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Interplanetary Transfers to the Outer Planets with Probe Release for the Timeframe 2025-2035

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Document Abstract

This document will be used as an input to the new call for ideas for the Cosmic Vision programme. The objective is to make a survey of potential interplanetary transfers between the Earth and the outer planets Saturn, Uranus and Neptune for the time frame 2025-2035. The main mission is probe release, either simple to the target planet, or double if it is possible in terms of mass. Two launchers have been contemplated: Soyuz-Fregat and Ariane 5 ECA, both launched from Kourou.

A first step in the analysis has been to find all potential transfers following well known and efficient sequences. The second step carried out was to filter out the huge amount of solutions by applying a system margin approach. This approach allowed to conclude whether or not a specific mission (simple vs double) with a specific launcher and target planet was feasible.

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List of Acronyms

DSM	Deep Space Manoeuvre
GA	Gravity Assist
GTO	Geosynchronous Transfer Orbit
JGA	Jupiter Gravity Assist
SGA	Saturn Gravity Assist

1 INTRODUCTION

1.1 Study Logic

The timeframe considered in this study is: 2025-2035.

The target planets are: Saturn, Uranus and Neptune.

Several parameters are relevant for the selection of a transfer:

- The transfer duration
- The spacecraft mass at arrival, the spacecraft being composed of the carrier and the probe(s)
- The infinite velocity at arrival because of its great influence on the aerothermodynamics results (mainly the peak heat flux and the heat load)
- The possibility to have a double probe mission (Venus-Saturn, Venus-Uranus, Venus-Neptune, Saturn-Uranus*)

As hundreds of potential solutions are generated, the results are presented in a format that eases the trade-off between these parameters.

The optimisation is a two-step process:

- Step 1: Finding the first guess. This consists in a global optimisation: for a given sequence of swing-bys (e.g. Venus-Earth-Earth Gravity Assist or VEE-GA or VEEGA), the launch date, swing-by dates and number of revolutions between two swing-bys are scanned. This step is based on a pruning technique such that the computational burden remains within acceptable limits.

  As mentioned above this step requires an input sequence. Because of the reduced time available for this study, only the most promising have been tested: VEE and MEE. Other sequences have quickly been assessed without giving promising results.

  In terms of propagation, Keplerian arcs are assumed between two swing-bys. This results in an infinite velocity mismatch at every swing-by. This is solved by assuming a spacecraft manoeuvre at infinity.
- Step 2: Based on Step 1, the most promising transfers are selected and optimised: this consists in a local optimisation. The manoeuvres together with the dates of the swing-bys are optimised to maximise the arrival mass†.

In this study, only Step 1 was performed mainly because all solutions cannot be optimised, it would be too much time consuming. Moreover the objective of the study is to give envelopes for the transfer time, arrival mass and arrival infinite velocity, not to give a very accurate solution. As

* Saturn-Neptune is excluded because it is not feasible over the considered timeframe

† Constraints can be added (e.g. a maximum arrival infinite velocity)

will be explained later, only a fraction of the Deep Space Manoeuvre (DSM) coming from Step 1 is taken into account (to simulate Step 2).

1.2 Launchers

Two launchers are assumed:

- Ariane 5 ECA from Kourou with direct escape
- Soyuz-Fregat from Kourou with injection into GTO

The AR5-ECA performance is summarised in Figure 1-1.

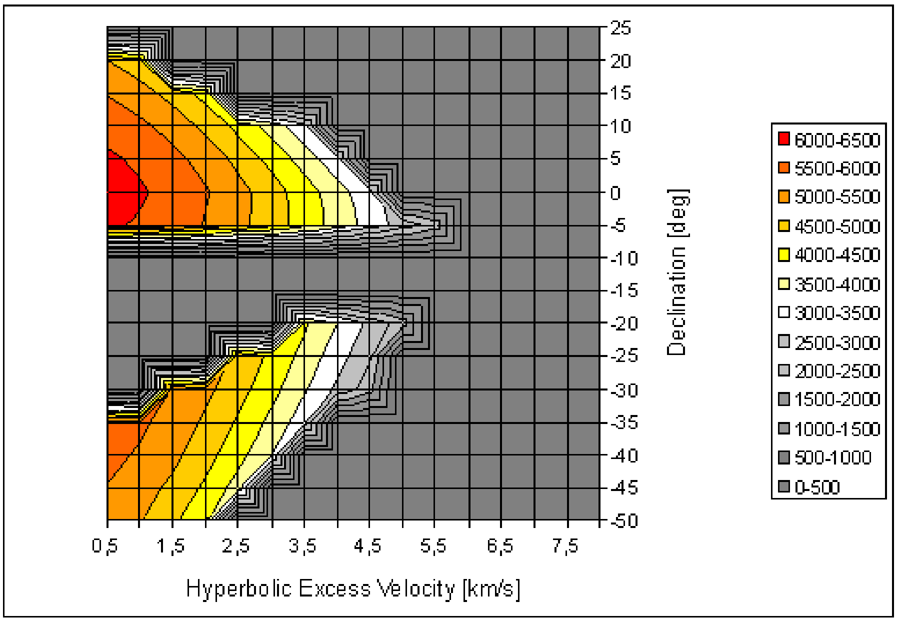

Figure 1-1 : AR5-ECA performance

The adapter mass for AR5 ECA is 150 kg. It has to be subtracted from the performance shown above.
Soyuz-Fregat performance is summarised in Figure 1-2 for the case of an injection into GTO. This strategy is based on 5 consecutive burns: the first 3 burns are perigee manoeuvres that raise the apogee, the fourth manoeuvre mainly corrects the inclination but also the line of apsides (to get the correct declination), the fifth burn gives the correct infinite velocity.
This strategy has an impact as a large DeltaV is needed for escape: the fuel tanks mass will be larger than if AR5 is used.

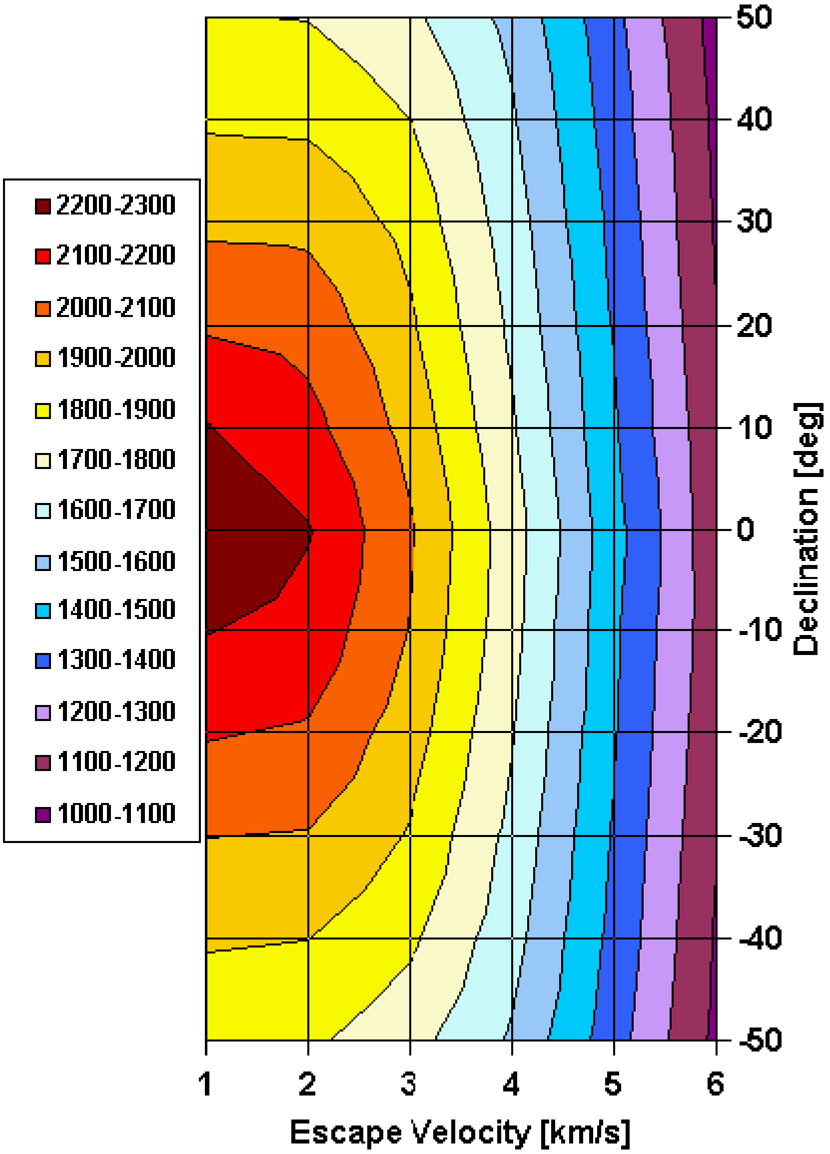

Figure 1-2 : Soyuz-Fregat performance in case of a GTO injection

For Soyuz the adapter mass is 110 kg. Because of the strategy with an injection into GTO, the adapter is released before the spacecraft performs its 5 manoeuvres. Therefore the adapter mass does not need to be subtracted from the performance given above.

The injection into GTO corresponds to constant launcher performance: 3070 kg without adapter. Depending on the system margin, the carrier-probe(s) system wet mass will be in general close to 3070 kg too.

1.3 *Propulsion*

The baselined carrier on-board propulsion is chemical with a specific impulse of 312 s. For the Earth escape sequence with Soyuz, an engine thrust of 450 N was assumed leading to non-negligible gravity losses. For all other manoeuvres gravity losses are neglected.

1.4 DeltaV Budget Philosophy

The DeltaV cost is the addition of several components:

- Launcher dispersions corrections: 30 m/s
- Launch window: 100 m/s
- Navigation: 25 m/s/GA for the inner planets, 10 m/s for arrival
- Probe separation: 30 m/s/probe is assumed
- Deep Space Manoeuvre (DSM): the a mount of DeltaV for the DSM de pends on each specific transfer. As Step 2 (local optim isation) is not perform ed in this study, it is assum ed that 25 % of the DSM can be saved from Step 1 to Step 2.

1.5 Mass Budget

In order to select a solution, som e assumptions have to be done on the target m ass for the syste m carrier-probe(s):

- Carrier dry mass: the reference mass is derived from the JGO[‡]
- Based on the PEP CDF, the probe unit mass is 300 kg.

The carrier dry m ass budget is calculate d following the assum ptions given in Table 1-1. They are based on a conservative evaluation of the Laplace CDF report.

Item	Mass variation [kg]
JGO dry mass	1500
Shielding	-100
Solar panels+battery	-350
RTG (1)	200
Tanks JGO	-150
Tanks structural index (2)	7%
Payload	-100
Design optimisation (3)	-100
Probe separation system	25/probe

(1): based on Cassini: 3 RTG x 60 kg/unit + booms

(2): because of the escape strategy, the tanks mass will be much larger for Soyuz than for AR5

(3): e.g. on structure or mechanisms

Table 1-1: Carrier dry mass budget

The carrier dry mass used in this study can be summarised by the formula:

$$m_{dry}=900\ kg + 7\%\ DeltaV + 25\ kg/probe$$

‡ Laplace-JGO is an on-going study aiming at designing a mission to Jupiter and its Galilean moons

It means that for a mission with one probe, a system dry mass of 1,225 kg + 7% DSM is required and with two probes 1,550 kg + 7% DSM are required.

1.6 Selection Philosophy

The criteria for the selection of a particular solution are given in order of importance:

- System margin: it has to be positive
- Arrival infinite velocity
- Transfer time

The system margin is computed as follows:

margin = [(system dry mass with launcher maximum capacity) / (system dry mass) -1] 100*

and is expressed in percentage.

1.7 The Earth to Earth arc

When the launcher performance is too low to get positive mass margin with a reasonable infinite velocity, one solution to improve the margin and/or decrease the infinite velocity is to introduce an Earth to Earth arc at the beginning of the transfer. The consequences are the following:

- The launcher performance does not depend on the declination any more, leading to a launcher performance increase
- The DeltaV for launch window is reduced from 100 m/s to 50 m/s. The DeltaV for navigation increases by 25 m/s because of the additional Earth-Earth swing-by
- The transfer time increases by roughly one year

1.8 The Planet Incoming Infinite Velocity Reduction

When comfortable system margin is available (with AR5) the margin can be used to reduce the planet incoming infinite velocity. Due to lack of time, each case could not be locally optimised. The methodology used consists in applying a DSM at infinity. The same ratio as in Paragraph 1.4 is applied on the DSM.

2 TRANSFER TO SATURN

The launch window is given in Figure 2-1.

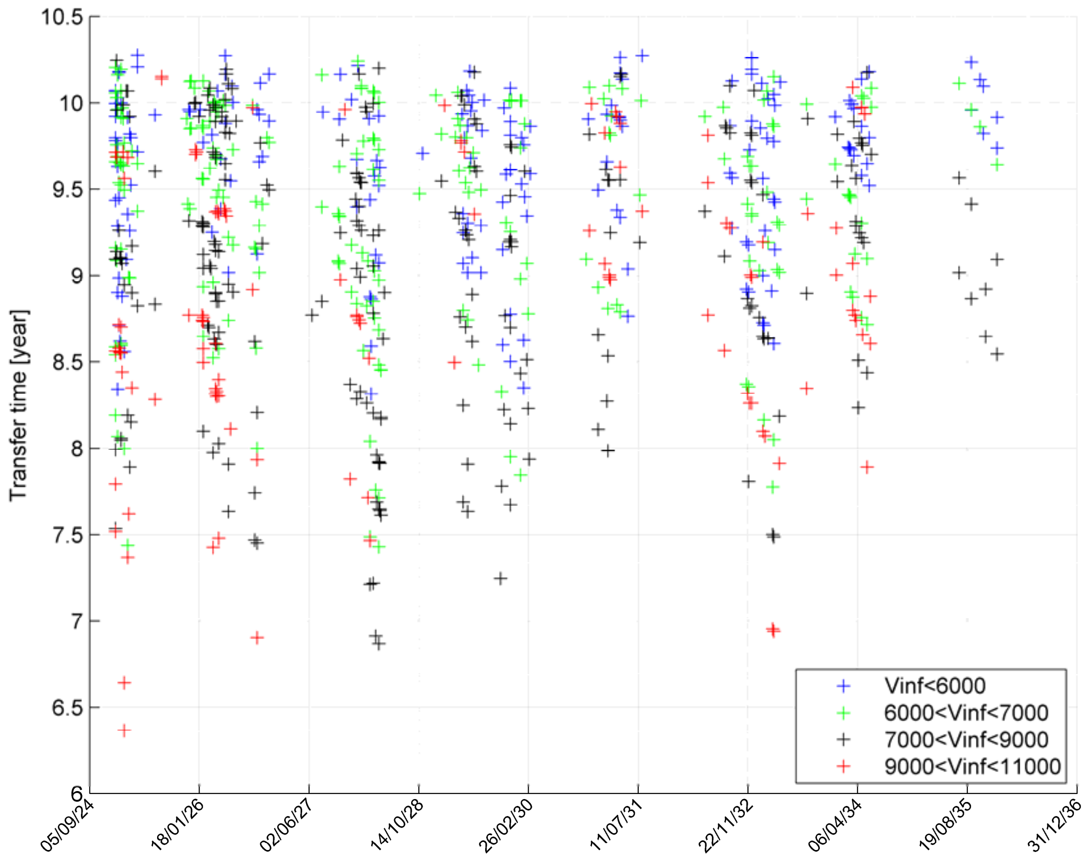

Figure 2-1: Launch window for Saturn. Transfer time as a function of the launch date for different arrival infinite velocities

Several remarks can be done:

- There are continuously launch opportunities
- Low arrival infinite velocity: the transfer time is always greater than 8.5 years and increases to more 9.5 years at the end of the timeframe
- Short transfer: transfers shorter than 7 years are possible every year till 2028. It increases to 8 years in 2030, decreases to 7 years in 2032 before increasing again to 8.5 years in 2035. All these transfers correspond to a high infinite velocity (>7 km/s).
- As a general remark that also applies for Uranus and Neptune, it has to be underlined that a very often a group of solutions correspond to the same local optimum.

2.1 *Soyuz-Fregat*

2.1.1 Overview

All solutions are presented in Figure 2-2 for both sequences in terms of final mass as a function of transfer time.

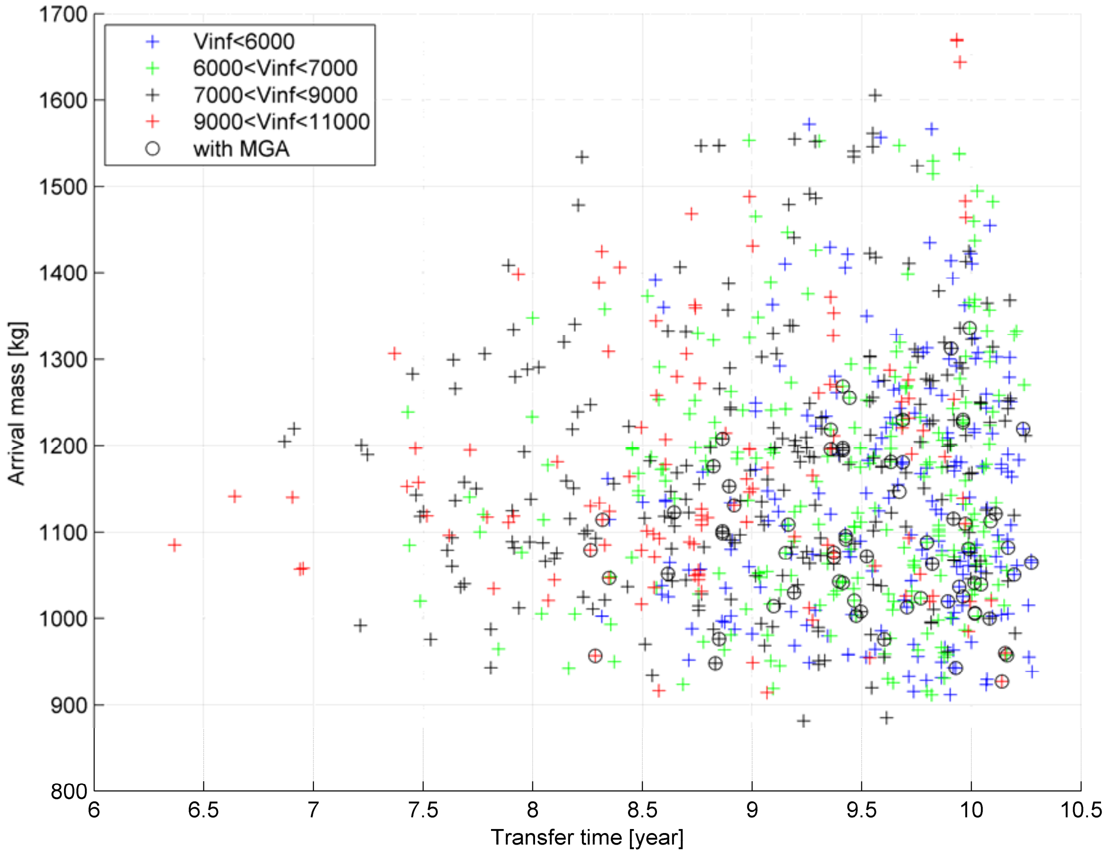

Figure 2-2: MEE and VEE sequences to Saturn with Soyuz. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

Before analyzing the trends, it can be pointed out that solutions with a Mars gravity assist do not bring much compared to Venus. The only reason to choose a sequence with Mars would then be the thermal worst case.

There trends are:

- If a short transfer is sought (<7.5 years), the arrival mass is low (<1200 kg) and the infinite velocity is high (>7 km/s)

- If a high mass is sought (>1500 kg), there are 2 sub-cases:
    - o A medium duration (8 years) with a high infinite velocity (>7 km/s)
    - o A long duration (>9 years) with a low infinite velocity (< 6km/s)
- If a low infinite velocity is sought (<6 km/s), there is a Pareto front as shown in Figure 2-3. The two extremes of the front are:
    - o A low final mass (1000 kg) with a transfer time of 8.3 years. The infinite velocity is 5.8 km/s.
    - o A high final mass (1570 kg) with a transfer time of 9.3 years. The infinite velocity is 5.9 km/s.

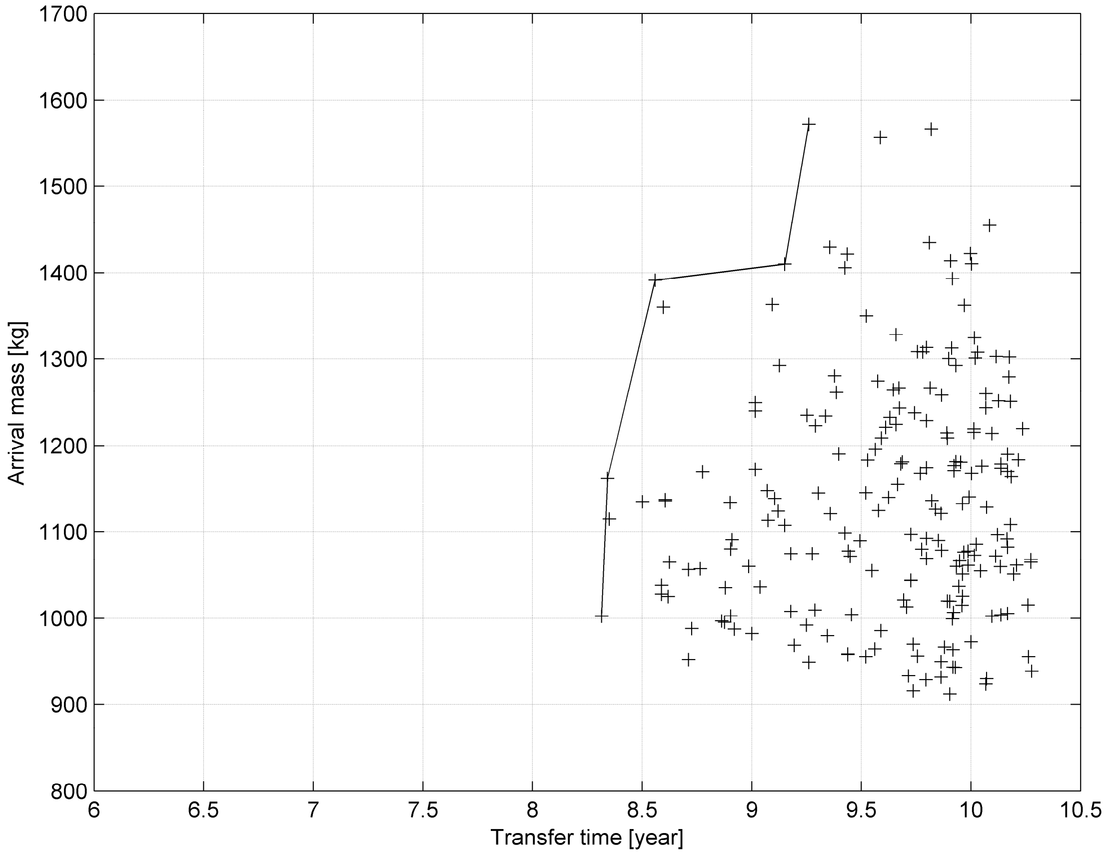

Figure 2-3: MEE and VEE sequences to Saturn with Soyuz. The arrival mass is given as a function of the transfer time. Only solutions with Vinf<6 km/s are plotted. The solid line represents the Pareto front

The envelope of solutions is summarized in Table 2-1.

Solution	Transfer time [y]	Final mass [kg]	Inifinite velocity [km/s]
Minimum time	6.4	1085	10.4
Maximum mass	9.9	1670	9.8
Minimum infinite velocity	10.1	1215	5.3

Table 2-1: Extreme solutions for the transfer to Saturn with Soyuz

2.1.2 One Probe

The system margin is given in Figure 2-4 for one probe.

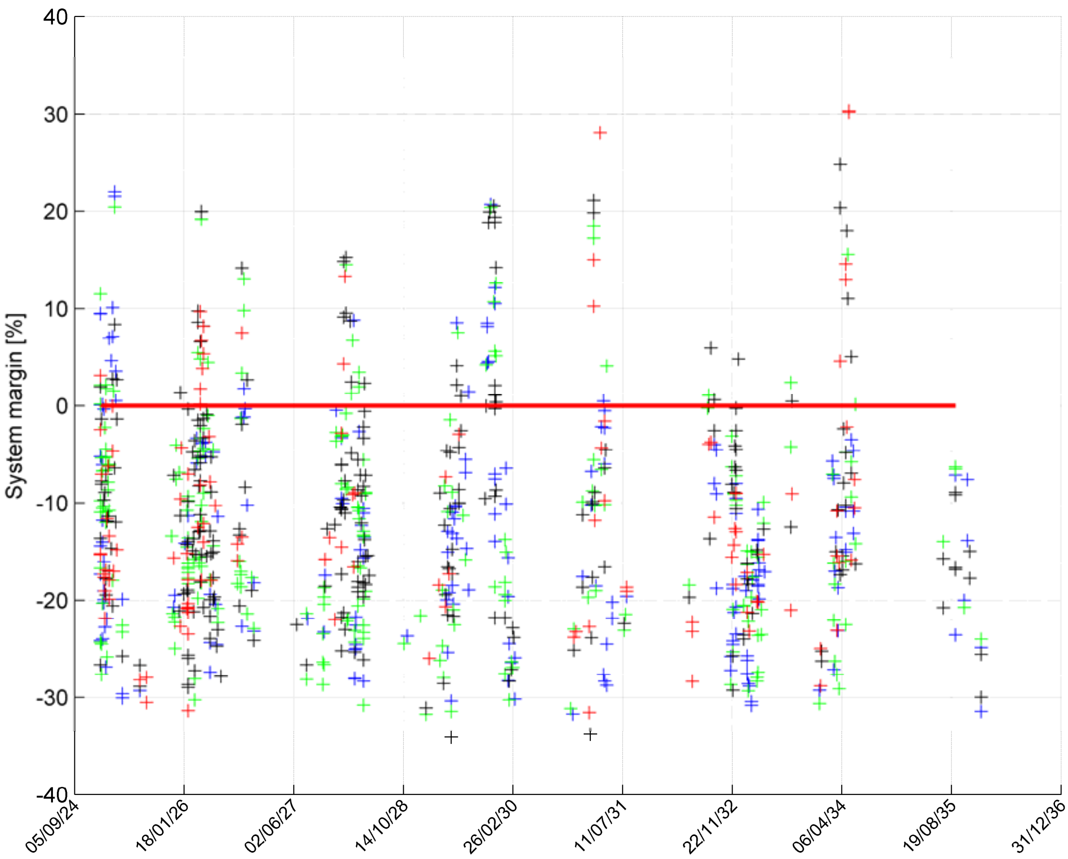

Figure 2-4: System margin for the set Saturn-Soyuz-1 probe

- Many solutions have to be discarded for negative system margins.
- There is a periodicity in the pattern: it r oughly corresponds to the synodic period between the Earth and Saturn.

- There are more solutions with low infinite velocity at the beginning of the time than at the end.

The analysis of this plot led to choose for every launch opportunity a solution with low infinite velocity: it means that 7 solutions will be kept (to be representative, the last interval shall be extended till 2036). Whenever several solutions exist, e.g. first opportunity, the one with the minimum transfer duration is kept. All solutions are presented in Table 2-2.

SOLUTION		DEPARTURE				ARRIVAL						System
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	margin [%]
1a	52	10/02/2025	4.0	12	1715	31/08/2033	5.8	-3	8.6	1005	2075	18
1b	298	08/10/2026	3.9	5	1755	06/10/2034	6.7	-2	8.0	1025	2545	0
1c	360	26/03/2028	4.1	-10	1715	03/04/2037	6.0	2	9.0	1025	2545	0
1d	531	01/11/2029	3.9	15	1735	05/06/2038	6.0	-4	8.6	1020	2520	1
1e	647	30/04/2031	4.2	-15	1650	27/05/2041	6.2	5	10.1	1020	2530	1
1f	733	20/12/2032	4.6	20	1500	13/01/2043	7.0	-2	10.1	1020	2500	1
1g	837	04/05/2034	3.8	-9	1810	11/05/2044	6.6	-1	10.0	1010	2230	12

Table 2-2: Selection of solutions for the transfer to Saturn with Soyuz and one probe

- There is only one solution for which the arrival infinite velocity is less than 6 km/s: 1a.
- The transfer time ranges from 8 years to 10 years.
- Because the best solutions often have a mass margin close zero, the system wet mass is always close to Soyuz-Fregat performance into GTO: 3070 kg (actually a bit less because of positive margin). However as the requirements in terms of departure infinite velocity and declination vary a lot, the escape mass is very different from one option to the next. This is then compensated by different requirements in DSM, leading to the same system, and thus carrier, dry mass. The carrier dry mass is close to 1020 kg.
- The compensation of the apogee raising/inclination manoeuvres DeltaV by the DSM DeltaV is visible in the column DeltaV, which exhibits only small variations. There are two exceptions (1a and 1g) where the DeltaV is significantly lower, thus leading to higher system margin. For solution 1g, it was not possible to find a solution with lower margin and lower transfer time.

2.1.3 Two Probes

This case corresponds to a one probe release at Venus and another one at Saturn. There is only one solution with positive margin as can be seen in Figure 2-5.

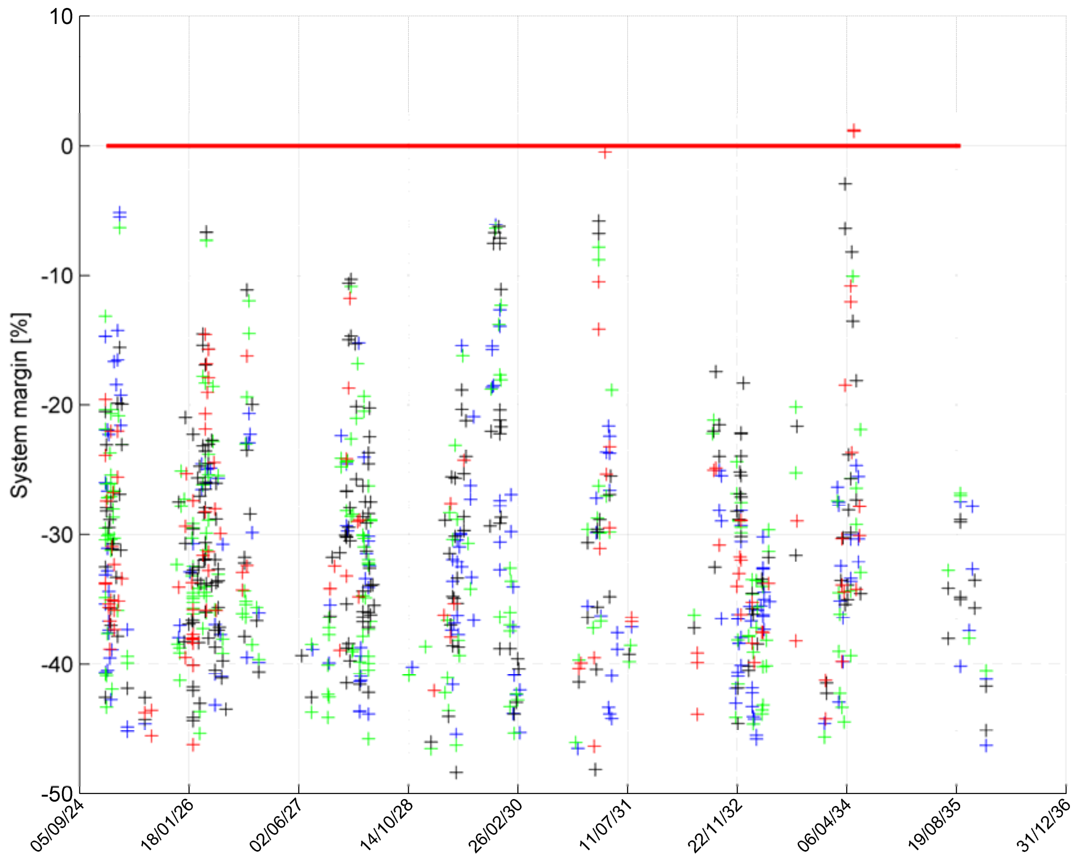

Figure 2-5: System margin for the set Saturn-Soyuz-2 probes

For sake of completeness Table 2-3 presents this solution.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
2a	840	05/09/2034	3.6	-17	1825	12/04/2044	9.8	-1	9.9	1000	1890	1

Table 2-3: Selection of solutions for the transfer to Saturn with Soyuz and two probes

The main conclusion is that it is not conceivable to embark two probes with Soyuz towards Saturn, at least with the assumptions made at system design.

2.2 AR5 ECA

2.2.1 Overview

All solutions are presented in Figure 2-6 for both sequences in term s of final mass as a function of transfer time.

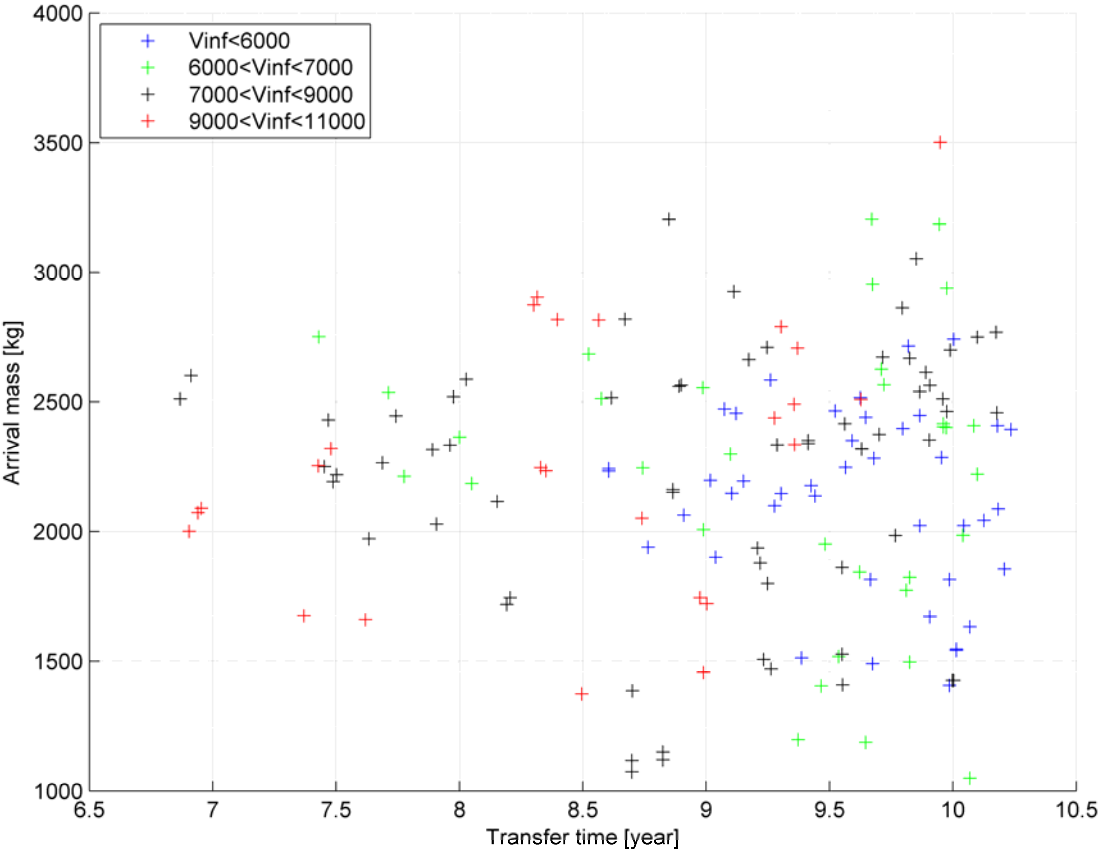

Figure 2-6: MEE and VEE sequences to Saturn with AR5. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

- The maximum final mass is much larger than for Soyuz: 3500 kg instead of 1700 kg.
- Low infinite velocity is obtai ned either for m oderate transf er tim e (>8.5 years) and for moderate final m ass (>1500 kg). From this pict ure it seems that even with AR5 perform - ance short transfer with low infinite velocity cannot be obtained. This could be answered by using some DeltaV prior to arrival to reduce the infinite velocity.

2.2.2 One Probe

The system margin is given in Figure 2-7 for one probe.

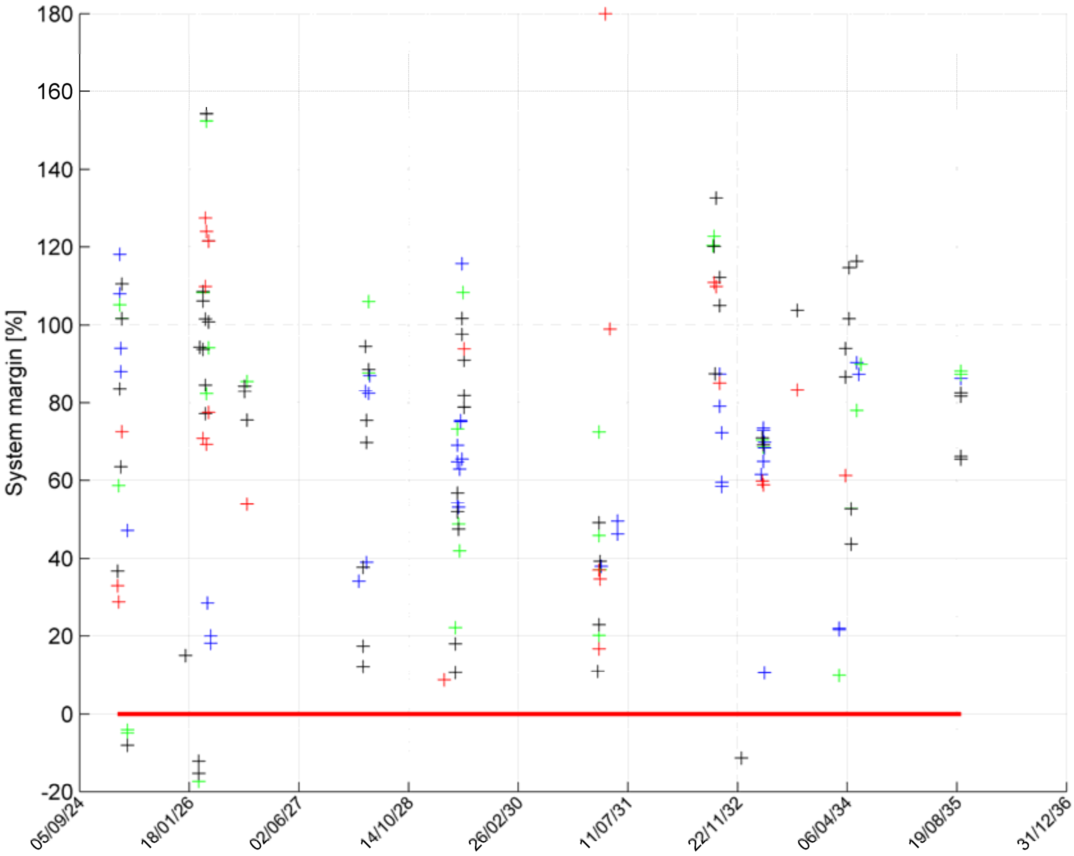

Figure 2-7: System margin for the set Saturn-AR5-1 probe

It is obv ious tha t th e s ystem m argin is v ery high (up to 100% if the few extrem e cases are removed). It would be therefore very useful to us e this margin to reduce the inf inite velocity. Figure 2-8 shows the same plot where the incoming infinite velocity is decreased by 2 km/s.

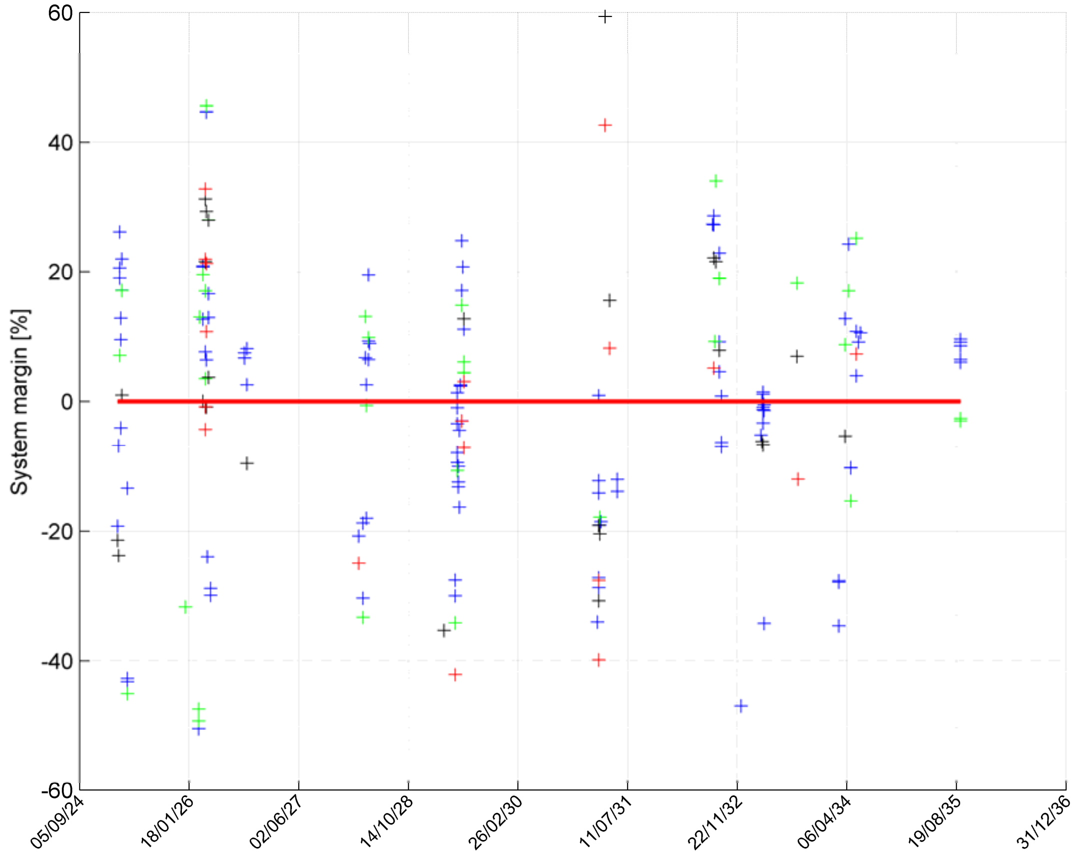

Figure 2-8: System margin for the set Saturn-AR5-1 probe with 2 km/s infinite velocity reduction prior to arrival

A selection of solutions is presented in Table 2-4.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
5a	2	07/03/2025	4.0	5	2840	24/01/2033	6.1	1	7.9	1000	2125	7
5b	61	28/09/2026	3.7	-1	3900	16/03/2034	5.9	-1	7.5	1070	2950	7
5c	78	15/04/2028	3.3	0	4330	18/09/2035	4.8	-5	7.4	1085	2890	20
5d	89	25/05/2029	3.8	-26	3275	18/02/2038	4.3	-4	8.7	1030	2655	1
5e	134	25/05/2031	4.3	-20	2970	05/06/2040	5.5	3	9.0	975	1370	46
5f	154	15/03/2032	4.3	-2	3270	12/09/2040	5.4	-2	7.5	1035	2685	0
5g	175	19/05/2034	4.1	-20	3255	22/06/2043	4.3	5	9.1	1030	2560	4

Table 2-4: Selection of solutions for the transfer to Saturn with AR5 and one probe

It can be seen that some solutions exhibit a lower incoming infinite velocity (e.g. 5d, 5e), but the main objective of the infinite velocity reduction manoeuvre was to allow choosing shorter transfers: 7.5 years for 5b, 7.4 years for 5c or 7.5 years for 5f. There was only one launch opportunity for which the infinite velocity reduction was inefficient: 5e. Indeed there were only solutions with very low infinite velocity (4.3 km/s) but no solution with short transfer time (~10 years). Therefore no reduction was applied. It explains the large system margin.

The DeltaV budget is close to 3 km /s for the worst ca ses (5b, 5c). This is com parable to JGO for which the D eltaV budget is considered as high. Theref ore 2 km/s infinite ve locity reduction is an upper limit in terms of tanks and spacecraft design.

2.2.3 Two Probes

The system margin for two probes and 1 km/s infinite velocity reduction is given in Figure 2-9.

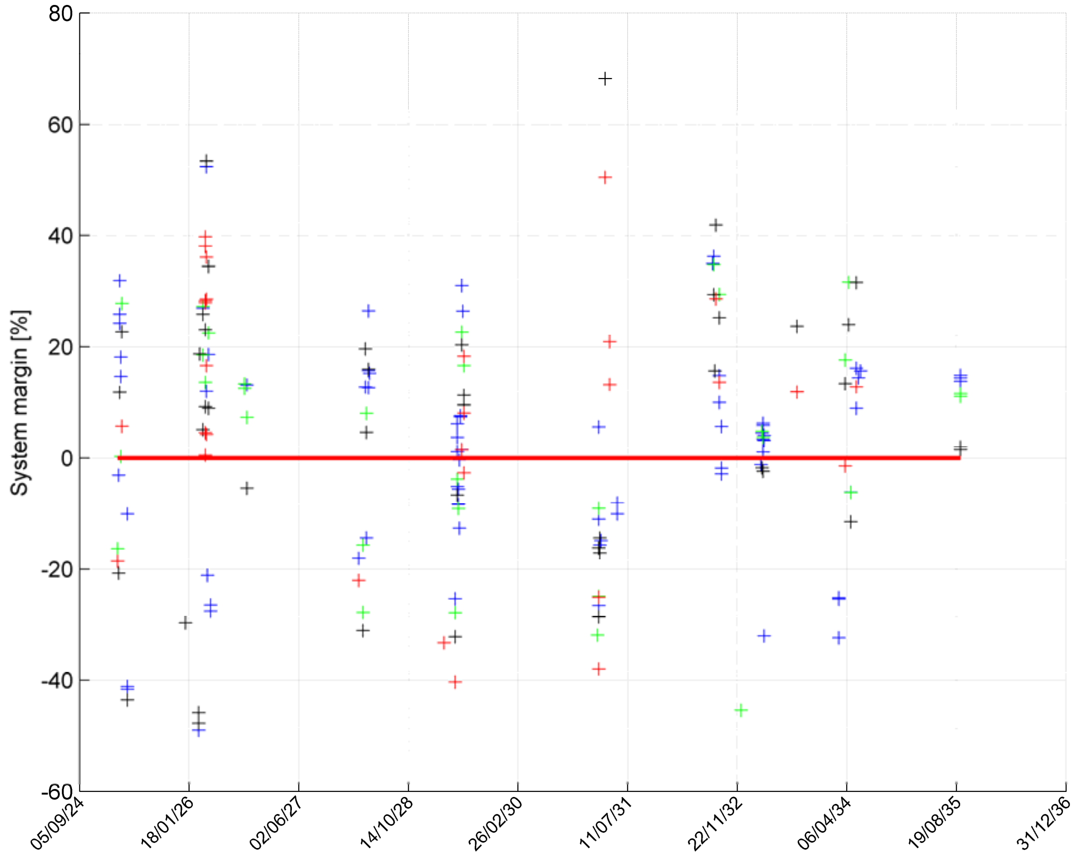

Figure 2-9: System margin for the set Saturn-AR5-2 probes with 1 km/s infinite velocity reduction prior to arrival

A selection of solutions is presented in Table 2-5.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
6a	8	12/03/2025	4.1	1	3115	05/05/2033	6.4	2	8.2	1000	1930	0
6b	62	28/09/2026	3.7	-1	3905	24/06/2034	6.2	-2	7.7	1040	2180	13
6c	78	15/04/2028	3.3	0	4330	18/09/2035	5.8	-5	7.4	1050	2140	25
6d	89	25/05/2029	3.8	-26	3275	18/02/2038	5.3	-4	8.7	1005	1905	6
6e	134	25/05/2031	4.3	-20	2970	05/06/2040	5.5	3	9.0	975	1370	17
6f	155	15/03/2033	4.3	-2	3270	21/12/2040	5.8	-3	7.8	1010	1940	5
6g	175	19/05/2034	4.1	-20	3255	22/06/2043	5.3	5	9.1	1000	1810	9

Table 2-5: Selection of solutions for the transfer to Saturn with AR5 and two probes

It can be observed that several solutions are the same as for one probe. The system margin is often quite large, which means the infinite velocity could be further reduced. However it would not change the trends.

The second probe will be released in Venus' atmosphere. The infinite velocity at Venus is given in Table 2-6 for all solutions from Table 2-5.

Solution	6a	6b	6c	6d	6e	6f	6g
Vinf [km/s]	9.0	7.2	6.4	5.8	8.9	9.3	8.1

Table 2-6: Infinite velocity magnitude at Venus in the case of a transfer to Saturn with AR5

There is a favorable period, from 2026 to 2029, where the infinite velocity is low. After 2029 the velocity increases a lot to reach 9.3 km/s for solution 6f. If needed new solutions could be searched reducing the infinite velocity at Venus, while keeping the infinite velocity at Saturn as low as possible.

3 TRANSFER TO URANUS

The launch window is given in Figure 3-1.

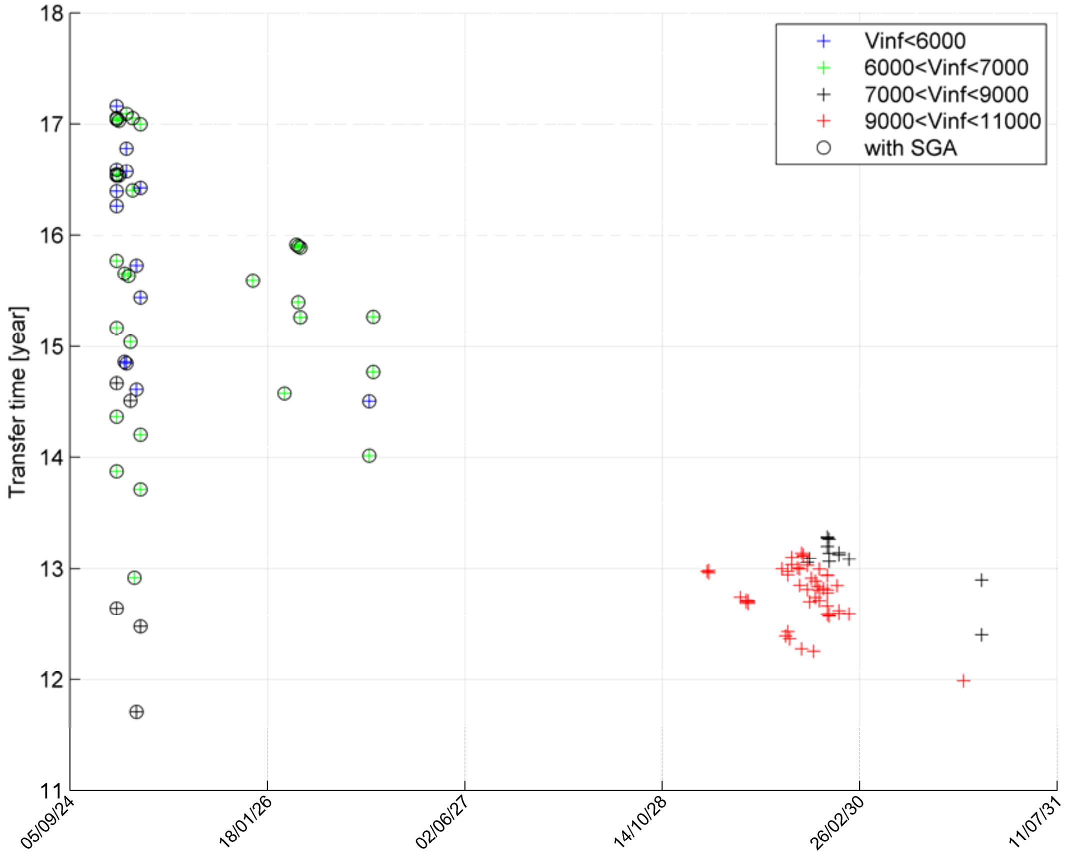

Figure 3-1: Launch window for Uranus. Transfer time as a function of the launch date for different arrival infinite velocities. Transfers with Saturn-GA are highlighted with circles

For this case there ar e only two groups of solutions: one group with V EESGA around 2026, another one with VEEJGA around 2030. The m inimum transfer time is 11.5 years, while the m aximum transfer time is 17 years.

Launching to Uranus can be done either at th e beginning of the 2025-2035 timeframe via Saturn, or later in the middle via Jupiter.

3.1 *Soyuz-Fregat*

3.1.1 Overview

All solutions are presented in Figure 3-2 for both sequences in terms of final mass as a function of transfer time.

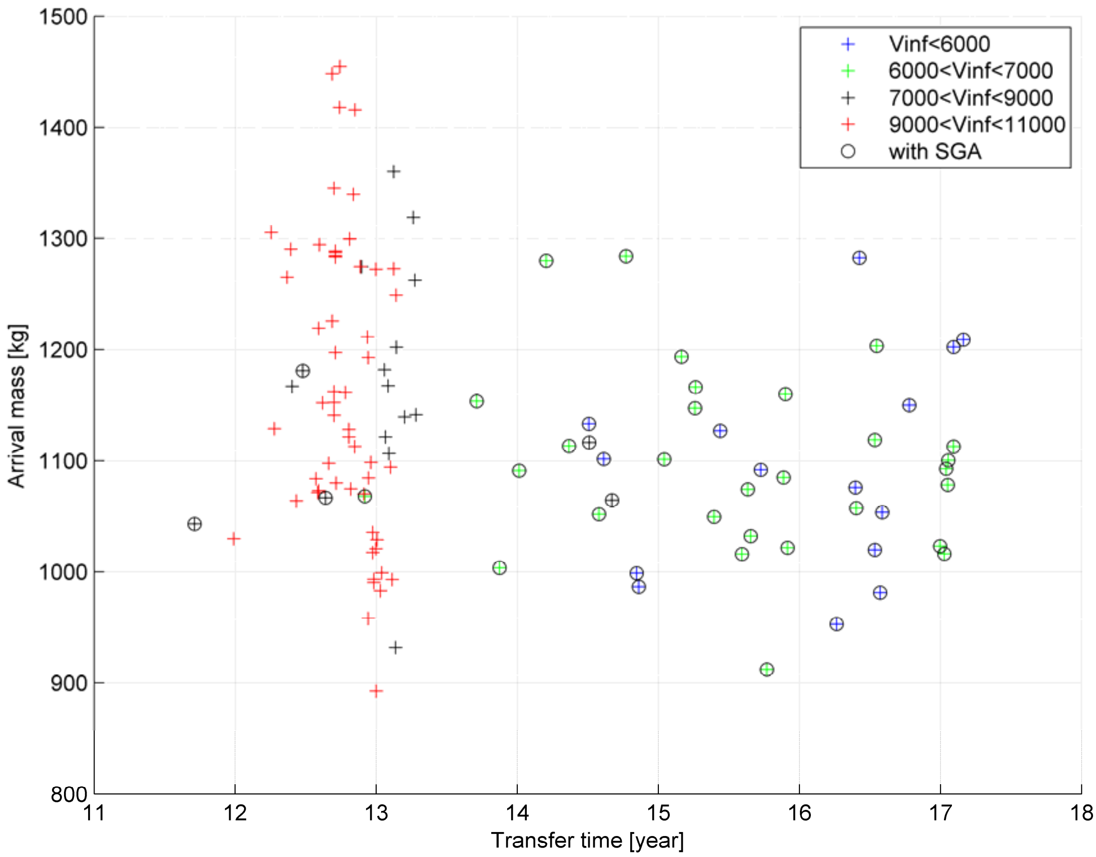

Figure 3-2: VEEJ and VEES sequences to Uranus with Soyuz. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

- The final mass is lower than for the transfer to Saturn: from 900 kg up to 1450 kg
- Solutions with a low infinite velocity correspond to a long transfer time (>14 years) and a low (>950 kg) to average (<1300 kg) final mass.
- The highest final mass is obtained for a high infinite velocity (>9 km/s)

3.1.2 One Probe

The system margin is given in Figure 3-3 for one probe.

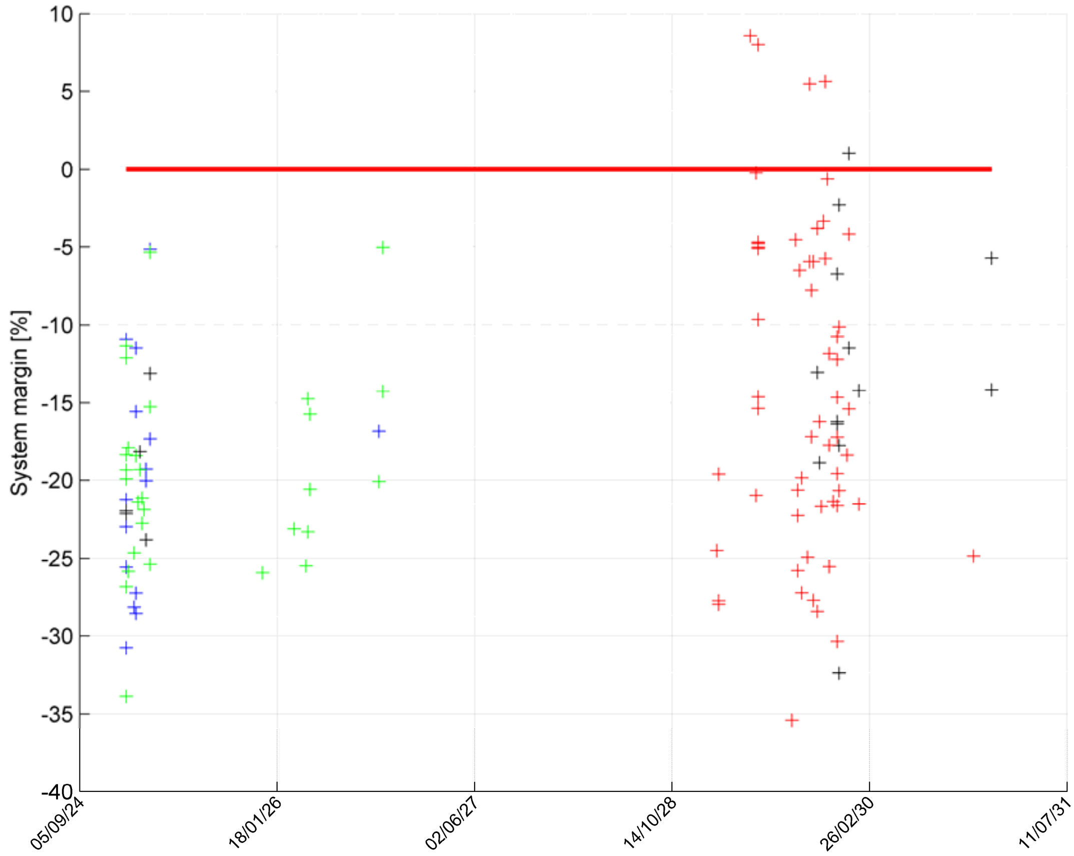

Figure 3-3: System margin for the set Uranus-Soyuz-1 probe

It is clear that very few solutions offer a positiv e system margin (none with SGA). A selection is given in Table 3-1 .

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
3a	98	20/05/2029	4.0	-26	1700	23/01/2042	10.9	0	12.7	1015	2330	8
3b	182	05/01/2030	4.6	17	1510	16/02/2043	8.8	0	13.1	1020	2510	1

Table 3-1: Selection of solutions for the transfer to Uranus with Soyuz and one probe

For both solutions (separated by 0.5 year), the incoming infinite velocity is high. On the other hand the transfer is short (~13 years). The system margin is larger for solution 3a because less DeltaV is needed. Assuming a common design, the tanks will not be filled for solution 3a.

At this stage, based on the system assumptions a launch with Soyuz is not recommended to Uranus. As mentioned in Paragraph 1.7, one option consists in using an initial Earth to Earth arc. The system margin is given in Figure 3-4 for one probe.

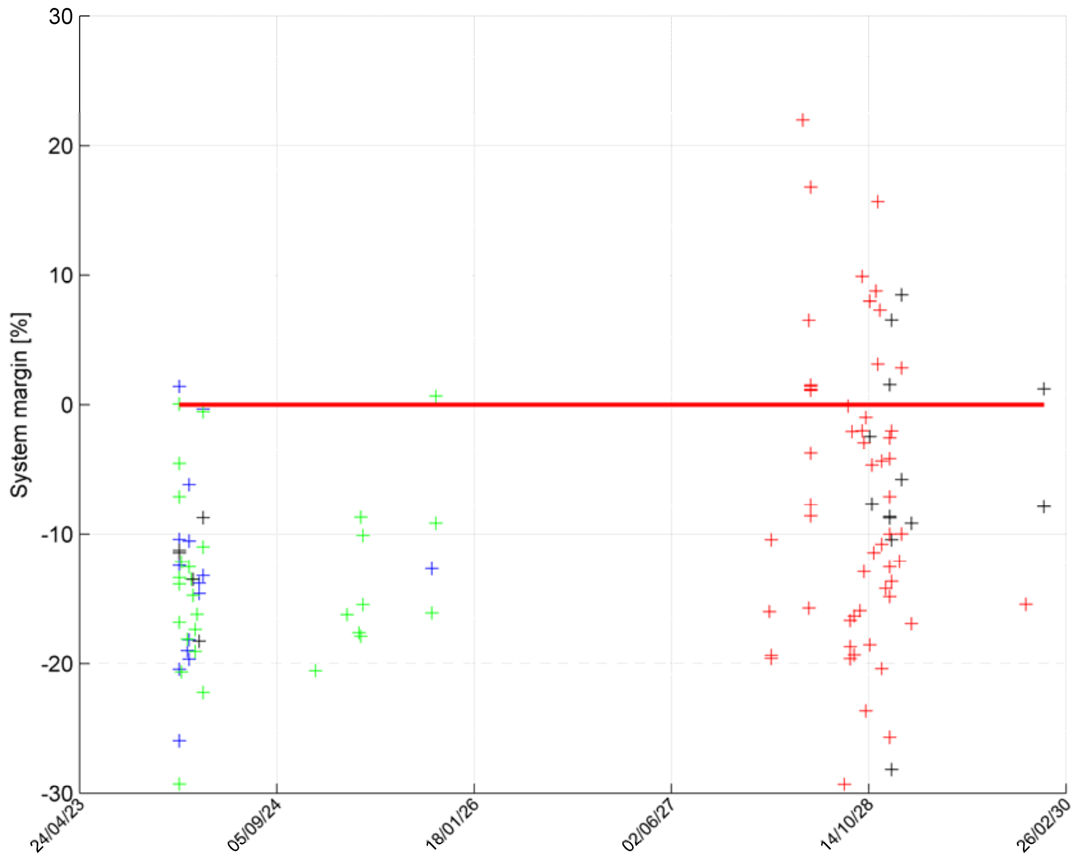

Figure 3-4: System margin for the set Uranus-Soyuz-1 probe with an initial Earth to Earth arc

There are two new solutions on the left side of the plot (with SGA), but they take place too early w.r.t. the timeframe. For the solutions on the right side of the plot (with JGA), the system margin is increased.

Based on these new results, two new solutions are proposed in Table 3-2.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
3c	249	13/10/2025	4.2	N/A	1685	17/07/2041	6.5	1	15.8	980	1940	1
3d	200	01/01/2030	4.8	N/A	1505	21/11/2043	8.1	0	13.9	980	1930	1

Table 3-2: Selection of solutions for the transfer to Uranus with Soyuz and one probe (with an additional Earth-Earth arc)

Solution 3c corresponds to a SGA. The transfer time is long, ~16 years, but the infinite velocity is low, 6.5 km/s. Solution 3d corresponds to a JGA. The transfer time is shorter, ~14 years, and the infinite velocity higher, ~8 km/s.

By combining Table 3-1 and Table 3-2, it seems that a mission to Uranus with Soyuz is feasible. However the system margin is very low; the number of potential solutions to establish the selection is also very limited. Finally the transfer time can be long and the infinite velocity high.

Therefore using Soyuz towards Uranus is feasible but marginal.

3.2 AR5 ECA

3.2.1 Overview

All solutions are presented in Figure 3-5 for both sequences in terms of final mass as a function of transfer time.

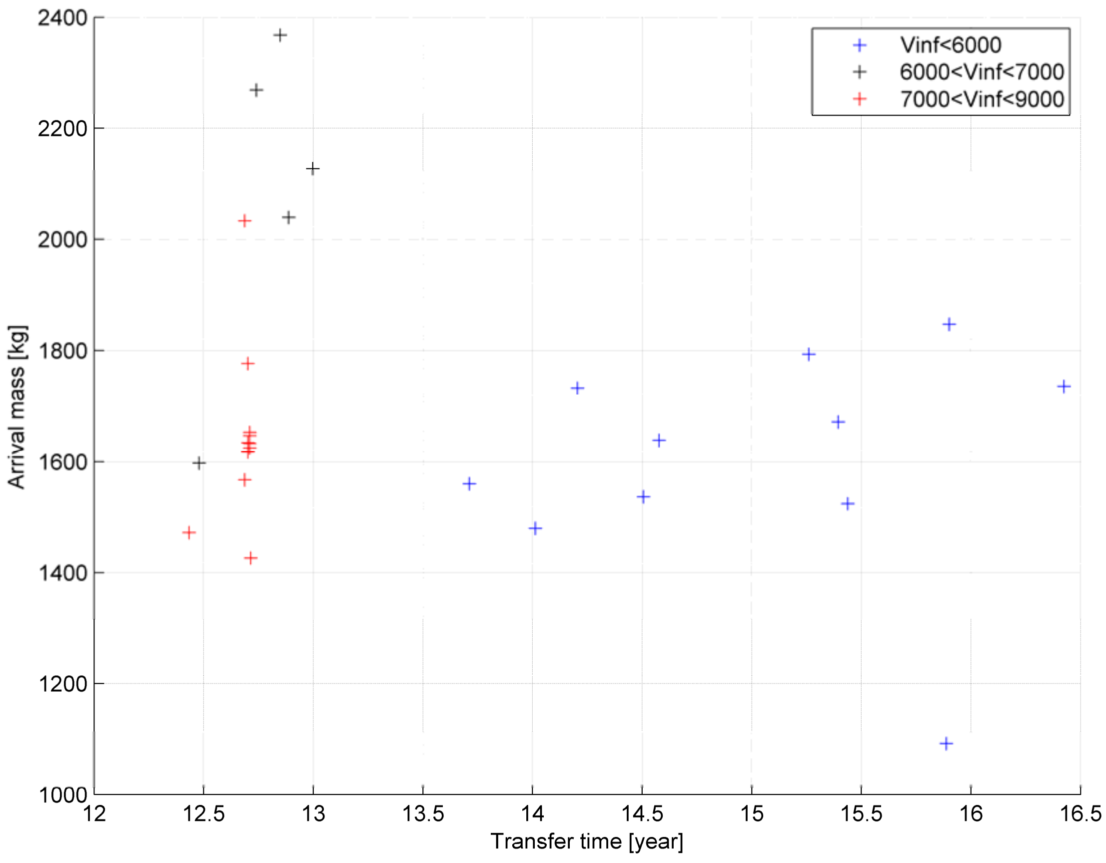

Figure 3-5: VEEJ and VEES sequences to Uranus with Soyuz. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

It can be seen that there are less solutions when compared with Soyuz. The reason is that many solutions require a combination (escape velocity- declination) that is not feasible with AR5-ECA. This could be overcome with a 5-burn strategy like for Soyuz, but the spacecraft wet mass would be prohibitive. It could also be overcome with an additional initial Earth to Earth arc.

3.2.2 One Probe

The system margin is given in Figure 3-6 for one probe and 1.5 km/s infinite velocity reduction.

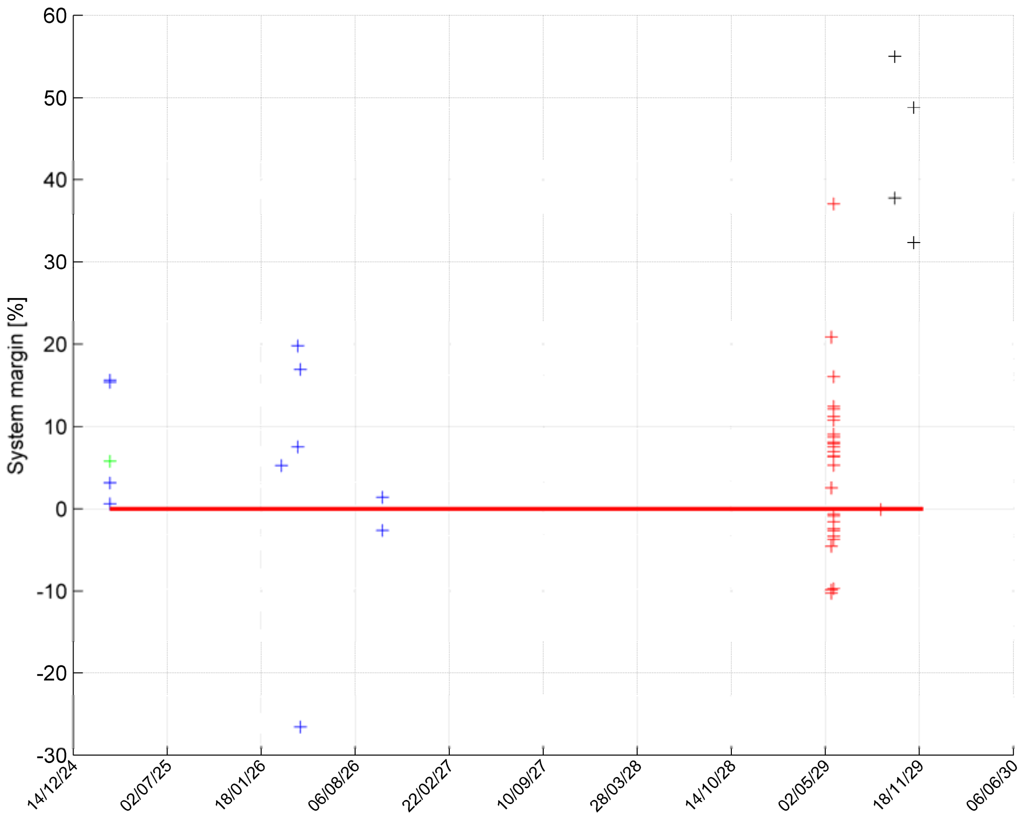

Figure 3-6: System margin for the set Uranus-AR5-1 probe with 1.5 km/s infinite velocity reduction prior to arrival

A selection of solutions is presented in Table 3-3.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
7a	56	03/03/2025	4.0	5	3005	14/11/2038	5.4	1	13.7	1015	2380	3
7b	66	03/10/2026	4.0	5	3015	02/04/2041	4.2	1	14.5	1015	2440	1
7c	50	06/11/2029	3	-27	3780	23/09/2042	6.8	0	12.9	1065	3015	2

Table 3-3: Selection of solutions for the transfer to Uranus with AR5 and one probe

In the first group of solutions (with SGA, left side of Figure 3-6), two good solutions were found with short transfer time (~14 years) and low infinite velocity. In the second group of solutions (with JGA, right side of Figure 3-6), the infinite velocity is quite high. A new reduction of the infinite velocity was applied: 2.5 km/s. While keeping a positive margin of 2%, a solution was found with 12.9 years transfer time and 6.8 km/s infinite velocity.

3.2.3 Two Probes

The objective is to keep the same solutions as for the case with one probe. To do so the reduction of the infinite velocity cannot be kept as is: for the first group of solutions, the 1.5 km/s is replaced by 0.7 km/s. For the second group of solutions, the 2.5 km/s is replaced by 1.7 km/s. This is the only way to keep positive margin.

The system margin is given in Figure 3-7 for 0.7 km/s infinite velocity reduction.

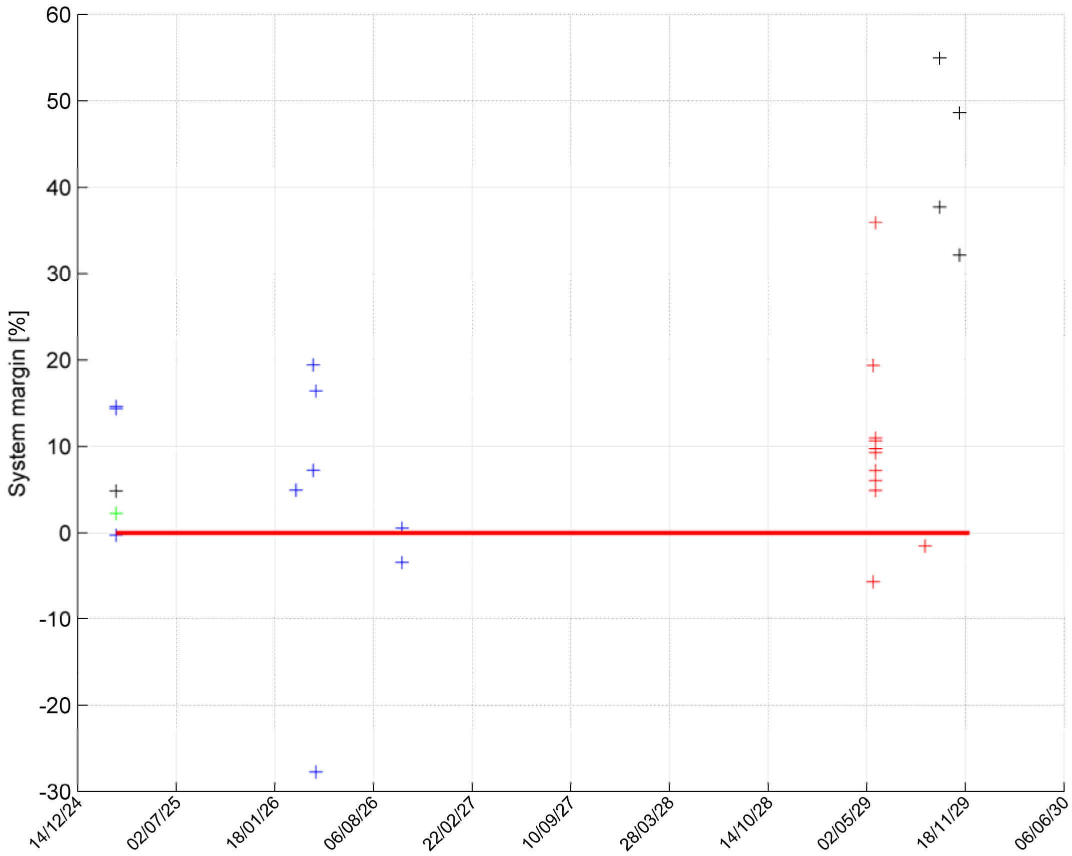

Figure 3-7: System margin for the set Uranus-AR5-2 probes with 0.7 km/s infinite velocity reduction prior to arrival

The solutions presented in the previous paragr aph are the s till the best. They are given in Table 3-4.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
8a	56	03/03/2025	4.0	5	3005	14/11/2038	6.2	1	13.7	995	1780	2
8b	66	03/10/2026	4.0	5	3015	02/04/2041	5.0	1	14.5	995	1840	1
8c	50	06/11/2029	3	-27	3780	23/09/2042	7.6	0	12.9	1045	2415	1

Table 3-4: Selection of solutions for the transfer to Uranus with AR5 and two probes

The increase of the infinite velocity is visible for the three solutions.

The first probe is of course released at Ura nus. Solutions 8a and 8b correspond to the sequence with a SGA: it m eans that the seco nd probe can either be released at Venus or at S aturn. In case Saturn is chosen, the incoming infinite velocity at Saturn is quite high, around 10 km/s. Solution 8c corresponds to a sequence with a JGA, which means the second probe must be released at Venus.

4 TRANSFER TO NEPTUNE

The launch window is given in Figure 4-1.

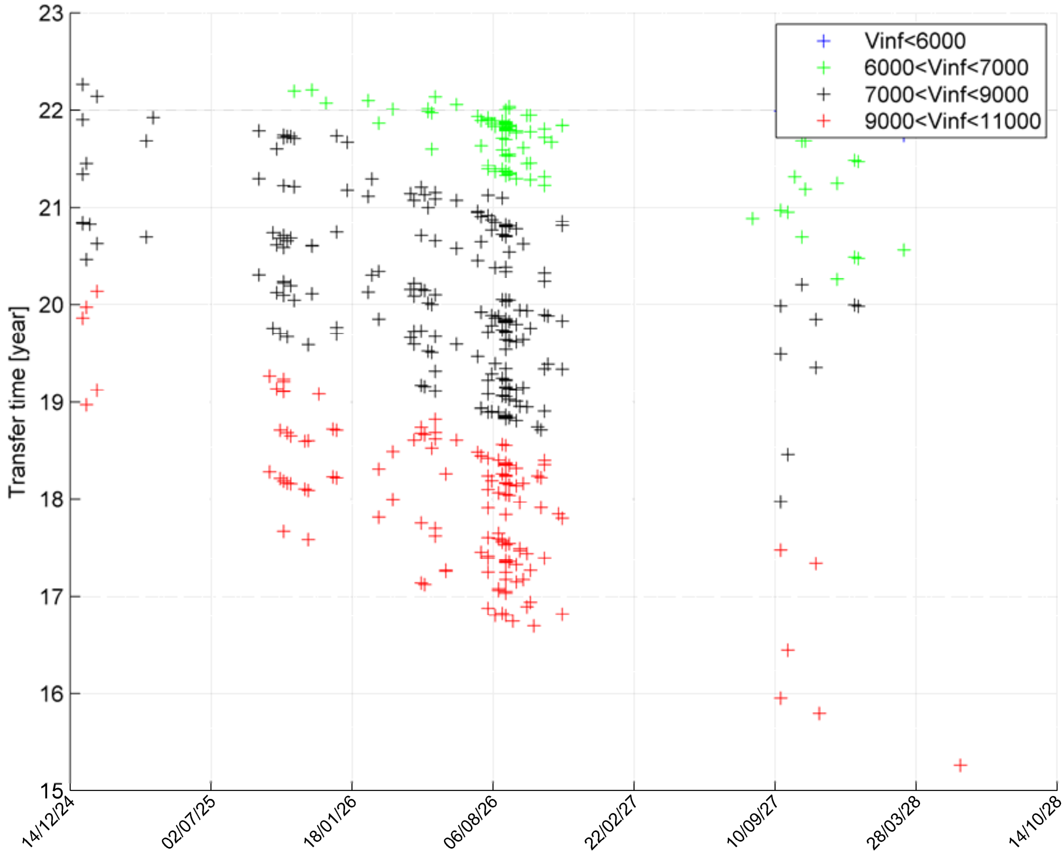

Figure 4-1: Launch window for Uranus. Transfer time as a function of the launch date for different arrival infinite velocities

- Only one sequence was used: VEEJ. The sequence VEES does not exist for this timeframe.
- It is almost impossible to get low infinite velocity. This statement should be confirmed by local optimisation of each candidate solution.
- For the same launch date, the infinite velocity can be traded-off against the transfer time: relatively low infinite velocity (> 6km /s) corresponds to a transfer time greater than 21 years, while a high infinite velocity (> 9km/s) corresponds to a transfer time greater than 16 years.
- Although most of the solutions are concentrated on the region Q3/2025-Q4/2026, there are some solutions in Q4/2027. On the overall launching to Neptune is only possible at the beginning of the 2025-2035 timeframe.

4.1 *Soyuz-Fregat*

4.1.1 Overview

All solutions are presented in Figure 3-2 for both sequences in term s of final mass as a function of transfer time.

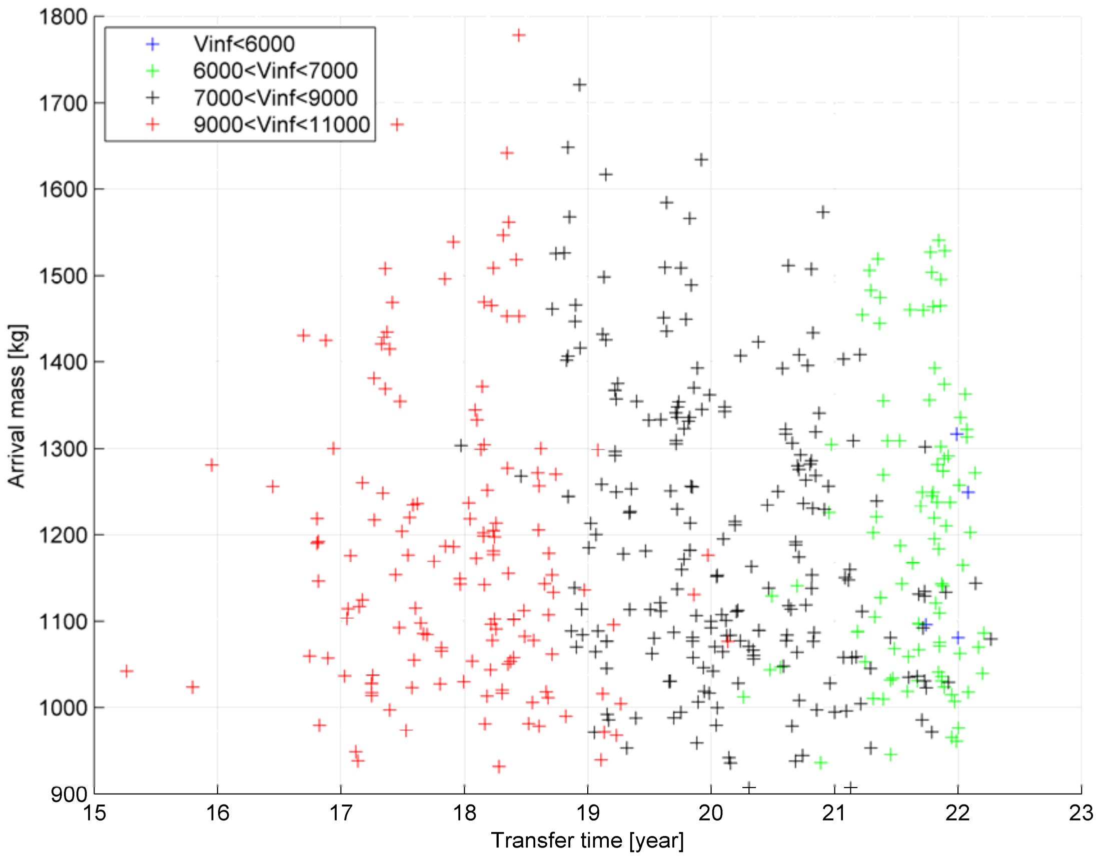

Figure 4-2: VEEJ sequence to Neptune with Soyuz. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

- The final mass ranges from 950 kg up to 1800 kg.
- The minimum transfer time (~15 years) is ob tained for high infinite velocity (>9 km /s) and a low final mass (1050 kg). The long transfer (~22 years) corresponds to low infinite velocity (~6 km/s). Fro the long transfer case, the final mass ranges from 950 kg up to 1550 kg.
- There is a d irect depend ence between the transf er tim e and the inf inite velocity (was already mentioned for Figure 4-1). It is interesting to notice that the final mass is independent of the transfer time.

4.1.2 One Probe

The system margin is given in Figure 4-3 for one probe.

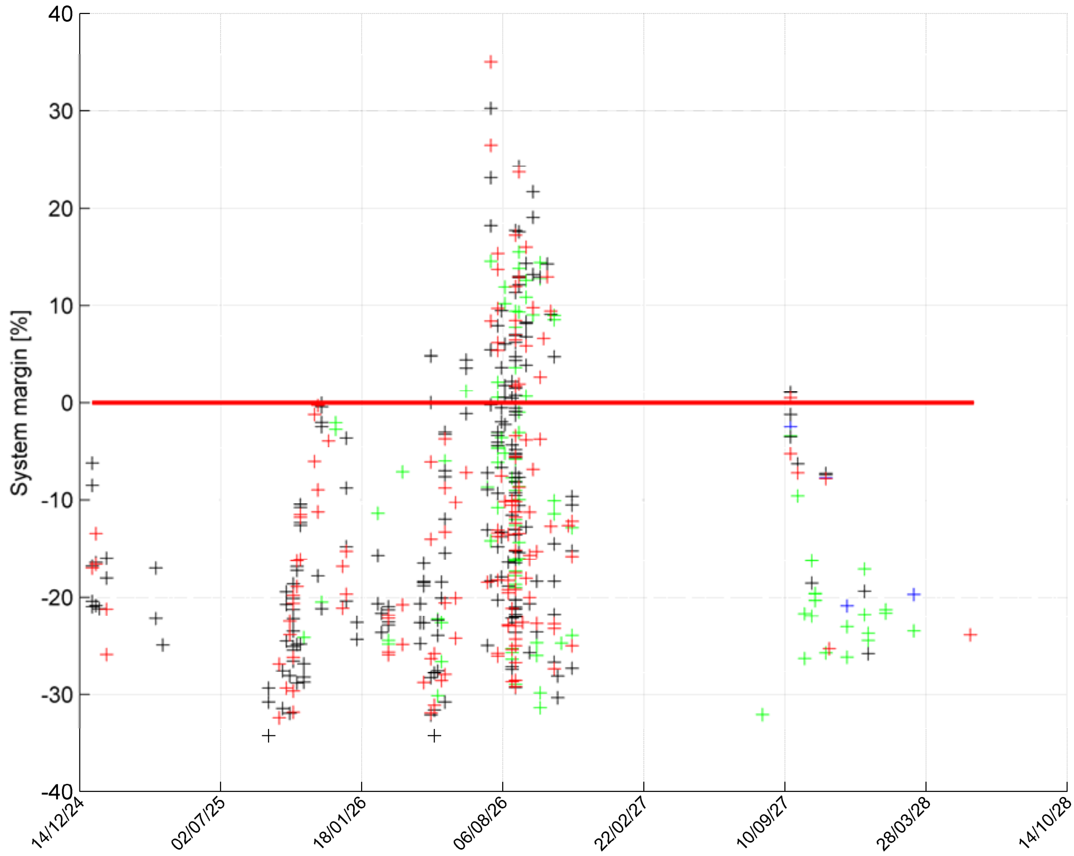

Figure 4-3: System margin for the set Neptune-Soyuz-1 probe

There is a bunch of solutions available mid-2026. A few solutions are also available mid-2027. As mentioned already before a lot of solutions correspond to the same local optimum. A selection of solutions is given in Table 4-1.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
4a	214	20/07/2026	3.0	-3	2010	05/06/2048	6.5	0	21.9	1010	2155	15
4b	599	18/09/2027	4.7	1	1525	08/09/2047	7.1	0	20.0	1020	2520	1

Table 4-1: Selection of solutions for the transfer to Neptune with Soyuz and one probe

The system margin is larger for solution 4a because less DeltaV is needed. Assuming a common design, the tanks will not be filled for solution 4a.

The transfer to Neptune seems feasible with Soyuz because solutions were found with relatively low infinite velocity. However the number of launch opportunities is much reduced. One way to extend it is to create another launch opportunity one year before by adding an Earth to Earth arc. This means that this solution 4aEE is identical to 4a except that the launch date is ~20/07/2025 and the transfer time ~22.9 years.

4.2 AR5 ECA

4.2.1 Overview

All solutions are presented in Figure 4-4 for both sequences in terms of final mass as a function of transfer time.

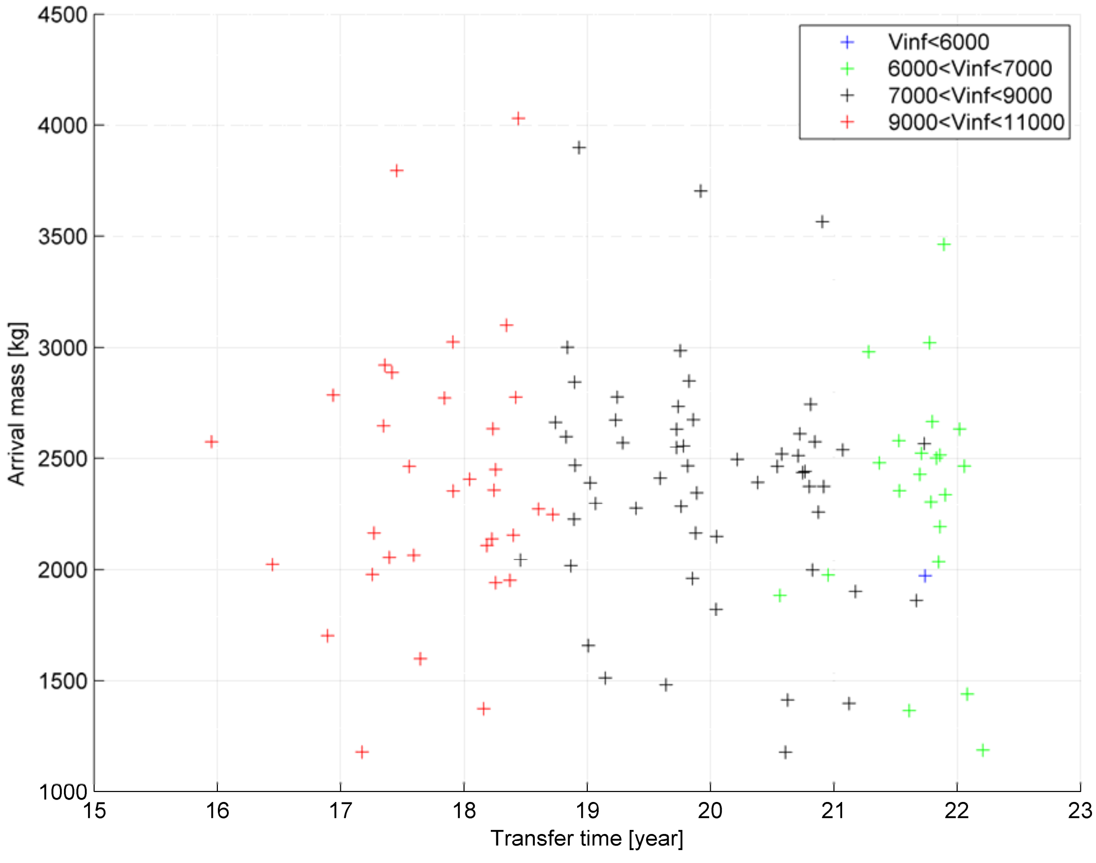

Figure 4-4: VEEJ sequence to Neptune with AR5. The arrival mass is given as a function of the transfer time for different arrival infinite velocities

It can be seen that there are less solutions when compared with Soyuz. The reason is that many solutions require a combination (escape velocity-declination) that is not feasible with AR5-ECA.

This could be overcome with a 5-burn strategy like for Soyuz, but the spacecraft wet mass would be prohibitive. It could also be overcome with an additional initial Earth to Earth arc.

4.2.2 One Probe

Because the number of solutions is smaller than for the cases, a specific optimization of the reduction of the infinite velocity was performed for each launch opportunity: getting smallest margin while keeping a DeltaV budget lower than 3 km/s. Therefore the standard plot with system margin cannot be presented because the infinite velocity reduction is different for each case.

A selection of solutions is presented in Table 4-2.

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
9a	1	11/01/2025	3.1	9	3625	04/11/2045	6.7	0	20.9	1055	2945	0
9b	16	20/07/2026	3.0	-3	4555	29/12/2043	6.9	0	17.5	1100	3030	19
9c1	149	28/09/2027	4.1	2	2735	05/03/2044	8.9	0	16.5	990	1970	9
9c2	150	28/09/2027	4.1	2	2735	05/03/2044	6.9	0	18.5	990	1940	10

Table 4-2: Selection of solutions for the transfer to Neptune with AR5 and one probe

- The transfer time ranges from 16.5 years up to 20.9 years. Solution 9a, although having a long transfer, is interesting because it adds a further launch opportunity.
- For solution 9b, the margin could have been further reduced, but the 3 km/s DeltaV budget was reached before.
- Solutions 9c1 and 9c2 correspond to the same local optimum. They permit to see the trade-off between transfer time and infinite velocity.

Even if these solutions are sufficient to demonstrate the feasibility of the mission, transfers with an initial Earth to Earth arc were analysed. Doing this the space of potential solutions is the same as for Soyuz. A selection of solutions is presented in Table 4-3

SOLUTION		DEPARTURE				ARRIVAL						System margin [%]
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	
11a	437	03/10/2025	4.3	N/A	3293	10/06/2043	7.9	0	17.7	1030	2600	4
11b	526	12/11/2026	4.0	N/A	3640	26/08/2043	8.9	0	16.8	1060	2955	0

Table 4-3: Selection of solutions for the transfer to Neptune with AR5 and one probe and an initial Earth to Earth arc

This option opens space for new solutions that can be compared in terms of transfer time and infinite velocity to the previous solutions. For the transfer time, the additional year coming from the Earth to Earth arc is compensated with shorter transfers. The lower final mass of the shorter transfers is compensated by the additional launcher performance, as the declination is not an issue anymore.

4.2.3 Two Probes

A selection of solutions is presented in Table 4-4.

SOLUTION		DEPARTURE				ARRIVAL						System margin
Case	#	date	vinf [km/s]	dec [deg]	Escape mass [kg]	date	vinf [km/s]	dec [deg]	Duration [years]	Carrier dry mass [kg]	DeltaV [m/s]	[%]
10a	1	11/01/2025	3.1	9	3625	04/11/2045	7.6	0	20.9	1035	2270	3
10b	16	20/07/2026	3.0	-3	4555	29/12/2043	7.4	0	17.5	1085	2660	10
10c1	149	28/09/2027	4.1	2	2735	05/03/2044	9.8	0	16.5	965	1295	11
10c2	150	28/09/2027	4.1	2	2735	05/03/2044	7.7	0	18.5	965	1270	12

Table 4-4: Selection of solutions for the transfer to Neptune with AR5 and two probes

An increase of the infinite velocity can be observed for each solution.

As it is impossible to find a sequence integrating a SGA for this timeframe, it means that the second probe must be released at Venus. The infinite velocity at Venus ranges from 5 to 7 km/s.

5 CONCLUSION

The main conclusion is that a mission with Soyuz-Fregat is feasible with one probe to Saturn. For Uranus and Neptune, the feasibility is marginal. Soyuz cannot be used for a mission with two probes.

If Ariane 5 ECA is used instead, one or two probes can be sent to Saturn, Uranus or Neptune, all of them with high system margin. This margin was used to decrease the infinite velocity of the reference transfers, thus opening space for shorter transfers with the same infinite velocity as the reference ones.

The selection of the solutions was based on the following important assumptions:

- Probe unit mass: 300 kg
- Carrier dry mass: m_{dry}*=900 kg + 7% DeltaV + 25 kg/probe*
- All manoeuvres with chemical propulsion

A modification of these assumptions, e.g. using RTG for electric propulsion or decreasing the carrier dry mass, would change the conclusions for Soyuz-Fregat.

5.1 Saturn

Soyuz:

- Launch opportunity every year
- Transfer time: 8 to 10 years
- Incoming infinite velocity: 5.8 to 7 km/s
- DeltaV: 2100 to 2550 m/s
- A mission with 2 probes is not feasible

AR5:

- Launch opportunity every year
- Transfer time: 7.5 to 9 years
- Incoming infinite velocity: 4.3 to 6.1 km/s
- DeltaV: 2100 to 2950 m/s
- 2 probes:
  - The solutions are comparable to 1 probe
  - The range of infinite velocity is the same although the average increases
  - DeltaV: 1800 to 2200 m/s
  - Infinite velocity at Venus: 5.8 to 9.3 km/s

5.2 Uranus

The launch window is reduced due to the phasing between (Jupiter or Saturn) and Uranus: 2025-2030.

Soyuz:

- Three solutions were found
- Transfer time: 12.7 to 15.8 years
- Incoming infinite velocity: 6.5 to 10.9 km/s
- DeltaV: 1950 to 2500 m/s
- Very few solutions, long transfer, high incoming infinite velocity, marginal feasibility
- A mission with 2 probes is not feasible

AR5:

- Three good launch opportunitie s were found: 2025 (base line), 2026 (backup 1) and 2029 (backup 2)
- Transfer time: around 13 years
- Incoming infinite velocity: 4.2 to 6.8 km/s
- DeltaV: 2400 to 3000 m/s
- 2 probes:
  - The incoming infinite velocity increases: 5 to 7.6 km/s
  - DeltaV: 1900 to 2400 m/s
  - Second probe at Venus: infinite velocity ~8..5 km/s
  - Second probe at Saturn: infinite velocity ~10 km/s

5.3 Neptune

The launch window is reduced due to the phasing between Jupiter and Neptune: 2025-2028.

Soyuz:

- Three solutions were found
- Transfer time: 20 and 23 years
- Incoming infinite velocity: 6.5 and 7.1 km/s
- DeltaV: 2150 and 2500 m/s

- Very few solutions, long transfer, marginal feasibility
- A mission with 2 probes is not feasible

AR5:

- Three good launch opportunitie s were found: 2025 (base line), 2026 (backup 1) and 2027 (backup 2)
- Transfer time: 16.5 to 21 years
- Incoming infinite velocity: around 7 km/s
- DeltaV: 1950 and 3000 m/s
- 2 probes:
  - The incoming infinite velocity increases: around 7.5 km/s
  - DeltaV: 1300 to 2700 m/s
  - Second probe at Venus: infinite velocity ranges from 5 to 7 km/s