RE-DESIGN OF THE ROSETTA MISSION FOR LAUNCH IN 2004

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ABSTRACT

The Rosetta mission was originally designed as a rendez-vous mission to comet Wirtanen with launch by Ariane-5/P1+ in January 2003. Although the S/C was ready in time, it was not launched within its 19 days launch slot in January 2003 due to technical problems with Ariane-5. The paper presents the subsequent mission redesign activities which resulted in a rendez-vous mission to comet Churyumov-Gerasimenko with asteroid fly-by's at Steins and Lutetia. The mission started successfully with its launch by Ariane-5/G1+ on 2 March 2004.

1. INTRODUCTION

The mission design for Rosetta started in the early nineties. After an extensive search for mission opportunities, the rendez-vous mission to comet Wirtanen with fly-by's at the asteroids Otawara and Siwa and with launch by Ariane-5/P1+ in January 2003 was selected as baseline for the Rosetta project [1]. The mission was relatively short and cheap in terms of fuel usage (about 9 years and 1540 m/s from launch to rendez-vous). Also design-driving parameters like launcher capabilities and minimum and maximum sun distance were not causing to much problems. Although the S/C was ready in time it was not launched within its 19 days launch slot in January 2003 due to technical problems with Ariane-5.

After the original mission opportunity to Wirtanen was lost, a new comet rendez-vous mission had to be found fitting a S/C, which was build to fly to Comet Wirtanen. This imposed rather tight constraints on the launch escape velocity and direction, on the fuel demand and on the minimum (thermal) and maximum (power) sun distance. In addition the new launch date should leave sufficient time for Ariane to recover from its technical problems. Also the rendez-vous should not be much later than for the original Wirtanen mission.

The mission re-design started with a search to identify candidate missions. From these, only the mission to Churyumov-Gerasimenko with launch in March 2004 satisfied the given mission constraints and had an acceptable fuel demand and mission duration.

The available fuel, however, did not allow to commit, already before launch, to include fly-by's at scientifically interesting asteroids since sufficient fuel had to be reserved to accommodate a launch window and hence launches not on the optimal date and for correcting the dispersion of the injection by the launcher. The launch took place close to the optimal date on 2 March 2004 and was very accurate. This led to the decision to include asteroid fly-by's at Steins and Lutetia.

2. MISSION CONSTRAINTS

As the S/C was tailored for the favorable mission opportunity to Wirtanen the mission re-design had to consider rather tight constraints as listed in Tab. 1.

Table 1. Mission constraints

S/C wet mass	3067 kg
Minimum allowable sun distance (thermal)	0.80-0.85 AU
Maximum allowable sun distance (power)	5.5 AU
Maximum distance for orbit burns (power)	4.4 AU
Minimum distance for Rendez-Vous	3.5 AU
Earliest launch date	Jan 2004
Maximum transfer duration	~ 11 years
Minimum height above Mars at swing-by's	250 km
Minimum height above Earth at swing-by's	200 km

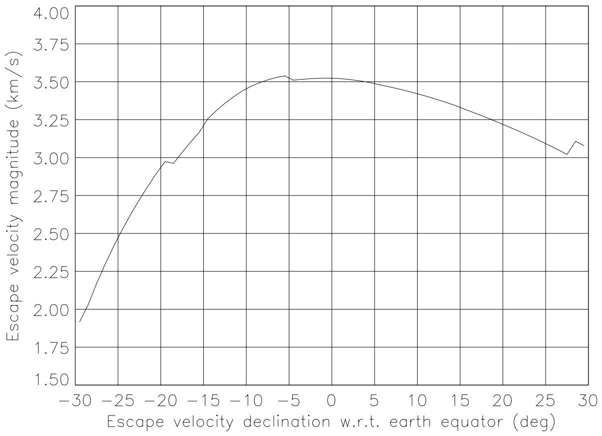
Table 2. DelaV budget

Nominal cruise and rendez-vous manoeuvres without asteroids	1715 m/s
Interplanetary navigation	75 m/s
Inclusion of asteroids	20 m/s
Near comet operations	120 m/s
Launcher injection correction	130 m/s
Contingency	62 m/s
TOTAL	2122 m/s

For programatic reasons, it was recommended to use Ariane-5/G+ as launcher, which is almost identical to Ariane-5/P1+.

Because it was decided not to open the tanks to avoid corrosion, the extra 20% tank capacity could not be used and the S/C wet mass and the DeltaV capacity was fixed. For this fixed mass, the DeltaV budget is given in Tab. 2 and the Ariane-5/G+ launcher performance is given in Fig. 1.

Fig. 1.AR-5G+ performance for S/C mass of 3067 kg



3. CANDIDATE MISSIONS

The results of the search for candidate missions is summarized in Tab. 2.

Table 3. Candidate missions (violations are shaded)

Comet	Wirt	Wirt	Chu-Ger	Temp-2	Howell
Launch	Jan 04	Apr 04	Mar 04	Sep 04	Sep 04
Launcher	AR5 ESCA	AR5 G+	AR5 G+	AR5 G+	AR5 G+
Lau Vinf (km/s)	4.500	3.100	3.515	3.515	3.515
Lau Decl (deg)	-5.4	18.0	-3.7	-4.3	-4.3
Swing-by's	Mars Earth Earth	Venus Earth Earth	Earth Mars Earth Earth	Earth Mars Earth Earth	Earth Mars Earth Earth
RDV @ 4.4 AU	Dec 11	Feb 12	Feb 14	Dec 13	Dec 13
DeltaV (m/s)	1502	1670	1739	1836	1990
Min Dsun (AU)	0.91	0.67	0.88	0.78	0.78
Max Dsun (AU)	5.26	5.25	5.36	4.73	4.73

The Wirtanen mission with launch in January 2004 would have recovered the original mission, as also asteroid Siwa could have been included easily. The risk of AR5-ESCA not being ready in time, however, was considered to large.

The Wirtanen mission with launch in April 2004 including a swing-by at Venus was rejected because of thermal problems when coming close to the sun.

The missions to Temple-2 and Howell were not possible as they come a bit to close to the sun. Moreover, the DeltaV required for the nominal cruise and rendez-vous manoeuvres did not fit at all into the available budget.

The mission to Churyumov-Gerasimenko satisfied all mission constraints. Although the DeltaV is on the limit, it was selected as new baseline, as it was the only choice left.

4. BASIC TRAJECTORY DESIGN

A fine tuning of the mission to Churyumov-Gerasimenko to get and optimal compromise between science quality, fuel demand and S/C safety resulted in the trajectory shown in Fig. 3, Fig. 4 and Fig. 5. It has fly-by's at Steins and Lutetia, a rendez-vous at 4.0 AU from the sun, a height at closest approach to mars of 250 km, and a height at closest approach to the earth well above 200 km.

The trajectory contains 3 swing-by's at the Earth and one swing-by at Mars. The details of the swing-by's are given in Tab. 4. The direction of the velocities at infinity for arrival and departure are given in a coordinate system with the X-axis along the direction sun to planet and the Z-axis along the angular momentum of the planet orbit around the sun For departure, also the earth equatorial declination is given.

Table 4. Details of planetary swing-by's

	Launch	Earth-1	Mars	Earth-2	Earth-3
Date	2004 Mar 02	2005 Mar 04	2007 Feb 25	2007 Nov 13	2009 Nov 13
V-inf (km/s)	3.547	3.863	8.809	9.362	9.379
Rad of peric (km)	6771	8341	3650	11680	8861
V-arriv ras (deg)		183.2	345.7	175.7	151.6
V-arriv dec (deg)		3.2	4.7	6.3	29.4
V-depar ras (deg)	184.5	84.4	331.4	151.4	109.8
V-depar dec (deg)	3.5	-12.5	-0.1	29.4	18.3
V-dep dec-equ-ear	-2.0	-34.1		18.6	24.4

Churyumov-Gerasimenko has its perihelion at 1.24 AU, its aphelion at 5.68 AU and hence a period of 6.45 years. Relative to the ecliptic, the inclination is 7 deg and the argument of perihelion 12.8 deg, which means that the apsidal line is close to the ecliptic.

The arc from the earth to the comet starts when the earth is near to the ascending node of the comet orbit w.r.t. the ecliptic and ends when the comet reaches the sun distance of 4.0 AU on its descending arc. The earth escape velocity is 9.379 km/s at an equatorial declination of 24.4 deg. The rendez-vous is achieved with 2 manoeuvres, one of 789 m/s before aphelion and one to break the arrival velocity at the comet of 794 m/s.

Ariane-5/G+ provides an earth escape velocity of 3,547 km/s at an equatorial declination of -2.0 deg. This escape velocity is reoriented and increased in magnitude as required for the final arc to the comet by 2 so called "DeltaV gravity assists".

The strongest "DeltaV gravity assist" is between the first and the second earth swing-by. At the first swing-by, the S/C is injected in a nearly 2 to 3 earth resonant (~1.5 years) orbit at an escape velocity of 3.863 km/s and an equatorial declination of -34.1 deg. After 1 revolution, a breaking manoeuvre of 32 m/s near perihelion reduces the orbital period and the aphelion. In the second revolution, a Mars swing-by occurs changing the heliocentric S/C velocity by 2260 m/s mainly opposite to the velocity. Further, a small breaking manoeuvre of 7 m/s is performed near aphelion. The result is that the S/C gets back to the earth after a bit less than 3 years with the desired arrival velocity of 9.362 km/s. Applying a DeltaV of 2267 m/s (Mars swing-by + manoeuvre), increases the velocity at infinity w.r.t. the earth by 5.499 km/s. The lowest DeltaV would have been obtained when applied at aphelion, but we have to use Mars were we can encounter it and this is earlier.

The earth approach velocity of 9.362 km/s at the second swing-by has to be rotated to the desired direction for reaching the comet. In one swing-by this would require a perigee radius of 3900 km, which is well below the earth surface. The rotation is therefore split over 2 earth swing-by's separated by one complete revolution of 2 years.

The weakest "DeltaV gravity assist" is between launch and the first earth swing-by. At launch, the S/C is injected towards the sun in a nearly 1 to 1 earth resonant (~1.0 year) orbit at an escape velocity of 3.547 km/s and an equatorial declination of -2.0 deg. A breaking manoeuvre of 158 m/s is performed near perihelion. The result is that the S/C gets back to the earth after nearly 1 year with an arrival velocity of 3.863 km/s at an equatorial declination of -2 deg. Applying a DeltaV of 158 m/s, increases the velocity at infinity w.r.t. the earth by 0.316 km/s, which is twice as much. A similar effect with a somewhat lower ratio could have been obtained with a manoeuvre at aphelion. The fist earth swing-by rotates the velocity at infinity from an equatorial declination of -2 deg to -34 deg, a declination which can not be achieved efficiently with Ariane-5/G+.

5. DATE OF RENDEZ-VOUS

Since orbit control manoeuvres can not be performed above 4.4 AU, this is the earliest possibility to rendez-vous with the comet. As can be seen in Tab. 5, delaying the rendez-vous saves a considerable amount of fuel.

Table 5. Influence of rendez-vous date

RDV distance (AU from sun)	RDV date	Total Delta-V (m/s)	Max Sun dist (AU)
4.40	14/02/25	1739	5.36
4.30	14/03/20	1720	5.35
4.20	14/04/11	1702	5.35
4.10	14/05/02	1686	5.44
4.00	14/05/23	1672	5.33
3.90	14/06/12	1658	5.32
3.80	14/07/01	1645	5.32
3.70	14/07/19	1632	5.31
3.60	14/08/06	1621	5.30
3.50	14/08/23	1610	5.30
3.40	14/09/09	1599	5.29
3.30	14/09/25	1589	5.29
3.20	14/10/11	1580	5.28
3.10	14/10/27	1572	5.28
3.00	14/11/11	1561	5.27

On the other hand, the lander has to be delivered before the comet gets active, which is considered to start near 3.0 AU. Also sufficient time must be available for the rendez-vous manoeuvre sequence, the approach to the comet, global mapping, close observation, lander delivery rehearsal and lander delivery proper.

A trade off between the different interests resulted in a rendez-vous at 4.0 AU from the sun on 23 May 2014.

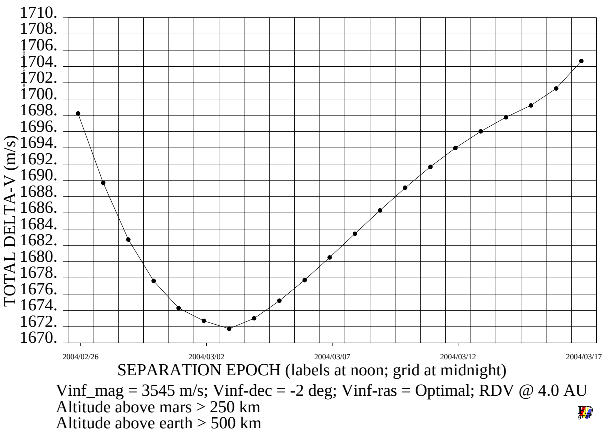
6. LAUNCH WINDOW

The solution obtained so far is for the optimal launch date on 3 March 2004. To have sufficient launch attempts, a launch window of at least 2 weeks needed to be established.

The DeltaV for nominal cruise and rendez-vous manoeuvres was computed for launch dates from mid February to end March. Based on these data, a launch window from 27 February to 17 March was selected. The associated DeltaV is shown in Fig. 2.

Up to the optimal launch date on 3 March, the trajectory has only a perihelion manoeuvre on the 1 year arc from launch to the first earth swing-by. From 15 March onwards, this arc contains only an aphelion manoeuvre. In between, we have a transition between both solutions, were the DeltaV is transferred gradually from the perihelion to the aphelion manoeuvre. This allow to keep the first earth swing-by near to the optimal date.

Fig. 2. Nominal DeltaV for cruise and rendez-vous



7. ASTEROID FLY-BY'S

In the DelaV budget (Tab. 2), 20 m/s was reserved for including asteroid fly-by's during cruise. Comparing the worst case DeltaV of 1705 m/s for a launch at the end of the launch window on 17 March 2004 (Fig. 2) with the available 1715 m/s from the DelaV budget, allows to increase the DeltaV available for asteroids to 30 m/s. This is not sufficient to include fly-by's at scientifically interesting asteroids.

After launch the DeltaV available for asteroids could be increased depending on the launch date. For the optimal launch date on 3 March 2004, 63 m/s would be available. The DeltaV budget also foresees 130 m/s for correcting the launcher dispersion. Whatever of this is not needed could also be used partially for including asteroids.

It was therefore decided to postpone the decision on the asteroids until after launch when it is known how much DeltaV is needed in total for the launcher dispersion correction, the cruise and the rendez-vous manoeuvres. For a prioritized list of options, set up by the scientific community before launch, this DeltaV as computed after launch is shown in Tab. 6.

Available in the fuel budget for launcher dispersion correction, cruise and rendez-vous manoeuvres is 1865 m/s (1715 + 20 + 130). Although priority 1 and 2 would fit within this envelope, it was decided to selects priority 3, Lutetia being the absolute scientific favorite and Steins having got an lately increased interest due to recent new observations. Moreover, this makes available 78 m/s to increase the budget for near comet operations and contingencies.

Details on the fly-by's at Steins and Lutetia are in Tab. 7.

Table 6. Asteroid options after launch on 2 March 2004

Priority	Asteroid on Earth to Earth	Asteroid on arc Earth to Comet	Total DeltaV (m/s)
	none	none	1676
1	Rhodia	Lutetia	1819
2	Luichewoo	Lutetia	1782
3	Steins	Lutetia	1787
4	Baetsle	Izvekov	1783
5	Baetsle	Fogolin	1860
6	Luichewoo	Izvekov	1706
7	Rhodia	Izvekov	1808
8	Rhodia	Fogolin	1810
9	Steins	Izvekov	1747
10	Sofala	Izvekov	1821
11	Steins	Fogolin	1738
12	Luichewoo	Fogolin	1706
13	Baetsle	none	1711
14	none	Izvekov	1682
15	none	Fogolin	1687

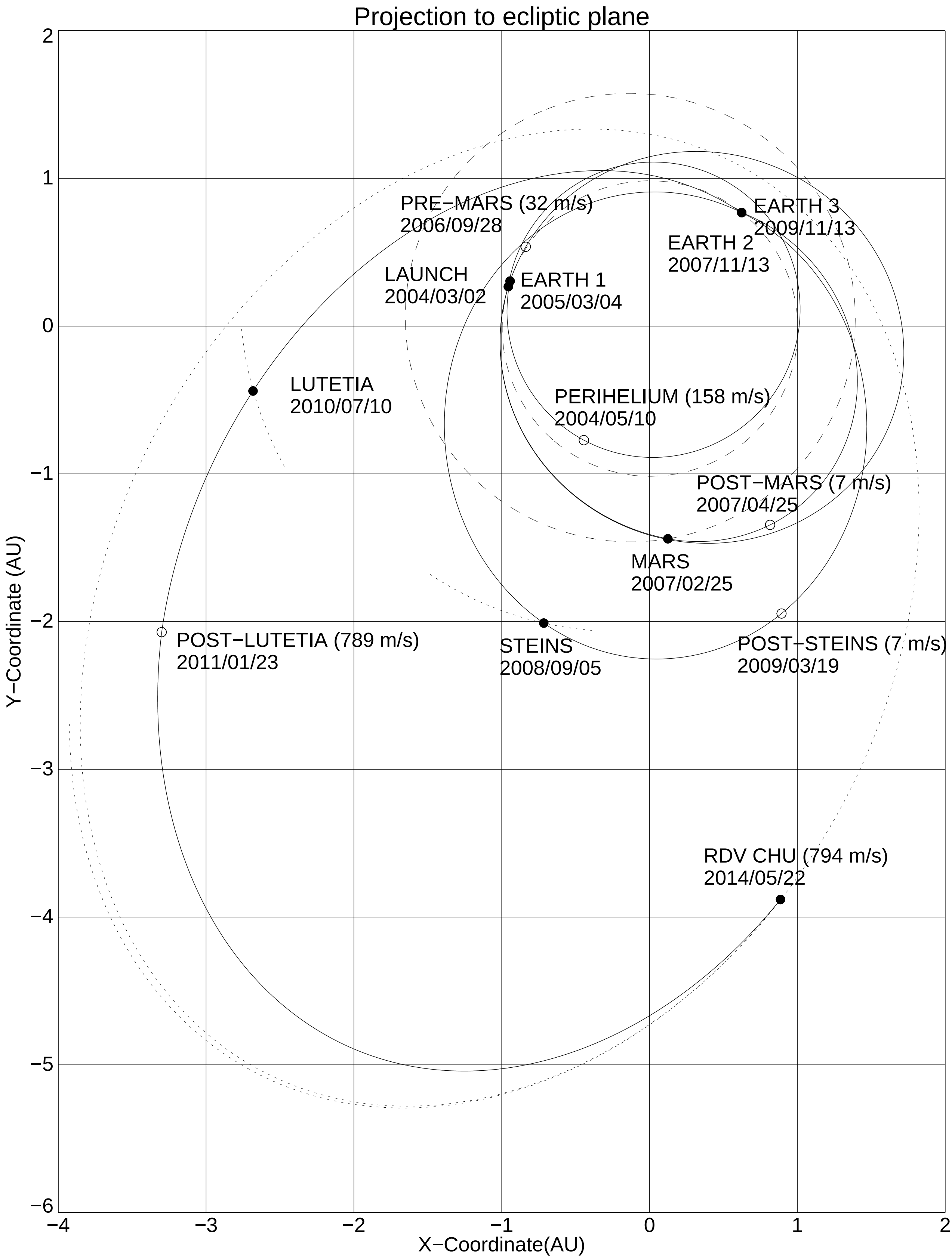
Table 7. Fly-by details for selected asteroids

	Steins	Lutetia
Date	2008 Sept 5	2010 July 10
Relative velocity (km/s)	8.616	14.994
Sun-S/C-Ast angle at approach (deg)	141.5	168.9
Ear-S/C-Ast angle at approach (deg)	163.9	171.5
Sun-S/C-Ear angle (deg)	24.7	19.2
Sun-Ear-S/C angle (deg)	62.3	61.9
Sun distance (AU)	2.14	2.72
Ear distance (AU)	2.41	3.05

8. REFERENCES

1 ROSETTA: Consolidated Report on Mission Analysis; Feb. 1999; RO-ESC-RP-5500; J. L. Pellon Bailon, J. Rodriguez-Canabal, A. Yanez-Otero (ESOC)

Fig. 3. From launch to rendez-vous.



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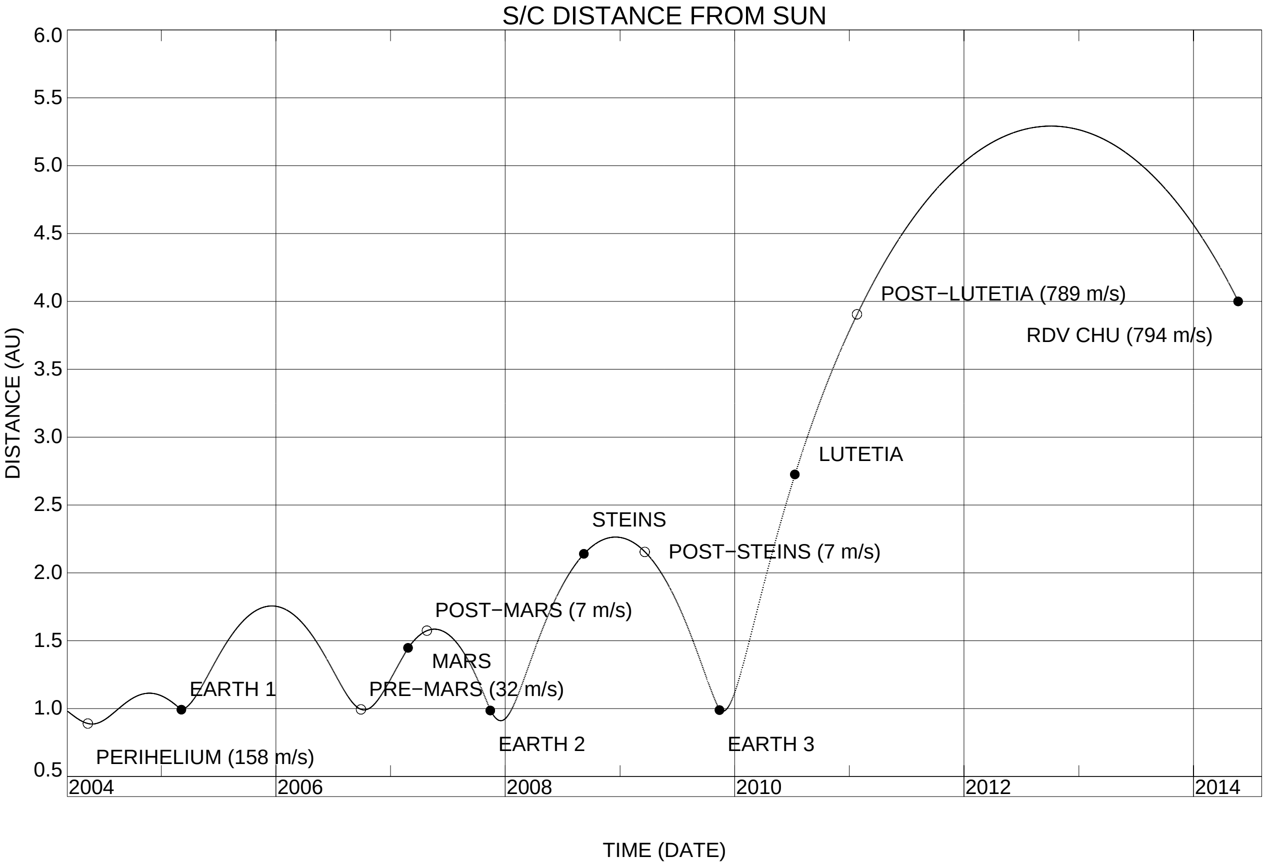

Fig. 5. From launch to rendez-vous.