Planck systematics

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Polarisation measurement

- we need different angles to measure I,Q,U
  \[ m_t = I(\vec{n}) + \rho [Q(\vec{n}) \cdot \cos(2\psi) + U(\vec{n}) \cdot \sin(2\psi)] \]

- Planck scanning strategy is such that we have
  - one orientation of the focal plane / sky pixel / survey
  - 2 pairs of identical surveys
  - 10 to 12 detectors per frequency

- pair- and time-differencing
  - we combine detectors at 90deg at different time of observation
    - need to have very precise inter-calibration to avoid I,Q,U mixing
    - Intensity signal is \(\sim 100\) to 1000 times larger than polarisation
PLANCK time-domain systematics

- **detector time response (very long time constants)**
  - seen at map level but not on Jupiter nor glitches
  - use empirical model
  - impact glitch removal

- **ADC non linearity**

- **4K cooler pick-up**
  - electromagnetic and microphonic interference from the 4K-cooler reaches the readout boxes and wires in the warm service module of the spacecraft and appears in the Planck data as a set of very narrow lines at multiples of 10Hz and at 17Hz
  - correlated with ADC non-linearity
Time response deconvolution
Jupiter crossing

Before deconvolution

After deconvolution

Time response function is modeled in Fourier space as a sum of 5-8 lowpass filters time constants vary from 1ms - 1.5s +electronics transfer function

\[ F(\omega) = \sum_{i=1,5} \frac{a_i}{1 + i\omega \tau_i}. \]
before projection of several detectors on maps, need to remove

- instrumental systematic effects
  - 1/f noise
  - ADC non-linearity corrections
  - gain coefficients (absolute and possibly time-dependent)
  - time constant residuals

- sky signal not constant in time
  - zodiacal light
  - orbital dipole (reference for calibration)
  - Far SideLobes

- sky signal not common to all detectors within a channel
  - foreground emissions mismatch due to different bandpass
  - Far SideLobes
we include templates of systematics in the map-making

\[ d_t = g \left( A S + \sum_i \Gamma^{(i)} T^{(i)} \right) + n_t \]

\[ = g [A, \Gamma] \begin{bmatrix} S \\ T \end{bmatrix} + n_t \]

different domains:
- time domain \( (t) \) / ring domain \( (r) \) / pixel domain \( (p) \)

In practice:

\[ d_t = g_r \left( I_p + \rho Q_p \cos 2\phi_t + \rho U_p \sin 2\phi_t + D_t + \sum f_i T_p^{(fg)} i + \sum c_i T_t^{(TF)} i \right) + \sigma_r + n_t \]

\( g \) gains non-linear system \( \rightarrow \) gain linearization
\( I, Q, U \) sky signal
\( f \) bandpass mismatch coefficients
\( c \) transfer function residual coefficients
\( o \) 1/f offsets
**PLANKK polarization systematics at low-$\ell$**

- **Instrumental systematics**
  - 1/f noise residuals
  - glitches (increase the 1/f)
  - inter-calibration leakage
  - time-constant residuals
  - ADC non-linearity residuals

- **Foreground systematics**
  - cleaning residuals

- **Need for simulations !**

- **PLANCK 100 E2E simulations**
  - no bias on 100x143
  - error budget extended by a factor 1.5 due to systematics uncertainties

![Graph showing C_\ell for noise, systematics, cosmic variance, and total uncertainty.](image)

Those residuals are in $\ell^{-\alpha}$ but not directly correlated between frequencies.
From CMB data:

1. **WMAP 9yr**
   - $\tau = 0.089 \pm 0.014$

2. **Planck 2013**
   - $\tau = 0.089 \pm 0.014$ (TT with WMAP Polar)
   - $\tau = 0.075 \pm 0.013$ (TT with WP&Planck dust)

3. **Planck 2015**
   - $\tau = 0.078 \pm 0.019$ (TT + lowP)
   - $\tau = 0.066 \pm 0.016$ (TT + lowP + lensing)
   - $\tau = 0.067 \pm 0.016$ (TT + lensing + BAO)

4. **Planck HFI EE low-$\ell$**
   - $\tau = 0.058 \pm 0.012$ (TT + lowHFI) 
     (lollipop)

$\tau = 0.058 \pm 0.012 \pm 0.009$ (stat) 
$\pm 0.003$ (sys)
PLANK major systematics at high-\(\ell\)

- **Instrumental systematics**
  - beam leakage due to beam mismatch
  - calibration uncertainty
  - cosmic rays inducing correlated noise

- **Foregrounds systematics**
  - impact of free parameters in likelihood
  - impact of the choice of the foreground modeling

- **Need for simulations !**
  - hard to perform because lack of knowledge on the physical processes of the foregrounds
  - PLANCK made extensive use of jack-knives
  - comparison with different foreground modelings or different data set (TE)
• Hillipop TE results **compatible** in mean and accuracy with TT

• PLANCK TE spectra are much **less affected** by foregrounds (only dust matters)

[Coludot et al. A&A 602 A41 (2017)]
Cosmology with the CMB (& systematics)

- **major Planck systematic residuals**
  - ADC non-linearity (affecting inter-calibration and inducing E-B leakage)
  - residual long-time constant
  - unidentified cross-correlation noise affecting TE auto-power spectra

- **the major consequence is that systematics are becoming no longer negligible in the error budget**
  - as a consequence, we need massive Monte Carlo to
    - check for biases
    - propagate properly the uncertainties
  - this has been underestimated in PLANCK

- **This is difficult**
  - because of the lack of current knowledge on the Galactic emissions (emission law with frequency are not measured with enough accuracy and difficult to simulate)
  - massive amount of data available

- **This can make some differences especially for extension on ΛCDM models**