Kyoto University
Research Reactor Institute

Innovation Lab Internal Report

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Overview

This document outlines the analysis conducted on time-series voltage data collected from a beam study experiment on October 26, 2015. The purpose of this experiment was to investigate the beam loss dynamics with respect to LINAC trigger delay and pulse width. The data that was analyzed was collected from the INU bunch monitor. During the experiment, two parameters were varied: LINAC trigger delay, and pulse width. The results of the analysis confirms that the beam loss is faster when the LINAC trigger delay is high, with a low pulse width.

Analysis Method

The following procedure was utilized to analyze the data collected from the experiment:

1. Cleaning data: removing noise, defining signal regions
2. Envelop generation: determining the positive envelope, defining fitting model
3. Extracting features: defining features and fitting models

Cleaning the Data

Firstly, a sample of the RF-noise was subtracted from all the data (Figure 1).
Now we can work with data that is, on average, closer to the signal that the beam monitor observes. To define the signal region, we simply exclude the first $10,000$ data points. The excluded data points include a region of non-dynamic behaviour of the signal (Figure 2).

Envelop Generation

The positive envelope is important to determine as it characterizes the dynamic behaviour of ground. Namely, as time progresses, the ground voltage rises due to an integrator-like effect. Data analysis should occur referencing ground to be 0 V, and in order to do this, the envelop must be determined. In order to create the envelope function for the signal, I implement a two-step process: peak-detection and fitting. My peak detection technique requires a window to determine if a given point is a peak. In order to find the positive envelope, I make the resolution of the peak detection algorithm high enough, so it can find any given peak. Then, I take these points and perform a nonlinear least squares fitting to a model function (Figure 3). The rest of the analysis is carried on $V_{clean} - V_{envelope}$ or the *ideal* data (Figure 4).

The model function used for the envelope is,

$$V(t; V_0, A_1, A_2, \omega_d, \beta) = V_0 + e^{-\beta t}(A_1 \cosh(\omega_d t) + A_2 \sinh(\omega_d t)), \tag{1}$$

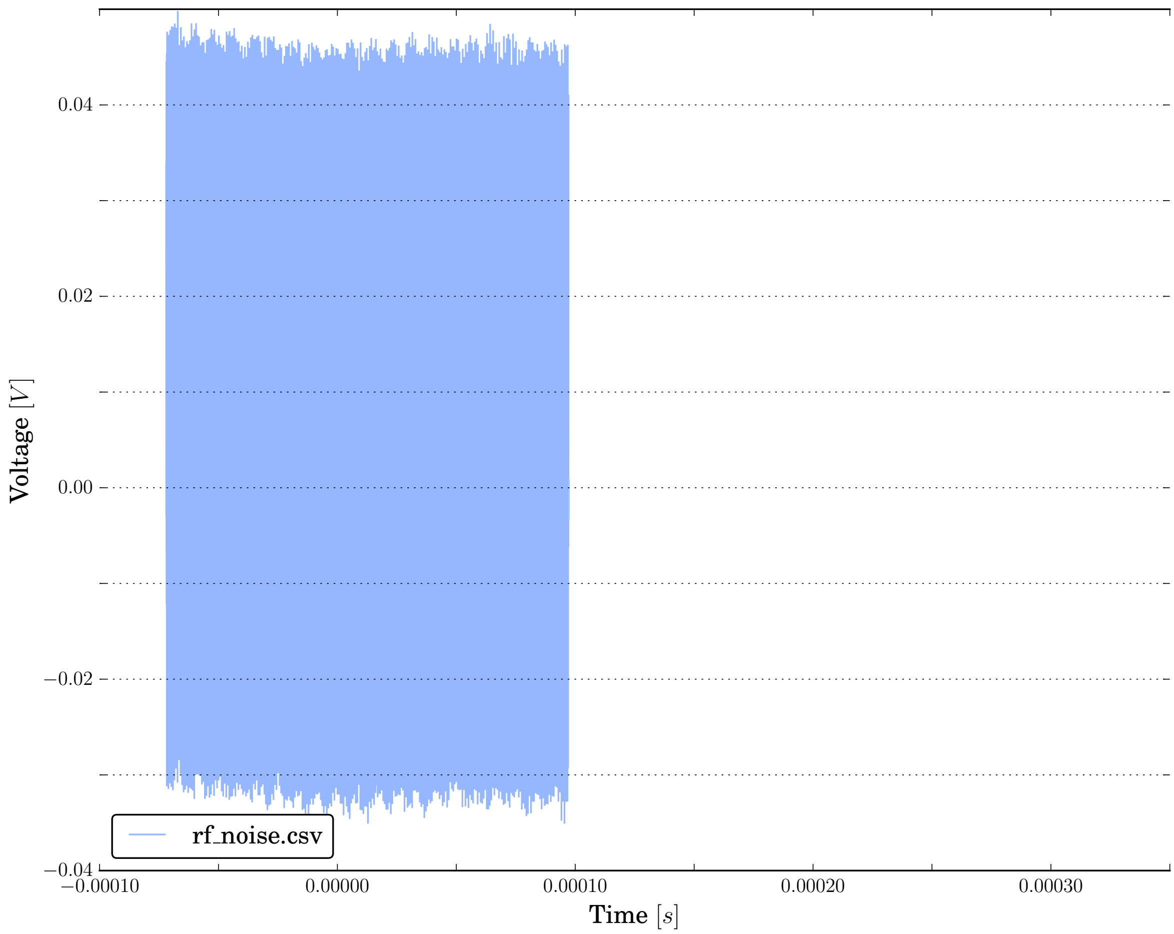

Figure 1: This is the measured rf noise. The negative time values simply means that the oscilloscope had a horizontal offset.

where the fitting parameters are: V_0, A_1, A_2, ω_d, and β.

Because the measurement setup can be seen as an RLC circuit, Equation 1 was used as a model function. However, by using Equation 1, I am asserting that the circuit is second-order and the output response is overdamped with a step input. This assumption can be loosely justified by considering the amount of resistance and inductance values of just the amplifier and the wire [1], [2]:

	BNC Coaxial Cable (RG58C/U)		SA-220F5 Amplifier
Resistance	1640Ω at 32.80Ω/m	**Impedance**	In: 1MΩ, Out: 50Ω
Inductance	16μH at 0.32μH/m	**VSWR**	In: –, Out: 1.3

Taking a naive standpoint, the large impedance values indicate that using an overdamped modeling function is a reasonable choice.

Extracting Features

The two main features extracted from the data were: α, and $\mathbf{P}$.

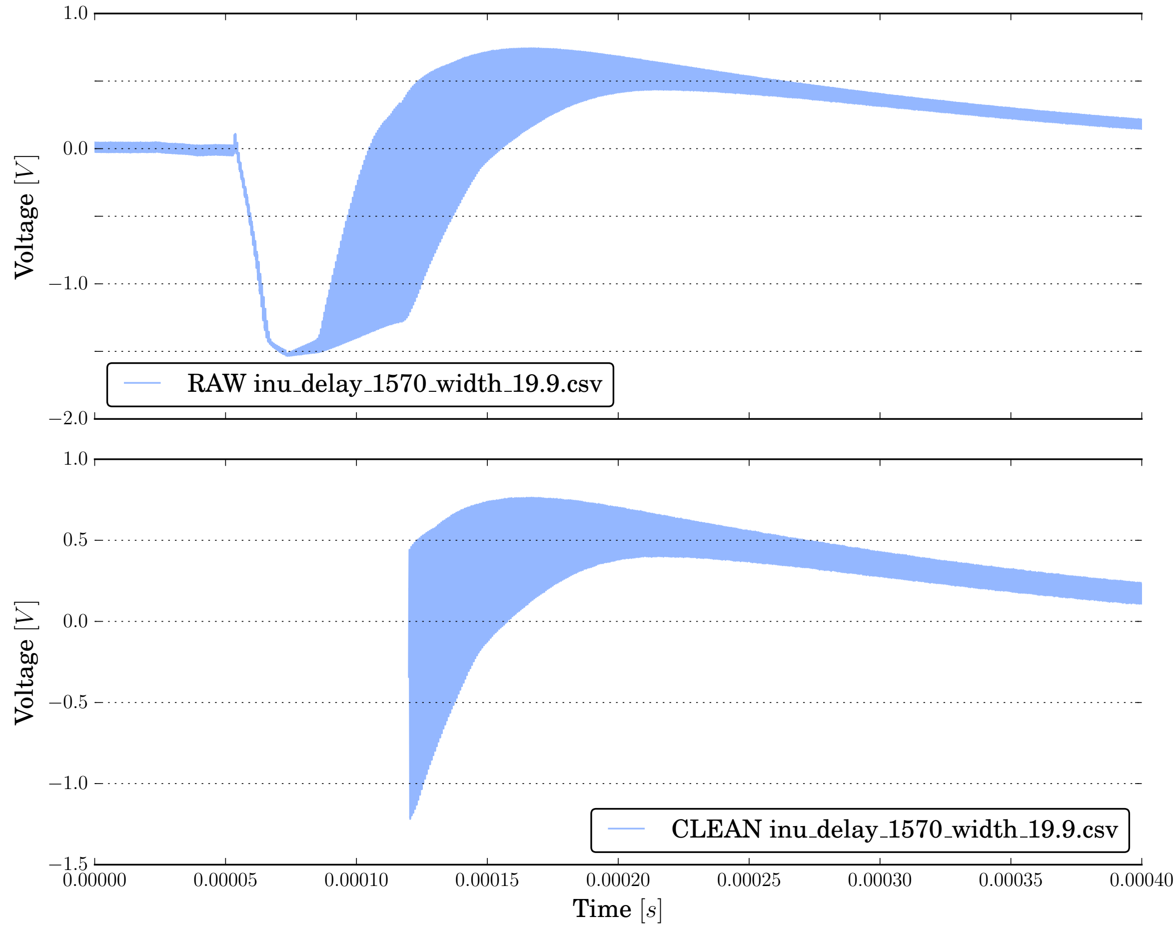

Figure 2: This figure shows an example of how the raw data is converted into clean data. The analysis occurs on the cleaned data. The top plot is the raw data, and the bottom plot is the raw data with the rf noise subtracted. Furthermore, the bottom plot, referred as the *clean* data, excludes the first 10,000 data points.

Extracting α

I first generate the bunch area difference per turn, defined as,

$$\Delta(t_i) = A_q(t_i) - A_q(t_{i-1}) = \int_{t_i - 1}^{t_i} V(t')dt'. \tag{2}$$

$V(t)$ is the ideal data (Figure 4) and $i \in [1, 2, 3, ..., N]$, where N is the number of data points collected. Physically, Equation 2 gives an idea on the magnitude of the amount of charge induced by the beam per time step i (or per turn, given the proper transformations). The distribution of $\Delta(t)$ contains information how the beam behaviour is changing – namely, the parameter α tells us information about the rate of beam loss (Figure 5). The relationship between $\Delta(t)$ and α is,

$$\Delta(t; V_0, A_1, A_2, \alpha, \omega_d) = V_0 + e^{-\alpha t}(A_1 \cos(\omega_d t) + A_2 \sin(\omega_d t)). \tag{3}$$

If we compare Equation 3 to Equation 1, it looks very similar, except that in this case, the output response to a step input is underdamped (the same assumptions apply as the previous

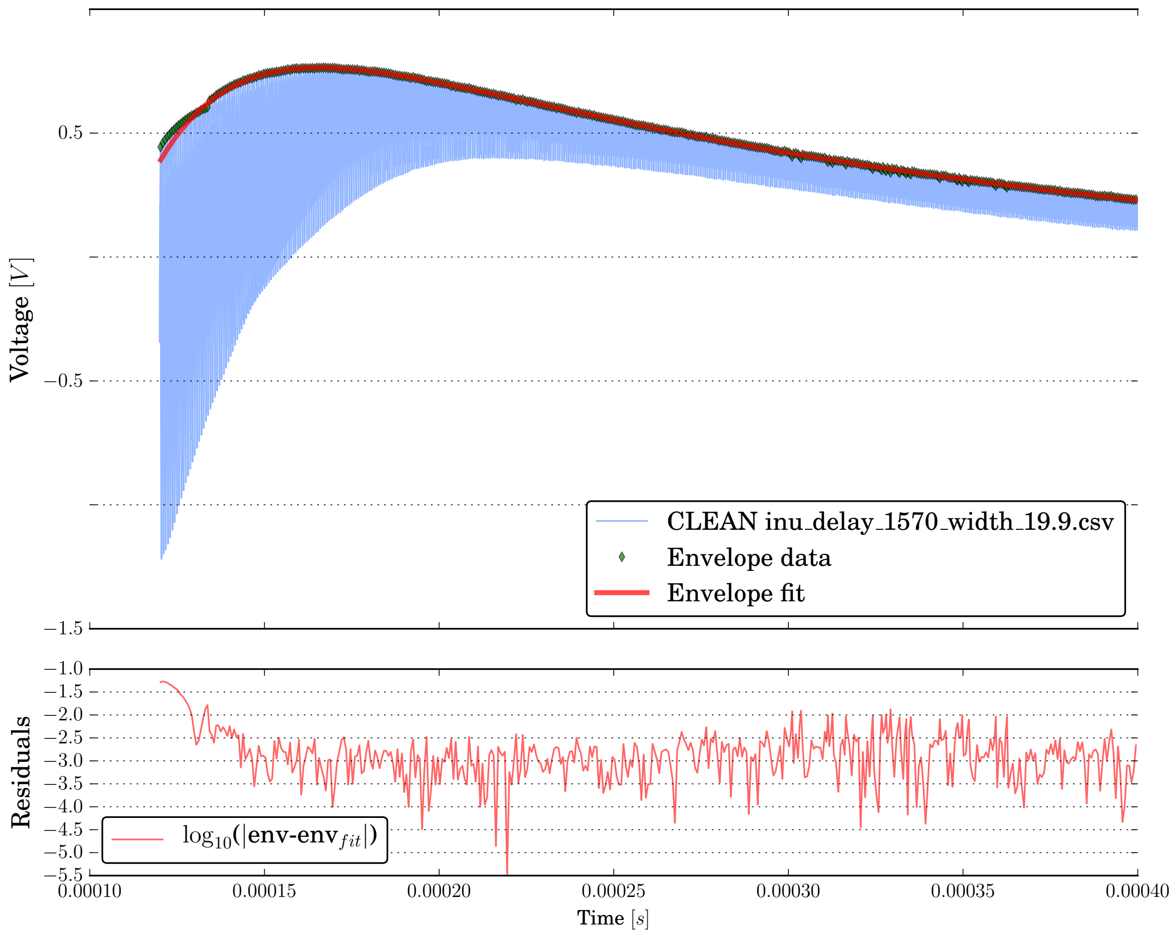

Figure 3: This figure shows an example of how the envelope generation works. On the top plot, the cleaned data is processed to determine the raw envelope data points (on the plot in green diamonds), then I use Equation 1 as a model to fit (in red). One can see that the model works well for most of the data, there a region in the beginning of the data where there there is slight error, but overall has minimal effect. On the bottom plot, the residuals show that the fitted envelope and raw envelope have low relative error.

case). As α increases, the decay rate is quicker – which gives a nice interpretation: rate of beam loss.

Extracting P

The definition of **P** is as follows,

$$\mathbf{P} = \int_{0.5f_0}^{1.5f_0} \mathcal{F}[V(t)](f)df. \tag{4}$$

Where the revolution frequency, at injection, is $\omega_0 = 2\pi f_0$, and $\mathcal{F}$ denotes the Fourier transform (FFT). Physically, **P** contains information about the frequency information around f_0 (Figure 6). Ideally it would contain only frequency components of the revolution frequency of the beam. In reality, however, there can be side-band frequencies that peak around the revolution frequency.

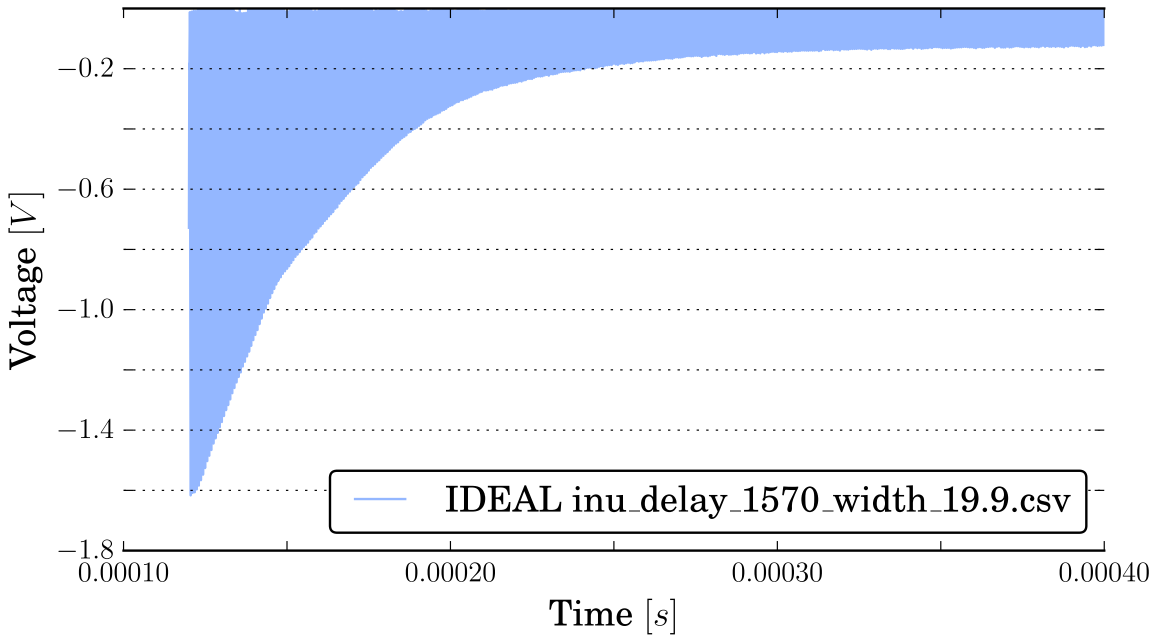

Figure 4: This plot shows the result of the cleaning process, the *ideal* waveform. It is defined as $V_{clean} - V_{envelope}$.

The value of this integral increases in two cases:

1. more frequency components are present (i.e. betatron oscillation) or
2. the peak of the spectrum is higher (there is more power). In this experiment, the beam was matched, so there is minimal betatron oscillation, so any change in the peak of the spectrum relates to the amount of beam power. So a high value of integral means low beam loss and low value means high beam loss.

Results

The results are shown in Figures 7, and 8. Figure 7 shows a heat map of the α results. The plot shows that the worst-case scenario (high α) occurs when the LINAC Trigger Delay is $1590\mu s$ and when the Pulse Width is $\leq 10\mu s$. However, there seems to have a sharp change because the best case is when the LINAC Trigger Delay is $1590\mu s$ and Pulse Width is $29.9\mu s$. There is about a factor of 2 difference in their respective α values, which translates to about a $e^2 \approx 7$ factor difference in beam loss time.

Next, Figure 8, shows a similar heatmap, but the colour bar shows the value of **P**. The value of **P** shown is normalized to the maximum of the dataset, which appears as the darkest red. There are two very clear trends. Firstly, for a given LINAC Trigger Delay value, the value of **P** increases with Pulse Width. Secondly, for a given value of Pulse Width, there seems to be a trend where the color becomes *lighter* as LINAC Trigger Delay increases. This means for values of $\mathbf{P} \leq 0.6$, **P** increases for increasing LINAC Trigger Delay (and constant Pulse Width) and the vice-versa for $\mathbf{P} \geq 0.6$. Since in this experiment, there was minimal betatron oscillation, **P** is directly related to the beam power. This shows that both LINAC Trigger Delay and Pulse Width effect the beam power.

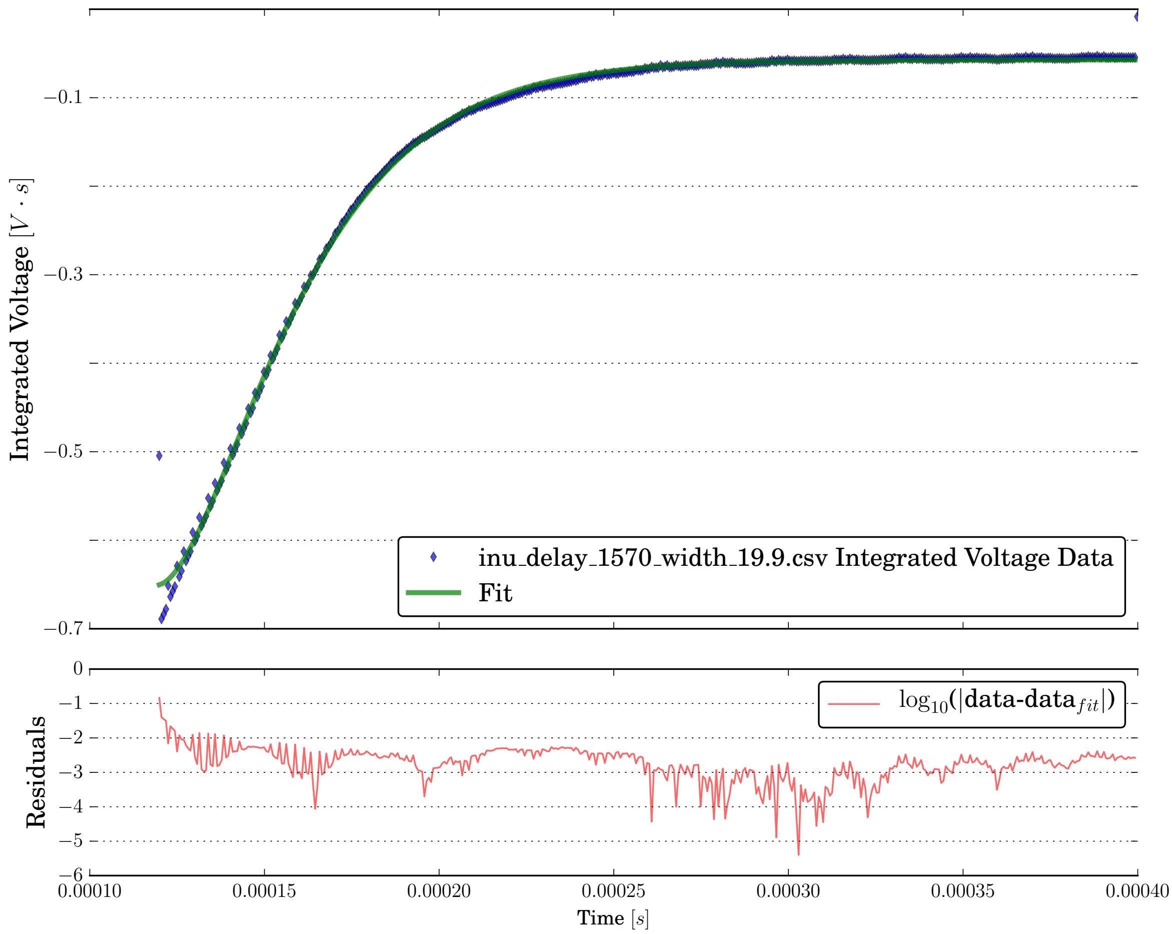

Figure 5: This figure shows an example of fitting $\Delta(t)$ with the model function: Equation 3. The raw data are shown in the top plot as blue diamonds, and the fit is shown in green. For this example I have scaled the x-axis to show the turn number. It starts at turn 100 because the cleaned data excludes the first 10,000 points. One can see that the model works well for most of the data, there a region where the data peaks where there is slight error, but overall has minimal effect. The residuals show that the fitted envelope and raw envelope have low relative error. This error is a combination of the error in the envelope generation (Figure 3) and the error in the numerical integration. The value for α can be found in the Results section (Figure 7).

Outlook

Points to discuss, improve upon for the future:

- A more precise interpretation and definition of α, why does Equation 3 model $\Delta(t)$ well?
- Improving upon the model of the circuitry, so the response can be predicted more accurately, (what does the circuit look like from beam monitor to the oscilloscope?).
- Determine the relationship between $\mathbf{P}/\alpha$ v.s LINAC Trigger Delay, $\mathbf{P}/\alpha$ v.s Pulse Width (so a projection of the shown results).

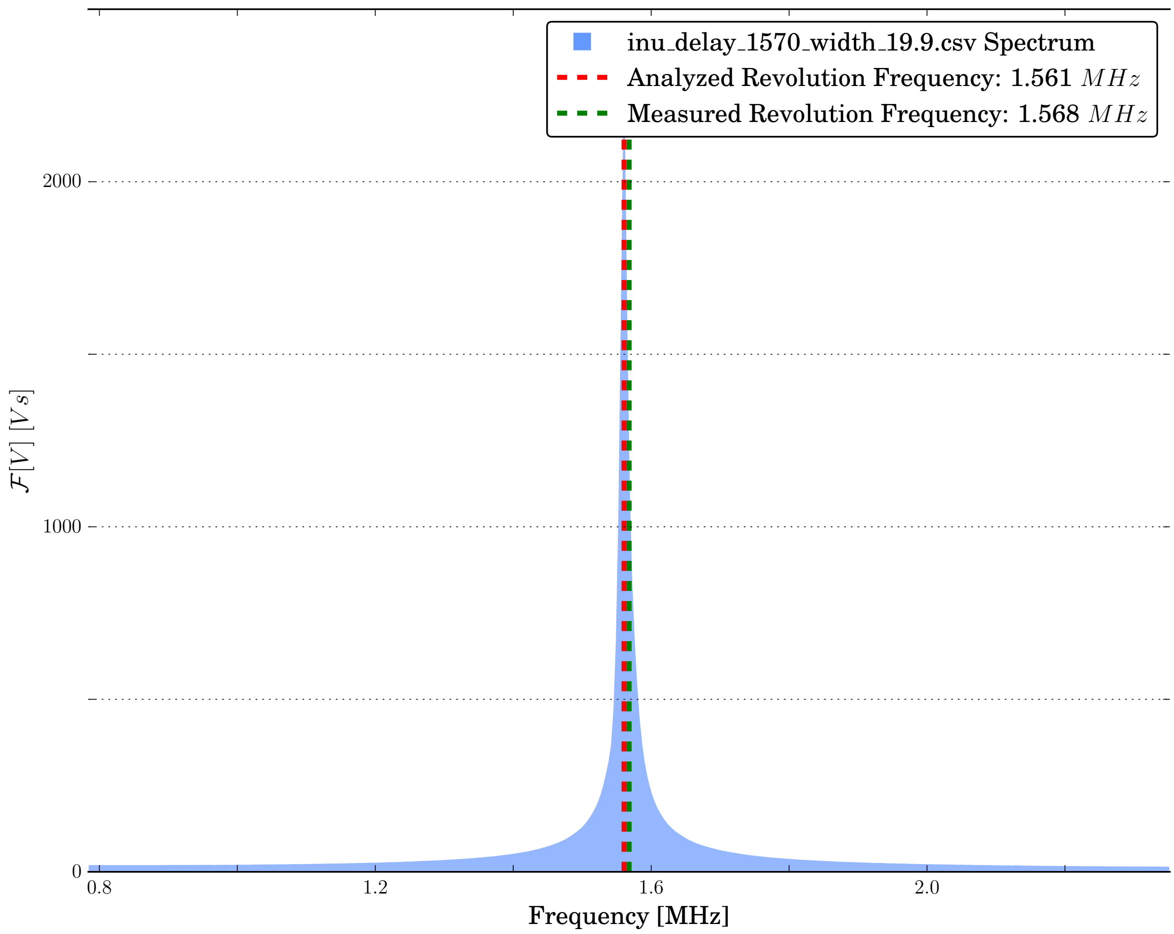

Figure 6: This plot shows an example spectrum plot. We see that the difference between the experimental revolution frequency (measured from experiment) and analyzed revolution frequency is low. The axis shows $0.5f_0 \leq f \leq 1.5f_0$ where f_0 is the experimental revolution frequency. **P** is exactly the value of the shaded area. The value of **P** can be found in the Results section (Figure 8).

References

[1] L-com *Connectivity Products* [online]. Cable Specification. [cited 4 November 2015]. Available from World Wide Web: ⟨https://www.l-com.com/multimedia/eng_drawings/RG58C-LCS.pdf⟩.

[2] NF Electronic Instruments. *Low Noise Amplifier* [online]. Specification Sheet. [cited 4 November 2015]. Available from World Wide Web: ⟨http://www.cosinus.de/_downloads/NF_DB_SA-220_230_430F5_915D1.pdf⟩.

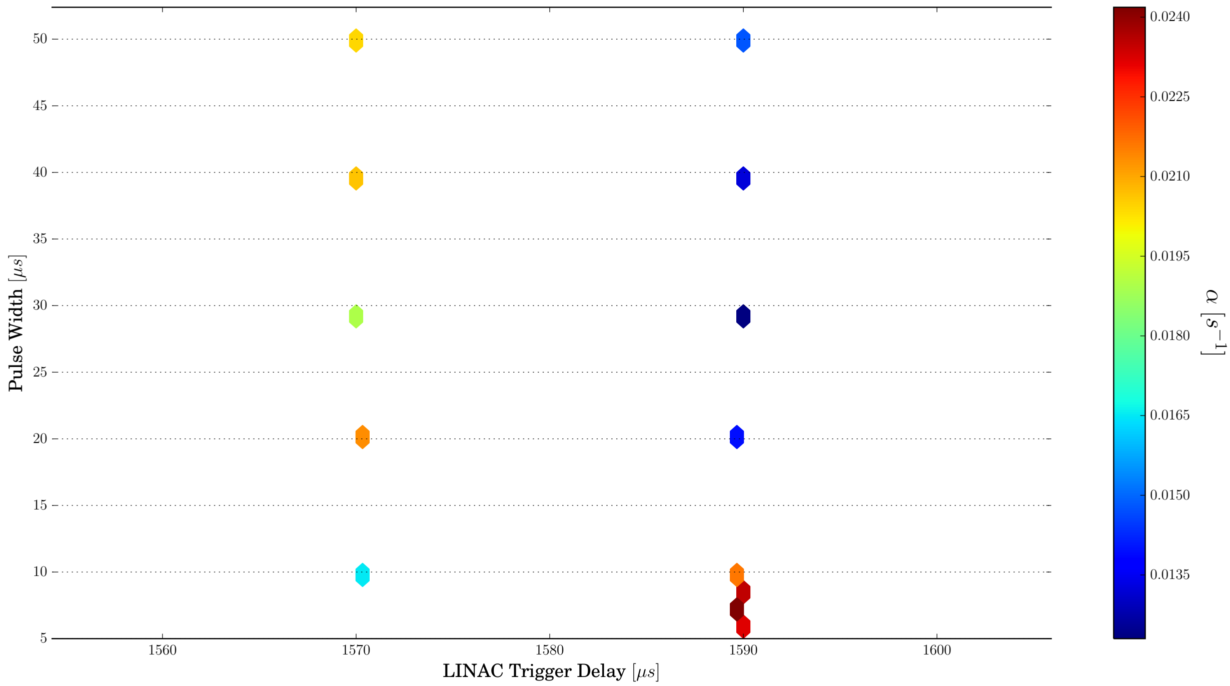

Figure 7: The results for α.

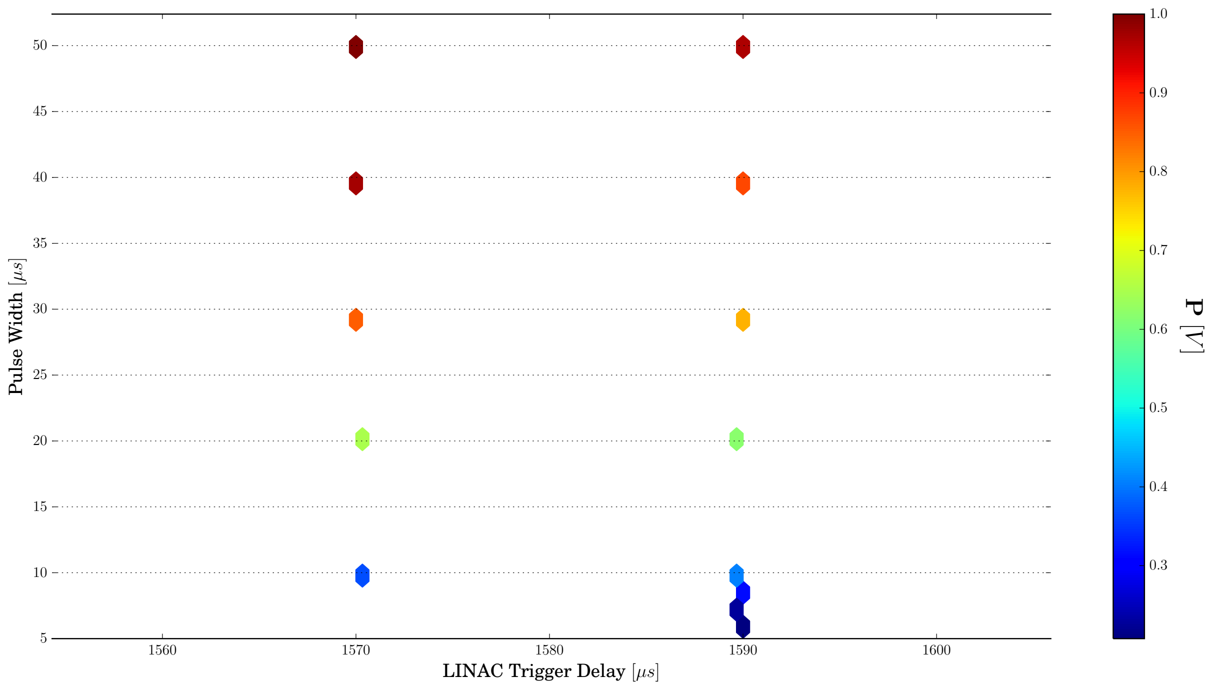

Figure 8: The results for $\mathbf{P}$.