Scanning strategies for the Planck mission

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1. INTRODUCTION

The selection of a scanning strategy for the Planck mission is an important part of the optimisation of the mission. The sky coverage and more generally the distribution of the total mission integration time over the sky depend on it. In addition, the ability to subtract systematic effects from the data might depend drastically on the scanning strategy, as has been illustrated on specific examples by Wright (1996) and Tegmark (1997).

At the time of the writing of this paper, no scanning strategy for Planck is fully specified yet, but constraints have been put which result from an iterative investigation of possible orbit for the spacecraft, of general observing strategy, and of the optical, mechanical and thermal design. This first order optimization, performed during the preparation phase of the project, has led to constraints specified in the Announcement of Opportunity by ESA. The satellite, on its halo orbit around the Sun-Earth L2 Lagrange point, 1.5 million kilometers away from the Earth, will be spun to 1 RPM. The optical axis is offset from the spinning axis by an “opening angle” $\Theta_o$ between 70 and 90 degrees, so that the beam of different detectors will scan the sky on large circles which exact angular radius will be $\theta_{\text{scan}} = \Theta_o + \delta\theta$, where the detector-dependent displacement $\delta\theta$ is set by the position of the relevant light collector with respect to the center of the focal plane, and ranges between $-2.5$ and $+2.5$ degrees. Every 60 scans or so, the spin axis position will be offset by a few arcminutes, and the beam of each detector will scan repeatedly a new circle on the sky.

The set of successive directions of the spin-axis can be optimized, within the constraint that the solar aspect angle (angle between spin axis and antisolar direction) cannot exceed about 10 degrees, and the earth aspect angle at the times of data dumping cannot exceed a limit set by the size of the main lobe of the telemetry antenna.

For our purpose, candidate scanning strategies are fully described by a small
number of free parameters, which are the trajectory of the spin-axis on the sky, the set of spin-axis positions on this trajectory, the time spent at each spinning position, and the opening angle $\Theta_o$.

In this paper we discuss the problem of the optimisation of the trajectory of the spin axis on the sky and the choice of the opening angle $\Theta_o$. There are two main classes of scan strategies: those for which the spin-axis is always anti-solar, and those for which it is allowed to move away from the anti-solar position. For the first class thermal and sidelobe effects due to the sun will be minimal. The drawbacks, as we shall see, are a reduced ability to estimate and remove systematic effects, and possibly missing polar caps on the sky coverage.

2. REQUIREMENTS

A good scan strategy should meet, as much as possible, the following requirements:

A Redundancy: There should be enough redundancy to test and correct for the presence of systematic effects in the data such as sidelobe stray signals or thermal low frequency drifts, in order to obtain after processing the cleanest maps possible and reliable error estimation.

B Minimization of systematics: As much as possible the scan strategy should minimize the level of signal contamination by such systematic effects in the data streams themselves.

C Sky coverage: As much as possible, Planck should provide full sky maps.

D Robustness: The scan strategy should be such that the inversion of the data (i.e. obtaining full sky maps from the data streams and useful cosmological and astrophysical information from the maps) is possible even if a few days of data are lost or if one detector fails during the mission.

E Adaptability: One should be able if necessary to select the best scan strategy in the light of the information gathered during the verification phase after injection at L2.

3. SCANNING STRATEGY, DATA STREAMS AND SKY MAPS

3.1. Systematics and sky maps

We first investigate the reprojection of scan-synchronous systematic effects on final maps of the sky. In the near-ideal situation where all instrumental uncertainties come from scan-synchronous systematics and pure white noise (very optimistic indeed!), data reduction can be trivially simplified to the simple problem of optimal reconnection of rings (obtained from averaging 60 scans or so) into a map of the sky. The data on each ring $i$ can be modeled as:

$$d_i(\phi) = u_i(\phi) + v_i(\phi) + n_i(\phi)$$

where $d_i$ is the data, $u_i$ the useful astrophysical signal from main beam, $v_i$ the systematics and $n_i$ noise on ring $i$, all functions of angle $\phi$ on that ring. In a discrete version, the angle $\phi$ along ring $i$ is binned in “pixels” so that $\phi$ takes discrete values.

The scan-synchronous systematics can be decomposed on a basis of orthogonal functions, for instance Fourier modes:
\[ v_i(\phi) = O_i + \sum_m C_{i,m} \cos(2\pi m \phi) + \sum_m S_{i,m} \sin(2\pi m \phi) \]

where \( m \) ranges from 1 to some maximum value \( m_{\text{max}} \).

For map making with proper estimation and correction of systematic effects it is necessary to invert the data set and solve for both the useful signal (temperature on the sky) and parameters \( O_i, C_{i,m} \) and \( S_{i,m} \) describing the systematic effects. This is possible only if the system is non-degenerate. For a scan strategy with antisolar spin axis and \( \Theta_0 = 90^\circ \), the data set for any detector located at the center of the focal plane would consist of great circles crossing at the south (SEP) and north (NEP) ecliptic poles. Taking the origin for angle \( \phi \) on each ring at the NEP, it is clear that constraints, which come only from ring intersections at the poles, cannot permit to disentangle systematic effects as for each ring we only constrain the linear combinations:

\[ O_i + \sum_m C_{i,2m} \quad \text{and} \quad \sum_m C_{i,2m+1} \]

with no constraint on the \( S_{i,m} \). If there is any scan-synchronous systematic effect, it cannot be estimated from the signal, nor removed, and would reproject on the sky as vertical stripes along great circles joining NEP to SEP.

In principle, the degeneracy is broken by the physical extent of the focal plane, as not all detectors in a given channel scan the sky on the exact same rings. Even so, the intersections providing the redundancy from which systematics can be estimated are very localized around the poles, at angles \( \phi \approx 0 \) and \( \phi \approx \pi \) along the rings, where the leverage on sine modes is small and low \( m \) cosine modes form a nearly degenerate system. This near-degeneracy extends to Fourier modes of the signal from the sky along rings.

It should be clear that this degeneracy is independent on the modeling of the problem. If another basis of functions (instead of Fourier modes) had been used, different combinations of parameters would have been degenerate (they can be obtained from those on Fourier modes by expanding each Fourier mode on the set of new functions and replacing in the above linear combinations).

The conclusion is that if there are scan-synchronous, ring-dependent systematic effects in the data, an antisolar spin axis with large opening angle (\( \Theta_0 \) close to 90 degrees) is not acceptable for Planck.

3.2 Low-frequency drifts

Even if there are no scan-synchronous systematics in the data, there will be spurious low-frequency drifts due to instabilities in the electronics (yielding the so-called \( 1/f \) noise), or to random thermal drifts of elements of the spacecraft radiatively coupled to the detectors, for instance. Such drifts can typically be modeled as a Gaussian random process \( n(t) \) to be added to the data, which spectrum \( S_n(f) \) is known to reasonable accuracy. We put into \( n(t) \) only that part of these drifts that cannot be estimated and removed from the data using additional information from thermometers, sensors, ...

The way this kind of noise reprojects on rings of data obtained from averaging consecutive scans is discussed in Delabrouille, Górski and Hivon (1998). All the noise power in a band of width \( f_{\text{spin}}/N \) centered on some harmonic \( f_m = m f_{\text{spin}} \)
of the spinning frequency contributes to the variance $\sigma_m^2$ of the noise in mode $m$ (the width of the band is set by the resolution in frequency, which is the inverse of the total duration of the useful signal, $N\text{_{spin}}$).

It is a good approximation, for most noise spectra and most methods to recombine $N \gg 1$ scans into one ring, to relate the variance $\sigma_m^2$ in each Fourier mode of the residual noise on the ring to the spectrum $S_n(f)$ of the noise on the data stream by:

$$\sigma_m^2 = \frac{S_n(m f_{\text{spin}})}{NT_{\text{spin}}}$$

Low frequency noise thus reprojects as low-$m$ Fourier modes on Planck rings, and can induce striping on the maps. These low-$m$ modes can be estimated and removed from the data as can be done for scan-synchronous systematics (see Delabrouille, 1998a) if the system that allows to estimate and remove them is not degenerate. Therefore, if there is significant low frequency noise at frequencies larger than the spinning frequency of the satellite, an antisolar spin axis with large opening angle $\Theta_o$, again, is not acceptable for Planck.

3.3. Minimizing systematics

A solution to solve the degeneracy problem discussed above is to change the solar aspect angle (angle between spin-axis and antisolar direction) during the mission to guarantee better ring interconnections, as illustrated in figure 1. It is clear, however, that such an approach is likely to result in solar aspect angle dependent scan-synchronous effects during the spinning of the spacecraft, induced by the pickup of scan-synchronous variations of the temperature of the payload, and by modulated sidelobe signals from the Sun – at the very least. An anti-solar spin axis minimizes such effects. There is thus a trade-off between redundancy for removing systematics by data processing, and minimization of scan-synchronous effects.

In order to make progress towards the optimal solution, we push the analysis a bit further: for a given solar aspect angle $\theta_{s,i}$ on ring $i$, the sun-induced scan-synchronous effect can be simply modeled as:

$$v_i(\phi) = O(\theta_{s,i}) + \sum_m C_m(\theta_{s,i}) \cos(2\pi m(\phi - \phi_i)) + \sum_m S_m(\theta_{s,i}) \sin(2\pi m(\phi - \phi_i))$$

This decomposition, which looks very similar to the Fourier expansion of paragraph 3.1, differs by the fact that there is not a set of independent constants ($O, C_m, S_m$) for each ring $i$, but one for each solar aspect angle. It should be valid if there are no long transients in the temperature evolution of the payload that depend on the spacecraft attitude history on timescales of the order of one hour or larger (period between displacements of the spin axis direction), or if these transients have only second-order effects on the 1 minute period fluctuations and its harmonics. Angle $\phi_i$ (for each ring $i$) is a phase, equal (for instance) to the angle $\phi$ for which the main beam has the closest approach to the Sun (equal to $\pi - \theta_{\text{scan}} - \theta_{s,i}$ for ring $i$). If many circles are scanned with the same solar aspect angle, the number of parameters needed to fit and remove the systematic effect is small, and if intersections between rings provide a good connectedness, removing the systematic effect should be easier.
It should be noted that thermal fluctuations of the payload will not be caused exclusively by the Sun: heat input due to the cycle of the sorption coolers, for instance, may generate significant temperature fluctuations of parts of the spacecraft, whose effect on the signal by pickup of corresponding stray radiation cannot be modelled as a random noise, nor as scan-synchronous systematics.

The optimal scan strategy thus depends on the exact properties of all such systematics and requires further studies, currently under way.

3.4. Sky coverage

A permanently anti-solar spin axis has the drawback that if the scan angle
θ_{scan} is different from 90 degrees for a given detector, polar caps around ecliptic poles are not covered with this detector. For Planck, even if the opening angle Θ_o is 90 degrees, the scan angle will be smaller for some detectors because of different locations in the focal plane. For some detectors and even some channels of Planck, small regions at the pole at least a few degrees in diameter (depending on the value of Θ_o) would not be covered (for a given detector, 0.85 to 2.5 per cent of the sky is not covered for Θ_o = 80°, depending on the location of the detector on the focal plane). Although this is not critical for characterizing the properties of Cosmic Microwave Background anisotropies, it is not particularly desirable either and should be kept in mind.

Another aspect related to sky coverage is the distribution of integration time over the sky. Maps of integration times for a selection of scan strategies can be found in the COBRAS/SAMBA report on the phase A study (Bersanelli et al., 1996) and in (Delabrouille, 1998b).

3.5. Robustness

The full observing strategy is reasonably robust as there are several independent detectors in each channel and the sky is expected to be covered completely twice during the mission. It is highly recommended, however, that it be possible to obtain maps from single detector data (at least for temperature measurements). If not, the final sensitivity may be degraded if detector noise levels or contamination by systematic effects is very detector-dependent. In addition, the ability to intercompare maps obtained with different detectors will be a useful check for consistency in the data.

3.6. Adaptability

The optimal solution for a scanning strategy depends on the importance of scan-synchronous systematics for various strategies and on the ability to process the data in order to clean the maps from such spurious signals. An accurate evaluation of the level of residual instrumental effects on maps after processing is difficult, as the estimation of systematics in various configurations depends sensitively on many instrument and mission parameters, which are not fully known yet. For instance, thermal tests performed before launch and mathematical models will be representative but probably not accurate enough to decide on the largest acceptable solar aspect angle. In addition, the development of optimal data processing algorithms is still in its infancy. It would not be wise, therefore, to fully specify a scanning strategy at this stage.

Simulations can be helpful to isolate a small number of acceptable scanning strategies, each of which is optimal or nearly so for some models of dominant systematic effects. But as it is quite possible that some aspects of the simulations will prove inaccurate or incomplete, it is very important that tests be performed after the injection of Planck on orbit, during a verification phase which will last a few weeks. Such tests will permit to evaluate the level and properties of systematics, check for consistency with models and simulations and, if no nominal strategy can be specified relying on simulations alone, decide at the very beginning of the scientific mission which one of a few pre-selected scanning strategies is optimal. Such a procedure could be repeated after one full sky coverage, and a different scanning strategy selected for the second sky coverage. This adaptability of the scanning
strategy is important to the success of the mission.

4. CONCLUSION

In this paper, we have identified a set of requirements for the Planck scan strategy, listed in section 2. In section 3, we have shown that a scanning strategy with anti-solar spin axis and an opening angle $\Theta_0 \approx 90^\circ$ is extremely dangerous for Planck, as it would preclude the possibility to check for scan-synchronous systematic effects or remove the effect of low-frequency drifts from the maps. Moving the spin-axis away from the anti-solar direction helps removing degeneracies, at the price of a likely increase of the level of scan-synchronous, solar-aspect-angle-dependent systematics. This must be quantified in order to decide which is the optimal scan strategy for Planck.

If tests show that moving the spin-axis significantly away from the anti-solar direction is impossible, then a reduced opening angle to $\Theta_0 < 90^\circ$ breaks the degeneracy, at the price of reduced sky coverage. Unfortunately, the opening angle cannot be readjusted in orbit, and should therefore be conservatively chosen so that data reduction is possible even for very pessimistic predictions of levels of possible systematic effects.

It is hard to evaluate at this stage which solution is the best without a precise knowledge of the properties of systematics in each configuration and of optimal ways of processing the data. An acceptable subset of optimal solutions for various properties of systematics can be identified by numerical simulations using as an input optimistic and pessimistic thermal models of the spacecraft, simulated noise and evaluations of antenna patterns. If models are unsecure, the final decision between possible solutions should be made in orbit after tests which will provide a better understanding of the behaviour of the instrument in various configurations.

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