Calibration of pulse generators – measurement uncertainty evaluation

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- **Introduction**
- Measurement of one spectrum line amplitude
- Fourier transform of time-domain pulse waveform
- Intermediate-frequency measurement method
- Calibration of other parameters
- Conclusion

- general measurement uncertainty formulas apply
- expanded uncertainty of the measurement $U_M = k \cdot u_M$
  (u_M = standard measurement uncertainty, k = coverage factor)
- standard measurement uncertainty (A and B components)

$$u_M = \sqrt{u_{MA}^2 + u_{MB}^2}$$

- type-A measurement uncertainty

$$u_{MA} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N \cdot (N-1)}} \qquad \bar{x} = \frac{1}{N} \cdot \sum_{i-1}^{N} x_i$$

- type-B measurement uncertainty $u_{BM} = \sqrt{\sum_{i=1}^{N} u_{BMi}^2}$

- full traceability – some of measurements challenging
  - digital real-time oscilloscope traceability
  - digital sampling-oscilloscope traceability
- only measurement uncertainty of most used methods will be discussed

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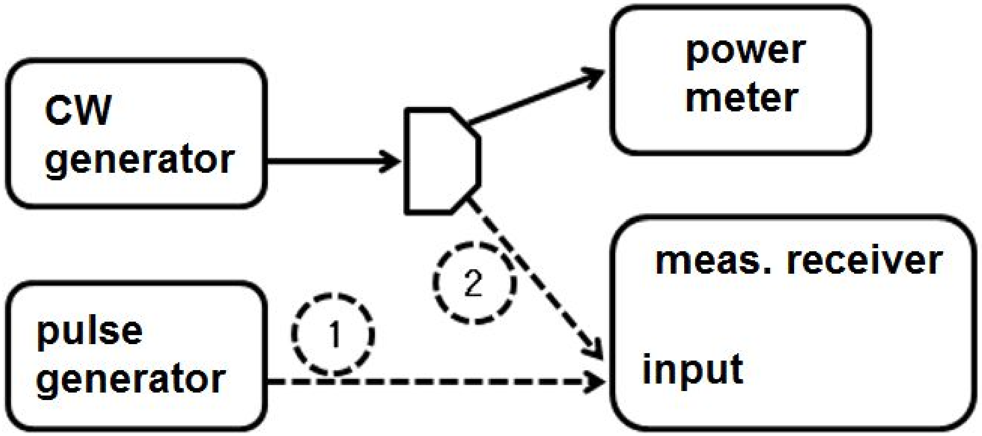
Measurement of one spectrum line amplitude

- measurement setup



- main uncertainty contributions

source	uncertainty
measuring receiver	resolution uncertainty
	other components
power sensor	harmonic signal level
measuring receiver? pulse generator?	other uncertainties of the method
impedance mismatch	pulse generator <-> measuring receiver
	power splitter <-> measuring receiver
	power splitter <-> power sensor

- resolution uncertainty

$$u_{BM1} = \frac{LSD}{2\sqrt{3}}$$

LSD = least significant digit

- other uncertainties of the receiver
  - time stability
  - repeatability of the reading

- level of harmonic signal
  - specifications or calibration certificate of the power sensor

- impedance mismatch

$$u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|)$$

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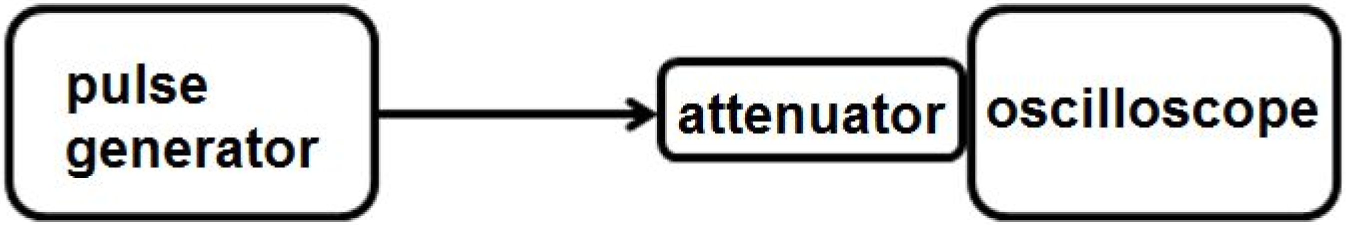
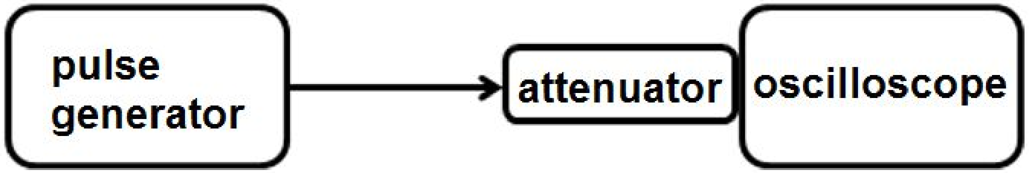
- direct acquisition of the pulse generator output using an oscilloscope and conversion to the frequency domain

$$S(f) = 2|V(f)|$$

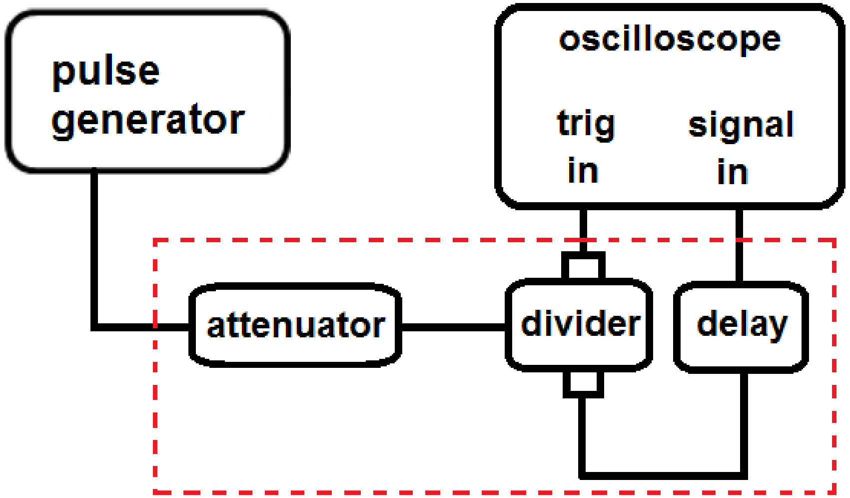


- method useful for base band pulse generators
- simple, time efficient
- oscilloscope, attenuator and cables may influence the pulse properties – correction must be taken into account

- oscilloscope
  - digital real-time oscilloscope (DRTO): triggers directly using the measured pulse



  - digital sampling oscilloscope (DSO): equivalent-time sampling, needs an external trigger signal



- main uncertainty contributions

source	uncertainty
oscilloscope	correction of the frequency response
	waveform acquisition
attenuator(s)	attenuation uncertainty
impedance mismatch	pulse generator <-> attenuator
	attenuator <-> oscilloscope (delay line <-> oscilloscope)
signal processing	interpolation of FFT

- correction of the oscilloscope frequency response
  - exact calculation rather complicated (uncertainty propagation between time and frequency domain, correlations)
  - uncertainty of the deconvolution and regularization
  - an overestimated guess is a safe option (ripple of the amplitude and phase response, numerical simulation)

M. Bieler et. al., "Rise-Time Calibration of 50-GHz Sampling Oscilloscopes: Intercomparison Between PTB and NPL, *IEEE Trans. Instrum. Meas.*, Vol. 56, No. 2, 2007

P. Hale et al., "Traceable Waveform Calibration With a Covariance-Based Uncertainty Analysis," *IEEE Trans. Instrum. Meas.*, Vol. 58, No. 10, 2009, pp. 3554-3568

- uncertainty of the waveform acquisition
  - time-base uncertainty

$$u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\%;\ \mathrm{div};\ \mathrm{div})$$

  - vertical resolution (from effective number of bits)

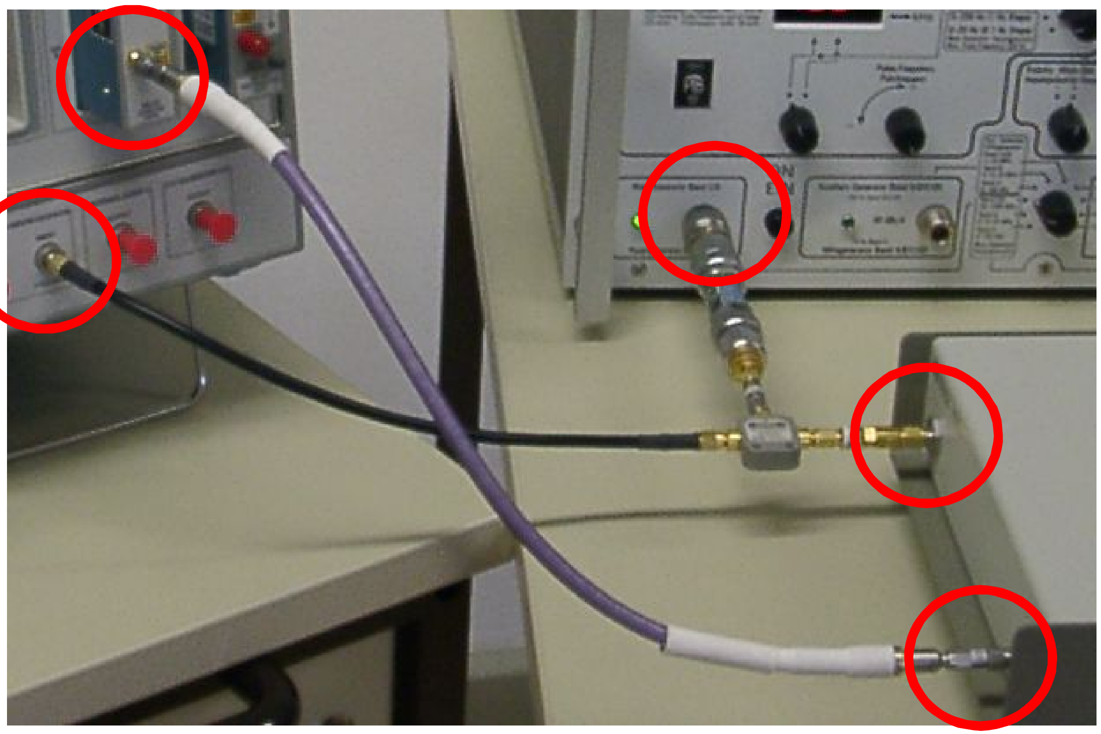
$$u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\%;\ \mathrm{div};\ \mathrm{div})$$

N is the effective number of bits
n is the number of vertical divisions
triangular distribution

- attenuation uncertainty
  - VNA measurement
  - repeatability, VNA uncertainties or manufacturer specification
  - combination of a cable, power splitter and attenuator parameters

Fourier transform of time-domain pulse waveform

- impedance mismatch (DSO example)
  - attenuator <-> oscilloscope
  - attenuator <-> power splitter
  - power splitter <-> delay line
  - delay line <-> oscilloscope



- signal processing
  - deconvolution, regularization
  - FFT uncertainties

➔ difficult to take into account, based on experience and deep understanding of the DSP algorithms

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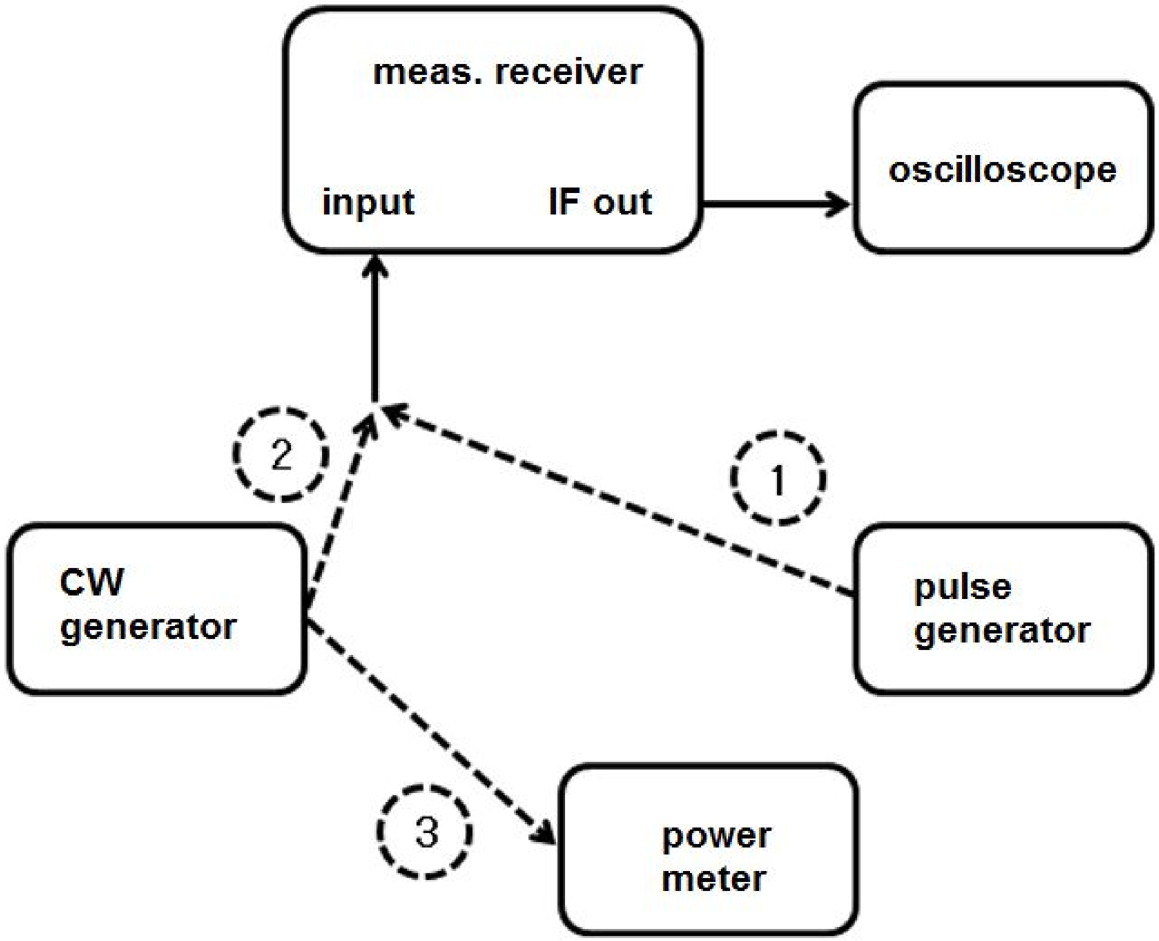
- measurement setup



Intermediate-frequency measurement method

- main uncertainty contributions

uncertainty source	uncertainty
oscilloscope	horizontal unc.
	vertical unc.
	transfer function, resolution
measuring receiver	impulse bandwidth (IBW) determination
	other uncertainties
power sensor / selective level meter	uncertainty of the level of harmonic signal
impedance mismatch	mismatch between the generator and meas. receiver
	mismatch between the CW generator and meas. receiver
	mismatch between the CW generator and the power sensor

- typical type-B uncertainty sources discussed

oscilloscope uncertainties

- only digital-real time oscilloscope unc. discussed (we are integrating an area under the envelope curve, difficult with analogue oscilloscope)
- vertical resolution

$$u_r = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} 2^{-N} \cdot 100 \quad (\%; \text{div}; \text{div})$$

N is the effective number of bits
n is the number of vertical divisions
triangular distribution

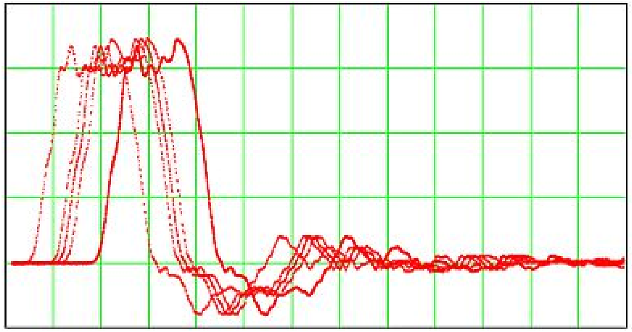
oscilloscope uncertainties

- horizontal resolution (time base accuracy)

$$u_{osc} = \frac{1}{\sqrt{6}} \frac{n_{total}}{n_{used}} \frac{1}{N_h} \cdot 100 \quad (\%; \text{div}; \text{div})$$

N_h = overall number of horizontal points at osc. screen
n is the number of horizontal divisions
triangular distribution

- trigger jitter – DSO needs 1000 trigger events for 1000 sampling points



oscilloscope uncertainties

- transfer function
  - not important, as we measure a low-bandwidth signal without sharp edges, the shape of the measured signal; is not significantly influenced by the oscilloscope
- DC gain – calibrated using a voltmeter & DC source
- noise contribution for small CISPR signal levels
- input reflection coefficient
  - scalar/vector network analyzer or manufacturer specifications (rectangular probability distribution)

$$u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|)$$

measuring receiver uncertainties

- impulse bandwidth
  - not easily measurable, see the presentation **Calibration of measurement receivers with quasi-peak detector**
  - typically measured using both methods recommended in CISPR 16-1-1 and the difference between results is taken as the measurement uncertainty
  - typ. 0.15 dB, rectangular distribution

- input reflection coefficient
  - scalar/vector network analyzer or manufacturer specifications (rect. distribution)

$$u_M = \frac{1}{\sqrt{2}} 20 \log(1 + |\Gamma_1||\Gamma_2|)$$

measuring receiver uncertainties

- level measurement
  - uncertainty of measurement at high level – comparison with a calibrated power sensor or manufacturer specifications
  - receiver linearity – using a calibrated step-attenuator or manufacturer specifications
  - rectangular probability distribution

power sensor uncertainties

- calibration factor
- impedance mismatch
- linearity

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- generator output reflection coefficient
  - difficult to measure, as the ON/OFF states have very different voltage reflection coefficients

- pulse repetition rate
  - frequency counter + uncertainties

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- limits of uncertainty in CISPR 16-1-1 / EN 55016-1-1 rather large
- different methods may lead to different uncertainties
- selection of the method dependent on the frequency and equipment available (oscilloscope, power sensor, measuring receiver)

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http://rfmw.cmi.cz/

Thank you for attention