Measuring Instrumentation

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Outline

Measuring System Model

Digital Multimeter
- Functional blocks
- DC and AC instrumental uncertainty
- Normal mode noise and loading effects
- Common mode noise

Oscilloscope
- Functional blocks
- Waveform acquisition
- Static accuracy and time accuracy
- Dynamic accuracy
  - analog section and connection
  - digital section

Passive Probe
- Source – instrument connection
- Compensated probe

Measuring system model

values must be in the allowed ranges to ensure effects negligible w.r.t. target uncertainty

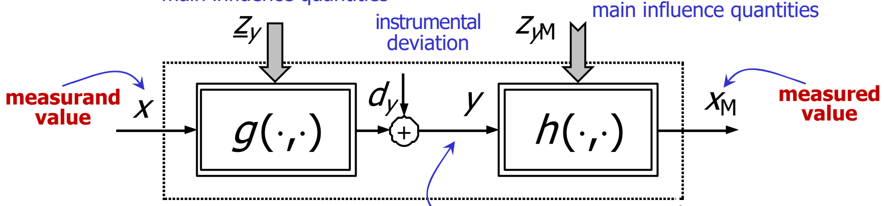
$\underline{\boldsymbol{w}}_y \in Wy$

secondary influence quantities

effects must be compensated since significant w.r.t. target uncertainty

$\underline{\boldsymbol{z}}_y \in Zy$

main influence quantities



transduction function (deterministic)

raw measurement data

measurement information extraction

deterministic function

very often (thanks to calibration)

measurement error (unknown)

influence quantities operating range

$$x_M = k(x, \underline{z}_{yM})$$

$$x_M = x + e_{xM}$$

$$\underline{\boldsymbol{w}}_y \in \underline{W}_y$$

Measuring system model

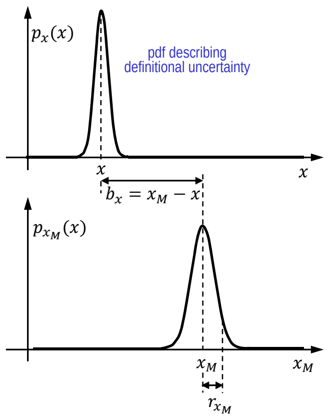
$$x_M = x + e_{xM} \qquad \underline{\boldsymbol{w}}_y \in \underline{W}_y$$

random + systematic contributions

assumption: no uncertainty is introduced by measuring system

max information achievable with the adopted model for the measurand:

p.d.f. of the measurand $p_x(\cdot)$



usual available information:

measured value

max instrumental uncertainty for a given $\underline{W}_y$:

$$x_M = x$$

$$\Delta_I = k_1 |x_M| + k_0$$

measurand value assumed equal to measured value (after possible compensations)

allows to determine $\max|e_{xM}|$

k_1 and k_0 are given and depend on the allowed range $\underline{W}_y$

type B uncertainty

Repeated measurement

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in the same way
and in short time

using the instrument **repeatedly**
different values can be obtained
due to small **short-time influence quantities fluctuations**

magnitude of **short-time variations** is usually
much lower than the width of **allowed operating ranges**

in instrumental uncertainty:
random contribution $\ll$ **systematic** contribution

evaluated using
type A methods

evaluated using
type B methods

repeat measurements is often **useless**

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DIGITAL MULTIMETERS

Digital Multimeters (DMM)

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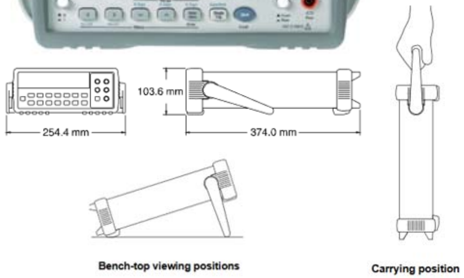
measured quantities:
$V_{DC}, V_{AC}, I_{DC}, I_{AC}, R, \ldots$

this class of DMM
is analyzed

benchtop
6½ digits



handheld

DMM: front / rear panels

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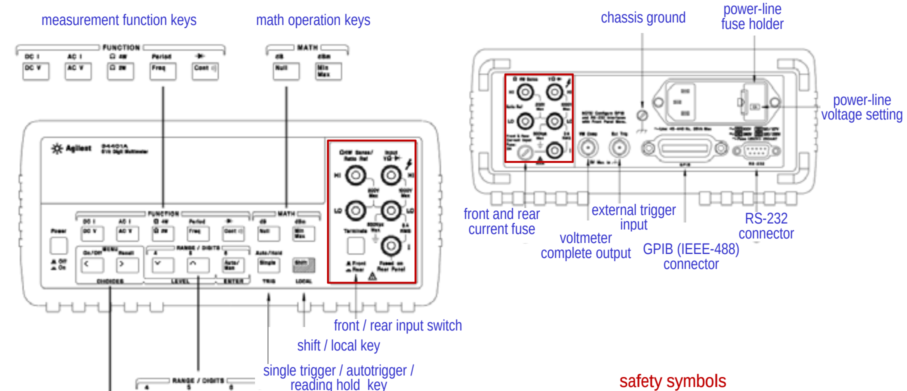
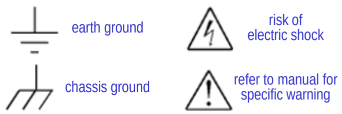


safety symbols

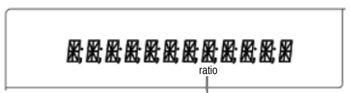


DMM: display

front panel display
6½ digits

half digit (only 0 or 1)
negative sign or blank (positive)
exponent m, k, M
full decimal digits
measurement unit VDC, OHM, HZ, dB, ...

-H.DDD,DDD EFFF



on for ratio measurement

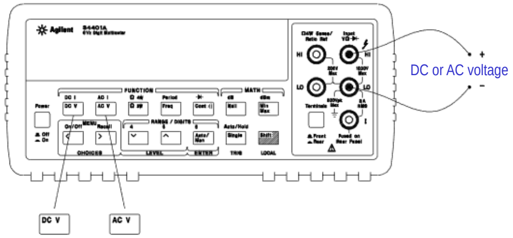
n° of digits displayed
depends on
measurement type and range

-10.123,5 VDC	10 VDC range 5½ digits displayed
-045.23 mVDC	100 mVDC range 4½ digits displayed
102.345,6 OHM	100 ohm range 6½ digits displayed

n° of digits can be reduced to **increase reading/s** in automatic measurements

DC or AC Voltage

AC voltage: **ac-coupled**



true RMS

$$V_{true-rms} \stackrel{\text{def}}{=} \sqrt{\frac{1}{T}\int_0^T v_{AC}^2(t)\,dt}$$

RMS

assumption: **sine-wave**

common in handheld DMM

based on average of rectified signal $\langle|v(t)|\rangle$

$$V_{rms} \stackrel{\text{def}}{=} \frac{\pi}{2\sqrt{2}}\frac{1}{T}\int_0^T |v_{AC}(t)|\,dt$$

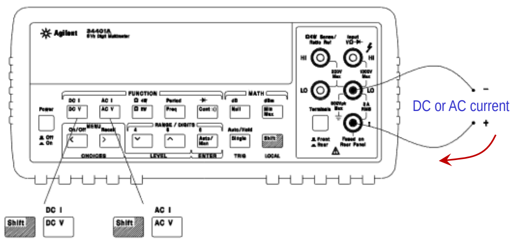
form factor $FF = \dfrac{V_{rms}}{\langle|v(t)|\rangle}$

some DMM measure $\max|v(t)|$ and divide it by the crest factor:
$CF = \max|v(t)|/V_{rms}$

DC or AC Current

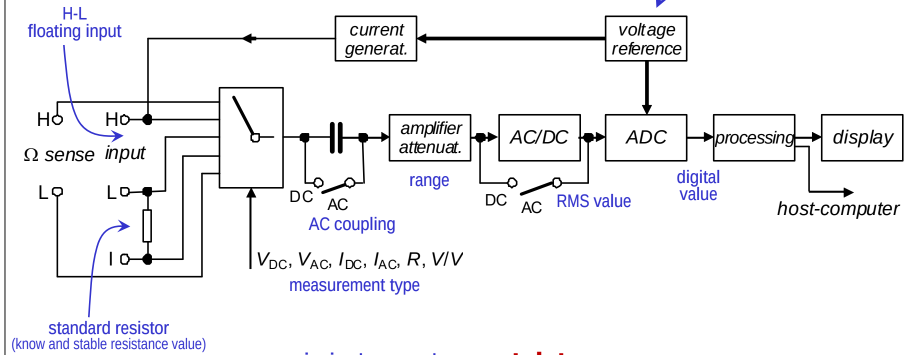
AC current: **ac-coupled**

true RMS or **RMS**



DMM functional blocks

basic measurement: **VDC**



main instrument **uncertainty sources**:

offsets, drifts, nonlinearities in the **analog section**;
wide band noise; interferences;
quantization; ADC nonlinearity; …

DC Instrumental Uncertainty

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$$\Delta_I = k_1|x_M| + k_0 R$$

adopted range

operating conditions $\underline{\boldsymbol{W}}_y$

6½ digit DMM:

relative to calibration

1-hour warm-up

Accuracy Specifications ± (% of reading + % of range) [1]

Function	Range [3]	Test Current or Burden Voltage	24 Hour [2] 23°C ± 1°C	90 Day 23°C ± 5°C	1 Year 23°C ± 5°C	Temperature Coefficient /°C 0°C – 18°C 28°C – 55°C
DC Voltage	100.0000 mV		0.0030 + 0.0030	0.0040 + 0.0035	0.0050 + 0.0035	0.0005 + 0.0005
	1.000000 V		0.0020 + 0.0006	0.0030 + 0.0007	0.0040 + 0.0007	0.0005 + 0.0001
	10.00000 V		0.0015 + 0.0004	0.0020 + 0.0005	0.0035 + 0.0005	0.0005 + 0.0001
	100.0000 V		0.0020 + 0.0006	0.0035 + 0.0006	0.0045 + 0.0006	0.0005 + 0.0001
	1000.000 V		0.0020 + 0.0006	0.0035 + 0.0010	0.0045 + 0.0010	0.0005 + 0.0001

last two digits fully affected by uncertainty

Ex: $x_M = 10.12345$ V, $\Delta_I = 4 \cdot 10^{-4}$ V

$x = 10.1234 \pm 0.0004$ V

Ex: $R = 10$ V, 1 year, 23°C ± 5°C:

$k_1 = 3.5 \cdot 10^{-5}$, $k_0 = 0.5 \cdot 10^{-5}$

$$\Delta_{IT} = \Delta_I + \delta_{IT} \qquad \delta_{IT} = (k_{1T}|x_M| + k_{0T}R)\,\big||T - T_{cal}| - 5°\big|$$

similarly for DC current, but greater values of k_1 and k_0 due to transduction

AC Instrumental Uncertainty

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6½ digit DMM:

$$\Delta_I = k_1|x_M| + k_0 R$$

greater values of k_1 and k_0 due to AC/DC conversion

20% over-range except 750 Vac

relative to calibration

1-hour warm-up slow AC filter sine-wave input

Accuracy Specifications ± (% of reading + % of range) [1]

Function	Range [3]	Frequency	24 Hour [2] 23°C ± 1°C	90 Day 23°C ± 5°C	1 Year 23°C ± 5°C	Temperature Coefficient/°C 0°C – 18°C 28°C – 55°C
True RMS AC Voltage [4]	100.0000 mV	3 Hz – 5 Hz	1.00 + 0.03	1.00 + 0.04	1.00 + 0.04	0.100 + 0.004
		5 Hz – 10 Hz	0.35 + 0.03	0.35 + 0.04	0.35 + 0.04	0.035 + 0.004
		10 Hz – 20 kHz	0.04 + 0.03	0.05 + 0.04	0.06 + 0.04	0.005 + 0.004
		20 kHz – 50 kHz	0.10 + 0.05	0.11 + 0.05	0.12 + 0.05	0.011 + 0.005
		50 kHz – 100 kHz	0.55 + 0.08	0.60 + 0.08	0.60 + 0.08	0.060 + 0.008
		100 kHz – 300 kHz [6]	4.00 + 0.50	4.00 + 0.50	4.00 + 0.50	0.20 + 0.02
	1.000000 V to 750.000 V	3 Hz – 5 Hz	1.00 + 0.02	1.00 + 0.03	1.00 + 0.03	0.100 + 0.003
		5 Hz – 10 Hz	0.35 + 0.02	0.35 + 0.03	0.35 + 0.03	0.035 + 0.003
		10 Hz – 20 kHz	0.04 + 0.02	0.05 + 0.03	0.06 + 0.03	0.005 + 0.003
		20 kHz – 50 kHz	0.10 + 0.04	0.11 + 0.05	0.12 + 0.05	0.011 + 0.005
		50 kHz – 100 kHz [5]	0.55 + 0.08	0.60 + 0.08	0.60 + 0.08	0.060 + 0.008
		100 kHz – 300 kHz [6]	4.00 + 0.50	4.00 + 0.50	4.00 + 0.50	0.20 + 0.02

sine-wave input >5% range

for inputs 1% - 5% of range and < 50 kHz add 0.1%

for 50-100 kHz add .13%

frequency is a further influence factor

Additional Low Frequency Errors (% of reading)

input signal filter used to reduce noise

Frequency	AC Filter Slow	AC Filter Medium	AC Filter Fast
10 Hz – 20 Hz	0	0.74	—
20 Hz – 40 Hz	0	0.22	—
40 Hz – 100 Hz	0	0.06	0.73
100 Hz – 200 Hz	0	0.01	0.22
200 Hz – 1 kHz	0	0	0.18
> 1 kHz	0	0	0

Additional Crest Factor Errors (non-sinewave) [7]

Crest Factor	Error (% of reading)
1 – 2	0.05%
2 – 3	0.15%
3 – 4	0.30%
4 – 5	0.40%

$CF = V_{max}/V_{rms}$

similarly for AC current

further contributions:

if slow filter not used

non-sine-waves

$$\Delta_{IT} = \Delta_I + \delta_{IT} + \delta_{IF} + \delta_{ICF} \qquad \delta_{IF} = k_{1T}|x_M| \quad \delta_{ICF} = k_{1CF}|x_M|$$

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DC VOLTAGE

Normal Mode Noise

Loading Effect

VDC: Normal Mode Noise

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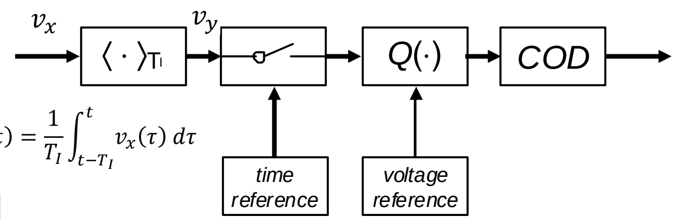
DMM input: $v_x(t) = V_x + v_n(t)$

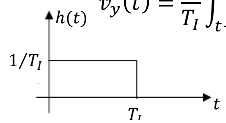
Normal Mode Noise

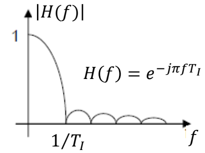
definitional uncertainty

functional blocks of an **integrating ADC**



$$v_y(t) = \frac{1}{T_I}\int_{t-T_I}^{t} v_x(\tau)\, d\tau$$





$$H(f) = e^{-j\pi f T_I}\frac{\sin(\pi f T_I)}{\pi f T_I}$$

$$v_n(t) = A\sin(2\pi f_0 t + \alpha)$$

$$v_y(t) = V_x + A|H(f_0)|\sin(2\pi f_0 t + \alpha + arg[H(f_0)])$$

T_I multiple of 20 ms (16.6 ms in USA) to fully reject power supply noise

VDC: Normal Mode Noise

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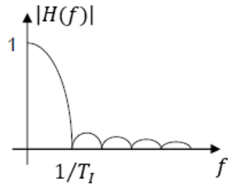

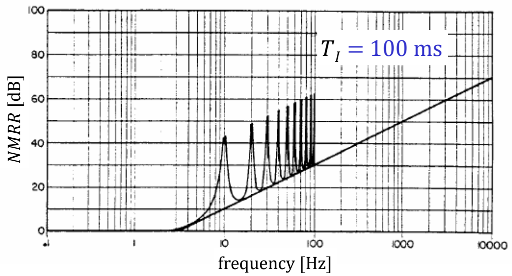

Normal Mode Rejection Ratio $NMRR(f) = -20\,log_{10}|H(f)|$ dB
(due to the integrator)

amplitude of residual **sinewave noise**: $A_n\,10^{-\frac{NMRR(f_n)}{20}}$
(of amplitude A_n and frequency f_n)

variance of the average of N **repeated measurements**: $\frac{1}{N}\left(\frac{A_n}{\sqrt{2}}\,10^{-\frac{NMRR(f_n)}{20}}\right)^2$
(due to sine-wave noise of amplitude A_n and frequency f_n)

VDC: Normal Mode Noise

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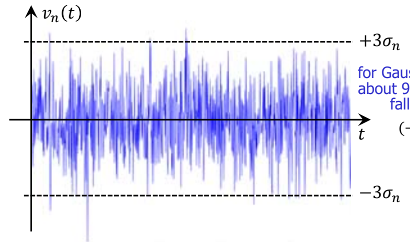
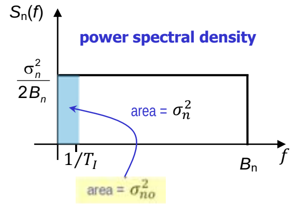
wide band noise: input white noise with bandwidth B_n and power σ_n^2:





$$\sigma_{no}^2 = \int_{-\infty}^{+\infty} S_{no}(f)df = \int_{-\infty}^{+\infty} S_n(f)\cdot|H(f)|^2 df = \int_{-B_n}^{+B_n} \frac{\sigma_n^2}{2B_n}\cdot|H(f)|^2 df = \frac{\sigma_n^2}{2B_n}\cdot\int_{-B_n}^{+B_n}|H(f)|^2 df$$

$B_n \gg {}^1/_{T_I}$

$$\int_{-B_n}^{+B_n}|H(f)|^2 df \cong \int_{-\infty}^{+\infty}|H(f)|^2 df = \int_{-\infty}^{+\infty} h^2(t)dt = \int_0^{T_I}\left(\frac{1}{T_I}\right)^2 dt = \frac{1}{T_i}$$

$$\boxed{\sigma_{no}^2 = \frac{\sigma_n^2}{2B_n}\cdot\frac{1}{T_i}}$$

VDC: Loading effect

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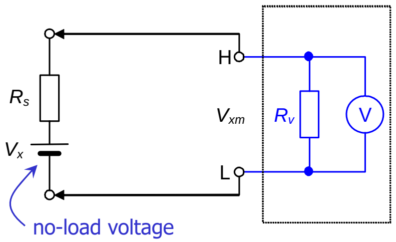
modeling source and DMM input as linear circuits:

sometimes linear model accuracy does not suffice

$$V_{xm} = V_x\frac{R_v}{R_s + R_v}$$



relative deviation on measured voltage:
relative interaction uncertainty

$$\gamma_x = \frac{\delta V_x}{V_x} = \frac{V_{xm} - V_x}{V_x} = -\frac{R_s}{R_s + R_v}$$

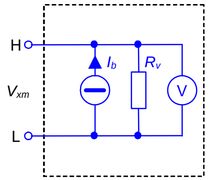
no-load voltage

negligible if $R_s \ll R_v$

more accurate models for instrument input could consider:

- bias current due to input electronic circuits
- thermoelectric voltages at the contacts, …

the related **effects** are **negligible** in most practical cases



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AC VOLTAGE

Normal Mode Noise

Loading Effect

VAC: Normal Mode Noise

NMN with **frequency** in the **band of the AC/DC block** is converted in DC voltage

NMN is not rejected by the integrator

contributes to the measured rms voltage like the input signal

measured RMS voltage:

$$V_{y,rms} = \sqrt{V_{x,rms}^2 + \sum_k V_{n_k,rms}^2 + \sigma_{n,wb}^2}$$

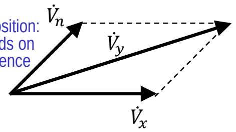
measurand

NMN spectral lines

NMN wideband component

if **signal and noise** are at the **same frequency**:

vector composition: value depends on phase difference



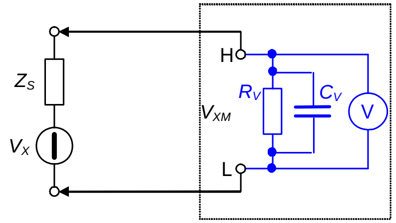
$$V_{x,rms} - V_{n,rms} \le V_{y,rms} \le V_{x,rms} + V_{n,rms}$$

VAC: Loading effect

modeling source and DMM input as linear circuits:

sometimes linear model accuracy does not suffice

$$V_{xm} = V_x \frac{Z_v}{Z_s + Z_v}$$



relative deviation on measured voltage:

relative interaction uncertainty

$$\gamma_x = \frac{\delta V_x}{V_x} = \frac{V_{xm} - V_x}{V_x} = -\frac{Z_s}{Z_s + Z_v}$$

negligible if $|Z_S| \ll |Z_V|$

DC or AC VOLTAGE

Common Mode Noise

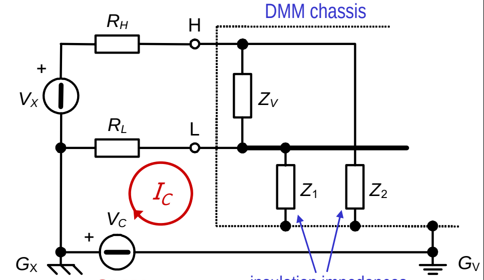
VDC or VAC: CMN

linear superposition principle:

$$V_{HL} = V_{HL}^N + V_{HL}^C$$

if $|Z_1| \gg R_L$, $|Z_2| \gg R_H$,
$|Z_V| \gg R_L + R_H$, $|Z_2| \gg |Z_1|$

$$V_{HL}^N \cong \left(1 - \frac{R_H}{Z_2}\right)\left(1 - \frac{R_L + R_H}{Z_V}\right) V_X \cong V_X$$



CMN
due to ground leakage currents, variable magnetic fields, …

insulation impedances

$$V_{HL}^C \cong \frac{R_L}{Z_1} V_C$$

$$|Z_1| = \frac{R_1}{\sqrt{1 + \omega^2 C_1^2 R_1^2}}$$

voltage drop through R_L due to the current generated by CMN

VDC or VAC: CMN

DMM data sheets provide the min. value for:

Common Mode Rejection Ratio $CMRR = 20\log_{10}\dfrac{|V_C|}{|V_{HL}^C|_{R_L=1\text{k}\Omega}}$ dB

$V_{HL}^C \cong \dfrac{R_L}{Z_1}V_C$

$|Z_1| = \dfrac{R_1}{\sqrt{1+\omega^2C_1^2R_1^2}}$

$$CMRR \cong 20\ \log_{10}|Z_1|_{\text{k}\Omega} = 20\ \log_{10}\frac{R_1|_{\text{k}\Omega}}{\sqrt{1+(\omega R_1C_1)^2}}$$

CMN attenuation for a given R_L value:

$$20\log_{10}\frac{|E_C|}{|V_{HL}^C|} \cong 20\log_{10}\frac{|Z_1|}{R_L}\bigg|_{\text{k}\Omega} = CMRR - 20\log_{10}R_L|_{\text{k}\Omega}$$

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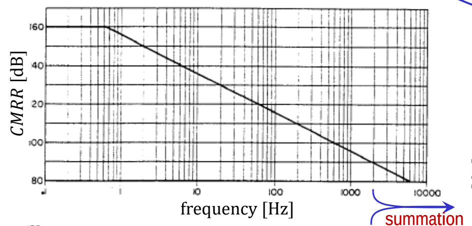
VDC: CMN and NMN

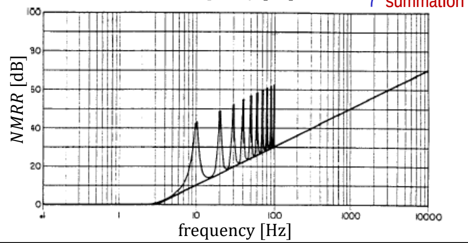
V_{HL}^C is a NMN, so that it is reduced by the $NMRR$ in **DC measurement**

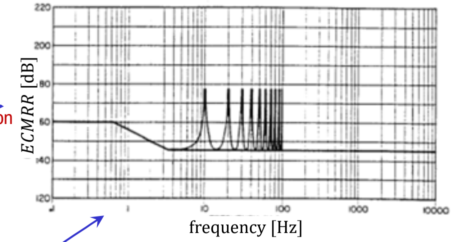
Effective CMRR $ECMRR(f) = NMRR(f) + CMRR(f)$ dB

total rejection



summation





effective attenuation of the CMN in VDC measurement

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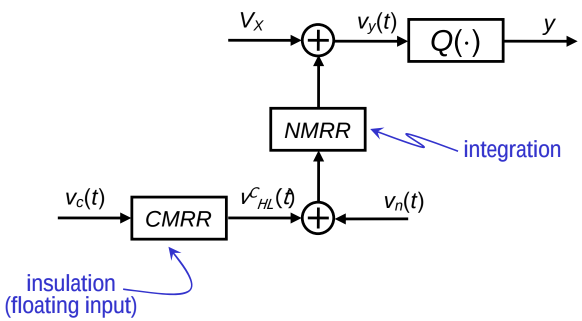
VDC: CMN and NMN

combined effect of **NMN and CMN** in **VDC** measurements:

$$V_y(f) = V_x\delta(f) + \frac{V_N(f)}{NMRR(f)} + \frac{V_C(f)}{NMRR(f)\,CMRR(f)}\frac{R_L}{1\,\text{k}\Omega}$$



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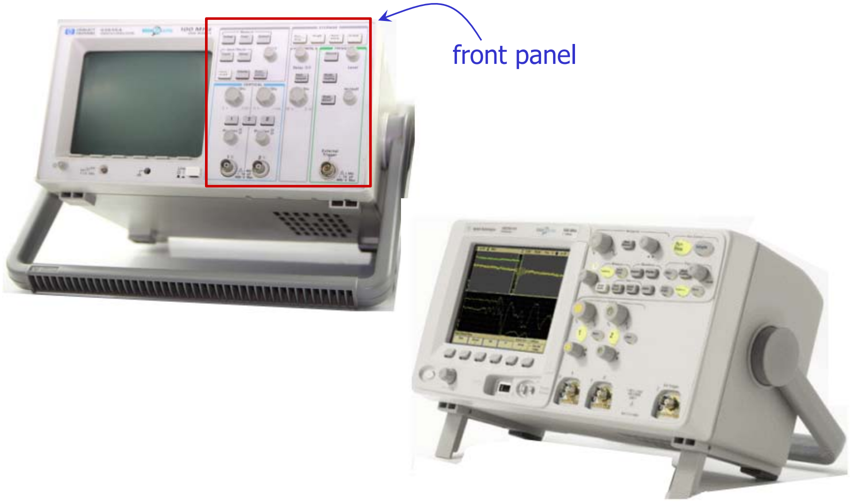
DIGITAL OSCILLOSCOPES

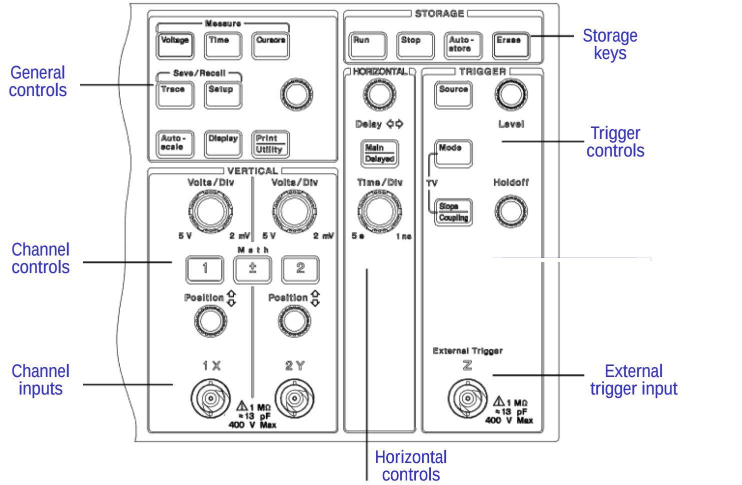
Digital Oscilloscope (DSO)

DSO is mainly aimed at displaying the time behavior of voltage signals

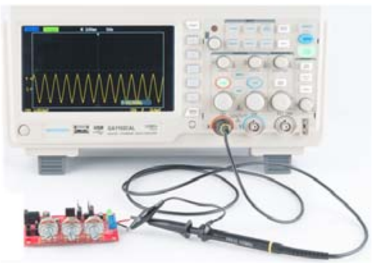


Digital Oscilloscope

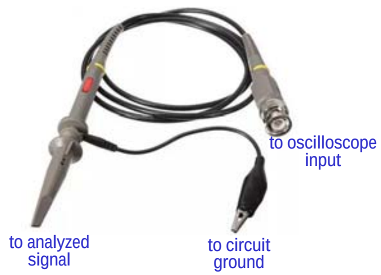
front panel controls



Connection to the circuit



passive probe



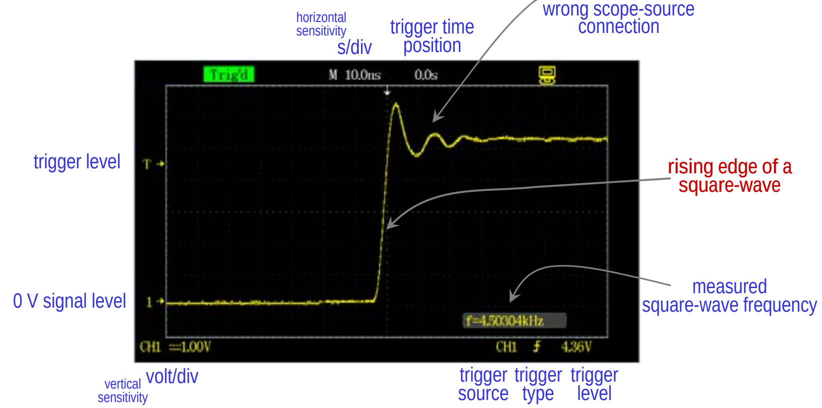
coaxial cable

only for very low frequencies
because of input signal distortion

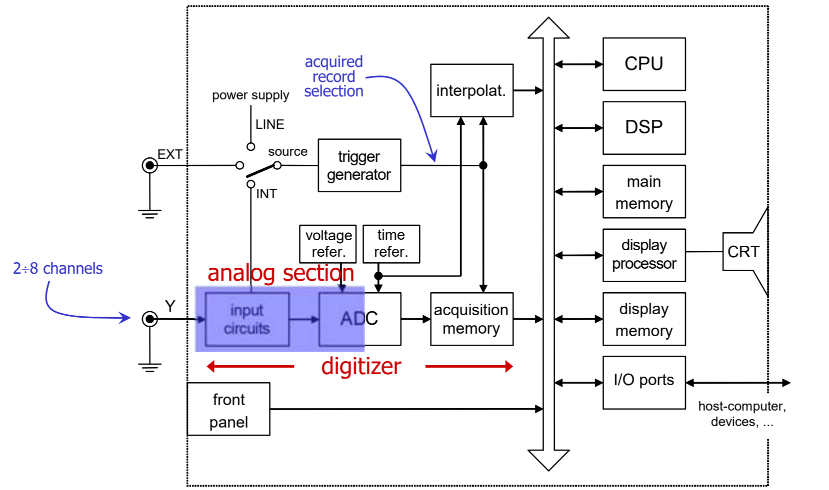
Oscilloscope screen

division:
one square of the screen

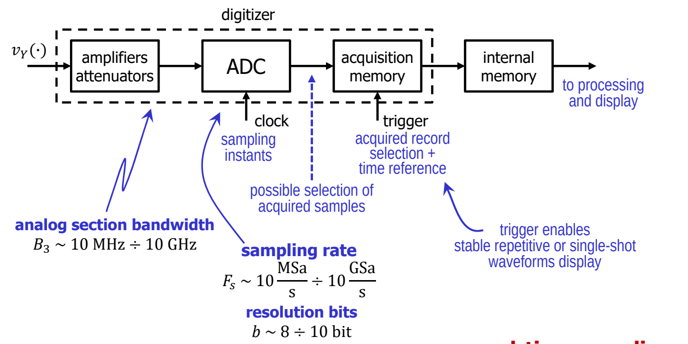
8 vertical divisions
10 horizontal divisions



Functional blocks



Scope digitizer



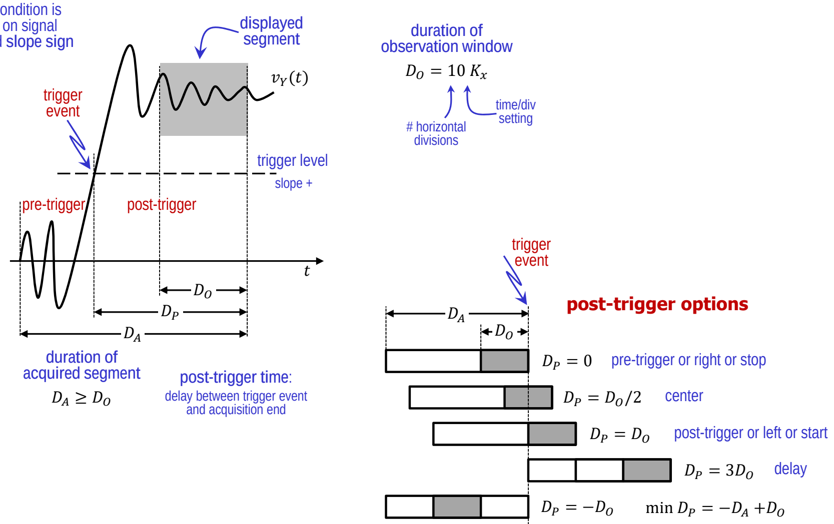
real-time sampling

some scopes uses also
equivalent-time sampling:
it is not analyzed here

Displayed segment selection

trigger event can be
defined in different ways

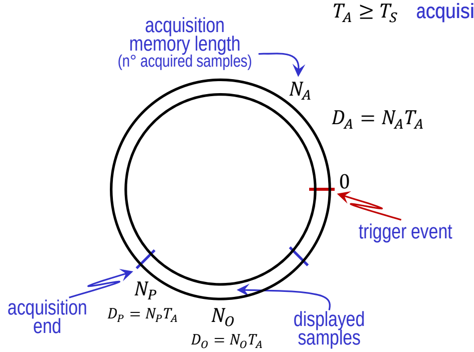
basic condition is
based on signal
level and slope sign



Waveform acquisition

$F_S = \frac{1}{T_S}$ sampling rate $\quad F_A = \frac{1}{T_A}$ acquisition rate

$T_A \geq T_S$ acquisition time



FIFO logic:
the first stored is
the first removed

acquisition starts with
circular **buffer empty**;
stream of samples is stored

when the buffer is **full**,
a subsequent sample is
overwritten to the oldest sample

trigger generation is **enabled**

when **trigger event** occurs
acquisition is stopped
after N_P samples

Waveform acquisition

length of displayed segment: $D_O = 10\,K_x$ **set by the operator**

$D_A \geq D_O$ acquired window must include displayed window

if **all samples** provided by the ADC are **stored**:

$T_A = T_S = 1/F_S$

$D_A = N_A T_A = N_A T_S$ **max D_O allowed**

Ex.: $N_A = 10\ \text{MSa},\ F_S = 1\ \text{GSa/s}$

$\max D_O = N_A/F_S = 10\ \text{ms}$

long segment

if selected $D_D > N_A T_S$,
due to **finite memory length**,
samples provided by the ADC are automatically **decimated** by the scope

instrument automatically set: $D_A = D_O$

$F_A = \dfrac{N_A}{D_V}$

memory limited mode (F_A limited by N_A)

decimation factor: $M_A = \dfrac{F_S}{F_A}$

Waveform acquisition

short segment

if selected $D_O < N_A T_S$

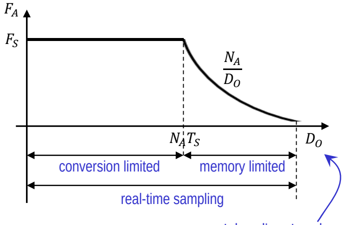
$F_A = F_S$ **conversion limited** mode (F_A limited by F_S)

$D_A = K_A D_O \quad K_A > 1$

acquired segment is longer than the displayed one

negative post-trigger D_P can be selected

n° of observed samples: $N_O = \dfrac{D_O}{F_S}$



takes discrete values according to sequence 1,2,5

if $D_O \ll N_A T_S$
only few samples are observed

location of samples on the screen requires to **measure the delay** between **trigger and sampling instants**

trigger ad sampling instants are asynchronous: delay takes values on $[0, T_S)$ with uniform distribution

temporal resolution T_S does not assure accurate sample location

measurement performed by a circuit called **interpolator**

further samples need to be calculated by **interpolation**

interpolation requires at least **few tens** of acquired samples fall in the observation window

min n° of samples depends on complexity of adopted interpolation

for shorter observation window, some scopes adopt the **equivalent-time sampling**

STATIC ACCURACY
and
TIME ACCURACY

Vertical static accuracy

voltage measurement

instrument **static vertical uncertainty sources**:

offsets, drifts, nonlinearities of analog section;
wide band noise in analog section;
interferences (trigger generator, other channels, power supply);
quantization; ADC nonlinearity and jitter; …

adopted range

$$\Delta_{YS} = k_1 |v_M| + k_0 R$$

or simply $$\Delta_{YS} = k_0 R$$

typical values
1-3%

Horizontal accuracy

time measurement

instrument **horizontal uncertainty sources**:

resolution, clock uncertainties (drift, phase noise, …),
trigger uncertainty, time-interpolator uncertainty, …

measured time interval — displayed time window length

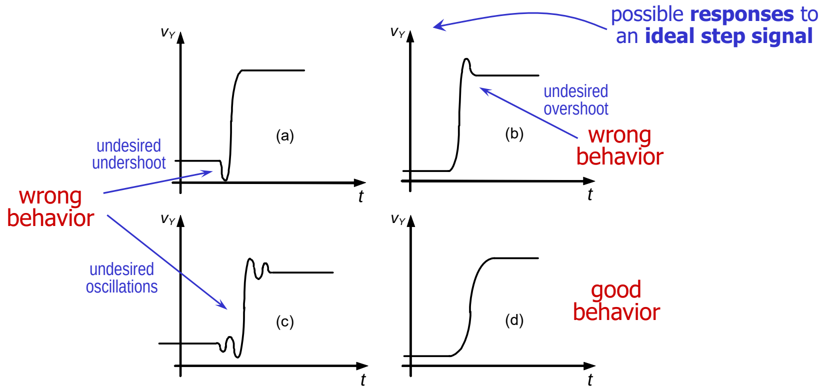
$$\Delta_T = k_1 T_M + k_0 W$$

or similar formulas reported in the user manual

DYNAMIC ACCURACY:
analog section and connection

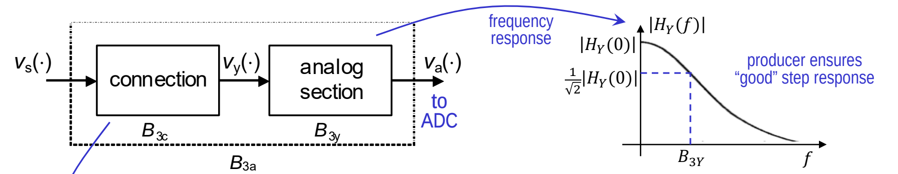
Linear distortion

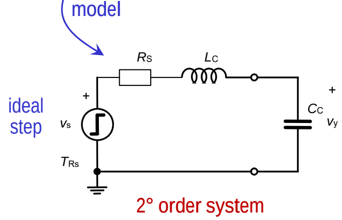
the frequency response of the **analog section** and **connection** may cause waveform distortion



wrong behaviors might
mask relevant features of the input signal

Frequency domain





$$f_0 = \frac{1}{2\pi\sqrt{L_C C_C}}$$ natural frequency

$$D = \frac{R_S}{2}\sqrt{\frac{C_C}{L_C}}$$ damping factor — no ripple if $D > 0.7$

$$B_{3C} = f_0\sqrt{\sqrt{(2D^2-1)^2+1} - (2D^2-1)^2}$$

if L_C is negligible:
1° order system

$$B_{3C} = \frac{1}{2\pi R_S C_C}$$

max signal distortion < static uncertainty (~1÷3%) if:

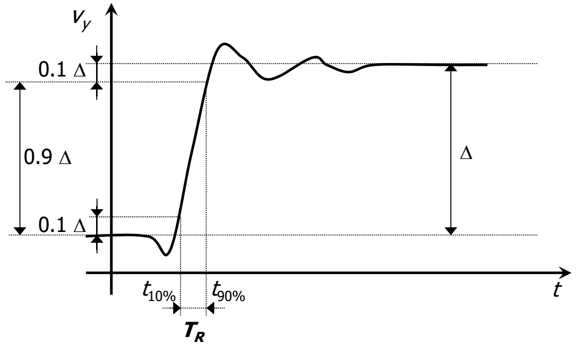
max input signal frequency

$B_s < (0.1 \div 0.2) B_{3C}$ and $B_s < (0.1 \div 0.2) B_{3Y}$

Time domain

waveform rise-time T_R:
time required for a step signal to change from a specified low value to a specified high value

typically, from **10%** to **90%** of step height



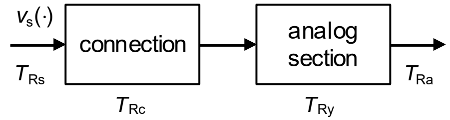
if the system step response has **no significant over/under-shoots**:
(independently of the frequency response shape)

$$T_R B_3 \cong 0.35$$

Time domain

if the **input step** and the **step responses** of **connection** and **analog section** has no significant over/undershoots, for most step shapes:

$$T_{Rs} < T_{Ra} < \sqrt{T_{Rs}^2 + T_{Rc}^2 + T_{Ry}^2}$$



$$T_{Ra}\sqrt{1-\frac{T_{Rc}^2+T_{Ry}^2}{T_{Ra}^2}} < T_{Rs} < T_{Ra}$$

Taylor series of (1-x)½

relative uncertainty of rise time measurement:

$$\Gamma_{T_{Ra}} \cong \frac{1}{4}\left(\frac{T_{Rc}^2+T_{Ry}^2}{T_{Ra}^2}\right)$$

smaller than static uncertainty (~1÷3%) if:

$$T_{Rs} > (3 \div 5)\sqrt{T_{Rc}^2+T_{Ry}^2}$$

DYNAMIC ACCURACY:

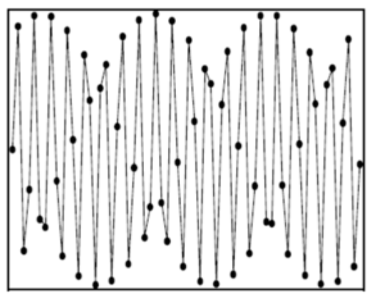
digital section

Frequency domain

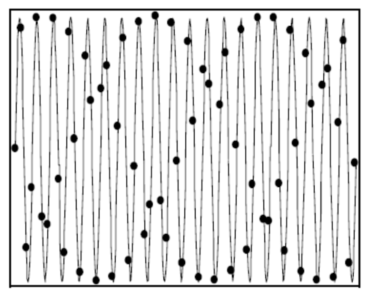
waveform distortion due to **sampling** and **interpolation**

sinewave wrongly displayed as triangular wave due to sampling and linear interpolation

amplitude modulation ?



amplitude modulation is an artifact due to sampling and linear interpolation



Frequency domain

distortion due to sampling and interpolation is **negligible** if
max input frequency < oscilloscope **Useful Storage Bandwidth**

$$USB = \frac{F_S}{SPP_{\min}}$$

sampling rate

theoretical $SPP_{min} = 2$ (Shannon th.)

min n° of **Sample-Per-Period** of an input sinewave at the **max allowed frequency**

linear interpolation:
using segments $SPP_{min} \approx 10$

nonlinear interpolation:
exploiting Shannon th. $SPP_{min} \approx 2.5 - 4$

max input frequency:
for which dynamic uncertainty is lower than static uncertainty

connection | vertical channel | sampling interpolation

$$B_{s,\max} = \min\left\{ \frac{B_{3c}}{5 \div 10}, \frac{B_{3y}}{5 \div 10}, USB \right\}$$

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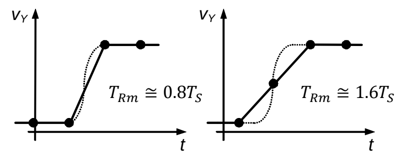
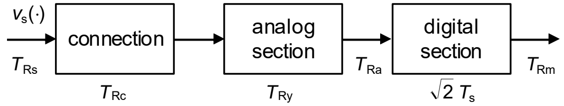
Time domain

Effect of sampling and interpolation
on **rise-time measurement**:

Ex.: step fully evolved exactly in 1 sampling period

sampling and signal are asynchronous





for **linear interpolation**: $T_{Rm} > (3 \div 5)\sqrt{T_{Rc}^2 + T_{Ry}^2 + 2T_s^2}$

constraint assuring that max error due to sampling and interpolation is of the order of few %

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PASSIVE PROBES

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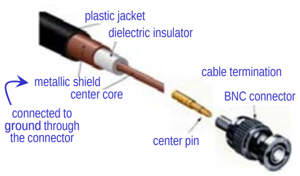
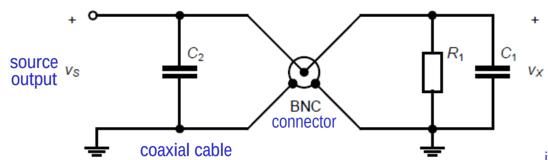
Source - Instrument connection





instrument input
$R_1 \sim 1\ \mathrm{M\Omega}$
$C_1 \sim 10 - 100\ \mathrm{pF}$

it depends on the channel, but not on the range

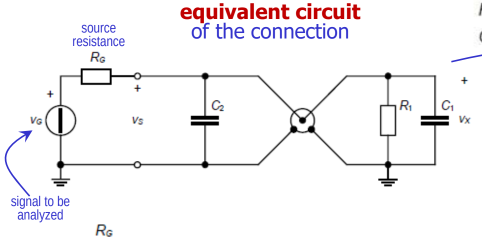
coaxial cable
not couple of conductors to avoid noise induced by coupled magnetic fields

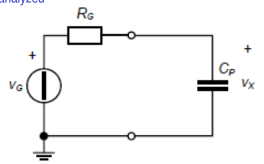
$C_2 \sim 0.5 - 1\ \mathrm{pF/cm}$
R_2 negligible
L_2 assumed negligible

further small and nonlinear inductive and capacitive components produce effects at high frequencies (above 100 MHz)

Source - Instrument connection

equivalent circuit of the connection





$R_P = R_I \,//\, R_G$

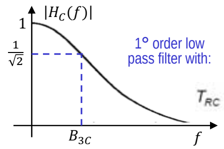
$C_P = C_I + C_2$

voltage divider — DC loading effect — 1° order low pass filter

$$V_x = V_G \frac{R_I}{R_I + R_G} \frac{1}{1 + j\omega R_P C_P}$$

often: $R_I \gg R_G$

$$V_X \cong V_G \frac{1}{1 + j\omega R_G C_P}$$



1° order low pass filter with: $B_{3C} = \dfrac{1}{2\pi R_G C_P}$

$T_{RC} = (\ln 9) R_G C_P \cong 2.2\, R_G C_P$

Ex:

$C_P = 50$ pF (~50 cm cable) $\to B_{3s} < 200$ kHz

$R_G = 1\ \text{k}\Omega \qquad B_{3C} = 3.2$ MHz $\quad T_{RC} \cong 110$ ns

$R_G = 10\ \Omega \qquad B_{3C} = 320$ MHz $\quad T_{RC} \cong 1.1$ ns

signal distortion if: $B_s > (0.1 \div 0.2) B_{3C}$

Source - Instrument connection

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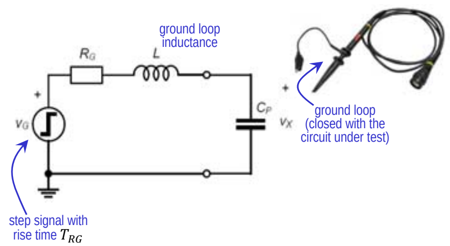
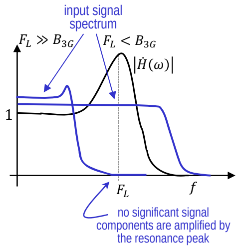


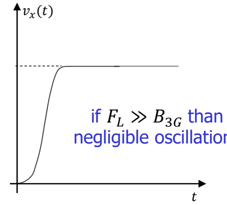
increased connection gain

series resonance at frequency:

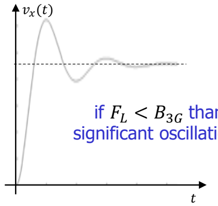
$$F_L = \frac{1}{2\pi\sqrt{LC_P}}$$



$$B_{3G} \cong \frac{0.35}{T_{RG}}$$



if $F_L \gg B_{3G}$ than negligible oscillations



if $F_L < B_{3G}$ than significant oscillations

Ex: ground loop $\varnothing = 5\text{-}10$ cm: $L \approx 100$ nH
50 cm cable $C_P \approx 50$ pF
$F_L \approx 70$ MHz

oscillations introduced by the connection are negligible if $T_{RG} \cong 0.35/B_{3G} \gg 0.35/F_L = 5$ ns

Compensated probe

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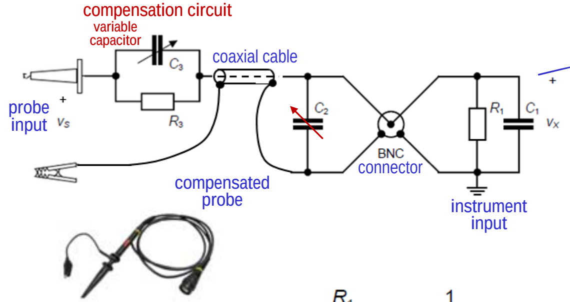
simplified circuit: many small spurious capacitive, resistive and inductive effects are neglected



$C_P = C_I + C_2$

voltage divider

$$V_X = \frac{\dfrac{R_I}{1 + j\omega R_I C_P}}{\dfrac{R_I}{1 + j\omega R_I C_P} + \dfrac{R_3}{1 + j\omega R_3 C_3}} V_S$$

compensation condition: $R_3 C_3 = R_I C_P$

$$V_X = \frac{R_I}{R_I + R_3} V_S = \frac{1}{\alpha} V_S$$

flat response

no distortion due to low pass filtering

fastest edges of input signal are reproduced faithfully

$\alpha > 1$ attenuation factor

satisfied using a **variable capacitor** C_3 or C_2

most probes have only one adjustment

very often: $R_3 = 9\,R_I$ $\quad C_3 = C_P/9 \qquad \alpha = 10$

probes for some more sophisticated scopes have **two types of compensation**:

- **low-frequency** (the one described here)
- **high-frequency** (which reduces the effect of spurious components and nonlinearities)

Source - Instrument connection

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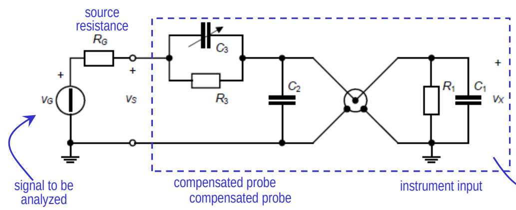
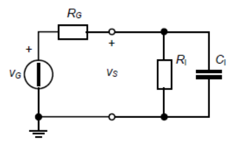
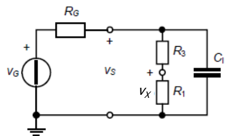


compensation condition fulfilled



$$R_l = R_I + R_3 = \alpha R_I$$

$$C_l = \frac{C_3 C_P}{C_3 + C_P} = \frac{1}{\alpha} C_P$$



$R_G \ll R_l$

$$V_X = \frac{R_I}{R_l + R_G} \frac{1}{1 + j\omega (R_G \| R_l) C_l} V_G \cong \frac{1}{\alpha} \frac{1}{1 + j\omega \dfrac{R_G C_P}{\alpha}} V_G$$

attenuated by α

B_{3C} increased by α

T_{3C} decreased by α

C_P/α

F_L increased by $\sqrt{\alpha}$

Probe compensation

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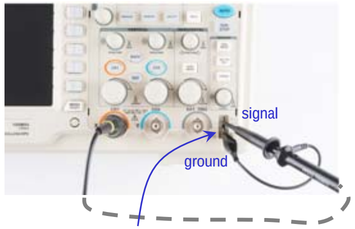
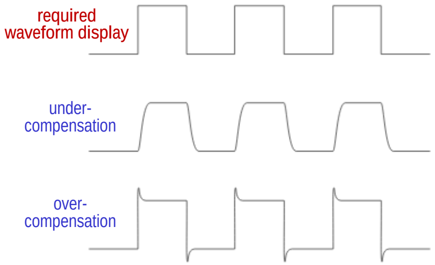


compensation performed by using a built-in **1 kHz square-wave** generator of the scope

square-wave amplitude is of the order of 1 V
(it is attenuated by a factor 10)



adjust probe capacitance until a square waveform is displayed

adjustment should be done:

- each time the scope or the scope input are changed
- from time to time, even the input is not changed

if probe is not compensated, displayed signals may exhibit **artifacts** due to wrong probe frequency response

probe capacitance is adjusted by rotating a recessed **screw head**

probe may include a **X1/X10 switch** in the **X1 position**:

- compensation capacitor is short-circuited
- resistive and capacitive load increase significantly