European cooperation for Accreditation of Laboratories

Publication Reference **EAL-G30**

Calibration of Oscilloscopes

PURPOSE

This document has been produced by EAL to harmonise oscilloscope calibration. It provides guidance to national accreditation bodies in setting up minimum requirements for the calibration of oscilloscopes and gives advice to calibration laboratories to establish practical procedures.

Authorship

This document has been revised by EAL Committee 2 (Calibration and Testing Activities), based on the draft produced by the EAL Expert Group "DC and LF Electrical Quantities".

Official language

The text may be translated into other languages as required. The English language version remains the definitive version.

Guidance Publications

This document represents a consensus of EAL member opinion and preferred practice on how the relevant clauses of the accreditation standards might be applied in the context of the subject matter of this document. The approaches taken are not mandatory and are for the guidance of accreditation bodies and their client laboratories. Nevertheless, the document has been produced as a means of promoting a consistent approach to laboratory accreditation amongst EAL member bodies, particularly those participating in the EAL Multilateral Agreement.

Further information

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Contents

1 Introduction

1.1 This document deals with the calibration of oscilloscopes. It does not claim to fully cover all metrological details of oscilloscopes even if important for calibration. In this document, relevant standards and publications (cf. section 8) have been allowed for. In addition, the manufacturer's data for the oscilloscope in question should be taken into account for the calibration.

2 Scope of application of the calibration

2.1 This document applies to the calibration of electron-beam oscilloscopes and here to both analogue oscilloscopes and digital storage oscilloscopes, and transient recorders.

2.2 When the calibration is carried out, the measurement procedures applied by the calibration laboratories shall be employed in conjunction with the calibration equipment such that all measurands necessary for calibration are **traceable** on the basis of the laboratory's accreditation for the calibration of oscilloscopes. The traceability to national standards as well as the basic measurement procedures for the calibration of oscilloscopes shall be documented.

3 Terms and abbreviations

Terms

B	bandwidth
b	correction factor
G_L	input conductance of the power meter
G_{OS}	conductance at the oscilloscope input
L	linearity of the time base
n	number of averaged curves
P	power of the generator
P_{inc}	incident power to a load
t_i, t_{i-1}	times
t_o	rise time of the oscilloscope
Tp	period
Tp_i	period for the i-th time interval
$\hat{U}$	peak voltage

U_E	voltage at the output
U_{IN}	voltage at the input
Z_0	reference characteristic impedance
Z_X	impedance
Γ	reflection coefficient
φ	phase error

Abbreviations

AO	analogue oscilloscope
DSO	digital storage oscilloscope
SNR	signal-to-noise ratio

4 Calibration equipment

4.1 Requirements to be met by calibration equipment

4.1.1 The calibration shall be carried out using measuring equipment and procedures enabling relative uncertainties of measurement which are small compared with the relative uncertainties of measuring for the oscilloscope.

4.1.2 Rise and decay times of rectangular calibration signals shall be significantly shorter than the rise times of the oscilloscope under consideration.

4.1.3 Connecting cables shall be of the coaxial type. It shall be ensured that, for high-frequency (HF) measurements, the output impedance of the measuring set-up and the input impedance of the oscilloscope are matched to one another.

4.2 Reference conditions

4.2.1 The calibration shall be carried out under the reference conditions (e.g. ambient temperature, humidity, voltage supply, harmonic distortion) specified for the oscilloscope and the measuring equipment. During calibration, the measuring set-up shall be in thermal equilibrium. The warm-up times specified by the manufacturers shall be complied with.

5 Preparation for calibration

5.1 Visual inspection

5.1.1 Prior to calibration, the general external condition of the oscilloscope shall be checked. Defects which might inadmissibly affect the function shall be eliminated before carrying out the calibration.

5.2 Functional test

5.2.2 The equipment to be calibrated shall be checked for correct operation, i. e. the trigger sensitivity.

6 Calibration

6.1 Design criteria of an oscilloscope

6.1.1 The oscilloscope is a measuring instrument important for displaying physical relations of a function

$$y = \mathrm{f}(x) \tag{1}$$

where a physical quantity transformed into an electrical signal can be shown on the Y-axis. The X-axis is a time function, but it can also correspond to another physical quantity. The oscilloscope is suitable for analysing DC, AC voltages, and AC voltages with DC components.

6.1.2 The design of an oscilloscope always comprises

- a vertical system,
- a horizontal system, and
- a visual display unit.

Tab. 1 shows the relations between the design of an oscilloscope and some associated important criteria.

Tab. 1 Construction and design criteria of an oscilloscope

Oscilloscope				
Vertical system		**Horizontal system**		**Visual display unit**
Construction	**Criteria**	**Construction**	**Criteria**	**Criteria**
input divider	bandwidth	trigger	linearity	beam brightness
	rise time	time base	accuracy	
preamplifier	sensitivity		sensitivity	sensitivity
delay line	pulse response			bandwidth
output amplifier	ripple			
A/D conversion	resolution			focusing
external divider	linearity			geometric distortion

6.2 Scope of calibration of an oscilloscope

6.2.1 The calibration covers

- vertical deflection,
- horizontal deflection,
- rise time and bandwidth, respectively,
- internal calibration signals, as far as an internal calibration signal is available on the front panel.

6.2.2 If the plug-in units of plug-in oscilloscopes are of the replaceable type, it will be necessary to separately calibrate individual configurations. Connected probe heads shall be covered by the calibration. For all calibrations, elements for adjusting deflection coefficients shall be in the defined positions.

6.2.3 When calibrations are carried out, the information given in Appendix A for the acquisition of measured data shall be considered. An uncertainty budget of the calibration procedures shall be documented in the quality manual. The centre line of the beam shall be used for the evaluation of signals. For digital storage oscilloscopes, it is recommended to take the mean of several recordings to reduce the influence of digitisation.

6.3 Calibration of the vertical deflection (amplitude calibration)

6.3.1 Carrying-out of the calibration

6.3.1.1 For calibrating the vertical deflection, any of the following items can be used:

- DC voltage,
- chopped DC voltage,
- AC voltage, or
- pulses.

The amplitude shall be measured in the linear range of the amplitude/frequency characteristic of the oscilloscopes (cf. Fig. 6, see p. 27). It is recommended to use a repetition frequency between 1 kHz and 100 kHz. For digital storage oscilloscopes (DSO), the measurement values should be recorded using ≥80 % of the grid (Fig. 1), but for analogue oscilloscopes (AO) about 70 % should be used. The operating ranges specified by the manufacturer shall be allowed for.

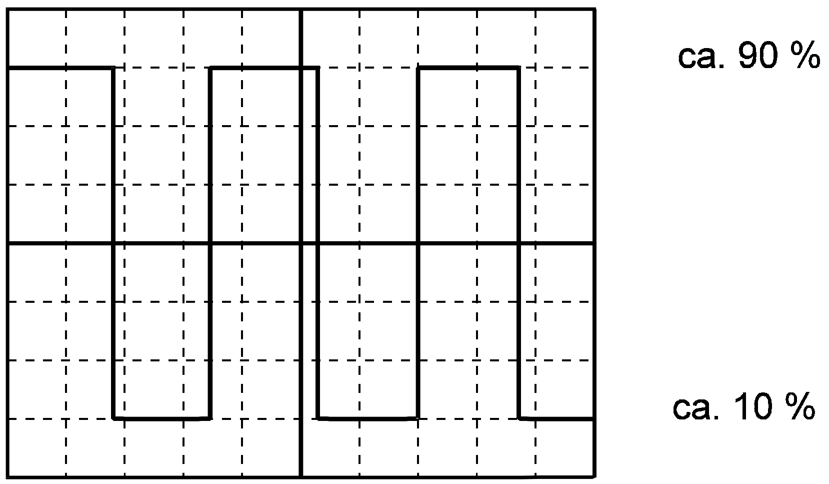

Fig. 1: Calibration of the vertical deflection of digital storage oscilloscopes

6.3.1.2 The calibration shall be carried out in each position of the voltage divider. If the input divider sensitivity is multiplied by a fixed factor (e.g. x 10), the additional deviation due to the multiplication shall be determined. In the case of multi-channel systems, the measurements shall be identified by the channel number. The calibration of the divider in a probe connected to an oscilloscope is valid only for the calibrated oscilloscope (specified in the calibration certificate). The calibration of the divider in a probe shall be unambiguously assigned to a channel. The divider probe shall be identified in the calibration certificate.

6.3.1.3 Table 2 gives an overview of the potential variants of traceability for the calibration of the vertical deflection of an oscilloscope. The variants of Table 2 are described in the text below.

Tab. 2: Variants of traceability for the calibration of vertical deflection

Variant	Standard procedure	Reference standard	Working standard
1	Accreditation for DC voltage	Digital voltmeter	Oscilloscope calibrator
2	Accreditation for AC voltage	AC calibrator	
3	Accreditation for pulse measurement	Pulse generator	

6.3.2 Variant I: Accreditation for DC voltage (Fig. 2)

6.3.2.1 The calibration of the vertical deflection is traceable through the measurand DC voltage. As a prerequisite, the laboratory shall be accredited for the measurand DC voltage with a sufficiently small uncertainty of measurement. A digital voltmeter or a DC calibrator can be used as a reference standard to calibrate the amplitude generator. Oscilloscopes are calibrated in the "chopped" mode of the amplitude calibrator. The uncertainty of measurement produced by the transition from the DC mode to the chopped mode shall be taken into account.

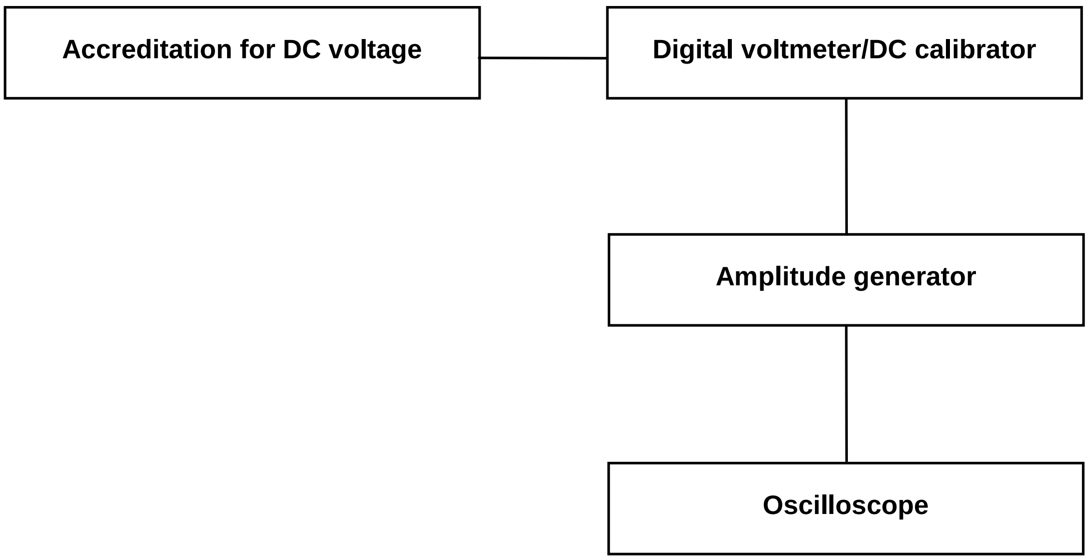

Fig. 2: Traceability through using the measurand DC voltage

6.3.3 Variant II: Accreditation for AC voltage (Fig. 3)

6.3.3.1 The calibration is traceable through using the measurand AC voltage. The calibration laboratory holds the accreditation for this measurand. The reference standard can be an AC calibrator or a digital voltmeter. The working standard is calibrated for AC peak voltage values in accordance with the accreditation. It shall be ensured by a harmonic distortion measurement that the shape of the AC voltage generator output signal deviates from sine shape only to such an extent that the determination of the peak value by form factor does not influence significantly the uncertainty of measurement.

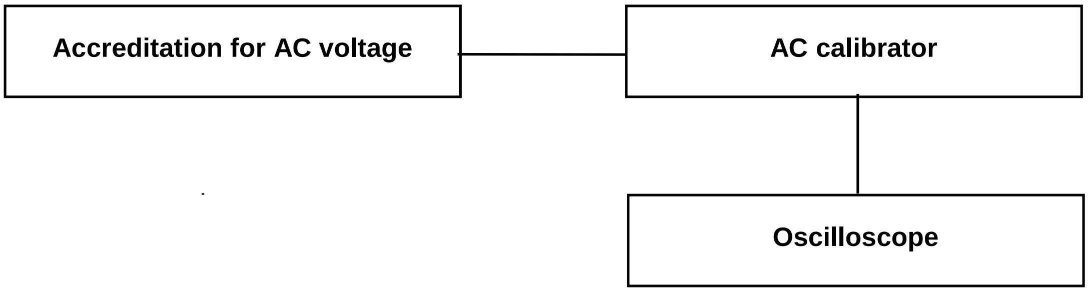

Fig. 3: Traceability through AC voltage

6.3.4 Variant III: Accreditation for pulse measurements (Fig. 4)

6.3.4.1 The calibration laboratory holds an accreditation for pulse measurements. A calibrated pulse generator is used for ensuring traceability.

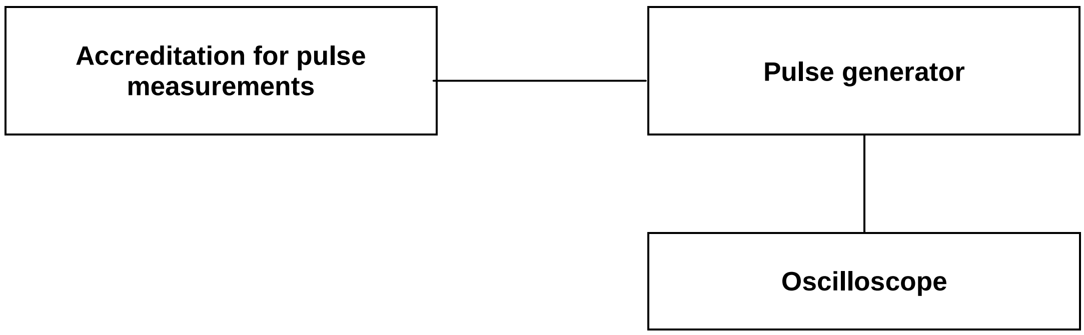

Fig. 4: Traceability through pulse measurement

6.4 Calibration of the horizontal deflection (time base calibration)

6.4.1 Time base calibration

6.4.4.1 The sweep generator shall furnish the correct deflection voltage (linear with time) in the whole frequency range up to 10 decades (cf. Appendix A). For each coarse range, only one setting point arbitrarily defined is regarded as calibrated. Expansion factors can be graded 1/2/5/10 or 1/3/10. A certain position of the fine controller (left or right stop, mechanical stop point, priority code for incremental adjustment) — often marked by LED or indication in the display — defines the nominal defined deflection velocity. The range of control of the fine controller shall ensure overlapping of the individual subranges which are of varying size, however, it is not to be calibrated. The additional expansion (switch-over of amplification) by the factor 5 or 10 shall be calibrated. The calibration is carried out

- for analogue oscilloscopes: in all time ranges
- for digital storage oscilloscopes: in a mean sweep range

In the case of double time-base deflections (sweep), the two time bases shall be measured independently of each other, each in the fine controller position marked as calibrated.

6.4.1.2 The phase deviation between the X and the Y channels shall be checked by simultaneously displaying the same sinusoidal measurement voltage through both channels (Lissajous figures). Correct branching shall be performed by power dividers (matching) with measurement cables of equal length between power divider and input connector (same delay). Simple reversing of X and Y connections and checking that the result does not change indicates whether any phase deviations have been introduced. The calibration shall be carried out at the nominal cut-off frequency of the oscilloscope and at half this value (or as agreed with the customer).

6.4.2 Calibration procedure

6.4.2.1 Calibration signals can be arbitrary periodic signals of sufficient stability and accuracy. The use of signals in pulse form, which are obtained by phase-locked frequency division from a traceable basic cycle, should be preferred. These should, ideally, have a well-defined edge to ease alignment with graticule marks.

6.4.2.2 This allows quartz oscillators to be used as pulse rate generators which have been made traceable by repeated calibration or synchronisation with a local frequency standard controlled by a radio transmitter, a television transmitter or other procedures (Fig. 5, see p. 12).

6.4.3 Evaluation of the horizontal deflection (time base)

6.4.3.1 The pulse frequency shall be so selected that at least one complete pulse period is imaged per main grid ruling. It is to start from the second graticule line from top (and end with the second from top) in order to prevent non-linearities near the edges of the screen influencing the results in the normal working area of the screen. The deviations between the pulse edges (in the area of maximum rise time) and the vertical main grid lines shall be determined as follows:

(a) at a non-variable pulse frequency: by reading/interpolation,

(b) at a variable pulse frequency: by adjustment to register with the main reticle lines and determination of the actual period. The registration at the first main raster line shall be set with the aid of the controller for the horizontal beam position and to be corrected after period adjustments.

6.4.3.2 To avoid reading interpolations, it will be expedient for the calibration if the pulse period can be fine-tuned. Fine-tuning can be carried out by synthesis procedures or microstepping and does not require additional measurements for the tracing-back during calibration. If an analogue pulse generator is used, the adjusted frequency shall be measured simultaneously using a time interval counter (Fig. 5).

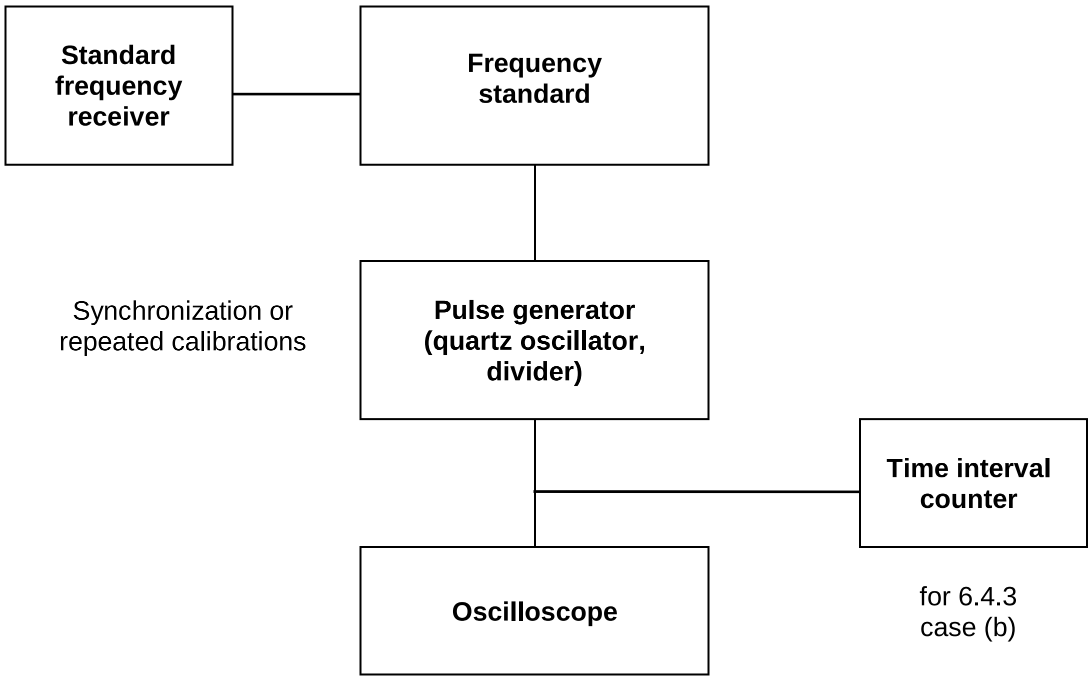

Fig. 5: Traceability of the time base

6.5 Determination of bandwidth and rise time

6.5.1 General

6.5.1.1 The frequency range within which the voltage amplitude response decreases by 3 dB is referred to as the bandwidth *B*. The high-end cut-off frequency is the upper limit of the bandwidth *B* (Fig. 6).

6.5.1.2 For time measurement, the rise time t_o of the oscilloscope is of interest with which an ideal voltage step is displayed on the screen. The rise time is measured on voltage steps between the points in which the signal has reached 10 % and 90 %, respectively, of the final value (Fig. 7).

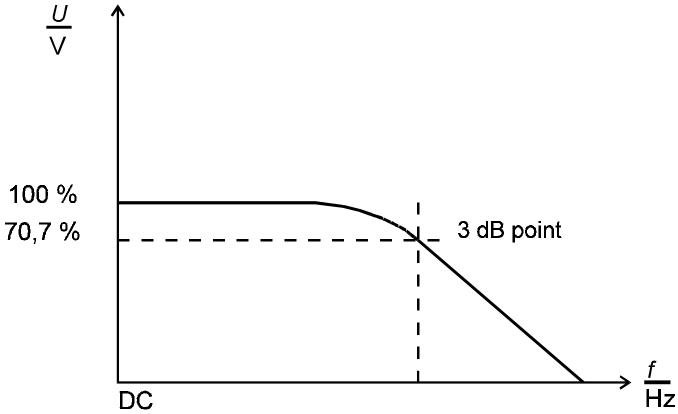

Fig. 6: Frequency response

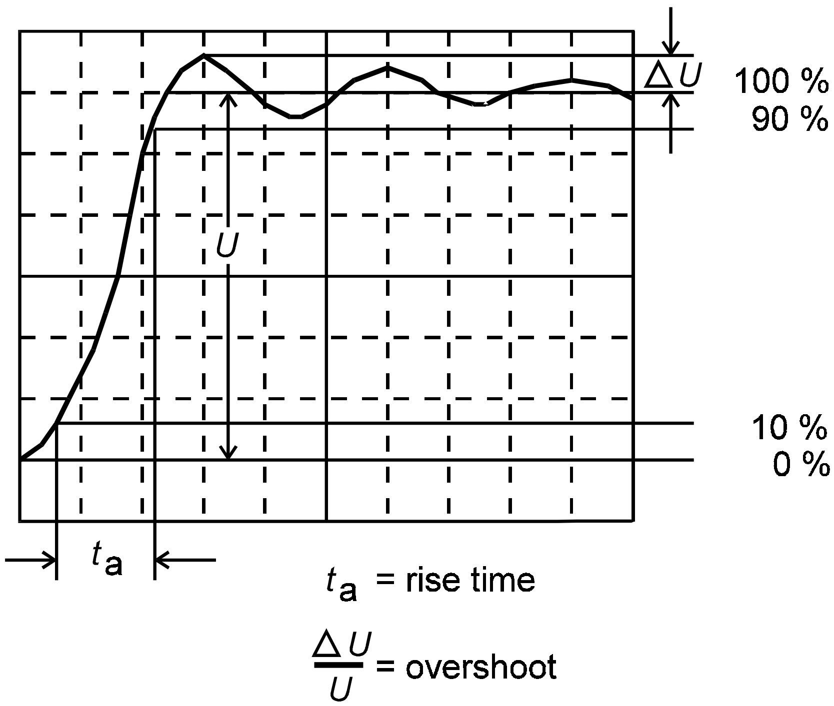

Fig. 7: Determination of the rise time

6.5.1.3 The low-pass effect of oscilloscope amplifiers can be described in many cases by the theoretical Gaussian low pass for which the relation between the rise time of the step response and the upper -3 dB bandwidth B_{-3dB}

$$t_0 = 0{,}35/B_{-3dB} \qquad (2)$$

is valid. This relation can be used to calculate the rise time of oscilloscopes from the measured -3 dB bandwidth if no measurement can be carried out with a calibrated pulse generator.

6.5.1.4 If the oscilloscope amplifier has higher-order and not Gaussian low-pass characteristics (many digital oscilloscopes), the numerical values will be different from those calculated from [ref. 5] (cf. Appendix A, section A3.2). The pulse rise time of the pulse signal shall be smaller than that of the oscilloscope (cf. Appendix A, section A3.2).

6.5.2 Measurement of the bandwidth

6.5.2.1 Amplitude measurements using a calibrated voltmeter

(a) As AC and HF voltmeters used for bandwidth measurement are often instruments indicating rms values, whereas, for this measurement, the amplitude (the peak value of the voltage) is usually calibrated, the generator used for the measurements shall be of sufficient spectral purity. A harmonic or spurious signal can cause an uncertainty of measurement approximating the difference of the sum of the peak values of the fundamental measuring signal and each harmonic or spurious contribution, and the peak value of the fundamental signal. A 10 % harmonic (-20 dB) in the measuring signal may cause as much as a relative uncertainty of measurement of about 10 %.

(b) At frequencies up to 1 GHz, small uncertainties can be attained for amplitude measurements using a calibrated HF voltmeter. The oscilloscope to be calibrated and the voltmeter are connected in parallel with the aid of a T junction (use a coaxial type at frequencies above 1 MHz) (Fig. 9).

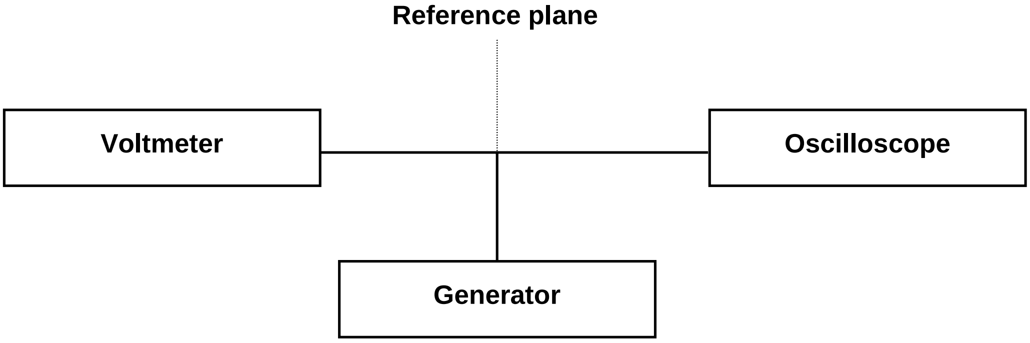

Fig. 8: Basic circuit for amplitude measurements using a voltmeter

(c) The voltage to be measured is fed into the T junction from a variable-frequency generator through the third connection (in the centre of T)(cf. Appendix A). When connected in parallel, calibrated HF power meters can be used instead of voltmeters if their input impedance or admittance is known with sufficient accuracy. Using a sinusoidal voltage as measurement signal, the amplitude or the peak value $\hat{U}$ of the voltage is obtained from the equation

$$\hat{U} = \sqrt{\left(2\ P\ /\ G_{\mathrm{L}}\right)} \tag{3}$$

with

P effective power at the input of the calibrated power meter, and
G_{L} input conductance of the power meter.

(d) When the power meter impedance equals the characteristic impedance Z_0 of the HF power system (in most cases 50 Ω), the well-known relation

$$\hat{U} = \sqrt{2\ P\ Z_0} \tag{4}$$

applies. The reference plane of the voltage measurement using power meters is the measurement plane of their input impedance or input admittance. The amplitude measurement with a T junction and a voltmeter (or power meter) can be used for oscilloscopes with a high and low (50 Ω) input impedance.

(e) For high-impedance oscilloscopes, an alternative method without a T junction is often used or specified by manufacturers. A generator with an output impedance of 50 Ω is terminated with a matched 50 Ω load, and the oscilloscope is connected in parallel with this load. The bandwidth is determined by the 3 dB roll-off of the voltage indicated by the oscilloscope. Further instructions of the manufacturers concerning the measurement of bandwidths shall be considered. Up to the highest frequency considered, the impedance shall be significantly larger than 50 Ω, otherwise additional uncertainties of measurement will be introduced.

6.5.2.2 Amplitude measurements using a calibrated power generator

(a) In the frequency range above 1 GHz, accurate voltage measurements are usually not carried out using a voltmeter connected in parallel with the aid of a T junction. At these frequencies, amplitude or voltage measurements are traceable to a power and impedance measurement (Fig. 9). For the amplitude measurement using an HF power generator, this generator is first calibrated using a calibrated power meter. The effective power P which the generator feeds into the input of the oscilloscope during this measurement produces a voltage with the peak value

$$\hat{U} = \sqrt{\left(2\,P / G_{\mathrm{OS}}\right)} \tag{5}$$

G_{OS} being the conductance at the oscilloscope input (Fig. 9).

(b) The method shown in Fig. 9 can be modified by using a power splitter with the power meter on one output port and the oscilloscope on the other output port, thus improving (often considerably) the source match (Γ_{G}). For a symmetrical power splitter, Eq.(5) is valid.

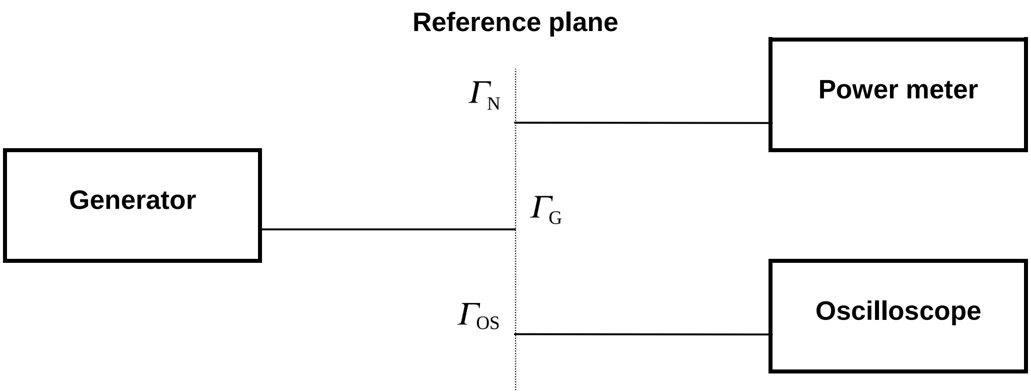

Fig. 9: Basic circuit for amplitude measurements using a power generator at high frequencies

(c) The voltage measurement described above concerns the HF voltage developed at the plane of the input connector of the oscilloscope. At higher frequencies, especially above 1 GHz, an alternative method is often applied for bandwidth measurements: The equipment described above with a matched power splitter and with a calibrated power meter and the oscilloscope at its two output ports is used. The power P_{inc} incident to the oscilloscope and obtained from the measurement value of the calibrated power meter using its calibration factor is determined. The amplitude of the incident voltage wave to the oscilloscope is ascertained by calculating $\hat{U} = \sqrt{\left(2\ P_{\mathrm{inc}}\ Z_0\right)}$. The method applied shall be mentioned in each bandwidth calibration.

(d) When calibrated voltage or power generators are used, the bandwidth measurement is traceable to AC and HF voltage standards or to HF power and HF reflection standards. Eq. (5) will be valid only if the reflection coefficients of the generator (Γ_G), the power meter (Γ_N) and the oscilloscope (Γ_{OS}) are negligibly small; otherwise the voltage $\hat{U}$ shall be multiplied by a factor b. The calculation of this factor is described in part A4 of the Appendix A.

6.6 Internal calibration signals

6.6.1 Amplitudes and frequencies of the internal calibration signals shall be calibrated in accordance with sections 6.1 to 6.4. Such measurements often require special techniques because internal calibration signals are often available as voltage (or current) pulse form appearing at a test output on the front panel.

7 Calibration Certificates

7.1 In the calibration certificate, values shall be stated with reference to the conditions and setting values relevant to the respective measurement. When parameter(s) are certified to be within specified tolerances, the measurement value(s), extended by the estimated uncertainty of measurement calculated in accordance with EAL-R2 [ref. 3], shall fall within the appropriate specification limit [ref. 2].

8 References

1 IEC 351 part 1. *Statement of the characteristics of electron beam oscilloscopes*. November 1981

2 EAL-R1. *Requirements concerning Certificates Issued by Accredited Calibration Laboratories*. November 1995

3 EAL-R2. *Expression of the Uncertainty of Measurement in Calibration*. 1990

4 IEC 1083-1. *Digital recorders for measurements in high-voltage impulse tests*. *Part 1: Requirements for digital recorders.* 1991

5 Schuon, E. ; Wolf, H.: *Nachrichtenmeßtechnik*. Springer-Verlag Berlin, Heidelberg, New York, 1981

6 Mellis, D.: *Schnelle Speicheroszilloskope*. Philips GmbH Kassel, 1989

7 Gans, W.: *Dynamic calibration of oscillopes and waveform recorders*. Conf. Record of IEEE Instrum. Meas. Tech. Conf., San Jose, CA, Feb. 13-15, 1989

8 Green, P. J.: *Automated test and evaluation center for waveform digitizer systems and components*. IEEE-IM 39 (1990)1, 101

APPENDIX A

A1 Data output

A1.1 The oscilloscope is used for determining signal patterns as a function of time:

$$Y = \mathrm{f}(t) \tag{A1}$$

Special transducers can be used to represent other physical quantities:

$$Y = \mathrm{f}(X) \tag{A2}$$

A1.2 The measured data are indicated via the display screen or specific data interfaces. The signals are adapted in their amplitude by means of amplifier/attenuator settings (and, if necessary, by additional external dividers) and in the time axis by changing the frequency of the deflection generator.

A1.3 To facilitate the interpretation of the wave form represented on the screen, the latter is provided with a graticule whose units correspond to volts/division for the vertical axis and to second/division for the horizontal axis. Superimposed alphanumeric captions or cursor functions can be used to assist the characterisation of the display (Fig. A1). With the digital storage oscilloscope, interfaces are available, which provide access to the curve data for further signal processing (e.g. in a computer).

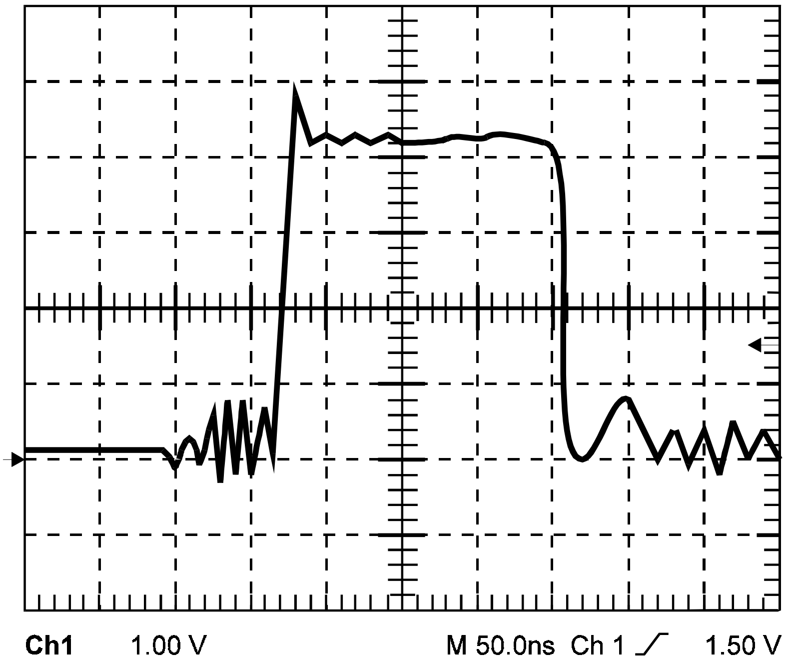

Fig. A1: Pulse representation on the display screen

A1.4 The graticule allows measurements of the amplitude, of the frequency and of the signal rise to be performed and further signal characterizations to be made, such as those of the transient effects, the decay behaviour and the tilt distortions. Most digital storage oscilloscopes have extended signal analysis capabilities such as integration, differentiation and Fourier transformation and calculate the signal parameters from the digitized data.

A2 Data evaluation

A2.1 Signal analysis by means of an oscilloscope is affected by uncertainties. The uncertainties result from the oscilloscope used, from the signal adaptation and the ratio between signal and oscilloscope parameters. In particular the bandwidth, the rise times of the signal and the signal representation, line terminations, input and output impedances as well as — in the case of the digital storage oscilloscope — the scanning frequency and the type of scanning shall be allowed for.

A3 Uncertainties of measurement in oscilloscope calibration

A3.1 Displaying system

A3.1.1 When the signal is analysed by using the screen, the raster type shall be taken into account. A distinction is made between external and internal graticules. The external graticule is applied to the cathode-ray tube from the front. The resulting spacing between phosphor layer and raster is at least equal to the glass thickness (according to the type). This gives rise to a parallactic uncertainty which can be considerably minimized by the use of an internal graticule. This is engraved on the inside glass face.

A3.1.2 Due to geometrical distortions of the beam deflection, only 60 % to 70 % of the vertical central range of indication is often used. As a result of noise and since focusing is limited, the beam width can be of the order of 1 % to 2 % of the range of indication. The centre of the beam interpolated by the eye is used as a reference point. With digital storage oscilloscopes provided with a graticule scan screen, the graticule is electronically produced in one plane with the signal beam. In the case of uncorrelated noise distributing the signal, the signal-to-noise ratio can be improved by averaging periodic signals; this has a positive effect on the image quality.

$$\mathrm{SNR} = \sqrt{n} \tag{A3}$$

SNR = signal-to-noise ratio

n = number of averaged curves

A3.1.3 Furthermore, the reading uncertainty can be minimized by the use of a *cursor* (which obtains the information from the digital values) and alphanumerical read-out as well as by the direct processing of digital values using an integrated computer (distinction between visual and numerical resolution).

A3.2 Vertical system

(a) For the analysis of amplitude-related measurands, the transfer characteristic of the vertical system is dominant. It is described by stating the bandwidth, the rise time, the sensitivity and the input impedance. The transfer characteristic is further determined by frequency response (waviness), phase behaviour (differences between the transit times of the individual harmonics), noise and reflections at the input. The properties referred to last are of special importance for the pulse behaviour. Rectangular pulses are therefore especially suitable for characterizing the performance (step response of the vertical system).

(b) In the vertical range, signal matching is realized by a divider/amplifier system. As the amplifier stages show an input capacitance in addition to their input resistance, the dividers (internal and external attenuator, e.g. a probe head) shall be frequency-compensated according to the divider ratio. Furthermore, the matching problems of the individual impedance components (e.g. generator, connecting cables used, and oscilloscope) shall be discussed. Impedances which are not matched to one another lead to reflections which, in pulse measurements and other higher-frequency measurements, give rise to signal falsifications. Particular attention shall be paid here to the input capacitance of oscilloscope inputs, which is parallel to the input resistance (e.g. 1 MΩ). The resulting resistive component at higher frequencies must not be neglected. This applies also to the use of external 50 Ω resistors connected to the oscilloscope input. Due to the parallel capacitance of the oscilloscope input, the input impedance changes with increasing frequency (and the inadequate matching leads to increasing signal reflection).

A3.2.1 Rise and decay time, intrinsic rise time of the oscilloscope

(a) The rise time is an important parameter for characterizing the oscilloscope. To avoid that initial transients or tilts or bandwidth boundaries might influence the accuracy of measurement, the rise time and the decay time are measured in accordance with the definition on the pulse edge of a signal between 10 % and 90 % of the pulse height.

(b) If the pulse slope shows pre- or overshoot, the 100 % value should not be related to the peak values but to the mean top heights. Neither dips nor voltage rises (glitches) near the slope should be taken into account. The measurement of the decay time is carried out by applying the same procedure as is used for the downward pulse edge of the signal. For very short times, besides the rise time of the oscilloscope t_0, also the rise time of the measurement signal from the pulse generator t_G shall be allowed for; when added geometrically, both times yield the measured total rise time t_a:

$$t_a = \sqrt{t_0^2 + t_G^2} \quad \text{(A4)}$$

(c) Eq. (A4) is valid only if the transfer characteristics of the individual components correspond to those of a Gaussian filter.

A3.3.3 Rise time and scanning frequency

(a) The transfer behaviour of analogue oscilloscopes can be specified by stating the bandwidth according to eq. (A5):

$$B \cdot t_0 = K, \quad \text{(A5)}$$

where B is the -3 dB bandwidth, t_0 the rise time and K a constant.

(b) Only under certain conditions can the bandwidth of an oscilloscope serve to specify the resulting rise time. The bandwidth/rise time product K is different for different low-pass filter types. The steeper the slope of the transition between passband and stop band, the greater the constant K (e.g. for a single-pole filter: K = 0,35; in contrast to this, for the tenth-order Butterworth filter: K = 0,488). As overshooting increases with increasing edge steepness, vertical amplifiers with a flat transition are normally used. If the transfer function of the oscilloscope is Gaussian, the minimum possible rise time is achieved without any overshoot.

(c) The evaluation criterion "bandwidth" and relation (eq. A5) are in general not valid for the digital storage oscilloscope, as both the frequency of scanning and the type of signal reconstruction enter into the representation and evaluation. Fig. A2 thus reveals that linear interpolation yields different rise times in dependence on the position of the scanning points. In Fig. A2 (bottom), the edge of the step lies between two scanning points so that a rise time of $t_a \sim 0{,}8\ T_A$ results from the representation.

(d) On the basis of these facts, when linear interpolation is used, a minimum measurable (effective) rise time is defined for the digital storage oscilloscope, which is related to the minimum scanning interval. For periodic signals or rising edges, the equivalent time scanning method can be used. With this method, for each individual signal sweep, only a part of the values required to fill the digital store are digitized, and the scanning frequency determines the number of sweeps which shall be complied with to obtain a complete record of the signal.

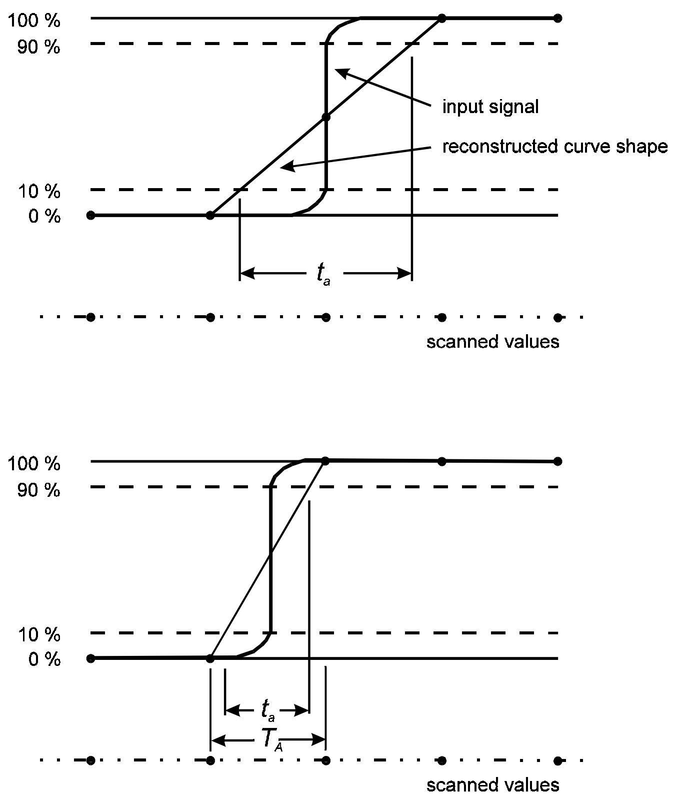

Fig. A2: Uncertainties of measurement of a step function

(e) The stages accountable for distortion-free signal reconstruction are the A/D transducer, which is characterized by low digitizing noise, the low-jitter trigger circuit, and the low-jitter A/D transducer time-delay module. If the properties of the stages are not satisfactory, this will make itself felt by positive and negative discontinuities amounting to a few digitizing steps in an ascending straight line. An improvement can be achieved by averaging.

(f) For single signal phenomena, the scanning frequency is dominant. To achieve a good signal reconstruction, the scanning frequency needs to be at least twice as high as the highest harmonic contained in the signal. The scanning points are not synchronous with the signal shape, i.e. if the scanning frequency corresponds to the rise of the signal, the measured rise value can differ by up to 50 % in dependence on the random position of the scanning points on the rising edge of the signal.

(g) Another problem is posed by the automatic parameter determination from digitized data. The algorithms used differ substantially regarding the inclusion of overshooting or undershooting in the rise time calculation. If the 0 % and the 100 % reference points are formed only from the voltage minimum and the voltage maximum, the position of the resulting 10 % and 90 % points will be incorrectly determined. This leads to a wrong value of the rise time being measured. In this case, the determination by a statistical method has proved reliable. The value distribution of the digitized curve shape is analyzed and unambiguous value maxima for the 0 % point and the 100 % point shape up (Fig. A3).

(h) The fundamental behaviour of an A/D transducer and of a digital storage oscilloscope follows from the quantization characteristic. It shows the relation between the value recorded by the digital storage oscilloscope and the DC voltage applied to the input, over the whole control range. For an ideal N-bit transducer, this characteristic is stepped, with 2^N steps. The deviation of the actually measured characteristic from the ideal curve is expressed by the differential and integral non-linearity. It characterizes the imperfect behaviour of a digital storage oscilloscope when slowly varying signals are recorded (Fig. A4).

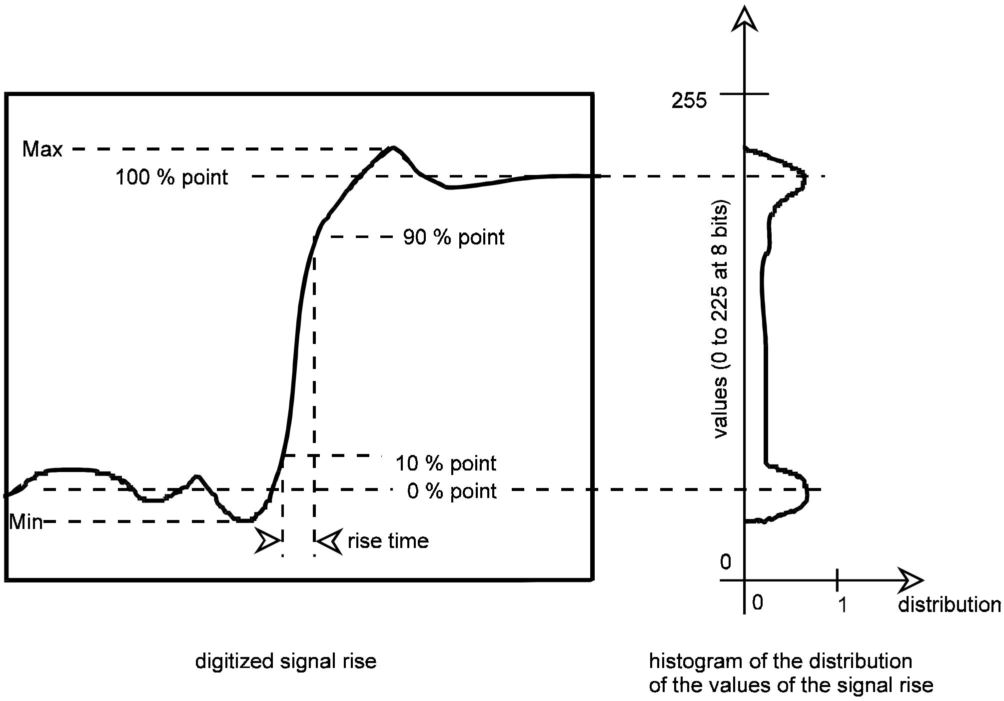

Fig. A3: Determination of the 0 % and 100 % points

(i) The quantization characteristic ascertained for DC voltage is frequently not sufficient for rapidly varying signals. With increasing slope of the measurement signal, certain quantization levels of the A/D transducer cannot follow the curve slope any longer, whereas neighbouring levels respond more frequently.

(j) This inadequate behaviour is expressed by the dynamic non-linearity which characterizes the failure of one or several quantization level(s) when ramp-shaped or triangular input signals with a specified slope are repeatedly recorded. The failure of individual quantization levels gives the impression that quantization of rapidly varying signals is carried out at a smaller number of bits. This failure can be clearly expressed by the "effective number of bits", which is determined with sinusoidal signals. Quantitative statements can, however, be derived only in rare cases.

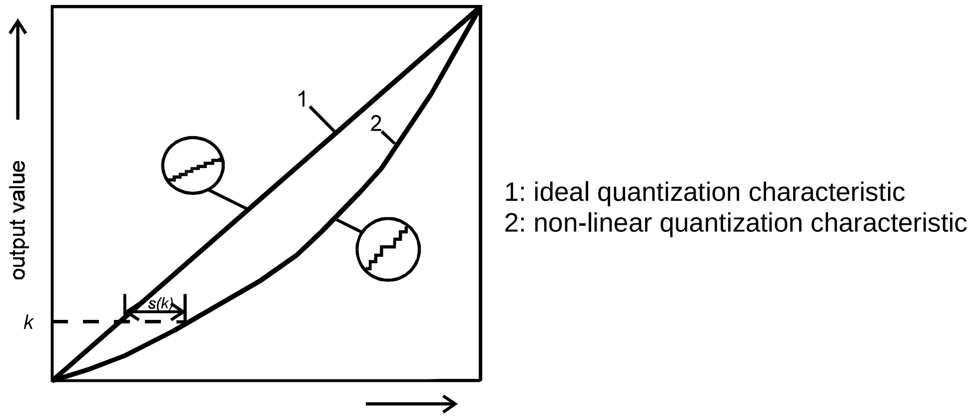

Fig. A4: Integral non-linearity *s*(*k*) at the quantization level *k*

(k) The effective number of bits is therefore of no importance for the measurement of amplitudes and peak values of higher-frequency measurement signals, as the signal variation is zero in this region. Then the whole number of bits is available and other error sources, such as, for example, too small a scanning rate, predominate.

A3.3 Horizontal system

(a) The accuracy, linearity and stability of the horizontal system are of decisive importance for time-related measurands. In analogue systems, due to the rise of the ramp component of the saw-tooth function, the saw-tooth generator determines the deflection velocity of the electron beam and, thus, the relation of the X-axis to time.

(b) For time and frequency measurements using digital oscilloscopes, the same relation as for analogue oscilloscopes is valid. The time-related measurement is conducted over the maximum period possible. For analogue oscilloscopes, the linearity problem is of somewhat lesser importance, as is the problem of the uncertainty of a scanning interval for digital oscilloscopes (cf. Fig. A6).

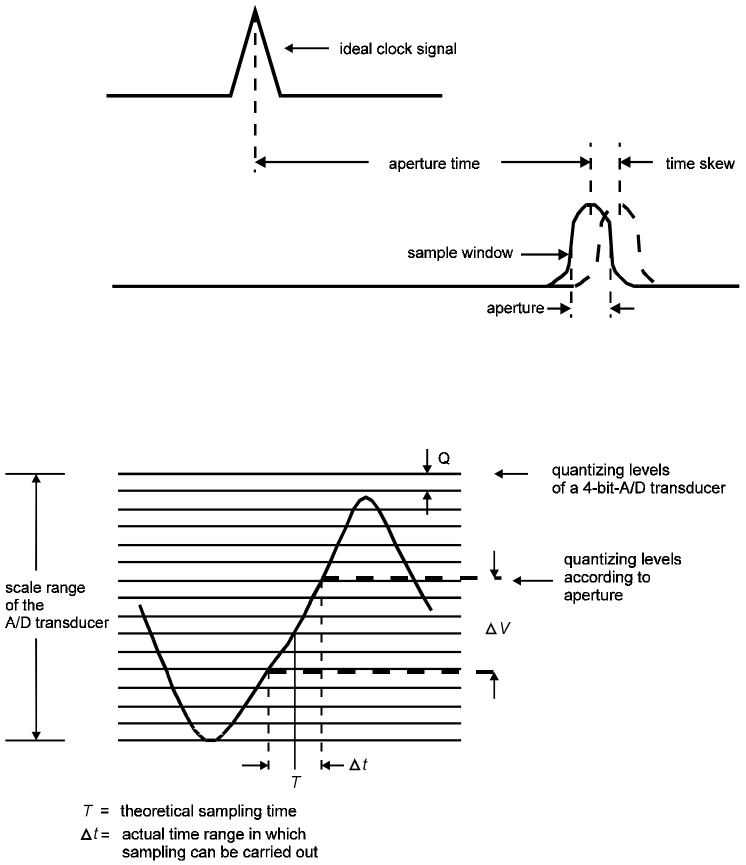

Fig. A5: Dynamic effect of the aperture error

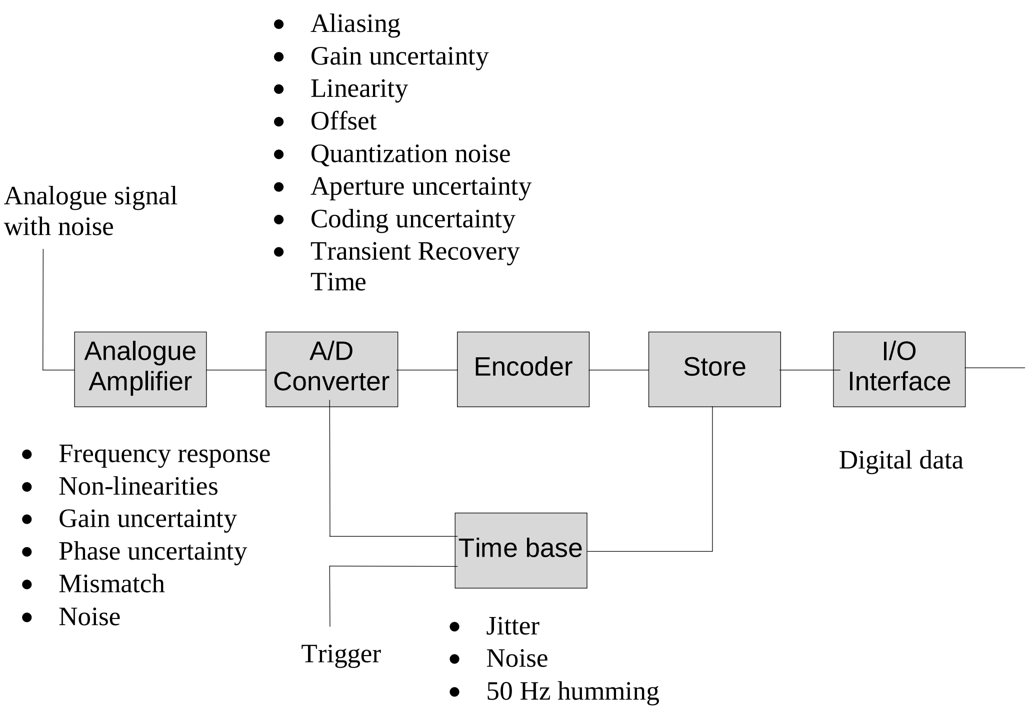

Fig. A6: Uncertainties of measurement in the digitizer, block diagram

A3.3.1 Linearity

(a) The deviation L from the linear shape shall be calculated from individual measurements between the main graticule lines within the scope of the time base measurement (Fig. A7).

$$L = \frac{T_{p_i\,\max} - T_{p_i\,\min}}{\overline{T}_p} \qquad L = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(T_{p_i} - \overline{T}_p\right)^2} \qquad \text{(A6)}$$

$T_{p_i}\max$	maximum period
$T_{p_i}\min$	minimum period
$\overline{T}_p$	averaged period

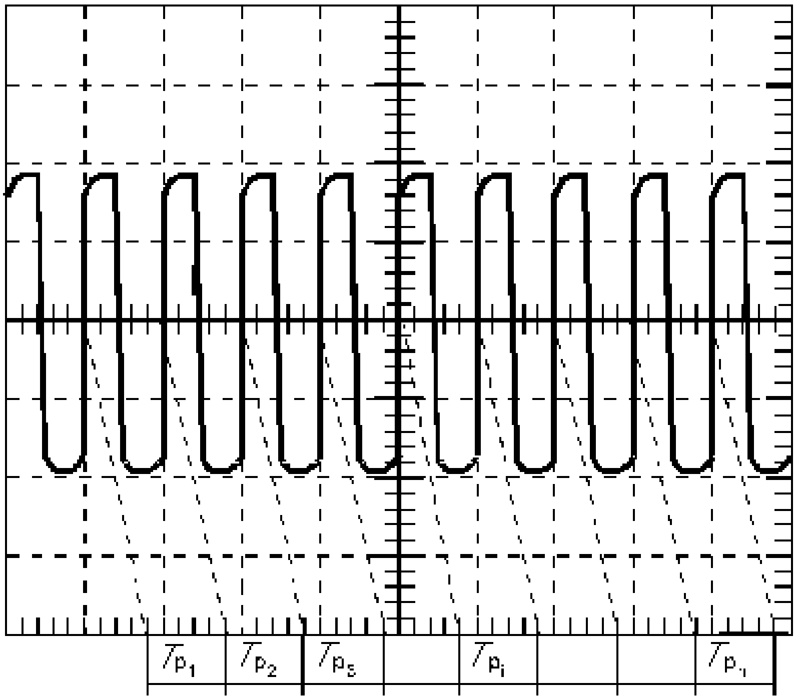

Fig. A7: Time base linearity check. Screen display in the completely balanced state at ideal linearity

A4 Calibration with HF voltage

(a) Up to 30 MHz, commercial AC voltage calibrators are available into which a generator and a voltmeter are integrated to form one device. Because of their good long-term stability, thermal converters are suitable as HF voltage standards. For frequencies up to 1 GHz, they are manufactured on a commercial basis with a coaxial T junction integrated into the coaxial housing (e.g. the Ballantine 1396A type). For commercial devices at frequencies up to 100 MHz (e.g. Fluke A55, Ballantine 1394A and 1395A), the junction shall be attached externally. Thermal converters can be calibrated with measuring uncertainties of ≤ 1 % by tracing them back to a national HF voltage standard at frequencies up to 1 GHz.

(b) For accurate HF voltage and amplitude measurements, the position of the reference plane shall be taken into account, for example, when adapters or connecting lines are used. The reflection of voltage waves will lead to a voltage standing wave along the line if the characteristic impedance of the line Z_l and the terminating impedance Z_E connected to the line are not equal. The magnitude of the voltage $|U_{IN}|$ at the input differs from the magnitude $|U_E|$ at the output of a loss-free line of electrical length L. For a loss-free line,

$$|U_{IN}| = |\cos(2\pi \cdot L/wl) + j \cdot Z_l/Z_E \cdot \sin(2\pi \cdot L/wl)| \cdot |U_E| \qquad \text{(A7)}$$

is valid, where wl is the wavelength of the HF signal. Likewise, the line attenuation can lead to a difference between $|U_{IN}|$ and $|U_E|$. Cable attenuations are proportional to the root of the measuring frequency. Thin cables can show attenuations of well over 1 dB/m at 1 GHz.

(c) Thermal converters are always, and power meters are predominantly, instruments measuring rms values. For oscilloscopes, however, usually the amplitude, i.e. the peak value, of the voltage is calibrated; therefore, as pure a sinusoidal measurement signal as possible shall be ensured, i.e. the generator shall be of sufficient spectral purity.

(d) The output and input impedances of commercial HF generators, oscilloscopes for higher frequencies and HF power meters as well as the characteristic impedance of the coaxial lines used are generally more or less well matched to the nominal value of the reference characteristic impedance Z_0 of the HF line system (in most cases 50 Ω). The deviation of an impedance Z_X from the nominal value is characterized by the reflection coefficient

$$\Gamma = (Z_X - Z_0)/(Z_X + Z_0). \qquad \text{(A8)}$$

(d) When voltage measurements are made with a calibrated power meter and a T junction (6.5.2.1) or with a calibrated generator (6.5.2.2), significant uncertainties can arise if the input conductance of the power meter (G_L) or oscilloscope (G_{OS}) is not known exactly. The input conductance G_{IN} of a device can be determined if its input reflection coefficient Γ_{IN} is known:

$$G_{IN} = G_O \frac{1-|\Gamma_{IN}|^2}{|1+\Gamma_{IN}|^2} = G_O \frac{1-|\Gamma_{IN}|^2}{\left(1+|\Gamma_{IN}|^2 + 2|\Gamma_{IN}|\cos\varphi\right)} \tag{A9}$$

and $G_O = 1/Z_O$. If only the modulus of $|\Gamma_{IN}|$ is known, the uncertainty of measurement can be estimated when G_O is used instead of G_{IN} (G_L in Eq.(3), G_{OS} in Eq.(5)). If $|\Gamma|^2 << |\Gamma| << 1$, (A9) will reduce to

$$G_{IN} \approx G_O \left(1-2|\Gamma_{IN}|\cos\varphi\right) \tag{A10}$$

(e) If the reflection coefficients of the generator (index G), of the power meter (N) and of the oscilloscope (OS) are not negligible when the voltage $\hat{U}$ is measured at the oscilloscope using a generator and a calibrated power meter (6.5.2.2), $\hat{U}$ is given by

$$\hat{U} = \sqrt{\left[\left(2\ P\ /\ G_{OS}\right)\ b\right]} \tag{A11}$$

where

$$b = \left(1 - |\Gamma_{OS}|^2\right) \frac{|1 - \Gamma_G \Gamma_N|^2}{|1 - \Gamma_G \Gamma_{OS}|^2} \tag{A12}$$

and P is the power fed into the oscilloscope (traceable to the calibrated power meter).

(f) If the phases of the reflection coefficient are not known and a correction is therefore not possible, Eq. (A12) can be used to estimate the resulting uncertainty of measurement of the voltage $\hat{U}$. If the generator and the oscilloscope are to be connected by a line, the generator shall be calibrated together with this line as a unit.

(g) As the uncertainties of the power measurement and of the conductance measurement, which may be of the order of a few percent, contribute to the overall uncertainty of the amplitude measurement, the relative uncertainty of amplitude measurement may be of the order of several percent when this method is used.