ORBIT DETERMINATION OF THE PLANCK SATELLITE

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ABSTRACT

The topic of this note is the orbit determination of the Planck spacecraft with emphasis on the effects of the satellite spin on the tracking data and on the orbit determination residuals and accuracy. An algorithm to remove the effects of the spin in the Doppler is developed and its performance is discussed. Operational results during LEOP, transfer and routine operations are presented.

1 INTRODUCTION

Planck is an ESA mission dedicated to observing the anisotropies of the cosmic microwave background. With Herschel, they are the first European missions to Sun-Earth Libration point L2. They were launched together by an Ariane V on May 14, 2009 to Lissajous orbits around L2.

1.1 Spacecraft

Planck is spin-stabilized and comprises two modules: the service module and the payload module. The service module handles the attitude and orbit control with two 1 N thrusters and six 20 N thrusters. Three Low Gain Antennas (LGA) and one Medium Gain Antenna (MGA) are mounted on this service module, all of which are located significantly off the spin axis. The payload module is mounted on top of the service module on the +X side of the spacecraft (see Fig. 1). It contains a telescope and a baffling system, two cooled instruments and a shield that isolates them from the service module.

The payload cooling system uses helium that is slowly vented out of the spacecraft. This venting is assumed to generate a null net acceleration since the venting occurs in two opposite directions and, moreover, these directions are almost orthogonal to the spin axis so that any residual net effect should average out over one spin period.

Planck is spinning at a nominal rate of one revolution per minute around its main axis of inertia which is approximately the spacecraft body frame X axis. The spacecraft may also exhibit a small nutation motion that is slowly and passively damped by the friction in the tanks. Both the rotation rate error and the nutation motion are actively corrected when they reach certain limits that depend on the spacecraft mode: the maximum permitted nutation angle is 4.64° and the maximum deviation from the nominal spin period is 3 seconds.

The spacecraft attitude is such that the Sun always lies within 10° of the -X direction and, because of the geometry, only one side of the spacecraft, the bottom side of the service module, can directly receive sunlight. This stringent attitude constraint implies that Orbit Control Maneuvers (OCM) may require the simultaneous firing of differently aligned thrusters which means the fuel efficiency is highly dependant on the maneuver direction.

The attitude is also constrained by the fact that the Earth has to be kept within 15° of the -X direction
to ensure a sufficient link budget for the MGA. Combined with the Sun direction constraint, this
implies that the spacecraft must follow a low amplitude Lissajous orbit.

1.2 Orbit determination system

The Planck orbit determination system uses the generic interplanetary orbit determination software
developed for Rosetta, Mars Express, Venus Express and Smart-1 [1]. Planck is the first spinning
spacecraft to be supported by this software.

During LEOP, two-way Doppler and range in X-band were acquired from ESA's 35 m deep space
antennas in New Norcia and Cebreros as well as 15 m antennas in Perth, Kourou and Maspalomas
and, for the first pass after launch only, angular measurements were recorded by the Perth
autotracking system. During transfer and in orbit around L2, only the deep space antennas in New
Norcia and, less often, in Cebreros are used.

The dynamic model includes:

- gravity of the Sun, the planets and the Moon including relativistic effects for the Sun.
- gravity field expansion for the Earth (only during LEOP).
- a simple flat plate model for Solar Radiation Pressure (SRP) assuming the spacecraft X axis to be
  exactly aligned with the direction Sun-spacecraft with nominal acceleration of $4.18 \times 10^{-8}$ m/s²
  at a distance of one astronomical unit.
- impulsive and finite-duration maneuvers.

2 EFFECTS OF THE SPIN ON THE TRACKING DATA

The spin of the spacecraft affects the tracking data in two ways:

- the radio-waves are circularly polarized and the rate at which the electric and magnetic vectors
at a fixed point along the line of sight rotate around the propagation direction differs in the spacecraft rotating frame and the inertial frame by an amount equal to the spacecraft spin rate. This introduces a shift in the Doppler data that is proportional to the spin-rate but independent of the position of the antenna on the satellite.

- the motion of the spacecraft antenna around the center of mass due to the spin superimposes a small amplitude sinusoid (“ripple”) in the Doppler and ranging data.

### 2.1 Constant shift in the Doppler due to the rotation of the antenna

This effect is fully described in [2].

The ground station is transmitting right hand circularly polarized waves. As seen from Earth the spacecraft is rotating in the clockwise direction. Because of the spin, the received frequency in the rotating frame linked to the spacecraft is lowered by the spin frequency. This uplink shift is to be multiplied by the transponder ratio. Because the spacecraft antenna is also transmitting right hand side polarized waves but in the opposite direction, the downlink frequency is again lowered by the same amount when switching from spacecraft frame to inertial frame (here we can neglect the ground station rotation with respect to the inertial frame since it is much slower).

Thus the two-way Doppler shift due to the spin is:

\[
\Delta_v = -f_s \cdot (1+k)
\]

where \( f_s \) is the spin frequency and \( k \) the transponder ratio.

The equivalent two way-range-rate corresponding to this Doppler shift is:

\[
2 \cdot \dot{r}_{eq} = \frac{f_s \cdot (1+k)}{f_r} \cdot c
\]

where \( f_r \) is the nominal frequency at reception and \( c \) the speed of light.

For Planck, the equivalent two-way range-rate is about \(+1.3\text{mm/s}\) for the nominal spin period of 60 seconds.

This is much larger than the typical Doppler residuals of the orbit determination process and thus has to be corrected.

In this simplified reasoning we have neglected the fact that, when the actual range-rate is non-zero, the measured range-rate is not only the sum of the actual range-rate and the constant shift due to the spin, but there is also a smaller coupled term.

### 2.2 Doppler and ranging ripple

Assuming a zero nutation angle, the velocity of the antenna in a frame centered on the spacecraft's center of mass with inertially fixed axes is:

\[
V_0 = \frac{2 \cdot \pi \cdot d}{T}
\]

where \( T \) is the spin period and \( d \) the distance of the antenna from the spin axis.

Projected onto the line of sight, this velocity is (neglecting the small motion of the line of sight due to the spin):

\[
v(t) = V_0 \cdot \sin(\theta(t)) \cdot \sin(\frac{2 \cdot \pi \cdot t}{T} + \phi)
\]

where \( t \) is time, \( \phi \) a phase angle and \( \theta(t) \) the angle between the line of sight and the spin
axis. The change in the downlink light-time over a few spin periods is small compared to the spin period and thus, the downlink light time can be assumed to be constant over short periods of time and absorbed into $\phi$ so that $t$ is the ground reception time.

Thus in the two-way range-rate data, a ripple of period $T$ and amplitude $2 \cdot V_0 \cdot \sin(\theta(t))$ is superimposed on the range-rate due to the motion of the center of mass relative to the station.

Likewise, in the two-way ranging data, a ripple of period $T$ and amplitude $2 \cdot d \cdot \sin(\theta(t))$ is superimposed on the range due to the distance of the center of mass from the station.

For a nominal spin period of 60 seconds, a station aspect angle of 15º and an antenna to spin axis distance of 1133 mm (corresponding to the MGA), the amplitudes are about 60 mm/s and 600 mm, respectively.

The effects on the range are within the size of acceptable orbit determination residuals, but the effects on the range-rate are not.

The tracking system at the ground station actually measures integrated two-way Doppler, i.e. two-way differenced ranging:

$$2 \cdot [r(t) - r(t_0)] = 2 \cdot \int_{t_0}^{t} v(t) \, dt$$

(5)

where $t_0$ is the time when the Doppler counter starts.

Let us assume here that $\theta(t) = \theta$ is constant (a valid approximation over short periods of time for a distant spacecraft since the station aspect angle varies slowly except during attitude re-orientation maneuvers). From Eq. 4 and Eq. 5, we get:

$$2 \cdot [r(t) - r(t_0)] = -\frac{V_0 \cdot \sin(\theta) \cdot T}{\pi} \cdot \cos(\frac{\pi \cdot t}{T} + \phi) + K$$

(6)

where $K$ is a constant.

During the pre-processing stage, the two-way integrated range-rate is sampled every sixty seconds (the Doppler compression time) and the difference between adjacent samples is computed to generate two-way range differences over the compression time $\Delta t$:

$$2 \cdot \Delta R(t) = 2 \cdot [r(t + \Delta t/2) - r(t - \Delta t/2)] = 2 \cdot \int_{t - \Delta t/2}^{t + \Delta t/2} v(t) \, dt$$

(7)

Thus:

$$2 \cdot \Delta R(t) = \frac{2 \cdot V_0 \cdot \sin(\theta) \cdot T}{\pi} \cdot \sin(\frac{\pi \cdot t}{T} + \phi) \cdot \sin(\frac{2 \cdot \pi \cdot \Delta t/2}{T})$$

(8)

It follows that the equivalent two way range-rate averaged over the compression time is:

$$\frac{2 \cdot \Delta R(t)}{\Delta t} = (2 \cdot v(t)) \cdot sinc(\frac{\pi \cdot \Delta t}{T})$$

(9)

where the cardinal sine function is defined as:

$$sinc(x) = \frac{\sin(x)}{x}, x \neq 0$$

$$sinc(0) = 1$$

(10)

This factor globally decreases when the compression time increases but it also vanishes locally when the compression time approaches a non-zero multiple of the spin period.

For Planck choosing a compression time of 60 seconds, the ripple is not visible with the default spin
period. However for a spin period of 58 seconds, the amplitude of the averaged range-rate is about 3.3\% of the instantaneous range-rate amplitude. The amplitude in the averaged two-way range-rate can then easily reach 2 mm/s which is larger than the range-rate noise and thus needs to be corrected. The period of the visible signature in the residuals is not 58 seconds since according to Nyquist theorem, the sampling frequency does not permit to see periods smaller than 120 seconds. The apparent frequency is:

$$f_a = \left| n \cdot f_{\text{sampling}} - f_{\text{spin}} \right|$$  \hspace{1cm} (11)

where $n$ is an integer such that:

$$f_a < \frac{f_{\text{sampling}}}{2}$$  \hspace{1cm} (12)

For a spin period of 58 seconds and compression time of 60 seconds, the apparent period is 29 minutes. For the same reason, if range is sampled every twenty minutes, the apparent period in the range residuals signature is about 65 minutes.

For Planck, the Doppler compression time is set to 60 seconds and the range sampling period is 5 minutes. Thus with the nominal spin period, no signature should be visible in the Doppler and range residuals.

2.3 Algorithm to remove effects of the spin from the observables

The effect of the spin in the Doppler tracking data is removed during the pre-processing stage to produce the virtual Doppler tracking data of the “equivalent” non-spinning spacecraft which is suitable for the orbit determination program.

Knowing the attitude, spin phase, and orbit of the spacecraft, it is theoretically possible to compute the amplitude, period and phase of the cosine function in Eq. 6. In order to remove the ripple it would suffice to subtract this cosine function from the integrated Doppler. However, this would make the orbit determination system highly dependant on the attitude reconstruction system. In order to avoid this dependency, it was decided to estimate the parameters of the ripple from the tracking data proper in a way similar to what is done for Cluster [3].

This estimation is performed using a square root information filter on the integrated Doppler, usually acquired at a rate of one Hertz. The integrated Doppler is modelled as the sum of a cosine term (Eq. 6) and a polynomial which represents the Doppler due to the motion of the center of mass of the spacecraft relative to the station. Using $m$ consecutive measurements, we get $m$ equations:

$$M_i = (A_0 + A_1(t_i-t_0) + A_2(t_i-t_0)^2) \cdot \cos(w_0(t_i-t_0) + \lambda(t_i-t_0)^2 + \phi) + \sum_{k=1}^{N} p_k(t_i-t_0)^k + r_i$$  \hspace{1cm} (13)

where $M_i$ is the integrated Doppler observable and $r_i$ the residual at time $t_i$.

The optional terms $A_1, A_2$ allow for a varying station aspect angle.

The optional term $\lambda$ allows for a linearly varying spin frequency.

The estimator will find the parameters $((p_k)_{k=1}^{N}, A_0, A_1, A_2, w, \phi, \lambda)$ that produce a local minimum for the sum of the square of the residuals.

An initial estimate for $\phi$ is determined in a linear first stage of the estimator where the model fitted is:

$$\alpha \cdot \cos(w_0(t-t_0)) + \beta \cdot \sin(w_0(t-t_0)) + \sum_{k=1}^{N} p_{0k} \cdot (t-t_0)^k$$  \hspace{1cm} (14)
where \( w_0 \) is set to a period of 60 seconds (or exceptionally taken from the attitude prediction or reconstruction) and kept fixed.

The a priori values for \( (p_k)_{k=1}^N, A_0, A_1, A_2, w, \phi, \lambda) \) for the second stage of the estimator using the non-linear model (Eq. 13) are computed from the results of the first stage in the following manner:

\[
(p_k)_{k=1}^N = (p_{0k})_{k=1}^N, \\
A_0 = \sqrt{\alpha^2 + \beta^2}, \\
A_1 = A_2 = 0, \\
w = w_0, \\
\phi = -\text{atan2}(\beta, \alpha), \\
\lambda = 0
\]  

(15)

The a priori phase computed in the first stage is only valid locally and the span over which it is valid decreases when the absolute difference between the actual spin period and the a priori value of 60 seconds increases. Therefore the span of the data batch used in the estimation must be limited. Once the frequency has been derived from the second stage, a larger batch can be used and the second stage can be run again using the solution of the previous run as a priori values.

The first stage is usually run on a 3 minutes interval and the second stage on a 3 to 15 minutes interval. The second stage can also be configured to run several times with ever-expanding estimation intervals. Usually, the degree of the polynomial is set to 7 and \( A_2 \) and \( \lambda \) are not estimated but kept fixed to zero.

The estimated values are accepted if the following conditions are met:

- the non-linear estimator has converged before the maximum number of iterations (by default 9) has been reached: the convergence criterion is that the difference between the root mean square of the predicted residuals computed at the end of the previous iteration and the actual residuals at the end of the current iteration is less than some pre-defined value (set to 0.01 mm).
- the estimated spin frequency \( w \) is within a pre-defined interval around the a priori value (by default the period must be between 55 and 65 seconds).
- If, for a previous adjoining batch, the estimates have been accepted, then the phase and amplitude difference at the boundary between the two data batches must be within certain limits (by default 15º and 20 mm, respectively).

If the values are accepted, the spin ripple is removed from the observables:

\[
\tilde{M}_i = M_i - (A_0 + A_1(t_i - t_0) + A_2(t_i - t_0)^2) \cos (w(t_i - t_0) + \lambda) \]  

(16)

Otherwise the observables are not corrected:

\[
\tilde{M}_i = M_i
\]  

(17)

Using the estimated spin frequency (or the nominal one when the estimation has failed) the integrated Doppler shift due to the circular polarization of the radio-waves (Eq. 2) is then computed and subtracted from the observation.

\[
\tilde{M}_i = \hat{M}_i - \int_{t_0}^{t_i} \left[ \frac{f_x \cdot (1+k)}{f_r} \right] \cdot c \, dt = \hat{M}_i - \left[ \frac{c \cdot (1+k)}{2 \cdot \pi \cdot f_r} \right] \left[ w(t-t_0) + \frac{\lambda}{2} (t-t_0)^2 \right]
\]  

(18)

with \( (w, \lambda) \) replaced by \( (w_0, 0) \) when the estimation has failed.

Then the observation points used in the orbit determination are computed in the following manner:
\[
\tilde{t}_i = t_{i:p}
\]
\[
\Delta t_i = t_{(i+1):p} - t_{i:p}
\]
\[
\tilde{M}_i = (M_{(i+1):p} - \tilde{M}_{i:p}) / \Delta t_i
\]

where \( \Delta t_i \) is the compression time and the positive integer \( p \) is such that \( \Delta t_i \) is equal to the requested compression time (usually \( p=60 \) since the compression time is 60 seconds and the data rate is one Hertz). The observation time tag \( \tilde{t}_i \) is the start of the Doppler count interval and \( \tilde{M}_i \) is the corrected range-rate averaged over the count time. If \( \tilde{M}_i \) has been computed using measurements for which the estimated values were not accepted, the observation is de-weighted in the orbit determination.

### 2.4 Performance of the spin correction

Fig. 2 shows how accurately the Doppler can be modeled as the sum of a polynomial and a sinusoid with linearly varying amplitude just after launch when the station aspect angle rate of change is higher than during the rest of the mission. To assess the performance of the spin ripple estimation, its results are compared with the theoretical spin ripple computed from the reconstructed attitude data. Fig. 3 shows the comparison in terms of the spin period and Fig. 4 shows the comparison in terms of the ripple amplitude. There are some bad estimates, mostly due to thruster firings. Also a few amplitude estimates with huge unrealistic values are outside the range of the plot. A quick analysis has shown...

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**Fig. 2.** Doppler spin-induced ripple estimation shortly after launch. The amplitude of the ripple is slowly decreasing with the station aspect angle. The period of the ripple is about 58 seconds. The plot shows the presence of another periodic signal (with a period of about 5 minutes) attributed to precession of the spin axis that cannot be corrected by the model.
that worst estimates can be easily filtered out by adding an acceptance criterion limiting the size of the estimated amplitude and amplitude rate.

The algorithm often fails to provide adequate estimates if there is thruster firing during the estimation interval because the discontinuities in the Doppler data cannot be modelled by the polynomial. During OCM, the thrusters are firing for a short time (about 10% of a spin period) every (or every other) spacecraft rotation. The Doppler signal due to the thrusting then shows a strong component at a frequency equal to the spacecraft spin frequency. In that case, the amplitude of the ripple is misestimated. This is not a problem, though: for practical reasons any single “pulse” of an OCM cannot be estimated separately in the orbit determination and therefore the data during OCMs are discarded.

2.5 Effects of the precession of the spin axis

Pre-launch analyses had shown that spacecraft nutation is affecting the Doppler data by superimposing on the data several sinusoids at different frequencies that depend on the spin-rate and mass distribution. Precession of the spin axis is the cause for three frequency components:

- a component at approximately 0.2 rpm that decreases with increasing station aspect angle and is proportional to the antenna distance from the principal axis of highest inertia.
- a component at approximately 1.2 rpm that increases with the station aspect angle and is proportional to the projection of the center of mass to antenna vector onto the principal axis of highest inertia.
- a component at approximately 1.4 rpm that is barely visible for a small nutation angle.

Fig. 3. Spin period estimate. The spin period is usually very close to 60 seconds except in early LEOP and during spin-up and spin-down tests (right-side of the plot).
Periodic change in the nutation angle due to asymmetry between the smaller two principal moments of inertia is also generating ripples at other frequencies, but since Planck's mass distribution exhibits almost cylindrical symmetry, these components are negligible.

The average nutation angle during early LEOP was about 1°. A Fast Fourier Transform (FFT) of the residuals of the spin-induced ripple correction around that time is presented in Fig. 5. It shows two main frequency components at approximately 0.2 rpm and 1.2 rpm (corresponding to periods of 300 and 50 seconds, respectively). From the analysis of the residuals, it is estimated that the amplitude of the signal due to precession in the two-way range-rate compressed to sixty seconds was about 1 mm/s in early LEOP. The nutation angle is expected to be much smaller during routine operations.

Removal of the signal due to precession is challenging:

- on short estimation intervals the lower frequency component is partially absorbed into the polynomial and the frequency resolution is small.
- on longer estimation intervals the frequency stability is challenged and it is barely possible to distinguish the frequency components from the noise in a Fourier analysis of the signal.

![Graph](image)

**Fig. 4.** Doppler ripple amplitudes estimates for the stations at New Norcia and Perth. The curve is computed using the station coordinates, the reconstructed orbit, the reconstructed attitude from telemetry, the reconstructed inertia matrix and center of mass and the spacecraft antenna coordinates.
3 OPERATIONAL EXPERIENCE

3.1 Launch accuracy assessment and first orbit correction

The launcher was to deliver the spacecraft to a highly eccentric transfer orbit with an apogee radius smaller than optimal for Herschel and larger than optimal for Planck so that a slight launch overperformance (or underperformance) would be advantageous for one spacecraft and disadvantageous for the other. Each spacecraft had then to perform a correction maneuver, essentially prograde for Herschel and retrograde for Planck. These maneuvers were planned on day 2 of the mission, this being a trade-off between fuel saving and duration of the tracking data arc for the orbit determination as well as time for initial checkout activities.
Lift-off happened exactly at the planned time. Separation occurred for both spacecraft about 3.5 seconds earlier than expected.

Planck was acquired by the station at Perth within a minute of the expected time at an altitude of almost 10000 km, while Herschel was acquired at New Norcia. During the Perth pass angular measurements were recorded with the autotracking system. Later, once uplink was established, two-way Doppler and range measurements were started. At about the same time, Arianespace issued an injection accuracy assessment based on telemetry from the launcher's inertial guidance system. It showed that the launch was nominal and the orbital elements of the upper composite at the individual separation times of either spacecraft were within one sigma of the pre-launch dispersion distribution. By that time the antenna pointing errors, mainly due to the difference between nominal and actual separation time, were already well below the beam width of the station and were still decreasing as the spacecraft range increased so that it was not necessary to update the station predictions. The second pass was over Maspalomas. Towards the end of that pass, it was decided to cut off the tracking data arc for an orbit determination upon which the optimization of the OCM on day 2 would be based.

The Doppler residuals of the orbit determination exhibited a very strong signature with a spread of more than 1 cm/s when estimating only the spacecraft state. Estimating piece-wise (3 hours pieces) constant random acceleration of unconstrained direction to absorb modelling errors allowed to flatten the residuals. The maximum estimated acceleration was about ten times higher than the expected influence of the SRP. The difference in the reconstructed orbits including and not including random accelerations were within 5 km for position, 5 cm/s for velocity and 1 km for semi-major axis. The estimated state vector showed that the semi-major axis at separation was approximately 604740 km, that is about 9700 km higher than targeted, this error being at the level of 0.45 sigma of the pre-launch dispersion distribution. The launcher overperformance was slightly disadvantageous for Planck. The subsequent maneuver optimization yielded a correction maneuver of magnitude 14.4 m/s; the pre-launch expected magnitude was 10.0 m/s.

3.2 Maneuver monitoring and calibration

Five OCMs were performed during LEOP and transfer. They are presented in Table 1. During a maneuver, the thrusters are ideally fired once per satellite revolution for a short duration, each time the phase angle matches the required maneuver direction. However thruster firings trigger some attitude disturbances, such as nutation. When these disturbances are above certain limits, they must be corrected and because of the time it takes to perform this correction, one revolution is often lost to the maneuver. It was thus not unusual for the maneuvers to last almost twice their initially expected duration.

Maneuvers that occurred under ground station coverage were monitored by means of both the tracking data and the telemetry. The Doppler measurements allowed to assess the performance along the line of sight (see Fig. 6). During the mid-course maneuver whose expected duration was about 23.5 hours, it could be seen early from the Doppler that the mean acceleration was about half of its anticipated value, which implied that the maneuver would last much longer and that the error in the station predictions at the end of the maneuver would reach about 250 mdeg. The 3dB antenna beam width for the deep space ground stations is 60 mdeg in X-band, so it was decided to update the station predictions using an orbit that was propagated with half the acceleration and twice the duration of the nominal maneuver. The actual duration of the mid-course maneuver was almost 46 hours.

The calibration of a maneuver was done using a tracking data arc that spanned at least a few days before and a few days after the maneuver. The measurements taken during the maneuver were discarded. The maneuver was modelled as a constant acceleration vector acting between start and end times provided by telemetry. The nominal delta velocity vector was used to derive the a priori acceleration. The three maneuver components as well as the maneuver start time were treated as uncertain in the orbit determination. From the third maneuver onwards, the reconstruction of the
pulses from telemetry had been sufficiently tested and thus this reconstruction was used as input for the orbit determination and it was no longer necessary to estimate the time of a maneuver.

Table 1: OCM during LEOP and transfer with their nominal parameters and the estimation of their performance by orbit determination. Maneuver 1B was cancelled when it was seen that the dispersion errors of maneuver 1A could be corrected during the mid-course maneuver without any significant increase in cost. Performance factors shown here are not to be interpreted directly in terms of satellite orbit control system performance as they are relative to the magnitude computed by maneuver optimization which differs slightly from what has actually been commanded.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
<th>Date</th>
<th>Nominal duration</th>
<th>Nominal magnitude</th>
<th>Estimated magnitude</th>
<th>Performance</th>
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<td>1A</td>
<td>Day 2 maneuver</td>
<td>2009-05-15</td>
<td>~3 hours</td>
<td>14.35 m/s</td>
<td></td>
<td>100.9%</td>
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<tr>
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<td>Touch-up</td>
<td>CANCELLED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>Mid-course maneuver</td>
<td>2009-06-06</td>
<td>~24 hours</td>
<td>153.65 m/s</td>
<td></td>
<td>101.3%</td>
</tr>
<tr>
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<td>Touch-up</td>
<td>2009-06-17</td>
<td>~4 hours</td>
<td>11.78 m/s</td>
<td></td>
<td>106.9%</td>
</tr>
<tr>
<td>3A</td>
<td>Injection</td>
<td>2009-07-02</td>
<td>~15 hours</td>
<td>58.80 m/s</td>
<td></td>
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</tr>
<tr>
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</table>

3.3 Overall performance of the orbit determination

The routine orbit determination is now performed on a weekly basis using four weeks worth of tracking data: two-way Doppler (about 3 hours per day) and two-way range (about 20 minutes per day). The estimated parameters are: the spacecraft state vector at an epoch in about the middle of the tracking data arc, the SRP factor, and performance factors for the thruster firings. For both orbit and attitude control pulses, a priori information for the thruster actuations is a time tagged list of pulses generated by the attitude monitoring team from telemetry. This list is preprocessed before the orbit determination run to combine pulses that belong to the same maneuver into a single substitute maneuver at the weighted mid-time, given that the maneuver is sufficiently short and outside visibility. These substitute maneuvers are treated as impulsive by the orbit determination system. Furthermore, substitute maneuvers may be assembled into a group and calibrated with a single set of estimation parameters. Provided that there are sufficiently many observables in between, groups are calibrated separately. The estimated calibration factors are the performance of each group in three orthogonal directions: the axes of the Earth Mean Equator of epoch 2000 (EME2000) system.

The plots at the top of Fig. 7 show typical post-fit residuals. There are some noisy points in the penultimate pass. They are due to incorrect ripple amplitude estimation because the spacecraft was performing spin-up and spin-down tests around that time (see Fig. 3 and Fig. 4 at about day 80). The plots in the middle of Fig. 7 show the post-fit residuals for Doppler measurements that were not corrected for the spin-induced ripple. The residuals are acceptable except for the Doppler in the last three passes because of the non-nominal spin period around these times (zooming in would show a signature containing pieces of sinusoids whose amplitudes and periods can be derived from Eq. 9 and Eq. 11, respectively). The plots at the bottom of Fig. 7 show the post-fit residuals for Doppler tracking data that were not corrected for the spin-induced Doppler shift. Neither the ranging residuals nor the Doppler residuals are acceptable.

An assessment of the orbit determination accuracy has been done by comparing the results of successive orbit determination runs on overlapping arcs and comparing results of orbit determination runs using arcs of different lengths. From this assessment it follows that the accuracy is better than 1 km in position and 1 cm/s in velocity. The EME2000 Z components of position and velocity show the worst accuracy as can be expected for a deep space satellite.
Comparing the reconstructed orbits for the three orbit determination results whose residuals are shown in Fig. 7, it can be seen that not correcting for the ripple yields differences of less than 1 km and 1 cm/s, but not correcting for the shift yields differences of a few kilometers and a few centimeters per second.

Comparing the reconstructed orbit with predictions from an earlier orbit determination, the prediction accuracy is estimated to be 30 km in position and 5 cm/s in velocity after three weeks, without using any prediction for the net effect of the attitude control pulses and provided that there is no OCM during the prediction arc.

### 3.4 Solar radiation pressure estimates

The SRP model used in the orbit determination is very simple and it was discussed whether a more complex model should be implemented taking into account the attitude of the spacecraft and expressing the acceleration in terms of the Sun-spacecraft direction as well as the spin axis direction in a way similar to what is done for Cluster [3].

The estimates for the SRP acceleration obtained early in the mission were several times the expected value from the flat-plate model. However the estimates have decreased with time, first at a fast rate, then very slowly and are now stable. The decrease in the estimate is relatively consistent when using short or long tracking data arcs (from one week to four weeks) or when estimating a rate of change of the SRP acceleration over a long arc. To assess the evolution of the estimate, orbit determination runs were performed on consecutive one week arcs and the values for the estimates for each week are
shown in Table 2. The reason for the decay is not known. A tentative explanation is that the SRP acceleration estimate is absorbing the unmodelled acceleration of an outgassing process. Estimating the SRP acceleration with only the first two passes after LEOP worth of tracking data yields a value of five times the expected acceleration and this value decreases very rapidly when the tracking data arc is expanded. In that case there is a signature in the residuals whose amplitude is about a millimeter per second. Such a signature could be explained by the rapid dynamics of the hypothetical outgassing process around that time and by the precession of the spin axis as explained in section 2.5.

Table 2: SRP estimates over consecutive one week arcs with one sigma confidence

<table>
<thead>
<tr>
<th>Arc</th>
<th>SRP estimate (unity is nominal value)</th>
<th>Sigma (unity is nominal SRP value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 18 – May 25</td>
<td>1.51</td>
<td>0.002</td>
</tr>
<tr>
<td>May 25 – June 01</td>
<td>1.43</td>
<td>0.002</td>
</tr>
<tr>
<td>June 01 – June 08</td>
<td>1.39</td>
<td>0.005</td>
</tr>
<tr>
<td>June 08 – June 15</td>
<td>1.35</td>
<td>0.004</td>
</tr>
<tr>
<td>June 15 – June 22</td>
<td>1.25</td>
<td>0.004</td>
</tr>
<tr>
<td>June 22 – June 29</td>
<td>1.19</td>
<td>0.004</td>
</tr>
<tr>
<td>June 29 – July 06</td>
<td>1.09</td>
<td>0.008</td>
</tr>
<tr>
<td>July 06 – July 13</td>
<td>1.13</td>
<td>0.004</td>
</tr>
<tr>
<td>July 13 – July 20</td>
<td>1.13</td>
<td>0.003</td>
</tr>
<tr>
<td>July 20 – July 27</td>
<td>1.12</td>
<td>0.002</td>
</tr>
<tr>
<td>July 27 – August 03</td>
<td>1.10</td>
<td>0.003</td>
</tr>
</tbody>
</table>

The current SRP estimate is about 10% higher than the expected value. Interestingly, this is close to the factors we get for other missions using a more complex SRP model: Herschel (10%), Rosetta (6-8%), heliocentric cruise of Mars Express and Venus Express (12%) which are assumed to be due to the additional acceleration from thermal radiation that acts virtually in the same direction as SRP.

4 CONCLUSION

Despite using a simplified model for solar radiation pressure and using tracking data affected by the spin, Planck orbit determination has reached an accuracy which fulfills the pre-launch expectations from mission analysis and which is more than one order of magnitude better than the scientific requirements (20 km in position and 1 m/s in velocity). It has also been operationally proven to meet the navigation needs. Although Herschel is three axis stabilized and its dynamic model is more complex, its orbit determination accuracy is slightly worse because of daily wheel off-loading maneuvers.

Since the range-rate data are compressed to sixty seconds which is equal to the nominal spin period, the spin-induced ripple in the range-rate data has barely any effects on the Doppler residuals and on the orbit determination accuracy. Thus it might seem that the correction for this ripple is not required. However, when the spin period is slightly different from nominal, this correction affects the distribution of the Doppler residuals by decreasing their scatter and making them almost signature-free. This improves our confidence in the navigation solution.
Fig. 7. Post-fit residuals (left: two-way Doppler, right: two-way range) of an orbit determination using a four weeks data arc. The upper plots show the residuals using Doppler data corrected for spin. The middle plots show the residuals using Doppler data not corrected for the spin-induced ripple. The lower plots show the residuals using Doppler data not corrected for the “constant” spin-induced shift. The light data points were acquired from Cebreros and the dark ones from New Norcia.

5 REFERENCES