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PMUs in Distribution Networks

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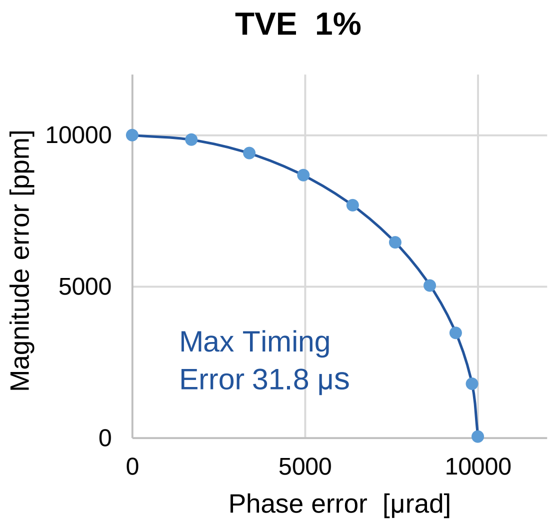
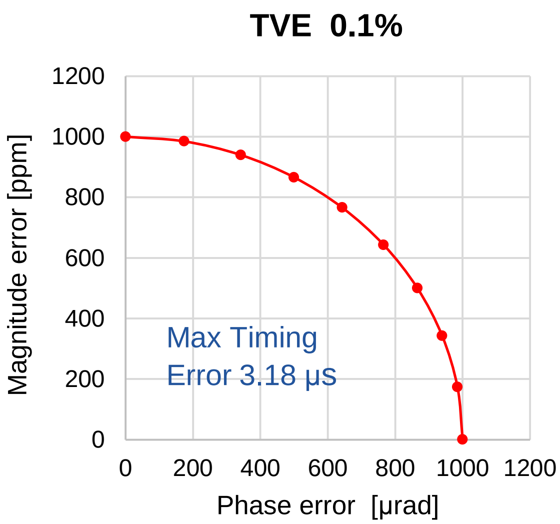
Requirements for an advanced PMU calibrator

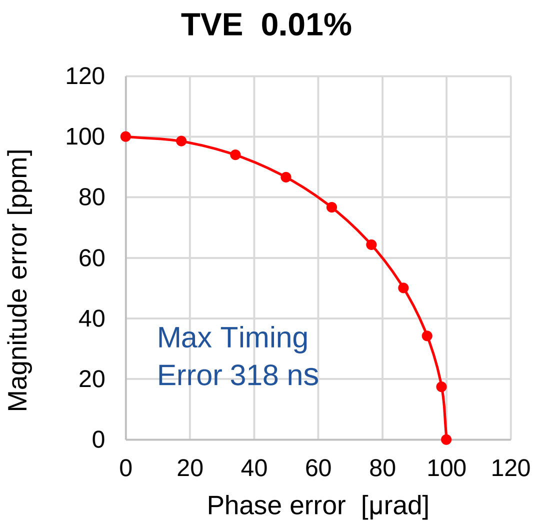
Error limits

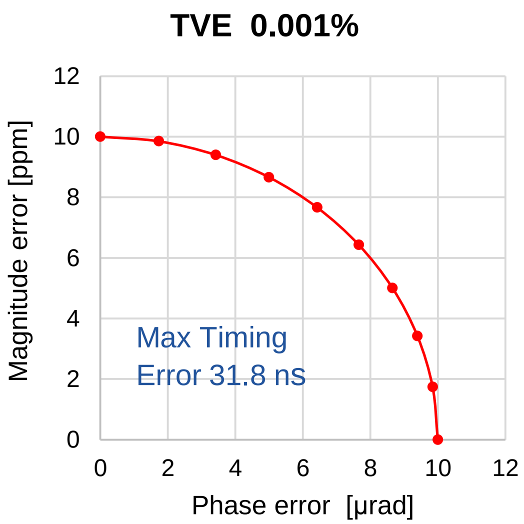


Improving the TVE error by a factor 10 demands:

Reduction of timing error *10x lower*
Reduction of magnitude error *10x lower*
Reduction of phase error *10x lower*





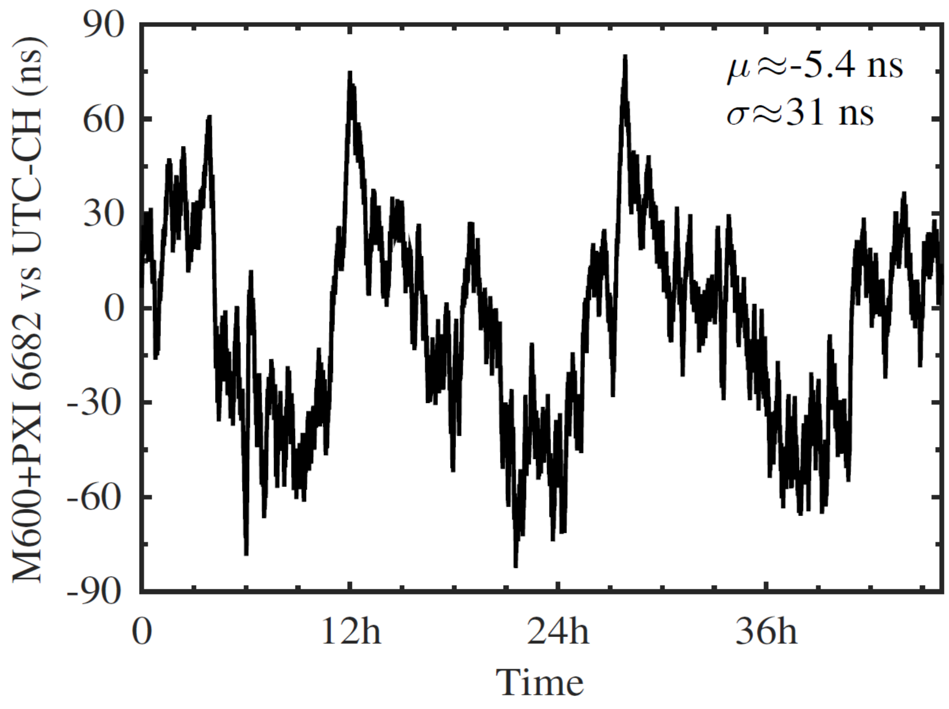


Hardware Improvement of Existing PMU Calibrator

Time Reference (1)

Correlation of two GPS receivers (PPS outputs)

- Identical geographical position
- Dissimilar GPS receivers
- Phase error up to 1.6 mdeg.

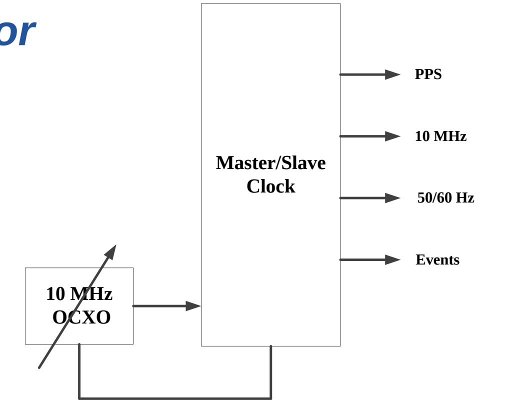


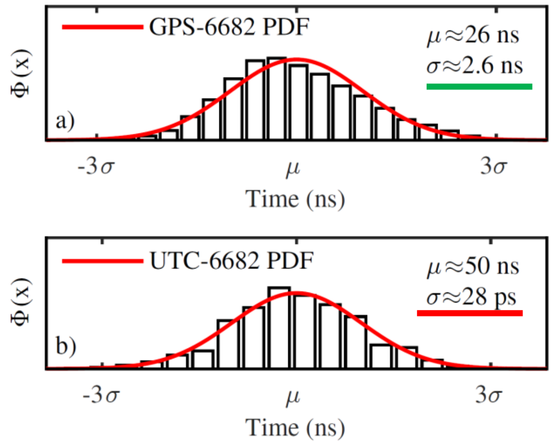
Hardware Improvement of Existing PMU Calibrator

Time Reference (2)

Existing PMU calibrator

IRIG-B
GPS
IEEE 1588



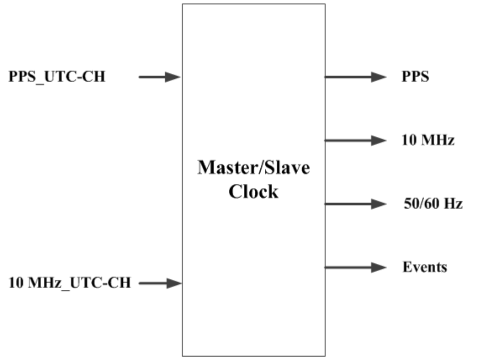


New PMU calibrator

NI PXI - 6682 & 6653

UTC CH
10 MHz & PPS

(National Time)

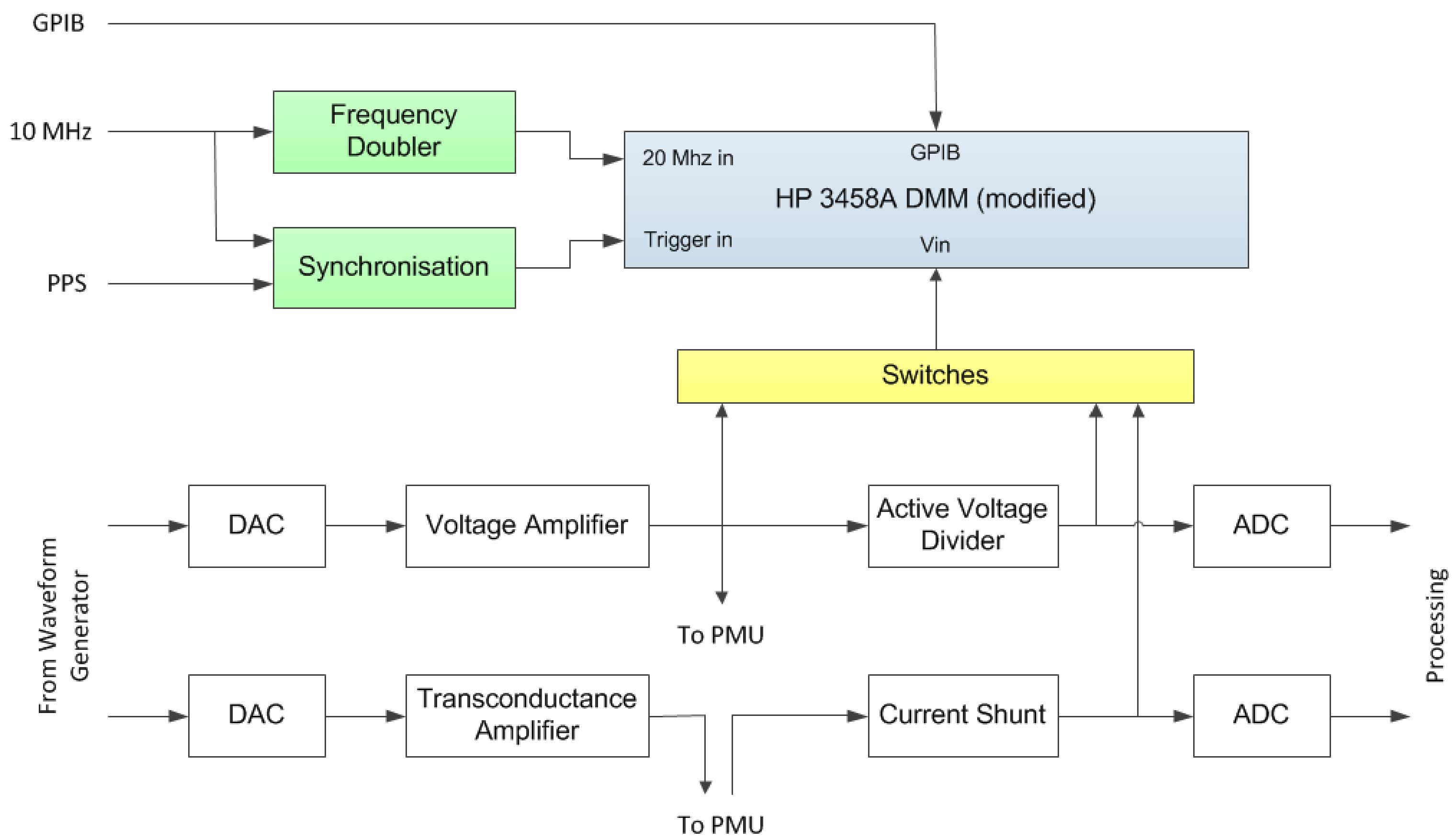


Timing traceable to UTC

Jitter reduced by a factor 100 !

Hardware Improvement of PMU Calibrator

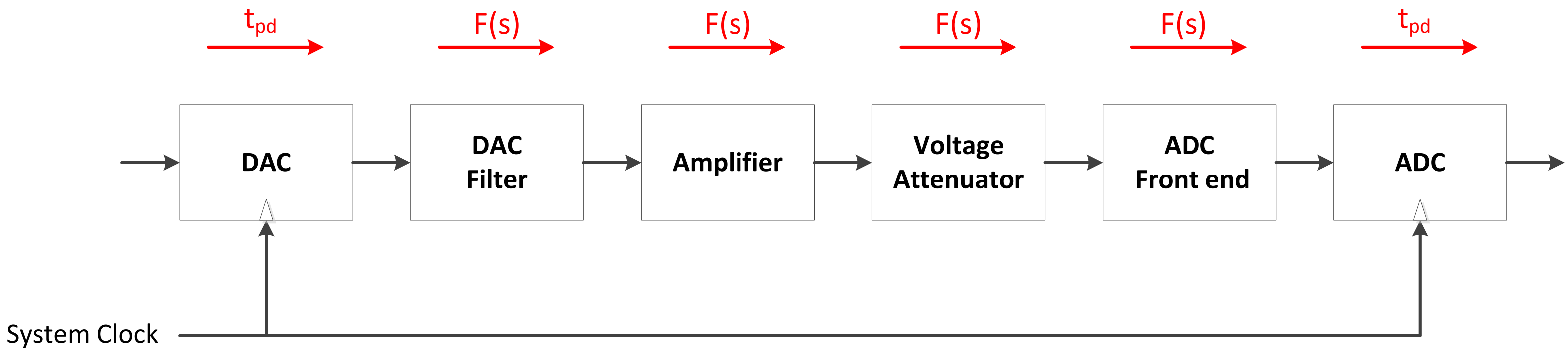
Active calibration



Aim: Voltage and current accuracy between 10 and 20 ppm

Limited Bandwidth of Amplifiers (1)

TVE %	Mag ppm	Pha deg.	Pha µrad.	Time µs
1	10000	0.5811	10142.1	32
0.1	1000	0.0573	1000.1	3.2
0.01	100	0.0057	100.0	0.32
0.001	10	0.0006	10.0	0.032

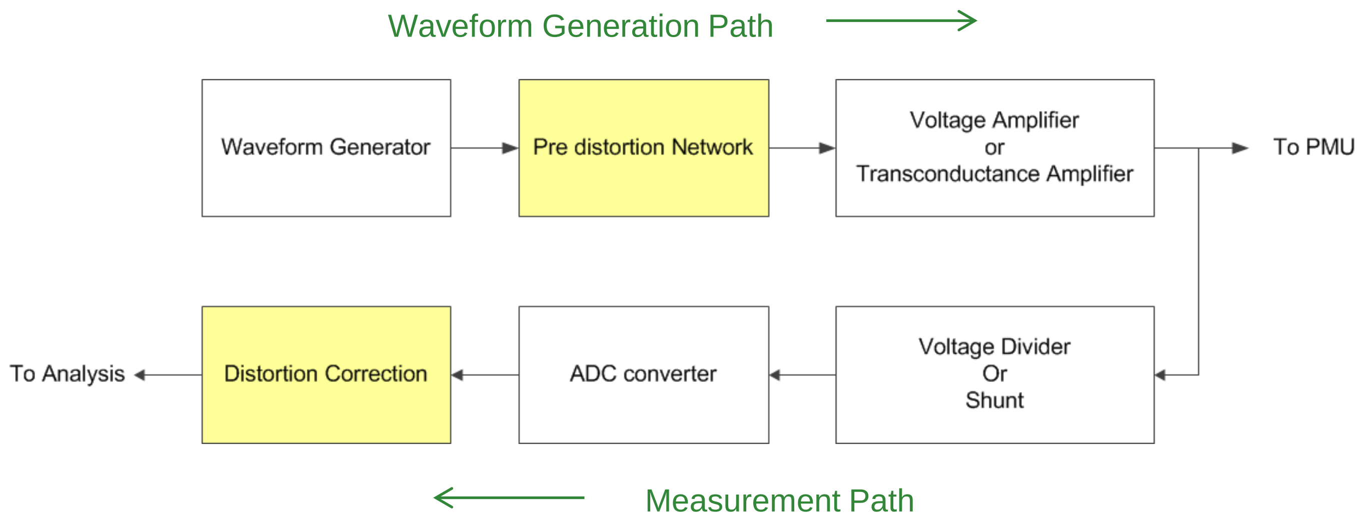


Impact of Amplifier
Bandwidth 6.5 kHz
(Single Pole model)

f Hz	Attenuation -	Attenuation ppm	Phase deg	Slope Att. ppm/Hz	Slope Pha. deg/Hz
45	0.999976	-24.0	-0.39666		
49	0.999972	-28.4	-0.43191		
50	0.999970	-29.6	-0.44073	-1.18	-0.00881
51	0.999969	-30.8	-0.44954		
55	0.999964	-35.8	-0.48480		
59	0.999959	-41.2	-0.52006		
60	0.999957	-42.6	-0.52887	-1.42	-0.00881
61	0.999956	-44.0	-0.53768		
65	0.999950	-50.0	-0.57294		

Limited bandwidth of amplifiers (2)

Equalisation of Frequency Response



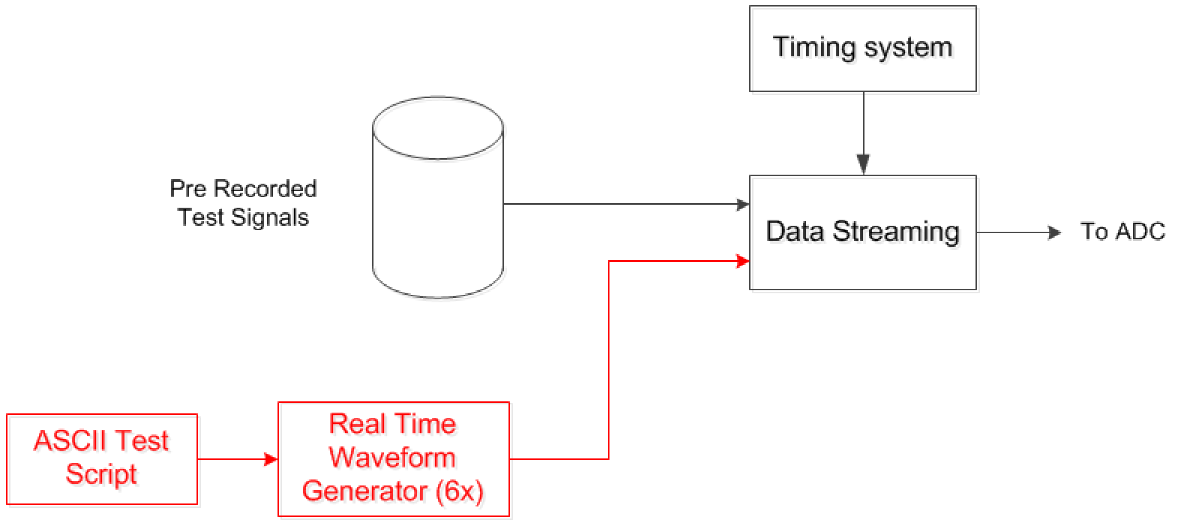
Digital filters used in both paths

- Must correct magnitude and phase errors
- Not identical corrections (measurement path has a wider bandwidth)

Aim: Flat frequency response between 45 and 65 Hz

Improvement of PMU Calibrator

Real time waveform generator

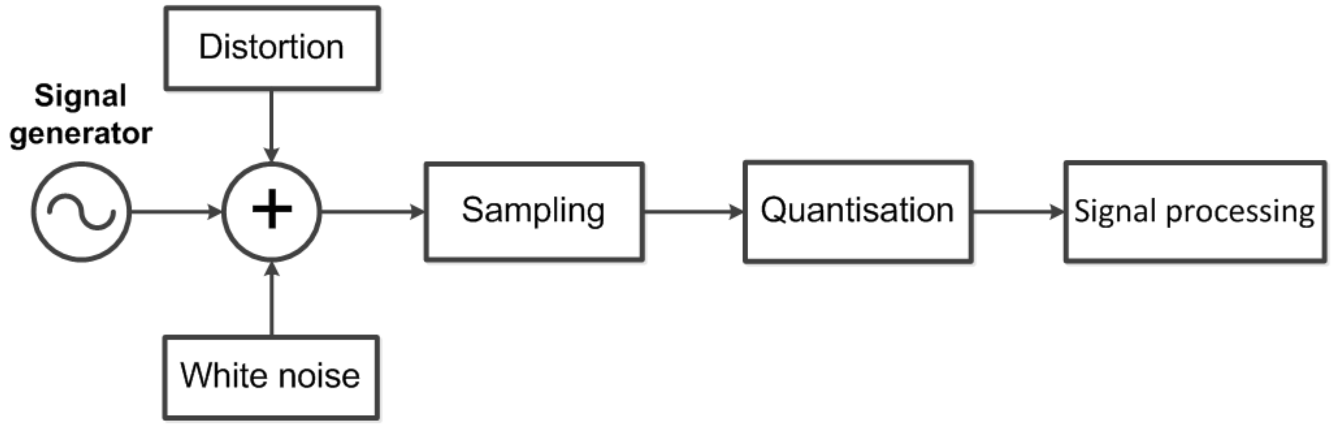


Benefits of a Real Time Waveform Generator

- Reduction in the amount of stored data (several Gbytes)
- Flexibility in the creation of special test scenarios (not part of C37.118.1)
- Permits to test PMUs for various PQ disturbances
- Expends the use of the PMU calibrator to PQ analysers
- Use of pre recorded test signals preserved (playback of field acquired waveforms)

Impact of estimation algorithms

Simulations



Quantisation:

- 16 or 24 bits resolution

Signal processing:

- Single sine wave fitting
- Dual sine wave fitting
- Frequency of signal known

Aim: To determine the impact of noise and distortion on incertitude

Impact of estimation algorithms

Single sine wave fit

1. Least Square Estimation of the three fitting parameters

$$\min_{A_0, B_0, C_0} \sum_{n=1}^{N} \{y_n - A_0 \cos(\omega_0 t_n) - B_0 \sin(\omega_0 t_n) - C_0\}^2$$

2. Equivalent matrix equation: $\min_{X_0} (Y - D_0 X_0)^T (Y - D_0 X_0)$

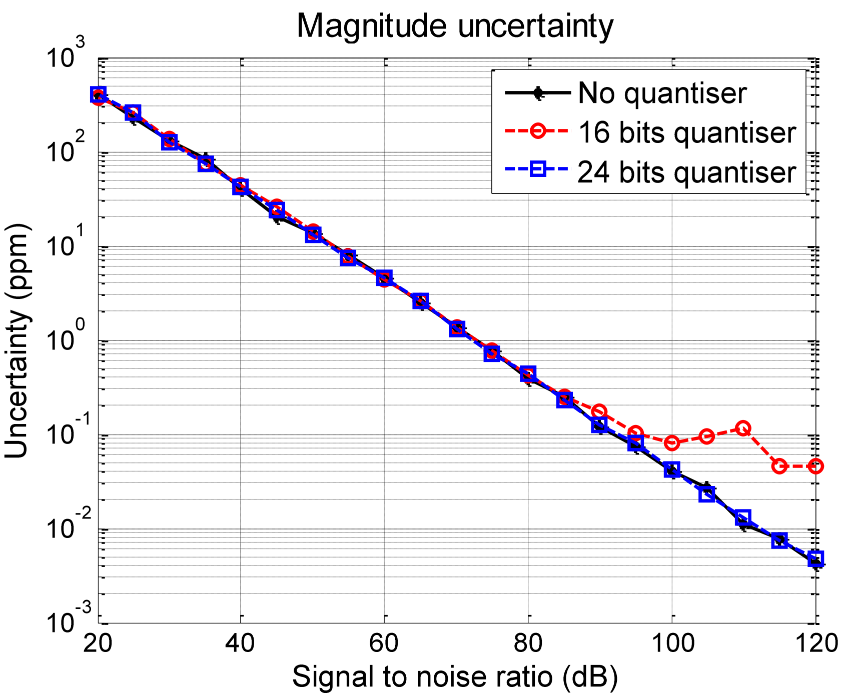
$$D_0 = \begin{bmatrix} \cos(\omega_0 t_1) & \sin(\omega_0 t_1) & 1 \\ \cos(\omega_0 t_2) & \sin(\omega_0 t_2) & 1 \\ \vdots & \vdots & \vdots \\ \cos(\omega_0 t_N) & \sin(\omega_0 t_N) & 1 \end{bmatrix}; \quad X_0 = \begin{bmatrix} A_0 \\ B_0 \\ C_0 \end{bmatrix}; \quad Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}$$

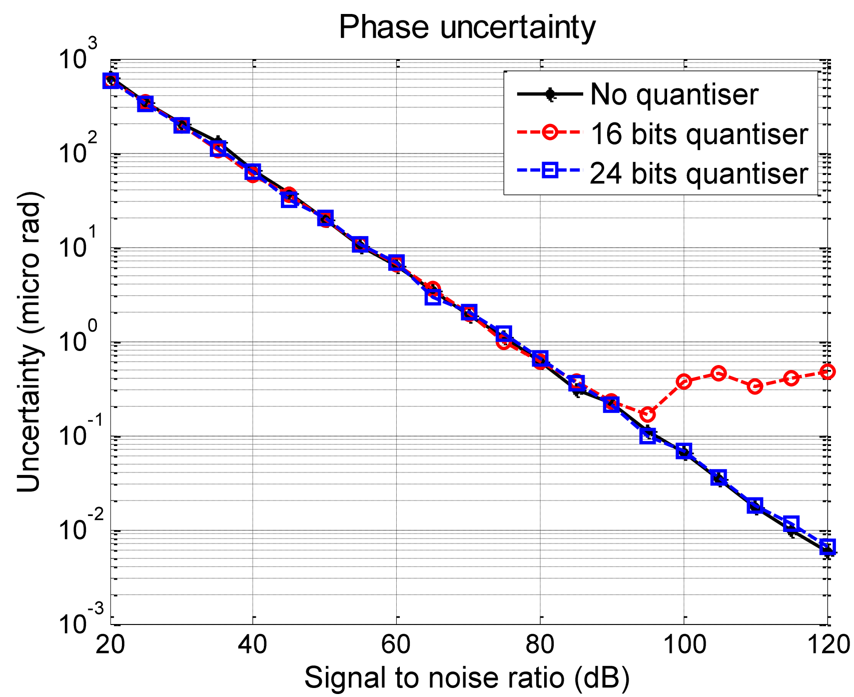
3. Unique solution to the minimisation problem

$$X_0 = (D_0^T D_0)^{-1} (D_0^T Y)$$

Impact of estimation algorithms

Single sine wave fit in the presence of white noise



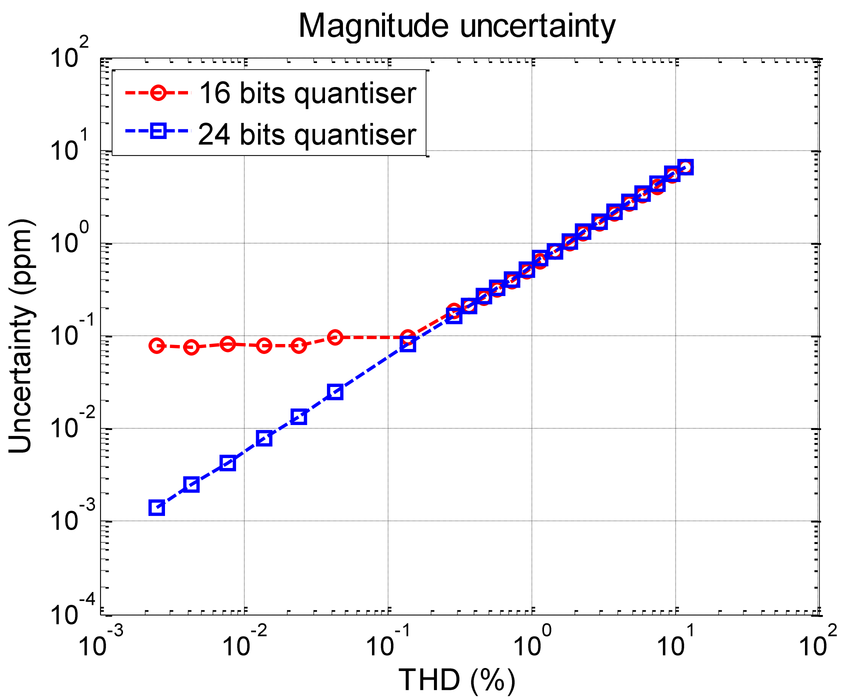


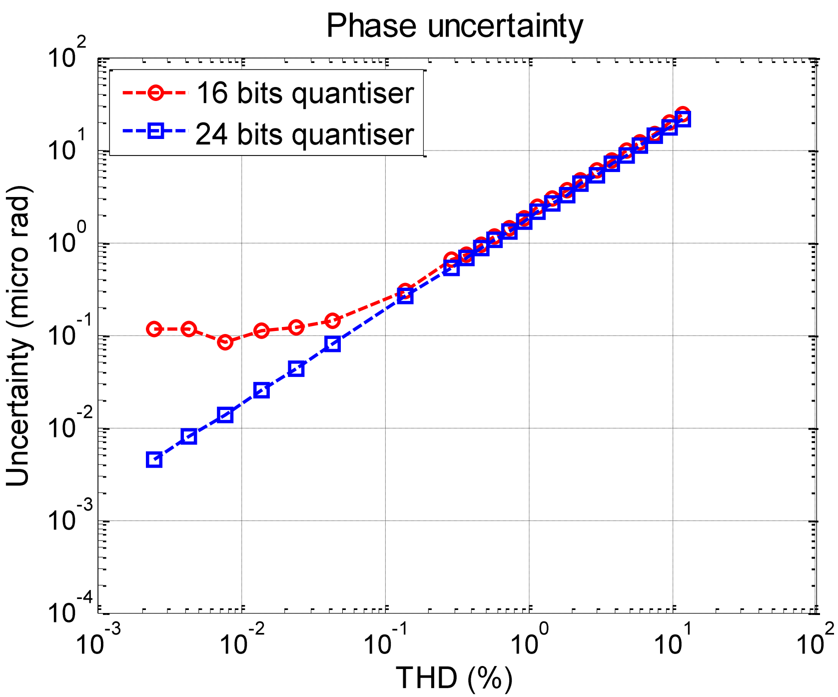
Simulation parameters

- Signal Frequency: 50 Hz
- Sampling Frequency: 18 kHz
- Measurement time : 1 s (50 Signal periods)

Impact of estimation algorithms

Impact of distortion on single sine wave estimation



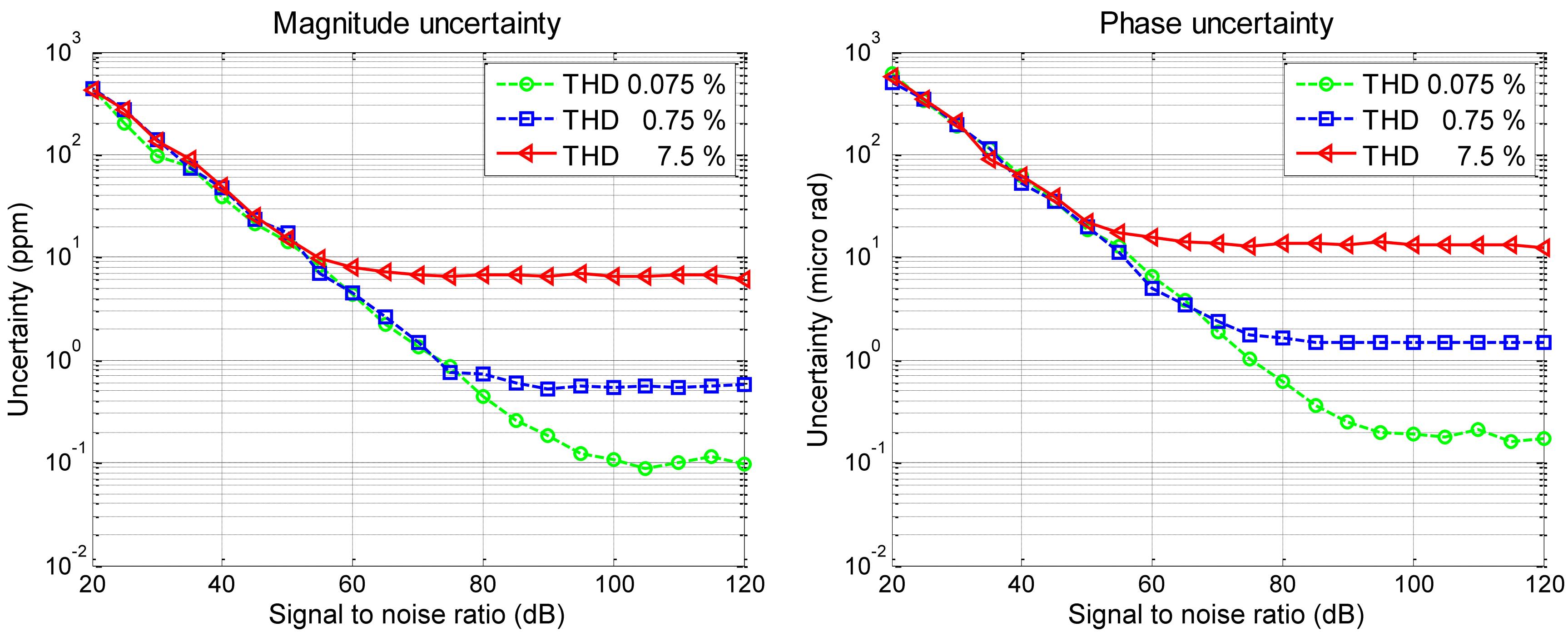


Simulation parameters

- Signal Frequency: 50 Hz
- Sampling Frequency: 18 kHz
- Measurement time: 1 s (50 Signal periods)
- Harmonic structure: 1/rank

Impact of estimation algorithms

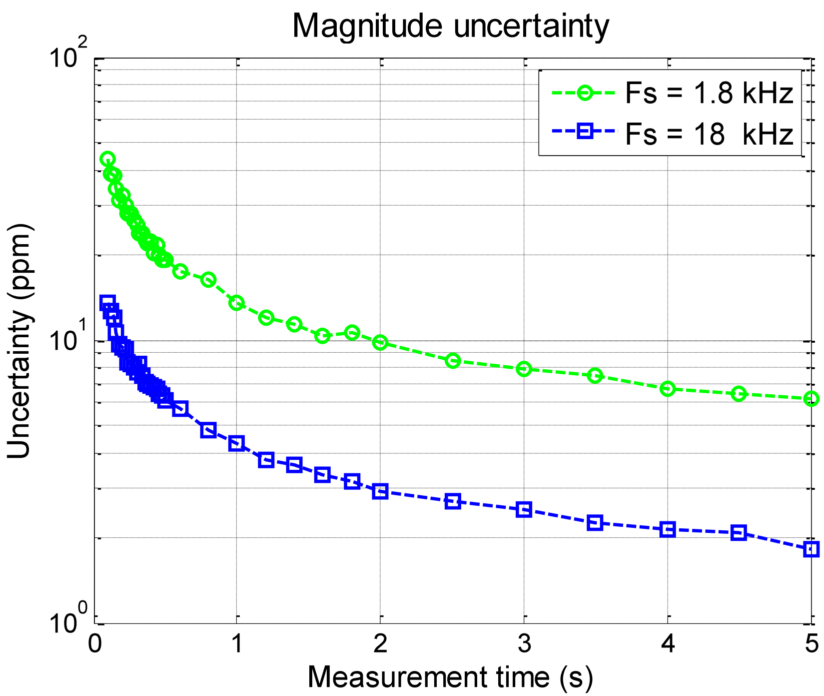
Combined impact of white noise and distortion

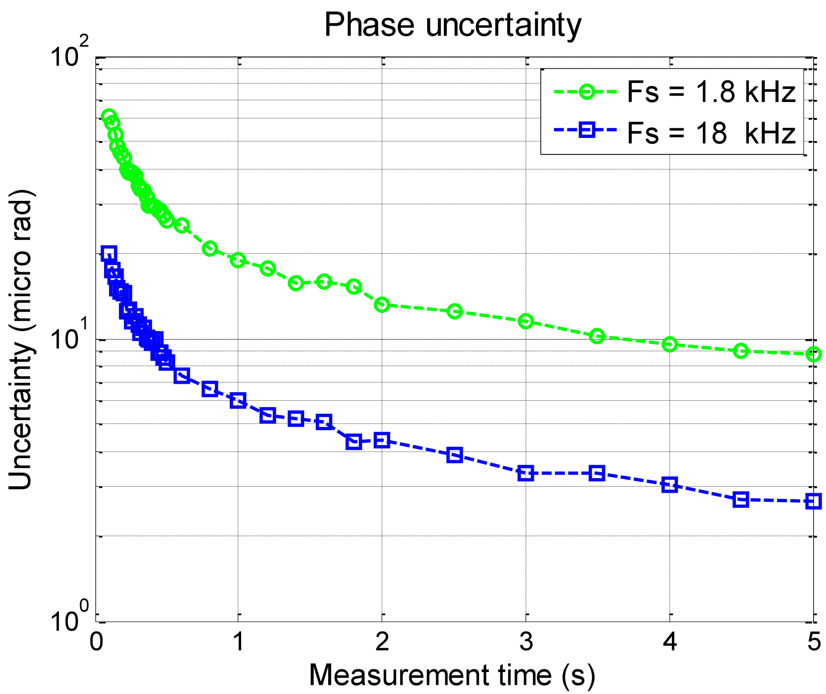


Simulation parameters

- Signal Frequency: 50 Hz
- Sampling Frequency: 18 kHz / 16 bits resolution
- Measurement time: 1 s (50 Signal periods)
- Harmonic structure: 1/rank

Impact of sampling rate and observation interval





Simulation parameters

- Signal Frequency: 50 Hz
- White noise: 16 dB
- THD: 0.75%
- Resolution 16 bits

Impact of estimation algorithms

Dual sine wave fit

Extension of the single sine wave fitting algorithm

1. Least Square Estimation of the five fitting parameters

$$\min_{A_0, B_0, C_0} \sum_{n=1}^{N} \{y_n - A_0 \cos(\omega_0 t_n) - B_0 \sin(\omega_0 t_n) - A_1 \cos(\omega_1 t_n) - B_1 \sin(\omega_1 t_n) - C_0\}^2$$

2. Equivalent matrix equation: $\min_{X_0} (Y - D_0 X_0)^T \, (Y - D_0 X_0)$

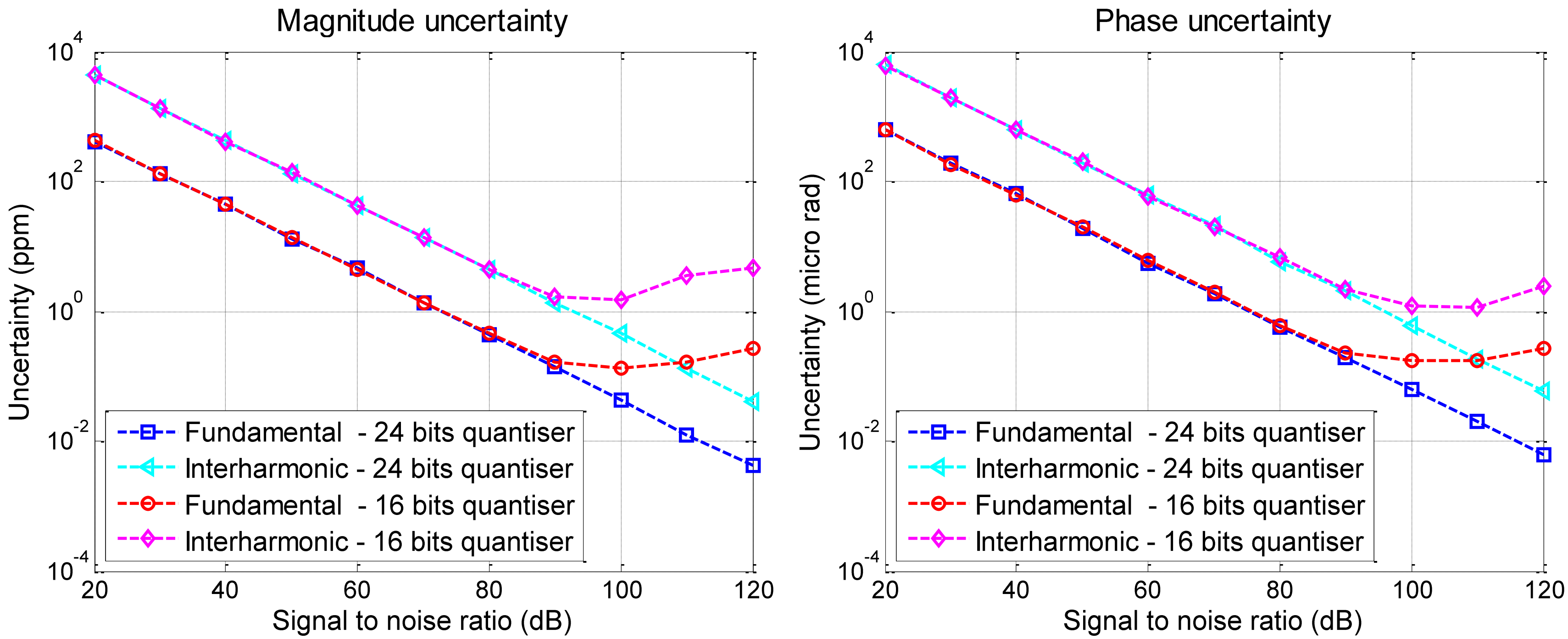
$$D_0 = \begin{bmatrix} \cos(\omega_0 t_1) & \sin(\omega_0 t_1) & \cos(\omega_1 t_1) & \sin(\omega_1 t_1) & 1 \\ \cos(\omega_0 t_2) & \sin(\omega_0 t_2) & \cos(\omega_1 t_1) & \sin(\omega_1 t_2) & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \cos(\omega_0 t_N) & \sin(\omega_0 t_N) & \cos(\omega_1 t_N) & \sin(\omega_1 t_N) & 1 \end{bmatrix}; \quad X_0 = \begin{bmatrix} A_0 \\ B_0 \\ A_1 \\ B_1 \\ C_0 \end{bmatrix}$$

3. Unique solution to the minimisation problem

$$X_0 = (D_0^T D_0)^{-1} (D_0^T Y)$$

Impact of estimation algorithms

Dual sine wave fit in the presence of white noise

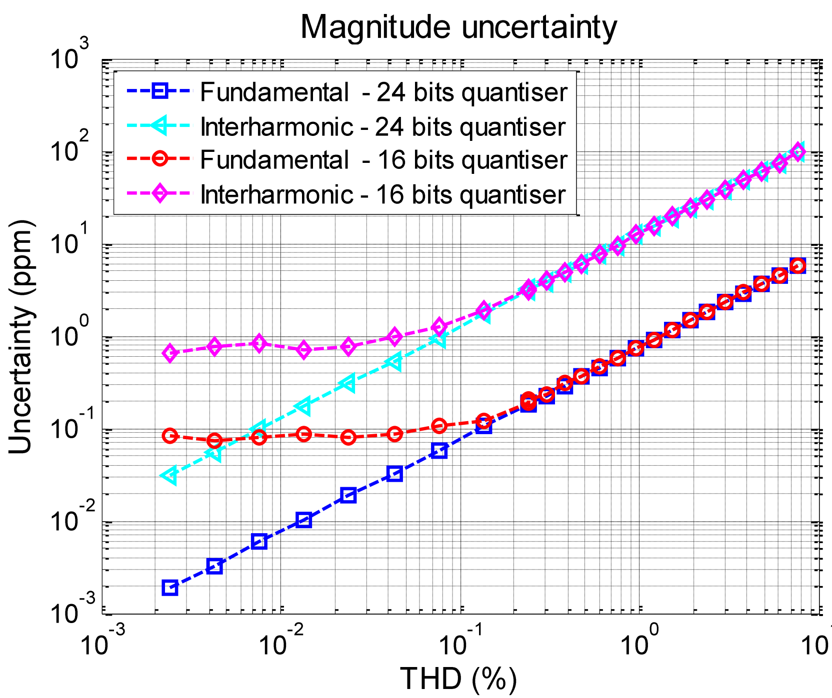


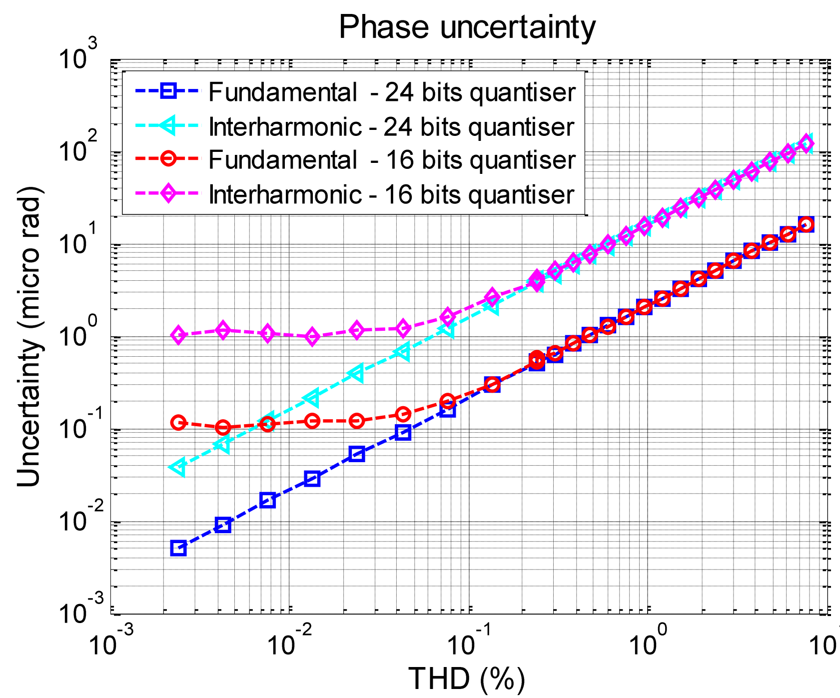
Simulation parameters

- Signal Frequency: 50 Hz
- Interharmoncic frequency: 75 Hz (Magnitude 1/10 of fundamental)
- Sampling Frequency: 18 kHz
- Measurement time: 1 s (50 Signal periods)

Impact of estimation algorithms

Impact of distortion on dual sine wave estimation



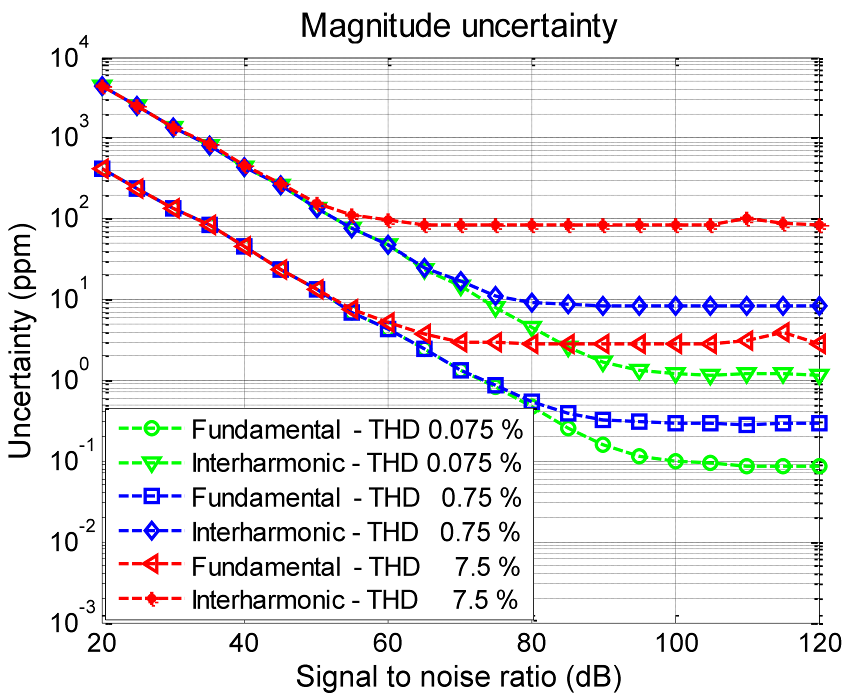


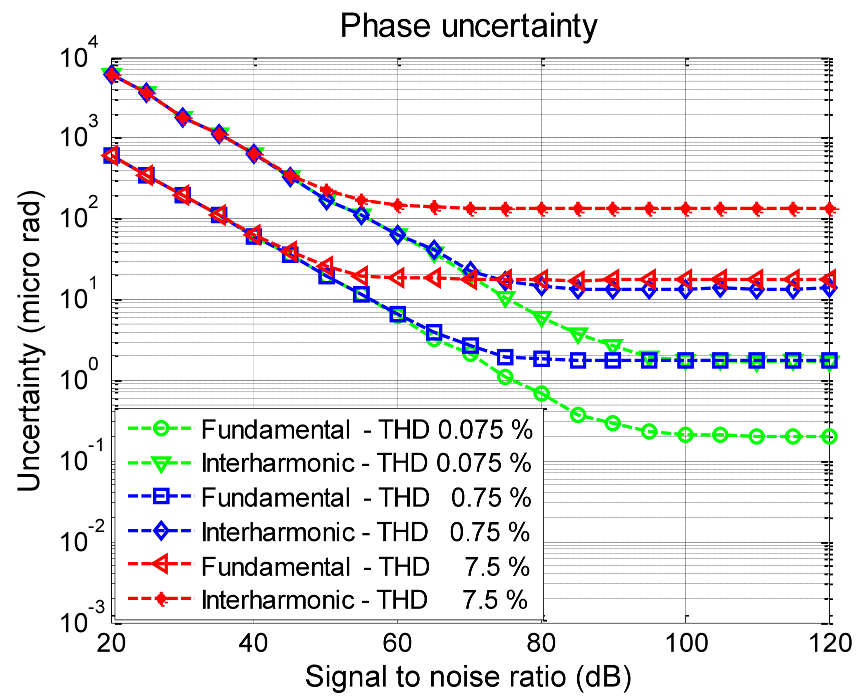
Simulation parameters

- Signal Frequency: 50 Hz
- Interharmoncic frequency: 75 Hz (Magnitude 1/10 of fundamental)
- Sampling Frequency: 18 kHz
- Measurement time: 1 s (50 Signal periods)

Impact of estimation algorithms

Combined impact of white noise and distortion





Simulation parameters

- Signal Frequency: 50 Hz
- Interharmoncic frequency: 75 Hz (Magnitude 1/10 of fundamental)
- Sampling Frequency: 18 kHz
- Measurement time: 1 s (50 Signal periods)
- Quantisation: 16 Bits

Conclusions

- The use of PMUs in distribution networks is subject to:
  - Significantly improved TVE performances compared to IEEE C37.118.1
  - Strong robustness to power quality disturbances
  - Appropriate calibration infrastructures
- Advanced PMU calibrators require:
  - Greatly improved magnitude, phase and timing accuracy
  - TVE in the order of 0.01 is feasible, but 0.001 is challenging
  - Flexible waveform generators for the tests of PQ disturbances

Metrology has been and remains an enabler of the PMU technology

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Thanks for your interest