OPERATIONAL MANEUVER OPTIMIZATION FOR THE ESA MISSIONS HERSCHEL AND PLANCK

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ABSTRACT

The ESA science spacecrafts Herschel and Planck were successfully launched on May 14, 2009, using jointly an Ariane 5 ECA. The rocket's upper composite was injected on a highly eccentric orbit, then, after separation, the spacecrafts were targeted towards Lissajous orbits around the outer collinear Lagrange point (L2) of the Sun-Earth System. The sizes of their Lissajous orbits are restricted by constraints on the Sun-Spacecraft-Earth angle, which are different for both spacecrafts. For Herschel the dynamic effect due to helium venting has to be considered especially during the LEOP, while for Planck the long term orbit is affected by small maneuvers required to follow a scanning law for science operations. The spacecrafts differ in attitude control, shading constraints, and require different maneuver modeling. Because of the precise launch on a date where only small compensations for the perigee velocity variation were required and because of relatively accurate orbit insertions, both missions have propellant margin to allow for extended missions, such that mainly the capacities of the cooling systems become the lifetime limiting factors. For Planck a change to a smaller orbit with 10 deg Sun-Spacecraft Earth angle, as well as an eclipse avoidance maneuver for an orbit extension beyond 2014 is found possible.

1. MISSIONS

Herschel is a multi-user observatory mission, dedicated to perform astronomical observations in the far-infrared and sub-millimetre wavelength range, covering the 60-670 µm band. The foreseen mission duration is 3.5 years, with possible extension to 4.5 years.

Planck is a survey type mission with the scientific objectives to map the temperatures anisotropies of the Cosmic Microwave Background over the whole sky and to map all major galactic and extragalactic sources of emission at frequencies of 25 to 950 GHz. The foreseen mission duration is 15 months which corresponds to 2 complete sky surveys, with possible extension to 2.5 years.

2. TARGET ORBITS

The restricted three-body problem has five equilibrium solutions, the Lagrange points L1 to L5 as sketched in Fig. 1 for the Sun-Earth system. In three of the solutions (L1-L3) the bodies are in line; in the other two, the bodies are at the points of equilateral triangles. Orbits around L1-L3 are unstable. Classes of quasi periodic orbits exist around the L1 and L2 point, where instability occurs on a timescale of approximately 23 days. These are the Lissajous orbits. Satellites positioned at L1 or L2 therefore need to perform regular orbit corrections to prevent escaping towards either the Sun or the Earth.

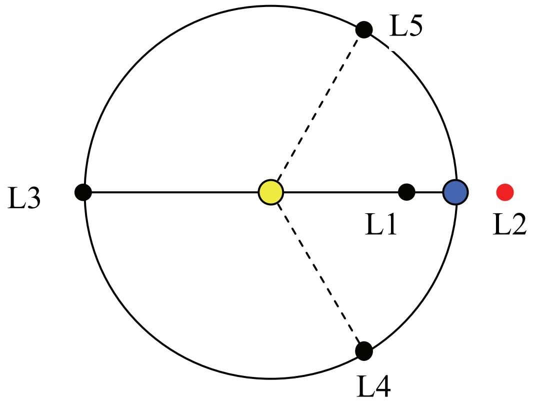

Fig. 1. Lagrange Points in the Sun-Earth system

The L2 point has been selected as the centre of the operational orbits of Herschel and Planck in order to maximize the scientific return within the technical constraints. It is located 1.5 million kilometers away from Earth (about 4 times the distance of the Moon), in the opposite direction to the Sun. This location has the following advantages: Sun and Earth are nearly aligned as seen from the spacecraft (S/C). This allows uninterrupted sky observations where only one direction, which moves 360 deg per year, is excluded from viewing. Spacecraft communications are possible with only one Sun-pointing medium gain antenna. With shielding from infrared emissions of Sun and Earth a stabile thermal environment can be provided for sensitive instruments. The L2 point is far enough from Earth to avoid high energy radiation.

Approximations to the orbits around L2 can be computed using the linear theory for the restricted circular three-body problem in a reference system rotating with the Earth around the Sun. The solutions consist of a harmonic motion in the ecliptic plane (x-y plane with x along the Sun-Earth line) and an uncoupled motion with different frequency orthogonal to it. In addition there are two exponential terms with the exponent depending on time, where one decays with increasing time while the other increases and causes the instability of the orbit, because any perturbation will grow exponentially in time. To give an example: A velocity error in the orbit inserted at a particular moment will grow by a factor 3 in 3 weeks. For operations the orbits are computed numerically, taking into account the gravity fields of the Sun, all planets, the Moon and the spherical gravity field of the Earth with 16x16 coefficients.

PLANCK will move around L2 in a smaller Lissajous orbit. The amplitudes of the motion are restricted by the maximum allowable Sun-Spacecraft-Earth angle of 15 deg. They are up to 350,000 km in the ecliptic plane and normal to the Earth-Sun direction (y) and 300,000 km normal to the ecliptic plane (z). HERSCHEL will move in a larger quasi-halo orbit around L2. The quasi-halo orbit is a special case of the Lissajous orbits, where the periods of the in-plane and out-plane oscillations are nearly matched such that the trajectory, when seen in the co-rotating frame, appears to be repeating. For HERSCHEL the amplitudes of the motion are restricted by the maximum allowable Sun-Spacecraft-Earth angle of 40 deg. They are up to 750,000 km in the ecliptic plane and normal to the Earth-Sun direction (y) and 450,000 km normal to the ecliptic plane (z).

The operational orbits of both spacecrafts computed on 2009-08-05 are shown in Fig. 2 in a rotating coordinate frame moving with the Earth around the Sun, where x points from the Earth opposite to the Sun direction, y is in the Earth’s orbital plane positive along the Earth velocity and z completing the right handed frame. The figure also shows day, delta-V, and location of each of the first five maneuvers for each spacecraft.

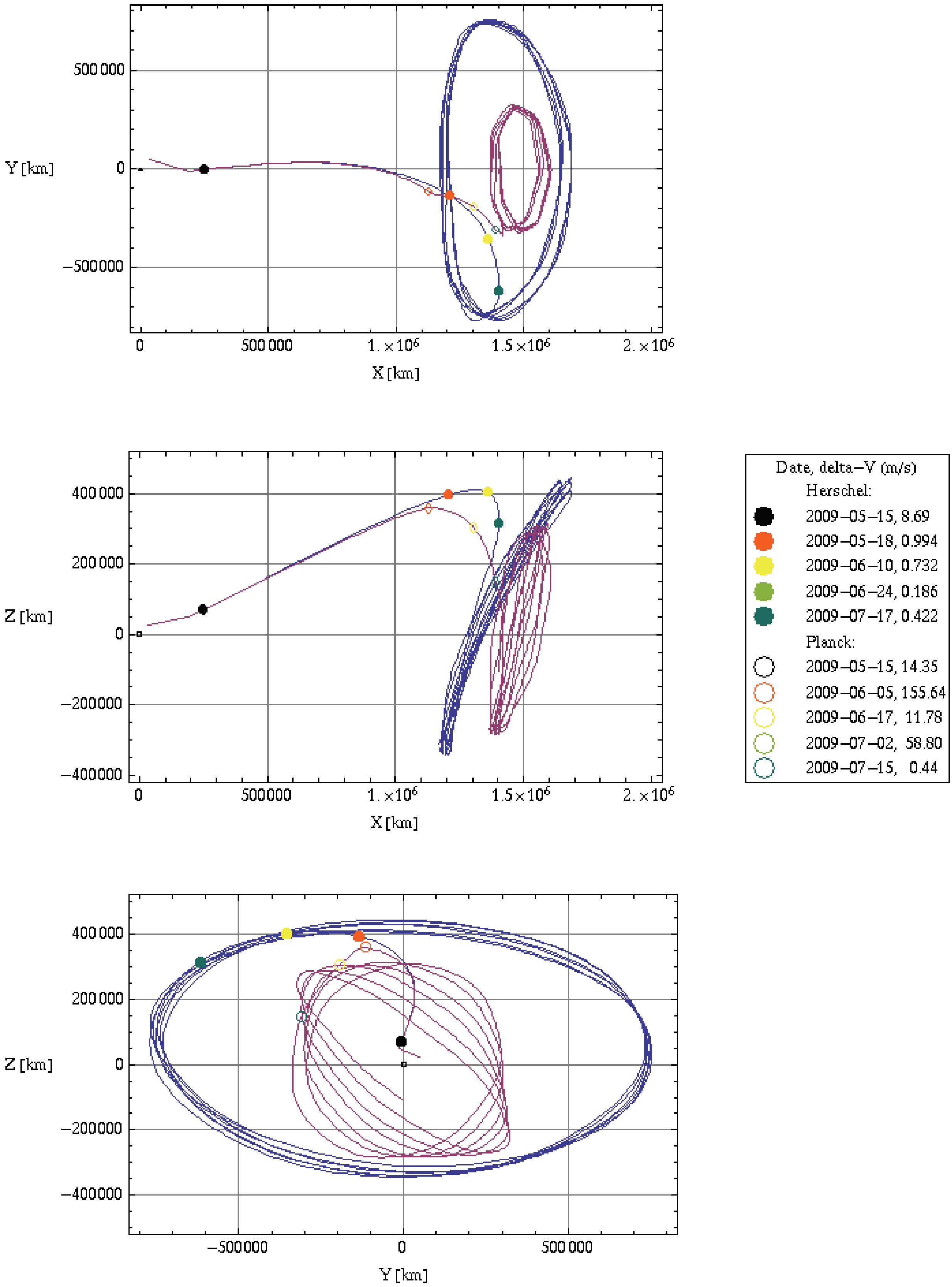

Fig. 2. Herschel and Planck orbits of 2009-08-05 in Earth centered rotating frame with x pointing from Earth opposite to Sun direction, y positive along Earth velocity and z completing the right handed frame. The Earth is indicated as small black circle, locations of executed maneuvers are indicated as colored dots for Herschel and as circles for Planck. The Day-1 maneuvers overlap.

3. HERSCHEL

3.1. Spacecraft

Herschel is a three-axis stabilized observatory weighting about 3377 kg with a 3.5-meter in diameter mirror to collect long-wavelength radiation in the far infrared to sub-millimeter range. It is shielded on the Sun-side and constantly outgases the coolant Helium which is required to keep the Focal Plane Units at temperatures close to zero Kelvin. The amount of Helium available (336 kg) limits the lifetime of the spacecraft. The spacecraft and its attitude constraints are shown in Fig. 3, where arrows also define the S/C attitude axis. Herschel is equipped with twelve 20N thrusters, arranged in two redundant independently operable branches of six thrusters each, which are located in the service module below the telescope.

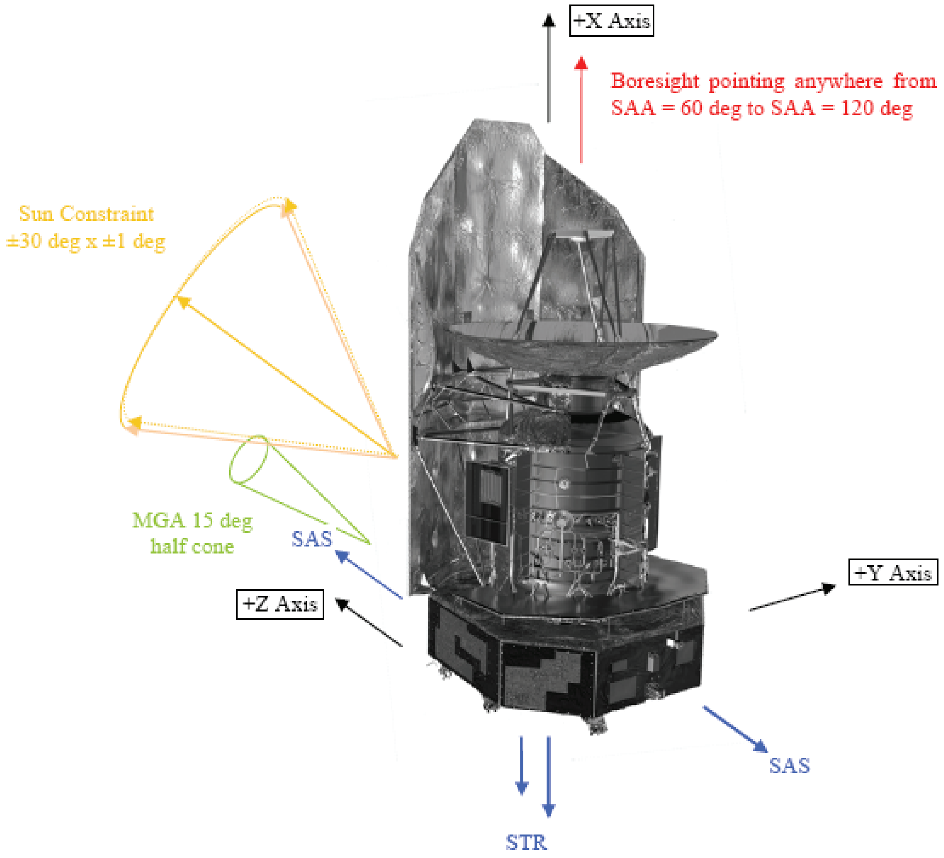

Fig. 3. Herschel Attitude Constraints, showing also the Medium Gain Antenna (MGA) cone, directions of the Mirror, the Star Tracker (STR), and the Sun Acquisition Sensor (SAS) bore sights. Allowed directions of the Sun as seen from the Spacecraft are indicated by the yellow arrows and shape. Source of original image: ESA/Herschel (AOES Medialab)

3.2. Constraints

Temperature (= shading) constraints restrict Herschel's attitude changes to rotations around the spacecraft-Sun direction (z-direction) and tilting within a limited rectangular range of the sun-aspect angle w.r.t. the spacecraft body axes (yellow shape as shown in Fig. 3).

The two star trackers (STR) point along the spacecraft -X axis. To avoid their blinding, the aspect angles of the X- axis with the S/C-Moon and S/C-Earth directions need to be smaller than 158 deg.

Operational constraints force interruptions of large maneuvers to update the on-board database. For example a maneuver between 30 and 47.9 m/s would need to be split into 2 parts separated by at least 35 minutes duration to allow the update. The first would be executed with 30 m/s.

The long-term orbit needs to satisfy communication and shading constraints for a lifetime of 4.5 years from the end of the commissioning phase. It is therefore restricted by the requirements of having no eclipses by the Earth during transfer and science phase and no eclipses by the Moon during the transfer phase. It is limited in size by the requirements of keeping the Sun-Spacecraft-Earth Angle below 40 deg (MGA half cone + 30 deg shading constraint) and by the spacecraft compatibility with a maximum distance to Sun of 154e6 km.

3.3. Maneuver modeling

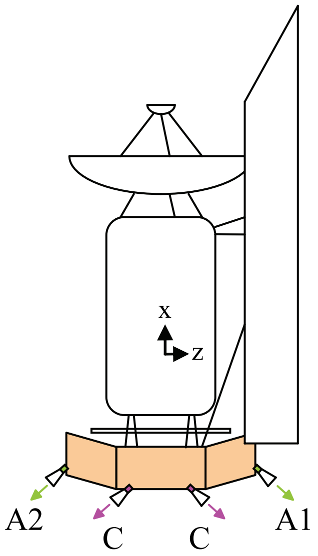

Fig. 4. Herschel with Service Module (orange), delta-V thrusters "A" and control thrusters "C". Arrows indicate the plume directions.

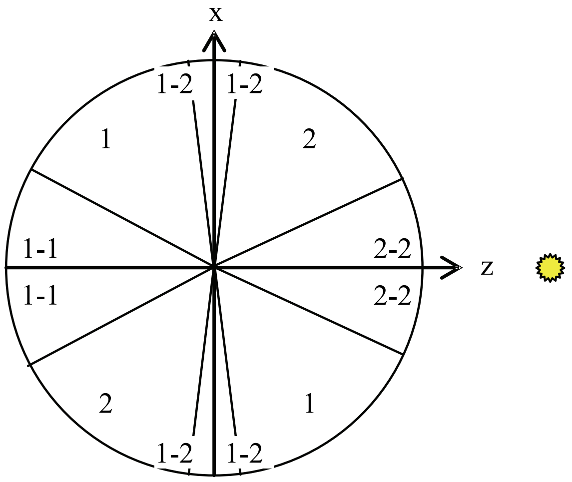

Fig. 5. Sectors of thruster combinations depending on delta-V to S/C-Sun direction (z). "1-1" and "2-2" require slews around the z-axis and 1-2 around the y-axis

Herschel's reaction control system (RCS) uses 2 thrusters ("A") located on the ± z sides of the Service Module to create delta-V and 4 control ("C") thrusters located on the ± y sides to create torques, see Fig. 4. The "A" thrusters are used only one at a time. While the control thrusters can create torques in any direction, the S/C needs to slew for certain delta-V directions because there are only 2 thrusters. Herschel needs dog-leg maneuvers (firing one thruster per maneuver part) as indicated in Fig. 5 to satisfy the shading constraints, which essentially allow only rotations around the z-axis and rotations limited to 30° around the y-axis.

For optimization the spacecraft attitude is modeled with Euler angles, such that the y axis is always perpendicular to the spacecraft-Sun direction because there is only a rotation of 1 deg allowed around the x-axis. The 30° constraint is imposed on rotations around y and the rotation angle around z is a free parameter. To select the thruster or thruster combination, two sequential maneuvers with different thrusters are optimized. Because of the fuel penalty involved by dog-legs (2 delta-Vs, each with components pointing off the optimal delta-V direction) the optimizer tends to select only one of them.

During early operations it was determined that in case of a forced maneuver interruption (for updating of the onboard database) both maneuver parts need to have the same inertial direction to avoid additional uncertainties and losses by slewing. Fortunately, application of this procedure was not required for the Day-1 maneuver.

4. PLANCK

4.4. Spacecraft

Planck is a 1920 kg surveyor of the cosmic microwave background, which is spin-stabilized at 1 rpm and operates due to power and shading constraints with its spin axis pointing less than 10° away from the Sun. The line-of-sight of its telescope is positioned at an angle of 85° to the spin axis and the instruments scan a circular sector of the celestial sphere once per spacecraft revolution. The solar array is on the bottom of the S/C. The spacecraft and its attitude constraints are shown in Fig. 6. Together with L2, Planck rotates around the Sun and the spacecraft spin axis is rotated with regular small maneuvers at the same rate in order to remain Sun pointed. To obtain full sky coverage, the spin axis is periodically pointed out of the ecliptic plane. This so called 'Scanning-Law' leads to small accelerations which are taken into account as external accelerations in the computation of the long term orbit.

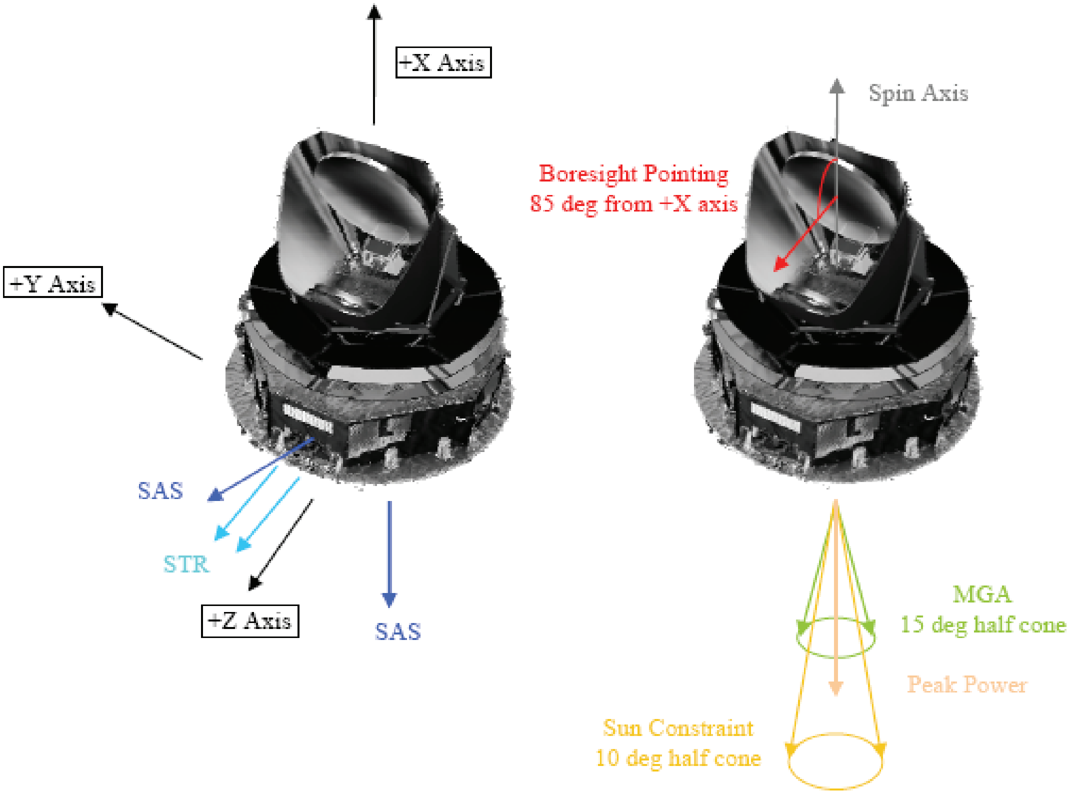

Fig. 6. Planck Attitude Constraints. Source of original image: ESA/Planck (D. Ducros)

4.5. Constraints

Due to power and shading constraints Planck's spin axis needs to be pointing less than 10° away from the Sun. During LEOP it was constrained to be (anti-) Sun pointing. In science operations it is fixed such that slews wrt. the scanning law are avoided.

A series of three maneuvers had been foreseen to achieve within 50 days after separation a small Lissajous orbit which satisfies communication and shading constraints for a lifetime of 690 days. The size of the orbit is constrained such that the Sun-Spacecraft-Earth angle remains below 15-degree. In addition, the spacecraft is only compatible with 154E6 km maximum distance to Sun.

The bore sights of the Star trackers are 85 degree wrt. the +X-axis. Their field of view of about 20 deg leads to an exclusion range of 75 to 115 deg for the Sun-Probe-Moon angle. This is a serious constraint because the direction of the spin-axes changes only slowly. In effect, the planned time of the Day-1 maneuver was selected such that there were 3 hours delay between end of Star tracker blinding by the moon and the start of the maneuver.

As for Herschel, no eclipses by the Earth may occur during transfer and science phases and no eclipses by the Moon during the transfer phase.

4.6. Maneuver modeling

Planck is equipped with twelve 20N thrusters and four 1N thrusters, arranged in two independently operable branches of eight thrusters each (six 20N thrusters and two 1N thrusters), where only the 20N thrusters are relevant for maneuver optimization. The naming and thrust direction of the 20N thruster pairs is sketched in Fig. 7, showing the projection of the thrust directions on a common plane. Their typical duty cycle is set to 10% (during LEOP) of the rotation period and the thrusters of each pair are operated together. The ‘Upper’ thrusters can be operated twice per cycle, such that sunward maneuvers, e.g. along the spin axis are possible. The optimizer therefore handles this pair as two effective thrusters ‘Up1’ and ‘Up2’. Each maneuver direction w.r.t. the S/C is achieved by super positioning the thrust of two thruster pairs in the sectors down-flat, flat-up1, or up1-up2. The resulting geometric composition and cycling losses lead to maneuver cost penalties which are shown in Fig. 8. The corresponding maneuver efficiencies are shown in Fig. 9. The peaks in this curve correspond to the pure thrust directions up (~0.81), flat (~0.99), and down (~1.0).

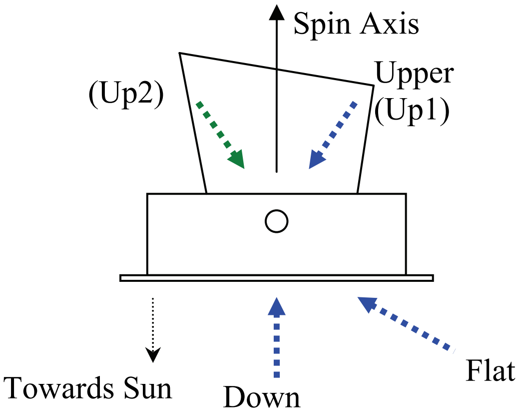

Fig. 7. Planck thrust directions

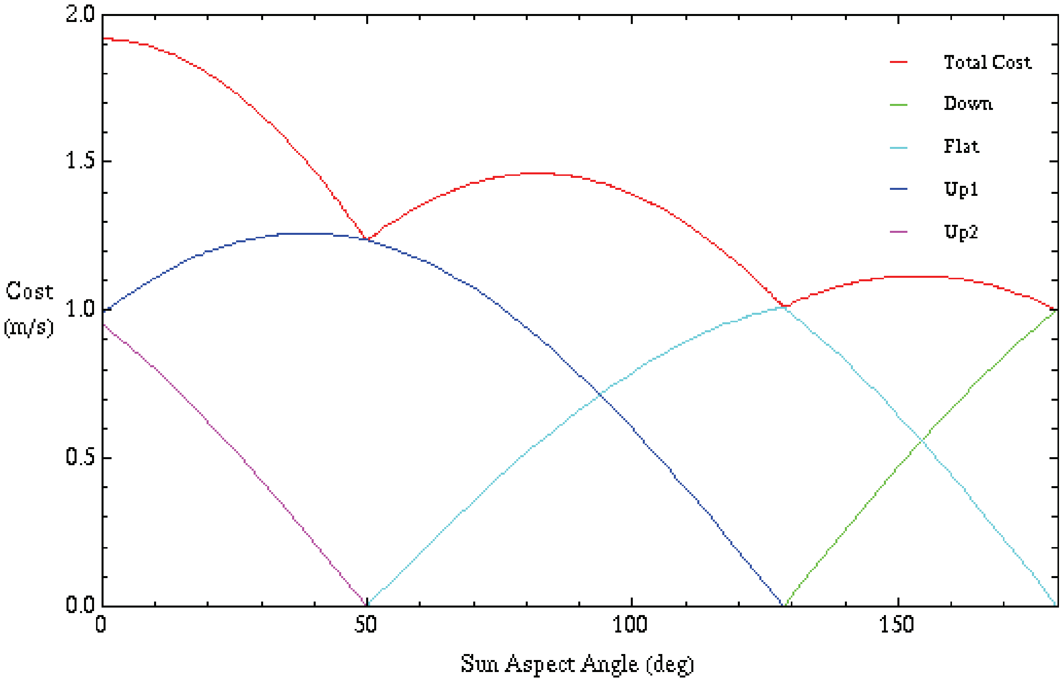

Fig. 8. Planck maneuver cost penalty caused by decomposition and cycling losses for a maneuver of 1 m/s as function of aspect angle between delta-V and Spacecraft-Sun direction

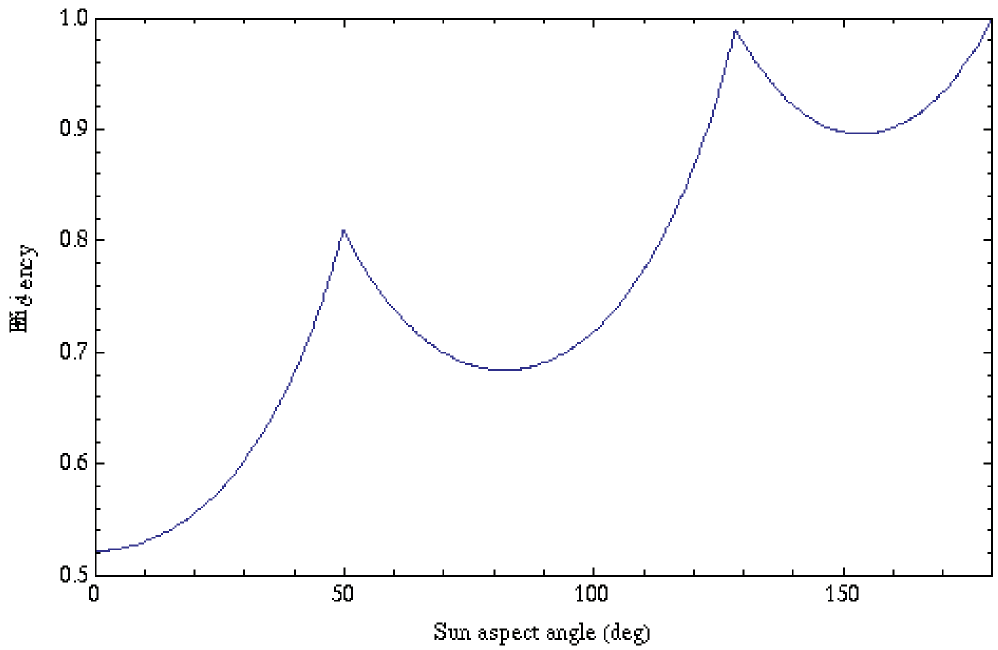

Fig. 9. Planck maneuver efficiency

The optimizer controls the thrust direction by pointing of the spin-axis (fixed/constrained to Sun-S/C direction at begin of maneuver), an azimuth angle of the Z-axis wrt. to the ecliptic north pole (to control a common plane of all (effective) thruster directions, which contains the spin axis), and a scaling factor for force and mass flow of each (effective) thruster which controls the aspect angle of the thrust wrt. spin axis. Constraints enforce these scaling factors to be between 0 and 1. Manual care needs to be taken that at least one but not more than two effective thruster pairs get the scaling factor 1.0 and that all others are zero. Usually this is done by obtaining first the best thruster combination with all four factors left free and then subsequently re-optimizing with the biggest factor forced to be 1.0 in case it has a smaller value.

5. HERSCHEL AND PLANCK COST FUNCTIONS

The cost functions used for optimization differ between the two spacecrafts. For Herschel the propagated mass state also contains the loss of mass by the helium venting, while maneuvers are computed such that only one of the two thrusters of a given branch is used. Therefore the accumulated delta-V magnitude (summed up norms of accelerations produced by the RCS) is used as cost function to be minimized. For Planck the loss of mass by venting is small and therefore neglected in the optimization. There is only one common delta-V state propagated for all effective thrusters. The integrated delta-V therefore does not reflect the dependence of the thruster efficiency for different Sun aspect angle directions, where as the expelled fuel mass does. Therefore for Planck the propagated total mass of the spacecraft is used as a cost function to be maximized.

6. HERSCHEL OPERATIONAL RESULTS

6.7. Launch/Separation

The separation took place 2009-05-14T13:37:54.897Z UTC. ESOC orbit determination confirmed that the separation was nominal, thus all orbital parameters were within the 1 sigma levels of the pre-launch dispersion covariance matrix. The most important orbital parameter, the semi-major axis, was 10200 km higher than nominal, which corresponds to the level of 0.45 sigma. The slightly higher performance led to a reduction of the Day-1 maneuver from nominal 11.7 to 8.7 m/s.

6.8. Maneuvers

One deterministic maneuver was foreseen to achieve Herschel's operational Lissajous orbit. It had to be as early as possible after separation and consolidated orbit determination for fuel efficiency. This 'Day-1 Maneuver' accounts for compensation of the perigee velocity variation, increasing the semi-major axis depending on the day within the launch window, and for removal of the launcher dispersion. A delta-V of 100 m/s (rounded) had been allocated, but only about 9.7 m/s were required, including the Touch-Up maneuver scheduled 3 days later, but not accounting for losses by attitude corrections. Table 1 shows the Day-1 maneuver, its Touch-Up, and the first three executed orbit maintenance maneuvers and their performances. The size of the Day-1 maneuver depended linearly on the execution day with an increase of about 2.2 m/s per day of delay.

The Herschel maneuver (4) performed on 24/06/2009 had a nominal magnitude of 18.55 cm/s. The orbit determination could not give reliable estimates of the individual maneuver performance mainly because of 3 Reaction Wheel Biases (RWB) before, that were very close in time, and where one had a delta-V magnitude of more than 1 cm/s. The estimated overall effect on the orbit from the maneuver and the 3 RWBs shows a difference to what was anticipated of -8 % in magnitude and 8 deg in direction. This is an example how significant the effects of the RWBs are on the orbit and its maintenance.

In fact, perturbations produced by RWBs were unexpectedly high at begin of the mission. In order to correct their orbit perturbations as early as possible, correction maneuvers were scheduled every two weeks. After a software update on July 2009, the method to execute RWBs was changed and their perturbations are expected to be smaller. Maneuver slots then were set every 4 weeks.

Table 1. Herschel maneuver performance

Num	**Start Date**	**Optmisation**	**Performance**		**Duration**	**Thruster**	**Purpose**
	UTC	DeltaV [m/s]	DeltaV [%]	Direction [deg]			
1	2009-05-15T15:16:26	8.691	+3.7	4.5	22 min	A1	Launch Window + Launch Dispersion correction
2	2009-05-18T18:10:35	0.995	+1.7	1.1	165 s	A2	Touch-up
3	2009-06-10T13:29:35	0.732	+1.0	3.1	136 s	A1	Orbit Maintenance
4	2009-06-24T07:45:35	0.186	-8.0±x	8.0±x	35 s	A1	Orbit Maintenance
5	2009-07-17T12:30:02	0.422	+0.2	1.4	84 s	A1	Orbit Maintenance

6.9. Fuel Budget and Propellant Situation

Table 2 shows the contributions which have been allocated for Herschel before launch and the operational results. The delta-V contributions in column 2 cover geometric decomposition as well as other losses, where the part of the geometric decomposition loss is 90%. The effective delta-V available for optimization is therefore slightly higher by a factor of 1/0.9. The fuel consumption for the first orbit correction includes the propellant for the Day-1 maneuver (1) and the Touch-Up (2). Fortunately the launch took place in a season where the maximum allowed delta-V is not an active constraint of the launch window. Depending on time of day and launcher dispersion the delta-V for the first orbit correction could have been up to 70 m/s.

The total fuel consumption from separation to end of the Touch-Up maneuver is 20.27 kg including the contribution for attitude control. The mass consumption for delta-V maneuvers after the Touch-Up until end of the Orbit Maintenance maneuver (5) on 2009-07-17 accumulates to 1.81 kg and the delta-Vs to 1.34 m/s. Maneuver locations in Fig. 2 indicate that these numbers can be compared to the allocations available for transfer navigation, although strictly speaking, there is no transfer to the operational orbit for Herschel after the Touch-up maneuver,. The total propellant consumption (including reaction wheel biasing and pointing slews) accumulates to 6.97 kg, meaning that 5.16 kg have been used for attitude corrections within about 88 days. Extrapolating this number to one year gives 21.46 kg, which is already more than the budget available for attitude control during the full mission. Results from extrapolating the (bracketed) numbers for delta-V and fuel consumption of delta-V maneuvers for 4.5 years mission duration also overshoot allocations for orbit maintenance. These results show again the value of the already mentioned software update for reduction of the Reaction Wheel Biases.

The mass budget available for first orbit correction, transfer navigation, orbit maintenance and attitude control adds to 217.04 kg plus 6.5 kg extra load, while 27.24 kg have been used overall until end of maneuver (5). This leaves 46.19 kg per year for the remaining mission duration of about 4.25 years. This number is much bigger than the total allocation for attitude control and orbit maintenance of 10.72 kg per year for the (extended) mission of 4.5 years.

Table 2. Herschel Fuel Budget

Contribution	**Delta-V Allocation [m/s]**	**Maneuver Efficiency**	**Delta-V effective [m/s]**	**Propellant Allocation [kg]**	**Delta-V performed [m/s]**	**Propellant Consumption [kg]**
First orbit correction = Compensation for perigee velocity variation + Removal of launcher dispersion	91	86%	101.11	160.150	10.02	14.81
Transfer navigation	5	86%	5.57	8.623	(1.34)	(1.81)
Orbit maintenance for mission lifetime including 39% mass margin	13.5	96%	15.00	27.257		
Attitude Control (RW biasing)				21.000		
Three Sun Acquisition and Sun Acquisition Safe Modes and the corresponding orbit recoveries				30.336		

6.10. Helium venting

Out-gassing of the coolant helium takes place through one big and two small nozzles located on the anti-sunward side of the spacecraft. Especially the force direction of the two small nozzles is such that the venting force counteracts the solar radiation pressure torque on the S/C. The big nozzle was switched off on 2009-06-08. The force exercised by the big and the small nozzles was taken into account in the optimizations until the switch-off. It contributed a delta-V penalty of 0.907 m/s. The maximum mass flow was 0.123e-05 kg/s. After switch-off the helium is vented only via the two small nozzles until end of the mission. In optimizations their force is neglected, only a small mass flow of 2.205e-06 kg/s is taken into account for the update of the mass state.

7. PLANCK OPERATIONAL RESULTS

7.11. Separation

The separation took place 2009-05-14T13:40:25.233Z UTC. The initial state was confirmed to be nominal. The semi major axis was 9700 km higher than nominal, which corresponds to the level of 0.45 sigma in the pre-launch dispersion covariance matrix. In contrast to Herschel, this led to an increase of the essentially retrograde correction maneuver from 10.0 to 14.4 m/s, because Planck required for the transfer to its Lissajous orbit a lower apogee radius than Herschel and the launcher target apogee radius had been selected to balance the propellant budget between both missions.

7.12. Maneuvers

Planck was supposed to be inserted on its Lissajous orbit by three deterministic maneuvers: A Day-1 maneuver (1a) to correct launcher dispersion errors and the seasonal compensation for perigee velocity variation, and two maneuvers (‘Mid-Course’, 2a and ‘Injection’, 3a) for the insertion itself. Each of these maneuvers had an associated touch-up slot (*b), where the latter two became deterministic by intentional maneuver splitting during operations. Table 3 shows the executed maneuvers and their performance. For the given launch date and time a delta-V up to 80 m/s could be expected for the Day-1 maneuver.

Table 3. Planck Maneuvers

Name	**Start Date**	**Optimization**	**Performance**		**Duration**	**Thruster**	**Purpose**
	UTC	**DeltaV [m/s]**	**DeltaV [%]**	**Direction [deg]**			
1a	2009-05-15T20:01:05	14.35	+0.9	1.3	2h 34min	up	LW+LDC
2a	2009-06-05T17:28:00	153.66	+1.3	0.4	45h 39min	flat	Mid-Course
2b	2009-06-17T16:46:00	11.78	+6.9	0.7	180 min	flat	Touch-Up
3a	2009-07-02T11:15:00	58.80	+1.9	2.2	15h 18 min	flat	Injection
3b	2009-07-15T11:00:00	0.45	+7.0	<1.0	7 min	down	Touch-Up

Maneuver 1a grew from nominally 10 m/s to 14.35 m/s because of the launcher over performance mentioned above. A touch-up maneuver (1b) was not necessary because the optimization showed that maneuver errors were absorbed by the Mid-Course (2a) and Injection maneuver (3a). As can be seen in Fig. 10, the orbit of Planck is very sensitive to this first maneuver. While for a delay up to 10 days the delta-V of maneuver 1a grows approximately linear, the total mission delta-V shows for delays of more than 5 days an exponential growth.

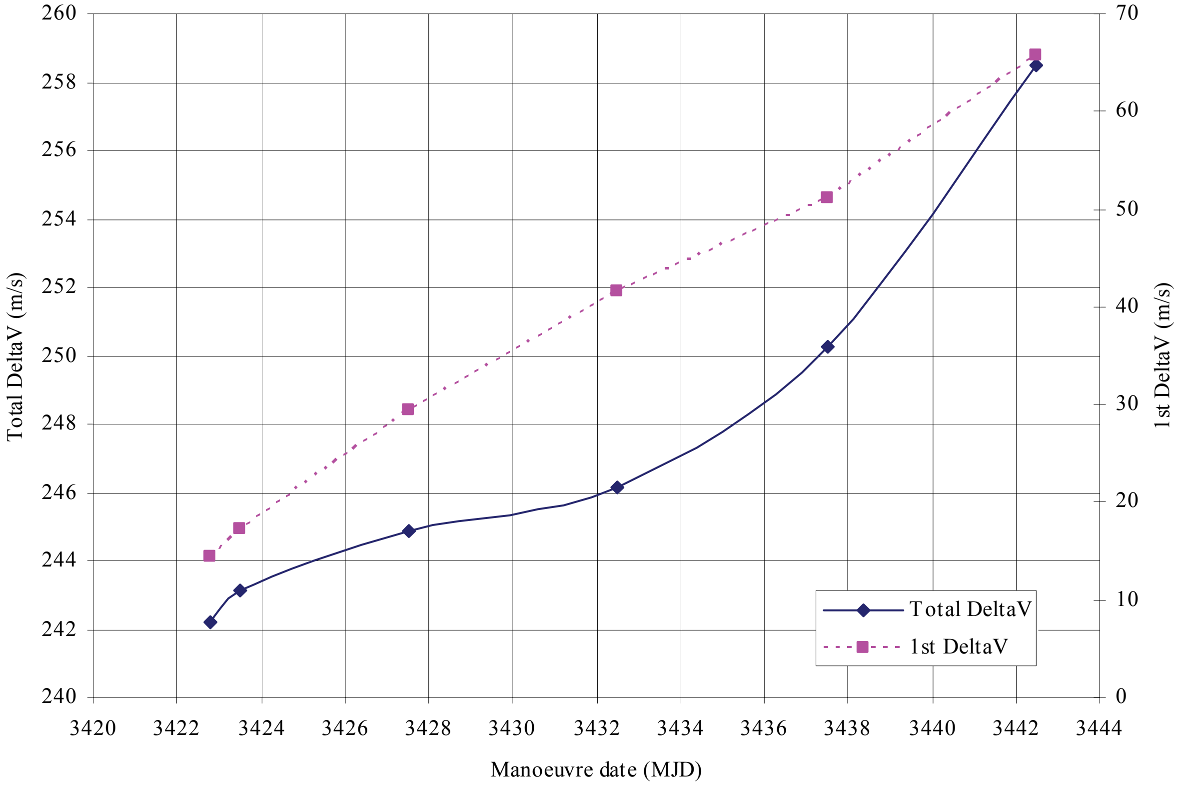

Fig. 10. Planck: Delta-V of maneuver 1a and total mission delta-V in case of maneuver delay

The penalty for an over-performance of the Mid-Course maneuver (2a) was much higher than for an under-performance, see Fig. 11. The uncertainty in delta-V of the Mid-Course maneuver was at 3.5%. Therefore the mid-course maneuver was consciously planned with an under-performance of 3.5% wrt. the optimal delta-V of 159.222 m/s. During the Mid-Course maneuver the attitude thrusters were fired once every 2 revolutions. This caused the maneuver duration to be much higher than the prediction and a shift of the central maneuver time by nearly half a day. As consequence the Touch-Up maneuver (2b) increased from planned 9.5 m/s to 11.78 m/s while the prediction of the insertion maneuver (3a) was reduced from 64.25 to 61.38 m/s, giving a penalty of 1.27 m/s.

The touch-up maneuver (3b) also was more sensitive to over-performance of the injection maneuver (3a) than to under-performance, see Fig. 11 again. The injection maneuver therefore was planned with an underperformance of 3% wrt. to the optimal delta-V of the injection maneuver. This value was a compromise between the risk of over-performance and the desire to keep the delta-V of the following touch-up maneuver (3b) at a small value such that another touch-up maneuver was not required before availability of the first maneuver slot in science operations.

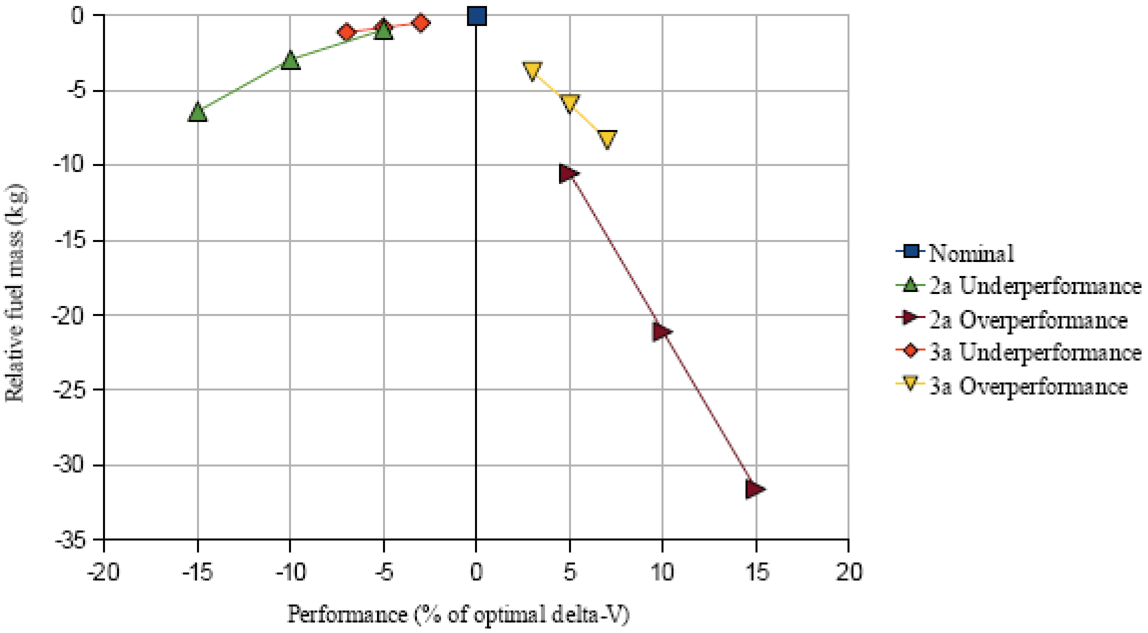

Fig 11. Change of fuel mass used for remaining maneuvers in case of under / overperformance (optimal delta-V +/- x %, maneuver direction kept fix) of midcourse (2a) or injection maneuver (3a)

7.13. Fuel Budget and Propellant Situation

The fuel budget allowed a Delta-V of 420 m/s for all maneuvers up to injection + 2 days. 20 m/s of these are allocated for touch-up maneuvers, leaving 400 m/s effective delta-V for the transfer optimization as used for the launch window calculations. The reserve for the touch-up maneuvers is meant to correct for the error introduced by not being able to predict the duration of the first maneuver because of autonomous attitude correction of the onboard controller, for a further cruise navigation maneuver, and for a first touch-up after the final orbit insertion maneuver. Additional contributions are included for orbit maintenance and attitude control. Table 4 summarizes the allocated contributions, their corresponding fuel masses and the performed / consumed contributions until orbit insertion.

Table 4. Planck Fuel Budget

Contribution	Delta-V Allocation [m/s]	Maneuver Efficiency	Propellant Allocation [kg]	Delta-V performed [m/s]	Propellant Consumption [kg]
Effective delta-V to orbit insertion + 2 days	420.0	100%	327.879	243.018	211.312
Orbit maintenance for mission lifetime	2.5	58%	4.173		
Orbit maintenance due to attitude control	2.0	58%	3.331		
Attitude Control	6.5	98%	7.691		1.14 until end 06/2009
Contribution for 3 times 7 days in survival mode analog to Herschel			1.050		

The total propellant used for orbit control maneuvers from launch to Insertion is 211.312 kg. This figure is based on fuel bookkeeping computed from the actual thruster pulses performed during the maneuver. After launch (i.e. already taking into account the launcher performance) the propellant needed for achieving the target orbit was coarsely assessed to 201 kg. The difference of roughly 5% between predicted and actual was not unexpected, as for prediction ideal performance of maneuvers was considered, without penalties for attitude control during delta-V and inaccuracies in the implementation of the maneuvers on-board.

The propellant consumption for attitude control outside delta-V maneuvers since launch accumulates to 1.14 kg up to end of June 2009. This results in a figure of about 0.6 kg/month. This figure, however, cannot be extrapolated for the future, since it is mainly driven by the large attitude slews performed during S/C commissioning. The propellant consumption to just follow the nominal scanning law will be much lower.

More propellant has been loaded on Planck than was required, leading to an additional margin of 28 m/s on top of the budget above. Starting from a load of 384.9 kg, excluding a small amount of 1.502 kg inaccessible propellant and the survival allocation, leaves 171.036 kg propellant remaining after insertion. This is an estimate where the accuracy is driven by the accuracy of the ground models for thruster propellant consumption. The system budget foresees overall 15.195 kg propellant for attitude control and orbit maintenance in the routine orbit for 2.5 years (extended) lifetime. While a figure for the actual average propellant consumption in routine operations is not available at time of writing, it is clear that propellant will not be a lifetime limiting factor. Even under the assumption that up to 70 kg of the propellant reserve is consumed to perform a change to a 10 degree (Sun-S/C-Earth angle) orbit as shown in the studies below, the remaining propellant would be enough to perform routine operations far beyond the nominal lifetime. Also for the case the mission should be extended beyond 2014 enough propellant should be available to perform an eclipse avoidance maneuver as shown below.

7.14. Change from 15 to 10 deg orbit

For particular cases of the 15 deg (Sun-S/C-Earth angle) orbits there is the possibility that moon-light impinges on the upper edge of Plank's primary reflector. Shortly before launch therefore the Planck project scientist requested to change the orbit amplitude towards a 10 deg orbit. Because of the risks involved in changing the planning and all setups at this late stage, the request was not fulfilled. Instead it was decided to continue with a 15 deg orbit as planned until orbit insertion and to study the possibility of a change thereafter.

Four cases have been analyzed for transfer orbits between the current operational 15 degree Planck orbit and Lissajous orbits with a size of 10 deg. Each of these transfers is achieved by a pair of maneuvers. The time of the first maneuver has been set at approximately Insertion + 2 months (Case 1), Insertion + 4 moths (Case 2), Insertion + 6 months (Case3) and Insertion + 8 months (Case4). The second maneuver in the pair has been left free. We define Insertion here as the time of the main part of the Insertion maneuver (3a), despite the fact that a small touch up maneuver was required to put the S/C formally in its target orbit. Strategies with later maneuvers are also possible. Maneuver details for the study cases are provided in Table 5.

Despite the fact that the cases 1, 2, and 3 have first maneuvers at different times, the arrival maneuver is approximately at the same time for all of them. The orbital geometry is also similar for the first three cases. In case 4 the optimizer chose the 1st maneuver to have zero size, hence resulting in a one maneuver strategy. This strategy has the smallest penalty and operationally also has the lowest risk.

Table 5. Summary delta-V and cost for study cases.

		Case 1	**Case 2**	**Case3**	**Case 4**
OCM1	**Epoch (UTC)**	2009-09-05T00:32:02	2009-11-02T23:58:54	2010-01-01T23:58:54	2010-03-02T23:58:54
	Delta-V (m/s)	12.38	0.95	13.30	0.00
OCM2	**Epoch (UTC)**	2010-01-27T08:57:57	2010-01-29T12:53:54	2010-02-03T12:00:43	2010-04-30T22:57:36
	Delta-V (m/s)	53.03	74.71	56.82	50.61
Overall	**Delta-V (m/s)**	65.42	75.67	69.12	50.61
	Delta Mass (kg)	-51.25	-62.96	-56.96	-56.05
	Earth Eclipses	2	1	2	2
	Moon Eclipses	4	7	11	6

Figure 12 shows the evolution of the Sun-S/C-Earth angle for the different cases, where CASE 0 is the nominal orbit. Note that the 10 degree condition has not been imposed beyond Insertion +960 days (similarly the 15 degree condition is also not imposed beyond this time for the nominal orbit). The case 1-3 nearly overlap.

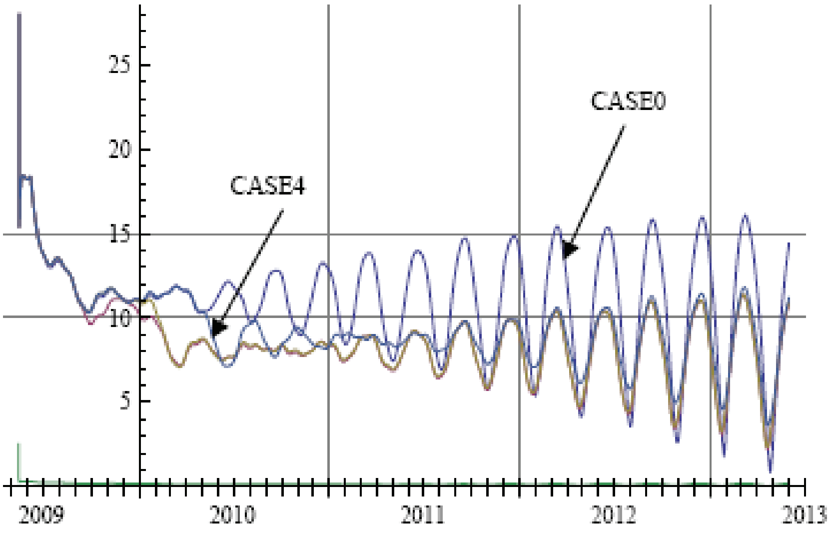

Fig. 12. Evolution of the Sun-S/C-Earth Angle for different cases

7.15. Avoidance of Earth eclipses

On Lissajous orbits around L2 at some point the S/C will enter the shadow of the Earth (eclipse) for an extended period of several days, but the S/C design is not compatible with such eclipse condition. Therefore eclipse avoidance strategies are desired. The first eclipse by Earth occurs mid 2013 for the nominal 15 deg orbit. For all the 10 deg orbits studied the first eclipse occurs between beginning 2014 and mid 2014.

A preliminary analysis has been performed by Carlos Casas to check what would be the cost of an eclipse avoidance maneuver. For instance for case 2 a maneuver of 7 m/s (7 kg) could be found which results in eclipse avoidance (next eclipse by the Earth is then 6 years later). Fig. 13 shows the YZ projection of the trajectory for this case. The trajectory is shown in blue up to the time of the avoidance maneuver (2014-02-14). The continuation of the trajectory without maneuver is shown in red. It is clear that this trajectory enters the Earth shadow (indicated by the small disk at the centre of the drawing). The trajectory after the eclipse avoidance maneuver is shown in green.

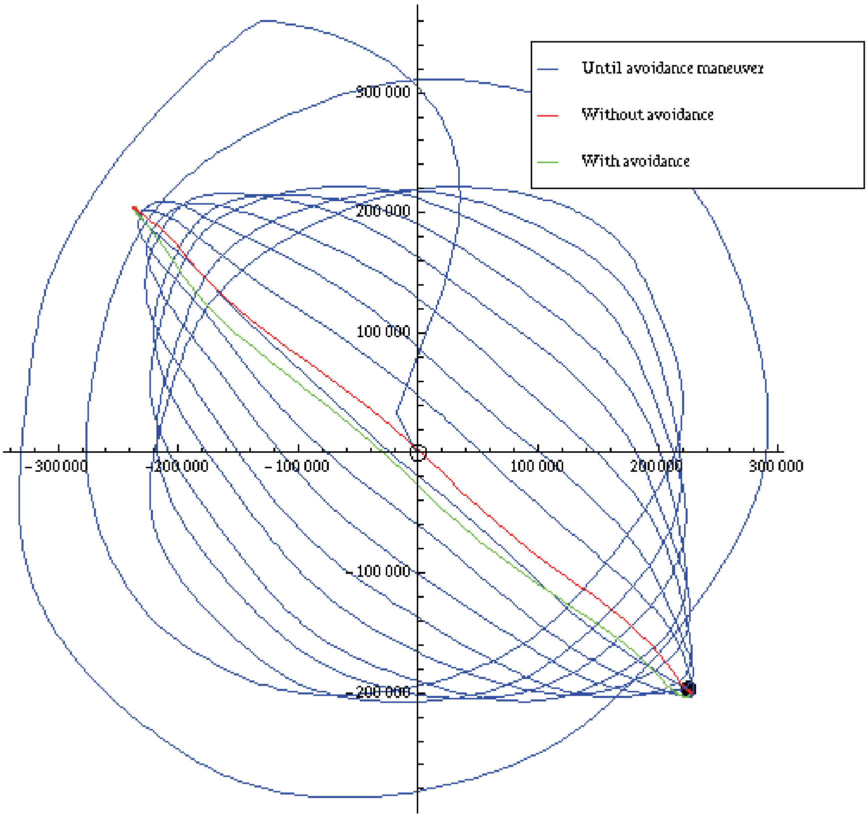

Fig. 13. Earth eclipse avoidance. Optimization by C. Casas

7.16. Moon eclipses

Moon eclipses were found in all cases studied above and have been indicated in Table 5. The eclipse durations were always below 8 hours and their depth (percentage of the Sun disk shadowed by the Moon) was in extreme cases 11%. The orbit maintenance strategy for Planck does not ensure flying accurately on a target orbit, but just staying in the neighborhood of an orbit. Therefore the data obtained for all cases above are statistically relevant in terms of maximum duration and depth, but it can neither be claimed that a given eclipse will have the duration and the depth predicted now, nor that the same number of eclipses will occur.

8. CONCLUSION

Operational orbits for Herschel and for Planck have been properly achieved. Due to the favorable launch date, the precise launch, and the relatively accurate orbit insertion maneuvers, there seem to be enough fuel reserves available on the S/Cs to complete and to extend both missions. Even under the assumption that up to 70 kg of the propellant reserve is consumed to perform for Planck a change to a 10 degree (Sun-S/C-Earth angle) orbit, the remaining propellant would be enough to perform routine operations far beyond the nominal lifetime. Also for the case the Planck mission is extended beyond 2014 enough propellant should be available to perform an eclipse avoidance maneuver as shown.

◄ BACK TO SESSION DETAILED CONTENTS ◄ BACK TO HIGHER LEVEL CONTENTS