17RPT03 DIG-AC

WP3: Task 3.3: Uncertainty estimation

Report on Uncertainty Estimation for Digital Measurements of Voltage Waveforms

19/05/2022

Madrid, Spain

Objectives **of the report**

- Evaluate the sources of uncertainties in digital measurement of waveforms
- Calculate uncertainty propagation for the whole traceability chain
- Provide models and approaches for fast on-site calculations of uncertainties

Uncertainty estimation is based on:

•Measurement procedures
•Algorithms used to obtain measurement parameters
•Uncertainty sources
•Current measurements are also based on voltage measurements

For these reasons the report is planned as follows:

Content of the report

- Detailed instructions on measurement procedure for **voltage** are presented. Including
  - Including equipment/systems which are available in the market
  - Possible measurement setups
  - Explanation of the calibration process which defines with which setup/configuration to use which algorithm
  - Presents ideas for choosing references to be used to reach the uncertainty goals.
  - Briefly steps of calibration for both voltage sampler and voltage source calibration are defined.
- Model functions of the measurements are given in detail including the uncertainty sources and their estimated values.
- Finally information about uncertainty calculations and
- The scope of the measurements is presented

Content of the report-Measurement Setups

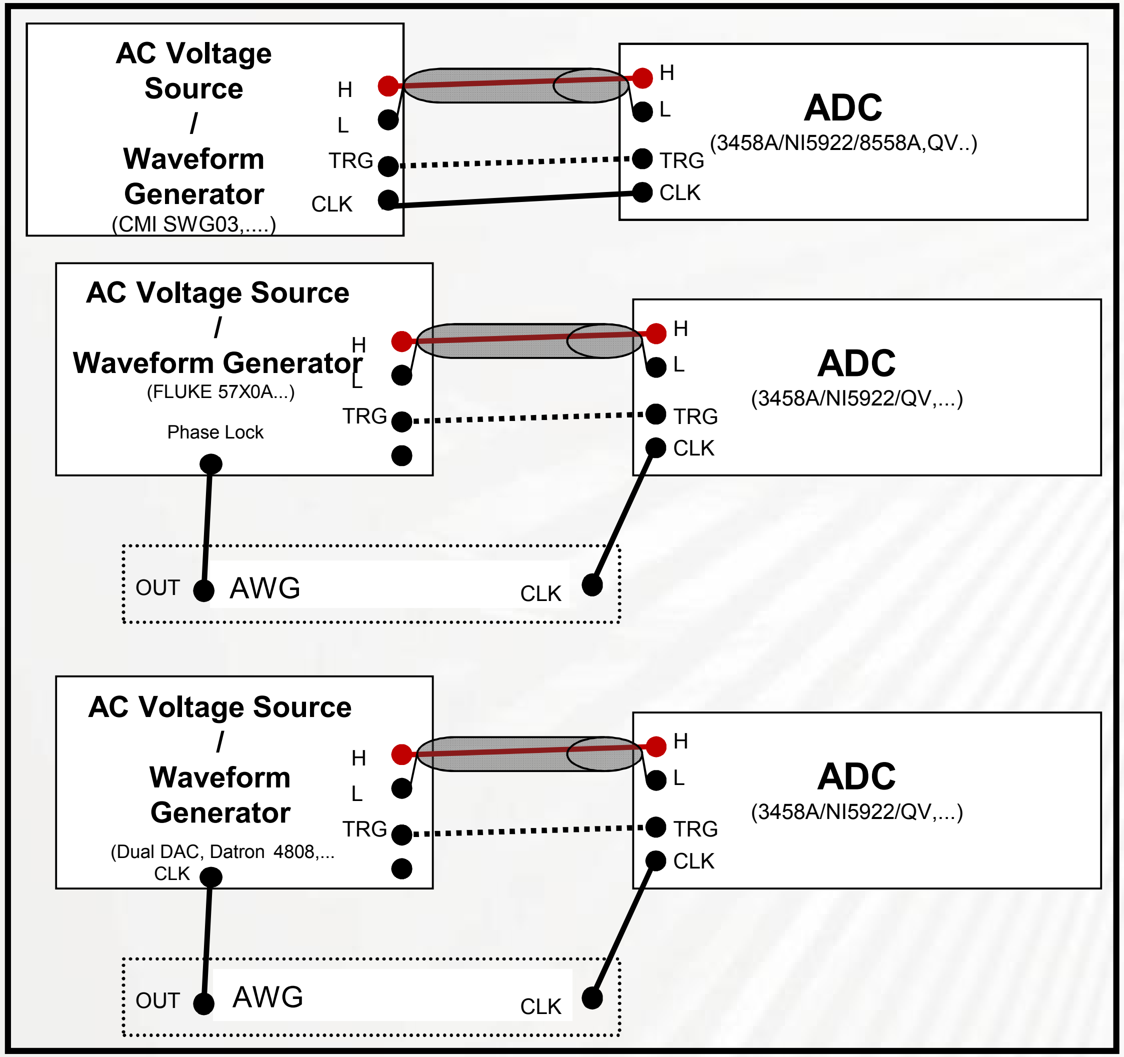


Figure 1. Synchronous Sampling

Content of the report-Measurement Setups

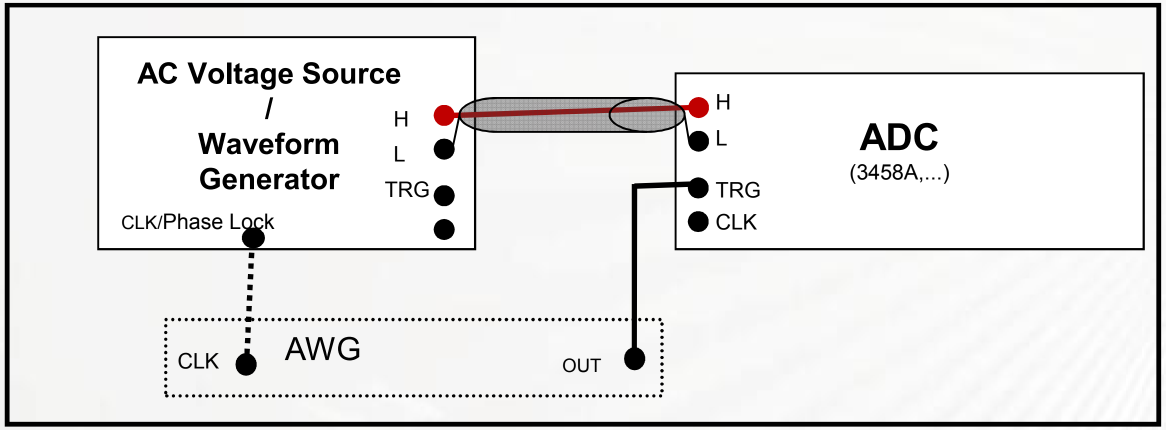


Figure 2. Semi - Synchronous Sampling

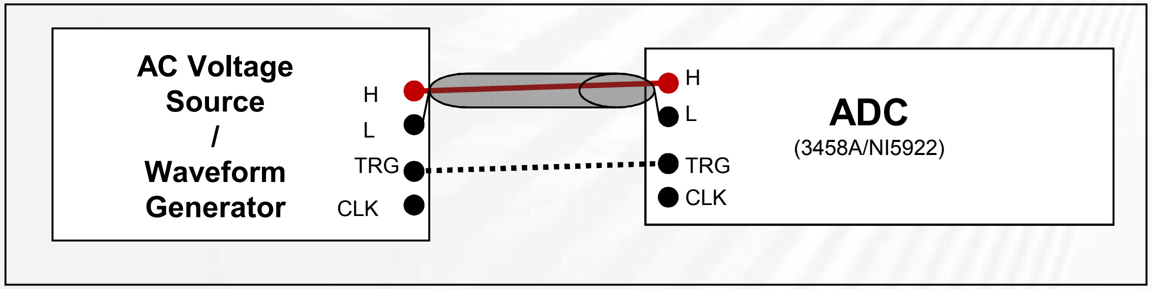


Figure 3. Asynchronous Sampling

Content of the report

Measurement Setups-Adviced Algorithms for Waveforms with Single Tones

TÜBİTAK UME

Table 1. Methods/Algorithms for Calculating Effective Value of Single Tone Voltage Waves

Measuring Setup	Sampler	RMS formula	Discrete Fourier Transform	3-Parameter Sine Fitting	4 Parameter Sine Fitting
Synchronous	IADC	✓	✓	✓[5]	✓[6]
	ΔΣ ADC	✓	✓	✓[5]	✓[6]
	QV	✓	✗[4]	✓[5]	✓[6]
Semi-synchronous	IADC	✓[1]	✓[1]	✓[1,5]	✓[1,6]
Asynchronous	IADC	✗[2]	✗[3]	✓[7]	✓[8]
	ΣΔ ADC	✗[2]	✗[3]	✓[7]	✓[8]

[1]- Half of the CLK period of the ADC should be considered as the jitter parameter.

[2]- Samples may not represent a whole period, as it may not be an integer when the sampling (f_s) frequency of the sampler (ADC) is divided to the frequency of the source (f_m). Therefore, instability between measurements may be high.

[3]- The window effect should be evaluated, as the ratio obtained when the sampling (f_s) frequency of the sampler (ADC) is divided to the frequency of the source (f_m).

[4]- Samples will not be evenly spaced in time domain when the QV's sampler is the NI5922.

[5]- Fitting frequency should be taken $f_m=f_s/N$

[6]- Starting frequency should be taken $f_m=f_s/N$

[7]- When f_m and f_s are determined according to the same frequency standard and time data of the sampler is corrected according to the frequency measurement result, the algorithm gives results with high accuracy. The amount of data must be greater than one period.

[8]- This algorithm can be used when fm is too small to be measured with a frequency counter. There must be at least five periods of data. When f_m is estimated correctly, the signal-to-noise ratio of the fitted curve (SNR=10*log($\frac{V^2_{RMS\_D}}{P_{error}}$)) is calculated within expected values. If the SNR is worse, by trying different starting frequencies for f_m, Iteration should be continued for the lowest SNR.

Content of the report

Measurement Setups-Adviced Algorithms for Multi Tones

TÜBİTAK UME

Table 2. Methods/Algorithms for Calculating Effective Value of Each Tone of Multi-Tone Voltage Waves [1]

Measuring Setup	Sampler	Discrete Fourier Transform	3-Parameter Sine Fitting	4-Parameter Sine Fitting
Synchronous	IADC	✓ → 2	✓ → 3	✓ → 3
Synchronous	ΔΣ ADC	✓ → 2	✓ → 3	✓ → 3
Synchronous	QV	✗	✓ → 3	✓ → 3
Semi-synchronous	IADC	✓ → 2	✓ → 3	✓ → 3
Asynchronous	IADC	✗	✓ → 4	✓ → 5
Asynchronous	ΣΔ ADC	✗	✓ → 4	✓ → 5

1- The footnotes given in Table 1 are taken into account.

2- Tones must be harmonics of fm ($k \times f_m$; k=0,1,2,3… ve $k \times f_m < f_s/2$).

3- Tones $f_k = k.f_s/(M.N)$; k=0,1,2,3… ve $f_k < fs/2$.

4- f_k frequencies must be estimated/measured correctly.

5- Footnote (8) in Table 1 should also be taken into account for f_k frequencies.

Content of the report

Reference Device - Unit Under Test Suggestions

Table 3. Amplitude Frequency Ranges and Least Possible Uncertainties of Reference Device/Systems

Calibration Object	Reference System/Device	Amplitude Range	Frequency Range	Possible Uncertainties
Voltage Source/DAC	IADC	5 mV - 750 V	1 mHz - 2 kHz	1,5 µV/V-55 µV/V
	ΣΔ ADC	<3 V	≤100 kHz	>100 µV/V
	QV	<8 V	1 Hz - 2 kHz	0,5 µV/V - 3 µV/V
Voltage Sampler	Calibrator (FLUKE 57X0A, Datron 4808..).	0,8 V - 700 V	10 Hz-100 kHz	>20 µV/V
	PJVS	<1 V	< 500 Hz	0,5 µV/V
	Aivon DualDAC	< 10V	6 Hz - 10 kHz	>50 µV/V
	CMI SWG03	<10 V	< 100 kHz	>50 µV/V

Content of the report
Model Functions & Uncertainty Sources

The model function of an x[n] sample is defined:

$$x[n]=V_J+\frac{1}{T_i+\delta_{JTi}}\left(1+\delta_{REF}+\delta_G+\frac{\delta_{LIN}+\delta_{RES}}{|V_{ADC}|}V_{FS}\right)\int_{v.T_a+\delta_{JTa}}^{v.T_a+\delta_{JTa}+T_i+\delta_{JTi}}\{v_i(t)+v_s(t)\}.dt+v_{sn}(t)$$

Table 4. Uncertainty Components

Component		Definition and Its Value	Probability Distribution Function	Uncertainty	Correlation Between Samples
1	V_J	• Quantum voltage of the n[th] sample when the sampler is QV • Its value is zero when sampler is 3458A, ΣΔ-ADC, ADC			
2	V_{FS}	Full Scale of the sampler			
3	V_{ADC}	Nominal Value of the samples obtained by the sampler.			
4	$v_i(t)$	Mathematical function of the signal applied to the sampler's input: $\sin\left(2\times\pi\times\frac{1}{T_o}\right)+\sin\left(2\times\pi\times k\times\frac{1}{T_o}\right)+\ldots$			
5	T_i	Integration/Sample-hold time • Value determined by APER command when sampler is 3458A and Ti=Ta-25 µs, Ti ≥ 10µs;Ti=100 ns×z; z∈ Z^+ • 17 ns when sampler ΣΔ-ADC • The value suitable for the sampler in the QV system when the sampler is QV			
6	δ_{JTi}	Jitter in integration time • 3458A • ΣΔ-ADC	Rectangular	• <500 ps • <3 ps	No

Content of the report

Model Functions & Uncertainty Sources

$$x[n]=V_j+\frac{1}{T_i+\delta_{JTi}}\left(1+\delta_{REF}+\delta_G+\frac{\delta_{LIN}+\delta_{RES}}{|V_{ADC}|}V_{FS}\right)\int_{v.T_a+\delta_{JTa}}^{v.T_a+\delta_{JTa}+T_i+\delta_{JTi}}\{v_i(t)+v_s(t)\}.dt+v_{sn}(t)$$

Component		Definition and Its Value	Probability Distribution Function	Uncertainty	Correlation Between Samples
7	T_a	Sampling period • Value determined by TIMER command when sampler is 3458A and Ti=Ta-25 µs, Ta=100 ns×z; z∈ Z^+ • If the sampler is NI5922, the period of the equivalent sampling frequency			
8	δ_{jTa}	Jitter in sampling period • 3458A internal CLK • ΣΔ-ADC • 3458A Semi-Synchronous	Rectangular	• <500 ps • 3 ps • 50 ns	No
9	T_o	Period of the input signal ($v_i(t)$)			
10	δ_{JTo}	Jitter in the period of input signal ($v_i(t)$)			No

Content of the report

Model Functions & Uncertainty Sources

$$x[n]=V_J+\frac{1}{T_i+\delta_{JTi}}\left(1+\delta_{REF}+\delta_G+\frac{\delta_{LIN}+\delta_{RES}}{|V_{ADC}|}V_{FS}\right)\int_{v.T_a+\delta_{JTa}}^{v.T_a+\delta_{JTa}+T_i+\delta_{JTi}}\{v_i(t)+v_s(t)\}.dt+v_{sn}(t)$$

Component		Definition and Its Value	Probability Distribution Function	Uncertainty	Correlation Between Samples
11	δ_{REF}	The correction of the reference voltage of the sampler. It is relative to the V_{ADC}, its value is 0 when calibrating the sampler. • 3458 A • ΣΔ-ADC	Normal	• 0,5 µV/V • <20 µV/V	Yes
12	δ_G	The correction of the gain of the sampler. It is relative to the V_{ADC}, its value is 0 when calibrating the sampler. • 3458 A < 100 Hz • 3458 A > 100 Hz • ΣΔ-ADC	• Normal • Rect. • Rect.	• 0,5 µV/V • int(0,002/Ti) – <30 µV/V • 30 µV/V	Yes
13	δ_{LIN}	The correction of the linearity of the sampler. It is relative to the V_{FS}, its value is 0 when calibrating the sampler.	Normal / Rectangular	It is the ADC's INL fault. It can be obtained from the SINAD parameter for dynamic measurements. δ_{RES}=0 can be obtained when obtained from SINAD	No
14	δ_{RES}	The resolution correction of the sampler is relative to the measuring range, the value is 0 in the sampler calibration • Dynamic • 3458A	Normal / Rectangular	• It is the resolution of the ADC. It can be obtained from the ENOB parameter of the ADC for dynamic measurements. δ_{LIN}=0 can be obtained when obtained from ENOB • (26) Calculated by Equation	No

Content of the report

Model Functions & Uncertainty Sources

$$x[n]=V_J+\frac{1}{T_i+\delta_{JTi}}(1+\delta_{REF}+\delta_G+\frac{\delta_{LIN}+\delta_{RES}}{|V_{ADC}|}V_{FS})\int_{v.T_a+\delta_{JTa}}^{v.T_a+\delta_{JTa}+T_i+\delta_{JTi}}\{v_i(t)+v_s(t)\}.dt+v_{sn}(t)$$

Component		Definition and Its Value	Probability Distribution Function	Uncertainty	Correlation Between Samples
15	$v_{sn}(t)$	The quantization noise of the sampler, In sampler calibration, the value is assumed as 0 • 3458A • ADC	Rectangular	• Calculated by Equation (22) • Calculated assuming one-bit error by Equation (23)	No
16	$v_s(t)$	The noise of the signal at the sampler input • 57X0, Datron 4808, .. • Aivon Dual DAC, CMI SWG03...	Rectangular	• Calculated by Equation (24) • Calculated by Equation (25)	No
17	G_{filt}	Coefficient of correcting the effect of the sampler's filters that suppress input noise (anti-aliasing filter)	Rectangular / Normal	Manufacturer's declaration / Calibration Result	
18	T_{tran}	The rate at which the applied voltage from the voltage source is transferred to the sampler due to stray circuit elements of the setup	Rectangular	The values of stray circuit elements given in Figure 4 are assigned and using their values the value of T_{tran} and its uncertainty is calculated according to electrical circuit theories.	No
19	$\delta V_{i\text{-}cal}$	Correction due to calibration of the reference voltage source	Normal	Obtained from the certificate	No
20	$\delta V_{i\text{-}D}$	Correction due to the drift of the reference voltage source over time since its last calibration	Rectangular	History or manufacturer's tolerance statement	No

Content of the report

○ Calculating Uncertainty Dependent on Used Algorithms

$$u(x[n])=\sqrt{\sum_{i=1}^{13}\{u_i(x[n])\}^2}$$

RMS Formula

$$V_{rms\_D}=\sqrt{\frac{1}{M.N}\sum_{n=1}^{M.N}x[n]^2}$$

$$u_n\left(V_{rms\_D}\right)=\frac{\partial V_{rms\_D}}{\partial x[n]}.u(x[n])$$

$$u(V_{rms\_D})=\sqrt{\sum_{n=1}^{N}\{u_n(V_{rms\_D})\}^2}$$

DFT

$$X[k]=\frac{2}{K}\sum_{n=0}^{K-1}\frac{x[n]}{\left|\mathrm{sinc}\left(\frac{\pi.T_1.k}{n.T_a}\right)\right|}e^{-j2\pi.f_k.n.T_a}e^{-j\frac{\pi.T_1.k}{n.T_a}}$$

$K=M.N$

$$C_{Re}(n,k)=\frac{\partial Re(X[k])}{\partial x[n]};\qquad C_{Im}(n,k)=\frac{\partial Re(X[k])}{\partial x[n]}$$

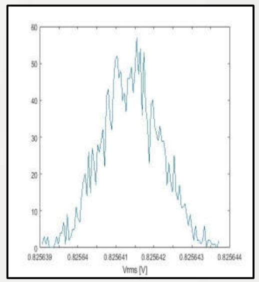
$$u^2(Re(X[k])=\sum_{n=1}^{K}\{C_{Re}(n,k).u(x[n])\}^2+u^2(Re_z,Re_y)+\int_f^{f+\frac{1}{M.N.T_s}}S(f)$$

$$u^2(Im(X[k])=\sum_{n=1}^{K}\{C_{Im}(n,k).u(x[n])\}^2+u^2(Im_z,Im_y)+\int_f^{f+\frac{1}{M.N.T_s}}S$$

3 Parameter Sine-Fit

$$A_0\cos(2\pi f_0 t_n)+B_0\sin(2\pi f_0 t_n)+C_0$$

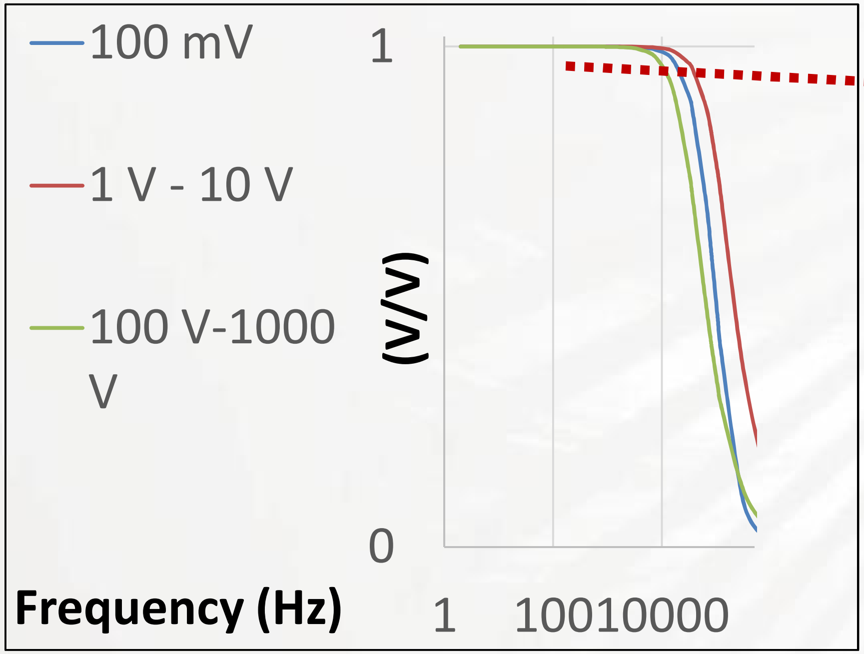
```
for n=1:length(uX)
duX(:,n)=uX(n)*(rand(200000,1)-0.5)*2;
duTa(:,n)=uT*(rand(200000,1)-0.5)*2;
duTi(:,n)=uT*(rand(200000,1)-0.5)*2;
end
```

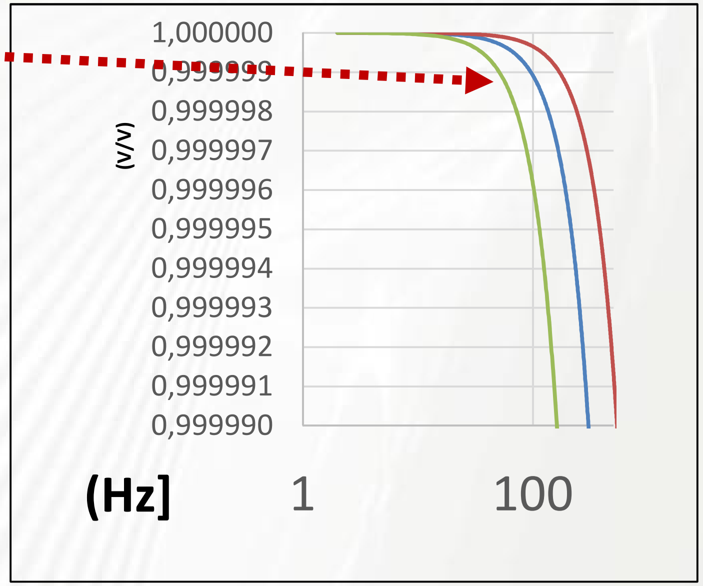


Content of the report

Correction for Sampler's Band-Pass Filters (G_{filt})

$$V_{RMS} = V_{RMS\_D} \cdot G_{filt}$$





Transfer functions of analog input circuits of 3458A

Agilent Technologies 3458A Multimeter User´s Guide 4th edition. Agilent Technologies, Santa Clara, CA, USA, Dec 2000.

Content of the report

Correcting the Effect of Stray Electrical Circuit Components in the Measurement Setup

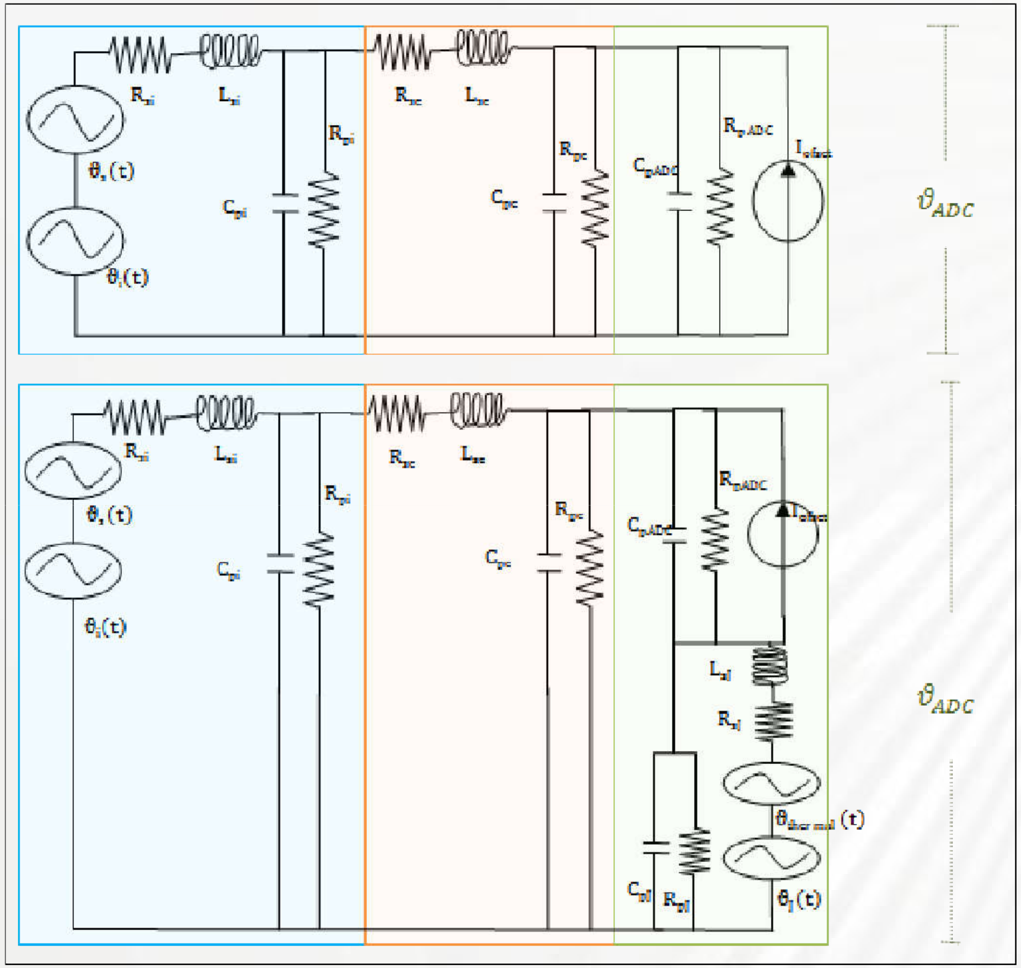


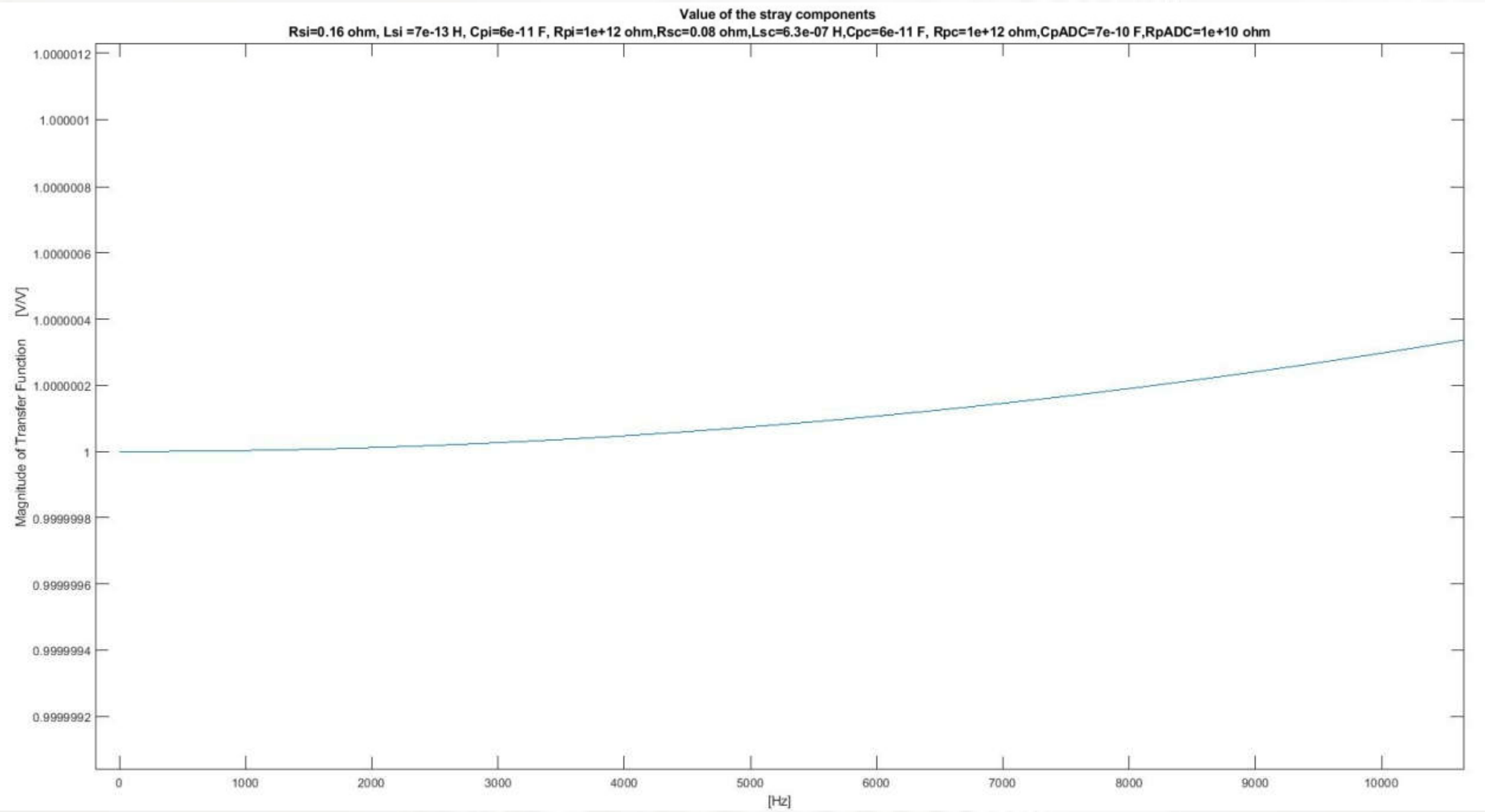
Figure 4. Electrical circuits showing the distribution of stray circuit components of the measurement setup

$$\vartheta_{ADC} = \vartheta_i(t) \times T_{tran}$$

Content of the report

Correcting the Effect of Stray Electrical Circuit Components in the Measurement Setup

$$V_x = V_i = V_{RMS} = \frac{V_{RMS\_D} \times G_{filt}}{T_{tran}}$$



Content of the report

Scope of the Measurements

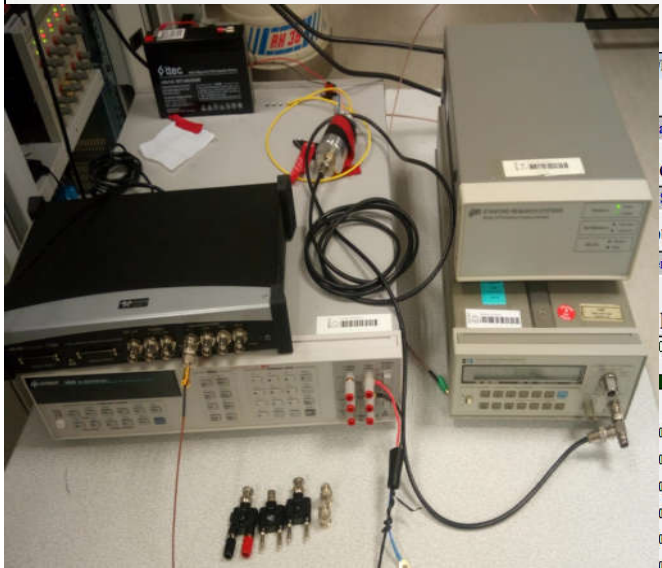
2.10. SCOPE

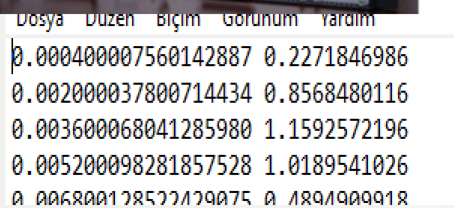
Quantity and Calibrated Instruments	Measurement Range	Measurement Conditions	Calibration and Measurement Capabilities (Expanded Uncertainty (k=2))	Remarks
Voltage / Voltage Source, calibrator	5 mV - 80 mV	≤ 100 Hz	180 µV/V - 20 µV/V	Calibration with modified IADC
		≤ 400 Hz	180 µV/V - 20 µV/V	
		≤ 1 kHz	180 µV/V - 20 µV/V	
	100 mV - 800 mV	≤ 100 Hz	10 µV/V - 1,5 µV/V	
		≤ 400 Hz	15 µV/V - 4 µV/V	
		≤ 1 kHz	55 µV/V	
	1 V - 8 V	≤ 100 Hz	1,5 µV/V	
		≤ 400 Hz	4 µV/V	
		≤ 1 kHz	55 µV/V	
	10 V - 80 V	≤ 100 Hz	6 µV/V - 4 µV/V	
		≤ 400 Hz	15 µV/V	
		≤ 1 kHz	55 µV/V	
	100 V - 700 V	≤ 100 Hz	6 µV/V - 4 µV/V	
		≤ 400 Hz	15 µV/V	
		≤ 1 kHz	55 µV/V	
	1 V - 3 V	≤ 100 kHz	110 µV/V	Calibration with ΔΣ ADC
	0,8 V - 8 V	≤ 1 kHz	0,8 µV/V - 0,5 µV/V [TIM 2020]	QV
	0,8 V - 8 V	≤ 100 kHz	[Subsampling]	QV
Voltage, Voltage Gain / Voltage Sampler, ADC	0,8 V - 8 V	≤ 100 Hz	0,5 µV/V	PJGS
	0,8 V - 8 V	≤ 400 Hz	2 µV/V	
	20 mV - 100 mV	≤ 400 Hz	< 20 µV/V [CPEM 2020 JAWS]	JAWS
	0,8 V - 3 V	10 Hz 100 kHz	50 µV/V - 30 µV/V	Reference Calibrator
	3 V - 700 V	≤ 1 kHz ≤ 100 kHz	50 µV/V - 30 µV/V No equipment in the market	Reference Calibrator

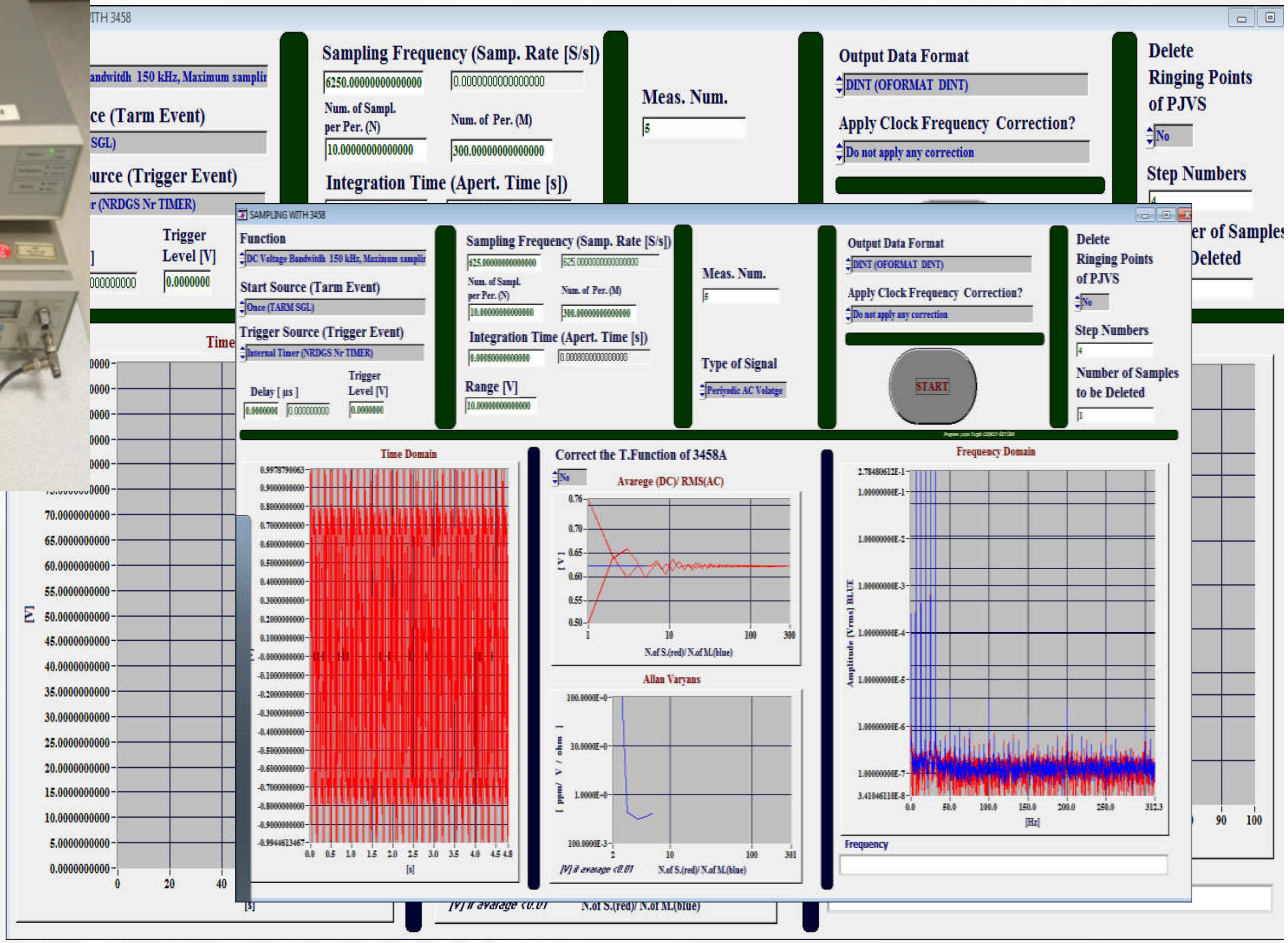
Measurements Carried out to Support the Report

SAMPLING SYSTEM BASED ON INTEGRATING ADC

Tezgül COŞKUN ÖZTÜRK, Mehedin ARİFOVİÇ , Sarp ERTÜRK, Ali TANGEL “Measurement of Arbitrary Waveforms at Low Frequencies “, , August 2020, CPEM 2020 Virtual Conference



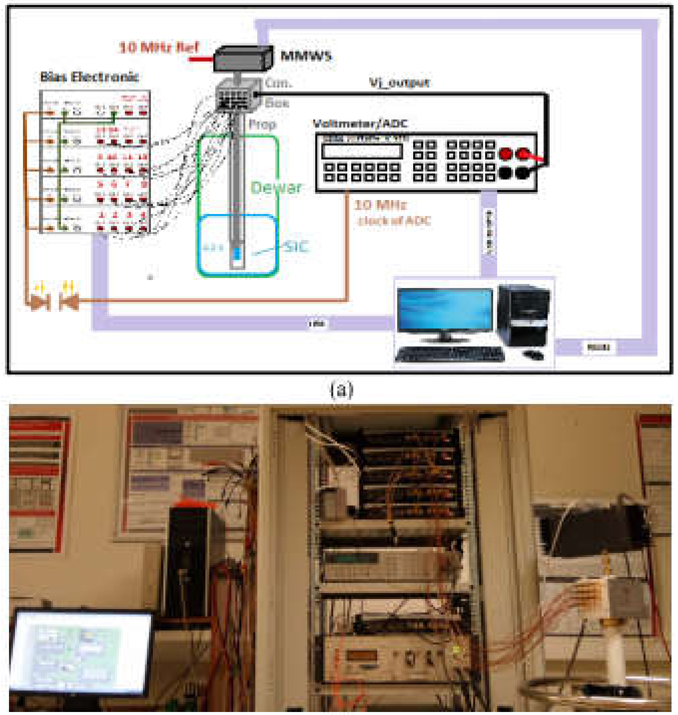




Measurements Carried out to Support the Report

STATIC GAIN&INL CHARACTERISATION BY USING QUANTUM STANDARDS

Coskun Ozturk, T., Erturk, S., Tangel, A., Arifovic, M. **"Using Programmable Josephson Voltage Standard for Static and Dynamic Gain Characterization of Integrating ADC",** IEEE Transactions on Instrumentation and Measurement, - :doi10.1109/TIM.2019.2941360 (2019) : 1-9



(a)

(b)

Fig. 1. (a) Connection diagram of the system [21]. (b) Photograph of the experimental setup of the system taken while the measurements were obtained.

Measurements Carried out to Support the Report

TÜBİTAK UME

IMPROVING STATIC GAIN&INL CHARACTERISATION BY USING QUANTUM STANDARDS

Coskun Ozturk, T., Erturk, S., Tangel, A., Arifovic, M.
"Using Programmable Josephson Voltage Standard for Static and Dynamic Gain Characterization of Integrating ADC",
IEEE Transactions on Instrumentation and Measurement, -:doi10.1109/TIM.2019.2941360 (2019) : 1-9

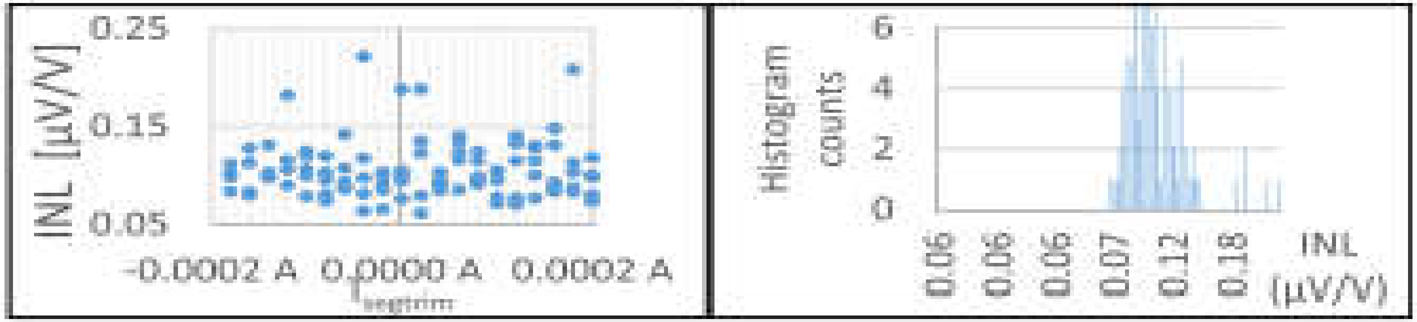


Fig. 4. $I_{segtrim}$ dependence and the corresponding histograms of the measured INL.

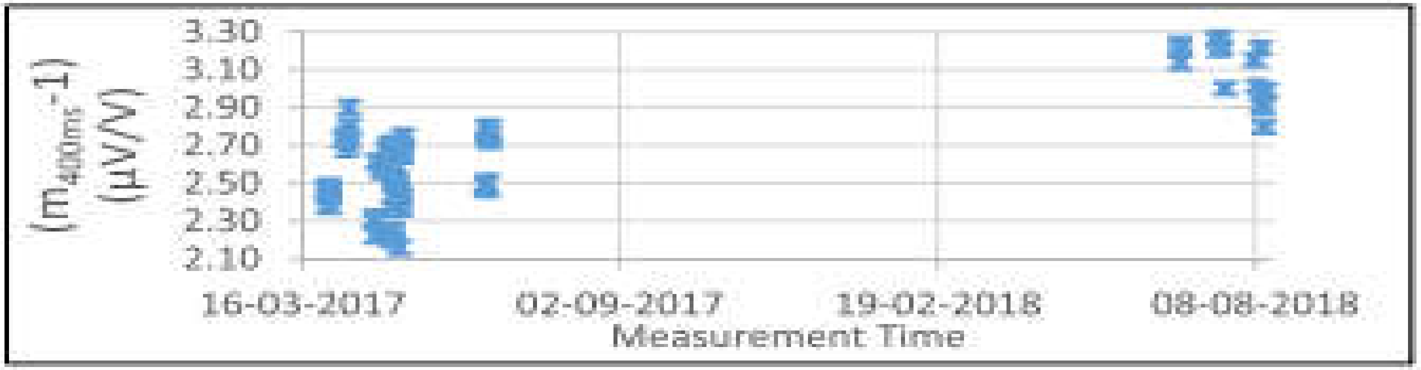


Fig. 5. Drift of the static gain.

Measurements Carried out to Support the Report

IMPROVING DYNAMIC GAIN&SINAD CHARACTERISATION BY USING QUANTUM STANDARDS

Coskun Ozturk, T., Erturk, S., Tangel, A., Arifovic, M. **"Using Programmable Josephson Voltage Standard for Static and Dynamic Gain Characterization of Integrating ADC"**, IEEE Transactions on Instrumentation and Measurement, - :doi10.1109/TIM.2019.2941360 (2019) : 1-9

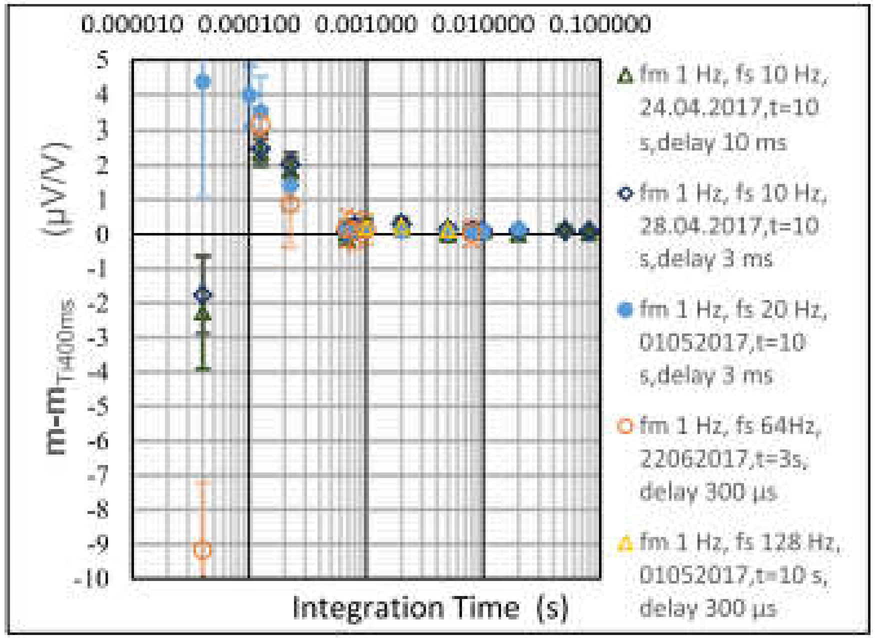


Fig. 7. Effect of integration time.

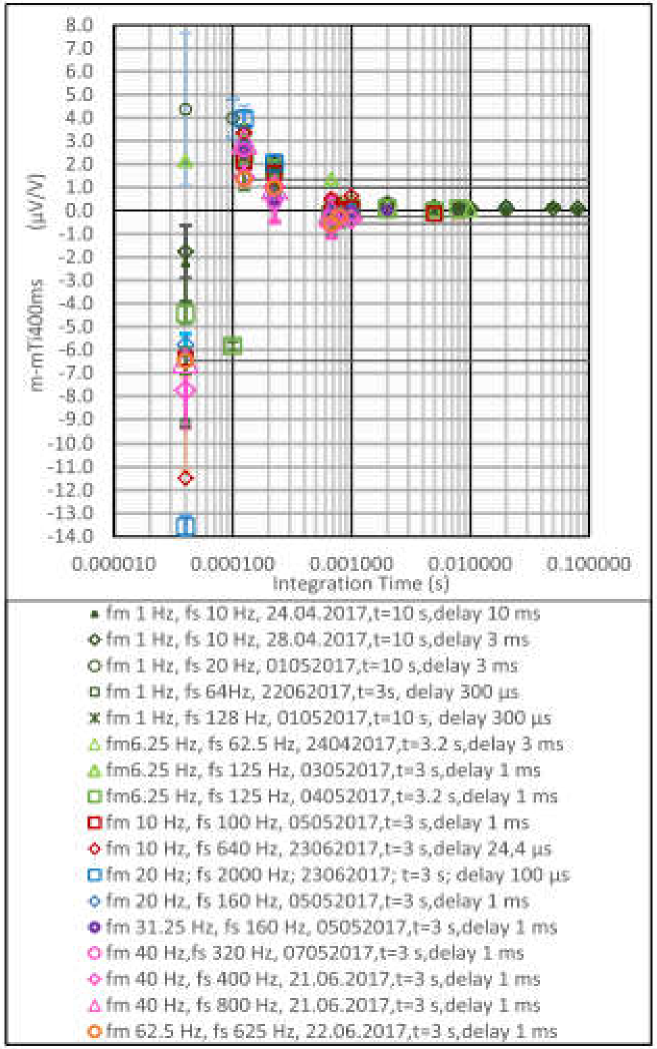
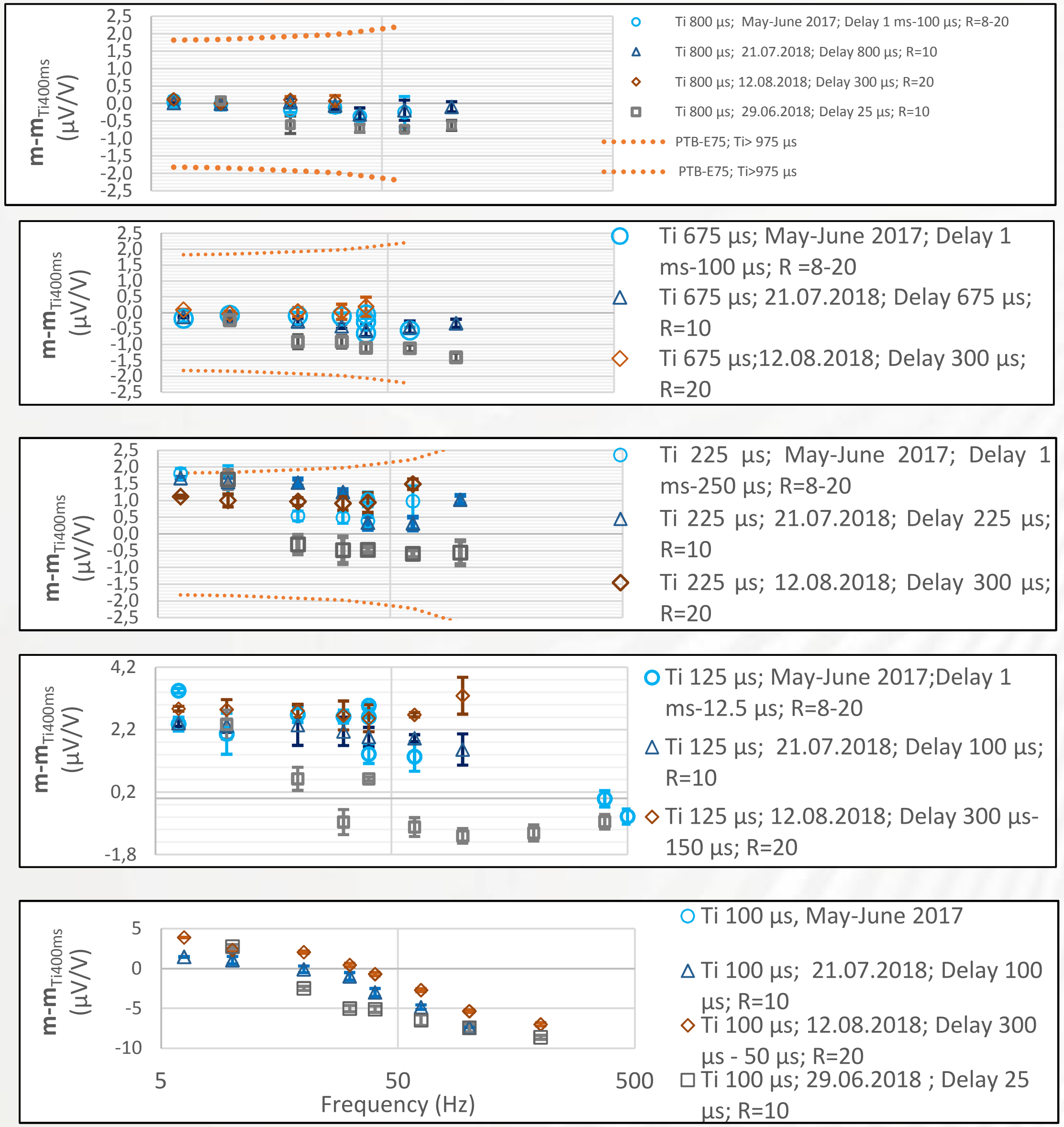


Fig. 8. Effect of signal frequency.

Measurements Carried out to Support the Report

TÜBİTAK UME

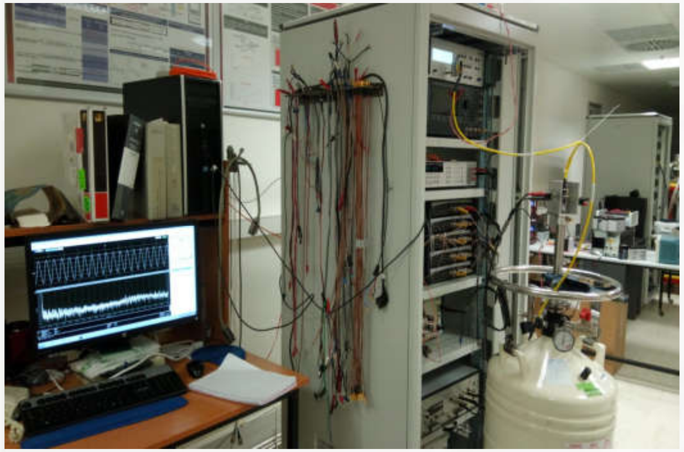


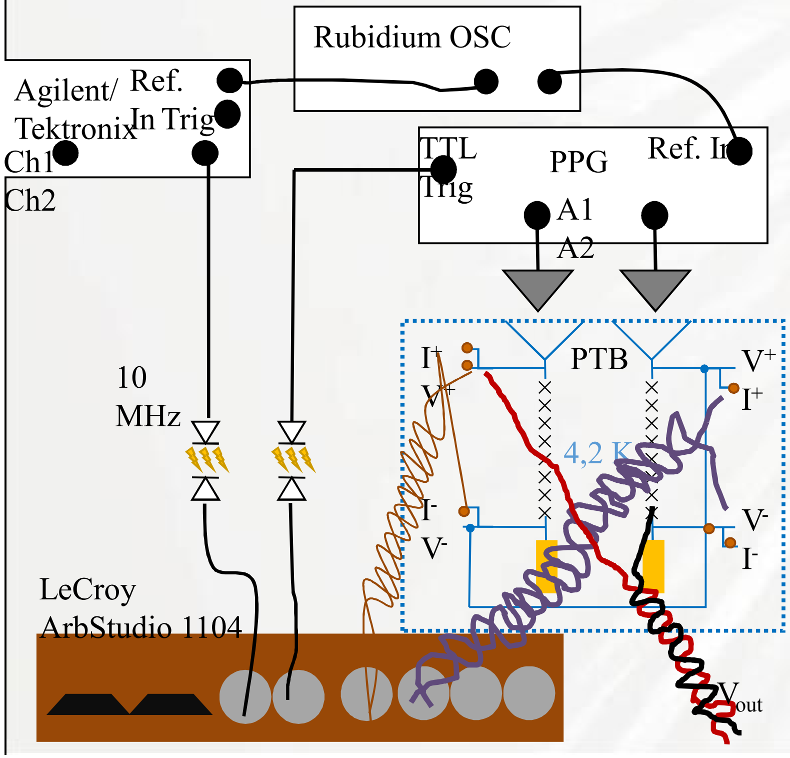
IMPROVING DYNAMIC GAIN&SINAD CHARACTERISATION BY USING PJVS

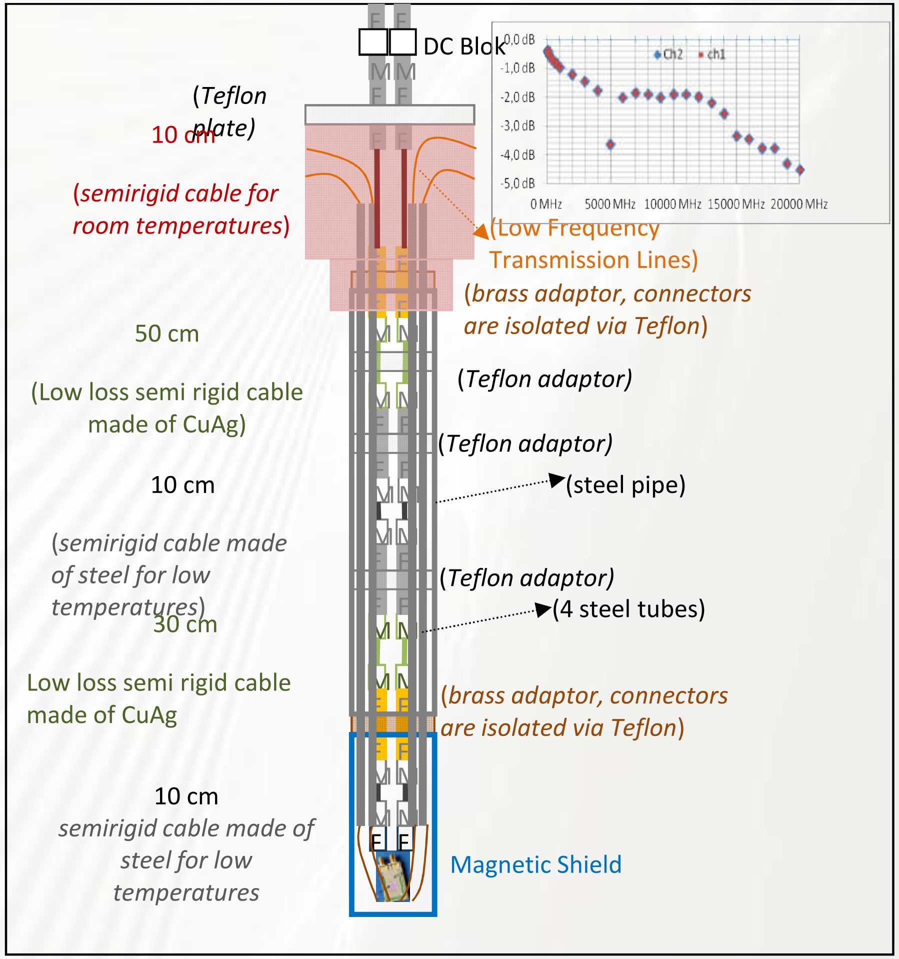
Coskun Ozturk, T., Erturk, S., Tangel, A., Arifovic, M. **"Using Programmable Josephson Voltage Standard for Static and Dynamic Gain Characterization of Integrating ADC"**, IEEE Transactions on Instrumentation and Measurement, -:doi10.1109/TIM.2019.2941360 (2019) : 1-9

Measurements Carried out to Support the Report

IMPROVING DYNAMIC GAIN&SINAD CHARACTERISATION BY USING JAWS







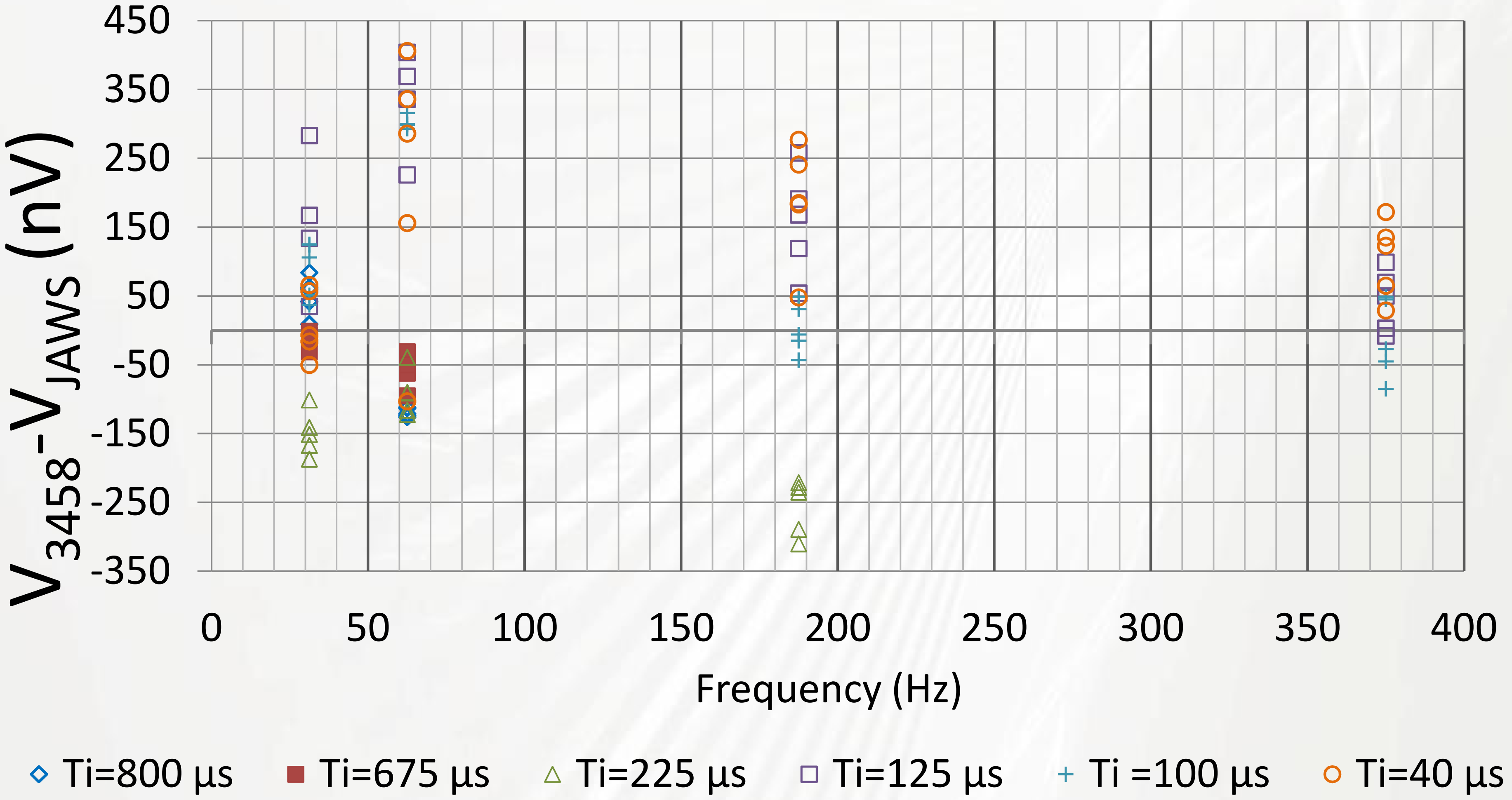
Tezgül COŞKUN ÖZTÜRK*, Mehedin ARİFOVİÇ*, Oliver KIELER†, Ralf BEHR,

"Testing the Sampling System Using Josephson Arbitrary Waveform Synthesizer Established in TÜBİTAK UME"

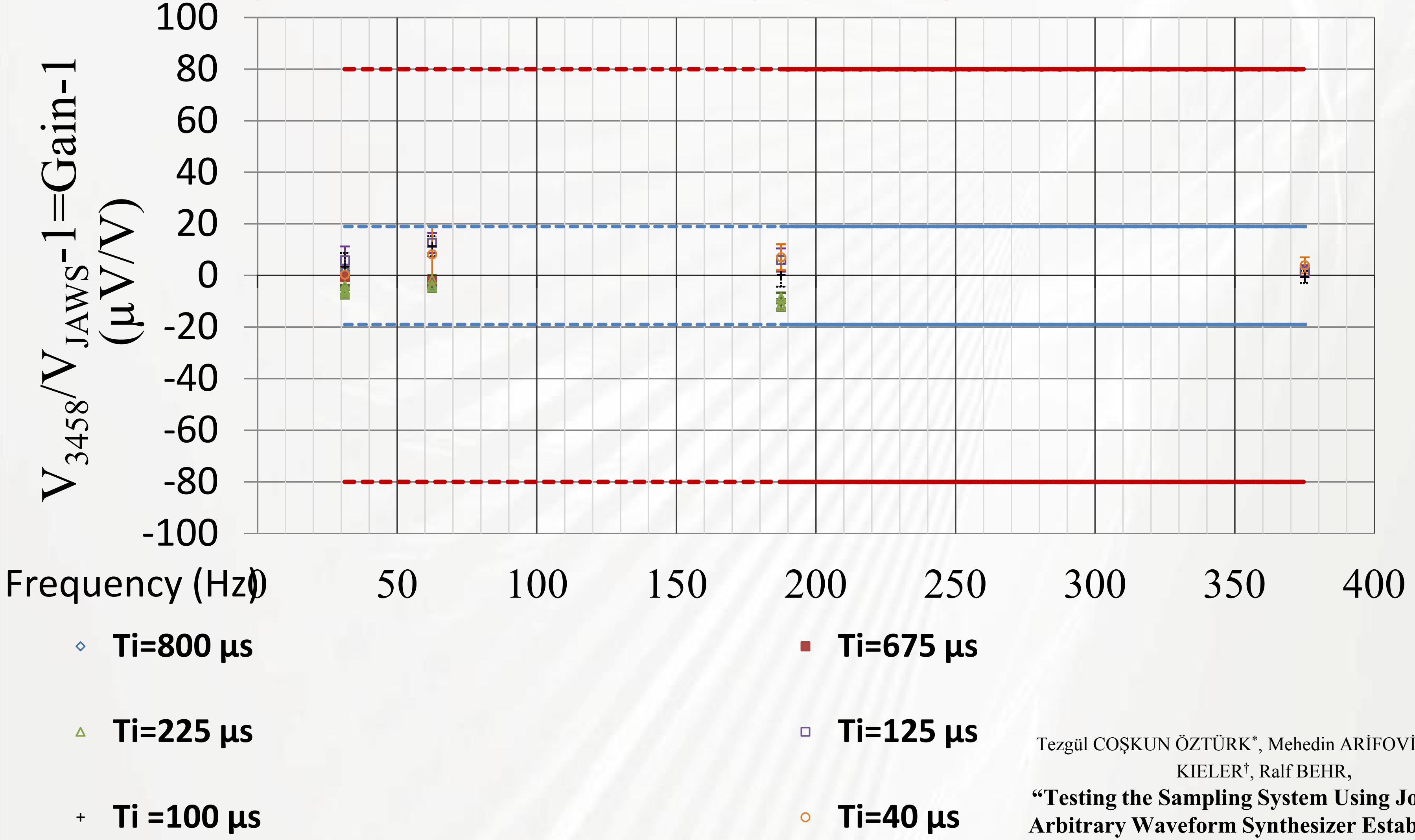
CPEM 2020

TÜBİTAK UME

MEASUREMENT RESULTS



MEASUREMENT RESULTS



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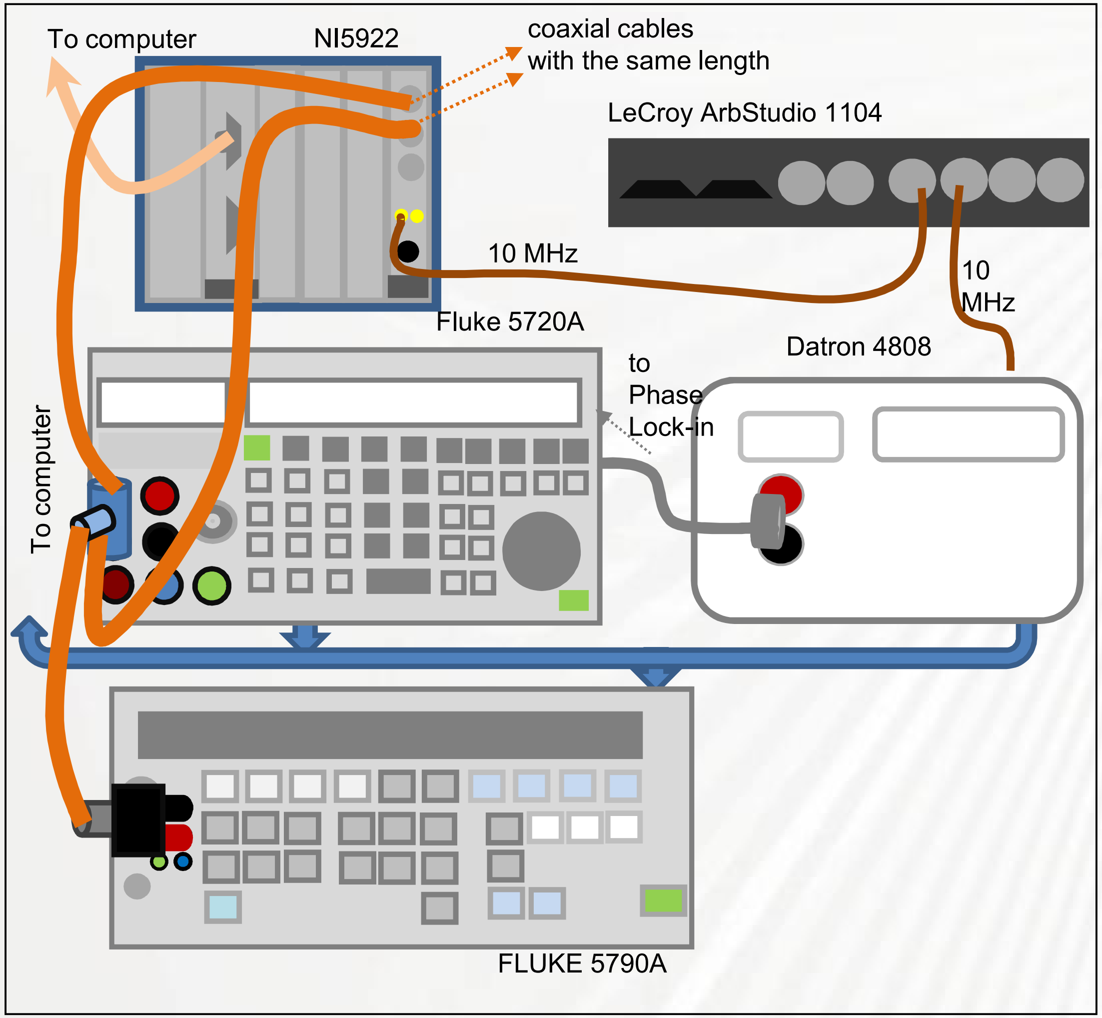
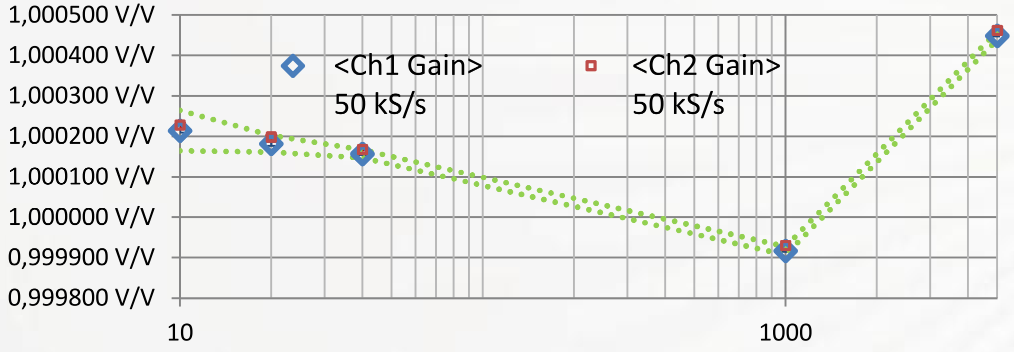
TÜBİTAK UME

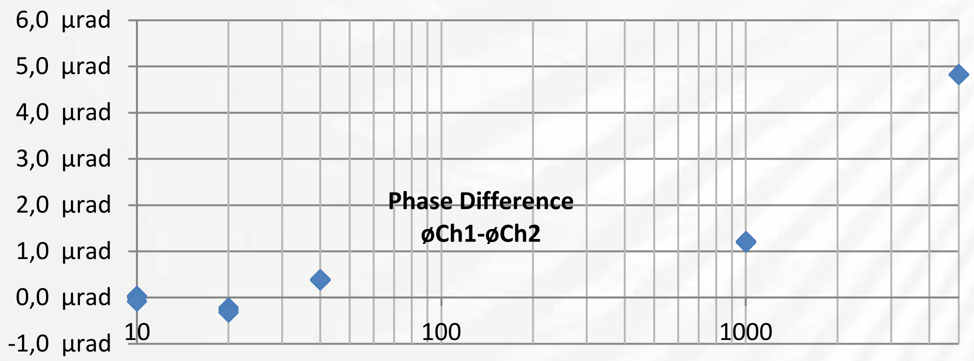
SAMPLING SYSTEM BASED ON ΔΣ ADC

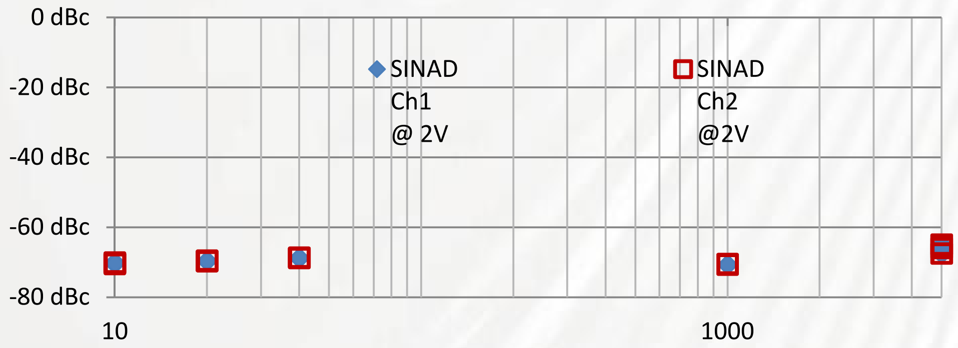


Measurements Carried out to Support the Report

SAMPLING SYSTEM BASED ON ΔΣ ADC



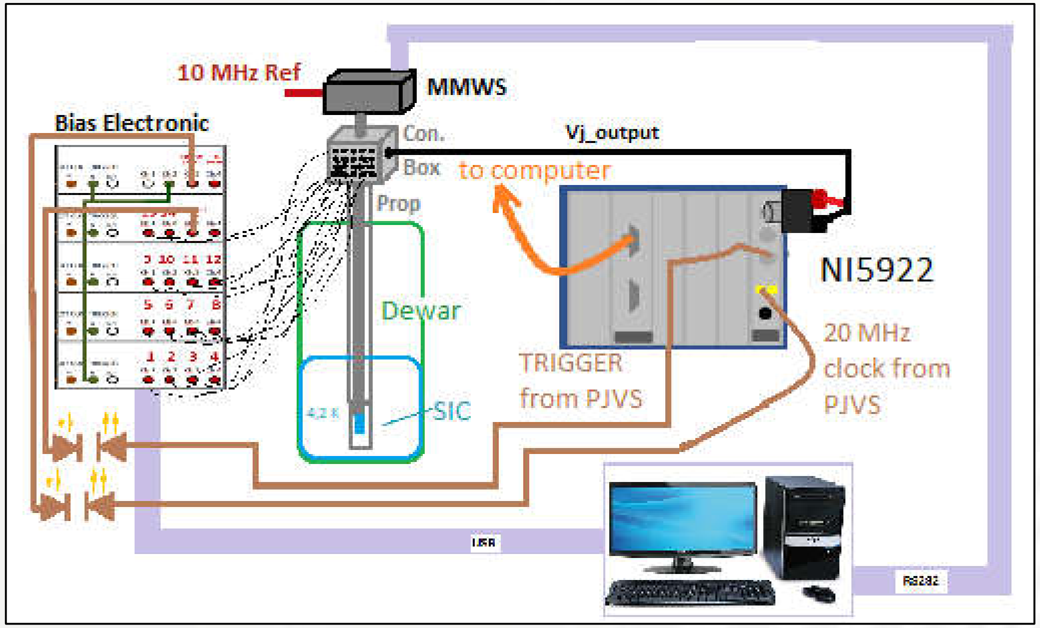


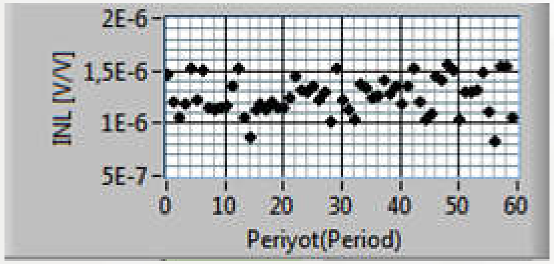


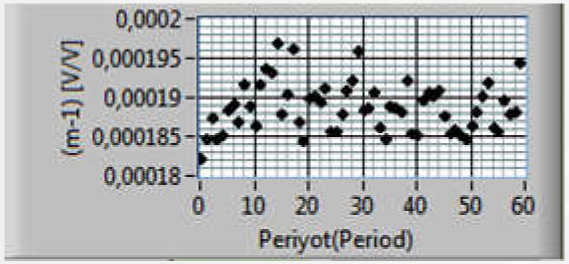
Measurement results obtained using Solidstate Standards.

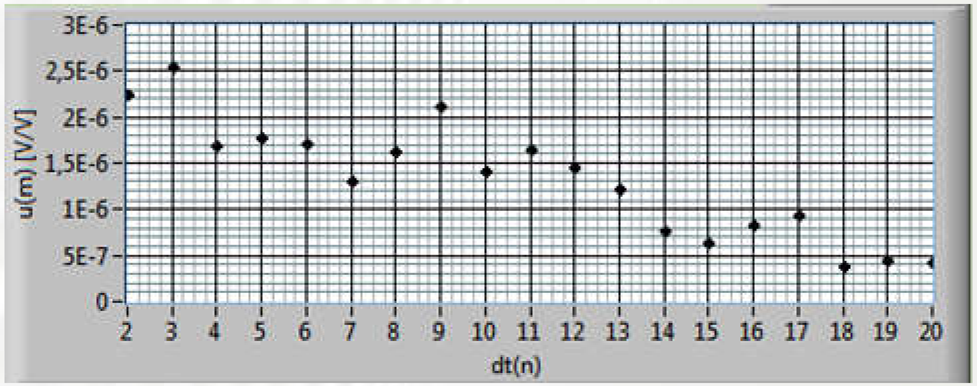
Measurements Carried out to Support the Report

IMPROVING DYNAMIC GAIN&SINAD CHARACTERISATION BY USING PJVS









Measurements Carried out to Support the Report

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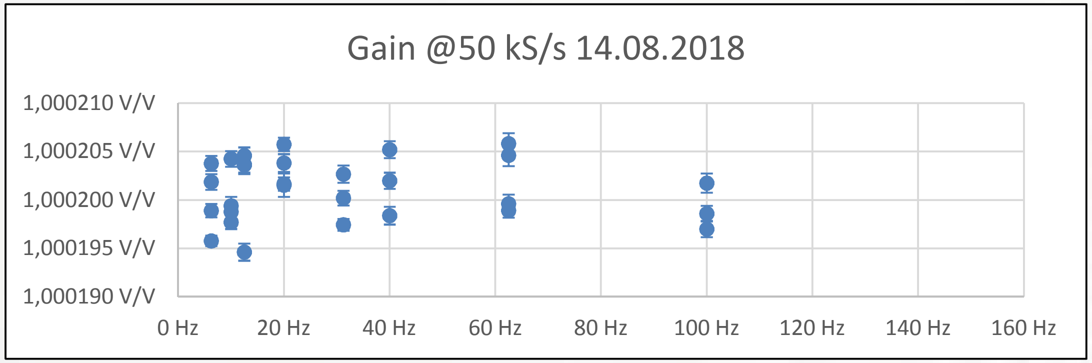

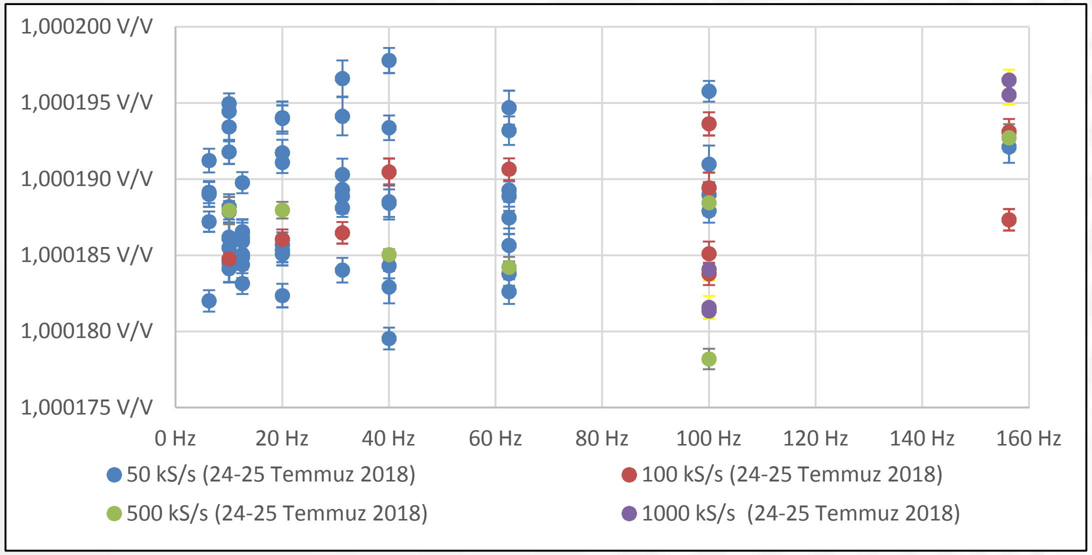

Measurements Carried out to Support the Report

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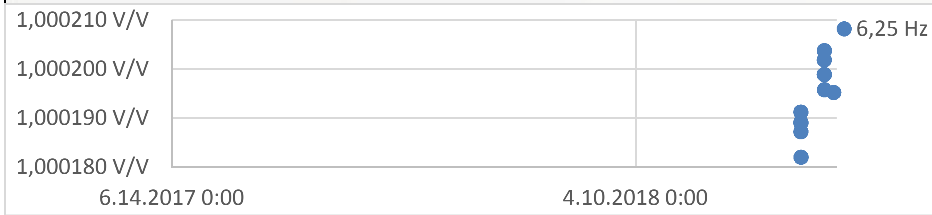
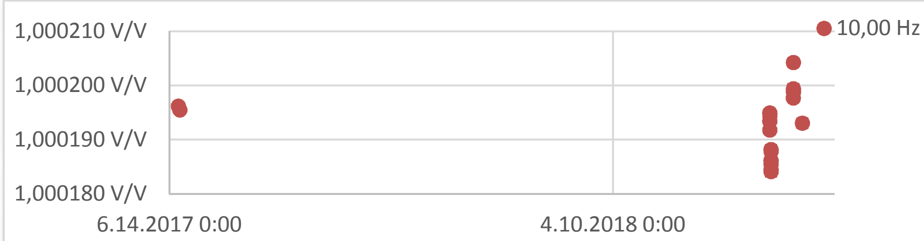
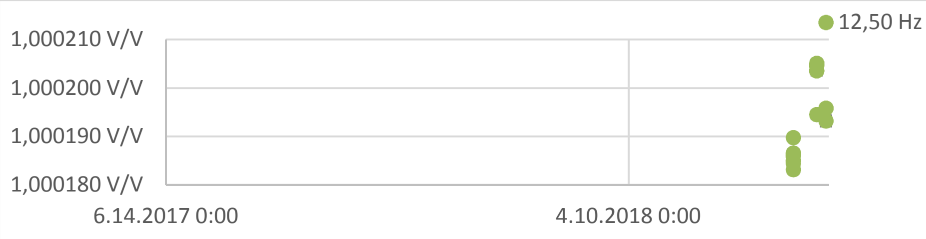
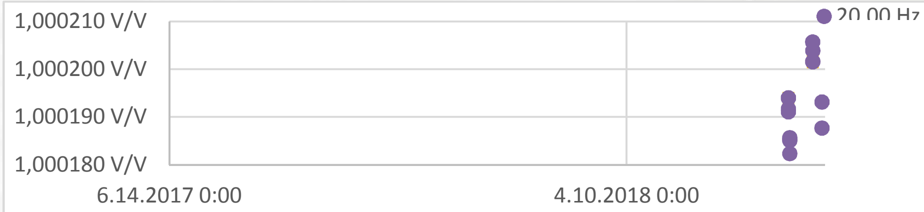
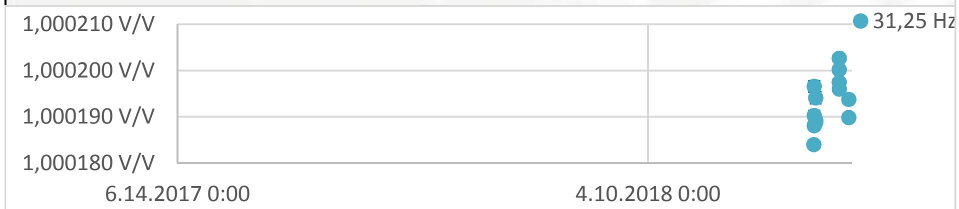
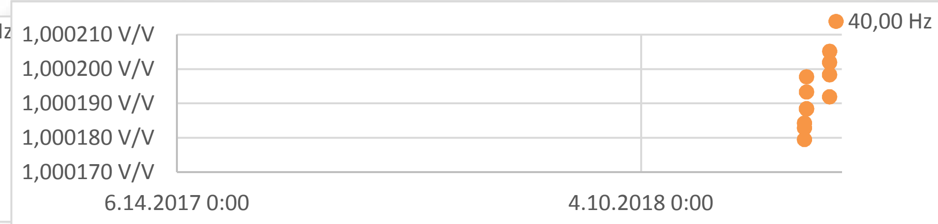


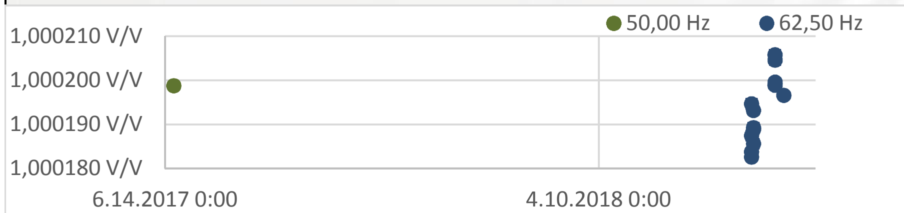


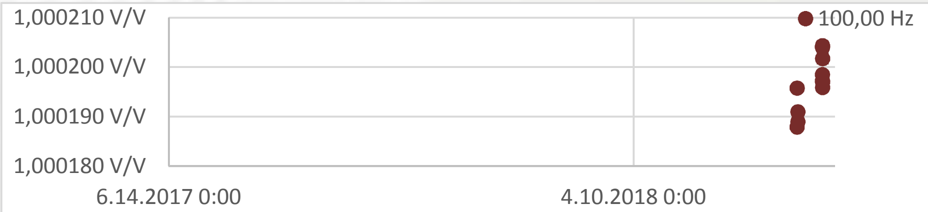






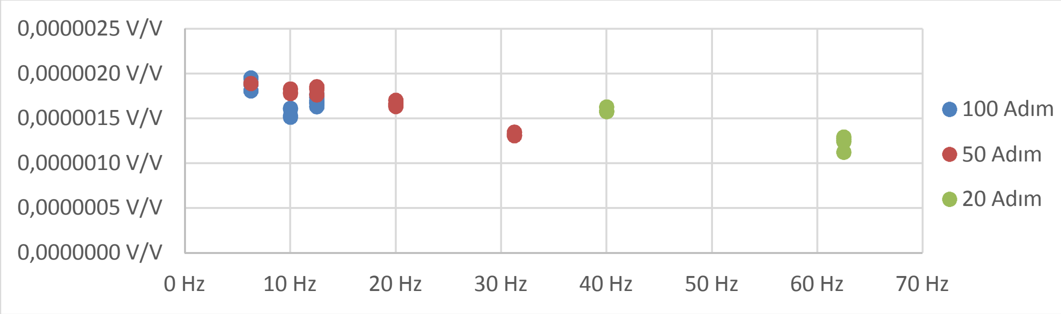


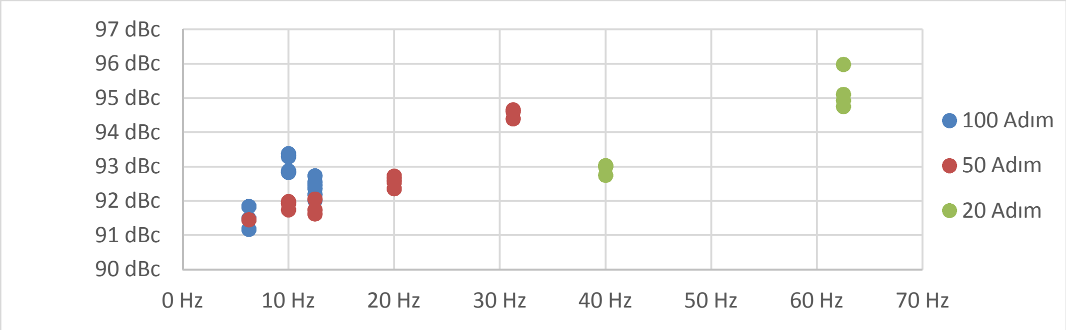


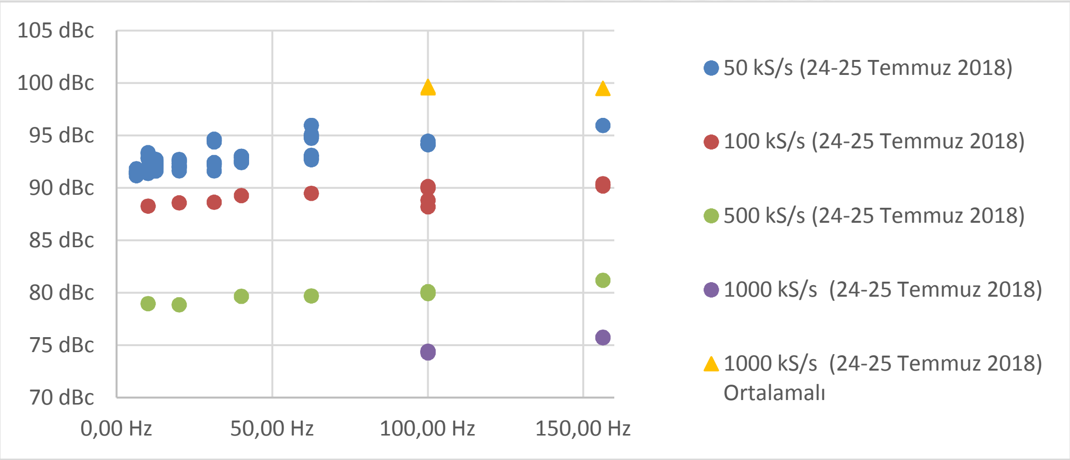


Measurements Carried out to Support the Report

IMPROVING DYNAMIC GAIN&SINAD CHARACTERISATION BY USING PJVS







Thank you for your attention!

Mehedin ARİFOVİÇ
Tezgül COŞKUN ÖZTÜRK
Naylan KANATOĞLU

TRUE
MEASUREMENT
EXCELLENCE