TracePQM – workshop

Uncertainty evaluation of PQ algorithms

27th May 2019

CMI, Brno

Presenter: Stanislav Mašláň, Czech Metrology Institute

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Traceability Routes for Electrical Power Quality Measurement

EMPIR Research Potential project

Project code: 15RPT04 TracePQM

Running time: June 2016 to May 2019

Consortium: 13 Partners + 1 RMG

7 already **developed** capability

2 in process of development

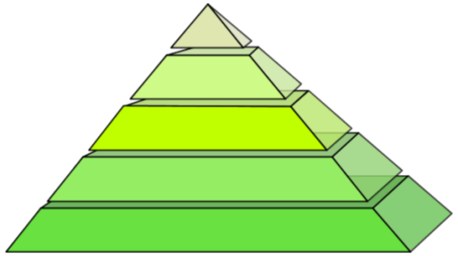
2 intend to develop

Potential to **knowledge transfer**

Coordinator:

Věra Nováková Zachovalová

Why Power Quality (PQ)?



Power Distribution Grid

- Many small "green" sources with **fluctuating power** in the grid
- Non-linear loads (appliances) - **distortion**
- Damage of highly sensitive electronic equipment
- In worst case risk of **blackouts**

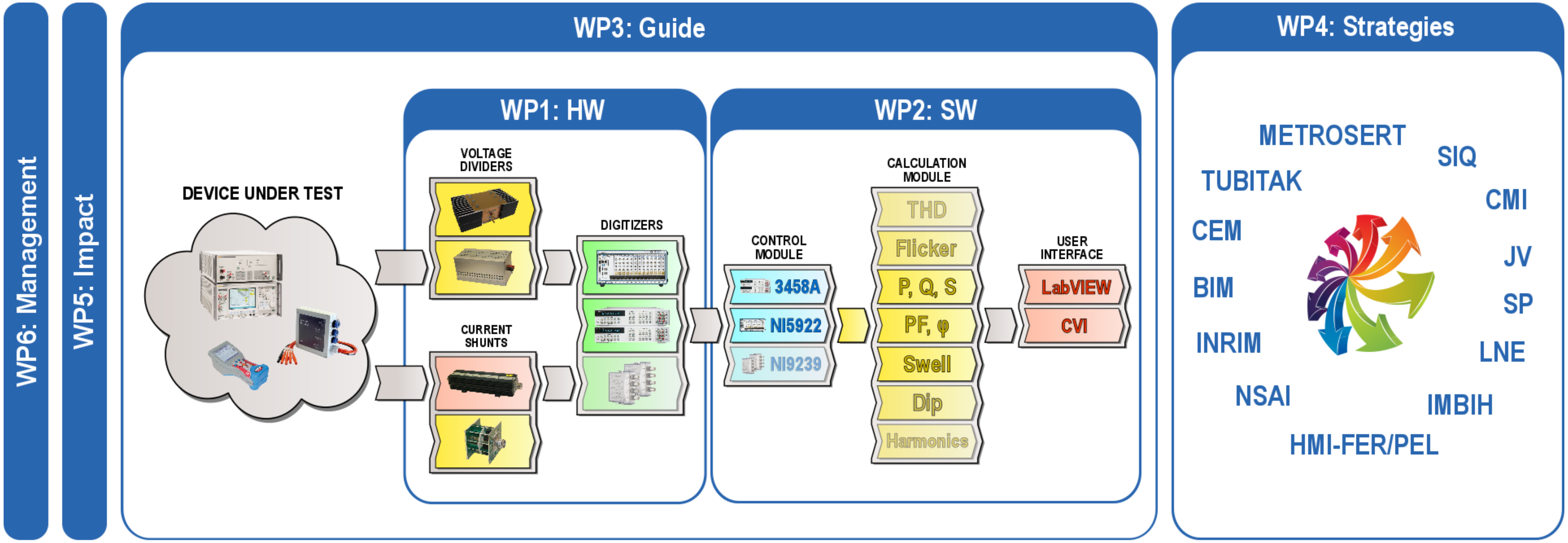
Power Quality Monitoring

- Large number of diverse parameters (harmonics, flicker, dips, swells, ...)
- IEC 61000-4-30, IEC 62586-2, IEC 61000-4-15, IEC 61000-4-7
- Wide range of measuring instrumentation

SI Traceability of PQ measurements is imperative to ensure comparability of results
BUT
Difficult to obtain traceability for all PQ parameters

Project structure

Overall goal: To **develop** and **validate** an **open**, **modular** and well **documented metrology grade system** for sampled power and PQ parameters measurements, which can be easily established at all NMIs and other interested parties.



Power, PQ and uncertainty evaluation

<u>Components of uncertainty:</u>

- Contribution of corrections/calibration uncertainty:
  - Calibration uncertainty of digitizer
  - Calibration uncertainty of transducers

- Contribution of algorithm error/bias:
  - Standard deviation – can be evaluated as type A or from a noise/jitter for single reading
  - Every algorithm has some estimation bias
  - Often ignored source!

- Contribution of wiring and interferences:
  - Loading corrections
  - Leakage currents
  - Magnetic couplings
  - Ground loops
  - Crosstalk

Power, PQ and uncertainty evaluation

Basic GUF method:

- Using partial derivations
- Example for Ohm's law: $R = \frac{U}{I}$,

$$u(R) = \sqrt{\left(u(U)\frac{\partial R}{\partial U}\right)^2 + \left(u(I)\frac{\partial R}{\partial I}\right)^2} = \sqrt{\left(u(U)\frac{1}{I}\right)^2 + \left(-u(I)\frac{U}{I^2}\right)^2},$$

- **Benefit**: Fast calculation
- **Problems**: Complicated or unusable for complex algorithms

Power, PQ and uncertainty evaluation

Basic GUF method:

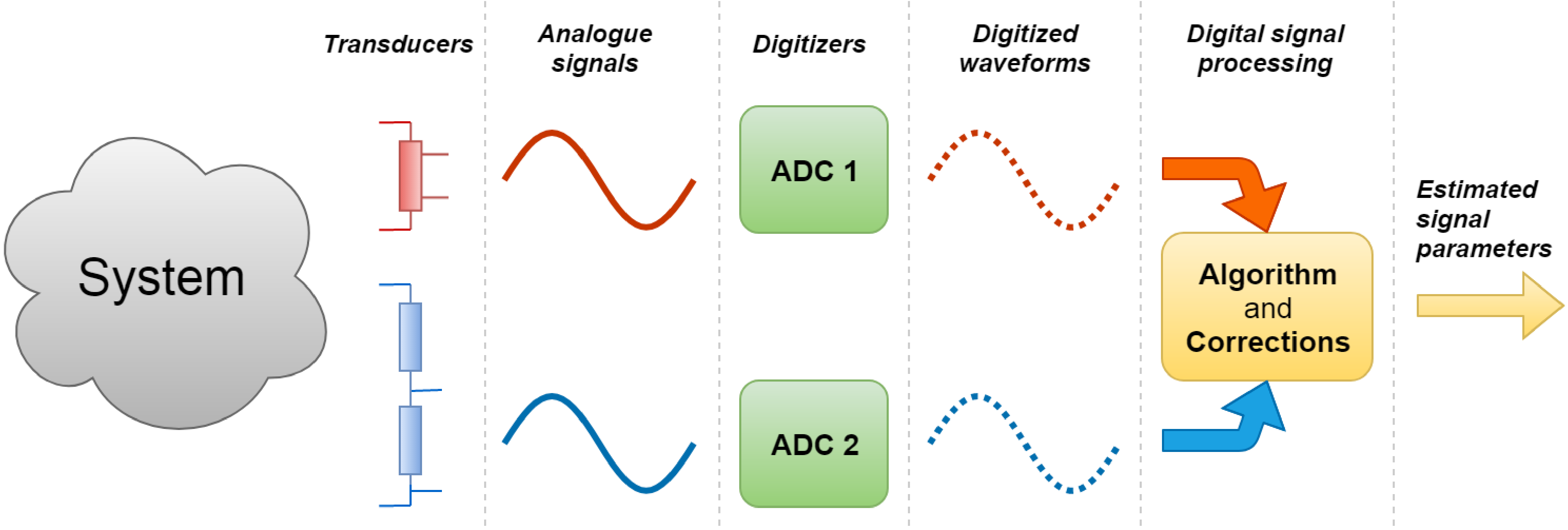
- Using partial derivations

- Example for single harmonic power: $P = U \cdot I \cdot \cos\varphi$

$$u(P) = \sqrt{\left(u(U)\frac{\partial P}{\partial U}\right)^2 + \left(u(I)\frac{\partial P}{\partial I}\right)^2 + \left(u(\varphi)\frac{\partial P}{\partial \varphi}\right)^2}$$

$$= \sqrt{(u(U) \cdot I \cdot \cos\varphi)^2 + (u(I) \cdot U \cdot \cos\varphi)^2 + (u(\varphi) \cdot U \cdot I \cdot \sin\varphi)^2}$$

Digital sampling measurement principle

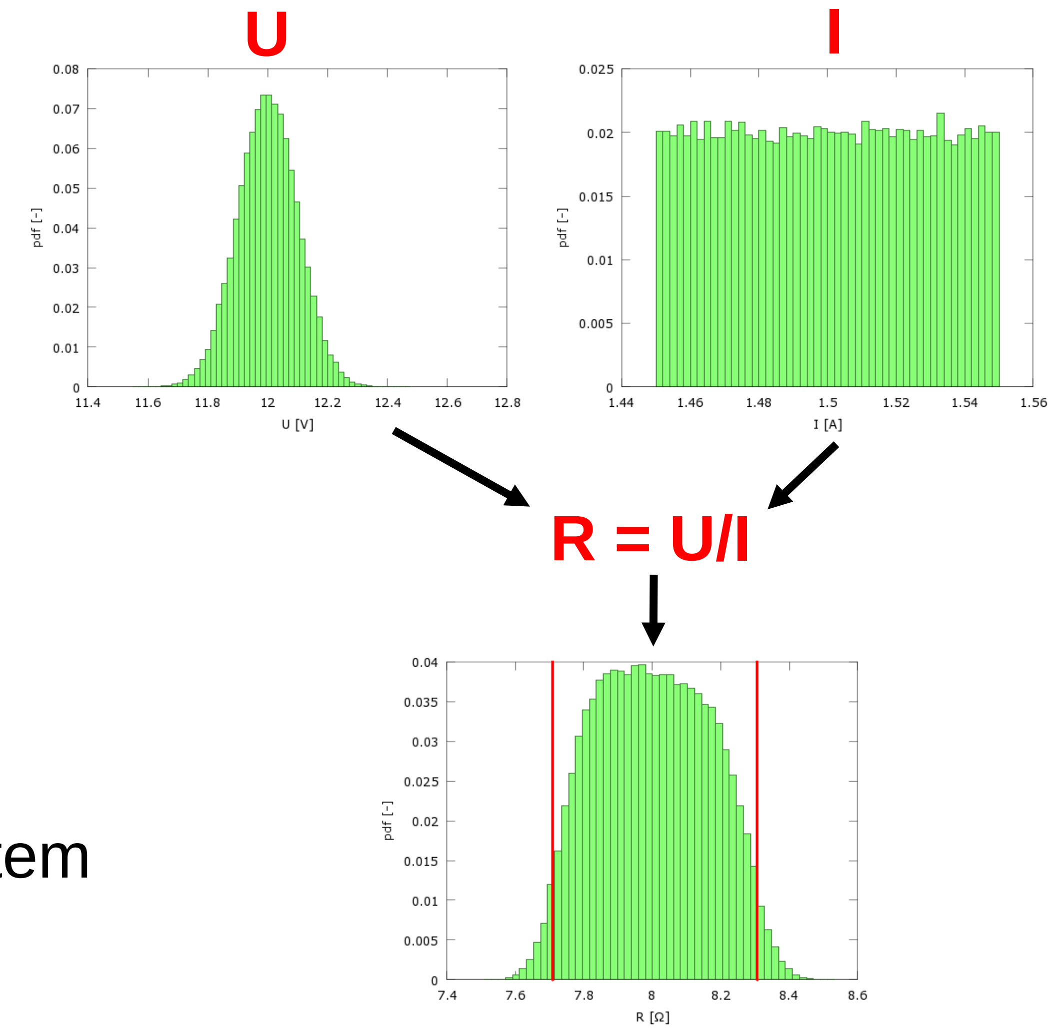


Power, PQ and uncertainty evaluation

<u>Monte Carlo – Numeric method:</u>

- Based on repeated calculation using randomized input quantities
- Example: $R = \frac{U}{I}$
- Pseudo code example:

```
FOR i = 1 TO 10000 DO
  u = U + u(U)*randn;
  i = I + u(I)*rand;
  r[i] = U/I;
ENDFOR
```

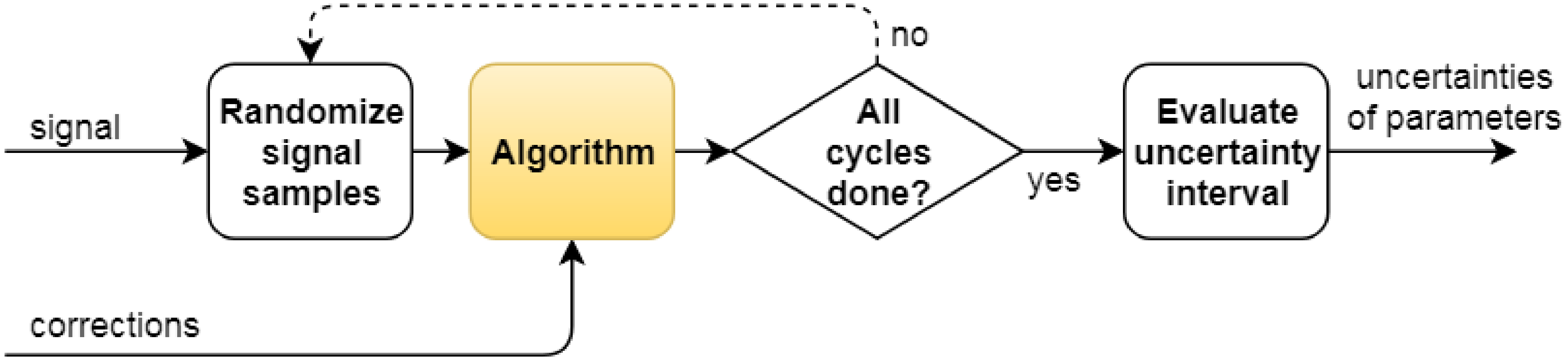


- **Benefits:** simple, applicable to system of any complexity
- **Problems:** Time consuming

Power, PQ and uncertainty – Monte Carlo

Monte Carlo for Sampling system:

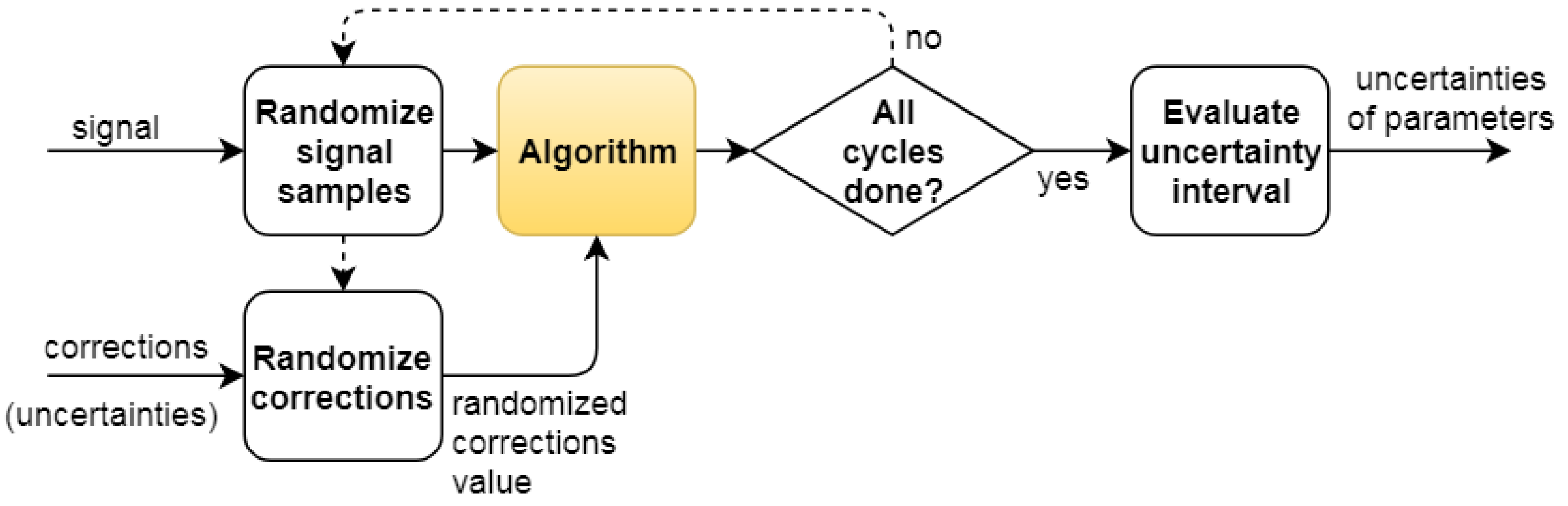
- Can randomize input samples (time and amplitude):
  - Jitter
  - Noise
- Cannot apply frequency dependent corrections
- Cannot simulate digitizer



Power, PQ and uncertainty – Monte Carlo

<u>Monte Carlo for Sampling system:</u>

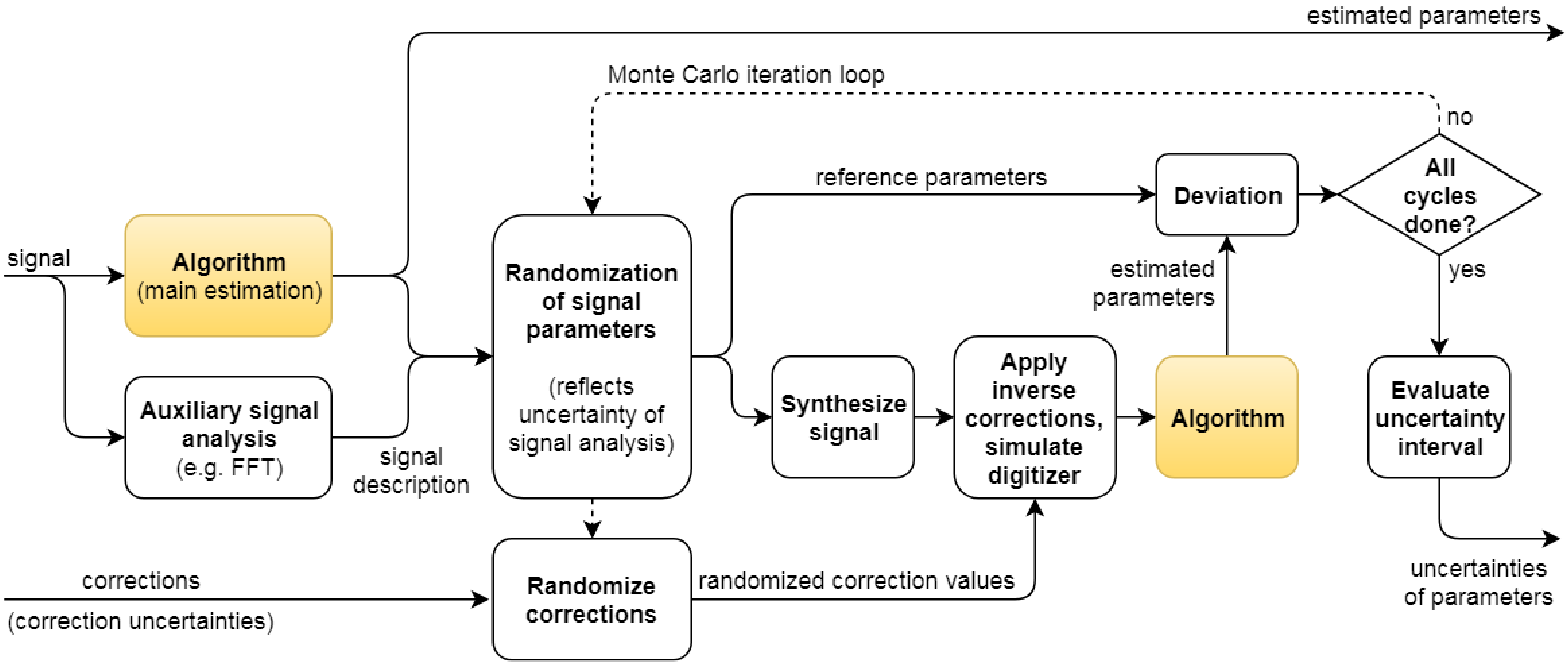
- Can randomize input samples (time and amplitude):
  - Jitter
  - Noise
- Can randomize frequency dependent corrections
- Cannot simulate digitizer, cannot apply additional distortions (SFDR, …)



Power, PQ and uncertainty – Monte Carlo

Monte Carlo for Sampling system:

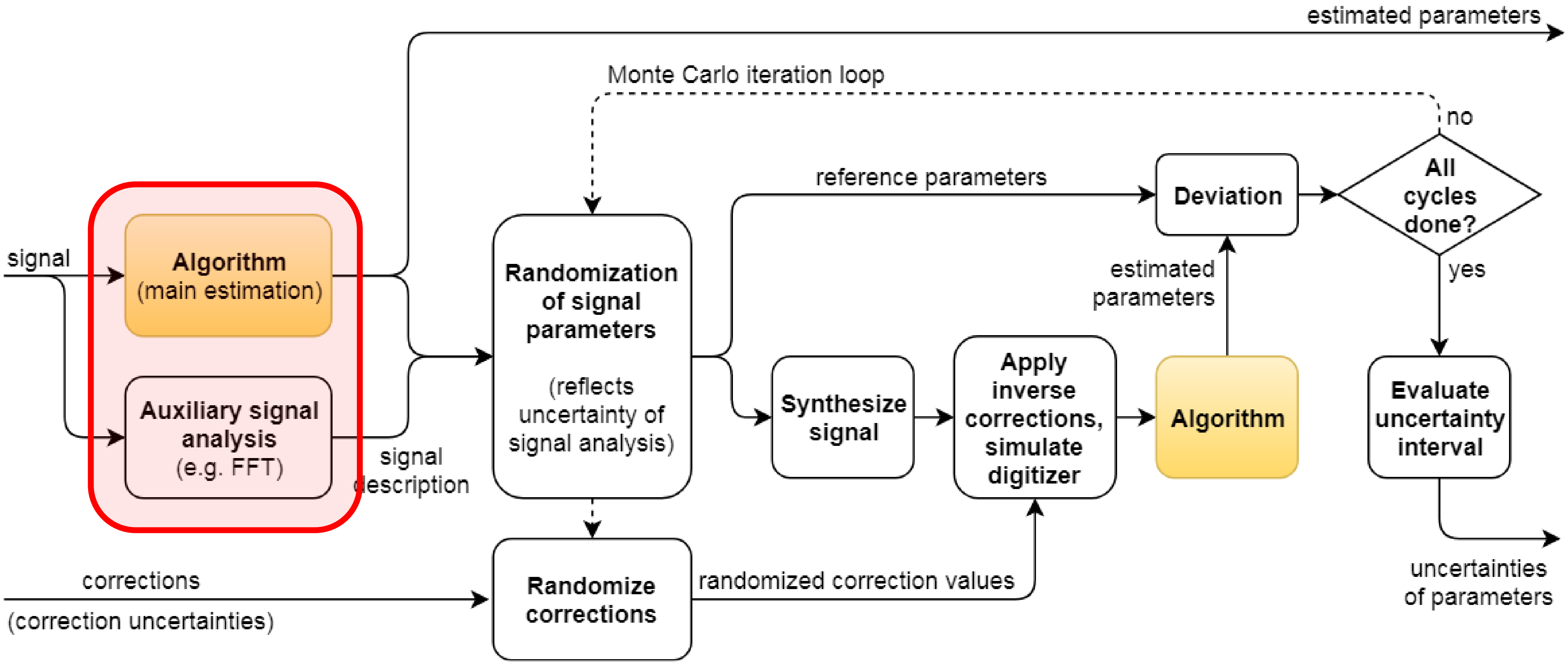
- Signal description, Synthesize signal, Apply model, Estimate parameters



Power, PQ and uncertainty – Monte Carlo

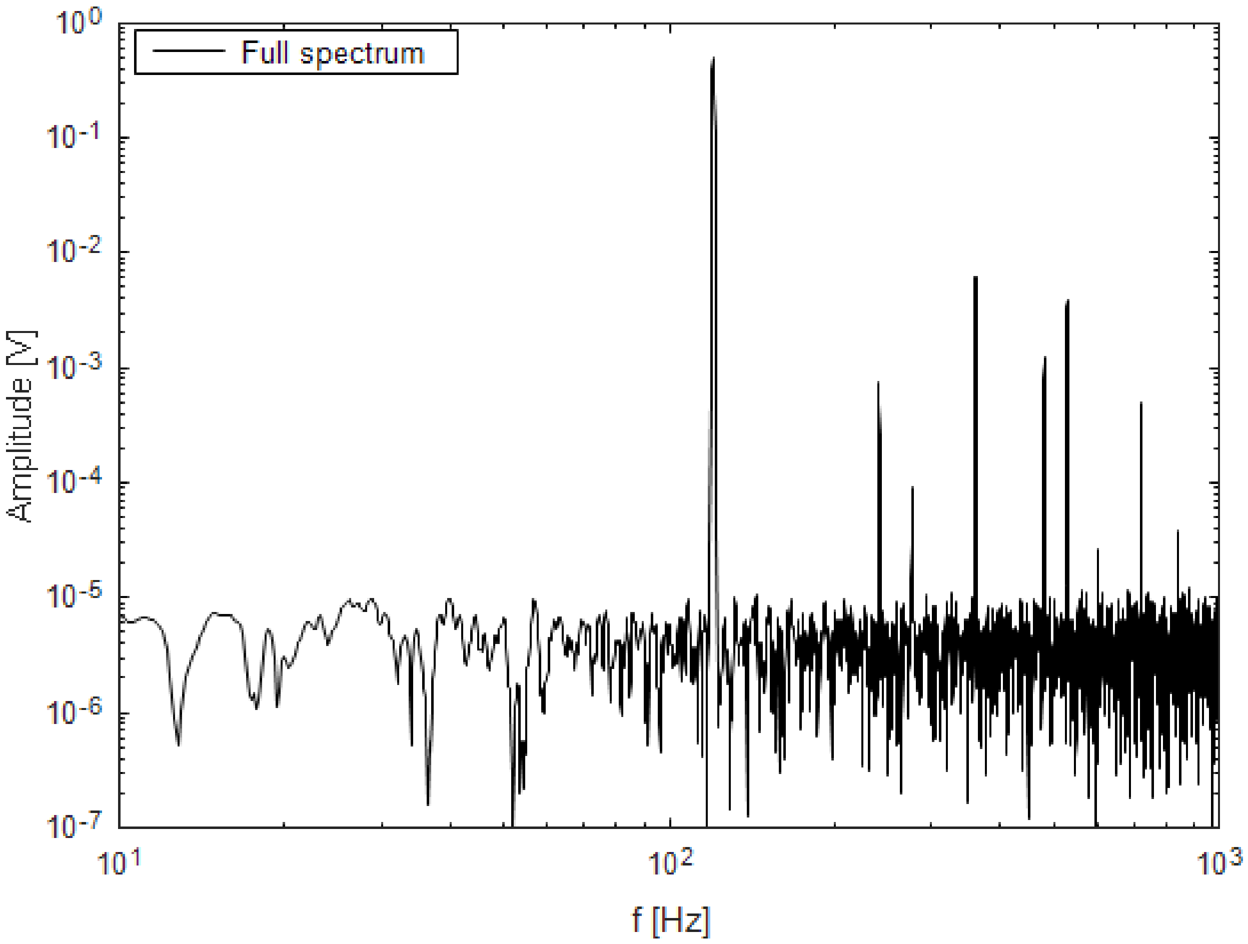
<u>Monte Carlo for Sampling system:</u>

- Signal description, Synthesize signal, Apply model, Estimate parameters



Power, PQ and uncertainty – Monte Carlo

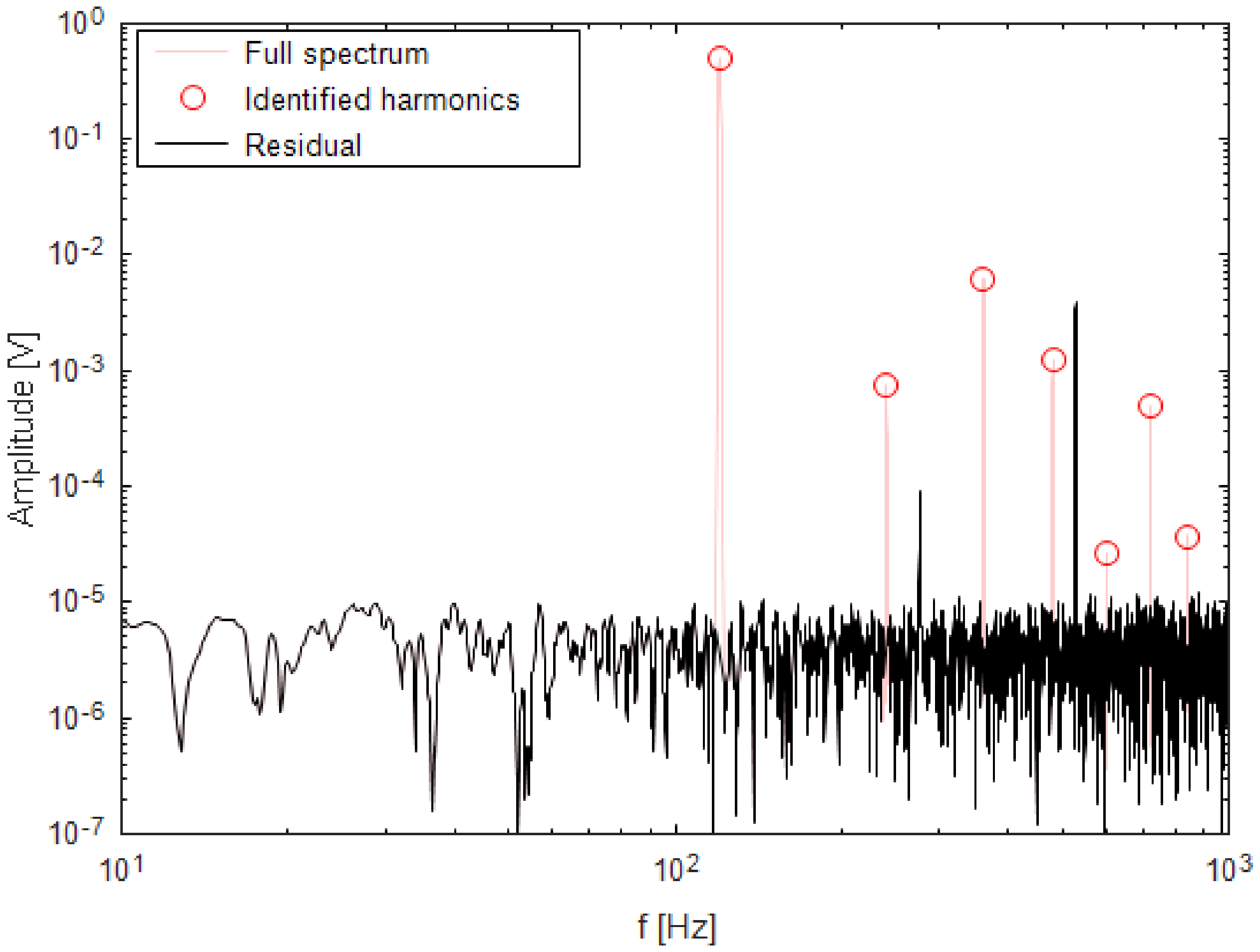
Analyzing signal using FFT – original signal:



- Known fundamental f_0 (e.g. PSFE fit)

Power, PQ and uncertainty – Monte Carlo

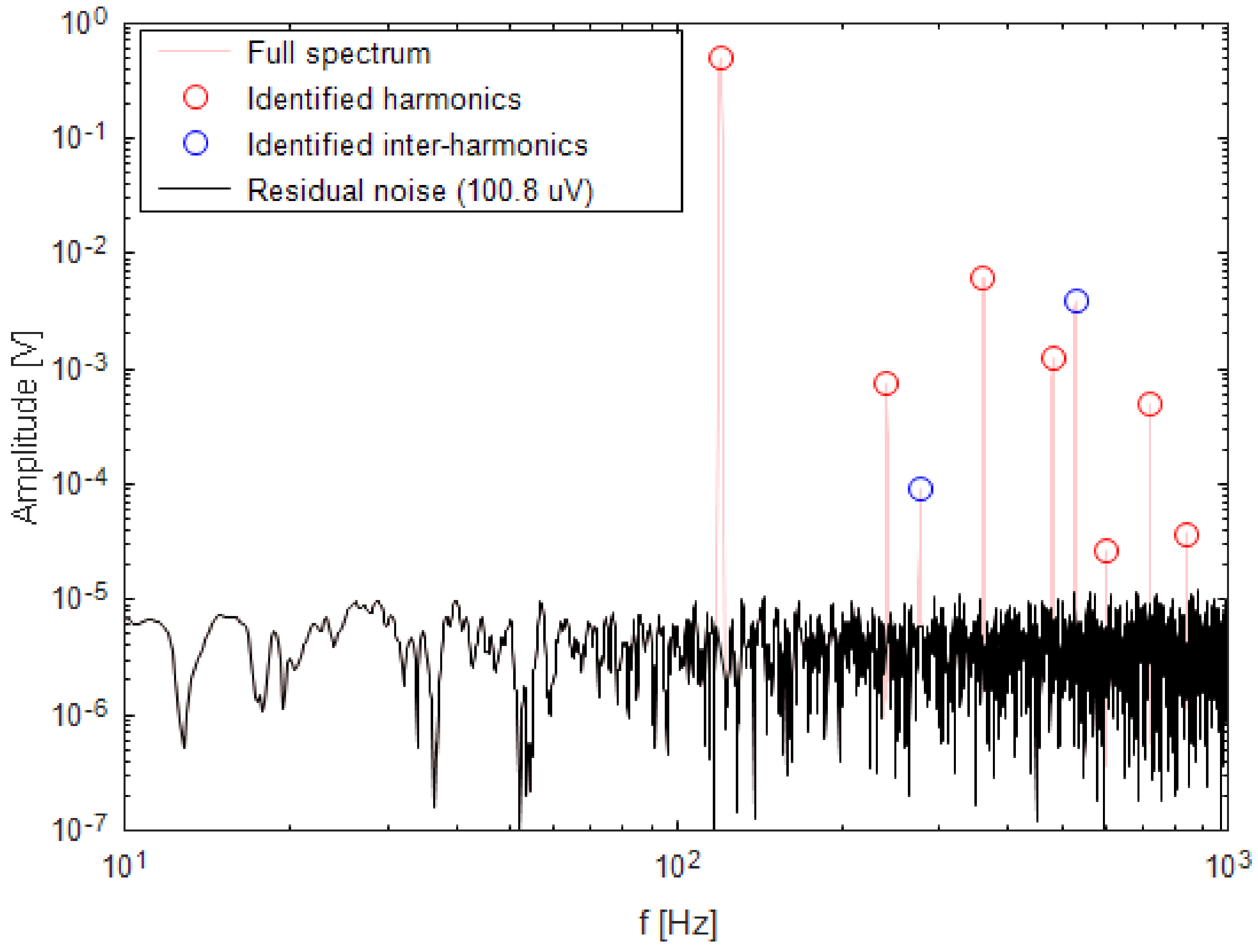
<u>Analyzing signal using FFT – searching and removing harmonics:</u>



- Known fundamental f_0 (e.g. PSFE fit)
- Extracting all harmonics $H*f_0$
- Replacing spectral components by nearest noise level

Power, PQ and uncertainty – Monte Carlo

Analyzing signal using FFT – searching and removing inter-harmonics:



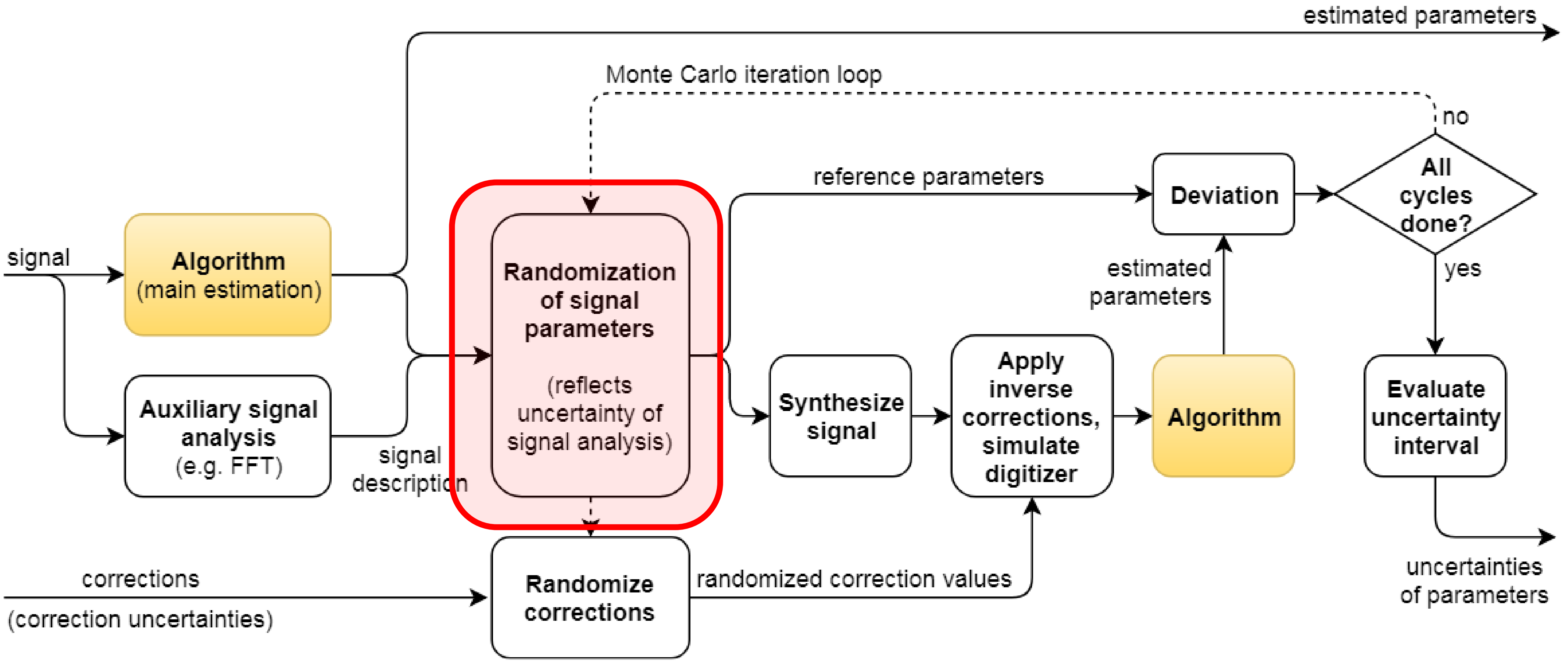
- Known fundamental f_0 (e.g. PSFE fit)
- Extracting all harmonics $H*f_0$
- Replacing spectral components by nearest noise level
- Searching up to *M* highest remaining components
- Replacing them by nearest noise level

- Residue can be processed as:
  - rms noise (assuming gaussian noise)
  - or spectral noise density (freq. dependent)

Power, PQ and uncertainty – Monte Carlo

Monte Carlo for Sampling system:

- Signal description, Synthesize signal, Apply model, Estimate parameters



Power, PQ and uncertainty – Monte Carlo

Randomize parameters:

- To reflect limited accuracy of signal model
- To be sure our model of signal covers actual signal

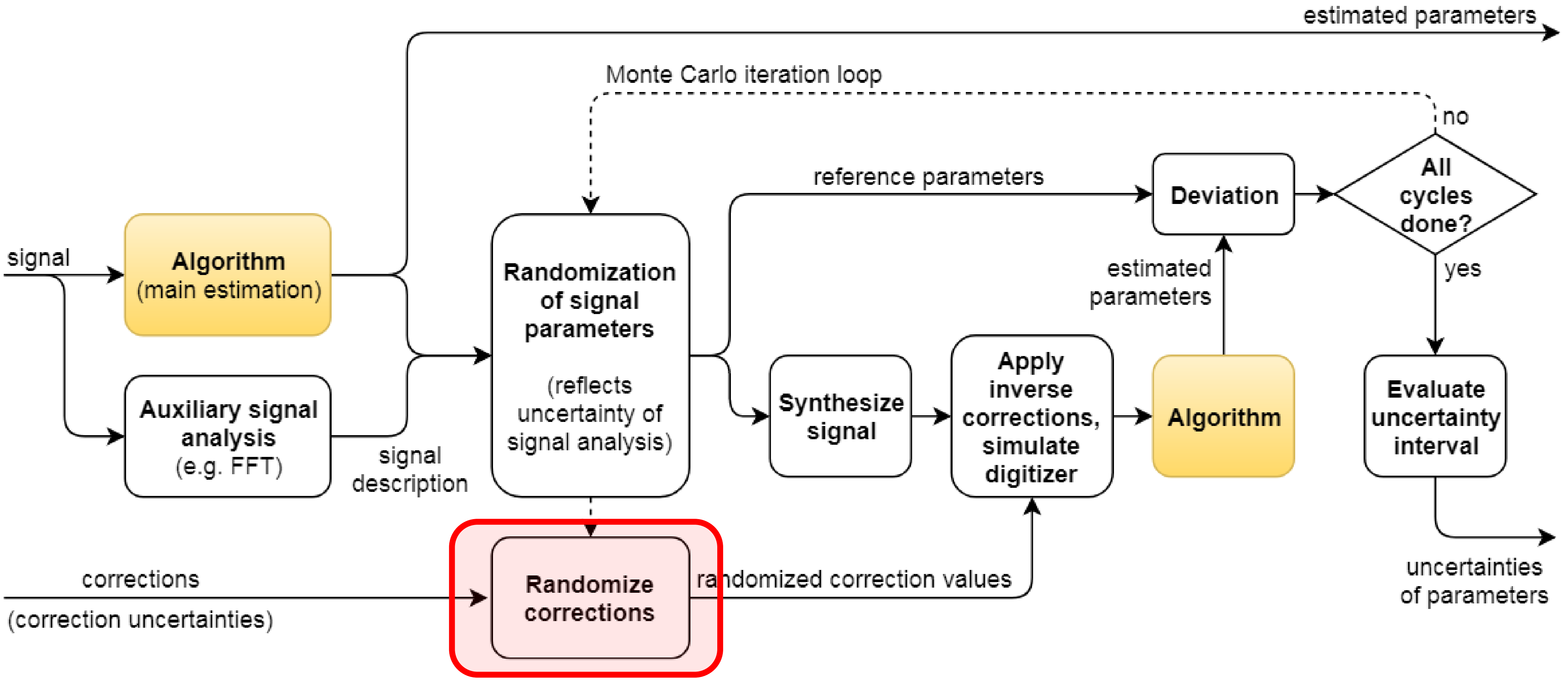
- FFT frequency resolution: for non coherent at least ±1 DFT bin
- Harmonic amplitude detection accuracy: pessimistic guess e.g. ±5%
- Phase angle is unknown for non-coherent sampling: randomize ±180°
- Randomize or overestimate noise

- Output of this step is reference signal

Power, PQ and uncertainty – Monte Carlo

Monte Carlo for Sampling system:

- Signal description, Synthesize signal, Apply model, Estimate parameters



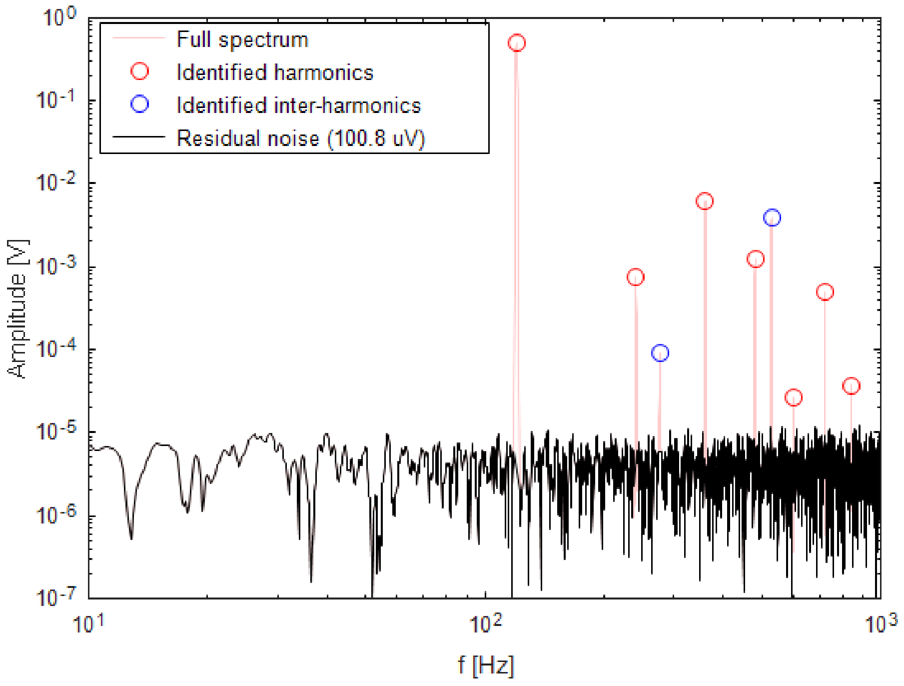
Power, PQ and uncertainty – Monte Carlo

Randomize corrections:

- Randomize each input correction according its uncertainty

- Randomize “non-correction” inputs (SFDR):
  - Harmonic analysis, does not say what part of signal was caused by ADC THD itself

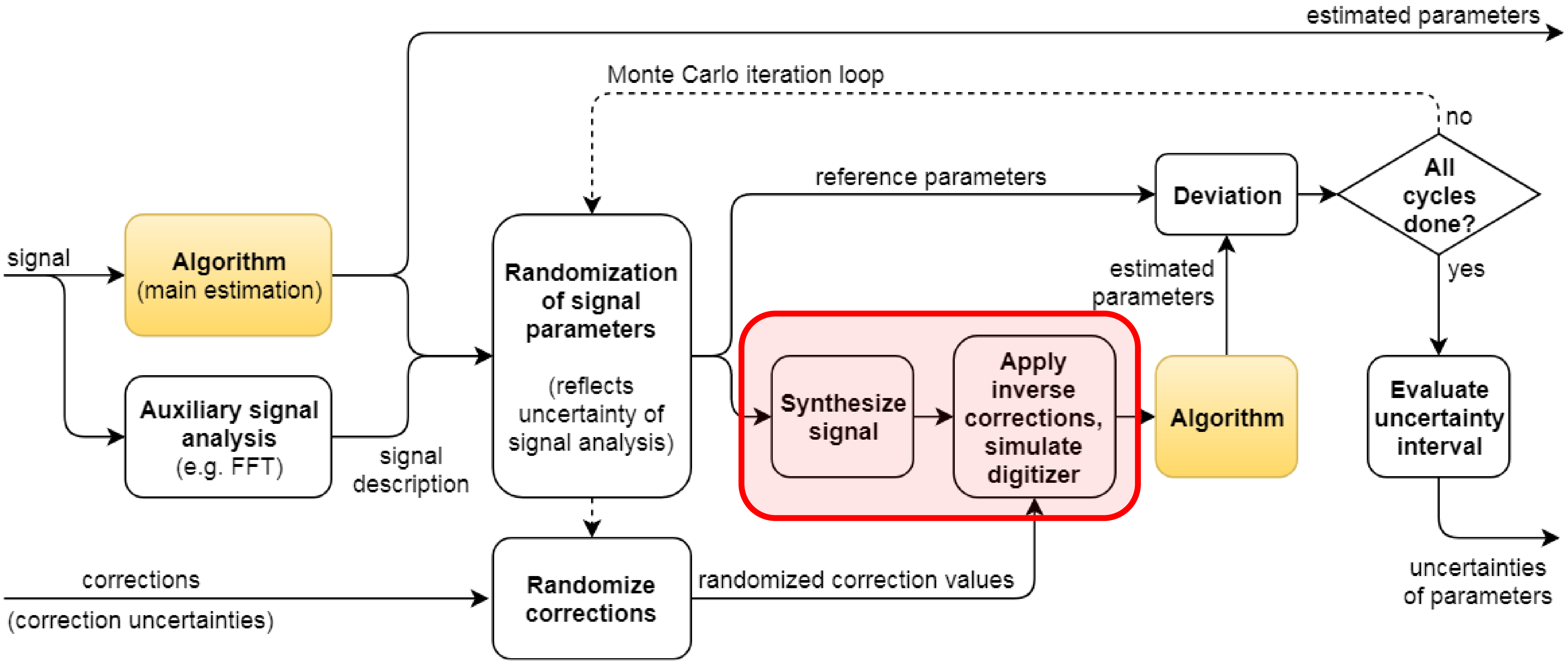
  - SFDR: generate up to *N* harmonics (spurs) with random amplitudes up to SFDR level
  - Spurs added to the signal in next step



Power, PQ and uncertainty – Monte Carlo

<u>Monte Carlo for Sampling system:</u>

- Signal description, Synthesize signal, Apply model, Estimate parameters

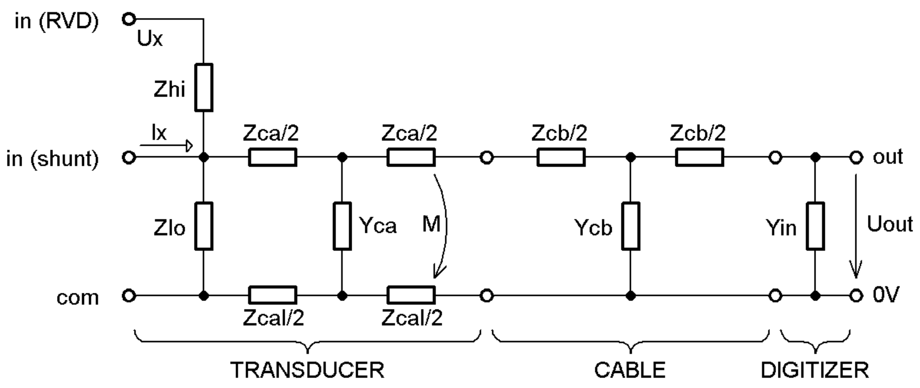


Power, PQ and uncertainty – Monte Carlo

Synthesis and applying setup model:

- Synthesize time-domain signal from a frequency domain signal model
- Apply inverse corrections:
  - Transducer errors (gain/phase)
  - Digitizer gain/phase/offset/…
  - Loading corrections according impedance model

Loading correction Z model:

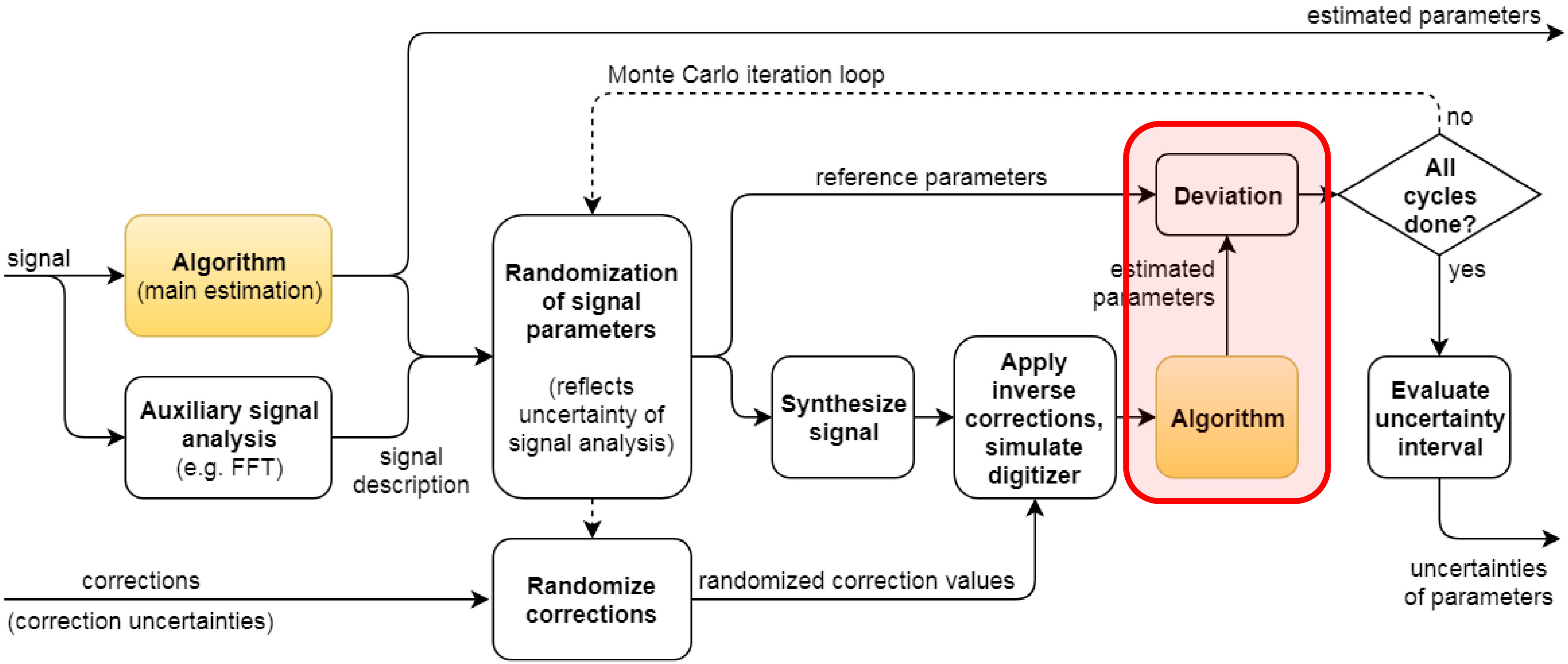


- Add spurs (SFDR) to the signal
- Add noise/jitter to the signal
- Simulate voltage quantization from known ADC bit-resolution

Power, PQ and uncertainty – Monte Carlo

<u>Monte Carlo for Sampling system:</u>

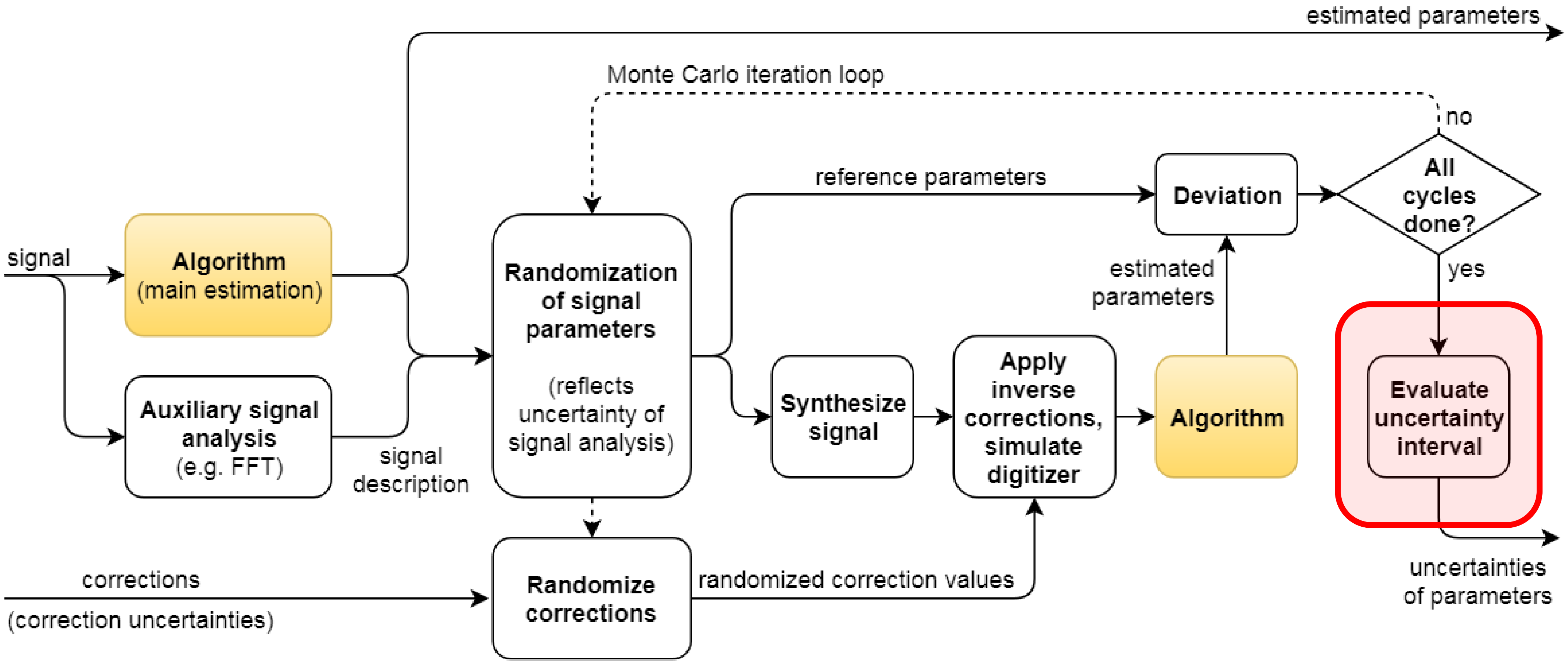
- Signal description, Synthesize signal, Apply model, Estimate parameters



Power, PQ and uncertainty – Monte Carlo

<u>Monte Carlo for Sampling system:</u>

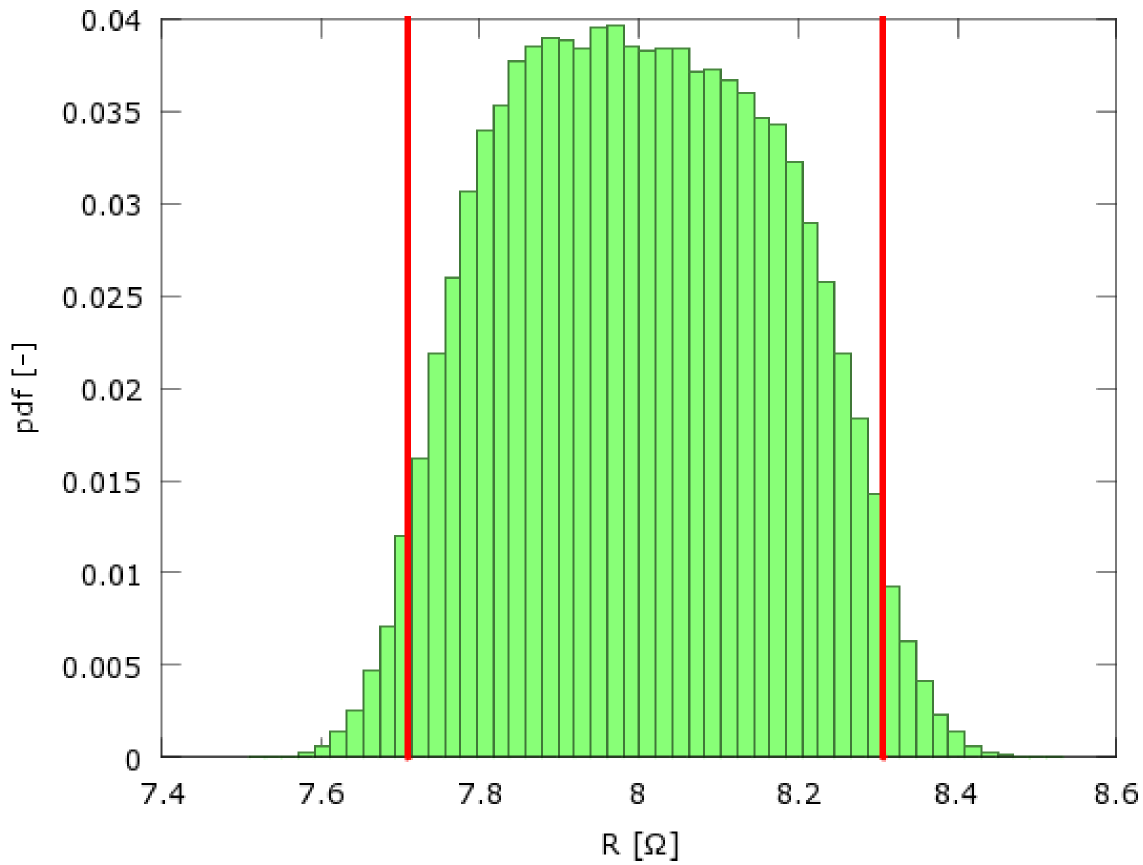
- Signal description, Synthesize signal, Apply model, Estimate parameters



Power, PQ and uncertainty – Monte Carlo

Uncertainty limits evaluation:

- Following GUM guide
- Searching shortest interval which contains level-of-confidence-% of results



Power, PQ and uncertainty – Estimator

Estimator of uncertainty:

- Empiric algorithm based on previous uncertainty analysis

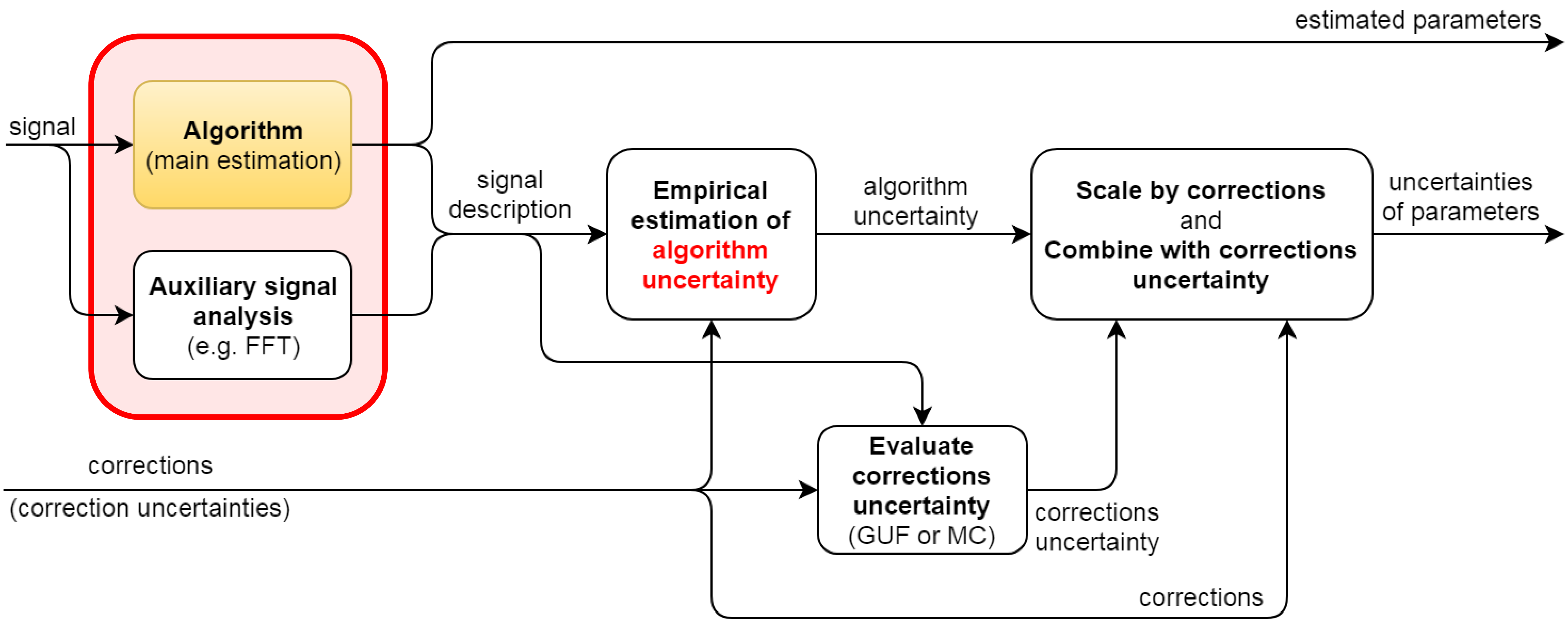
- **Benefit:** Fast calculation
- **Problems:** Limited to predefined cases, usually overestimating

- **Challenges:**
  - Algorithm contains tens of correction constants and matrices of complex coefficients – hundreds to thousands of degrees of freedom!

  - Cannot perform full sensitivity analysis:
    Correlations between quantities requires multi-dimensional sensitivity analysis
  - Too many degrees of freedom

Power, PQ and uncertainty – Estimator

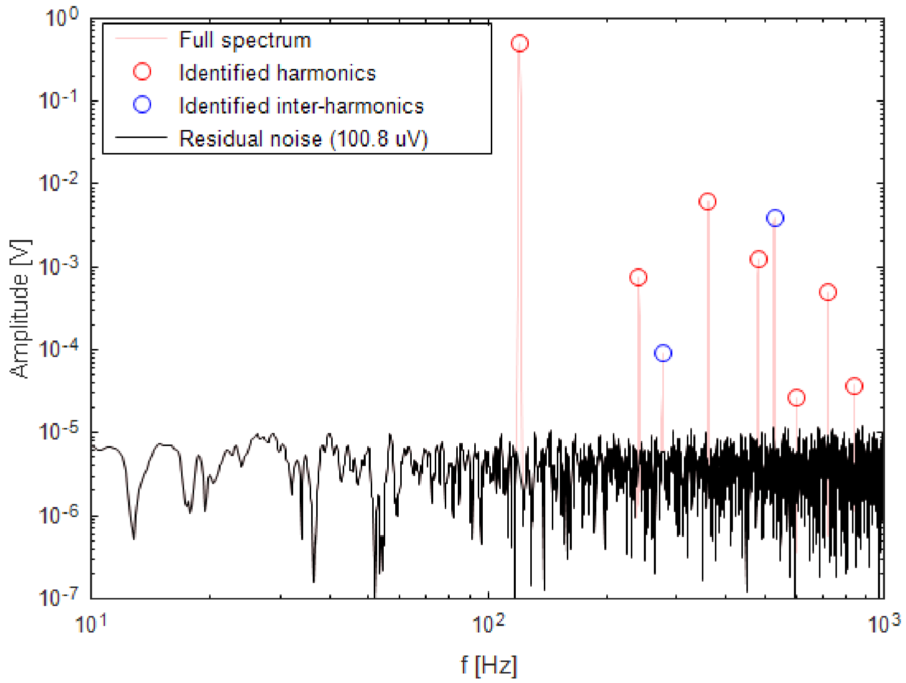
<u>Uncertainty estimator:</u>



Power, PQ and uncertainty – Estimator

Signal description:

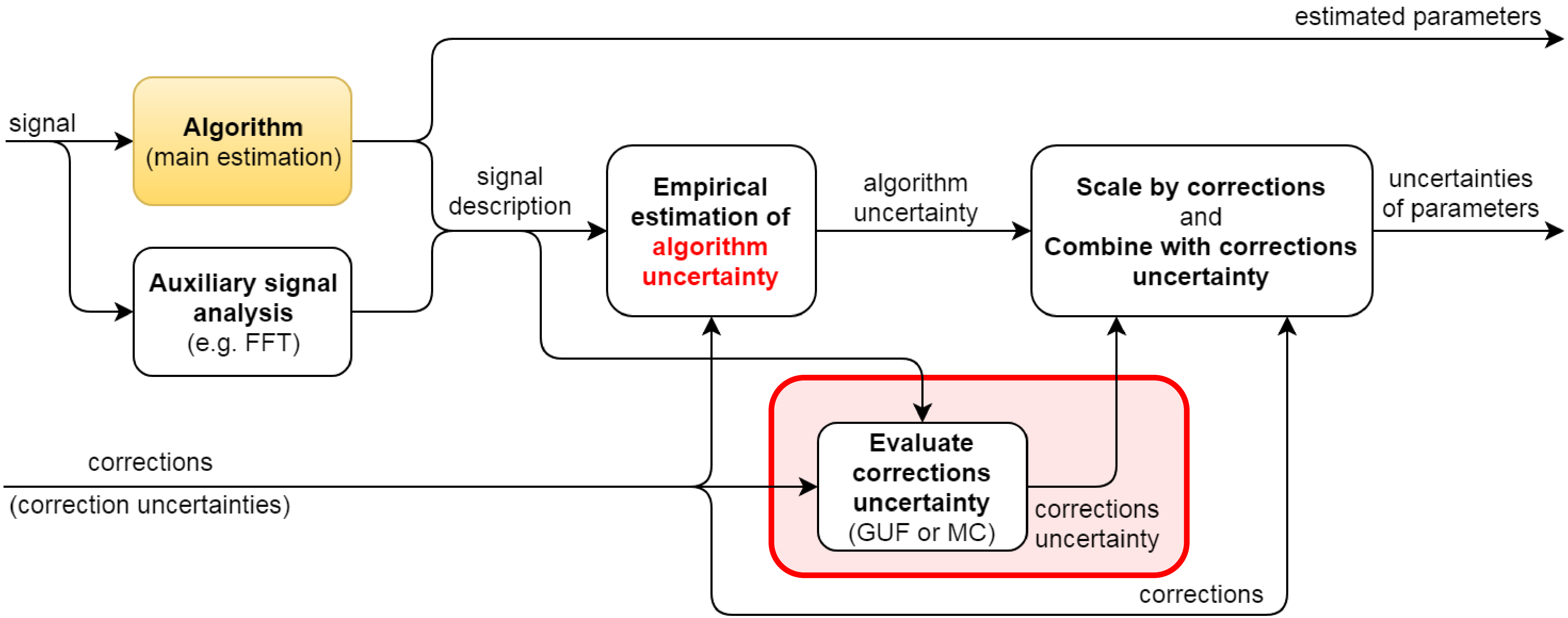
- Use estimator parameters and auxiliary FFT to find minimalistic description of signal waveform



- Exclude all parameters whose contribution to uncertainty can be calculated separately (GUF or Monte Carlo)

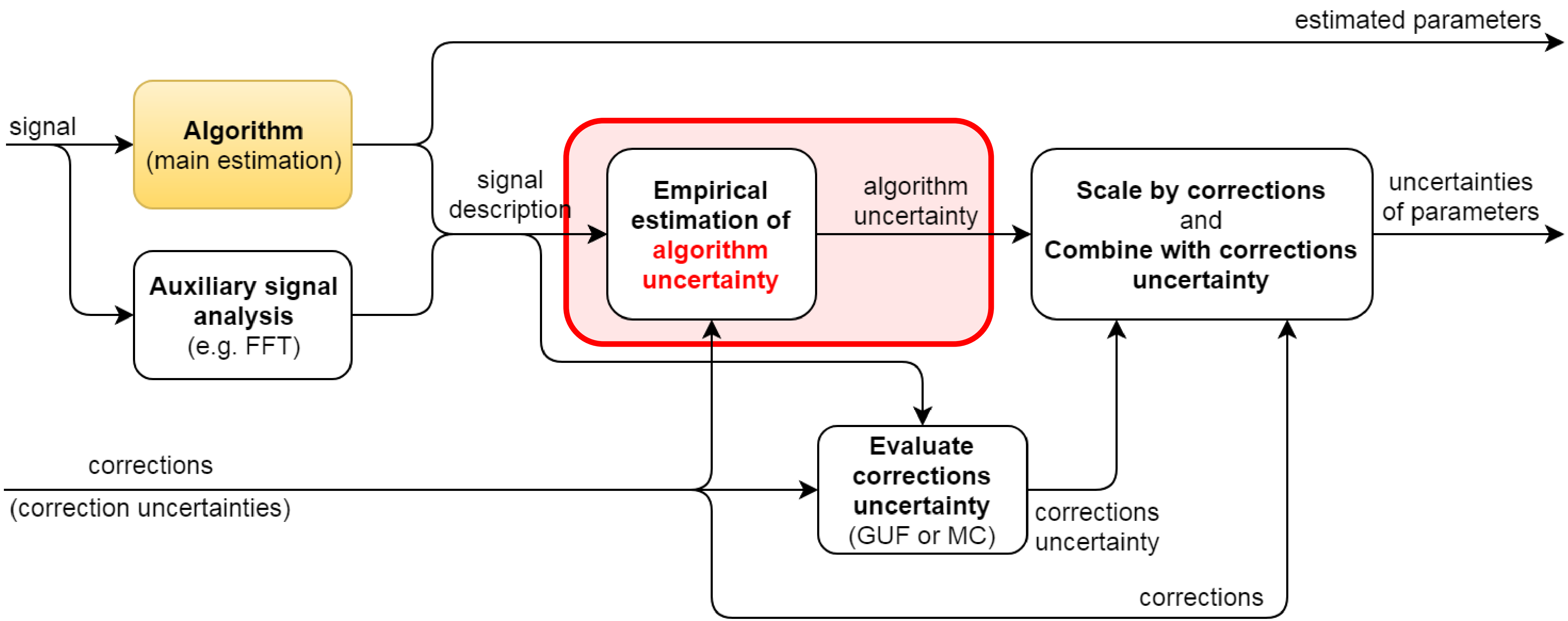
Power, PQ and uncertainty – Estimator

Uncertainty estimator:



Power, PQ and uncertainty – Estimator

Uncertainty estimator:



Power, PQ and uncertainty – Estimator

Algorithm uncertainty estimator:

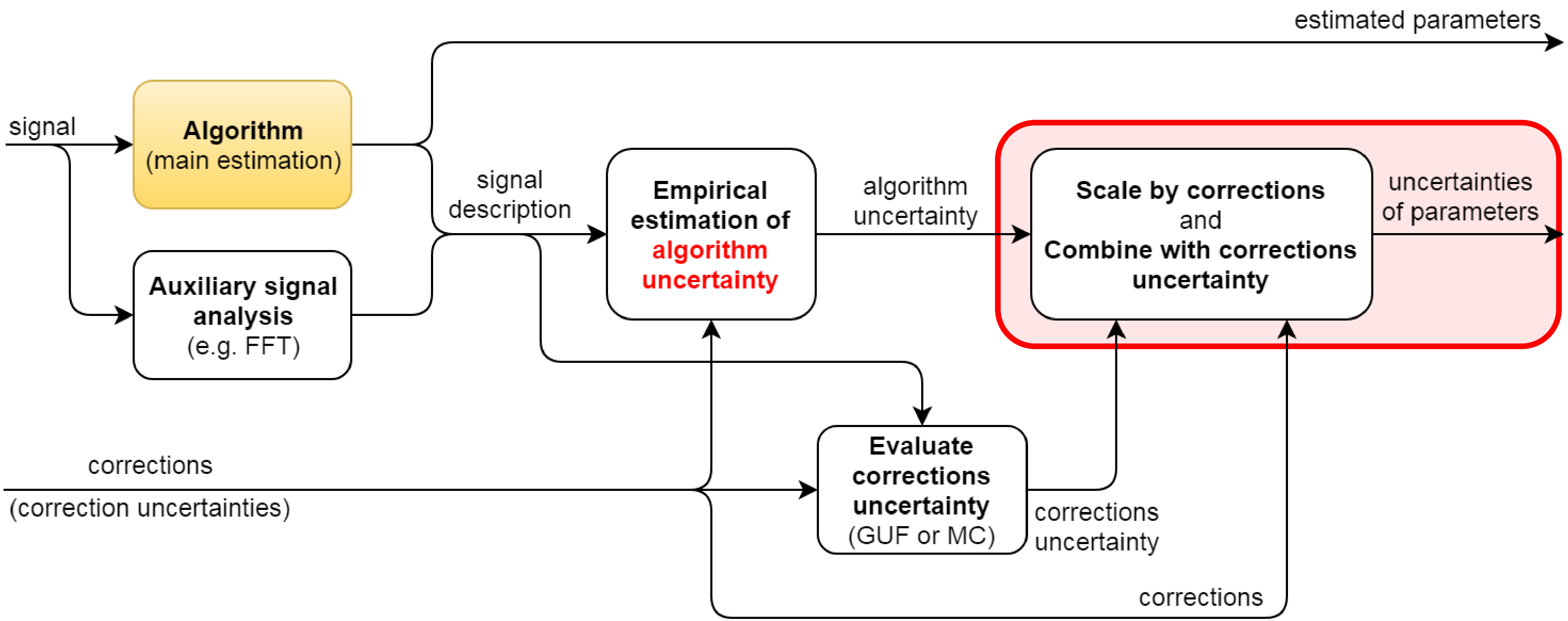
- Empiric algorithm based on previous uncertainty analysis

- Inputs to estimator:
  - Parameters calculated by algorithm itself
  - Record length, samples count per period of signal, …
  - Auxiliary parameters of signal: Noise, harmonics, inter-hamonics, …
  - Calibration constants of HW components:
    resolution of digitizer, SFDR, jitter, …

- Realization:
  - Empirical formulas
  - Pre-calculated look-up tables (LUT) of uncertainties

Power, PQ and uncertainty – Estimator

Uncertainty estimator:



Power, PQ and uncertainty – Estimator

Scaling and combining uncertainty:

- Scaling algorithm uncertainty by correction mean values
  (Estimator calculates at digitizer signal level)

- Combining algorithm uncertainty with correction uncertainty

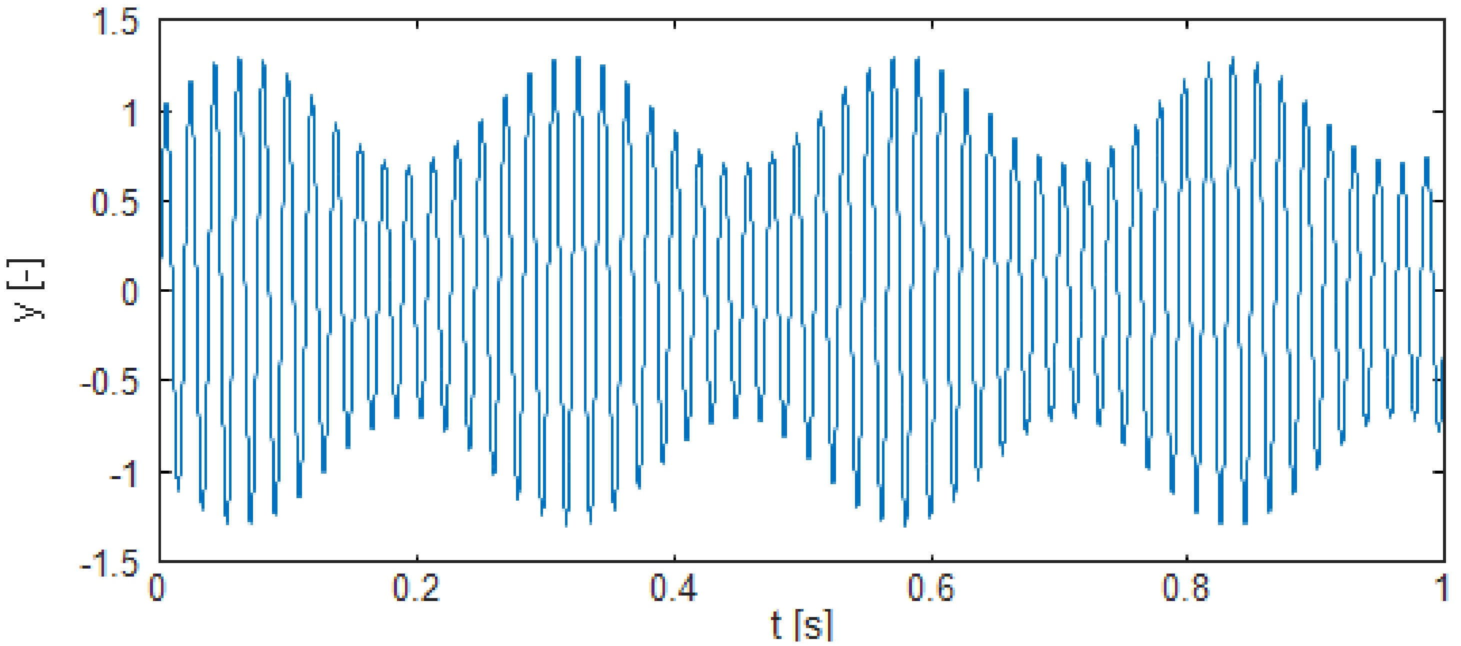
Power, PQ and uncertainty – Estimator Example

Example

Power, PQ and uncertainty evaluation – Estimator Example

MODTDPS - Principle function:

- Estimation of carrier f_0 of signal y using PSFE [1]

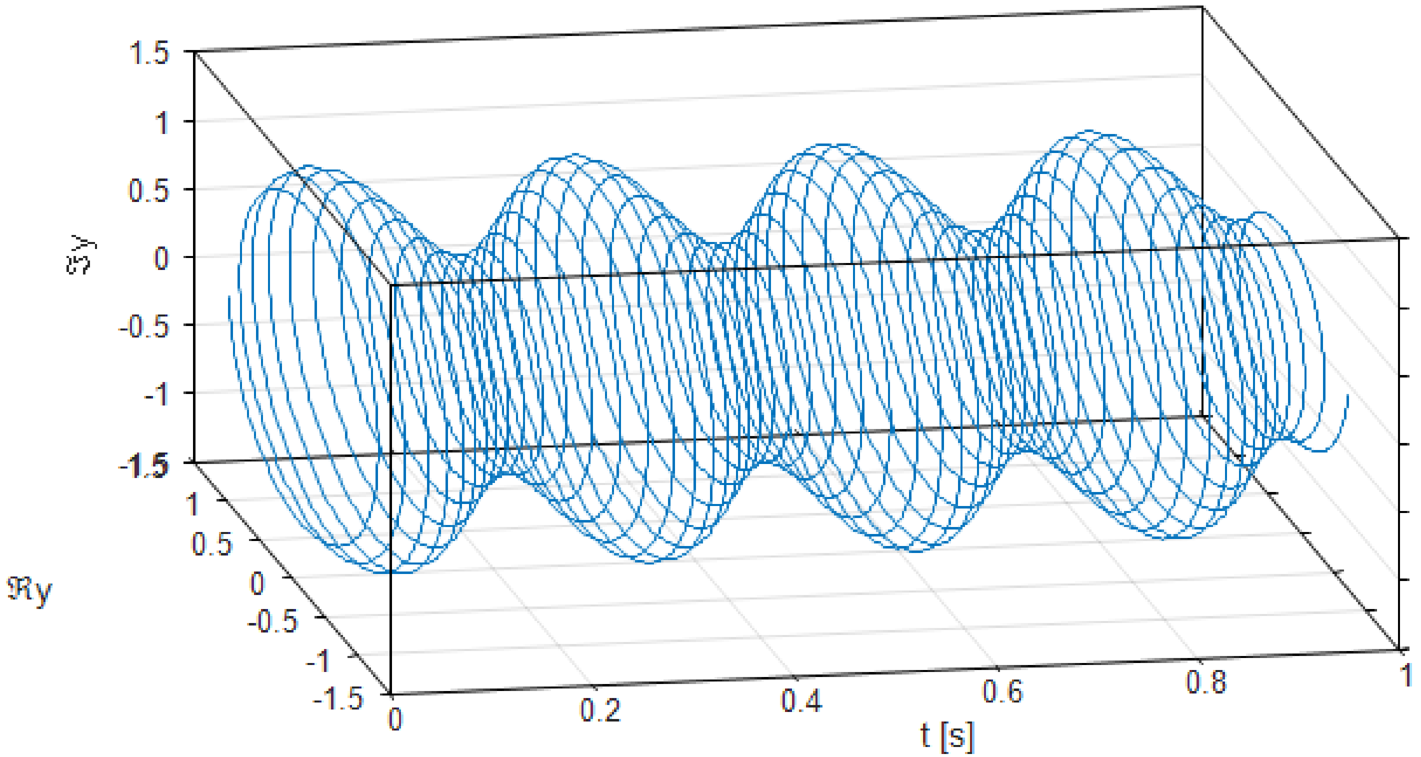


[1] R. Lapuh, "Phase sensitive frequency estimation algorithm for asynchronously sampled harmonically distorted signals," *2011 IEEE International Instrumentation and Measurement Technology Conference*, Binjiang, 2011, pp. 1-4.

Power, PQ and uncertainty evaluation – Estimator Example

<u>MODTDPS - Principle function:</u>

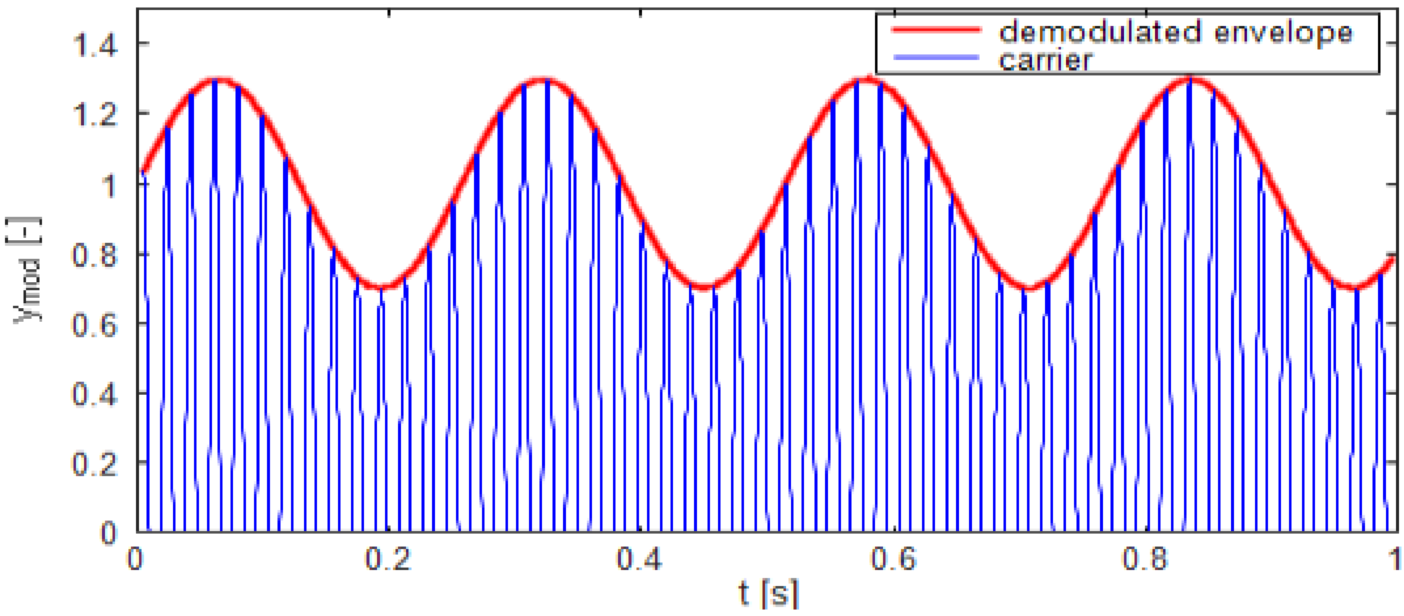
- Building complex analytical signal:
  - $y_c(t) = y(t) + j \cdot y_d(t) = y(t) + j \cdot y\left(t + \frac{0,25}{f_0}\right)$,



Power, PQ and uncertainty evaluation – Estimator Example

<u>MODTDPS - Principle function:</u>

- Calculation of modulation envelope (magnitude):



- Estimation of modulation parameters f_m, A_m using PSFE

Power, PQ and uncertainty evaluation – Estimator Example

MODTDPS - Principle function:

- Estimation of carrier using windows average:

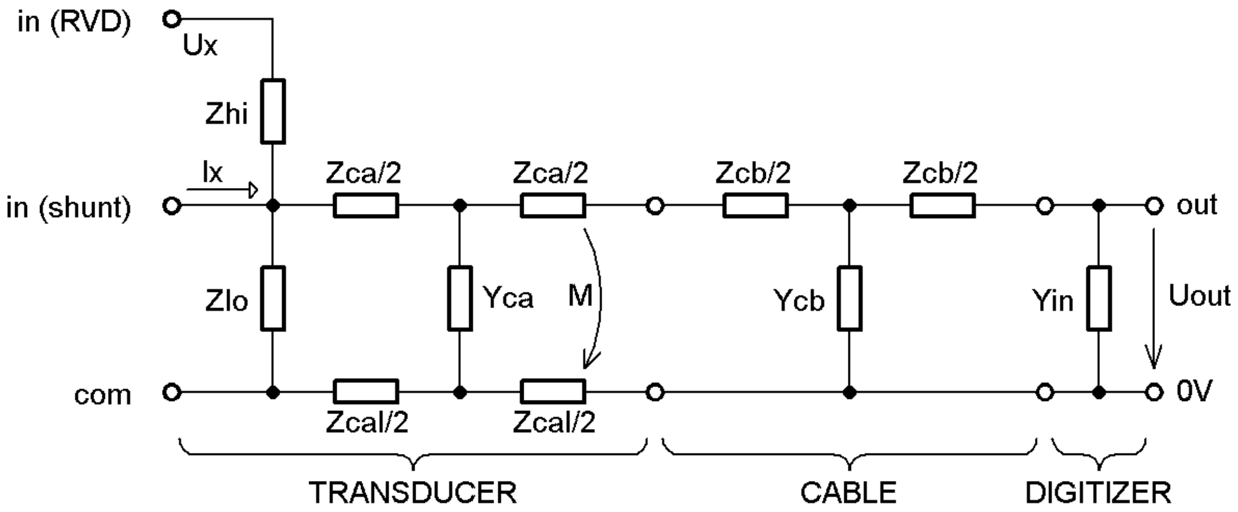
$$A_0 = \frac{\sum_{t=1}^{N} w(t) \cdot y_{\mathrm{mod}}(t)}{\sum_{t=1}^{N} w(t)},$$

- Self-correction of error of algorithm by using reconstructed signal

Power, PQ and uncertainty evaluation – Estimator Example

<u>MODTDPS - Principle function:</u>

- Scaling of modulating parameters f_0, A_0, f_m, A_m to actual input scale:
    - Gain and Phase of digitizer, Gain and Phase of transducer (voltage-frequency space)
    - Correction of digitizer aperture errors
    - Correction of time-base frequency error of digitizer
    - Loading correction (approx. 10 frequency dependent complex corrections):



Power, PQ and uncertainty evaluation – Estimator Example

Estimator of uncertainty:

- Algorithm contains tens of correction constants and matrices of complex coefficients – hundreds to thousands of degrees of freedom!
- Cannot use Monte Carlo directly – too slow for interactive operation
- Cannot perform full sensitivity analysis:
  - Correlations between quantities requires multi-dimensional sensitivity analysis
  - Too many degrees of freedom

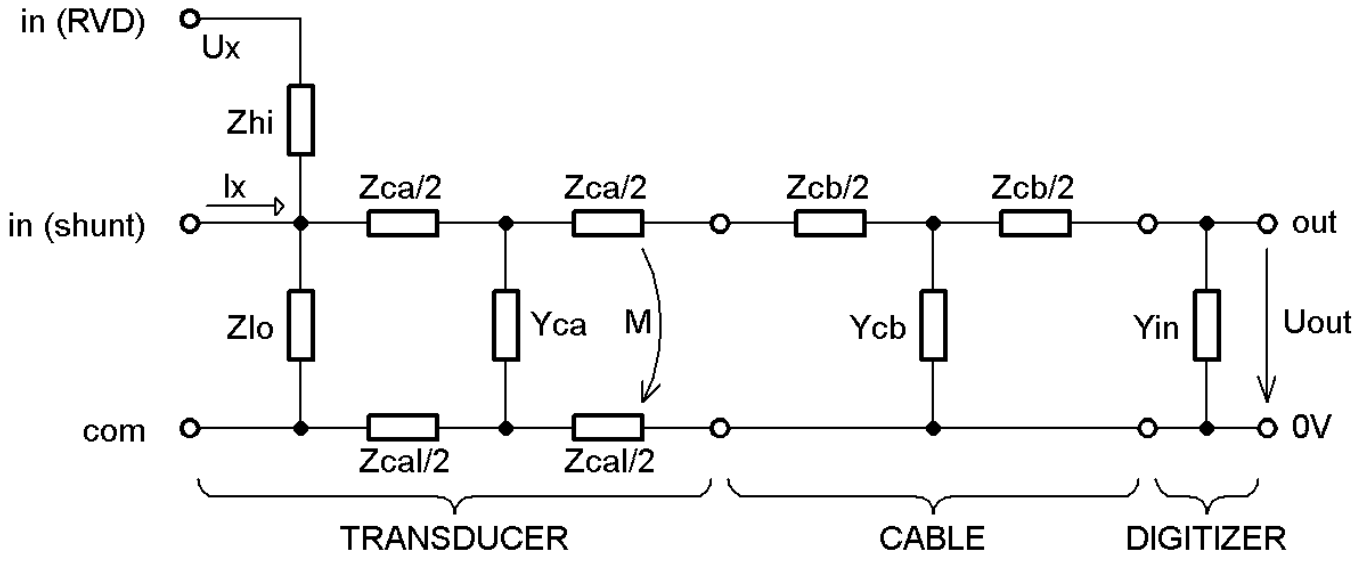
Estimator design process:

1) Exclude all components which can be calculated using GUF
2) Find minimalistic description of the signal shape
3) Perform sensitivity analysis
4) Analyze 3) and build LUT of uncertainties or empiric formulas
5) Combine components 1) and 4)

Power, PQ and uncertainty evaluation – Estimator Example

1) Components calculable using GUF:

- Correction of Gain and Phase of digitizer
- Correction of Gain and Phase of transducer
- Correction of DC offset of digitizer
- Correction of time-base error of digitizer
- Loading correction (analytic or auxiliary Monte Carlo)



Power, PQ and uncertainty evaluation – Estimator Example

2) Minimalistic description of the signal (7 parameters):

- Sample per period of carrier: f_s/f_0
- Periods of modulating signal in record: f_m*N/f_s
- Relative modulation frequency: f_m/f_0
- Modulation depth: A_m/A_0
- Effective bit resolution relative to signal size: *bits*/(max(y) – min(y))
- SFDR (highest spur level)
- RMS jitter (also effective RMS noise which can be converted to jitter)

Power, PQ and uncertainty evaluation – Estimator Example

3) Sensitivity analysis (7 parameters):

- Correlated parameters – need full 7D analysis
- Selection of simulation step:

Parametr	Rozsah
Samples per period	Logarithmic step: 10 to 100, 5 steps
Period of modulating signal	Logarithmic step: 3 to 30, 6 steps
Relative modulation frequency	Logarithmic step: 0.01 to 0.33, 8 steps
Modulation depth	Logarithmic step: 0.01 to 0.99, 8 steps
Effective bit resolution	Logarithmic step: 6 to 24, 6 steps
Total SFDR	Linear step: {120; 80; 60; 30}, 4 steps
RMS jiter/noise	Logarithmic step: 10^{-9} to 10^{-2}, 5 steps

- 5x6x8x8x6x4x5 = 230400 combinations!

Power, PQ and uncertainty evaluation – Estimator Example

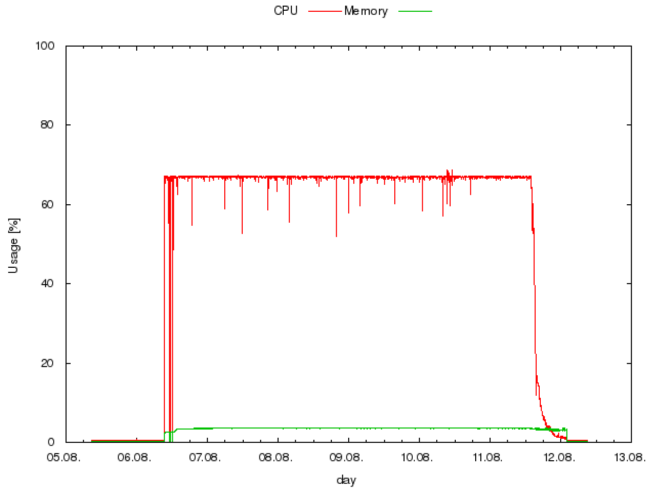
3) Sensitivity analysis (7 parameters):

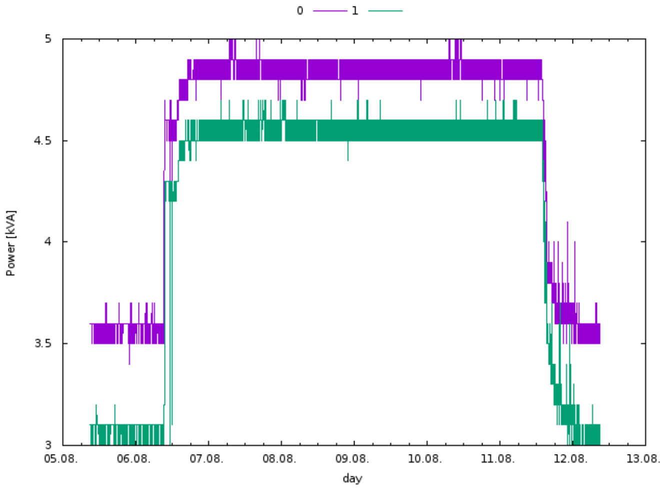
i. Generate combination of parameters E_{REF}.
ii. Randomize E_{REF} in small range (±%) to avoid local extremes,
iii. Generate auxiliary random parameters: DC offset, random phase of modulating signal, random spurs (SFDR), jitter, …
iv. Synthesis of signal y_x of known parameters E_{REF}.
v. Distortion of signal y_x: spurs, jitter, quantization according bit resolution.
vi. Estimation of parameters E_X of signal y_x using the algorithm (MODTDPS).
vii. Evaluation of error of estimated parameters E_X from generated E_{REF}: $\Delta E(i) = E_X - E_{\mathrm{REF}}$, where i is index of Monte Carlo iteration.
viii. Repeat from ii).
ix. Evaluate maximum error of algorithm for particular modulating parameters: $\Delta E = \max|\Delta E(i)|$.
x. Repeat from step i) for each combination of 7D space of parameters.

Power, PQ and uncertainty evaluation – Estimator Example

3) Sensitivity analysis (7 parameters):

- Total of 230 mil. Iterations of algorithm!
- Calculation performed using CMI supercomputer [2]
- Evaluation time approx. 2 days using 400 parallel instance of GNU Octave
- Result is 7D LUT of calculated uncertainties of parameters f_0, A_0, f_m, A_m
- Note: supercomputer used approx. 400 kWh of electricity





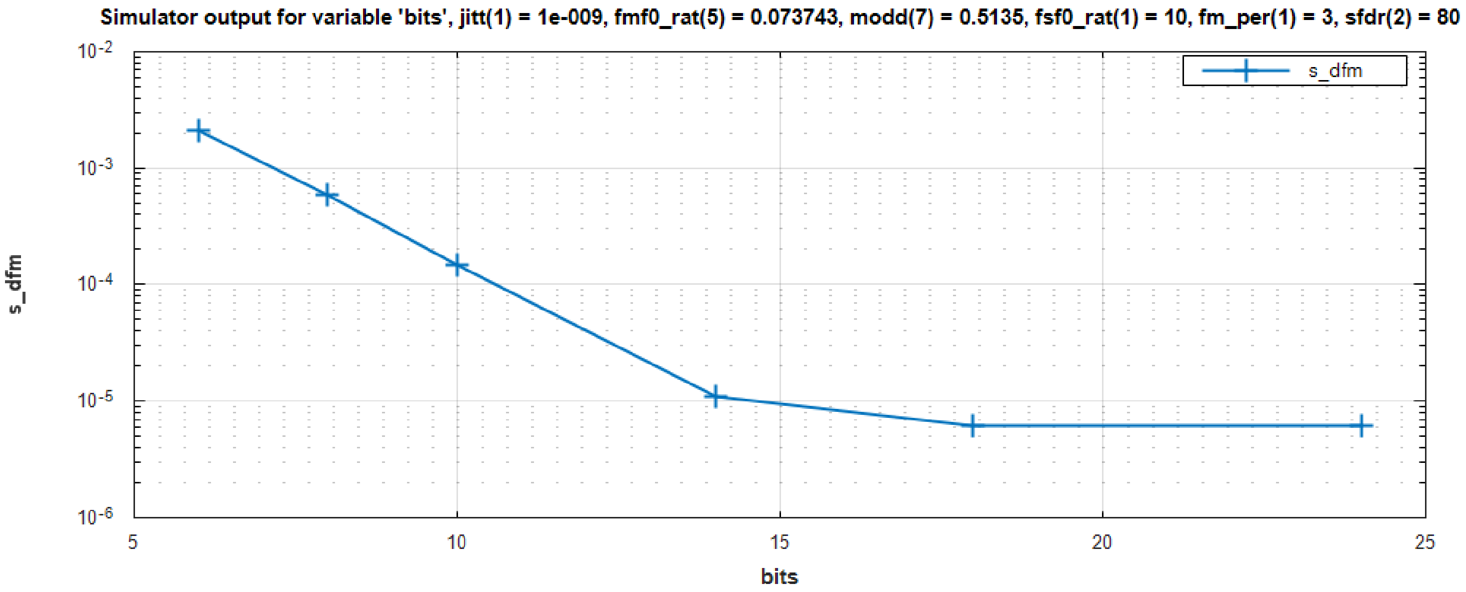
[2] Supercomputer ČMI „Čokl“, url: http://prutok.cmi.cz/sc/doku.php?id=system

[3] Eaton, John W. GNU Octave - Scientific Programming Language, url: https://www.gnu.org/software/octave/

Power, PQ and uncertainty evaluation – Estimator Example

4) Composing LUT of uncertainty:

- Manual 1D and 2D inspection of the 7D space:



- Trying to reduce the 7D space to lower dim. Using empiric formulas
- In this case too complex – all 7D had to be used
- LUT created and compressed to 1.7 Mbyte

Power, PQ and uncertainty evaluation – Estimator Example

5) Function of the estimator:

a) Calculation of the input parameters from correction data and signal parameters: (i) Sample per period of carrier; (ii) Modulating periods; (iii) Relative modulation frequency; (iv) Modulation depth; (v) Relative bit resolution.

b) Auxiliary spectrum analysis of signal y to obtain: (i) Harmonics and inter-harmonics (excluding the signal components); (ii) RMS noise. The parameters are used to calculate SFDR and effective jitter and combined with correction data (SFDR and jitter).

c) Interpolation of uncertainty of the low-level algorithm from the LUT using parameters a) a b).

d) Scaling of uncertainty c) to input scale using corrections (gain, phase, loading).

e) Evaluation of contribution of corrections uncertainties.

f) Combining the d) and e) to resulting uncertainties of f_0, A_0, f_m, A_m.

Power, PQ and uncertainty evaluation – Estimator Example

<u>Validation:</u>

a) Comparison to another system
b) Validation using mathematical simulation

Goal:

- Test if the deviation of estimated parameters are within the assigned uncertainties
- We need to calculate with probability:
    - Confidence interval 95% ($k \approx 2$)
    - Approx. 95% of repeated test should have error lower than uncertainty

Power, PQ and uncertainty evaluation – Estimator Example

Validation by modelling:

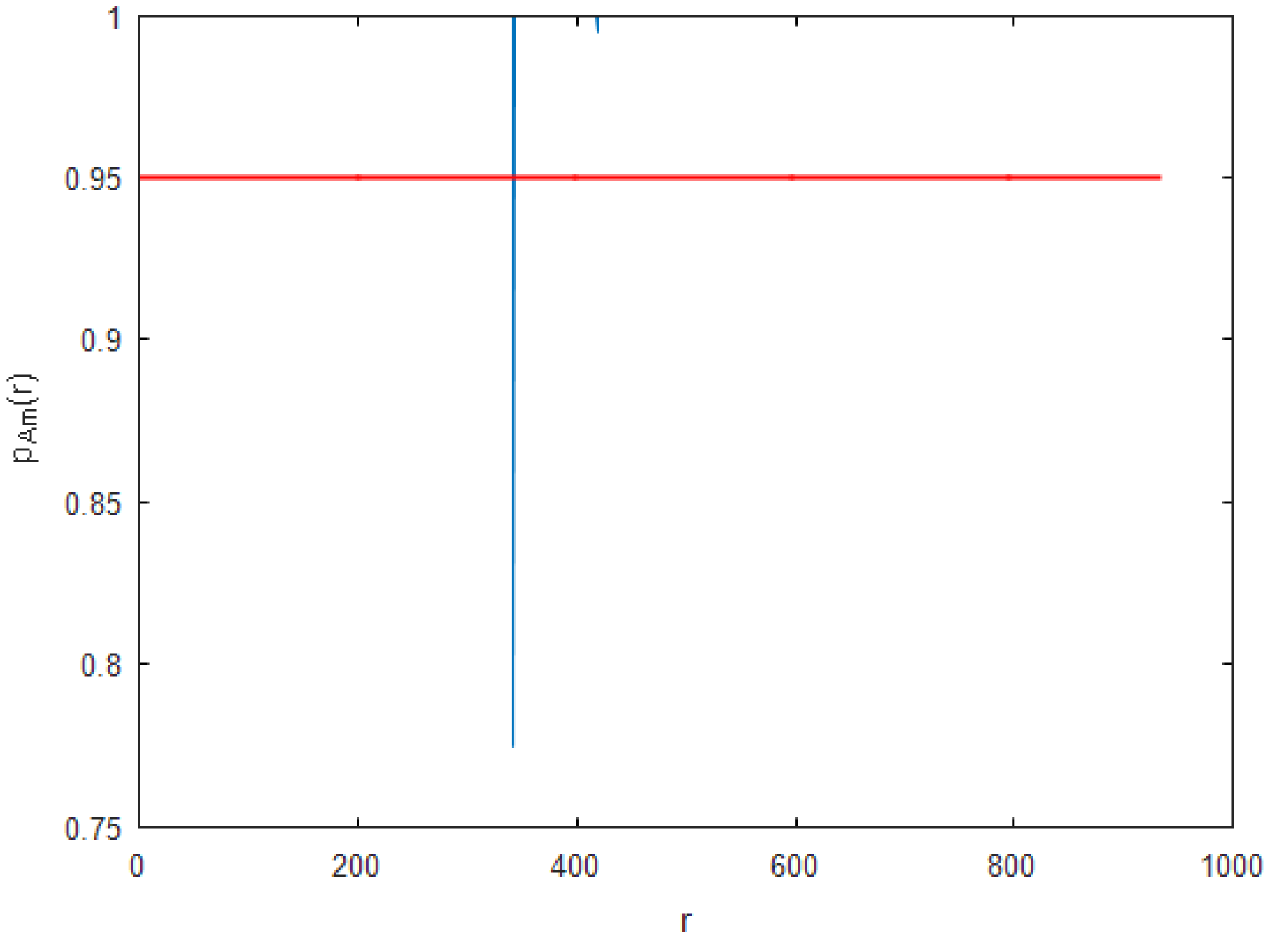
1) Generate signal of known parameters E_{REF}
2) Apply model of input circuits and digitizer (THD, gain errors, phase error, DC offset, quantization, jitter, …)
3) Run algorithms: obtain parameter and uncertainty E_{X}
4) Calculate deviation: $\delta E(i) = |E_{\mathrm{X}} - E_{\mathrm{REF}}| / \mathrm{u}(E_{\mathrm{X}})$
5) Repeat from 1) at least N > 1000x
6) Evaluate average success rate $p = \frac{1}{N} \sum_{i=1}^{N} (\delta E(i) < 1)$

Repeat for MANY different signals and input correction combinations:

a) For lower degrees of freedom: **Systematic approach** – Varying one parameter while keeping all others constant
b) For high degrees of freedom: **Random approach** – Random generation of all parameter in expected ranges

Power, PQ and uncertainty evaluation – Estimator Example

Validation example – average success rate > 99%, but one fail:



Power, PQ and uncertainty evaluation – Estimator Example

Validation example – average success rate > 95%: