Planck/LFI: Scientific Impact of Signal Quantization and OnBoard Processing

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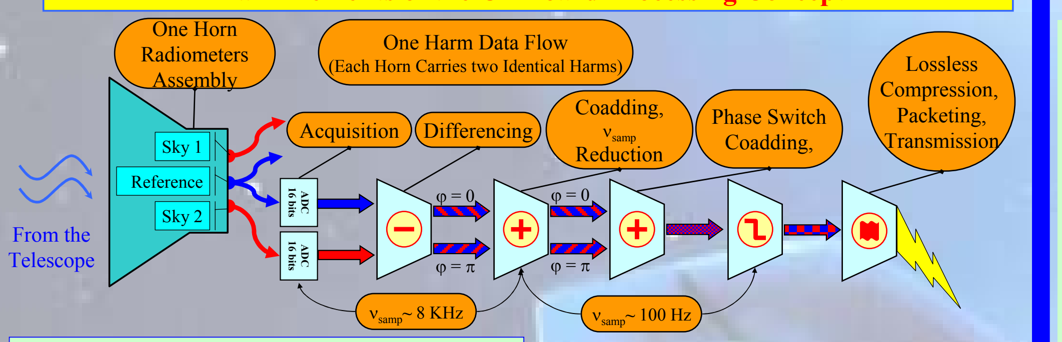
Real processing of the data produced by the PLANCK - Low Frequency Instrument, such as: on board acquisition, processing and transmission and ground processing, introduces systematic effects which have to be quantified and when possible removed. Signal quantization (i.e. discretization) has been the first one of such effects studied in a quantitative way in order to asses its impact on the LFI scientific performances. The main effect of quantization is equivalent to add a baseline to the power spectrum. Such baseline is equivalent to a $\delta C_l / C_l < 0.01$ or 10% of the noise plus CMB r.m.s. but may be very well modeled, estimated and removed from power spectrum.

Main Elements of the On Board Processing Concept



Most of these operations are mirrored at the Ground Segment by reverting operations.

Other details about this scheme and the terms here used are reported in other contributions to this conference [1, 2, 3, 4].

Some of these operations are

LOSS LESS

+ Do not introduce any information loss.

+ Completely reverted by Ground Segment operations.

Other operations are intrinsically

LOSSY

they cause information loss adding systematic effects.

All the aforementioned operations are LOSSY apart from the last step: Lossless Compression, Packeting and Transmission (in ideal conditions).

The presence of **Lossy** operations in the data processing is forced by constraints such as:

- the numerical accuracy of the onboard processor,
- the amount of onboard memory
- effective bandwidth allowed for data down-link,
- the rate of operations failures (example: transmission failures).

The impact of LOSSY operations on science shall be accurately evaluated, limited and as long as possible removed from data.

The Quantization Problem

The way in which the quantization problem has been studied is paradigmatic of the method of evaluation of the systematic effects induced by the data processing.

The quantization process transforms a continuous variable $T \in \Re$ sampled by the radiometer, into a discrete one $\mathtt{T} \in N$ (eq. 1) .

The process is reversed (eq. 2) at the ground segment generating a quantized-reconstructed signal $\tau \in \Re$. The effect of quantization is evaluated through the quantization error Q_E:

$$\mathtt{T} = \mathbf{discr[}\ (T - \min(T)) / q\ ]\ , \qquad (1)$$

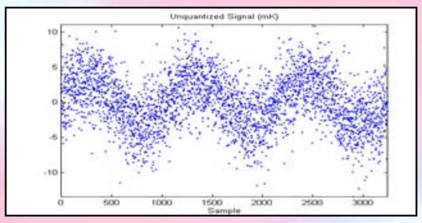
$$\tau = q \bullet (\mathtt{T} + offset) + \min(T), \qquad (2)$$

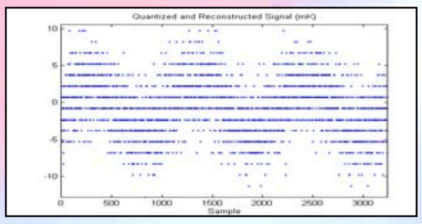
$$Q_E = \tau - T. \qquad (3)$$

where **discr[]** is the discretization operator (usually truncation), q is the quantization step, *offset* is an offset whose value is fixed by **discr[]** introduced to remove the bias (if any) induced by **discr[]**. Note intrinsecally non linear process nature of the quantization process.

For the 16 bits ADC converters q is fixed, being the range of T fixed by the input signal which must not saturate the ADC: $q = (\max(T) - \min(T)) / 2^{16}$. The present baseline fixes $q \approx 0.3$ mK for the ADC.

The characteristics of the second quantization in the previous scheme are instead determined by the Bandwidth Constraints, the overall Compression Efficiency and Data Rate.


Unquantized Signal (mK)


Quantized and Reconstructed Signal (mK)

Bandwidth Constraints, Data Rate and Compression Efficiency [5, 6]

+ Expected scientific uncompressed data rate from LFI	~ 77.1 Kb/Sec
+ Bandwidth allowed for LFI by ESA and operation constraints	~ 20 Kb/sec
+ Best compression rate allowed by the statistic of the LFI signal	Cr ~ 3.8 / (log(q/1 mK) - 0.41)
+ Quantization step required to asses the required Cr (100 GHz)	q ~ 0.5 rms(noise) ~ 1.5 mK
+ Typical rms of CMB fluctuations	~ 0.1 mK

What is the Impact of such a large quantization step on the LFI Science?

Quantization Impact Evaluation Strategy

Systematic effects induced by quantization are evaluated both by analytical and numerical methods.

Numerical methods have had a two - fold role in this work:

- Quantitative evaluation of the quantization effects in a realistic situation.
- Choice, assessment and calibration of valid analytical methods, optimized for Planck/LFI.

The second role is justified by the peculiar nature of the LFI signal.

Signal Features Assumed in Standard Methods

+ quantization step **small** respect to the signal amplitude,
+ pure, **uncorrelated** white noise,
+ very **high** signal/noise ratio,
+ Residual effects **smaller** than noise RMS unimportant
+ Small deviations from normality for error distribution unimportant.

LFI Signal Features (at TOD Level)

+ quantization step **comparable** to the signal amplitude,
+ white noise plus **correlated 1/f** noise,
+ very **low** signal/noise ratio (at TOD level S/N ~ 1/10)
+ Residual effects important up to ~ 10% of noise RMS
+ Small deviations from normality for error distribution are of scientific relevance.

The goodness of standard methods shall be validated before to draw any conclusion from them.

Analysis is performed comparing simulated signals, generated by an accurate Mission Simulator [1], WITHOUT and WITH performing quantization + reconstruction, taking in account of the sky signal composition, realistically simulated and 1/f noise, the scanning strategy and different options for the quantization process.

Both not - quantized and quantized data streams are piped in the DPC prototypal data reduction pipeline in order to produce destriped unquantized and quantized Maps and Power Spectra (C_l).

At each step of the reduction chain a full statistical analysis of the quantization error (as defined in eq. 2) is evaluated.

Simulation results are used both to validate and calibrate simple analytical models.

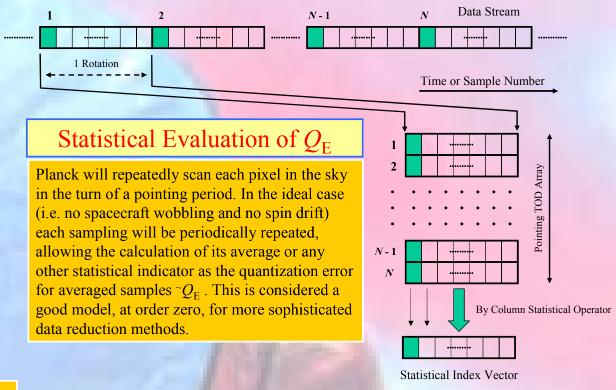
Results

Results confirms the adequacy of the standard *noise model* [7] to describe the quantization effect in the present situation.

According to this simplified model the effect of quantization is **to introduce a top-hat distributed, uncorrelated white noise** in the signal which affects the signal variance i.e. the total power of the power spectrum.

The variance for this source of noise being:

$$\sim q^2 / 12$$



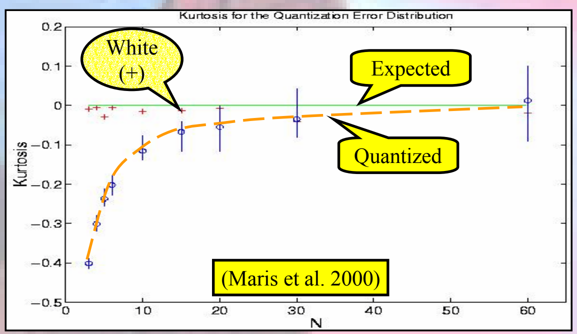
Statistical Evaluation of Q_E

Planck will repeatedly scan each pixel in the sky in the turn of a pointing period. In the ideal case (i.e. no spacecraft wobbling and no spin drift) each sampling will be periodically repeated, allowing the calculation of its average or any other statistical indicator as the quantization error for averaged samples $\tilde{Q}_E$. This is considered a good model, at order zero, for more sophisticated data reduction methods.

Q_E in the Data Stream

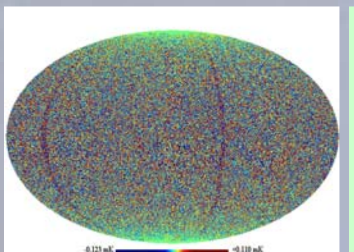
According to the evaluation procedure in the previous box, the quantization error of single measures Q_E (3) may be replaced with the quantization error $\tilde{Q}_E$ for averaged measures related to the same pointing in the sky. According with the *noise model,* while Q_E is not normally distributed, as the number of samples which enters the average increases, $\tilde{Q}_E$ will be more and more normally distributed. Leaving smaller and smaller residual skewness and kurtosis in the final averaged data stream.

The Figure demonstrate such behavior. The bars do not represent errors, but just the range of variation of the kurtosys of the $\tilde{Q}_E$ distribution as a function of q, for which no systematic trend appears. The + represents the kurtosis for the distribution of unquantized averaged samples.


Kurtosis for the Quantization Error Distribution

(Maris et al. 2000)

Maps

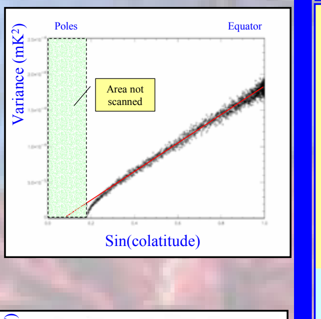


The quantization affects maps.

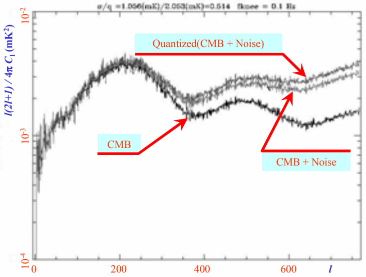
On the left is a map of the quantization noise for $q \sim 2\sigma$ obtained taking the difference between a map generated from quantized and reconstructed signals and a map from the same signals unquantized.

Since in the making of maps the number of samples from the data streams entering the map pixels increases near the ecliptical poles, the quantization noise per pixel will be, as the white noise, a function of the ecliptical colatitude.

The same is true for other statistical indexes such as: skewness and kurtosis.



Power Spectrum



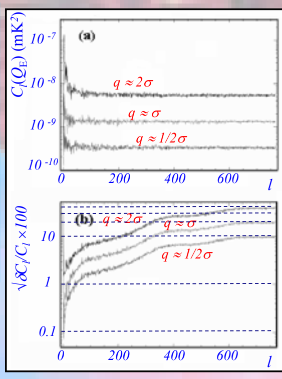
Power spectra are extracted from maps generated from quantized and unquantized data streams.

The figure on the left represents the effect of the signal quantization over the C_l power spectrum, after 1 Year of Mission for one horn of the LFI 30 GHz Channel, as a function of the Multipole ***l***.

The q of choice at left is larger than the baseline to enhance the effect visibility.

On the right the quantization error power spectra changing q, expressed as C_l (a) and as $\sqrt{\delta Cl/Cl}$ (b).

The effect does not change with f_{knee} (here assumed to be 0.1 Hz).



Conclusions and Work in Progress

+Even in the present case, the quantization process may be at first order approximated as a source of white noise.

+The quantization noise is at a first approximation normal, residuals may lead to some spurious non gaussianities which should be accounted for before to search for non gaussianities in the LFI data.

+At least for $l > 30$, the power excess introduced in the power spectrum by quantization is constant. For l < 30 the power execess is no rigorously constant since interactions with the destriping process. However, the deviation from a constant is in general small.

+For the nominal case ($q \approx \sigma/2$) quantization will induce an increment of C_l of up to 1%. When this is translated into temperature, the r.m.s. quantization error is up to 10% of the noise plus CMB r.m.s..

+Quantization may be one of the major sources of systematic errors and shall be removed. This may be done quite accurately in the power spectrum since its constant contribution may be quite will estimated from a good simulation of the mission plus the data reduction process once q is know.

Work is in progress or planned in order to:

1) Build a calibration curve associating the maximum compression rate achievable with a given q with the corresponding Q_E.

2) Look for the possibility to perform Q_E removal even on TOD and maps instead of just on power spectra.

3) Investigate the impact of quantization on components separation.

4) Investigate the impact of quantization on non-gaussianity tests for CMB and on signal correlations.

5) Investigate the effect of quantization on polarization measurements.

References

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