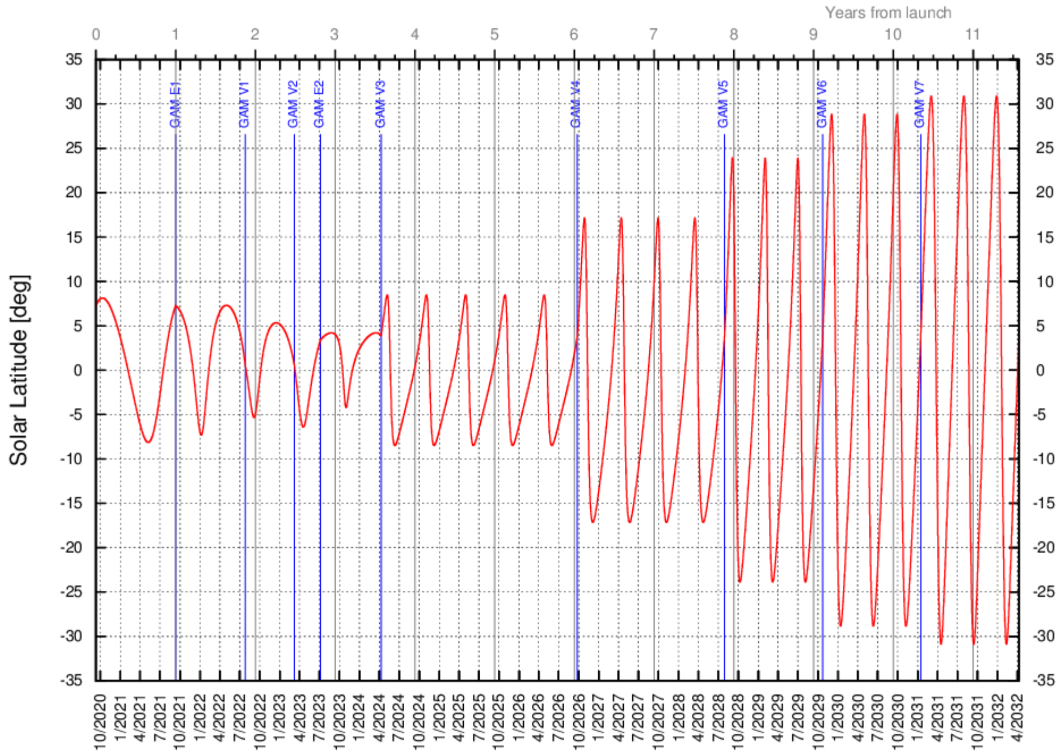


Figure 37: 2020 September –Solar latitude

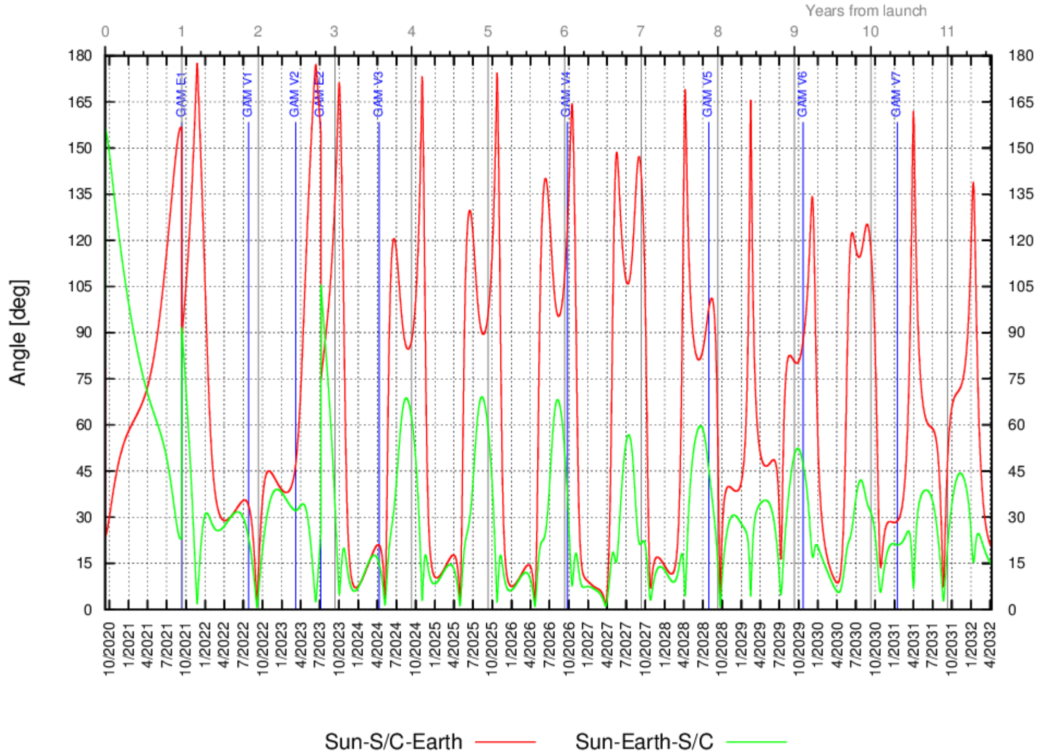


Figure 38: 2020 September – Communication angles SES and SSE

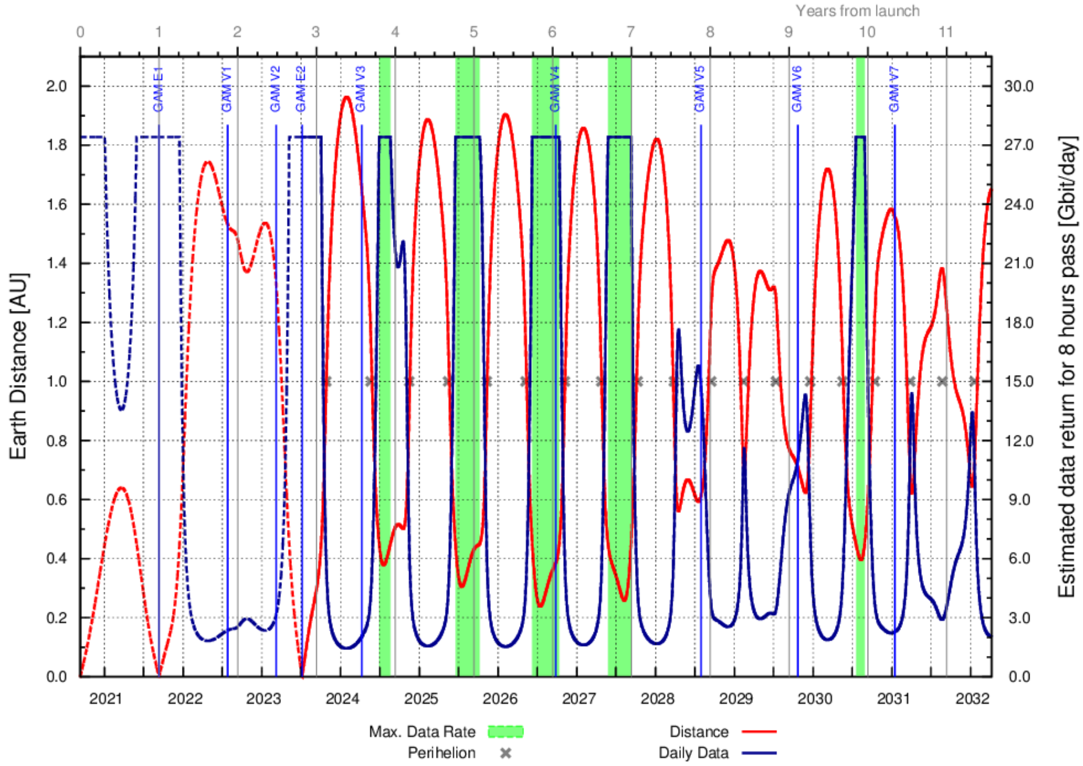


Figure 39: 2020 September – Distance to Earth and potential daily data downlink

Solar Conjunction Periods
SES<3 deg

	Type	Start	End	Duration [days]	Min SES [deg]
1	Inferior	2021-11-21	2021-11-25	3.4	1.8
2	Superior	2022-08-31	2022-09-08	7.6	0.6
3	Inferior	2023-06-10	2023-06-13	3.1	2.6
4	Superior	2024-05-04	2024-05-09	5.8	1.4
5	Inferior	2024-10-31	2024-11-01	0.5	3.0
6	Superior	2025-04-26	2025-05-02	6.7	1.2
7	Inferior	2025-10-23	2025-10-24	1.8	2.5
8	Superior	2026-04-17	2026-04-25	7.9	1.0
9	Superior	2027-03-15	2027-04-01	17.6	1.1
10	Superior	2028-09-19	2028-09-24	4.6	0.8
11	Superior	2031-08-21	2031-08-23	2.0	2.8

Safe Mode Blackout Periods
SES<=5 deg OR SSE<=3 deg

	Start	End	Duration [days]
1	2021-11-20	2021-11-27	6.7
2	2022-08-29	2022-09-11	13.0
3	2023-06-07	2023-06-16	8.6
4	2024-05-01	2024-05-11	10.6
5	2024-10-29	2024-11-02	4.0
6	2025-04-23	2025-05-05	12.0
7	2025-10-21	2025-10-26	4.6
8	2026-04-14	2026-04-28	14.1
9	2027-02-28	2027-04-05	36.5
10	2027-10-20	2027-10-31	10.5
11	2028-09-18	2028-09-26	7.9
12	2031-08-18	2031-08-26	7.6

(Only periods longer than 3 days)

Table 11: 2020 September - Solar Conjunctions

Figure 40 shows the evolution of the SES and SSE angles close to the Venus GAMs for which these angles are small. For E2 during a period of about 10 days starting at GAM-30 days the SES angle gets below 5 deg and only for a few days below 3 deg. For V3 there is a solar superior conjunction at about 30 days after the GAM. Both angles are above 10 deg before the GAM and until 7 days after the closest approach. None of these geometries is expected to have a significant impact for the navigation operations.

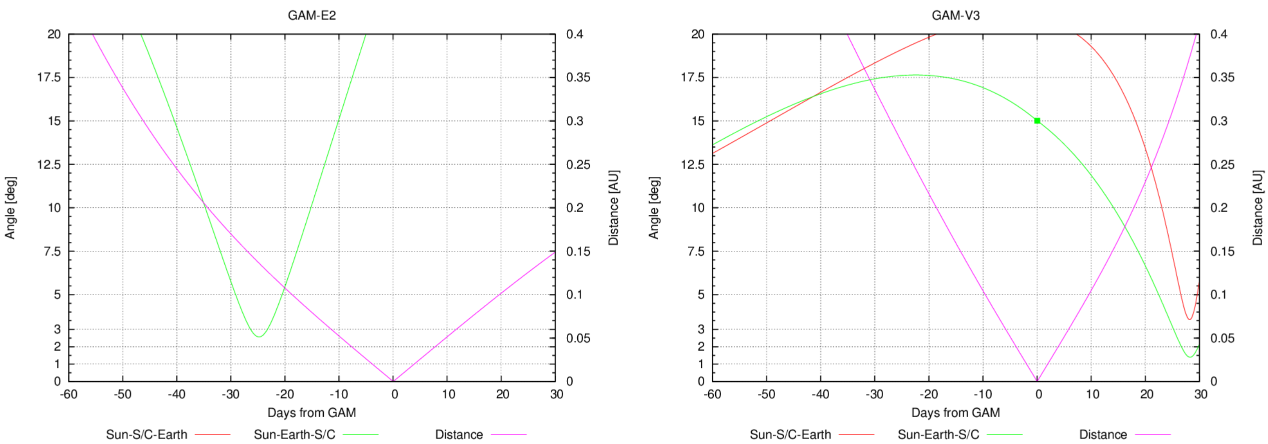


Figure 40: 2020 September – Communication angles SES and SSE around several Venus GAMs

3.3.2 Launch window analysis

A launch period of 33 consecutive days from August 20 to September 21[2] has been identified for this launch option. The launch period is limited at both extremes by appearance of Delta-V manoeuvres. Both launch options, inwards and outwards, were investigated for a preliminary fixed value of DLA equal to +15 deg. At the launch period open only the outwards option is feasible. The altitude of GAM-E1 decreases until a value of about 500 km for launch on Sep 11. From this launch day the inwards option is feasible with GAM-E1 altitude starting at about 500 km an increasing with the launch day. For September 11 both launch options are feasible.

Table 12 provides a summary of trajectory properties for this launch window. The engineering constraints are satisfied for any launch day. The occultation at GAM-V3 reaches a maximum duration of 190.5 minutes for launch on Sep 21. A final solar inclination at the end of the mission (after V7) of at least 30 deg will be achieved. If the mission stops before V7, there will be a degradation of the science as a solar inclination of only 26.6 to 29 deg will have been reached.

The figures in the next pages show the variation of different parameters with the launch day. Both launch options, inwards and outwards, are considered for the following launch window results.

Launch vehicle	Atlas V 411
Launch period (days)	33
Launch dates	Aug-20 – Sep-21
Escape velocity (km/s)	5.200 – 5.518
DLA (deg) – MEE2000	15
RLA (deg) – MEE2000	180.7 – 336.1
Final solar inclination (deg)	30.0 – 31.3
Final solar inclination after V6 (deg)	26.6 – 29.0
Max. Sun distance (AU)	1.190
Longest eclipse (min)	19.8 (E1)
Longest occultation (min)	190.5 (V3)
Longest safe-mode blackout (days)	

Table 12: 2020 September launch windows summary

[2] Notice that the trajectory is named September although the launch period is actually open in mid-August. Given that the launch window is wide and the first days are not the best performing for the science, it could be considered to start the launch window later, i.e from September 1st. This will have to be analysed in more detail in the future.

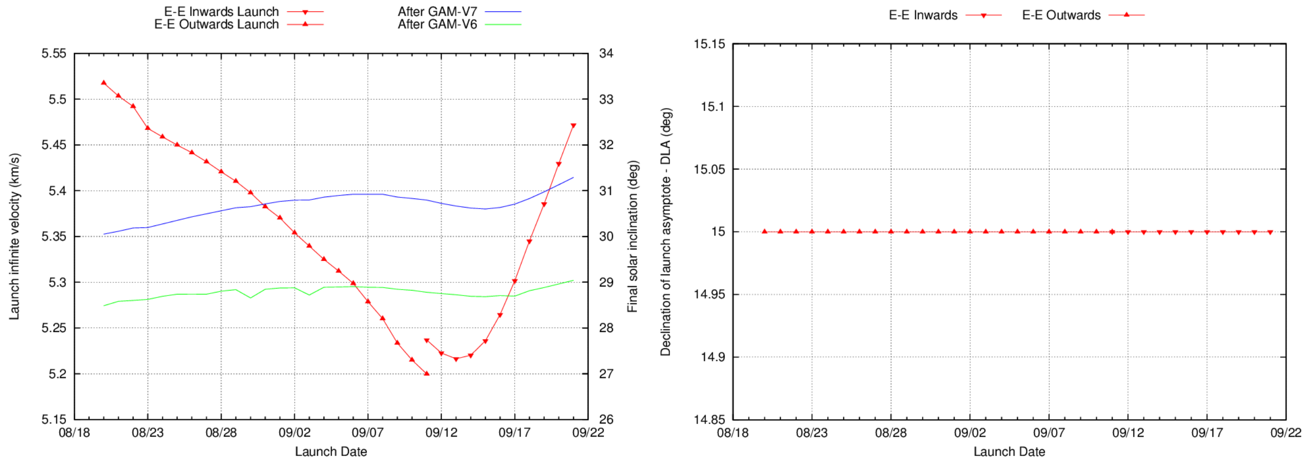


Figure 41: 2020 September launch window – Launch targets and solar inclination

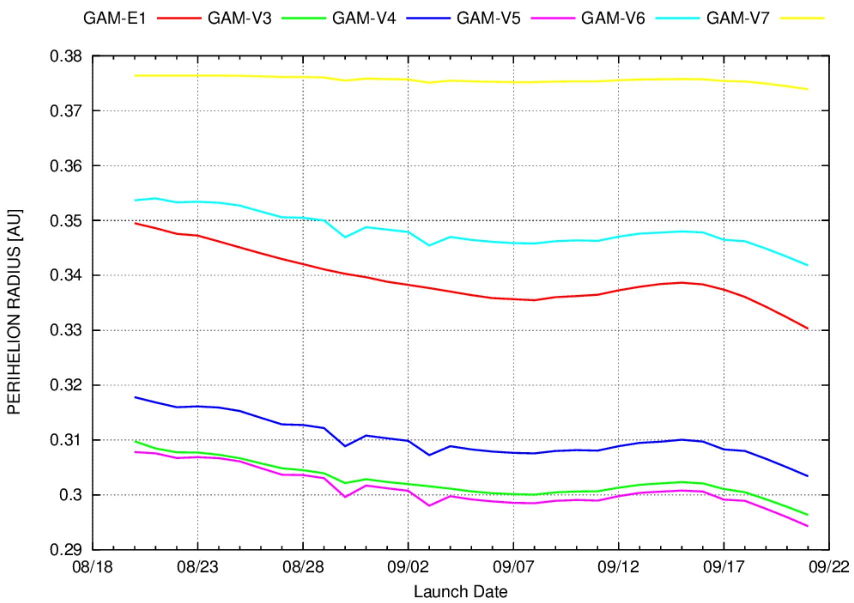


Figure 42: 2020 September launch window – Perihelion of science orbits

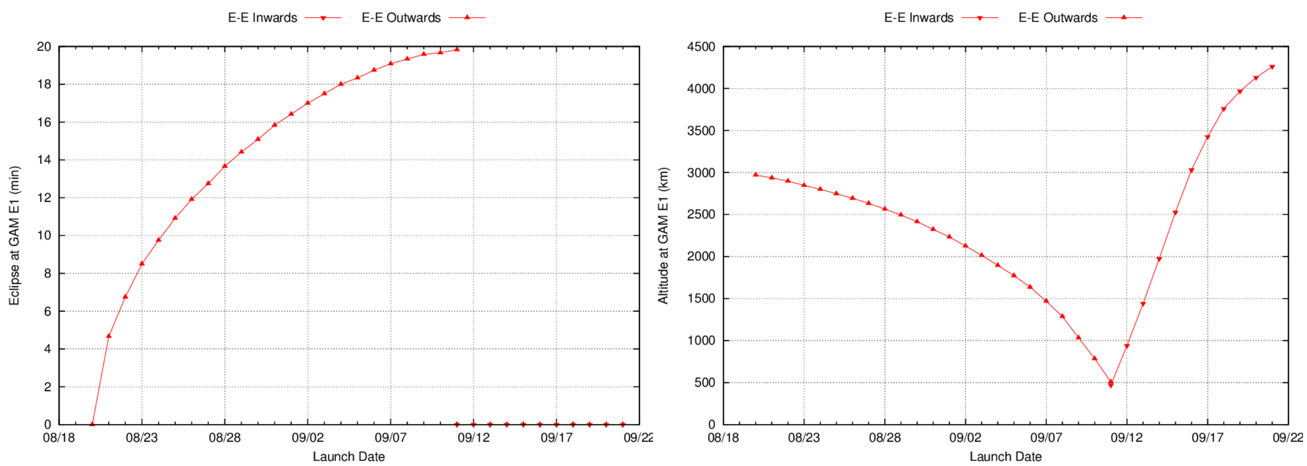


Figure 43: 2020 September launch window – GAM-E1 eclipse duration and minimum altitude

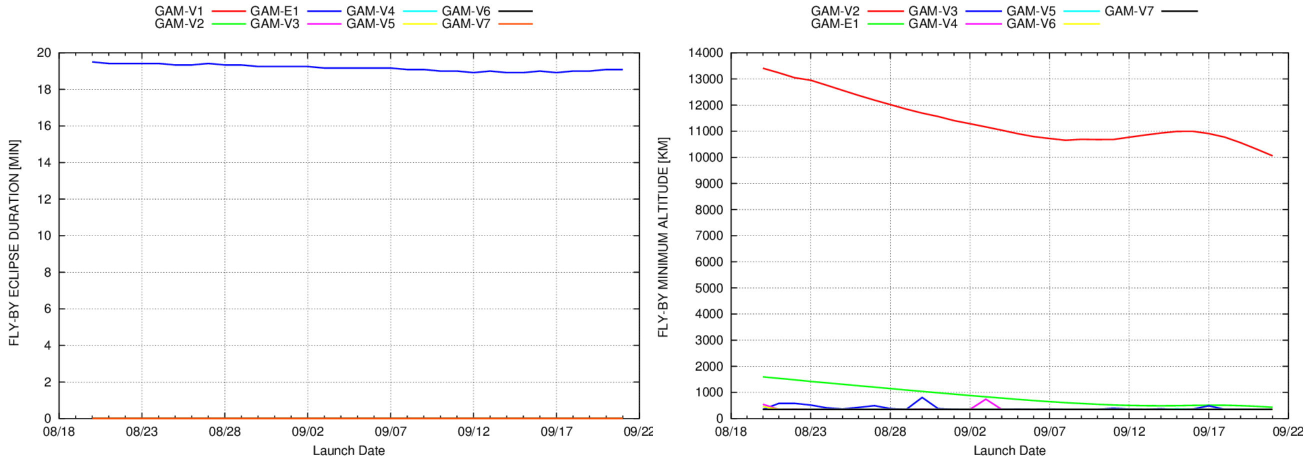


Figure 44: 2020 September launch window – GAM eclipse duration and minimum altitude

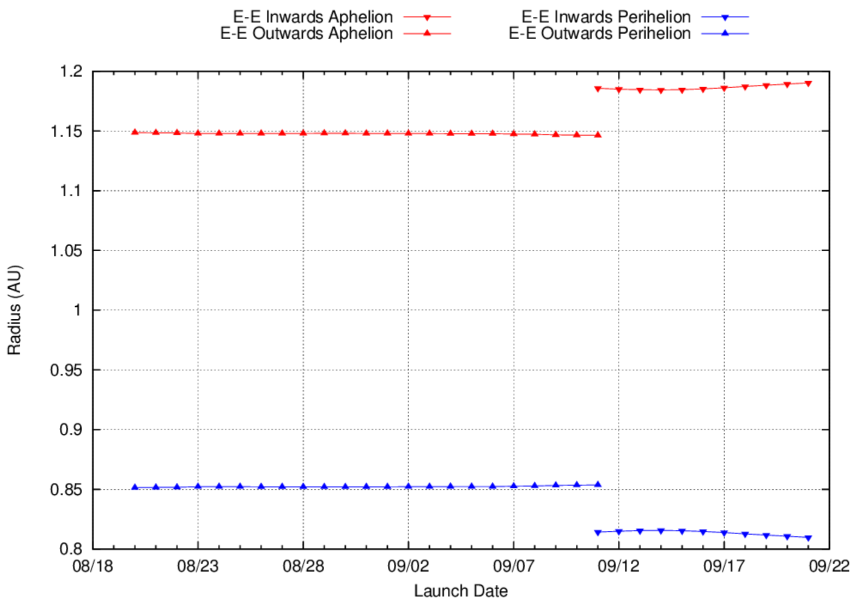


Figure 45: 2020 September launch window – Perihelion of science orbits

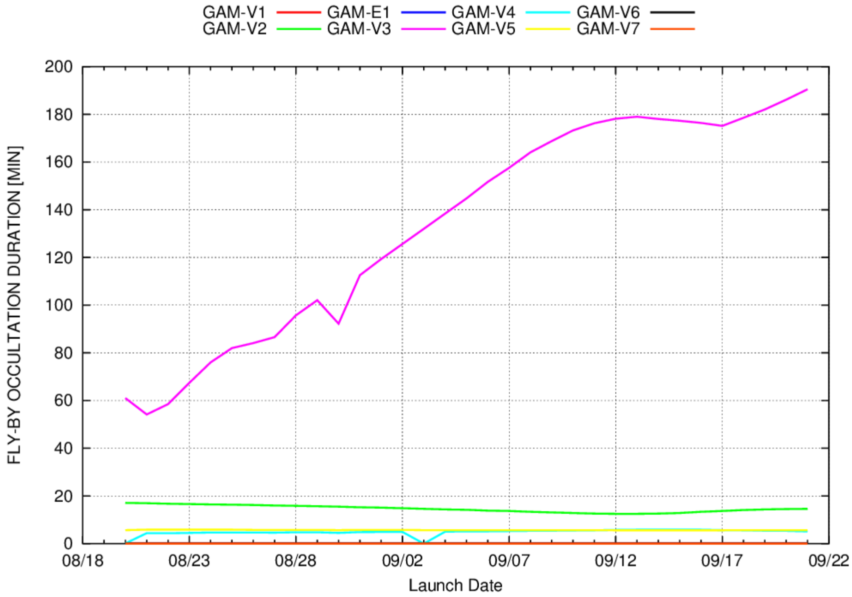


Figure 46: 2020 September launch window – Perihelion of science orbits

3.4 Summary of Trajectory Options

The following tables summarize the main characteristics of the proposed trajectories for launch in 2020. For comparison, the 2019 February (previous baseline) and the 2020 February (current baseline) trajectories are also given in the same table.

Case	2019 Feb	2020 Feb	2020 Jul A	2020 Jul B	2020 Sep
Cruise sequence	EEVVEV	EVVEV	EVVEV	EVVEV	EEVVEV
Venus resonances sequence	5:4 4:3 3:2 3:2	5:4 4:3 3:2 3:2 3:2	4:3 3:2 3:2 5:3	4:3 4:3 3:2 3:2	5:4 4:3 3:2 3:2 3:2
Launch					
Earliest launch	02-05	02-05	06-28	06-28	08-20
Latest launch	02-23	02-23	07-16	07-16	09-21
Feasible launch period	19	19	19	19	33
Maximum Vinf (km/s)	5.639	5.618	5.612	5.612	5.518
Max. |declination| (deg)	15.0	28.7	-18.6	-18.5	15
Durations & Times					
Total duration (y)	10.3	10.6	10.6	10.6	11.6
Cruise duration (y)	2.80	1.80	3.19	3.19	2.82
1st perih. < 0.3 AU (y)	3.68	2.68	4.57	4.57	8.01
Time to is 30 deg (y)	9.11	8.11	8.77	9.38	10.34
Time max. solar lat. (y)	9.35	9.58	8.92	9.62	10.58
NMP+EMP duration (y)	7.54	8.77	7.4	7.4	8.7
Science properties					
Min Sun distance (AU)	0.284	0.284	0.287	0.297	0.298
# Perih < 0.3 AU	12	12	7 (11)	4	3
Time spent < 0.3 AU (d)	77	77	38.0	14.2	8.4
# Below 0.4 AU	16	22	17	16	19
Time spent < 0.4 AU (d)	406	461	436	361.3	448.8
Max. solar i (deg)	30.2	33.4	32.0	32.5	30.0
Max. angular rate (deg/d)	7.67	7.67	7.59	7.48	7.32
Engineering constraints					
Integrated $1/Rs^2$ ($1/AU^2$)	28.6	31.8	30.5	28.2	31.5
Number of GAMs (E/V)	2/6	1/7	1/6	1/6	2/7
Max Sun distance (AU)	1.017	1.017	1.178	1.178	1.190
SM Blackouts: longest (d)	70.1	70.1	20.0	20.0	36.5
Conjunctions: longest (d)	24.0	24.0	7.7	7.7	17.6
Longest eclipse (min)	18.8	18.8	19.3	17.9	19.8
Longest occultation (min)	17.0	17.0	22.5	22.9	190.5
Min. SES at V-GAM (deg)	13.1	13.1	5.5	6.4	14.6

Table 13: Trajectories Summary

The evolution of perihelion radius and solar inclination through the mission for the trajectories under analysis is provided in the next figures. The time scale is given both as an absolute by the calendar date and as years from launch.

In the perihelion evolution it can be seen that all the backups will start the science phase at least 18 months later than the 2020 February baseline. Both July options dip just below 0.35 AU at the start of NMP when at the same time the 2020 February trajectory has spent almost 1 year with perihelion below 0.3 AU. Only the July A backup recovers a similar number of perihelions <=0.3 AU than the February baseline.

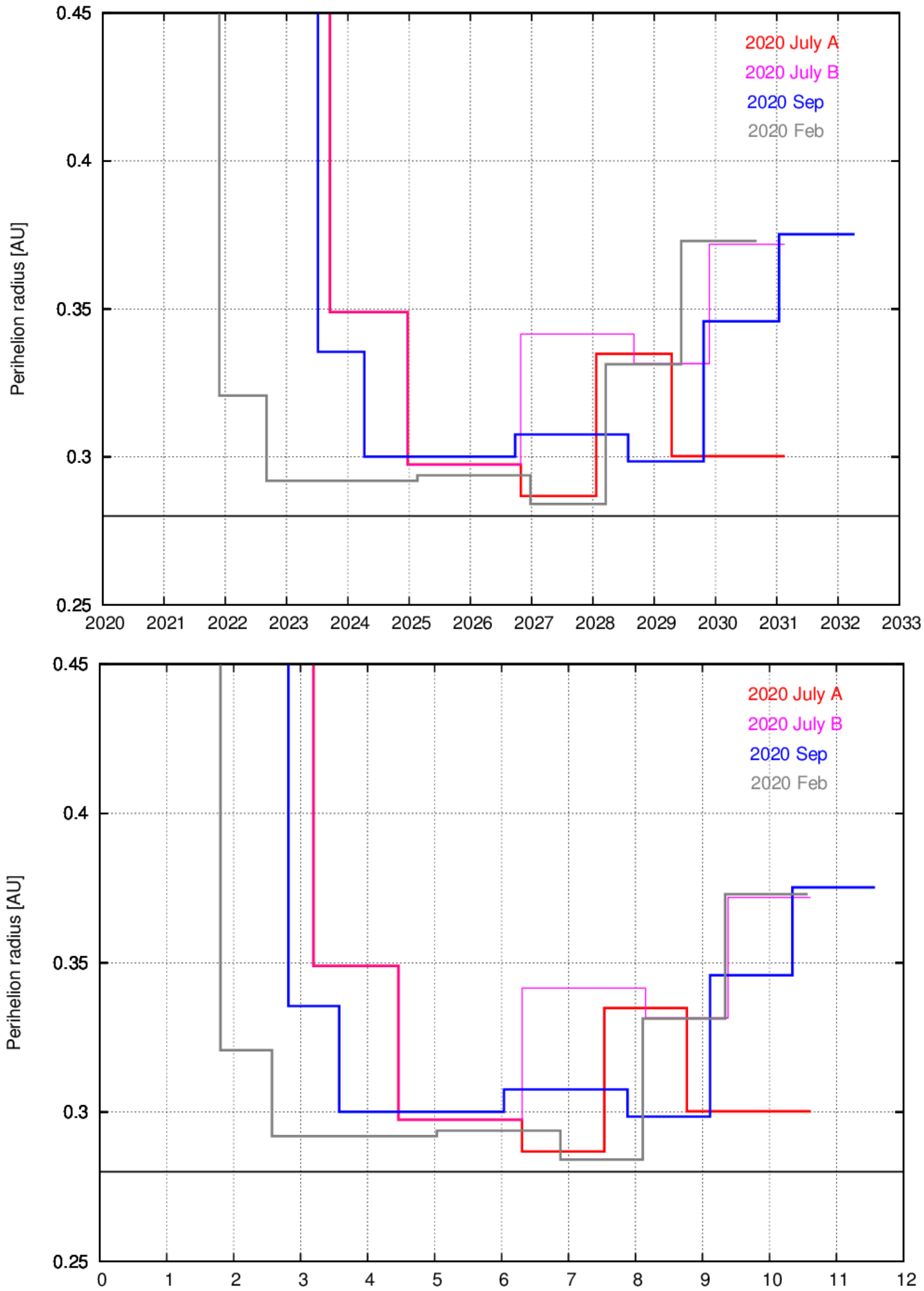


Figure 47: Evolution of perihelion radius for trajectory candidates

The evolution of the solar inclination shows that both July backups are able to recover about the same rate of inclination increase as the February baseline, while the September backup lags about 1.5 to 2 years behind.

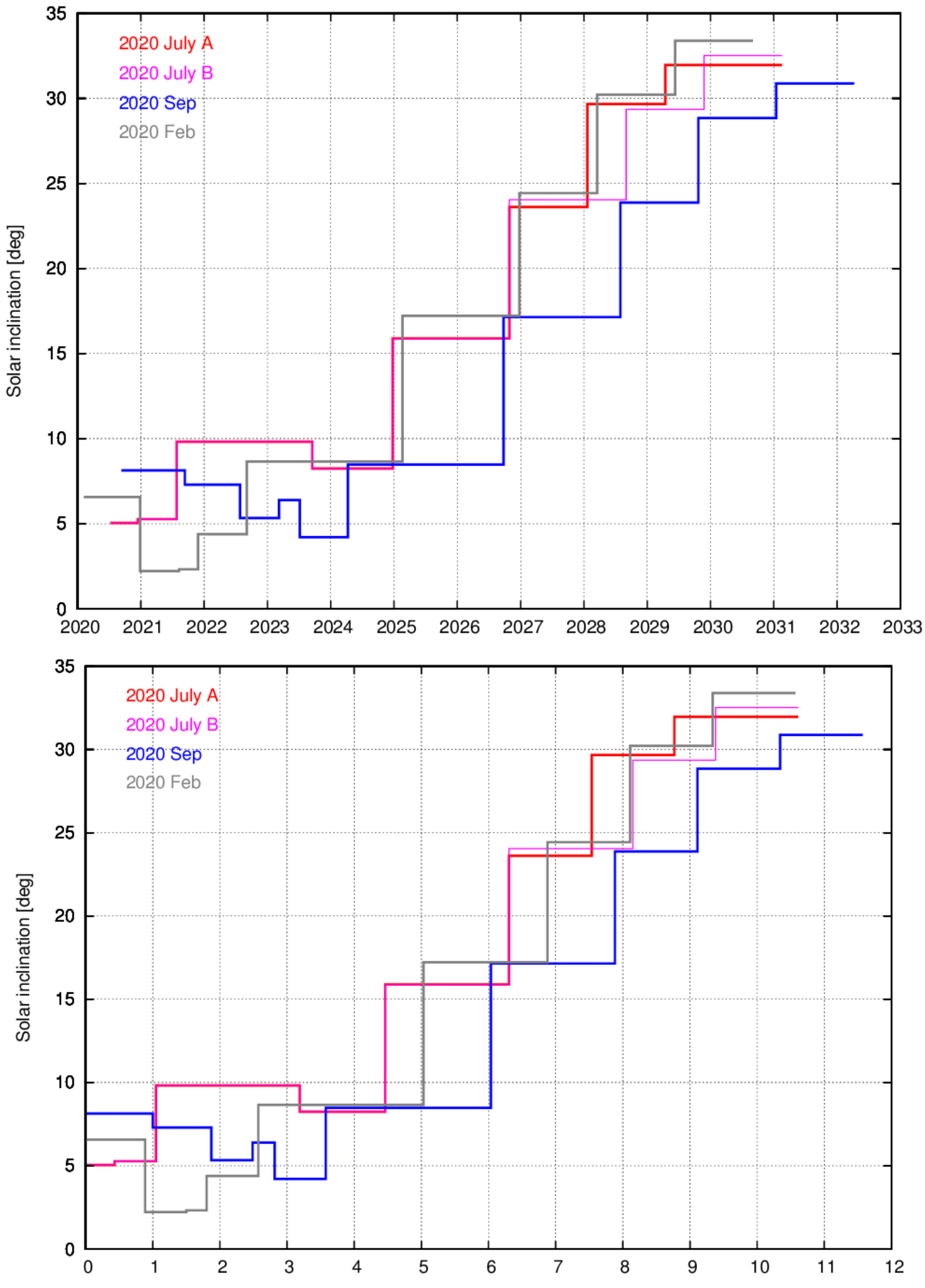


Figure 48: Evolution of solar inclination for trajectory candidates

Table 14 gives the downlink index for different periods over the mission (Earth-Venus arc excluded from the calculation even if considered to be part of NMP). The following conclusions are derived:

- Of the new launch options 2020 September is the overall best performing for data return, with excellent capability during NMP even slightly higher than the February baseline.
- Both July trajectories have excellent data return capability during the core 4:3 science orbit and during NMP being overall comparable with the 2018 Option E trajectory and not far below the 2020 February reference.

	Reference 2018 Option E	Reference 2020 Feb	2020 July A	2020 July B	2020 Sep
Core 4:3 or 5:4 science orbit (1st in NMP)	2.09	2.42	2.14	2.14	2.41
NMP (except E-V arc if any)	1.74	1.91	1.54	1.81	2.20
EMP	1.41	1.30	1.39	1.30	1.18
NMP+EMP (except E-V arc if any)	1.55	1.72	1.54	1.61	1.75

Table 14: Summary of downlink index

In addition, a parameter relevant for the spacecraft design and the environmental specifications is the accumulated solar flux on the spacecraft given by the integral of $1/Rs^2$ over the entire trajectory, where Rs is the Sun range. Figure 49 shows the evolution of this parameter for the new trajectories as well as for previous baseline trajectories described in the CReMA (RD 1), namely 2018 Option E and 2020 February. Both July trajectories have an evolution well below the previous baselines. The September trajectory follows a similar evolution, but due to the extended duration will reach a final level slightly above the current February baseline.

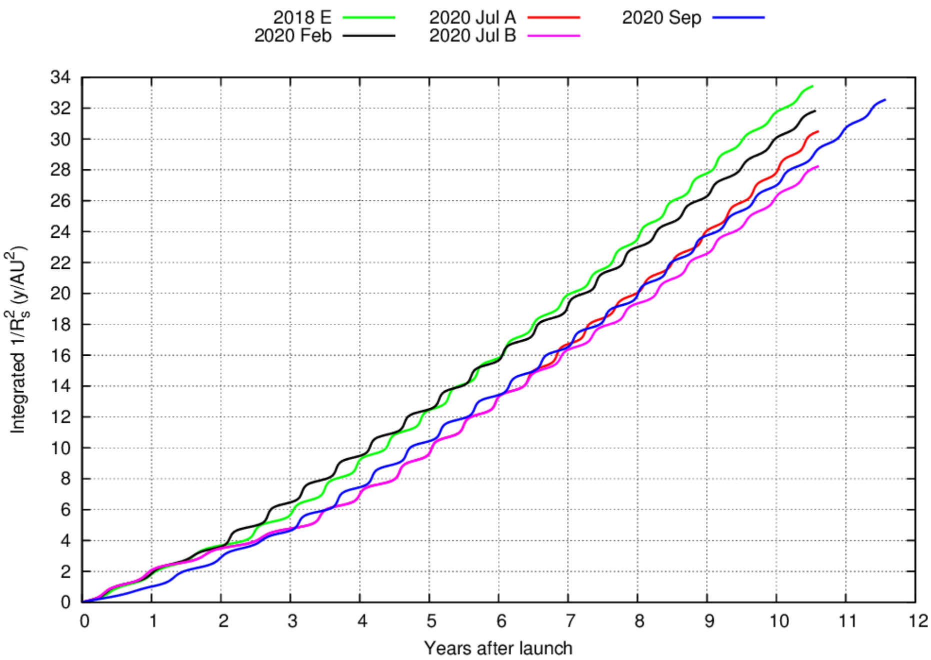


Figure 49: Evolution of integrated solar flux proxy ($1/Rs^2$)

4 CONCLUSIONS

ESOC Mission Analysis has carried out a comprehensive analysis for launch options for Solar Orbiter in 2020 aimed at finding additional launch opportunities after the current 2020 February baseline. The analysis aimed at satisfying the entire set of mission and engineering constraints and 2 promising trajectories have been identified with launch period starting on June 28 2020, thus almost 5 months later than the start of baseline launch period on February 5. Of the two July trajectories the July A option seems to recover better the science return performance of the baseline.

An additional launch option in September 2020 is described in this document. This trajectory requires to relax the mission duration constraint (+1 year) and increase by one the number of GAMs to a total of 9, 2 Earth and 7 Venus GAMs. The launch period for this trajectory starts on August 20, thus 6.5 months later than the current baseline. In terms of the science return, this trajectory is outstanding for the data return capability, in particular during NMP and overall at the same level than the February baseline. However, the trajectory has a lower number of Sun close perihelions (<=0.3 AU) and will have a lower rate of increase of the solar inclination.

The September launch opportunity repeats in 2021 with a mission duration of 10.6 years and a total of 8 GAMs (1 Earth + 7 Venus) and so respecting the current set of mission and engineering constraints.