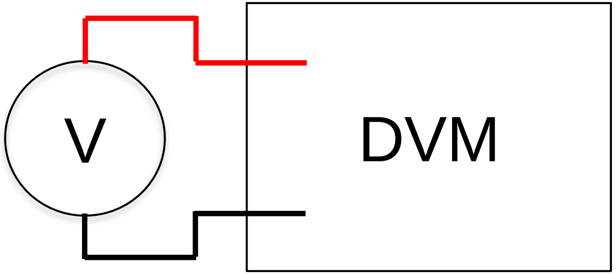
Voltage references, Voltage standards and Josephson Voltage standards

High performance digitizer and DC metrology meeting

Luis Palafox
FB 2.6 Electrical Quantum metrology

Motivation

From https://www.elso.sk/sk/uvodna-stranka/wavetek-datron-1271-1281-multimeter-3018.html



In reality, the measurement is relative to the voltage reference inside the DVM

Motivation

ADC specifications do not include the performance of the voltage reference used

Digitizer or Digital Voltmeter specifications **MUST include it!**

Content

- Introduction to the Allan deviation
- Voltage references & Voltage standards
- Josephson Voltage Standards (JVS)
    - Programmable Josephon Voltage Standards (PJVS)

Introduction to the Allan deviation

Metrologia 11, 133—138 (1975)

An Accuracy Algorithm for an Atomic Time Scale

D. W. Allan, H. Hellwig, and D. J. Glaze

Frequency and Time Standards Section, National Bureau of Standards, Boulder, Colorado, U.S.A.

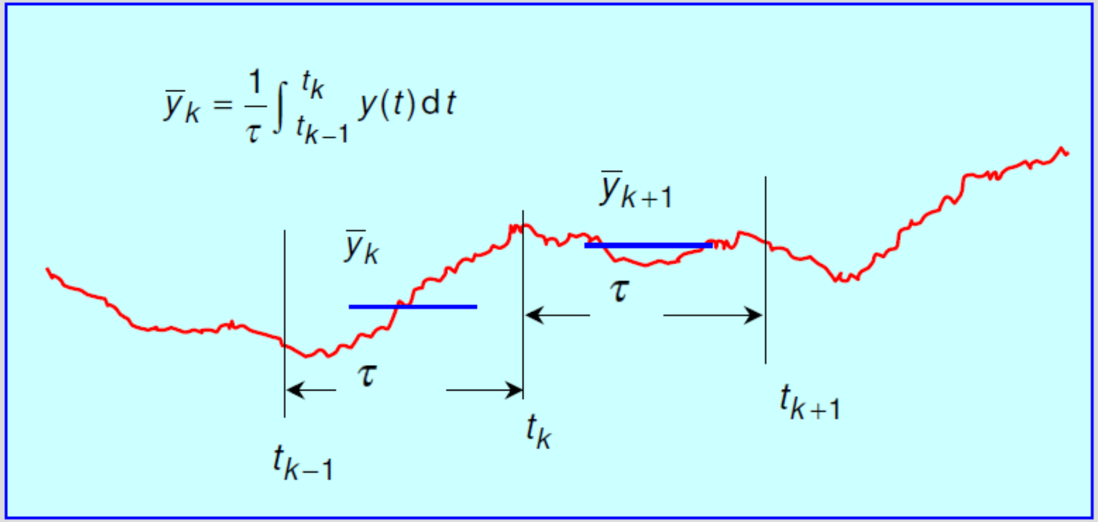
Received: February 11, 1975

NBS is now NIST

Introduction to the Allan deviation

Introduced to electrical metrology by Tom Witt (BIPM) from 2000

Introdu



Define Allan variance:

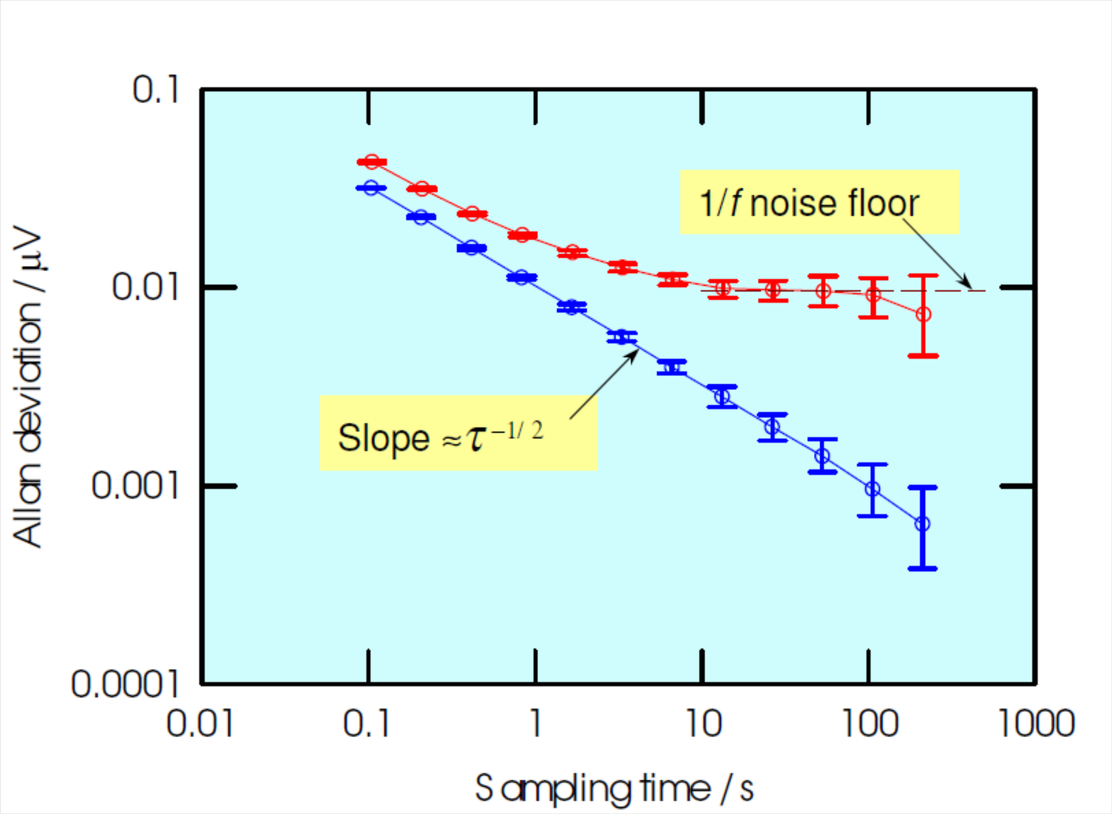
$$\sigma_y^2(\tau) = \left\langle \frac{1}{2}(\bar{y}_{k+1} - \bar{y}_k)^2 \right\rangle$$

Calculate Allan variance:

$$\hat{\sigma}_y^2(\tau) = \frac{1}{2p}\sum_{k=1}^{p}[\bar{y}_{k+1}(\tau) - \bar{y}_k(\tau)]^2$$

Introduc

Allan deviations as functions of sampling times for comparison of 2 Zeners at 1.018 V (red) and equivalent source resistance, 2 kΩ, (blue)



EM DC & QM expt 16 Jun03

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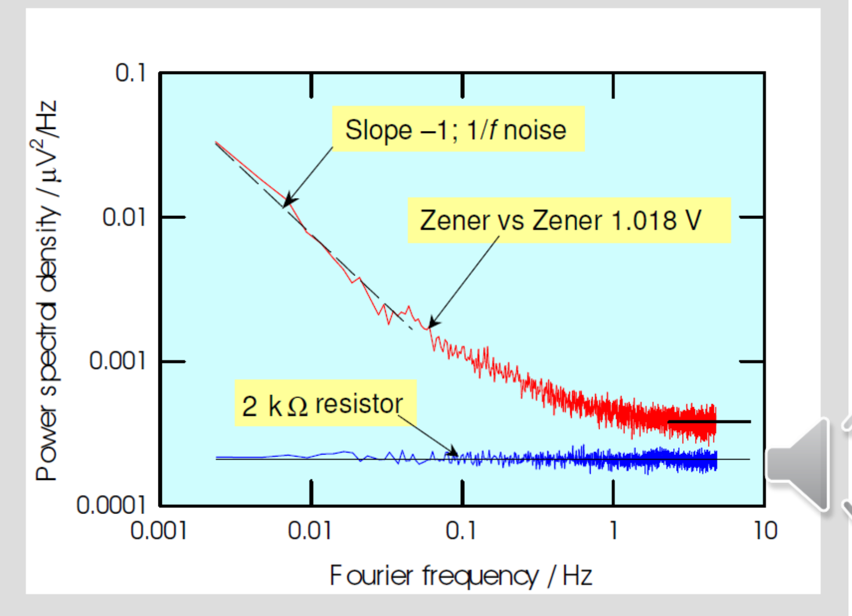
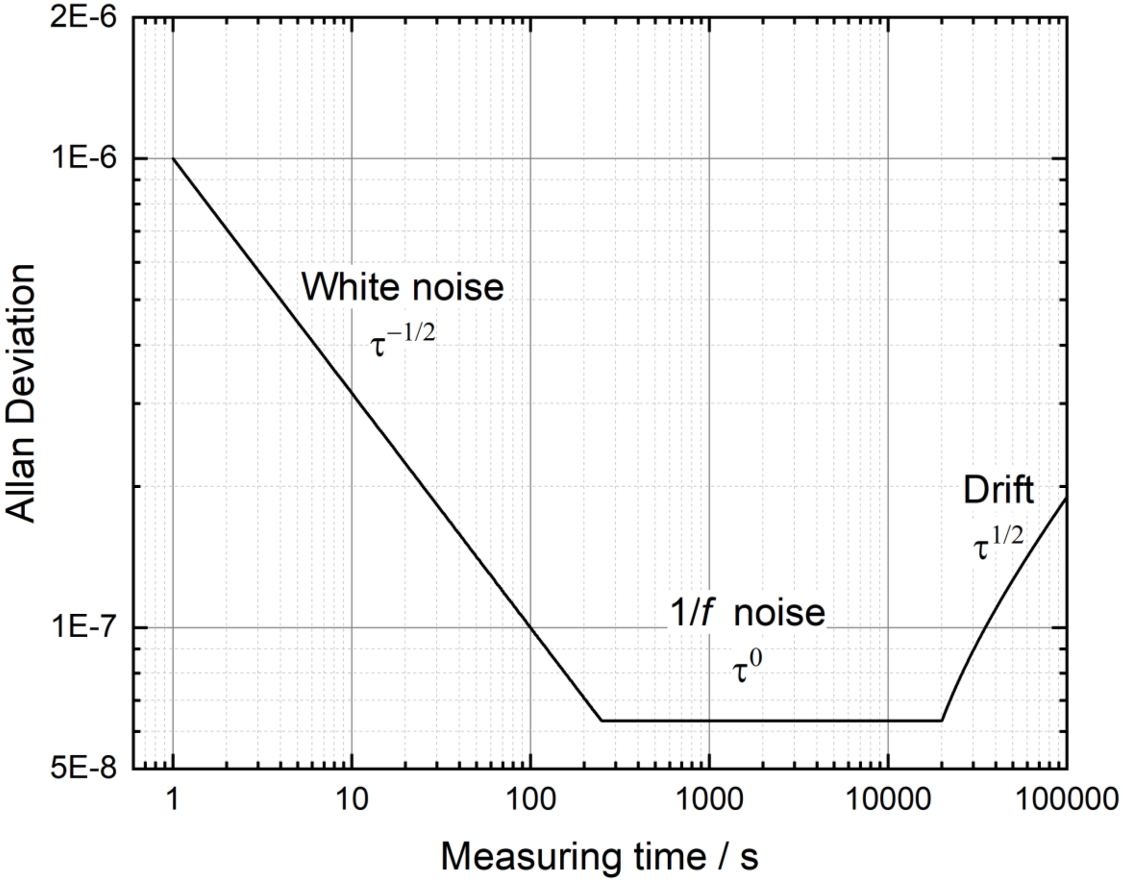
Introduction to the Allan deviation

The same information is available in the power spectral density, but you have to know the bandwidth of your measurement system to calculate the uncertainty of your measurement.

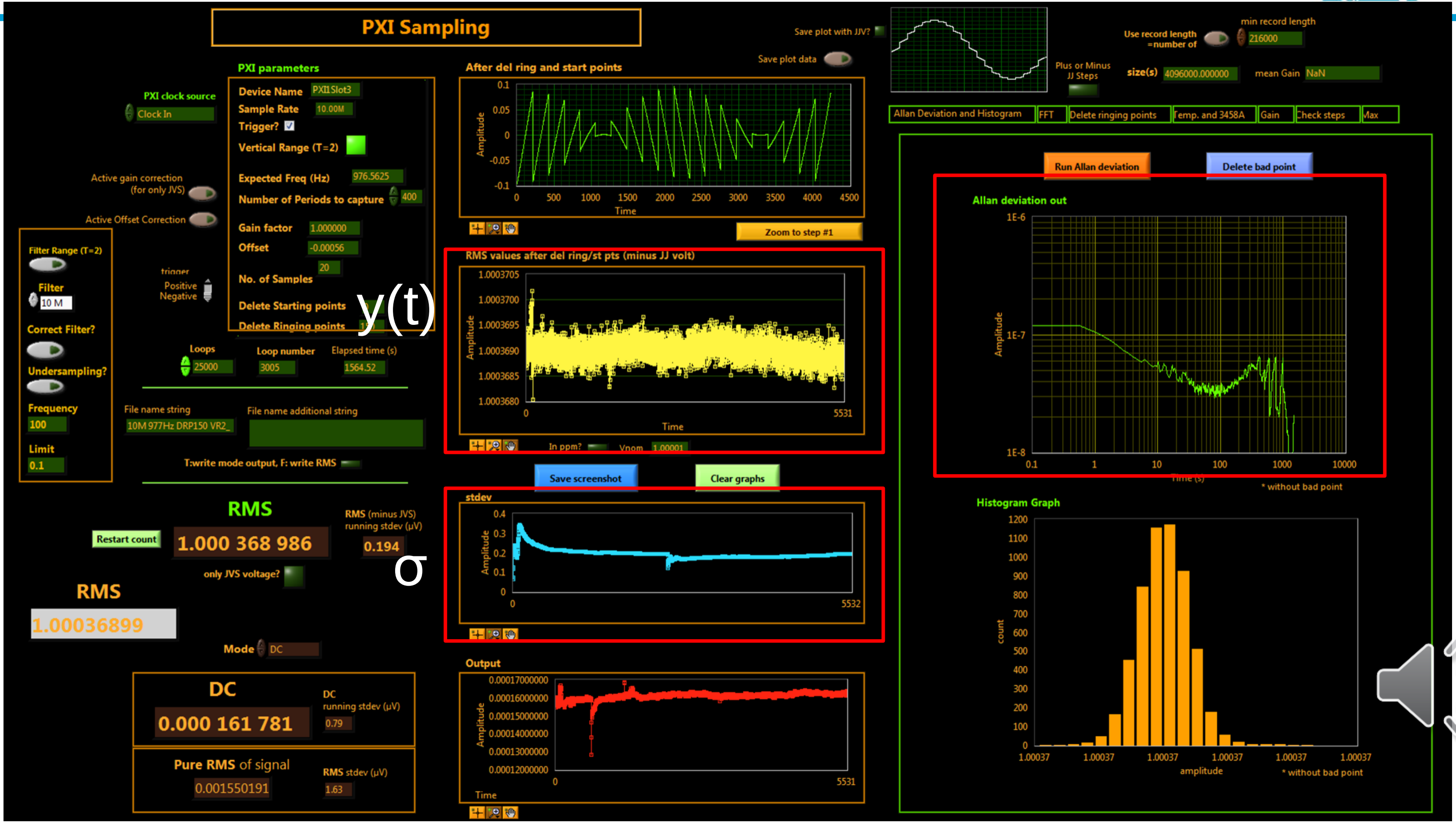


Introduction to the Allan deviation



Introduction to the Allan deviation

Introduction to the Allan deviation



Introduction to the Allan deviation

$$\frac{\sigma}{\sqrt{n}} = 3\ \text{nV}\ \text{, but}$$

Allan dev ≈ 30 nV

Introduction to the Allan deviation

Advantages:

- Directly type A uncertainty of measurement (*k* = 1)
- Prevents “too good” estimate
- Lets you choose optimum measurement time
- Identifies white, 1/*f* noise and drift visually
- also random walk noise (not usual in electronics)

Disadvantage:

- Needs a measurement at least 2x long

Voltage references & Voltage standards

A Voltage reference can be:

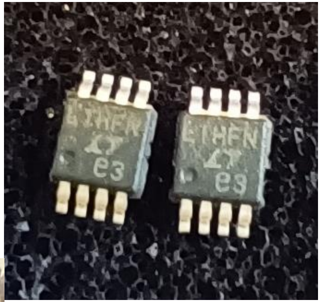
A battery (poor performance)

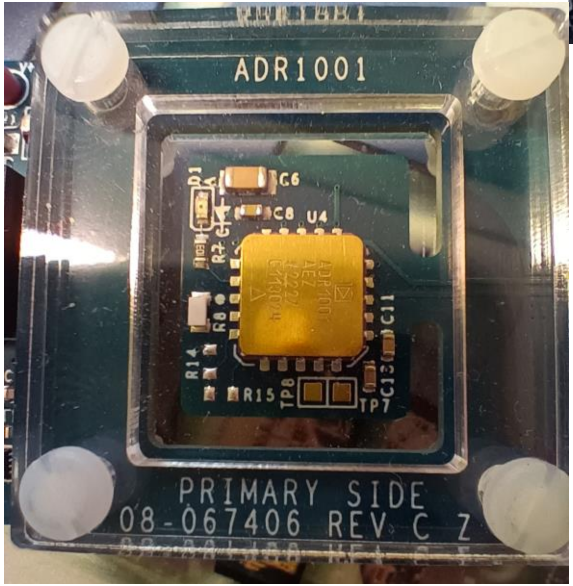
Zener diode

IC based on:

- Zener diode
- Bandgap reference

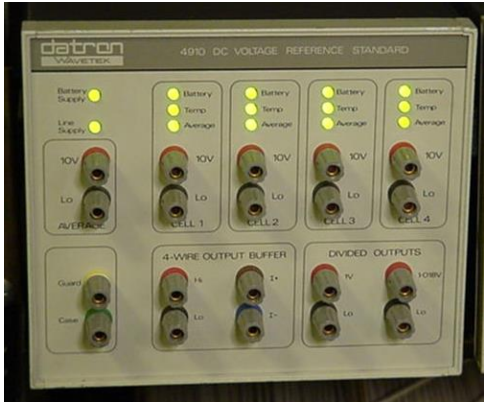
Part of an IC





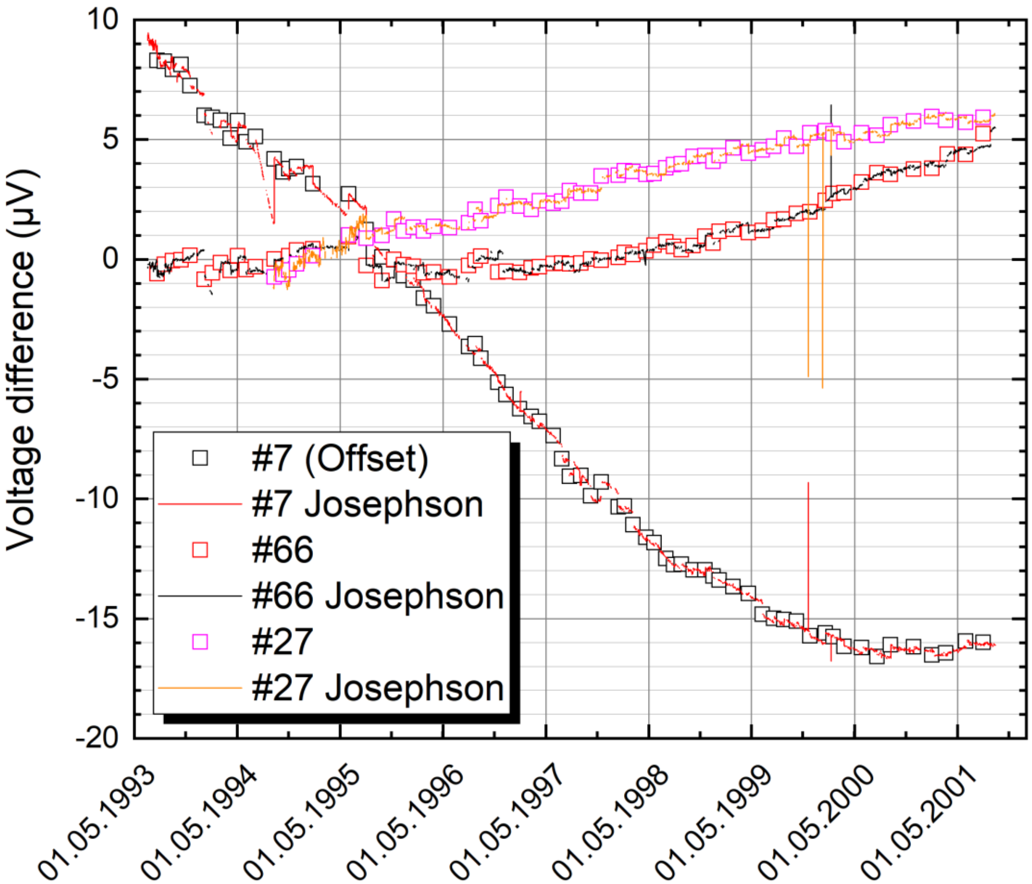
Voltage references & Voltage standards

A Voltage standard is an instrument that includes a voltage reference and typically an oven and scaling amplifier

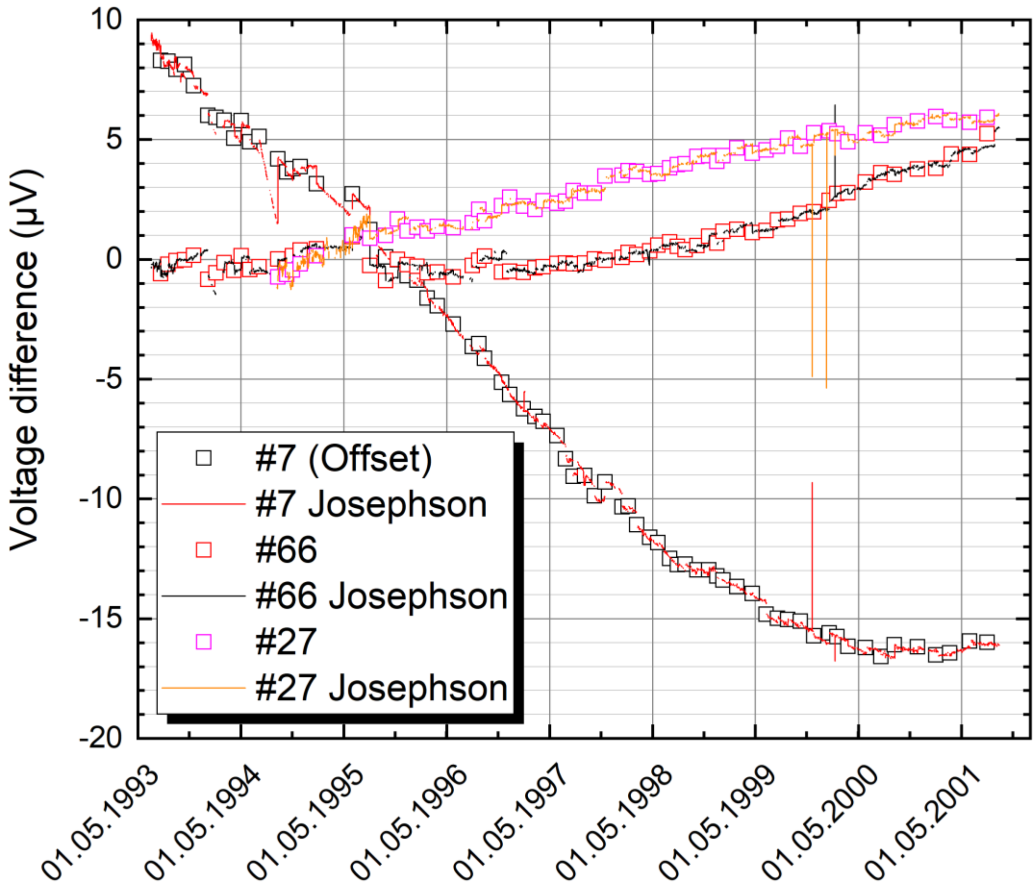


Images from https://us.flukecal.com/products/electrical-calibration/electrical-standards/732c-734c-dc-voltage-reference-standards
http://lionelectroniclabs.com/fluke-datron-4910-dc-voltage-reference-standard/
http://friedrich-messtechnik.de/index.php/messtechnik/dc-standards
https://mintl.com/products/8110a-10-volt-reference/

Voltage references & Voltage standards



Voltage references & Voltage standards

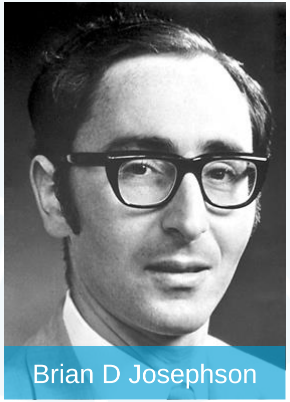


To reduce the influence of the voltmeter

Images from https://upload.wikimedia.org/wikipedia/commons/4/4b/Balanced_scale_of_Justice_%28blue%29.svg

Josephson Voltage Standard

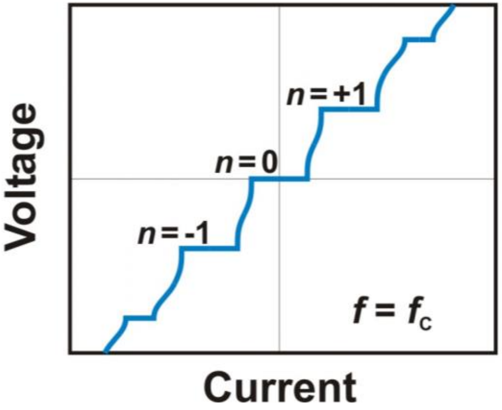
- Predicted 1962, observed 1963
- Based on natural constants



Bildquelle: http://www.nobelprize.org

$$U(f,n) = n \cdot f \cdot \frac{h}{2e} = n \cdot \frac{f}{K_J}$$

But $\frac{h}{2e} = 2\,\frac{\mu V}{GHz}$



So, for 10 V using 70 GHz, we need 69 632 Josephson Junctions (JJ)

Josephson Voltage Standard

Based on a quantum effect, so independent from materials in the JJ, time, temperature, pressure, ...

Josephson Voltage Standard

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See: J. Clarke, *Phys. Rev. Let*. 21, 23, Dec 1968

junctions. In addition, the variation of the following parameters, although generally affecting the shape of the current-voltage characteristic and the amplitude of the steps, did not give rise to any observable difference in the voltage across the junctions: (i) temperature, from 1.2°K to 2.2°K; (ii) the thickness of the barrier; (iii) the level of the applied rf power, over a factor of 5; (iv) the rf frequency, from 100 kHz to 1 MHz (to 1 part in 10^7 at 100 kHz); (v) the order of the steps on which both junctions were biased, up to the fourth order; (vi) the position on the induced step; (vii) the ambient magnetic field, up to ±1 G; (viii) the direction of the bias current through the junctions.

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PTB

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Josephson Voltage Standard

To further dispel doubts, see A.K. Jain et al., Test for Relativistic Gravitational Effects on Charged Particles, *Phys. Rev. Let.*, Vol. 58, No. 12, March 1987

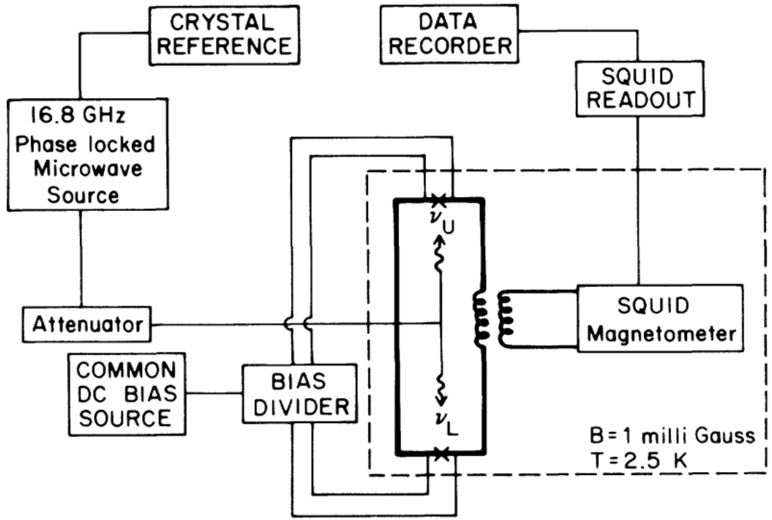

FIG. 1. Schematic of the measurement circuit. The crosses denote the Josephson batteries. The darker lines indicate superconducting portions of the circuit.

Josephson Voltage Standard

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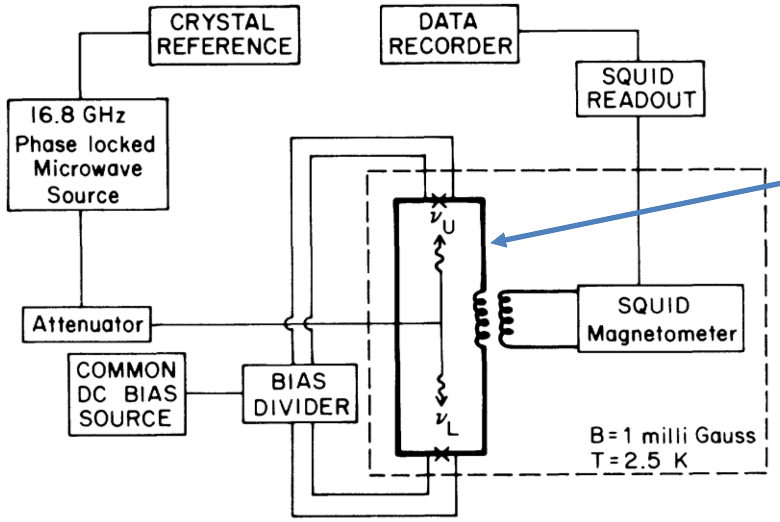

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EMF @loop < 1 x 10^{-22} V

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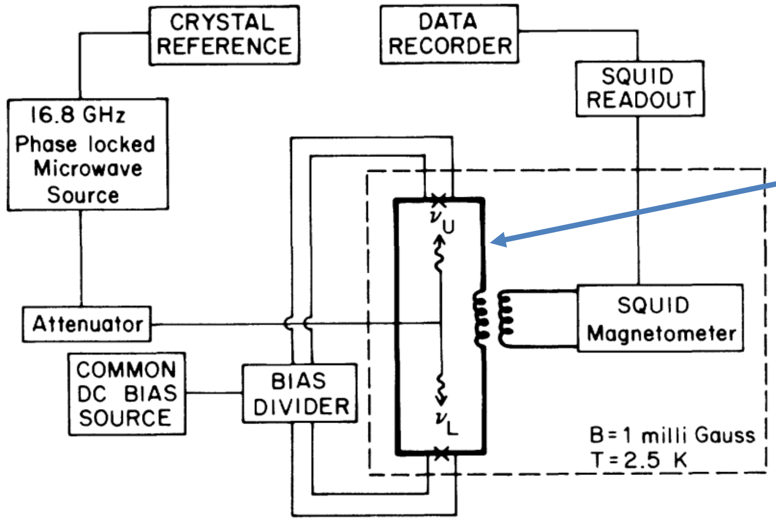


FIG. 1. Schematic of the measurement circuit. The crosses denote the Josephson batteries. The darker lines indicate superconducting portions of the circuit.

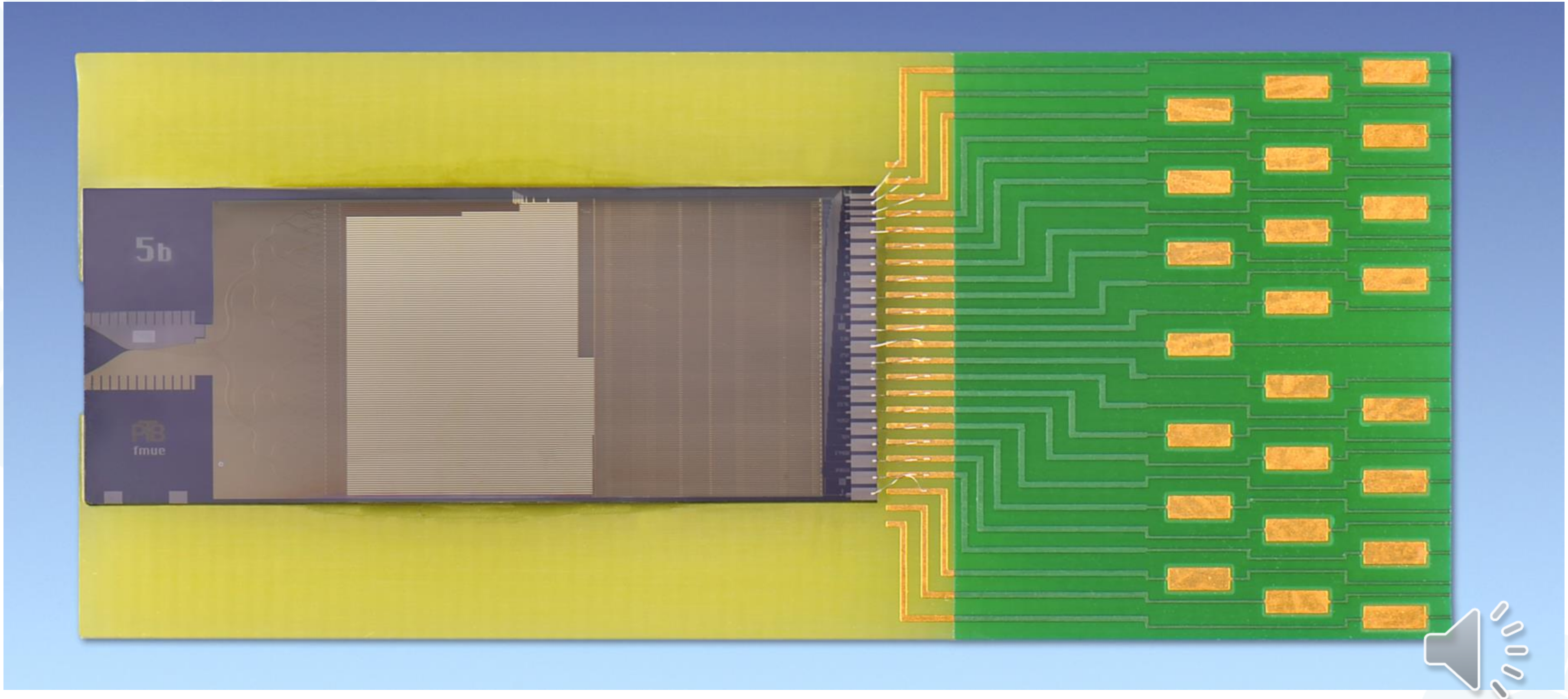
EMF @loop < 1×10^{-22} V

7.2 cm

Red shift of electrons

$\Delta V = 2.35 \times 10^{-21}$ V

Josephson Voltage Standard



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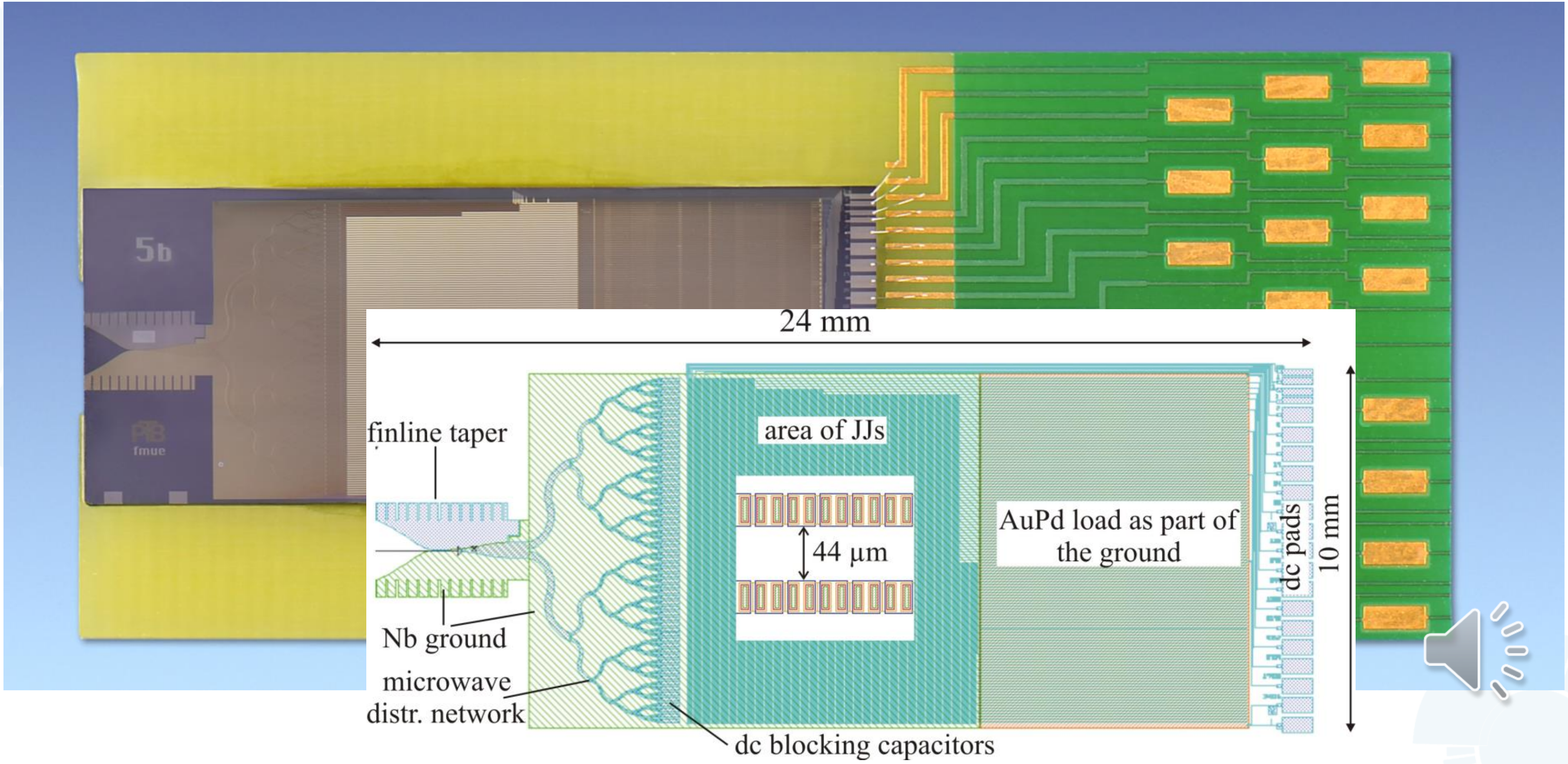

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Uses superconductors, so needs low temperatures

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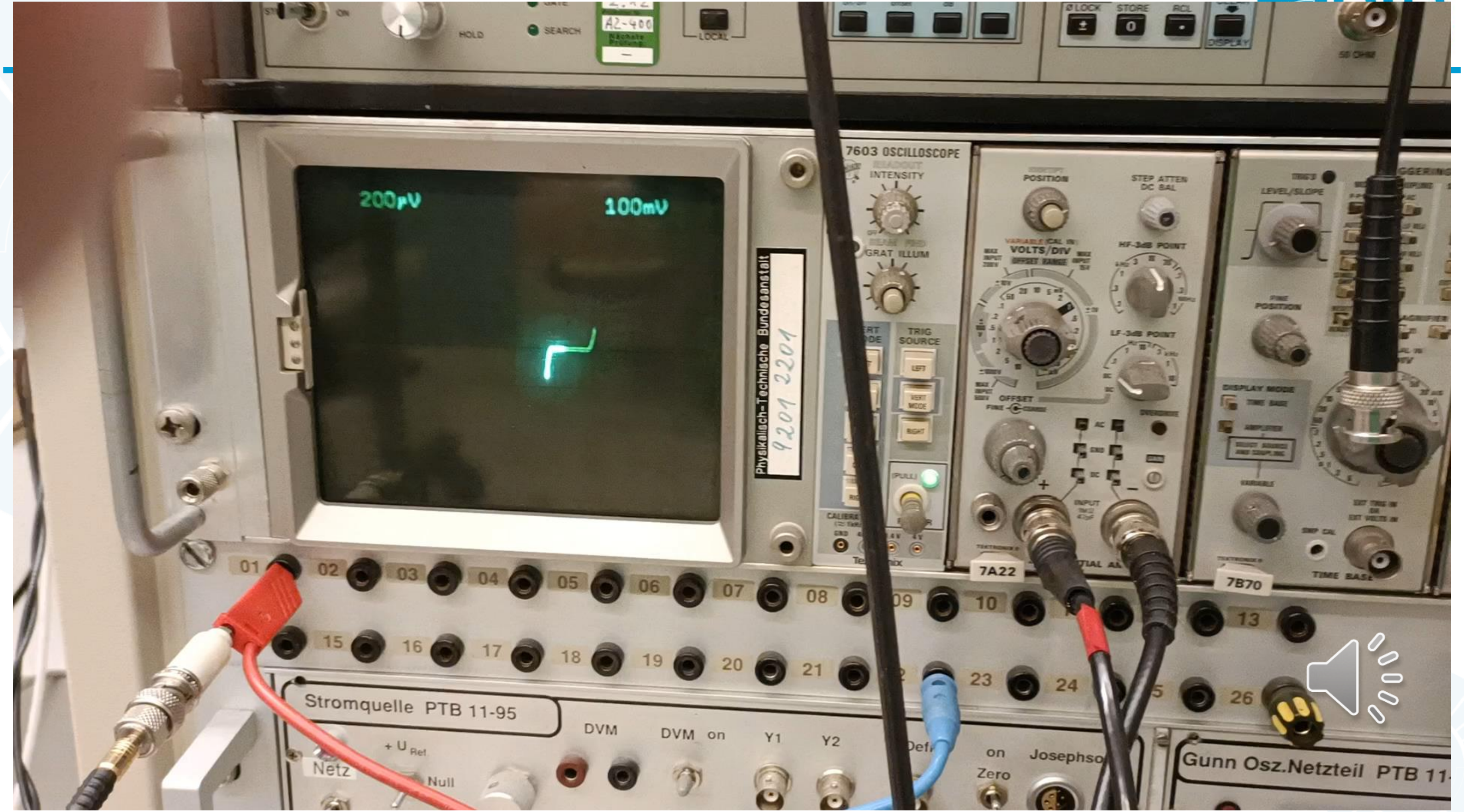
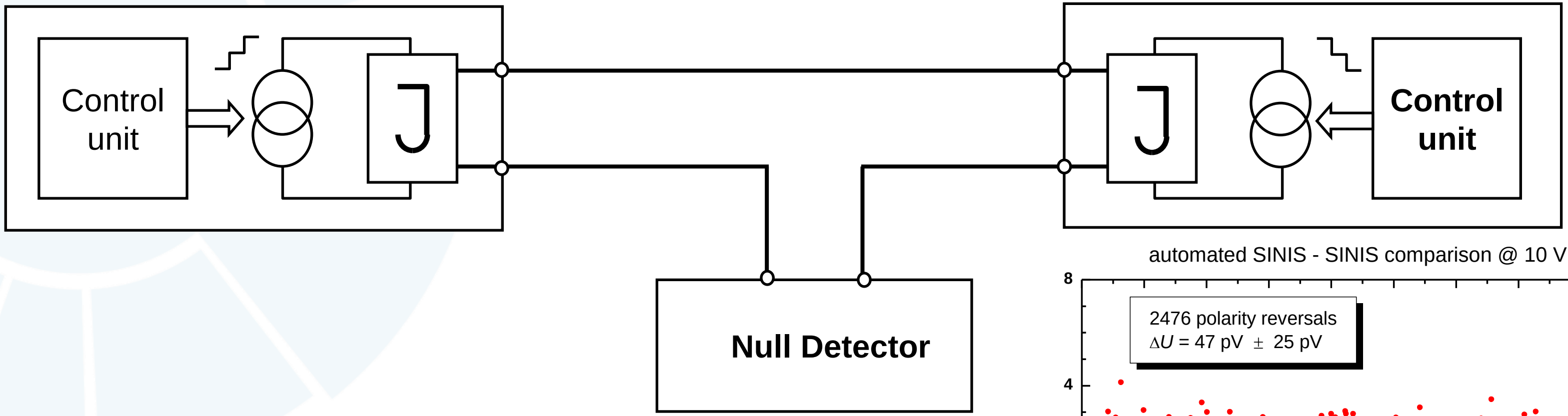
Uses superconductors, so needs low temperatures

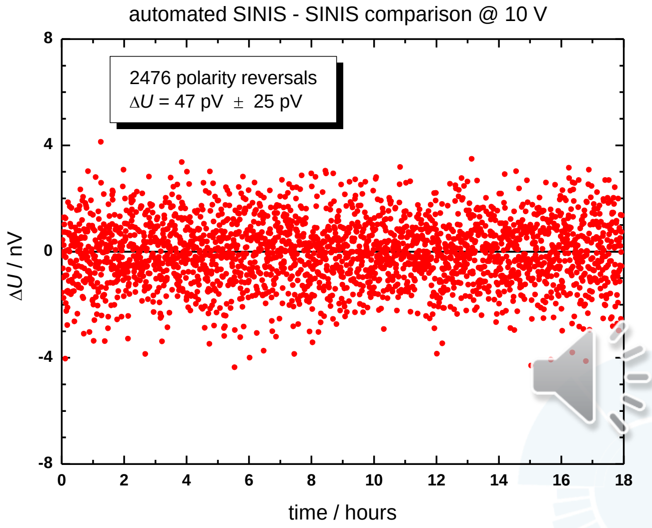
- So far needs 4.2 K or 10 K


200µV
100mV
7603 OSCILLOSCOPE
INTENSITY
GRAT ILLUM
TRIG SOURCE
LEFT
RIGHT
Physikalisch-Technische Bundesanstalt
9201 2201
VOLTS/DIV
POSITION
STEP ATTEN DC BAL
HF-3dB POINT
LF-3dB POINT
OFFSET
7A22
7B70
TIME BASE
DISPLAY MODE
LEVEL/SLOPE
FINE POSITION
Stromquelle PTB 11-95
DVM
DVM on
Y1
Y2
Netz
+ U Ref
Null
on
Zero
Gunn Osz.Netzteil PTB 11-
LOCAL
HOLD
SEARCH
STORE
RCL
DISPLAY
50 OHM

Josephson Voltage Standard

Compared instead of calibrated





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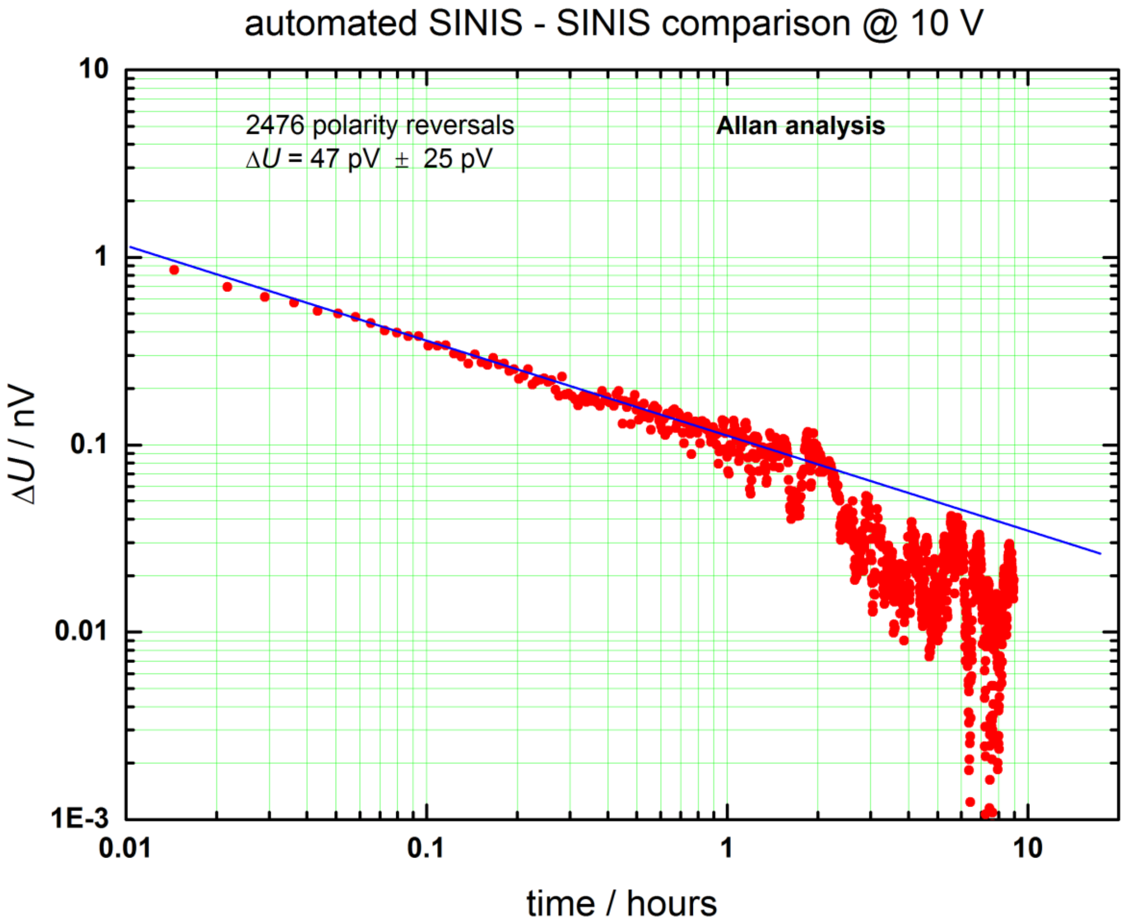

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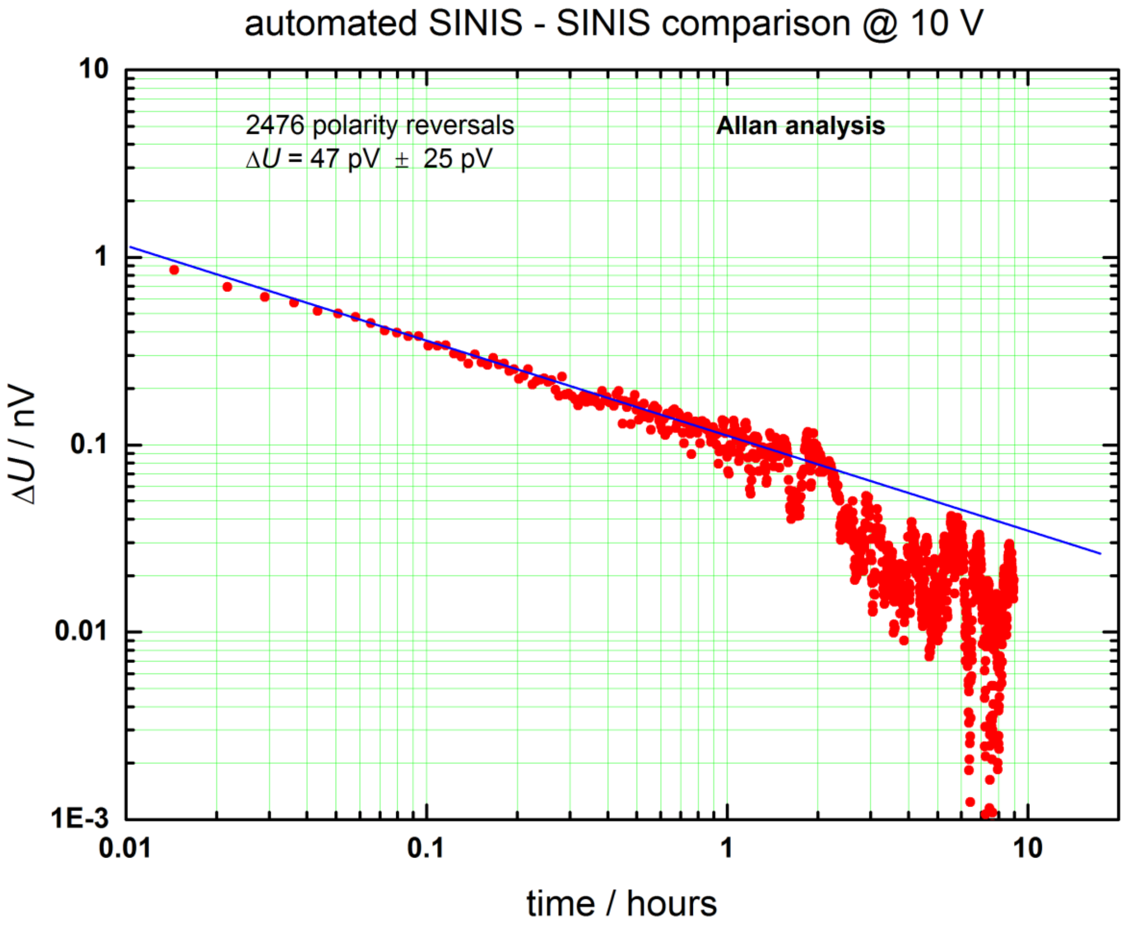
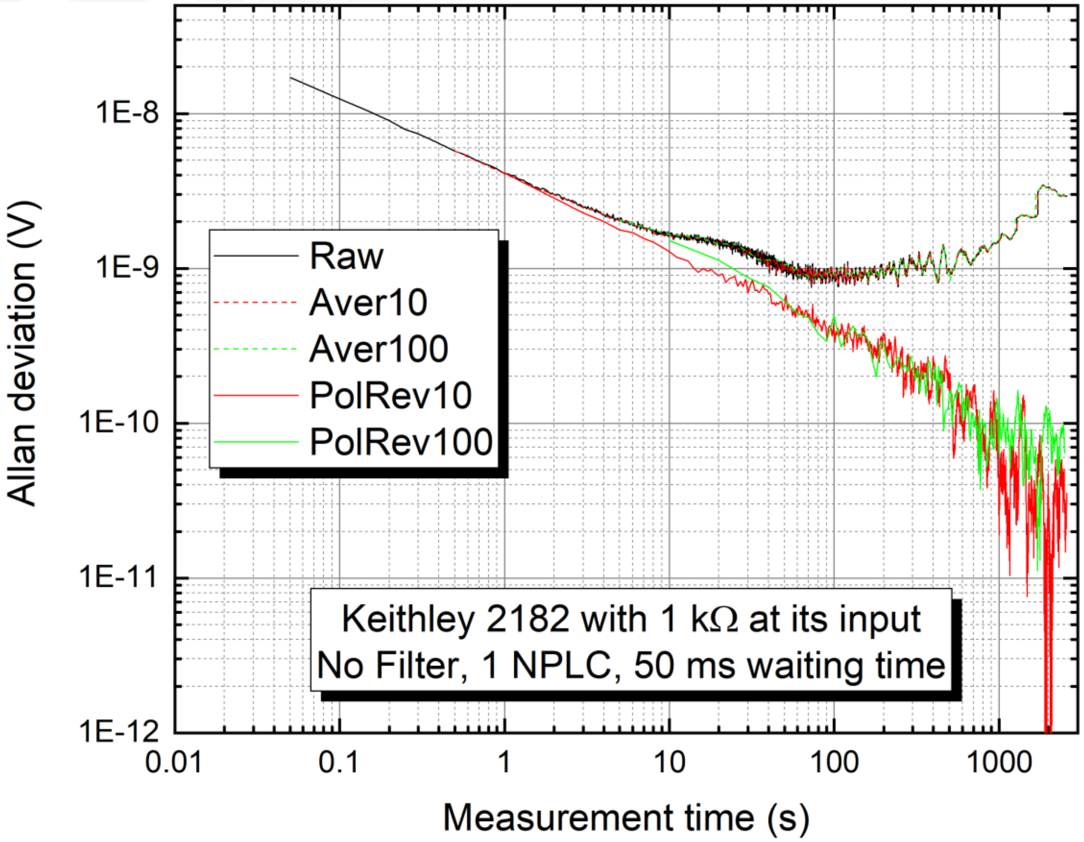
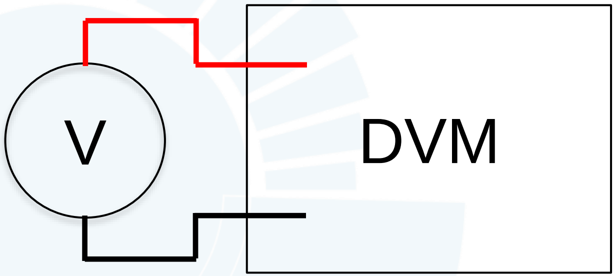


Noise of
Null Detector
removed!

Why do we prefer polarity reversals in metrology?



Voltage measurements



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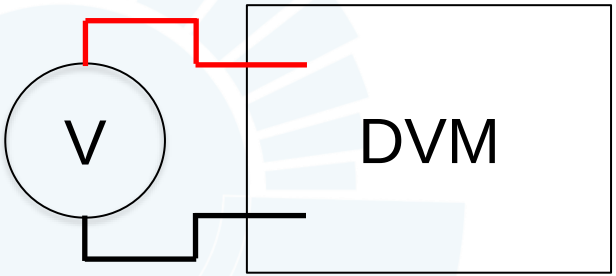
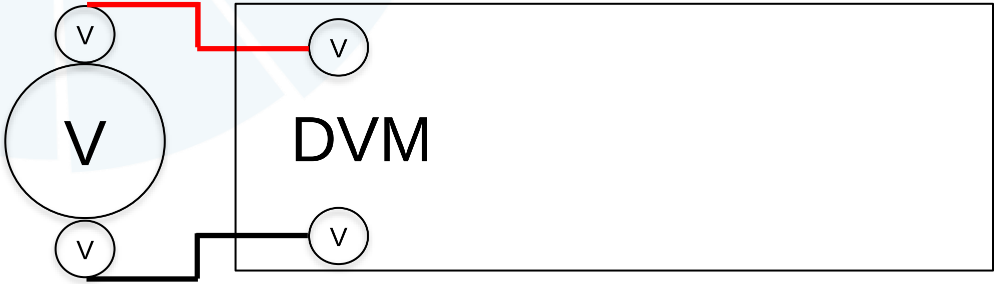


Terminals have EMF‘s,



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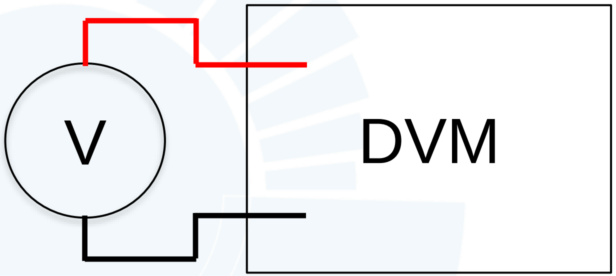
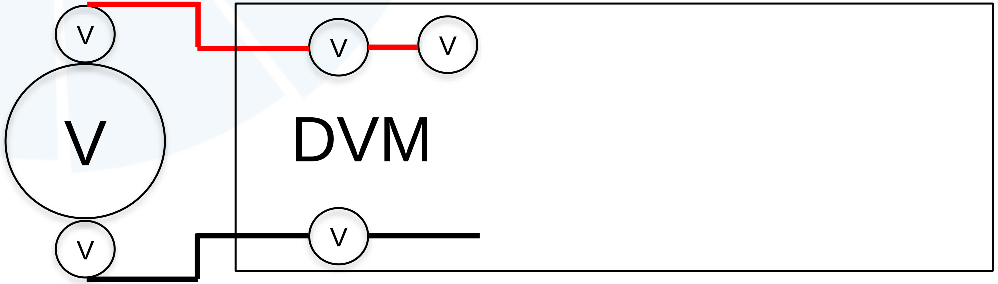


Terminals have EMF‘s, DVM input stages have an offset voltage,



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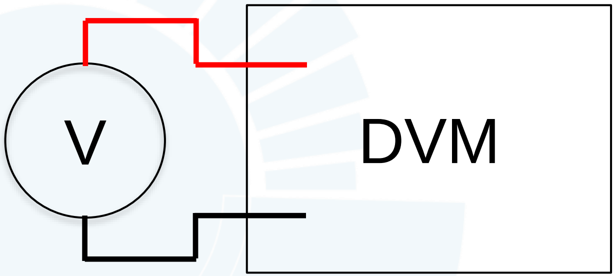
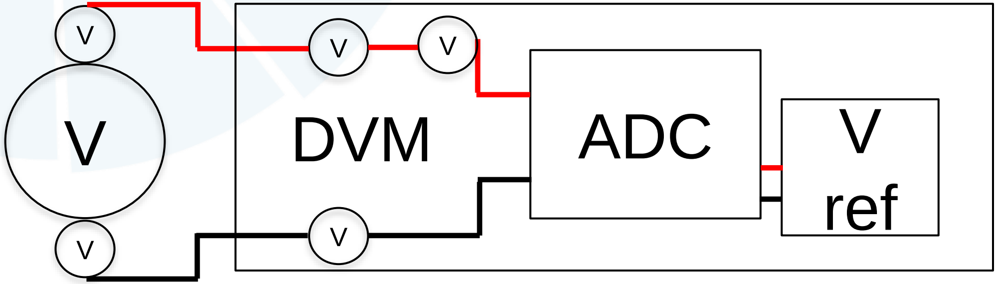


Terminals have EMF‘s, DVM input stages have an offset voltage, what about the voltage reference?



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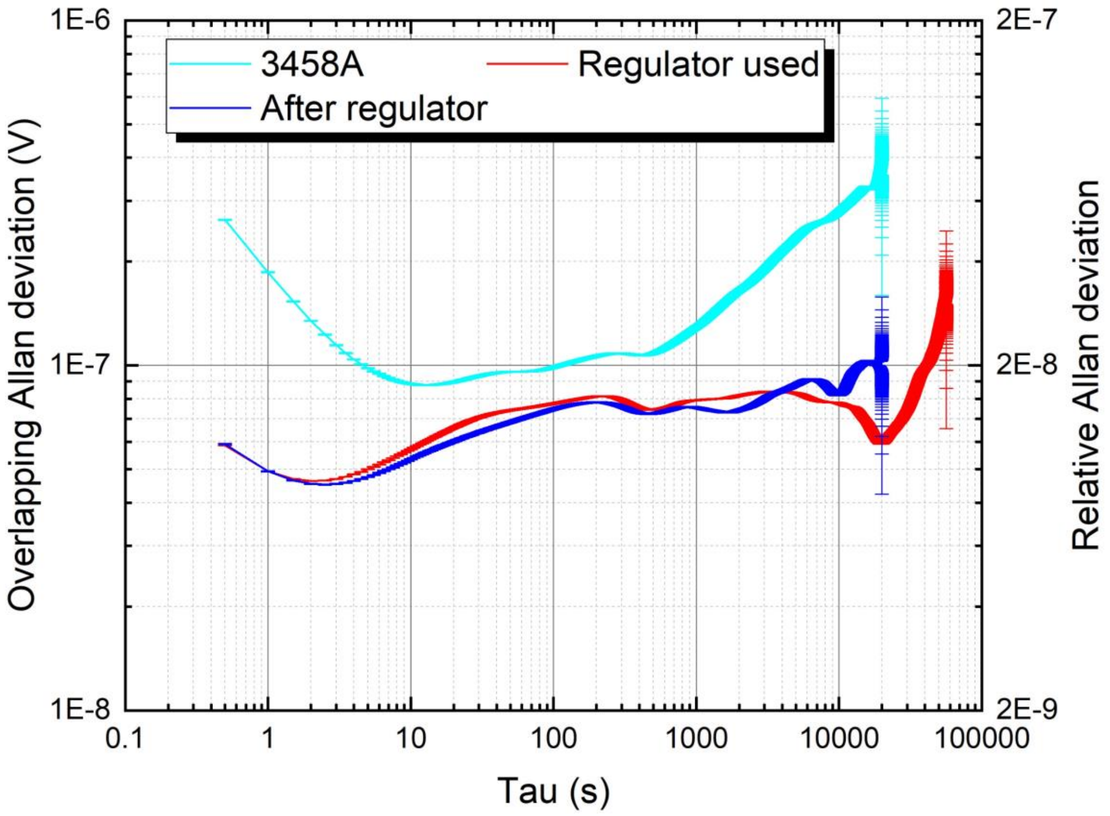
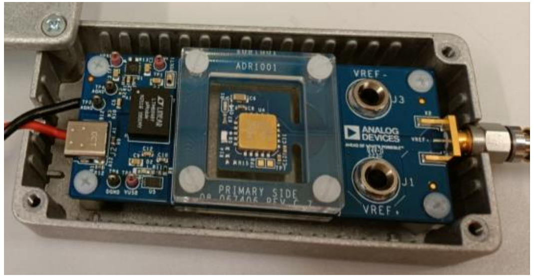
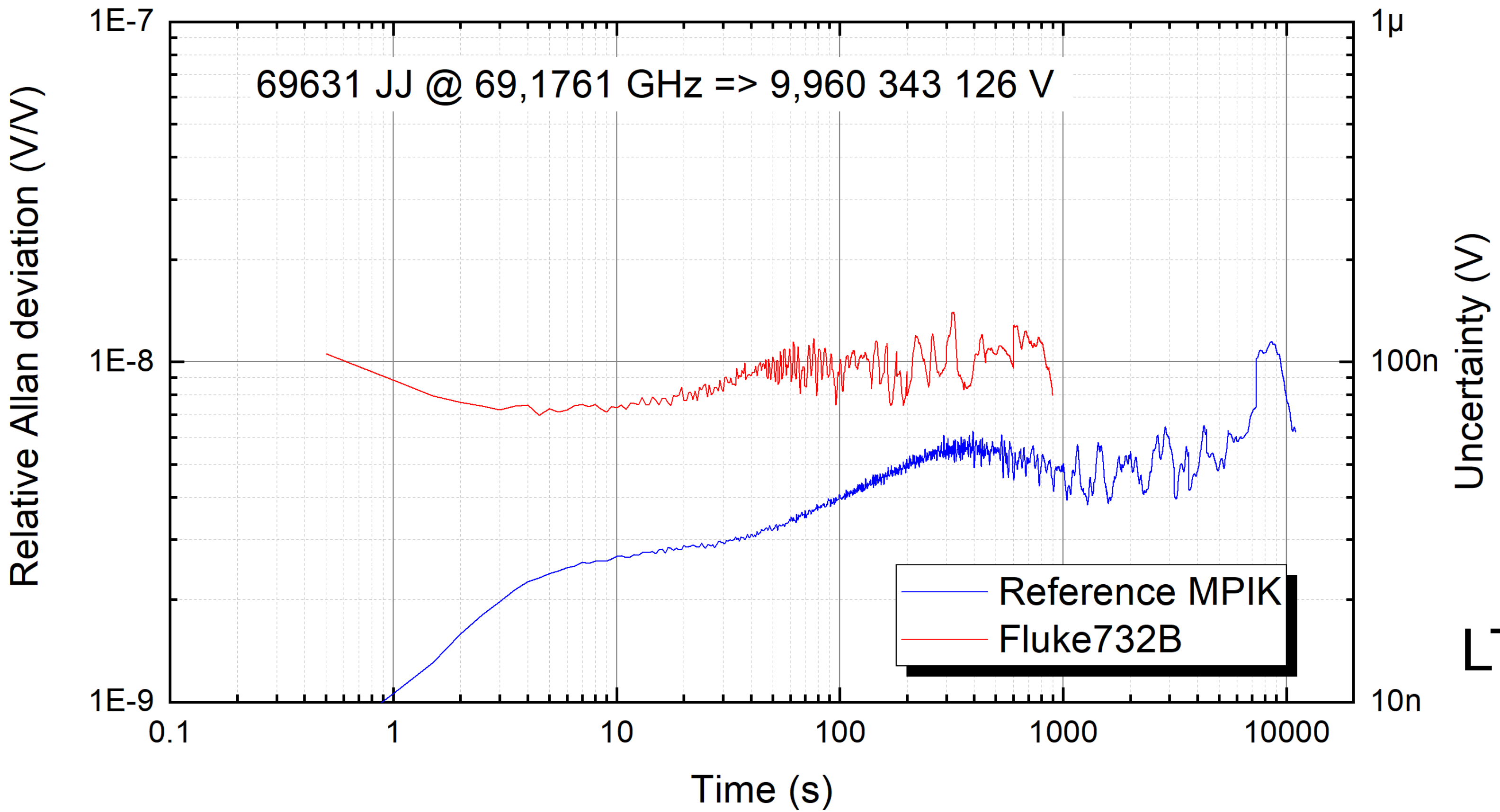




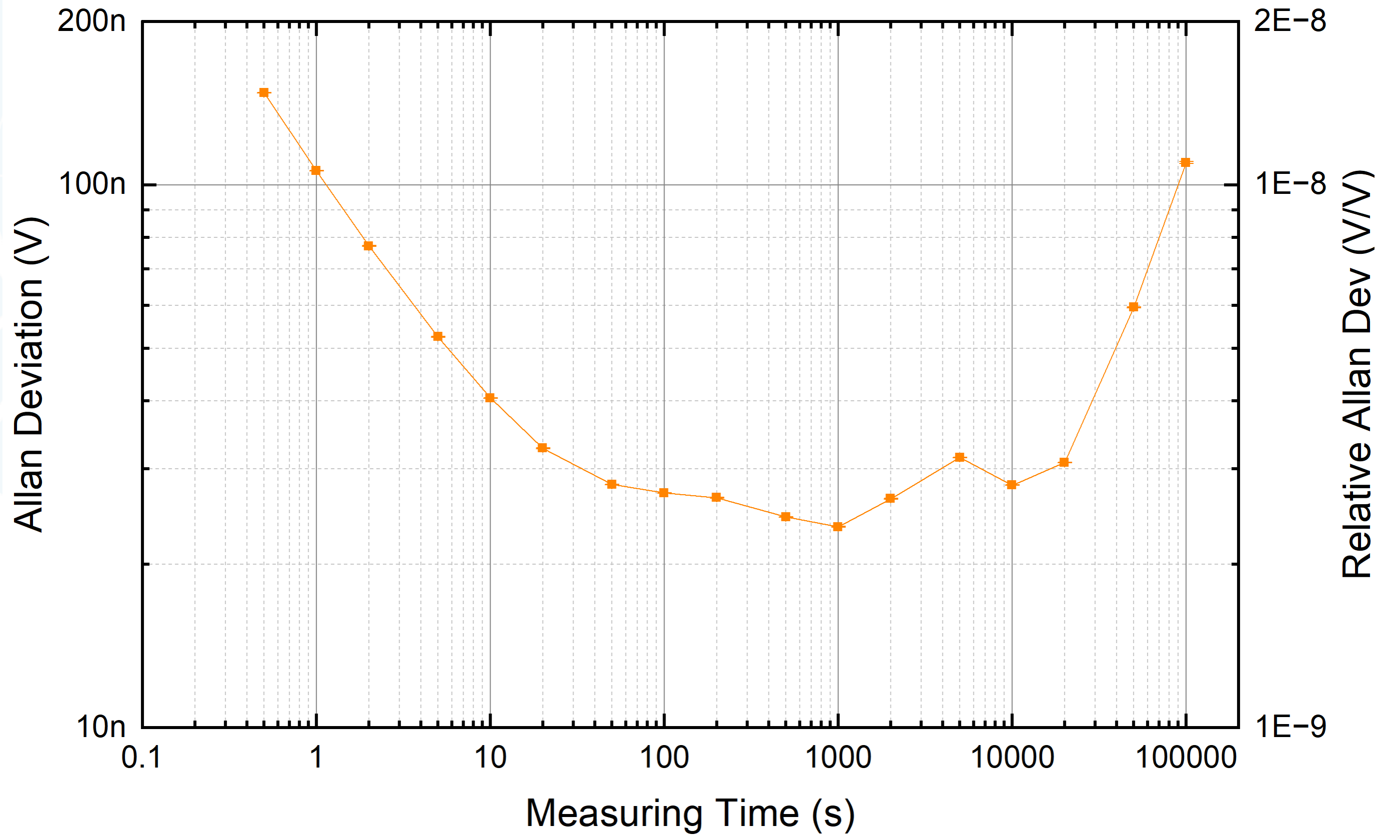
ADR1001
5 V

Voltage measurements



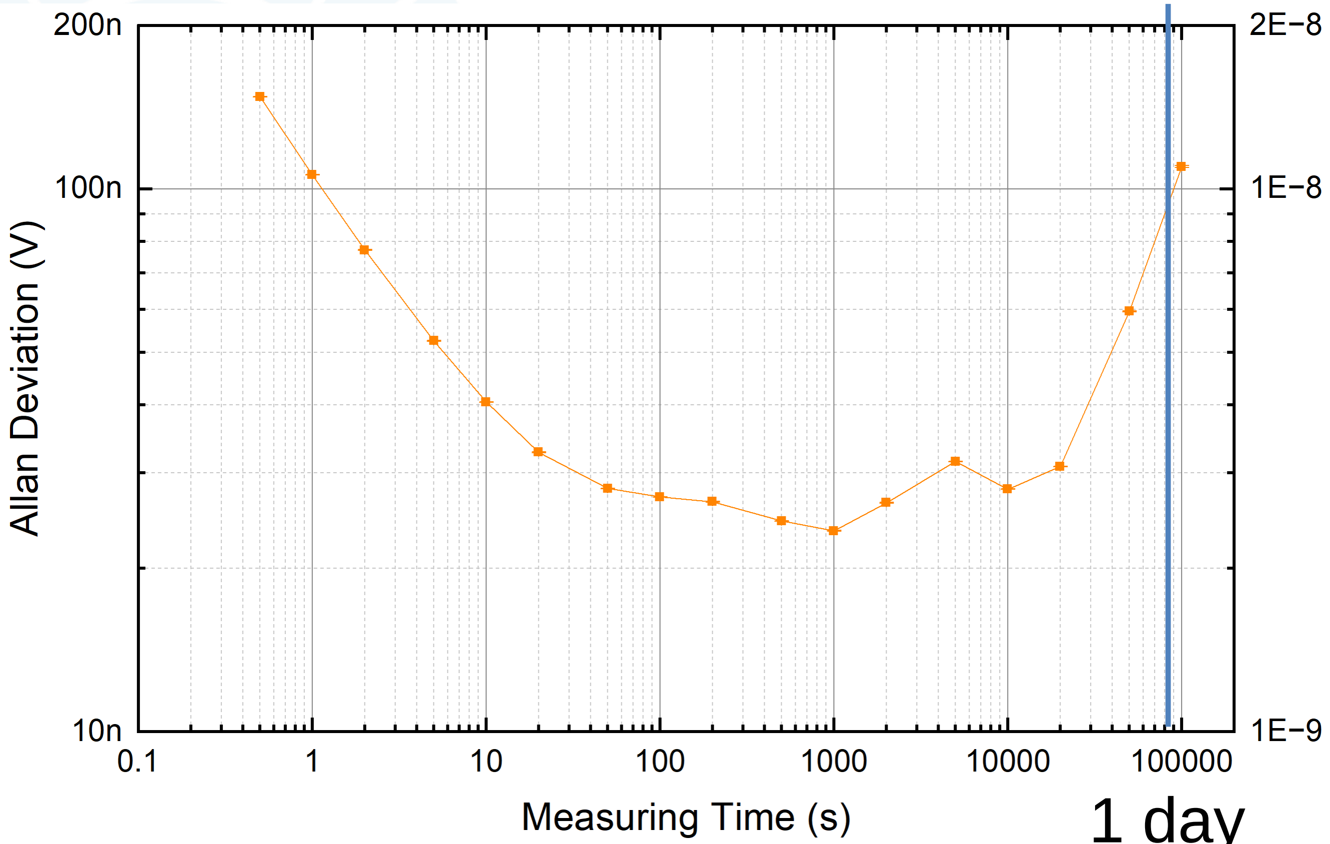
16x
LTZ1000

Voltage measurements



1xADR1000

Voltage measurements



1 day

1xADR1000

Conclusions

- Allan deviation is very powerful tool
- Voltmeter / Digitizer performance must include performance of voltage reference
- Voltage standards are good to 10^{-8} over 1 day
- Promising new reference ADR1000

Acknwolegment

Ralf Behr
Mattias Brennecke

Nikolai Beev
Daniel Valuch

John Pickering

Genauigkeit

Objektivität

Leidenschaft

PTB
Physikalisch-Technische Bundesanstalt
Das nationale Metrologieinstitut

Dr Luis Palafox
AG 2.63 Josephson Effect, Voltage
Telefon: 0531 592-2140
E-Mail: luis.palafox@ptb.de