SUCHAI Physics Payload

Technical specifications for the onboard physics experiment

Change log

Version	Date	Author	Changes
1.0	05/07/16	José Ogalde	Initial documentation.
2.0	07/22/16	José Ogalde	Filtering and range of operation included.
2.1	08/16/16	José Ogalde	Fixing simulation figures.

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Physics Experiment Overview

Given that electronics are the main resource for automation, control and data acquisition for complex systems, its of paramount importance to characterize their behaviour in hostiles environments such as space, in particular when considering environmental strains and attacks on normal behaviour of electronic components by the interaction of its parts with its surroundings.

This document presents an experiment that constitutes one of the payloads in the SUCHAI cubesat. The experiment main goal is to study the hostility of space environment on electronics due to several effects such as extreme low-high temperature cycles and EM radiation. This can be accomplished by measuring the statistical properties of the fluctuations of energy flux in a dissipative system -such as a simple RC circuit- when driven with a stochastic input. Previous work by Falcón (2009) [1] gives a reference for the expected results for outer space. Hostility of the environment could be inferred comparing space with laboratory statistics.

Because of the simplicity in their constructions, cubesats present as excellent candidates to perform this kind of studies for electronics. For this purpose, the SUCHAI cubesat has an RC circuit driven with a pseudo-random voltage as one its payloads.

Experimental Setup

The circuit is a SISO system driven with a known pseudo-random voltage $v_{in}(t)$, that has a characteristic frequency f_c, and the output voltage $v_{out}(t)$ is then measured. The purpose of this experiment is to measure the output voltage $v_{out}(t)$ for different values of f_c.

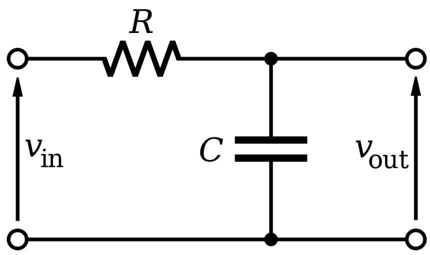

Figure 1

A PIC microcontroller controls the input voltage through an DA converter (DAC). The DAC receives the pseudo-random values generated by the microcontroller and outputs the corresponding analog values at a constant rate T_{DAC}. The analog output voltages are measured with an AD converter (ADC) at a T_{ADC} rate. The digital values are stored in the SUCHAI internal memory for posterior analysis.

T_{ADC} and T_{DAC} are configured by the user through command line. The payload was programmed in a way that T_{ADC} is always smaller than T_{DAC} to avoid aliasing and T_{DAC} is four times greater than T_{ADC} (Equation 1). Is important to mention that T_{ADC} and T_{DAC} could not be configured separately by the user, T_{ADC} is the only variable that is directly manipulated, T_{DAC} is set automatically using Equation 1.

$$T_{DAC} = 4 \cdot T_{ADC} \tag{1}$$

$$f_c = 1 / T_{DAC} \tag{2}$$

The pseudo-random variable generated by the microcontroller is the same in every payload execution. This means that the seed of the random generator is kept constant for all executions independent of the frequency of the input signal or other parameters. The input voltage resembles an uniform distribution $U_{(-0.8,\, 0.8)}$ between $[-0.8,\ 0.8]$. Figure 2 shows probability density function of the input signal measured in the laboratory.

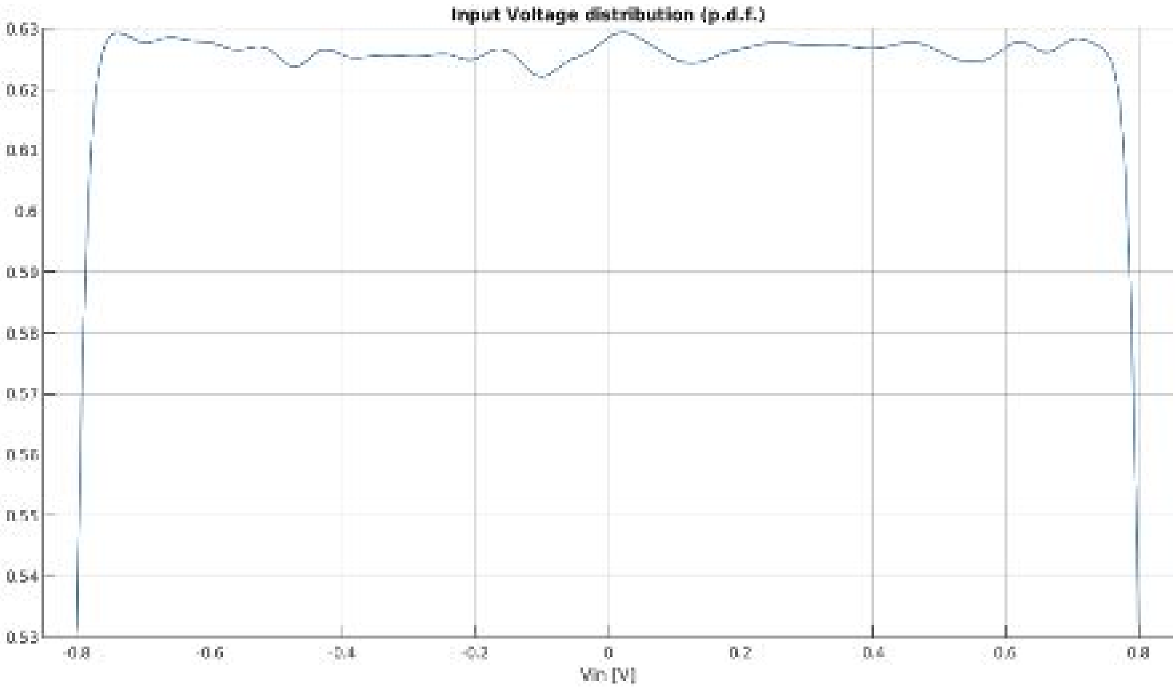

Figure 2.

The duration of a frequency execution is ruled by the number of values (N) that the PIC outputs to the DAC. The number of values generated by the DAC during the mission is fixed to $N = 1000$, therefore a total of $S = 4 * N = 4000$ samples are taken for each frequency execution (Equation 1). This means that, for every DAC value, the ADC samples 4 times.

Notice that the number of input values passed to the DAC is set in the firmware of the microcontroller and cannot be changed through tele-commands.

Finally, the instruments used are a 16 bit DAC -Texas Instruments DAC8551- and a 10 bit ADC included inside the PIC microcontroller.

Implementation considerations

Because of the reduced static memory of the PIC microcontroller, a buffering technique is used to store the output voltage measurements. This means that a frequency execution is implemented as a collection of smaller executions from portions of the original input signal, filling an intermediary buffer to transfer the measures to a larger memory and then resuming to the next portion of the frequency execution.

The size of the intermediary buffer is fixed to 200 samples, so every execution pauses when the buffer has 200 new samples and resumes after transferring all the samples to the larger memory (SD card). Therefore, there are a total of $\frac{4000}{200} = 20$ pauses because of this buffering to complete a whole frequency execution.

This buffering technique induces a transient response in the circuit every time the content of the buffer is transferred to the SD card. Because of the original purpose of the experiment is to measure the steady state response of the circuit, this transient response impairs circuit statistics, therefore all samples that belongs to the transient response must be filtered during posterior data processing phase, otherwise this transient response could introduce wrong conclusions. A simple way to filter the transient is proposed in section *Transient response Filtering*.

Execution through Commands

SUCHAI payloads can communicate with earth station through a command interface. The structure of the commands is pretty simple because is composed of a *header plus a integer*, for example:

```
exe_cmd 0xABCD 12345
```

This example means to execute the command `0xABCD` with the number `12345` as argument.

The physics experiment has only one command available that handles its execution and is used to set the frequency f_{signal} to which excite the circuit. The name of the command is `0x602A` and the argument is a number between $[0, 2^{16} - 1]$. That number sets the value of the period register of the ADC, which sets T_{ADC} and T_{DAC} through the Equation 1.

In order to avoid complicated calculations to find the number that excite the circuit with a specific frequency, a linear fit between the argument number and f_c was made (f_c measured using T_{DAC}, Eq. 2).

Figure 3 shows the fit of the regression to fifteen different f_c values. The coefficients of the linearization are shown in Equation 3.

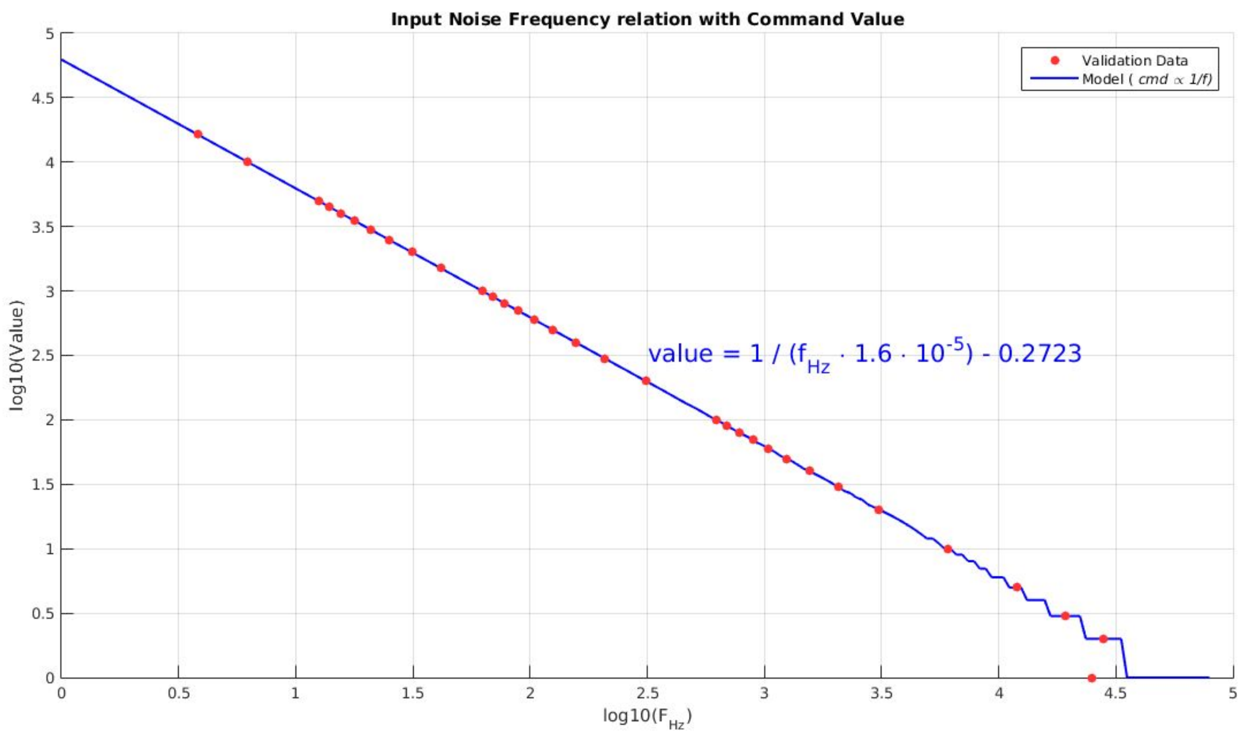

Figure 3.

$$command_{value}(f_c\,[Hz]) = \left[1 / (f_{Hz} * 1.6 \cdot 10^{-5}) - 0.2723 \right] \tag{3}$$

For example, if an input signal of frequency $f_c = 2\,KHz$ is desired, compute the Equation 3 gives: $\left[1/(f_c * 1.6 \cdot 10^{-5}) - 0.2723\right] = [30.97] = 31$. So, executing the experiment with $f_c = 2\,KHz$ through SUCHAI command line will be like the following:

```
exe_cmd 0x602A 31
```

Is important to note that this model works well if the frequency f_c is less than 23KHz, after that the value doesn't relates well to the real frequency executed.

Eq. 3 works well if:

$$f_c < 23\,KHz \tag{4}$$

Transient response Filtering

The way that the experiment was built always sends the output voltages without considering a filter for the transient response, so to avoid this transient a filter must be implemented *after* the data is downloaded by the earth station. In this section a simple filter it's shown using the cumulative mean as a metric of the transient effect.

The voltage time series $v_{out}(t)$ is divided in windows of the size of the buffer. Then the cumulative mean is computed for each window and since the mean of the input signal is zero $E\{v_{in}\} = 0$ (Figure 2), the mean for the output $v_{out}(t)$ will be zero in steady state $E\{v_{out}\}_{steady\ state} = 0$. So, the cumulative mean is computed for each window and when it reaches a zero mean.

A threshold of $\pm 5\,[mV]$ set around zero volts, so in each window the cumulative mean is computed and when it reaches this threshold, all the samples before that point are discarded/filtered and the remaining samples are considered *in steady state*.

$$If\ E\{v_{out}|_{t=a}^{t=b}\} \in [-5\,mV,\ 5mV] \Rightarrow steady\ state\ reached\ in\ t \in [a,b] \tag{5}$$

Here $v_{out}|_{t=a}^{t=b}$ is the portion of the output voltage in the current window $[a,b]$. Figure 4 shows the percent of data that belongs to the steady state versus the characteristic frequency f_c.

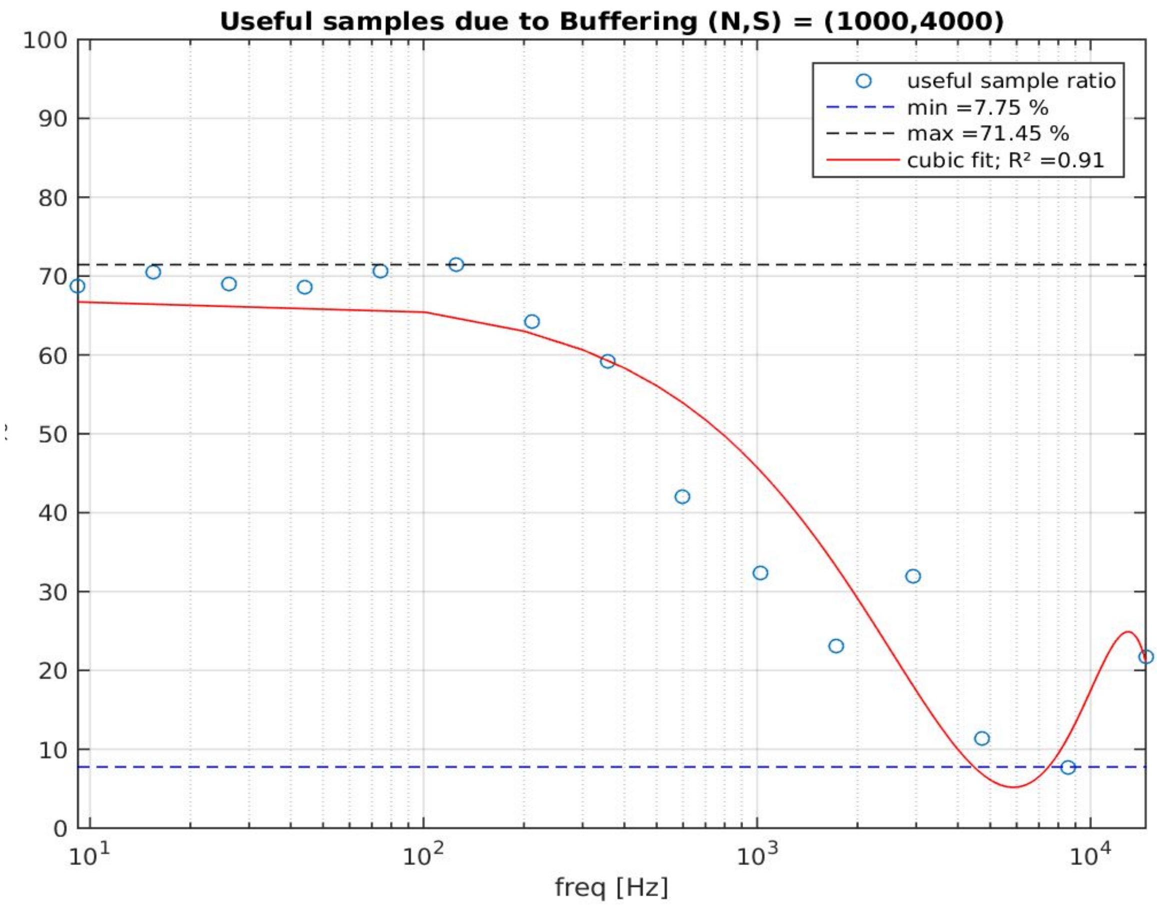

Figure 4.

Figure 4 shows that data efficiency decreases as a cubic polynomial and a $\sim 50\%$ of efficiency is reached approximately at $f_c \sim 800\ Hz$. The best efficiency ($\sim 70\%$) is reached for lower frequencies $f_c < 300\ Hz$ and worst case ($\sim 7\%$) is reached at higher values $f_c \sim 5\ KHz$. The saddle point is estimated at $f_c \sim 650\ Hz$.

An interesting effect is the higher number of samples taken of the experiment. This is shown in Figure 5 where the number of samples is increased 10 times en relation of Figure 4 and overall lower efficiency is reached.

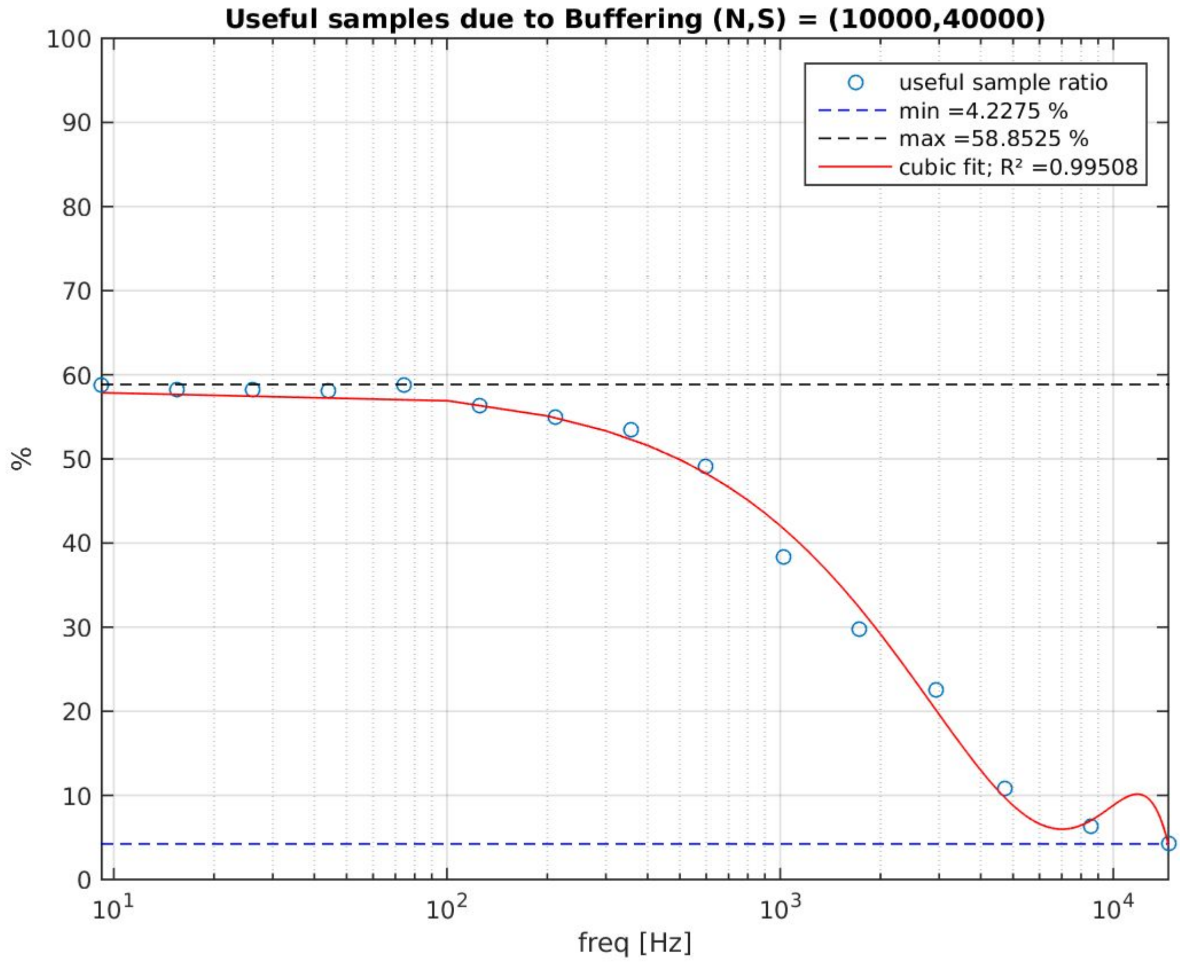

Figure 5.

The best efficiency ($\sim 60\%$) is reached for lower frequencies $f_c < 300\ Hz$ and worst case ($\sim 4\%$) is reached at higher values $f_c \sim 5\ KHz$. The saddle point is estimated at $f_c \sim 650\ Hz$.

Experiment Characterization On-Earth

In order to make meaningful analysis from the data obtained during the mission, the experiment was executed and documented inside the lab. Mission data can be compared with the data obtained inside the lab and then make better analysis.

The experiment used inside the laboratory is a replica of the original experiment inside SUCHAI. Several executions and measurements were made with this replica such as varying differents parameters and trying different processing techniques. The following results comes from executions with a replica of the experiment inside the laboratory using the following setup:

1. The experiment replica has the following parameters:
    a. Voltage range $[0\ -3.3]$ Volts.
    b. $R = 1.21\ K\Omega$ and $C = 1.47\ \mu F$.
    c. Measured cutoff frequency $f_{cutoff} =\ 92\ Hz$.
    d. Pseudo-random numbers uniformly distributed as Figure 2.
    e. Input voltages values generated by the 16-bit DAC ranges between $[0, 3.3]$ V.
    f. Output voltages values acquired by the 10-bit ADC ranges between $[0, 3.3]$ V.
2. A total of fifteen differents frequencies executions were executed and stored.
    a. All fifteen frequencies are logarithmically spaced
        i. $f_{signal}\ =\ \{9, 15,\ 26,\ 44,\ 74,\ 125,\ 211,\ 356,\ 600\}\ Hz$ and
        ii. $f_{signal}\ =\ \{1020,\ 1725,\ 2940,\ 4710,\ 8600,\ 14650\}\ Hz$ approximately.
    b. For each frequency the experiment was executed **twice,** each time the input signal having different amount of points:
        i. $N\ =\ 1.000$ points and $S\ =\ 4.000$ samples (same as in SUCHAI).
        ii. $N\ =\ 10.000$ points and $S\ =\ 40.000$ samples.
3. Characteristic frequency f_c and acquisition timing for the ADC is ruled by Equation 1.
4. The input and output voltages were stored and used to estimate their probability density functions $v_{in}(V, f_c),\ v_{out}(V, f_c)$ and the instant power on the capacitor $p_{inj}(mW,\ f_c)$ computed. The density function estimation were made in two ways:
    a. *Filtered Data:* Filtering the transient effect due buffering.
    b. *Raw Data:* Without filtering.
5. For each one of the previous frequencies and number of points, a simulation made in Matlab/Simulink was made to contrast the empirical data with a response that doesn't have buffering issues (*simulation data*).
6. The *Theoretical Response* was inferred by making a big simulation similar to point 5 for each frequency, but with $N\ \sim 3 \cdot 10^{\ 6}$ points ($10^{\ 3}$ times bigger than experimental implementation).
7. Finally, the density estimations obtained from previous measurements were compared with different metrics:
    a. Kullback-Leibler divergence.
    b. Normal distribution parameters (mean and variance).

An analysis for each of the output variables v_{out} , p_{inj} is made to show statistical properties and the range of operation of the experiment.

Output Voltage Analysis

Figures 6, 8, 10, 12 shows the time series for the output voltage $v_{out}(t)$ and Figure 7, 9, 11, 13 shows the density function estimation for different frequencies. Notice that in all the figures there are four data sets compared:

1. ***Filtered Data**:* corresponds to data described in point 4.a.
2. ***Raw Data**:* corresponds to data described in point 4.b.
3. ***Simulation**:* corresponds to simulation without buffering that has the same number of samples as *Raw Data.* It's described in point 5.
4. ***Theoretical**:* corresponds to a "bigger" simulation without buffering that is described in point 6.

Notice that time series plots are only for raw data so the peaks come from the transient response discussed in section "*Implementation considerations"*. Density estimations were made with a gaussian kernel implemented in Matlab using the `ksdensity()` function.

Because this RC circuit is a low pass filter, one can see that while the frequency decreases the time series for the output signal looks more like the input signal. Furthermore, for lower values of frequency the effect of buffering decreases (Figure 4,5).

Since the input signal distribution is uniform $v_{in} \sim U_{(-0.8,\, 0.8)}$ and the circuit behaves as a first order low pass filter, the expected distribution for the output voltage should be a normal distribution dependent on the frequency $v_{out}(V, f_c) \sim N(0, \sigma^2(f_c))$. The *theoretical* function estimation in Figures 7, 9, 11 and 13 proves this statement.

Is important to notice that the *filtered data* function is more similar to the *theoretical* and *simulation* functions than *raw data* function. This is because the transient response appears inside the *raw data* function impairing the steady state distribution. If the number of samples increases, this noisy effect on the density function would vanish, but since the SUCHAI platform has difficulties downloading big amount of data, the payloads needs to generate smaller data volumes. The filtering technique helps to accomplish that restriction.

Lastly, the *simulation* function should be the same distribution as the *theoretical* function. Their only real difference is the number of samples they have, *simulation* has the same number of samples than the on-board experiment ($S = 4000$) and *theoretical* has $\sim 10^3$ times more samples.

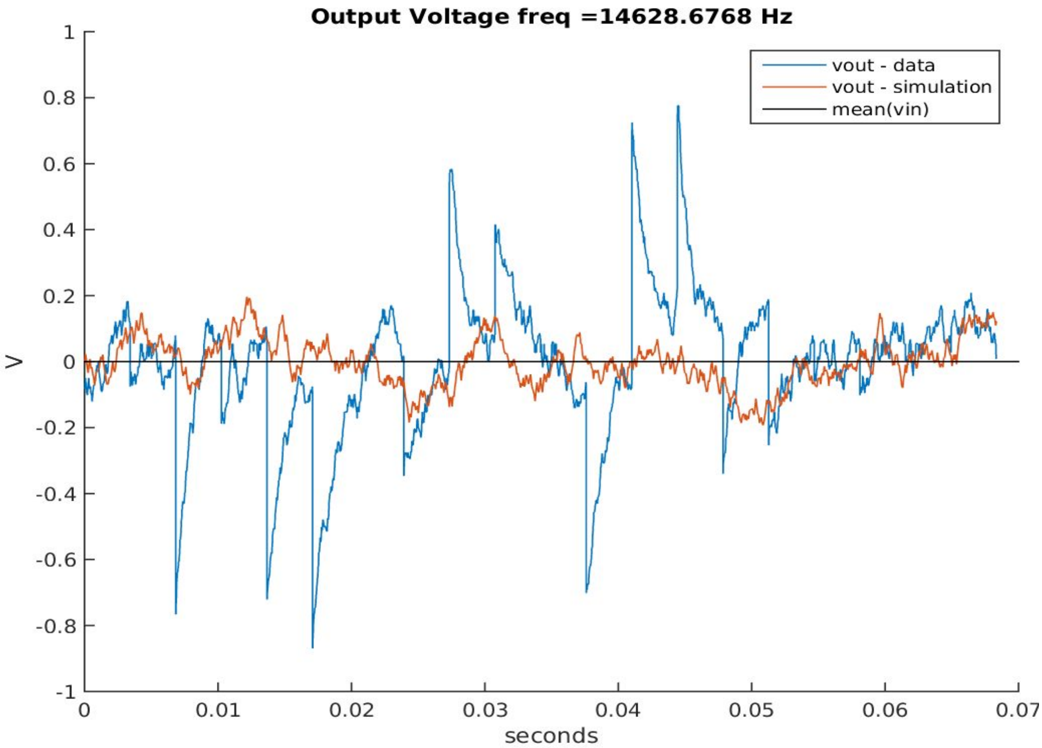

Figure 6

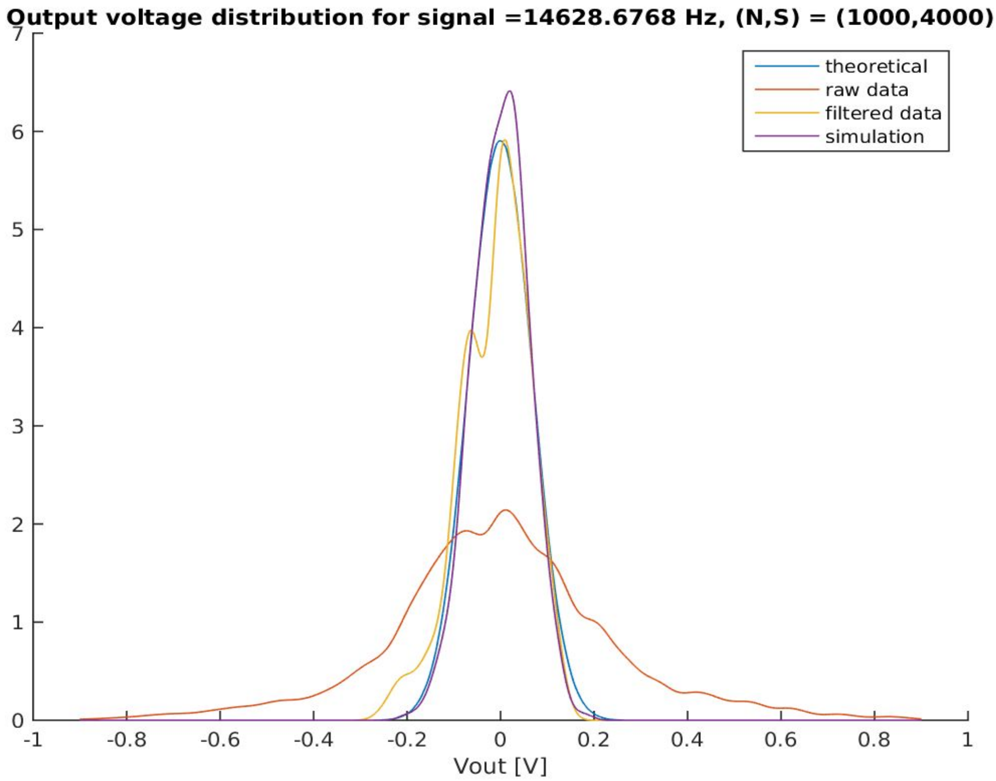

Figure 7

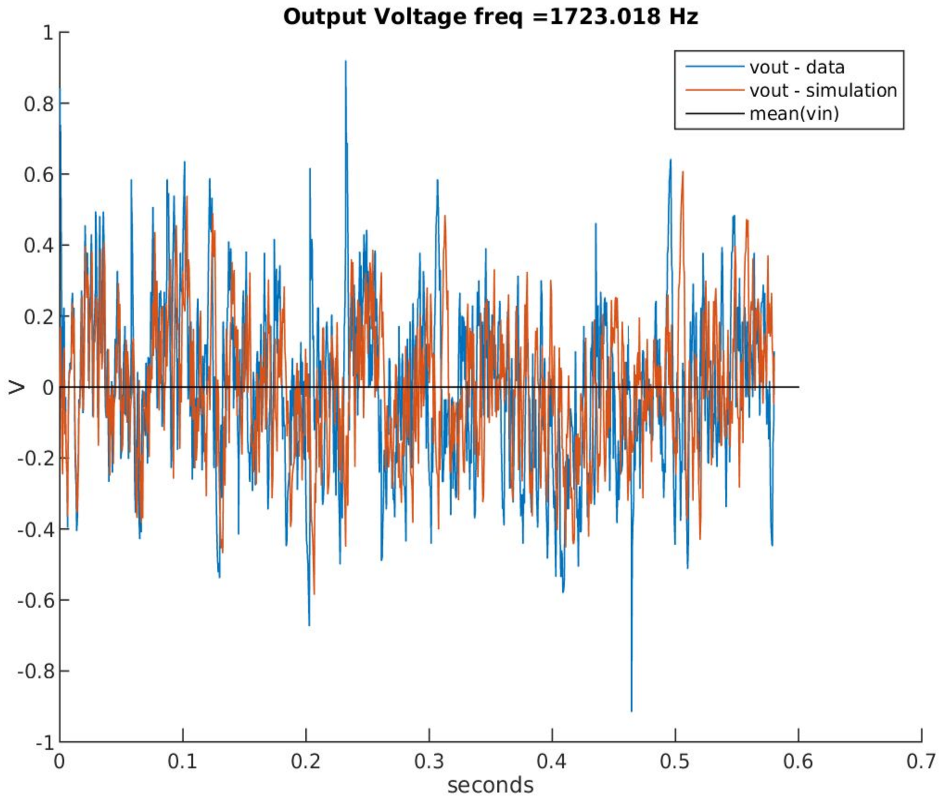

Figure 8

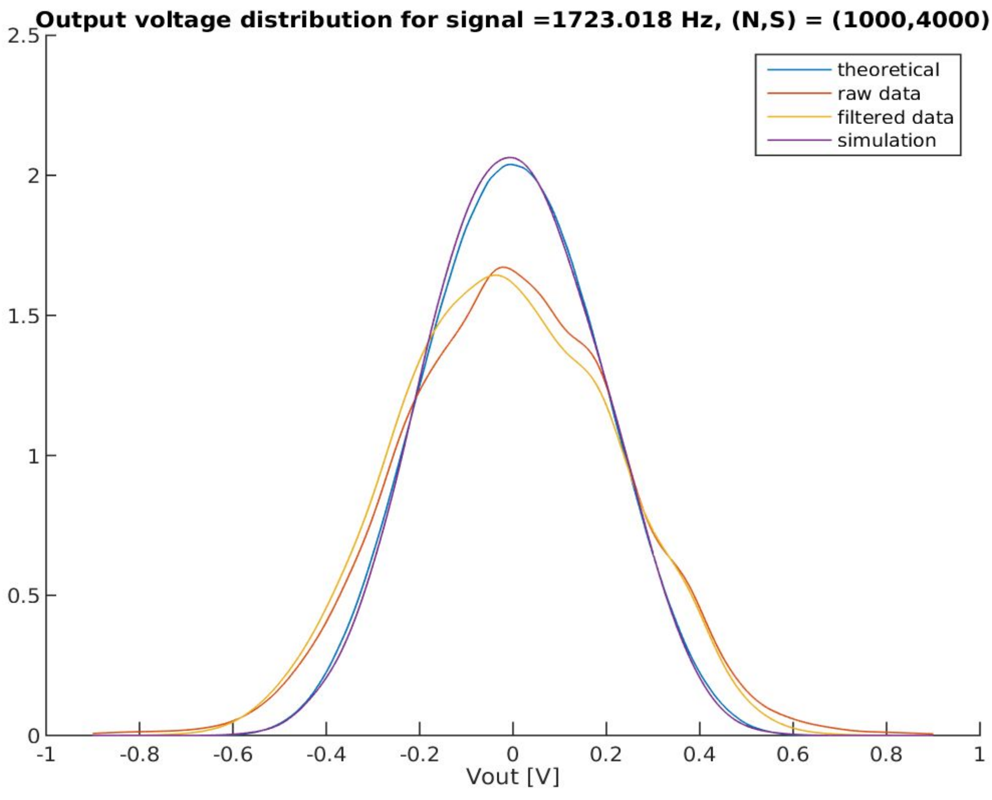

Figure 9

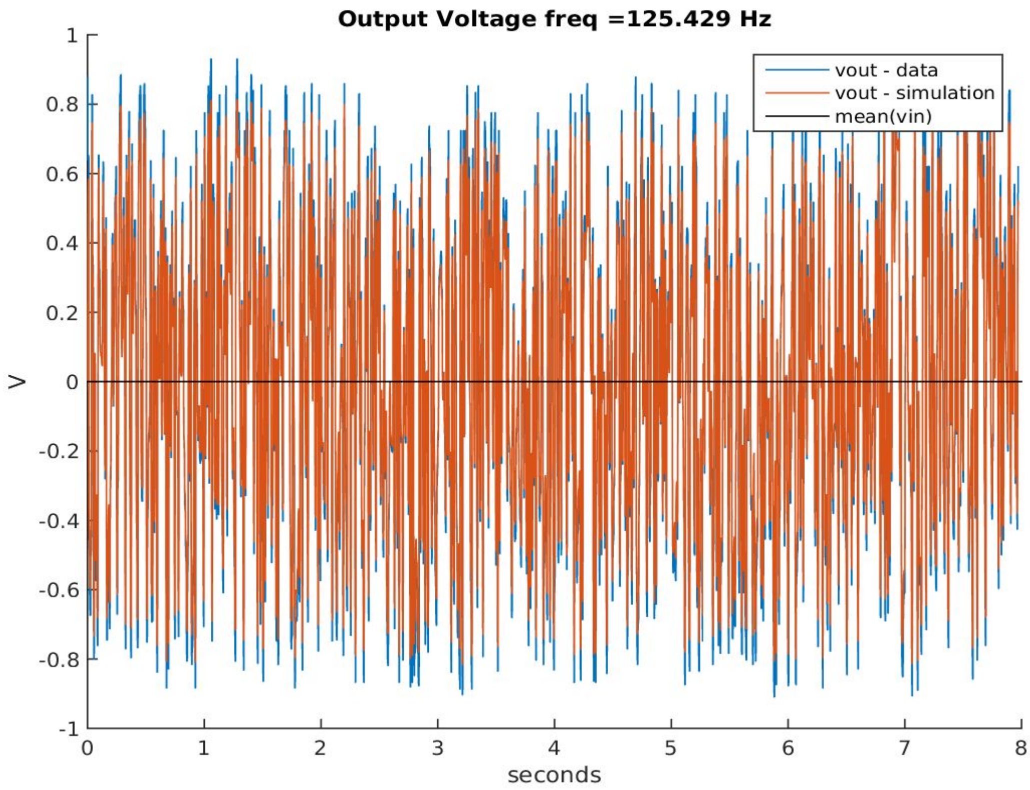

Figure 10

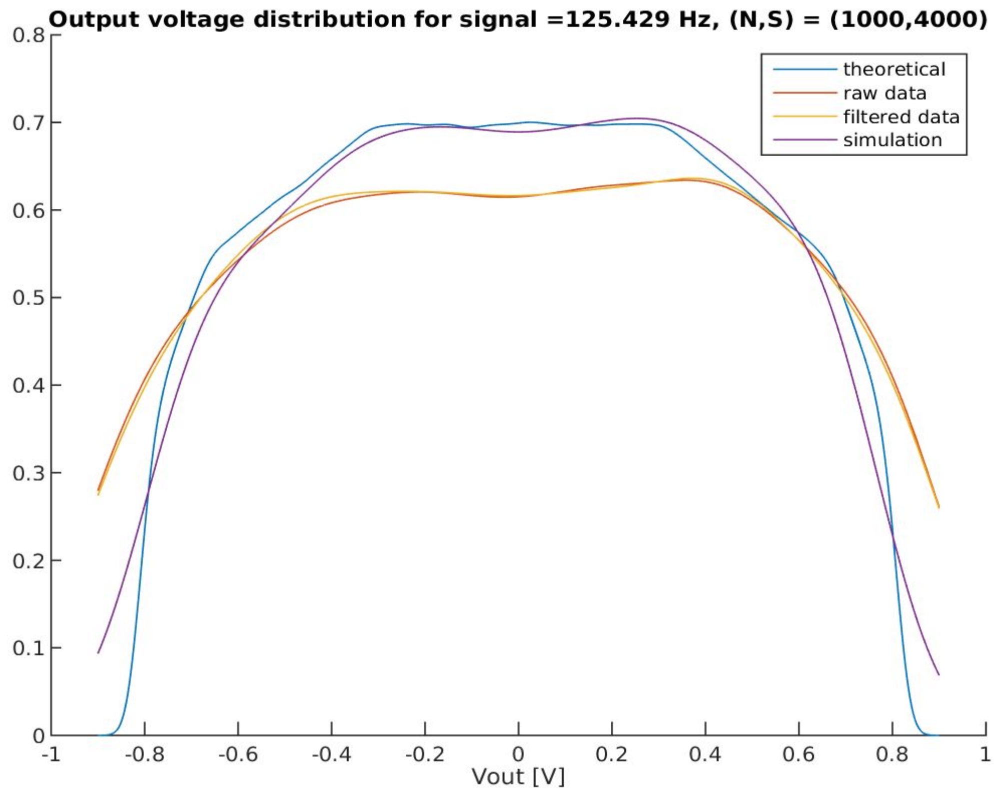

Figure 11

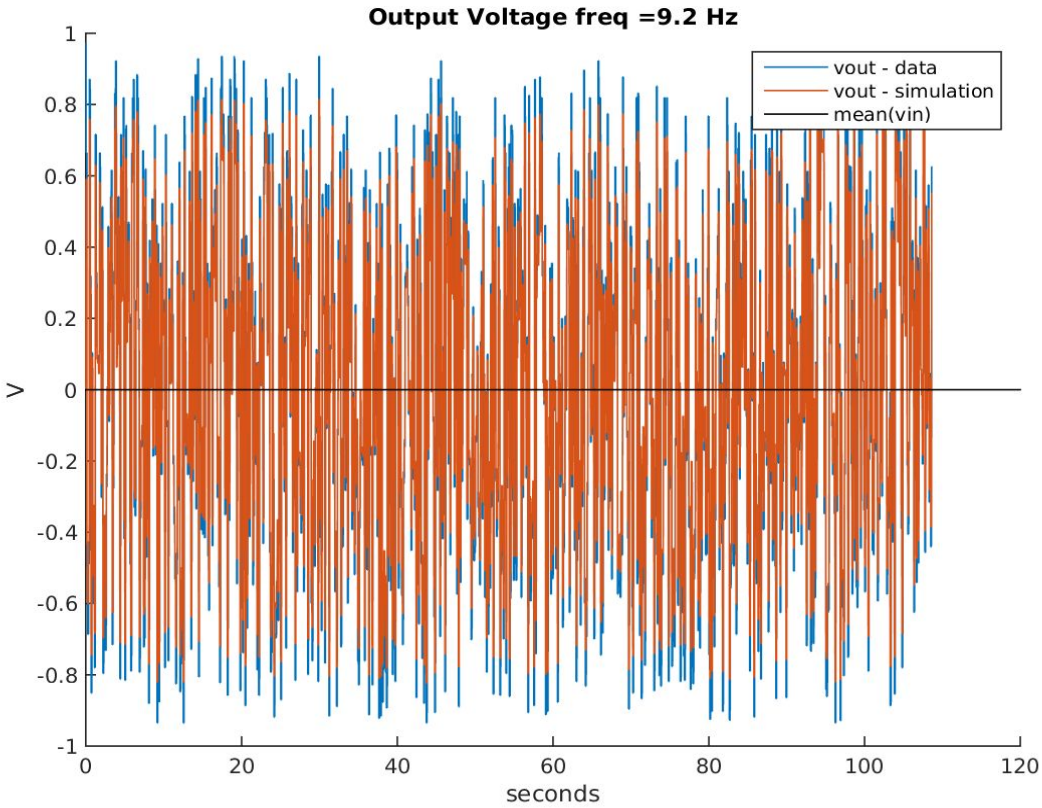

Figure 12

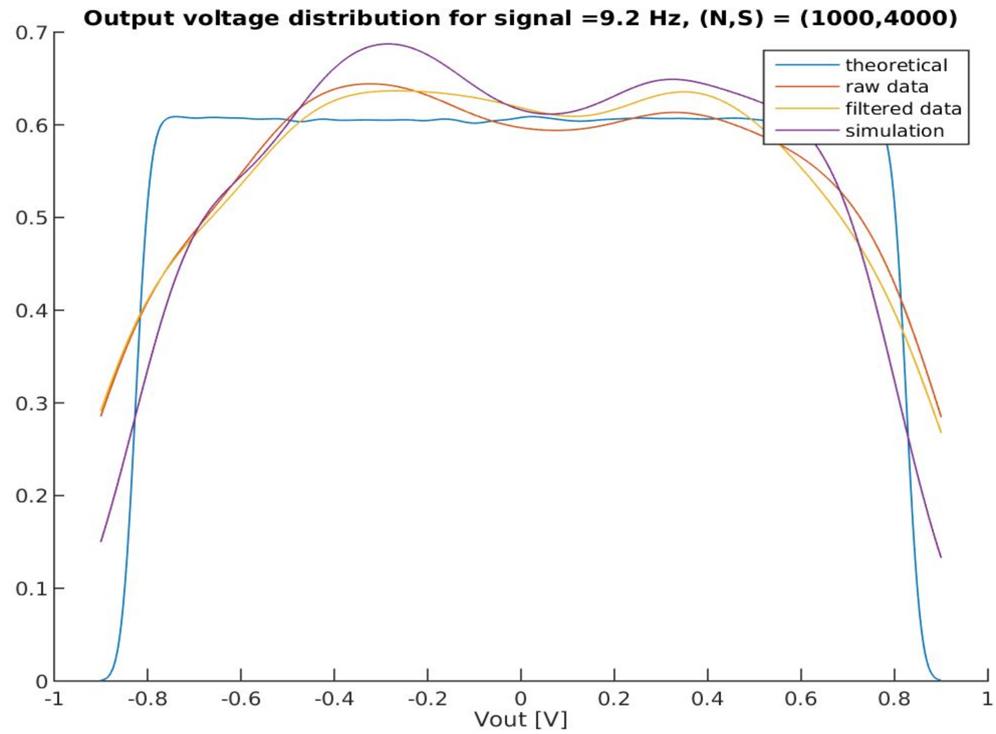

Figure 13

Injected Power Statistics

Similarly as for the output voltage statistics, the Figure 14, 16, 18 and 20 show the time series for the injected power and the Figure 15, 17, 19 and 21 show their density function estimates.

The *theoretical* density function appears to be symmetric for high frequencies (Figure 15 and 17) and asymmetric for lower frequencies with higher probability for positive values. The *filtered* function appears to show the same kind of symmetry.

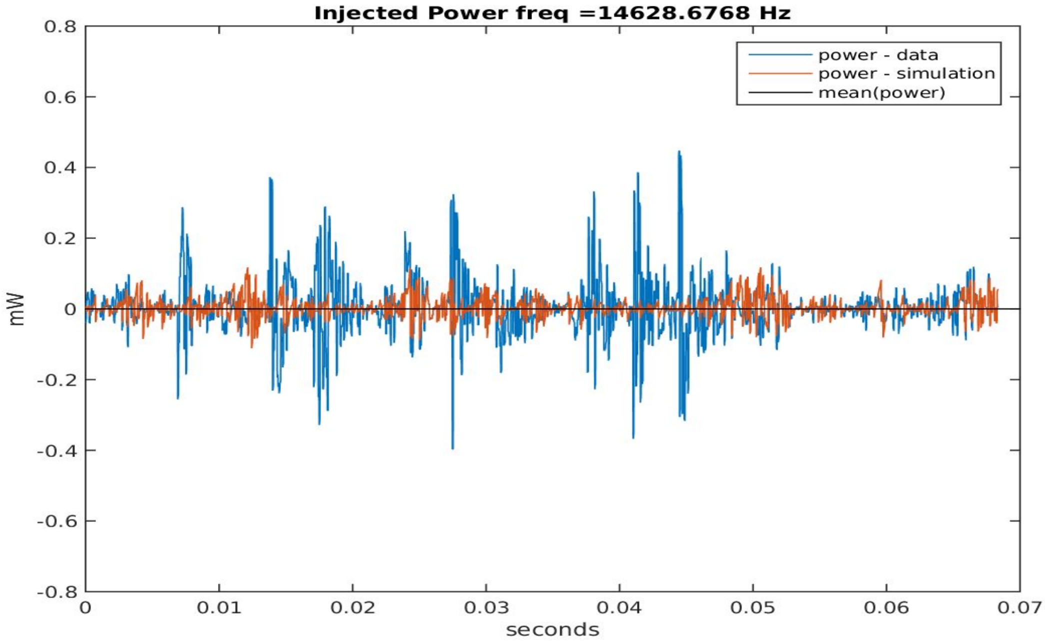

Figure 14

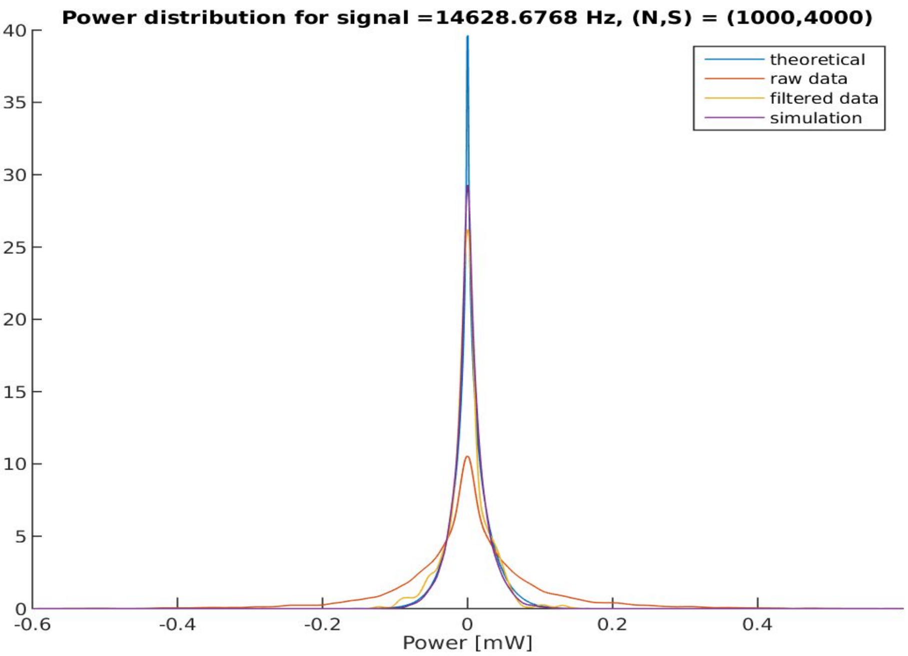

Figure 15

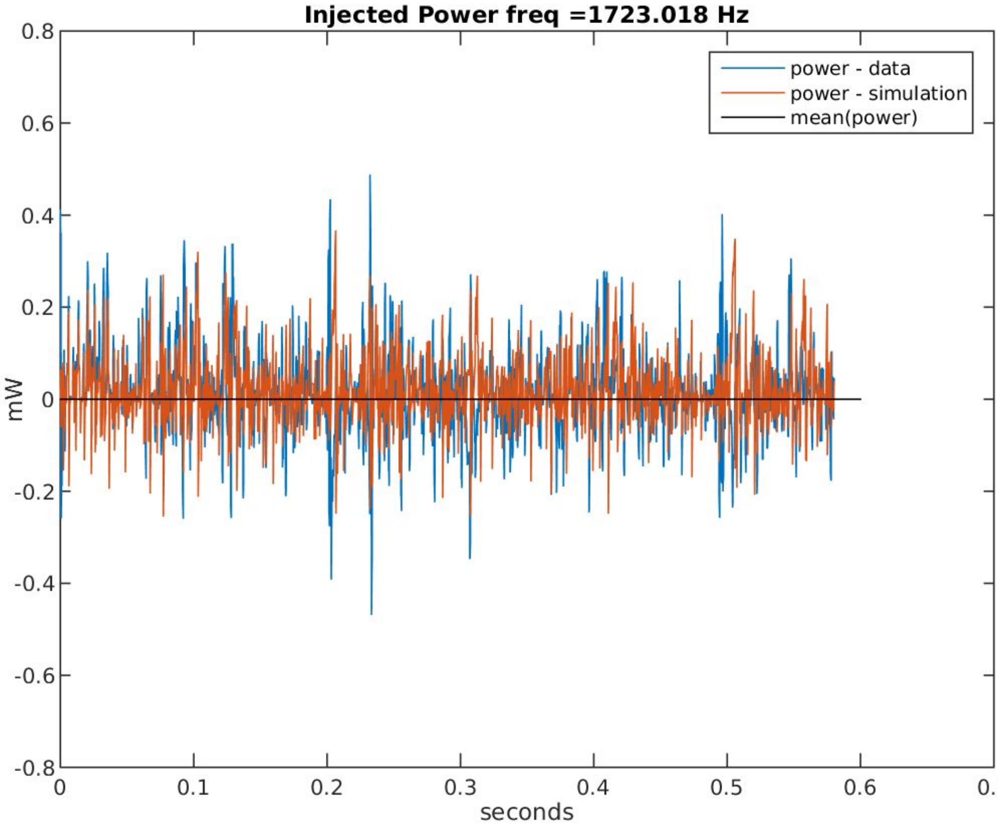

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Figure 16

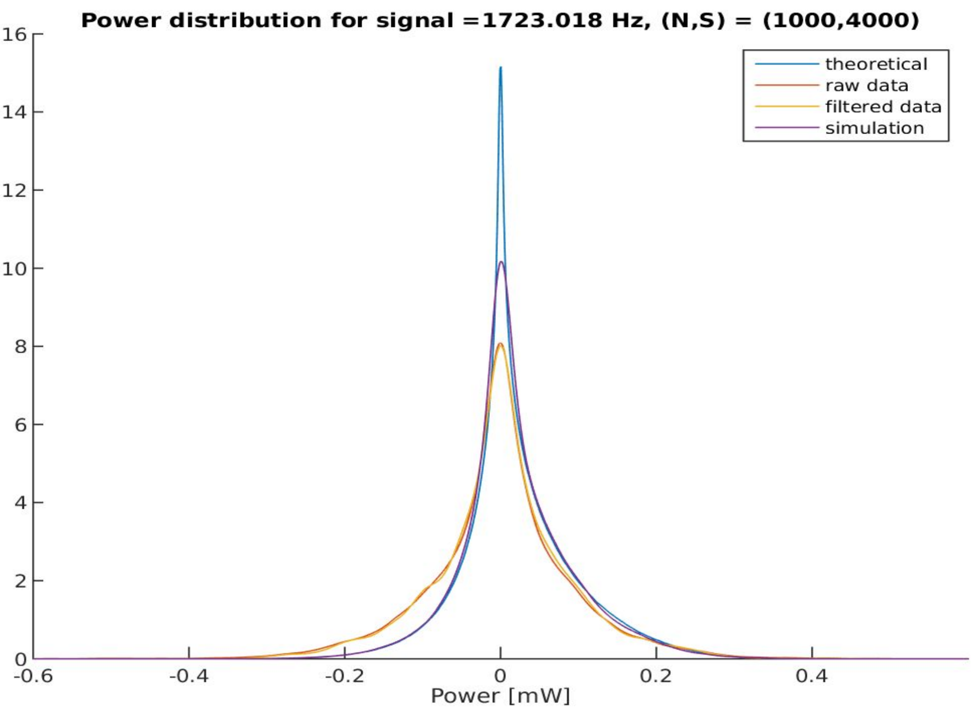

Figure 17

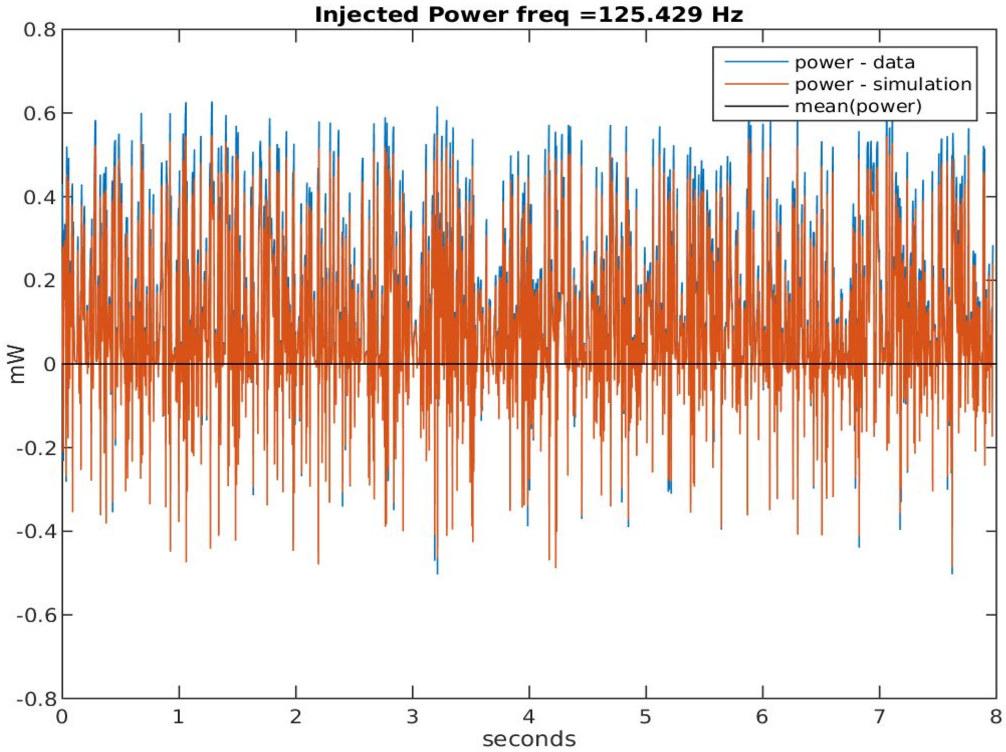

Figure 18

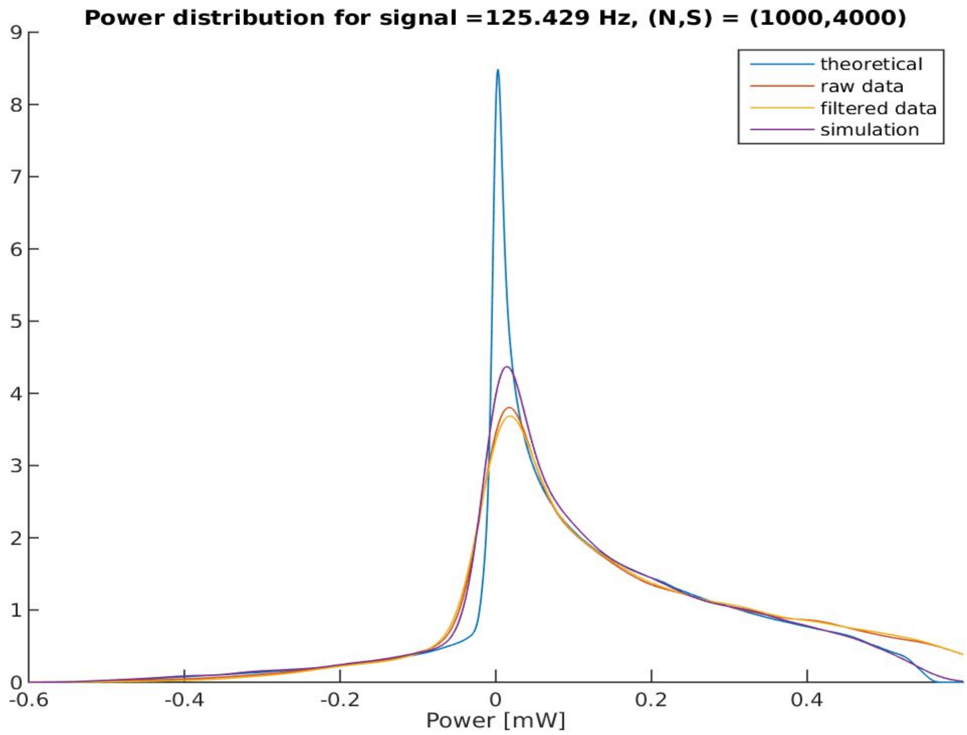

Figure 19

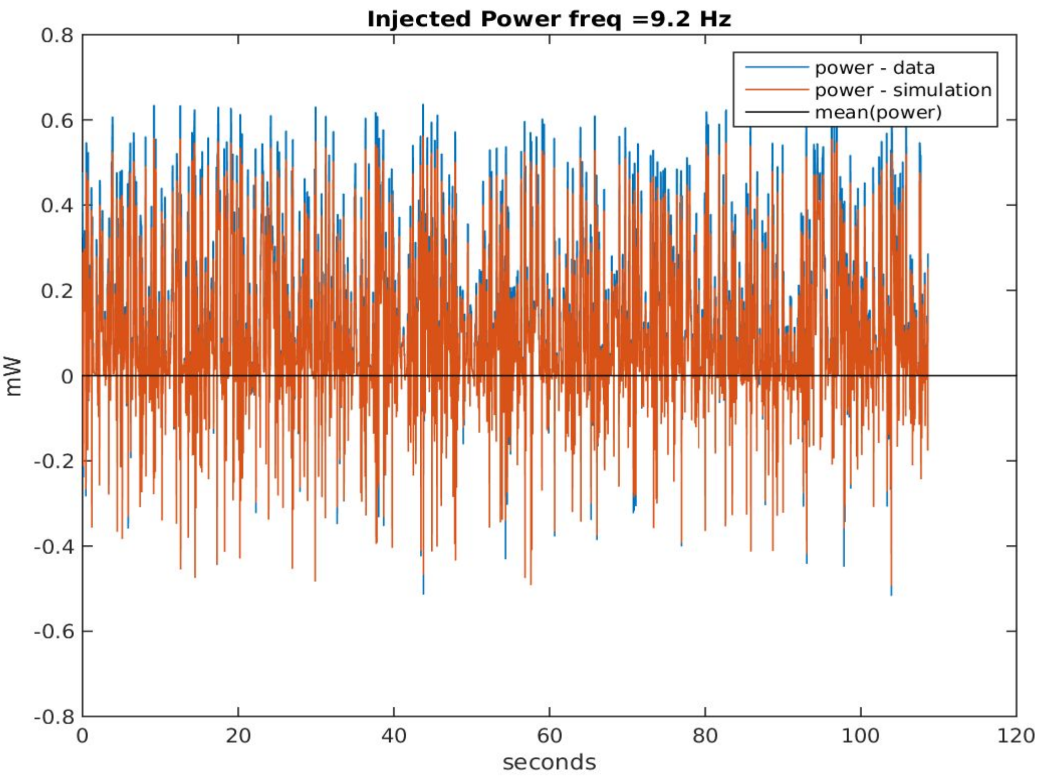

Figure 20

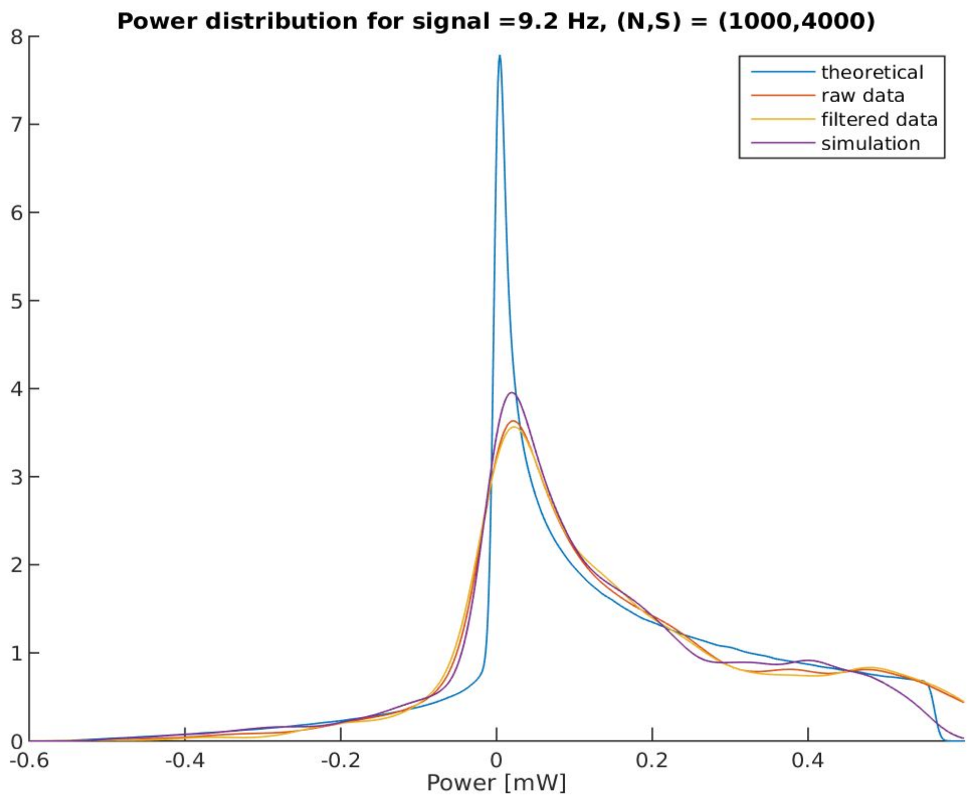

Figure 21

Inferred Density Functions Analysis

Depending on the execution frequency f_c, both variables v_{out}, p_{inj} have density functions pretty similar to the *theoretical* and *simulation* functions. A method to quantify this similarities is needed.

Assuming that the empirical distribution has a known distribution the simplest way to compare with the *theoretical* function is computing the parameters of the empirical distribution and compare with the parameter of the *theoretical* distribution. Given that the input signal distribution is always the same, the output voltage seems to distribute normal for a range of frequencies $v_{out}(V, f_c) \sim N(0, \sigma^2(f_c))$ and a gaussian fit could be used to measure the variance as dependant on the frequency $\sigma^2(f_c)$.

In the other hand $p_{inj}(mW, f_c)$ doesn't distribute normal or in a known function, so other metrics must be used.

The *Kullback-Leibler Divergence* (KL Div) is introduced as a metric to quantify the difference between two arbitrary distributions. This is a metric from information theory that helps to analyze the differences between the empirical results obtained through the replica and the simulated/theoretical model.

So, the metrics used for each distribution are the following:

1. For $v_{out}(V, f_c)$
    a. Kullback-Leibler divergence.
    b. Normal distribution parameters (mean and variance).
2. For $p_{inj}(mW, f_c)$
    a. Kullback-Leibler divergence.

When computing the KL Divergence for each distribution $P_{v_{out}}(V)$ and $P_{p_{inj}}(mW)$, the comparisons made are:

1. ***Filtered Data* vs *Theoretical Response***: This shows how the experimental results differs from the expected or theoretical response.
2. ***Unfiltered Data* vs *Theoretical Response***: This shows how the experimental results differs from the expected or theoretical response when no filtering is used.
3. ***Filtered Data* vs *Simulation (Simulink)****:* This shows how the experimental results differs from an ideal implementation with the same number of samples.
4. ***Filtered Data* vs *Unfiltered Data:*** This shows the effect of the transient response in the density function estimation.

Figure 22-25 shows a frequency dependent graph that shows this comparisons using the KL Divergence for the output voltage distribution.

Comparing Figure 22 and 23, one can see that the transient response impairs drastically the density function for high frequencies $f_c > 1\ KHz$, that is why the filtering mitigates this effect having a nearly constant difference between the empirical data versus the theoretical distribution.

Figure 24 shows how for high frequencies the real implementation differs from an ideal implementation of the experiment. This helps to decide the upper limit for frequencies executed during the mission.
Lastly, Figure 25 shows the effect of filtering in the function estimation. Clearly, for low frequencies the functions are pretty similar to unfiltered case, but for high frequencies the filter helps much better to the density estimation.

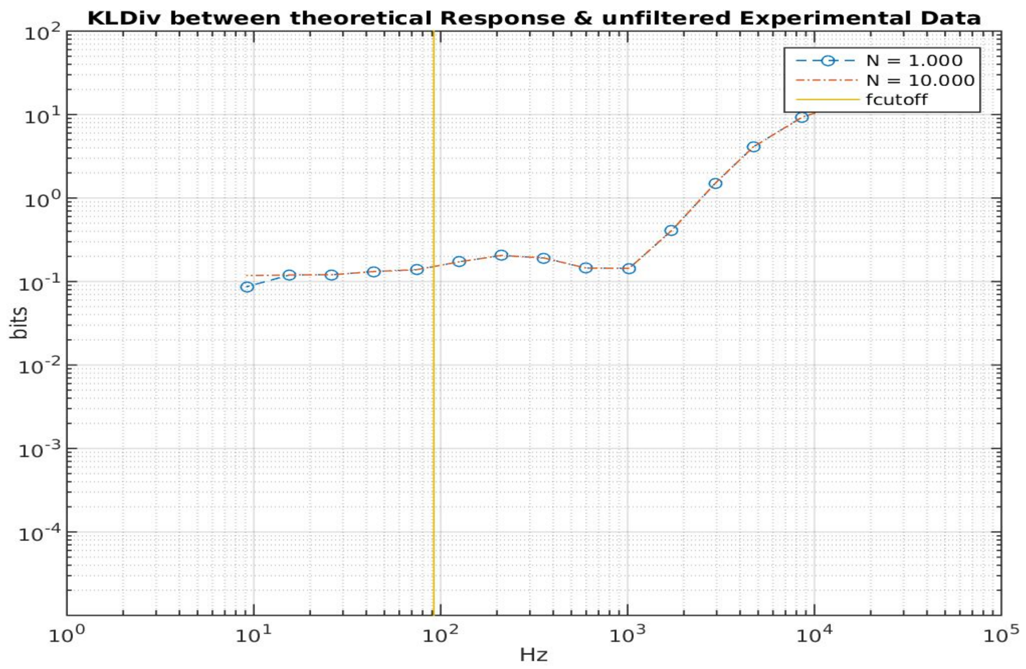

Figure 22

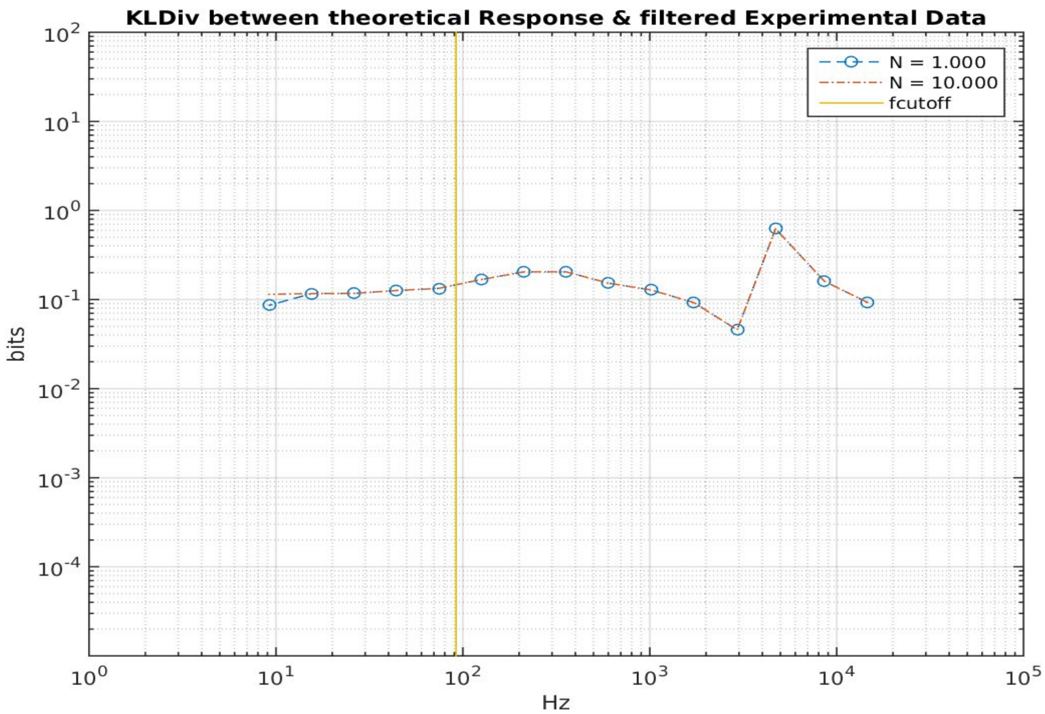

Figure 23

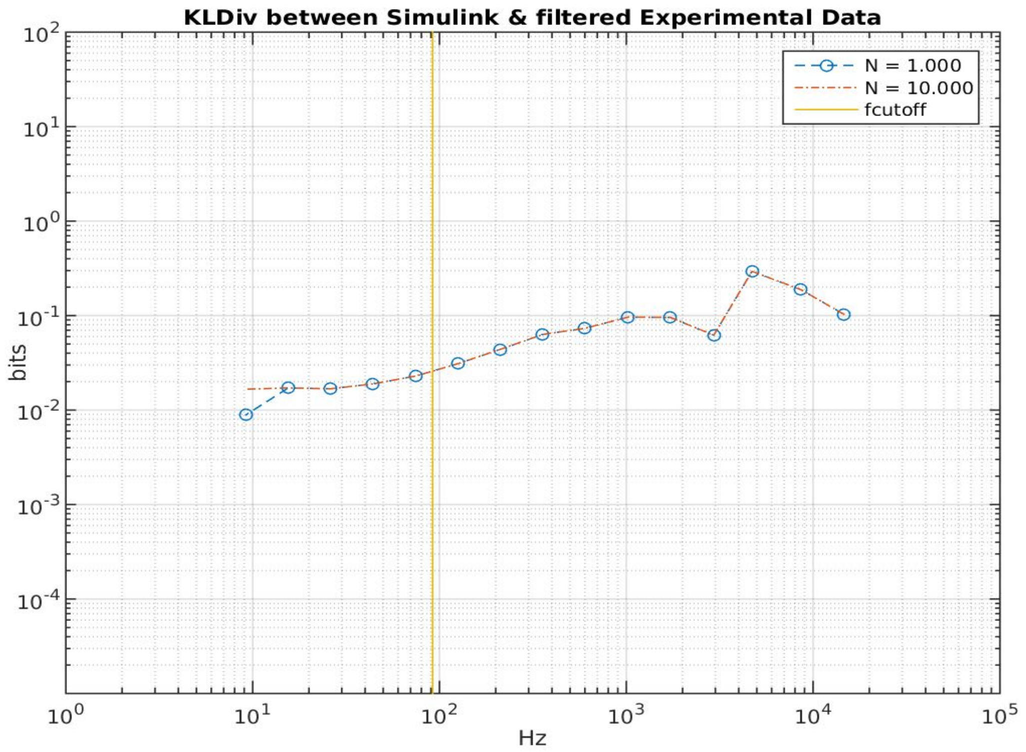

Figure 24

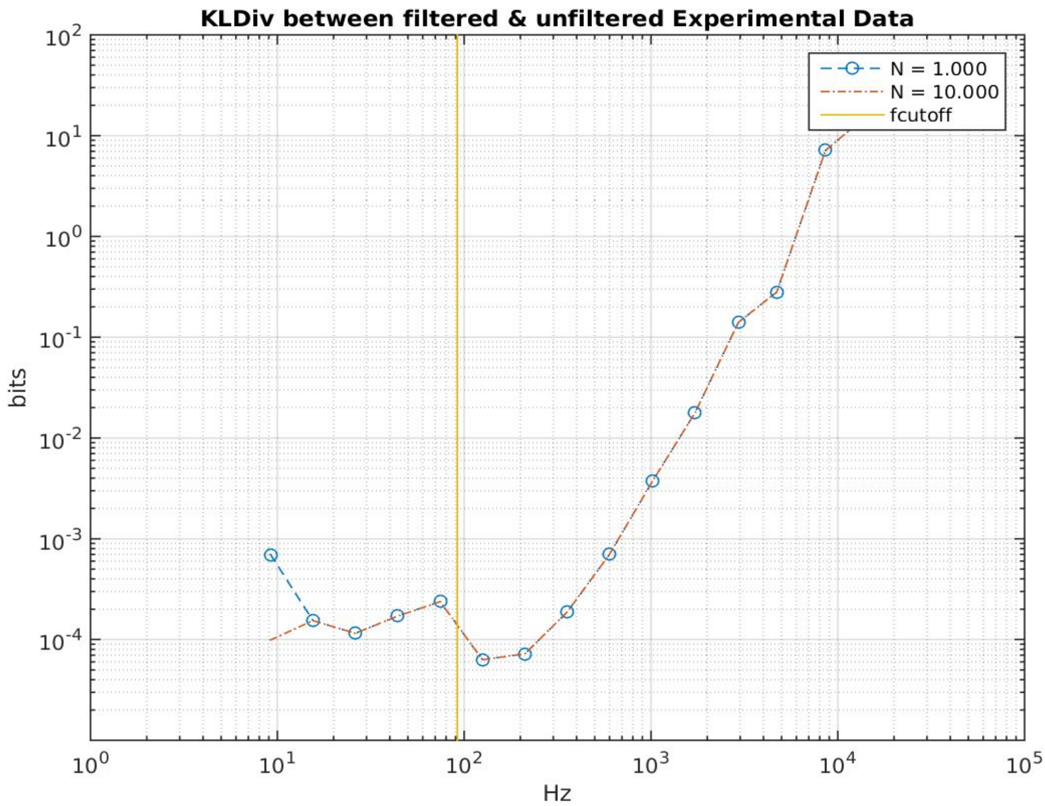

Figure 25

Figure 26 shows the variance dependency over the frequency was inferred from the output voltage distributions estimated, and the equation fitting:

$$\sigma^2(f_c) = \frac{a*f_c}{(f_c+b)^2} \quad (6)$$

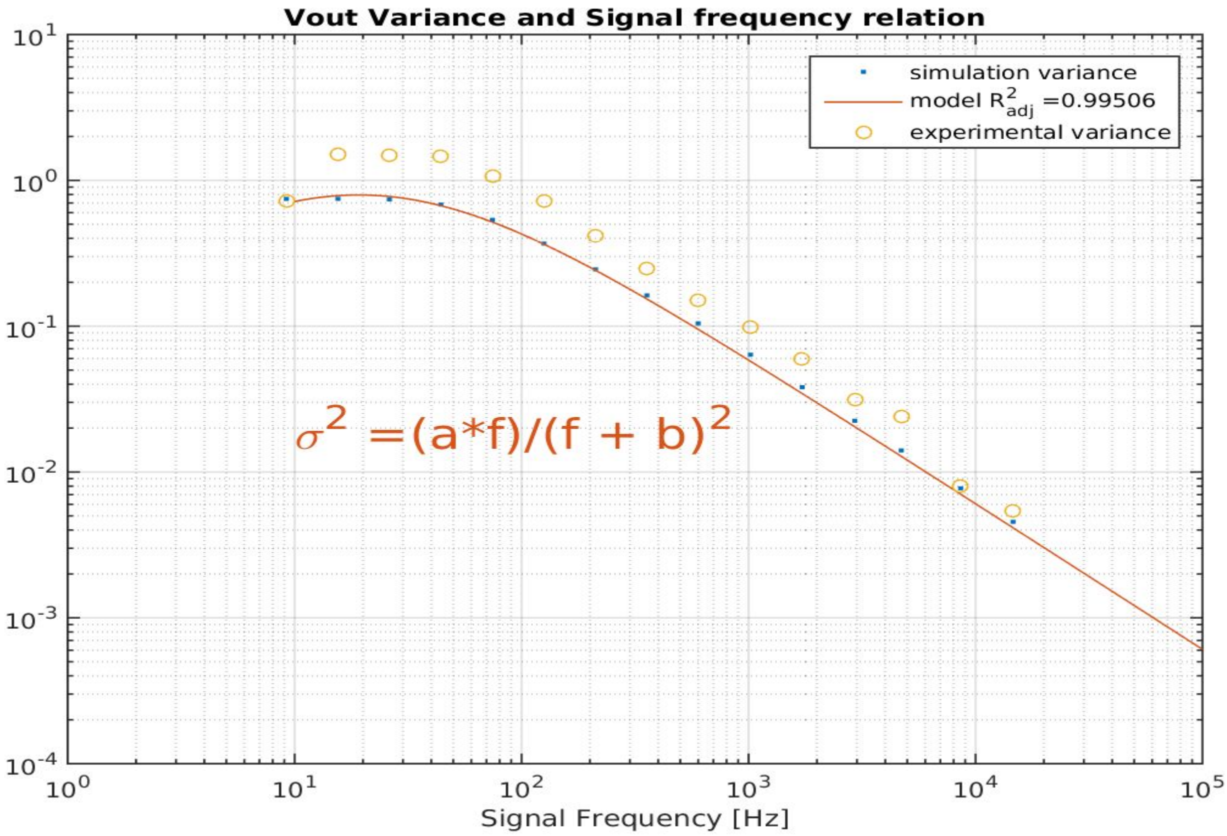

Figure 26

Now the variance for the filtered data versus the expected variance is shown (Equation 6, Figure 27). Unlike others metrics, the fitted variance improves with higher frequencies, this is because for lower frequencies v_{out} doesn't adjust well to a normal distribution (see Figure 11 and 13) compared to high frequencies (see Figure 7 and 9). Because of this, the variance appears to be less convenient than KL divergence since the v_{out} does not distribute normal for every frequency.

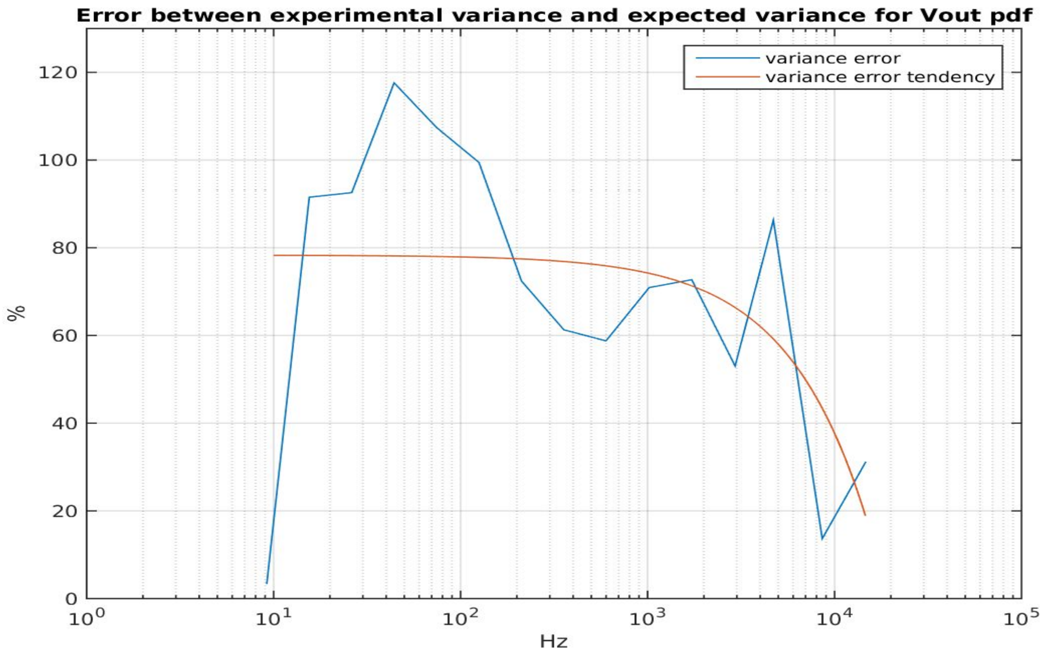

Figure 27

Figure 28 - 32 shows the same plots, but for the injected power distribution:

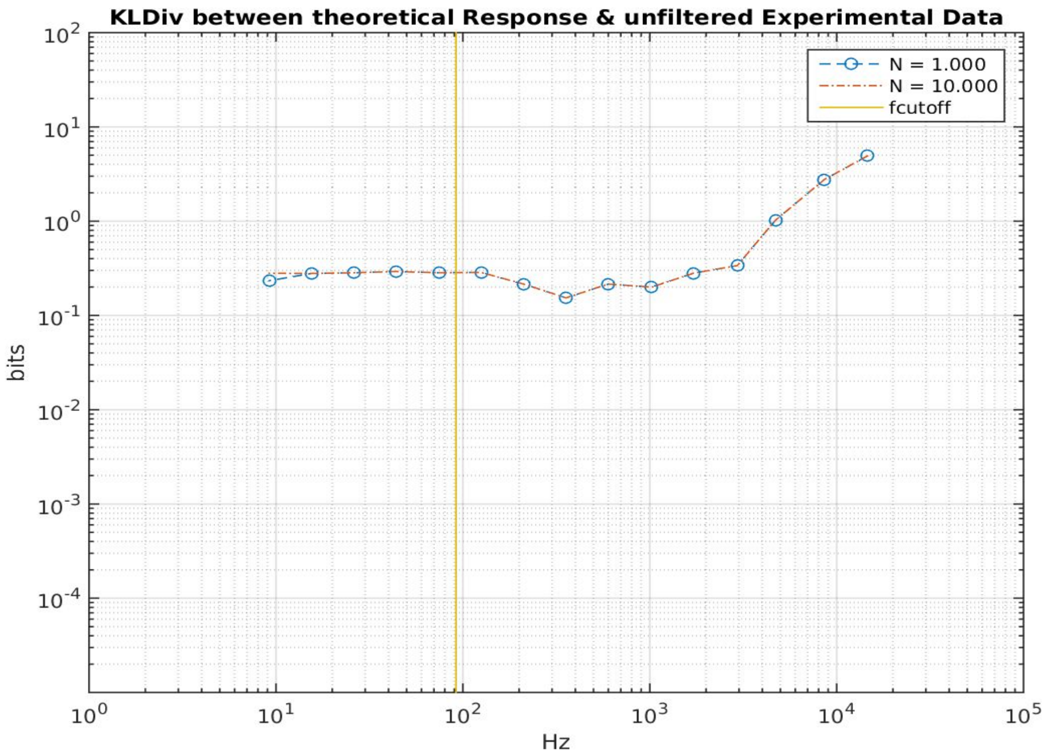

Figure 28

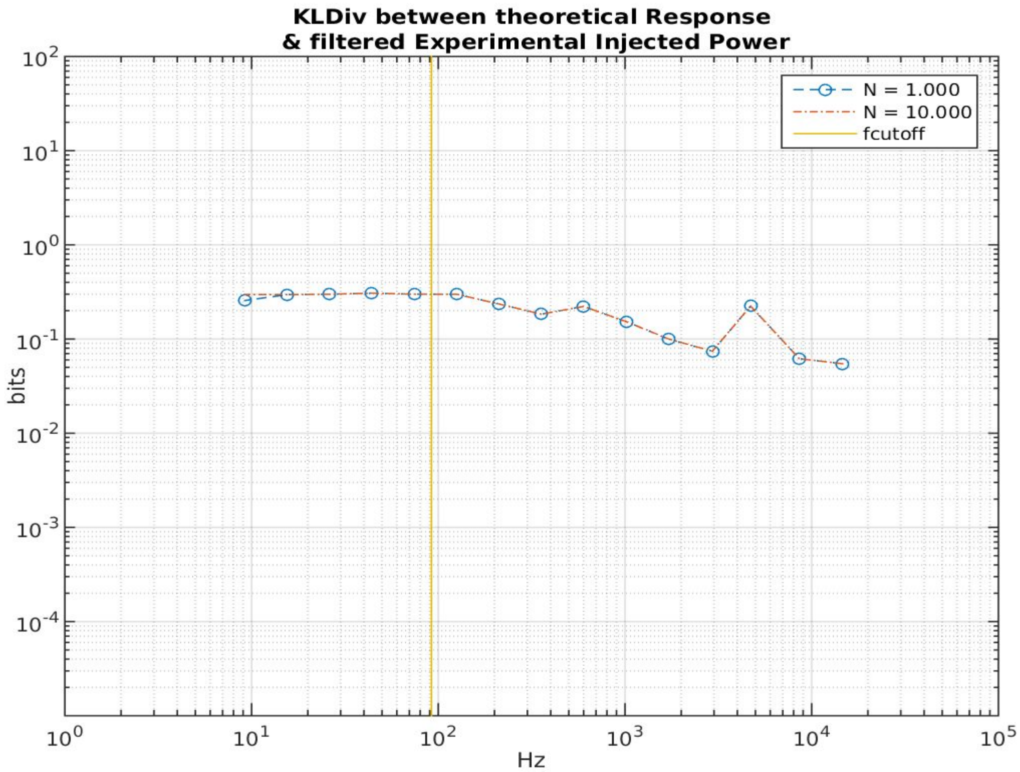

Figure 29

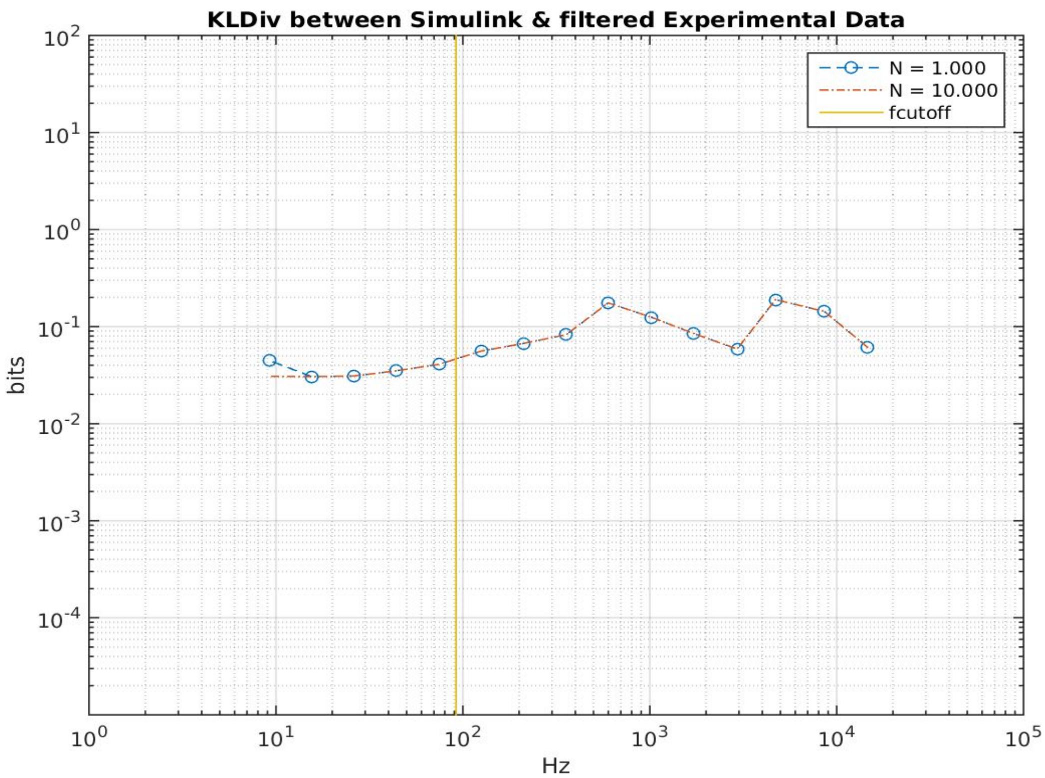

Figure 30

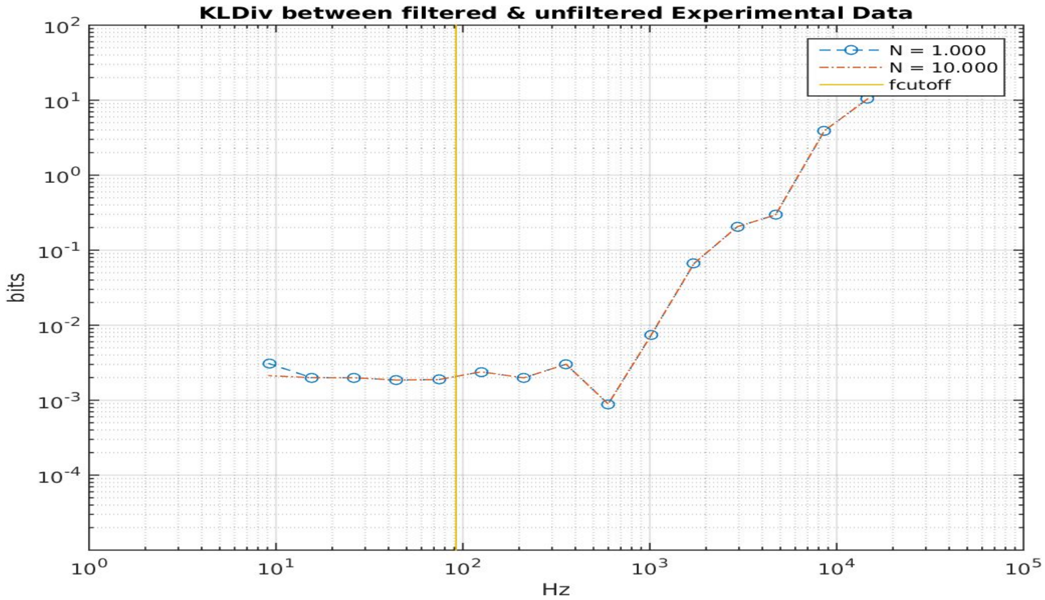

Figure 31

Finally, notice that a greater number of samples $N/S = 10.000/40.000$ doesn't seem to add more information than the on-board experiment ($N/S = 1.000/4.000$), since all graphs of KL Divergence are the same for each case.

Finally, a maximum range of frequency operation must be set. Looking the *filtered-theoretical* comparison of KL Div for v_{out} and p_{inj}, a maximum frequency of $max(f_c) = \ 2.5\ KHz$ should work. So, the experiment range of operation should something like:

$$f_c \ \in [10, 2500]\ Hz \tag{7}$$

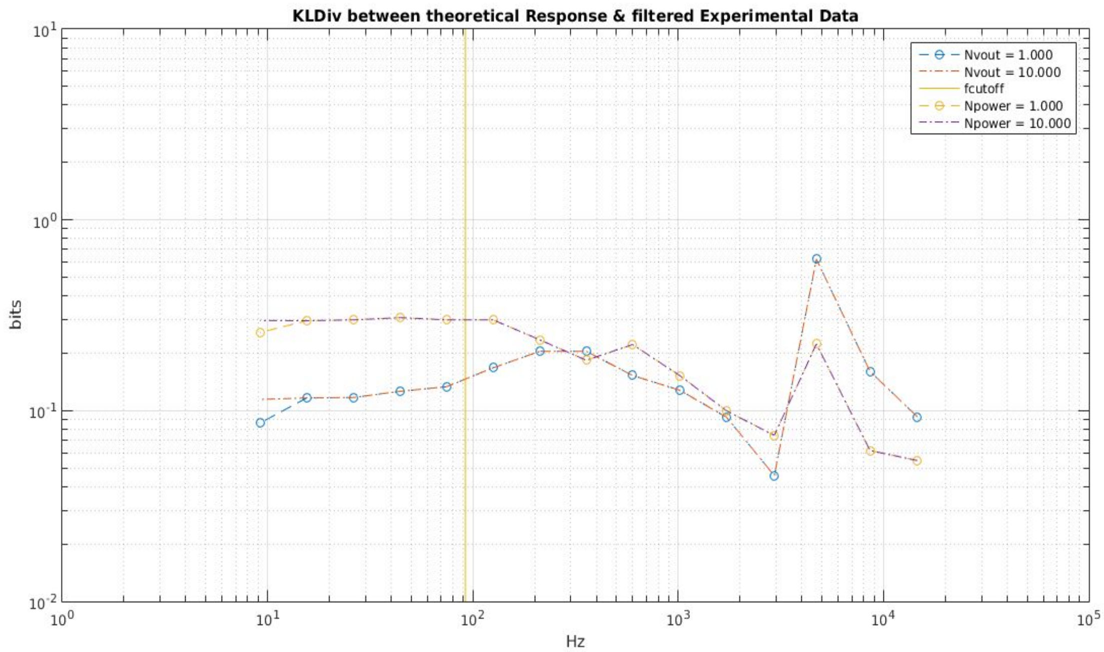

Figure 32

Conclusions

A full documentation of the physics experiment aboard the SUCHAI cubesat has been presented. Besides its simple objective and implementation, several processing techniques and methods have been used to analyze the data acquired.

The main objective of the experiment was discussed in the beginning of this document, as well as its expected results were documented. The execution of the experiment through earth-station was explained too and a fixed range of frequencies was proposed.

Analysis of the experiment was made inside the laboratory with a replica, executing several times and changing fixed parameters such as: range of frequencies and total amount of samples. A simple analysis centered in information theory metrics such as the Kullback Leibler Divergence has been made to find the maximum range of frequency operation for this experiment and the effect of the amount of samples in the density function estimation.

Future work should consider eliminate the transient response introduced by the buffer used to save the voltage measurements. The density function estimation inside the cubesat is the best option to decongest the communication with the earth station, but because of the reduced computation power on SUCHAI this choice was discarded. Easier and more intuitive methods to operate the experiment through command line are considered for future work and similar experiments inside SUCHAI 2.

References

[1] Falcón, C., & Falcon, E. (2009). Fluctuations of energy flux in a simple dissipative out-of-equilibrium system. Physical Review E, 79(4), 041110.