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CSL REBA calibration results and Recommendations for the Flight Calibration

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Abstract

This document is divided in two parts. In the first part we present an overview of the algorithms used by the REBA to compress the voltage output of the Planck/LFI radiometer. We also sum up the results of the REBA calibration and verification activity done during the Planck Integrate Satellite tests in Liége. We present them in terms of the σ/q parameter, in order to allow for a better comparison with other similar requirements from HFI. We also explain the advantages of *not* using σ/q as a measurement of the quantization error.

In the second part of the document, we discuss which are the expected differences between the calibration of CSL data and the calibration that is going to be done in flight. It is expected that a number of effects not considered during the CSL tests will require a more careful tuning of the compressor, in order to take into account the sky signal and the impact of total-power quantization noise on the data analysis.

1 Applicable and Reference Documents

Applicable Documents

[AD1] M. Tomasi, M. Maris, and A. Mennella. REBA calibration and verification. Technical Report PL-LFI-PST-PR-061, UniMi/UniTs, August 2008.

Reference Documents

[RD1] A. Gersho and R. M. Gray. *Vector quantization and signal compression*. Springer, 3 edition, 1993. ISBN 0792391810.

[RD2] M. Maris. Characterization of the Compression Rate for the New Baseline for the Scientific Data Streams Coding. Technical Report PL-LFI-OAT-TN-029, OAT, March 2004.

[RD3] M. Maris. Planck LFI Characterization of the Onboard Processing Parameters. Technical Report PL-LFI-OAT-TN-030, OAT, March 2004.

[RD4] M. Maris, D. Maino, C. Burigana, and F. Pasian. Data streams from the Low Frequency Instrument on-board the PLANCK satellite: statistical analysis and compression efficiency. *Astronomy & Astrophysics*, 2000.

[RD5] M. Maris and M. Tomasi. Metricsforthequantizationerroranddefinitionofa“fictious” σ/q. Technical Report PL-LFI-OAT-TN-055, OAT, August 2008.

[RD6] M. Maris, M. Tomasi, M. Bersanelli, O. D’Arcangelo, D. Maino, A. Mennella, A. Zonca, S. Lowe, R. Leonardi, P. Meinhold, M. Miccolis, M. J. Salmon, L. Mendes, J.M Herreros, S. Hildebrandt, R.C Butler, C. Burigana, F. Cuttaia, E. Franceschi, M. Malaspina, N. Mandolesi, G. Morgante, M. Sandri, L. Terenzi, L. Valenziano, F. Villa, P. Binko, M. Meharga, N. Morrisset, R. Rohlfs, M. Turler, S. Fogliani, M. Frailis, S. Galeotta, F. Gasparo, A. Gregorio, G. Maggio, P. Manzato, F. Pasian, F. Perrotta, and A. Zacchei. Optimization of Planck/LFI on–board data handling. *J-Inst*, submitted, 2009.

2 Introduction

The LFI SPU is a module of the REBA whose main purpose is to compress the scientific data acquired by the radiometers and digitized by the DAE. The data compression is a crucial feature of Planck, since its angular resolution and high data acquisition frequency forbid the transmission to Earth of the full data acquired during the mission. It is worth to note that Planck is the first CMB space mission that implements an on board software compressor.

The compressor uses a mix of high-level techniques that reduce the data size by reducing data redundancy and discarding information that is either scientifically not relevant or dominated by the intrinsic radiometric noise. It is therefore extremely important to calibrate the SPU so that no scientifically relevant information is discarded during the compression.

During the CSL tests we performed a calibration of the REBA with the objective of achieving a compression ratio (c_r) of 2.4 and a quantization noise as lower as possible. We expect that things will be different during flight, because of a number of factors: (1) the presence of the sky signal, (2) the requirement to have a low quantization error in the total power, (3) possible effects that alter the statistics of the radiometric signal over long time scales (a few days and more).

In the first part of this document we present a short summary of the results presented in [AD1]. Even if it is not the best representation of the quantization error (see [RD5]), we present here the results in terms of the σ/q quantity in order to make our numbers better comparable with others, e.g. HFI quantization requirements.

In the second part of the document we explain what are the expected differences between the calibration done in CSL and the flight calibration performed during the CPV.

3 Schematics of the Compression Algorithm

The SPU implements this schema to quantize and compress the total-power data x_{sky} and x_{ref}:

$$\begin{pmatrix} x_{\text{sky}} \\ x_{\text{ref}} \end{pmatrix} \to \begin{pmatrix} x_{\text{sky}} - r_1 \times x_{\text{ref}} \\ x_{\text{sky}} - r_2 \times x_{\text{ref}} \end{pmatrix} \to \text{quantization} \to \text{compression}. \tag{1}$$

The quantization and compression phases are *not* applied to the raw sky/reference signals, but instead to their mixed counterparts $m_{1/2} = x_{\text{sky}} - r_{1/2} \times x_{\text{ref}}$. This allows to reduce the $1/f$ noise, therefore helping the compressor to achieve a better compression rate.

The role of r_1 and r_2 is similar to the gain modulation factor $r = \langle x_{\text{sky}} \rangle / \langle x_{\text{ref}} \rangle$: they are a tool which allows to reduce the $1/f$ component of the noise in the signal to compress. Note however that they cannot be exactly r at the same time, because in this case the system would not be invertible. They must be optimized according to the target compressor performances, namely the compression rate c_r and the quantization error ϵ_q.

The optimization of the compressor involves not only the search for the best pair of mixing parameters (r_1, r_2), but also the best quantization parameters, namely s_q ("second quantization") and Δ ("offset"). The latter allows to optimize for the dynamical range of the REBA, while the former controls the level of quantization q of the resulting signal. Quantization q is a crucial parameter that is related both to the quantization error of the mixed signal (as we shall see later) and to the theoretical compression ratio c_r, according to the following formula:

$$q \propto \frac{\sigma}{2^{16/c_r}}. \tag{2}$$

Note that, because of the presence of the exponential, a small increase in c_r can lead to a dramatical increase in q.

4 Characterization of the Quantization Error

The results of the CSL REBA calibration discussed in [AD1] were expressed in terms of three quantities, namely the ratio ϵ_q/σ between the quantization error ϵ_q and the RMS of the signal σ for the sky signal, the reference signal and the differenced $(x_{\mathrm{sky}} - r \times x_{\mathrm{ref}})$ signal. We chose to use ϵ_q instead of σ/q because the latter does not offer an estimate of the quantization error that is easy to understand, as explained in [RD2], [RD3] and [RD5]. Here we summarize the main points of these documents.

Historically, expressing the quantization errors of the SPU through the σ/q quantity was motivated by the fact that in the old baseline the SPU quantized and compressed the differenced signal onboard. The q value was the quantization step of the differenced signal, being related to the induced quantization RMS (ϵ_q) by the following relation:

$$\epsilon_q = \frac{q}{\sqrt{12}}, \tag{3}$$

which holds if ϵ_q is smaller than the intrinsic RMS of the uncompressed signal. This relation can be derived by simply using the definition of RMS over a signal where each datum x has an error uniformly distributed in the $[x - q/2, x + q/2]$ range[1]. Writing the normalized probability distribution as $p(x) = 1/q$ when $x \in [\bar{x} - q/2, \bar{x} + q/2]$ (with $\bar{x}$ being the average) and zero elsewhere, we have that

$$\epsilon_q^2 = \int_{-\infty}^{+\infty} (x - \bar{x})^2 \, p(x) \, \mathrm{d}x = \frac{q^2}{12}. \tag{4}$$

With the new design described in paragraph 3, q is *no longer* the quantization applied to the sky and the reference signal, but instead to the mixed signal. Therefore, the relation between q for the mixed signal and ϵ_q for the quantized total-power output $x_{\mathrm{sky}}, x_{\mathrm{ref}}$ is more complex and depends on r_1 and r_2 as well:

$$\epsilon_q \propto \frac{q}{|r_1 - r_2|} \tag{5}$$

(refer to [RD5] for a full derivation). At the same time q is a less significative measurement of the quantization error, while ϵ_q/σ has the advantage of providing an immediate measurement of the impact of the quantization on the overall noise σ. Therefore, the LFI team is now urging to use (ϵ_q/σ) for characterizing the quantization effect of the two total-power signals and the differenced signal[2].

In the analysis presented in this report we show the results reported in [AD1] by applying relation (3) to our results straightforwardly. It should however be clear from the discussion so far that in this context q is the quantization expected if the REBA were compressing the total-power and differenced signals directly, and should not be mismatched with the true q at the level of the mixed signal.

5 Results of the REBA Calibration in the CSL Tests

The results of the REBA calibration in [AD1] have been presented in terms of the quantity ϵ_q/σ for the three datastreams (sky, reference and difference). In table 1 we present the same result

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[1] This assumption obviously applies only if the quantization is small. In general, the quantization error has not the characteristics of the white noise, but in this situation they are quite the same.

[2] Only the sky and reference signal are compressed onboard. Once these data are sent to Earth and are retrieved and consolidated, the LFI pipeline calculates the differenced signal, which therefore does *not* experience any compression onboard. However, it is of the uttermost importance to characterize the induced effect of the quantization noise on this datastream as well, as it is the one used to do the science.

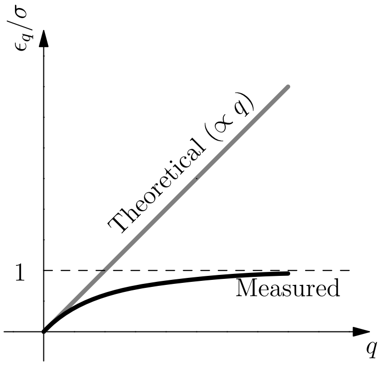

Figure 1: Correlation between the theoretical ϵ_q/σ ratio as a function of quantization q (eq. 3) and the same quantity measured according to the explanation provided in 4 and used during the CSL tests. For small q the two quantities are the same, but the greater the q the more significative the discrepance. Eventually ($q \gtrsim 2\sigma$) the measured ϵ_q/σ converges asymptotically to 1 even if the quantization gets worser and worser, thus giving the false impression that quantization is under control. This is a problem which affected many of the total-power data compressed during CSL.

expressed in terms of σ/q, scaled according to equation (3).

The results show that an hipotetical $\sigma/q > 2$ requirement would have been fully met only for the differenced signal. For the two total-power signals (sky and reference) the situation is worse. In fact, only 8 out of 43 channels[3] met the old $\sigma/q > 2$ requirement on all the three datastreams, namely #1800, #1801, #1810, #1811, #2210, #2211, #2310 and #2311. Such a behavior can be easily seen also through the ϵ_q/σ parameter, which in such cases is ~ 1: figure 4 shows the quantization in the reference signal of #2510 (for the reference signal, $\epsilon_q/\sigma = 0.85$ and $\sigma/q = 0.34$).

6 Possible Caveats for the Flight Calibration of the REBA

In this section we discuss a number of points that must be taken in account when calibrating the REBA compressor for flight operations.

6.1 Estimation of the Quantization Error

As expressed in [RD6], the estimation of ϵ_q can be done analytically or by measuring the RMS of the difference between the quantized and the uncompressed data. However, the two calculations do not always provide the same value. It is a well known result of signal quantization theory (see e.g. [RD1] p. 166) that the quantization error cannot be strictly considered an additive white noise. However, M. Maris used this hypotesis as the baseline of [RD6], because the approximation holds if $\epsilon_q/\sigma < 1$, which is the desired behavior for LFI. Once the data no longer satisfy the inequality, the theory fails. This was the case of total-power data in CSL tests.

The problem can easily understood by looking at figure 4 top: if the quantization level is too large, then the quantized signal x_{COM5} (shown in grey) will become a constant K (and it will generally *not* be equal to the average value of the uncompressed signal x_{AVR1}, shown in black).

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[3] Channel #2701 was not analyzed because of a problem during the data acquisition phase. See [AD1].

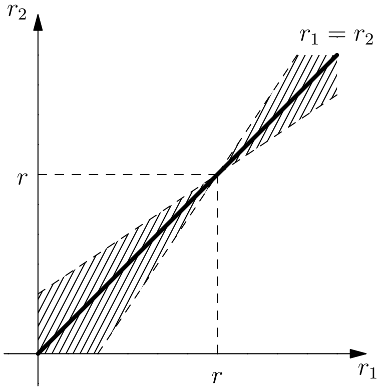

Figure 2: During the calibration of CSL data OCA2, the REBA calibration software, looked for solutions that were near the $r_1 = r_2$ line. Provided that $r_1 \neq r_2$, these are the solutions that guarantee the best compression ratio. However, when considering flight data one has to minimize the error on the gain modulation factor r too. In order to keep its error under a desired level, the pair (r_1, r_2) must not fall within a region around the $r_1 = r_2$ line (the hatched region in the figure).

Therefore, for high q the value of ϵ_q will become equal to the value of σ:

$$\mathrm{RMS}(x_{\mathrm{COM5}} - x_{\mathrm{AVR1}}) \approx \mathrm{RMS}(K - x_{\mathrm{AVR1}}) = \mathrm{RMS}(x_{\mathrm{AVR1}}) = \sigma.$$

We can express this effect with the following limit:

$$\lim_{q \to \infty} \left(\frac{\epsilon_q}{\sigma} \right)_{\mathrm{measured}} = 1. \tag{6}$$

This means that if our measure of ϵ_q/σ from the data is roughly one, then the real impact of quantization can no longer be quantified by this parameter.

The theory required to study the case where $\epsilon_q/\sigma \gtrsim 1$ is not available. Such a study should be made almost from scratch and would require considerable effort and manpower.

6.2 Determination of the Gain Modulation Factor

The total power data coming from LFI (i.e. the undifferenced sky and reference data streams) are crucial to determine the *gain modulation factor* r used to difference the data. Its definition is

$$r = \frac{\langle x_{\mathrm{sky}} \rangle}{\langle x_{\mathrm{ref}} \rangle}, \tag{7}$$

where both x_{sky} and x_{ref} are the uncompressed data streams. Using compressed data streams leads to an error $\epsilon_q(r)$ in the determination of r, which is desirable to keep below the error $\epsilon_\sigma(r)$ caused by the intrinsic variance of $\langle x_{\mathrm{sky}} \rangle$ and $\langle x_{\mathrm{ref}} \rangle$. We can introduce some threshold Θ:

$$\frac{\epsilon_q(r)}{\epsilon_\sigma(r)} < \Theta < 1. \tag{8}$$

It can be proven (Maris, in preparation) that the region on the (r_1, r_2) plane where this condition does *not* hold is a region of the plane centered around the (r, r) point and whose axis is the $r_1 = r_2$

line (see fig. 2). Unfortunately, the best compression rates are achieved around this line[4].

Therefore, in order to better reconstruct the value of r (crucial for the scientific analysis of the LFI data) we are likely to be forced to reduce the compression rate by moving r_1 and r_2 away from the $r_1 = r_2$ axis.

6.3 Presence of the Sky and of Long Drifts in the Radiometric Signal

The presence of the dipole is likely to make the optimization of the REBA more difficult. Already in 2000 [RD4] explained the impact of the sky signal on the compressor performances, but it will be the calibration of flight data that will allow us to measure for the first time the true impact of this effect.

Moreover, because of the variable sky signal and of possible instrumental instabilities on timescales of days and weeks, we expect the characteristics of the signal to change during the mission. It is therefore likely we will have to redo the REBA calibration regularly[5]. This will induce fluctuations in the telemetry produced by LFI, which must therefore be kept within the allowed limits.

Since it is *not possible* to assess the entity of these effects from the analysis of only a few hours of acquisition, this is likely to be done only once the “First Light” phase will be concluded.

7 Conclusions

This note has presented the results of the REBA calibration tests done in CSL already presented in [AD1] in light of the recommendations found in [RD5]. The data from CSL have shown that the quantization induces a significative quantization over the total-power signal, while at the same time showing a little effect on the differenced signal. This is due to a strong correlation between the quantization error on the sky and on the reference signals.

There are three possible problems for the incoming REBA calibration in flight:

1. The case $\epsilon_q/\sigma \sim 1$ means that the mathematics used in the paper by Maris [RD6] is no longer valid for the CSL total-power data because our theory underestimates the impact of the quantization error – see the discussion around eq. (6). During flight we must therefore reduce the quantization on the total power signal. This will be done at the expense of the quantization on the differenced signal.

2. The optimization used in CSL ignored the error on the determination of the gain modulation factor r. Taking into account this point will likely lead to a worse compression ratio.

3. Long-scale instabilities (from a few days to a few weeks) caused by the sky signal and possible instrumental drifts are likely to require changes in the calibration of the REBA. Such calibration will not require additional tests because it can exploit the double AVR1/COM5 acquisition during the nominal phase of the mission. However, re-calibrating the REBA will cause variations in the telemetry amount produced by LFI. Hopefully, after the “First Light” phase we shall be able to better characterize such effects.

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[4] This is easy to understand: the more r_1 and r_2 are similar, the more the noise properties in the two mixed datastreams (eq. 1) are similar and therefore the compressor is able to compress them better. Of course, the degeneracy problems explained in paragraph 3 still hold, and in such a nearly-degenerate case round-off errors cause high quantization.

[5] This will be a no-cost calibration from the point of view of the operations, as in nominal acquisition we can exploit the presence of an AVR1 datastream of a few tens of minutes per day for each radiometer.

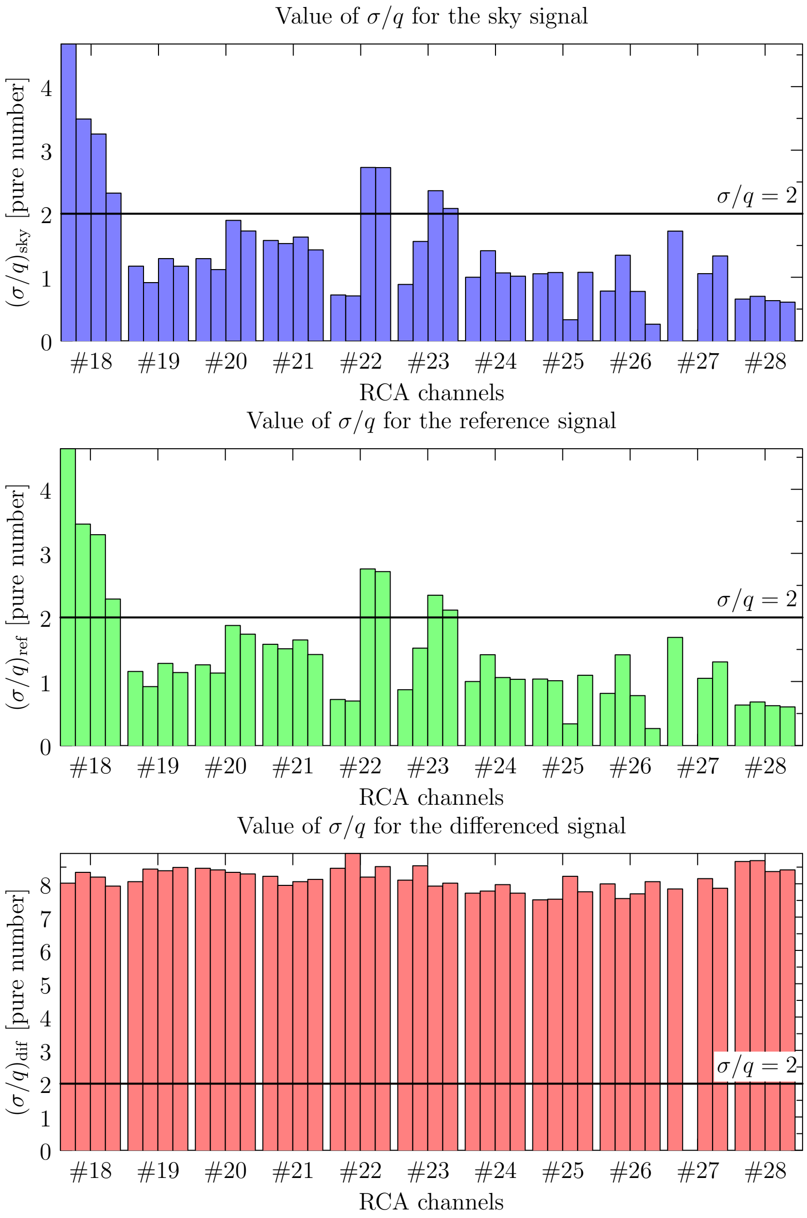

Figure 3: Plot of the σ/q quantity for the 43 channels calibrated during the CSL tests. This is an alternative plot of fig. 2 in [AD1], which presented the results in terms of the ϵ_q/σ quantity for sky, reference and differenced signals. Here we only show the numbers for the "verification" dataset. Note that channel #2701 is not represented because of a problem during the test that invalidated the acquired data. The $\sigma/q = 2$ level is shown here. Note that the differenced signal is within the requirement for all the 43 channels, while only a few channels met the requirement for the total-power signal. The latter is most likely caused by non-idealities in the REBA data processing algorithms.

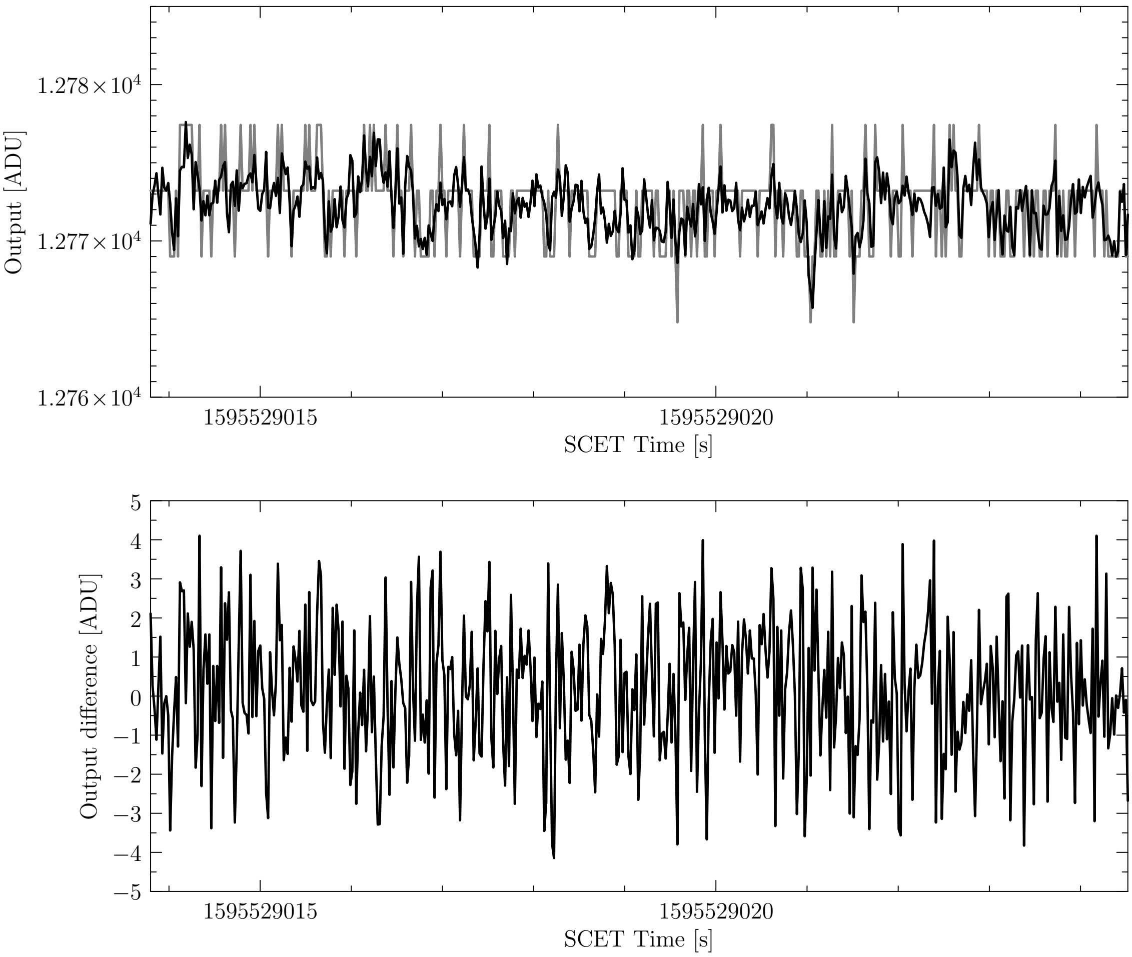

Figure 4: **Above**: Quantization of the compressed COM5 signal (gray line) plotted over the uncompressed AVR1 signal (black line) for channel #2510 (data taken during the CSL tests). The total power signal coming from the reference is plotted here. Its quantization is related to the value of s_q, one of the four REBA parameters tuned during its calibration. Channel #2510 has the lowest value of σ/q for the reference channel (~ 0.3). **Bottom**: the difference between the COM5 and the AVR1 #2510 signals shown in the plot above. The standard deviation of this datastream is equal to the value of $\epsilon_q^{\mathrm{ref}}$ for this channel ($\epsilon_q = 1.7134$).

Feed horn	$(\sigma/q)_{\mathrm{sky}}$	$(\sigma/q)_{\mathrm{ref}}$	$(\sigma/q)_{\mathrm{dif}}$
1800	4.6711	4.6336	8.0188
1801	3.4906	3.4572	8.3432
1810	3.2545	3.2916	8.2010
1811	2.3243	2.2874	7.9306
1900	1.1749	1.1566	8.0636
1901	0.9161	0.9205	8.4408
1910	1.2939	1.2824	8.3917
1911	1.1744	1.1401	8.4904
2000	1.2933	1.2600	8.4655
2001	1.1211	1.1321	8.4162
2010	1.8954	1.8745	8.3432
2011	1.7286	1.7390	8.2953
2100	1.5792	1.5809	8.2244
2101	1.5306	1.5106	7.9525
2110	1.6328	1.6486	8.0636
2111	1.4312	1.4213	8.1317
2200	0.7217	0.7193	8.4655
2201	0.7068	0.6954	8.9097
2210	2.7285	2.7572	8.2010
2211	2.7259	2.7157	8.5155
2300	0.8874	0.8719	8.1089
2301	1.5638	1.5209	8.5407
2310	2.3623	2.3470	7.9306
2311	2.0828	2.1148	8.0188
2400	1.0006	0.9999	7.7186
2401	1.4179	1.4179	7.7810
2410	1.0688	1.0621	7.9745
2411	1.0172	1.0343	7.7186
2500	1.0555	1.0384	7.5176
2501	1.0751	1.0122	7.5372
2510	0.3318	0.3385	8.2244
2511	1.0780	1.0976	7.7601
2600	0.7832	0.8145	7.9965
2601	1.3471	1.4165	7.5569
2610	0.7775	0.7798	7.6980
2611	0.2615	0.2659	8.0636
2700	1.7265	1.6882	7.8444
2710	1.0570	1.0497	8.1547
2711	1.3358	1.3056	7.8658
2800	0.6571	0.6326	8.6689
2801	0.7003	0.6804	8.6950
2810	0.6322	0.6224	8.3674
2811	0.6084	0.6032	8.4162

Table 1: Values of σ/q quantity for the 43 channels calibrated during the CSL tests. This table matches table 2 in [AD1], which presented the results in terms of the ϵ_q/σ quantity for sky, reference and differenced signals. For further information, refer to figure 3.