

# Voltage references, Voltage standards and Josephson Voltage standards

High performance digitizer and DC metrology meeting

Luis Palafox

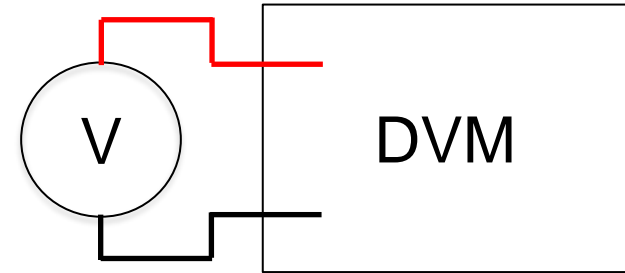
FB 2.6 Electrical Quantum metrology



# Motivation



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



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



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

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



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



*Metrologia* 11, 133—138 (1975)

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## **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

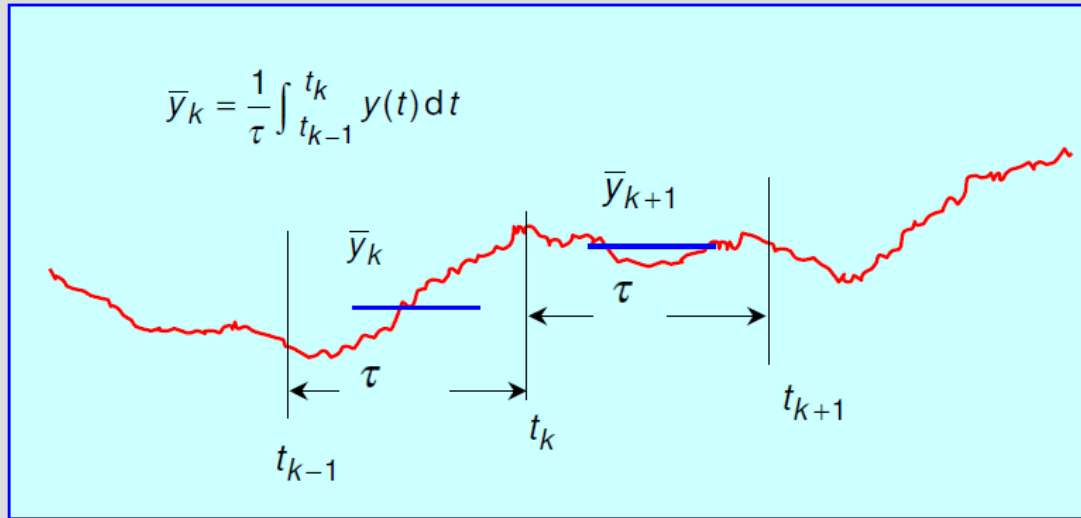


# Introduction to the Allan deviation

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





Define Allan  
variance:

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

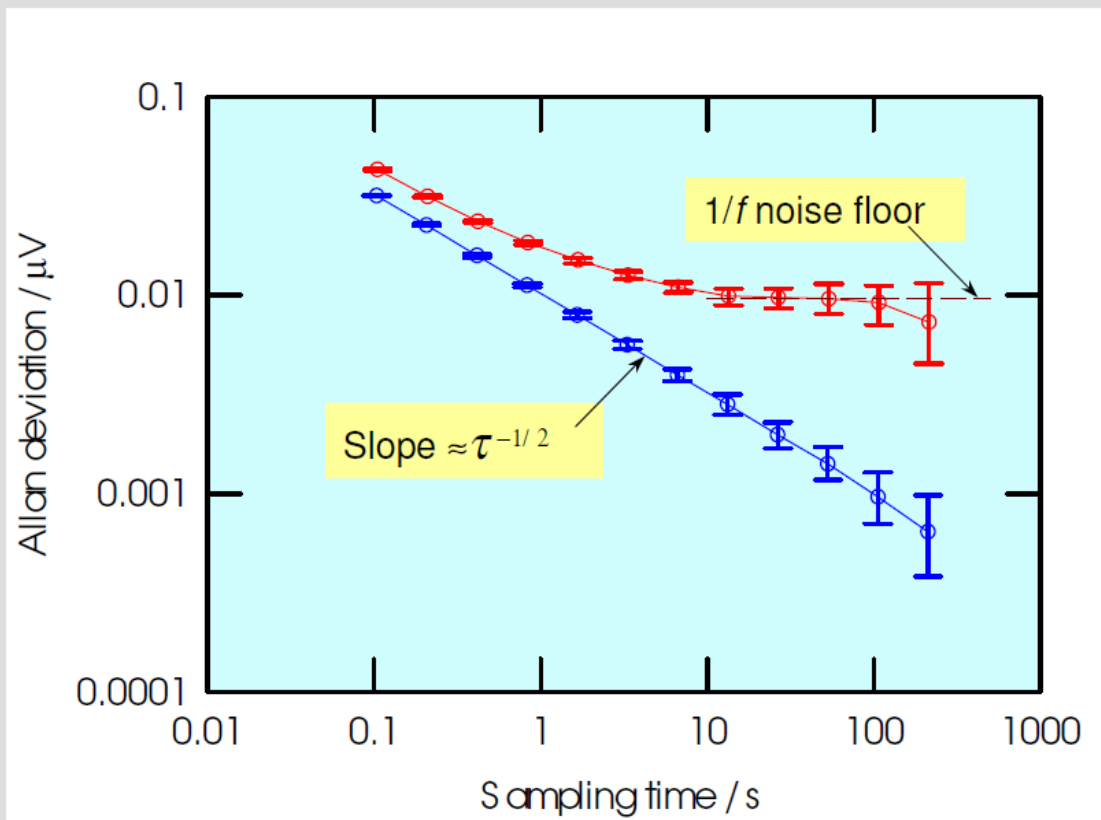
Calculate Allan  
variance:

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



# Introduc

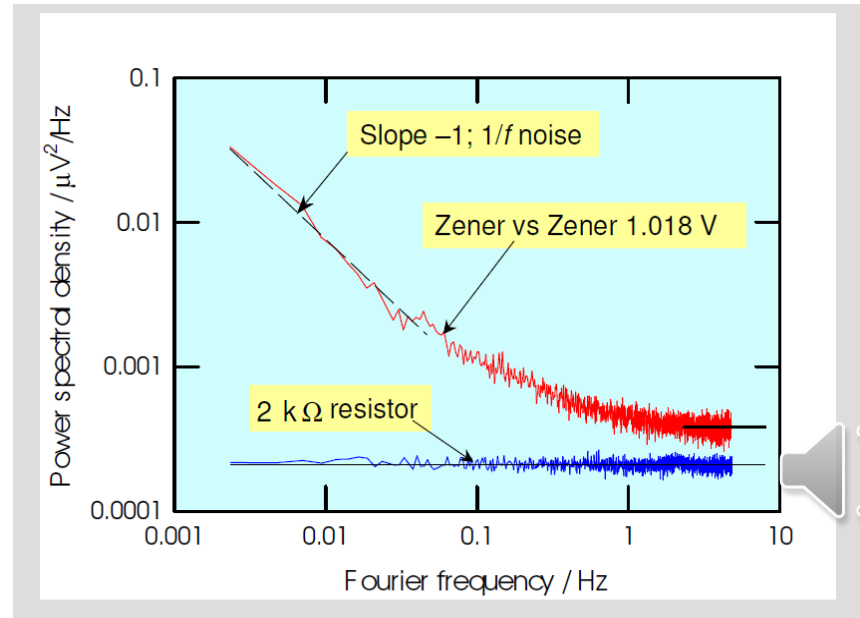
Allan deviations as functions of sampling times for comparison of 2 Zeners at 1.018 V (red) and equivalent source resistance, 2 k $\Omega$ , (blue)



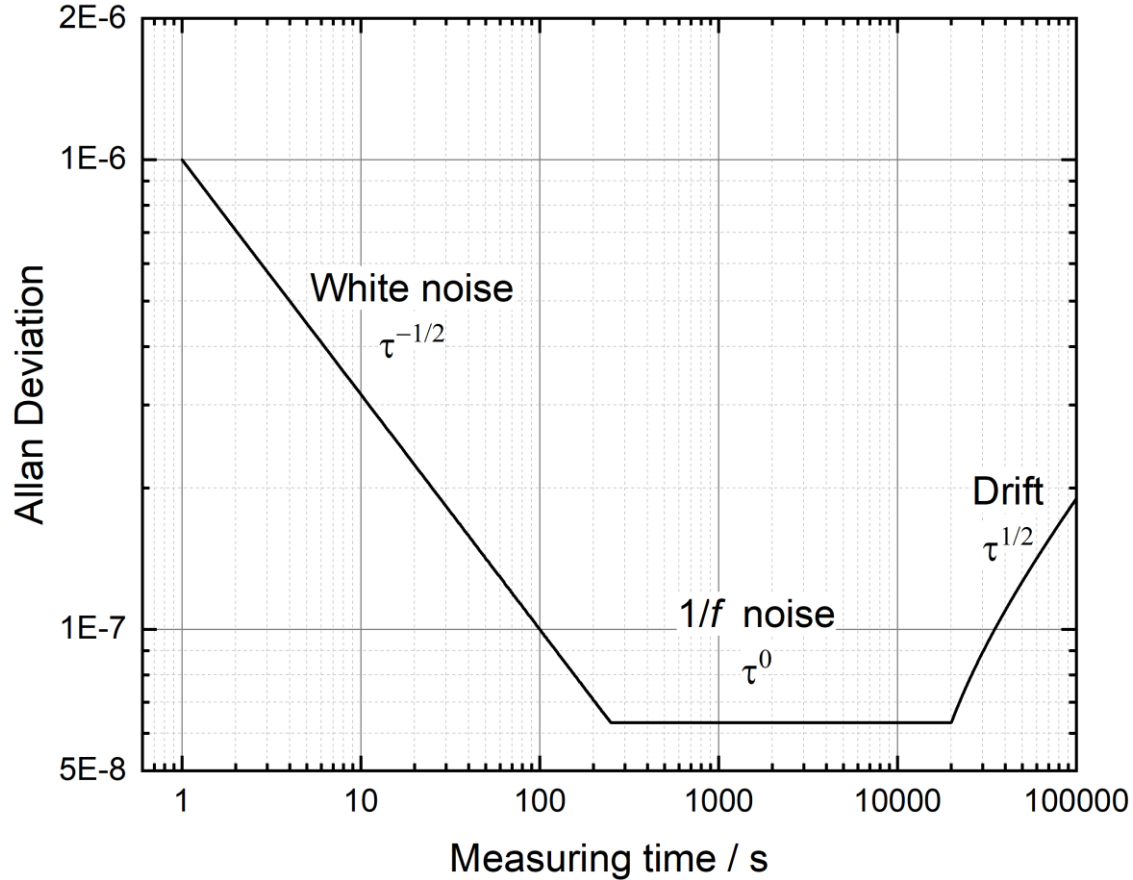


# Introduction to the Allan deviation

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

### PXI Sampling

**PXI parameters**

Device Name: PXI Slot3  
 Sample Rate: 10.00M  
 Trigger?:   
 Vertical Range (T=2):    
 Expected Freq (Hz): 978.5625  
 Number of Periods to capture: 400  
 Gain factor: 1.000000  
 Offset: -0.00096  
 No. of Samples: 20  
 Delete Starting points: 0  
 Delete Ringing points: 150

Gain correction:  Active  
 Offset Correction:  Active  
 Filter Range (T=2):  Trimmer  
 Filter: 10 M  
 Correct Filter?:   
 Undersampling?:   
 Frequency: 100  
 Limit: 0.1  
 File name string: 10M.977Hz.DRP150.VR2  
 File name additional string:    
 Loops: 25000, Loop number: 3005, Elapsed time (s): 1564.52  
 Twrite mode output, F: write RMS:

**RMS**

Restart count: 1.000 368 986  
 RMS (minus JVS) running stdev (µV): 0.194  
 only JVS voltage?:

**RMS**

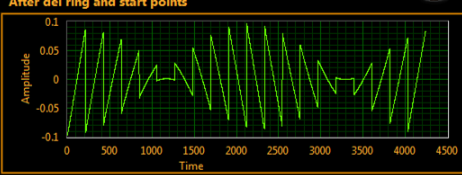
1.00036899

Mode: DC

**DC**

DC running stdev (µV): 0.000 161 781  
 DC: 0.001550191  
 RMS stdev (µV): 1.63

After del ring and start points



Amplitude vs Time (0 to 4500)

Zoom to step #1

RMS values after del ring/st pts (minus JJ volt)

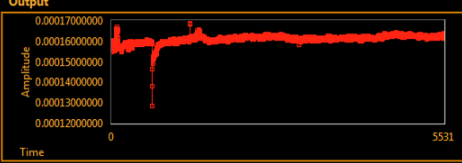


Amplitude vs Time (0 to 5531)

In ppm?   Vnom: 1.00001

Save screenshot | Clear graphs

Output



Amplitude vs Time (0 to 5531)

Use record length = number of  min record length: 216000

Plus or Minus JJ Steps:   size(s): 4096000.000000 mean Gain: NaN

Allan Deviation and Histogram | FFT | Delete ringing points | Temp. and 3458A | Gain | Check steps | Max

Run Allan deviation | Delete bad point

Allan deviation out



Amplitude vs Time (s) (0.1 to 1000)

\* without bad point

Histogram Graph



count vs amplitude (1.00037 to 1.00037)

\* without bad point

# Introduction to the Allan deviation

### PXI Sampling

**PXI parameters**

Device Name: PXI Slot3  
 Sample Rate: 10.00M  
 Trigger?:   
 Vertical Range (T=2):    
 Expected Freq (Hz): 976.5625  
 Number of Periods to capture: 400  
 Gain factor: 1.000000  
 Offset: -0.00096  
 No. of Samples: 20  
 Delete Starting points:    
 Delete Ringing points:  

Loops: Loop number: 3005, Elapsed time (s): 1564.52

File name string: 10M 977Hz DRP150 VR2

Frequency: 100  
 Limit: 0.1

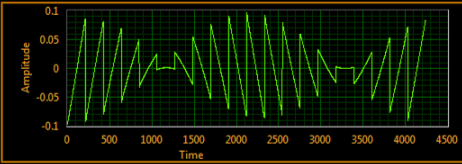
Restart count: 1.000 368 986

RMS: 1.00036899

DC: 0.000 161 781

Pure RMS of signal: 0.001550191

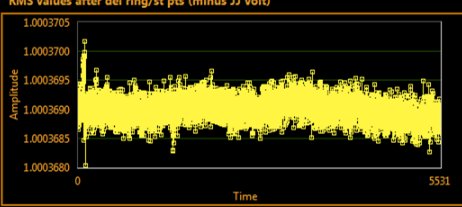
**After del ring and start points**



Amplitude vs Time

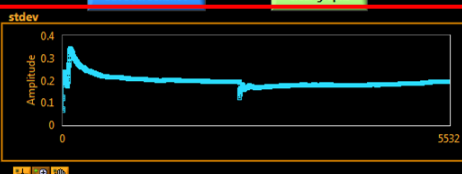
Zoom to step #1

**RMS values after del ring/st pts (minus JJ volt)**



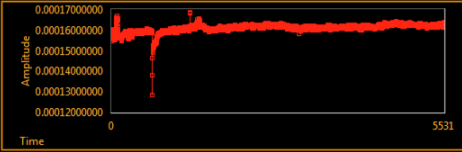
Amplitude vs Time

**stdev**



Amplitude vs Time

**Output**

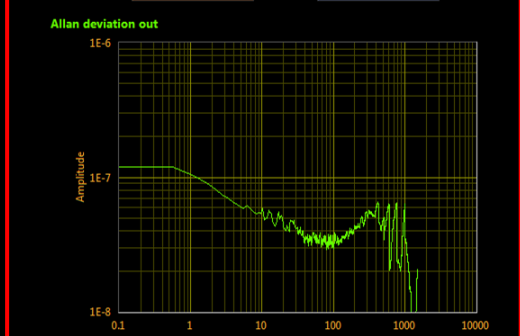


Amplitude vs Time

Use record length = number of: 216000  
 Plus or Minus JJ Steps:    
 size(s): 4096000.000000  
 mean Gain: NaN

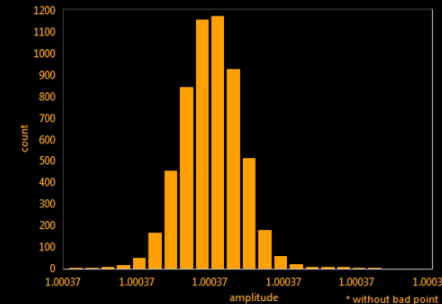
Run Allan deviation    Delete bad point

**Allan deviation out**



Amplitude vs Time (s)

**Histogram Graph**



count vs amplitude

$y(t)$

$\sigma$



# Introduction to the Allan deviation

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**PXI parameters**

Device Name: PXI Slot3  
 Sample Rate: 10.00M  
 Trigger?   
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 Expected Freq (Hz): 978.5625  
 Number of Periods to capture: 400  
 Gain factor: 1.000000  
 Offset: -0.00096  
 No. of Samples: 20  
 Delete Starting points: 0  
 Delete Ringing points: 0

Loops: Loop number: 3005, Elapsed time (s): 1564.52

File name string: 10M 977Hz DRP150 VR2

Frequency: 100  
 Limit: 0.1

Restart count: 1.000 368 986

RMS: 1.00036899

DC: 0.000 161 781

Pure RMS of signal: 0.001550191

After del ring and start points

Zoom to step #1

RMS values after del ring/st pts (minus JJ volt)

In ppm? 1.00001

stdev

Output

Use record length = number of: 216000

size(s): 4096000.000000, mean Gain: NaN

Plus or Minus JJ Steps: 0

Allan Deviation and Histogram: FFT, Delete ringing points, Temp. and 3458A, Gain, Check steps, Max

Run Allan deviation, Delete bad point

Allan deviation out

Amplitude vs Time (s) \*without bad point

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

Allan dev  $\approx 30 \text{ nV}$

## 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)

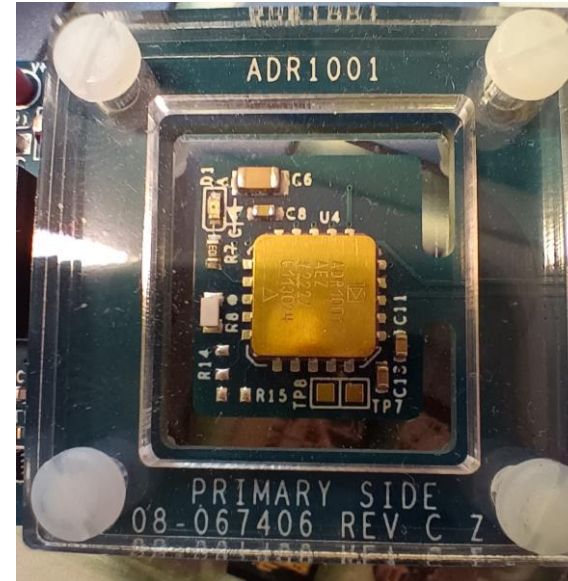
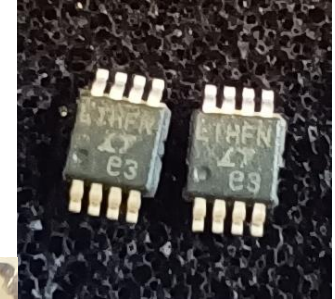
## Disadvantage:

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

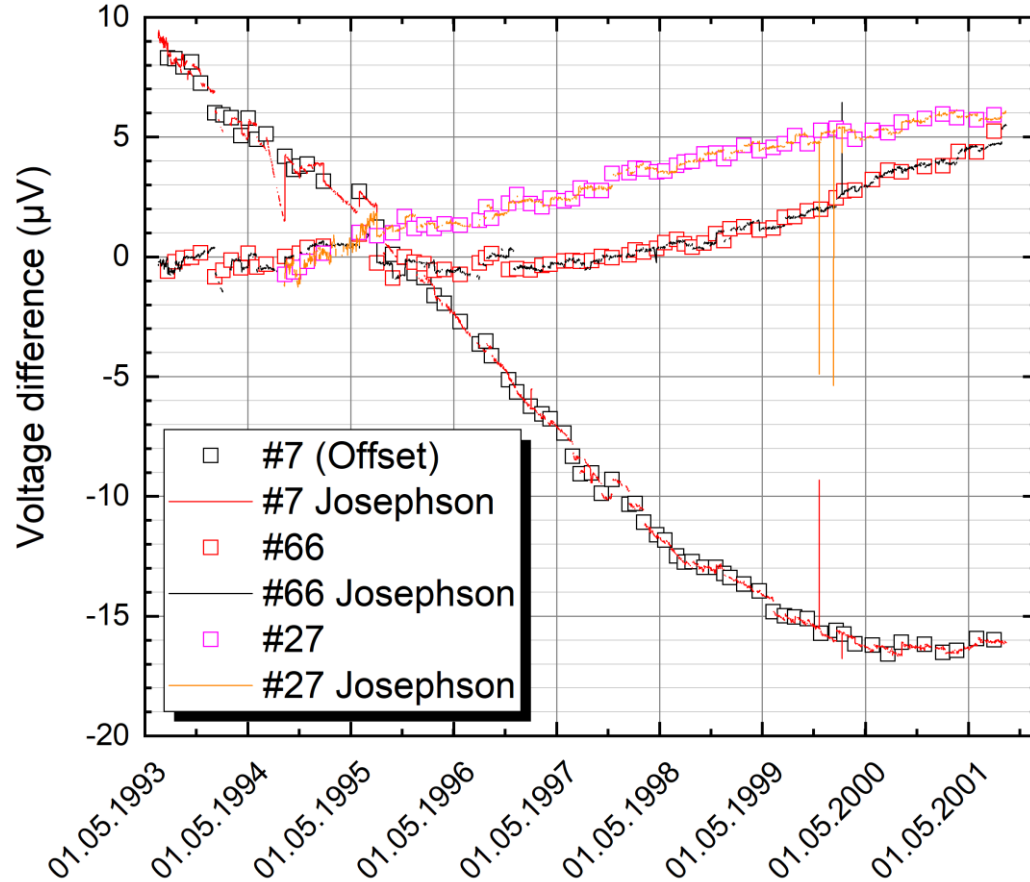


Images from <https://us.flukecal.com/products/electrical-calibration/electrical-standards/732c-734c-dc-voltage-reference-standards>  
<http://lionelectroniclabs.com/fluke-datron-4910-dc-voltage-reference-standard/>  
<http://friedrich-messtechnik.de/index.php/messtechnik/dc-standards>  
<https://mintl.com/products/8110a-10-volt-reference/>

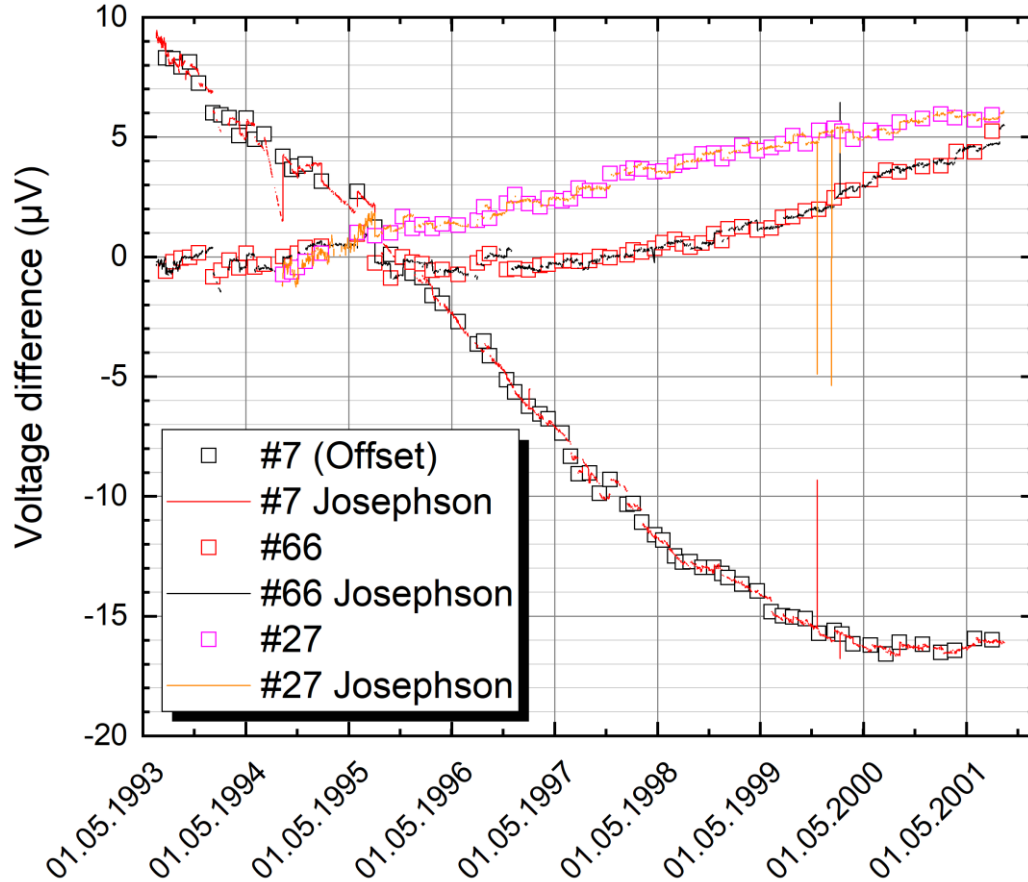




# Voltage references & Voltage standards



# 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](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

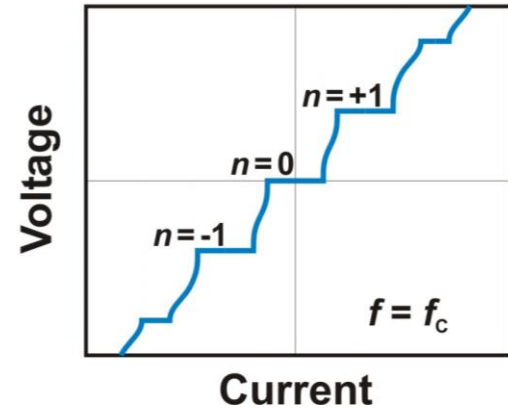


Brian D Josephson

Bildquelle: <http://www.nobelprize.org>

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

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



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



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



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

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  $\pm 1$  G; (viii) the direction of the bias current through the junctions.



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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

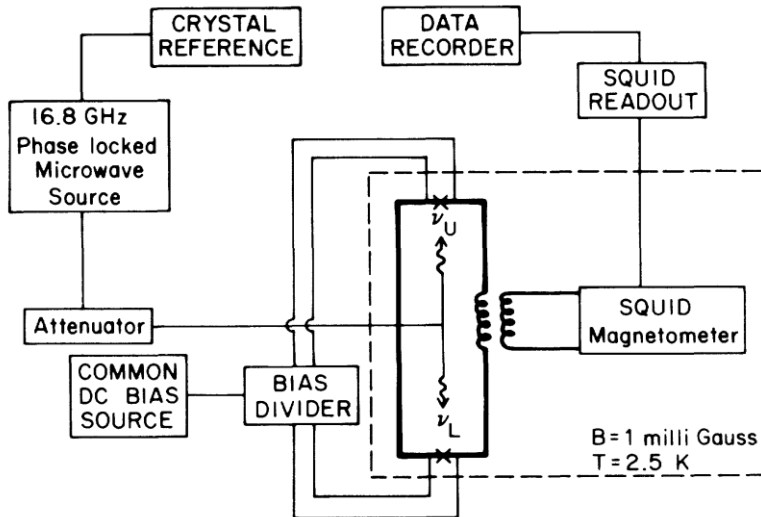
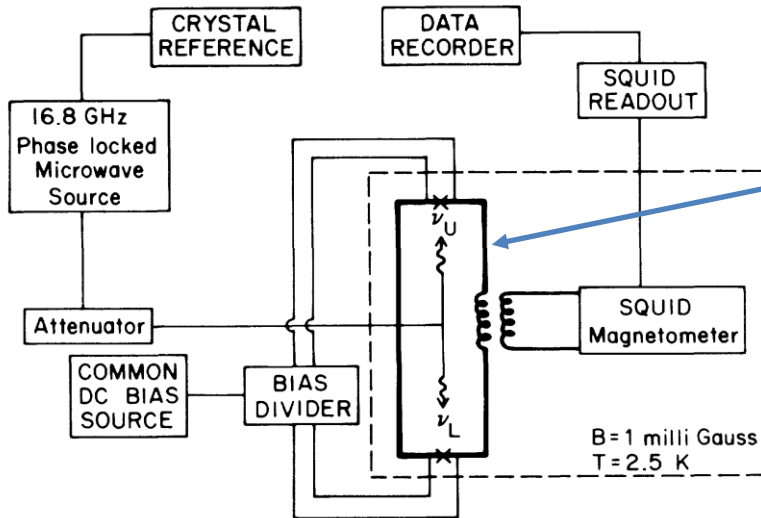


FIG. 1. Schematic of the measurement circuit. The crosses denote the Josephson batteries. The darker lines indicate superconducting portions of the circuit.



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



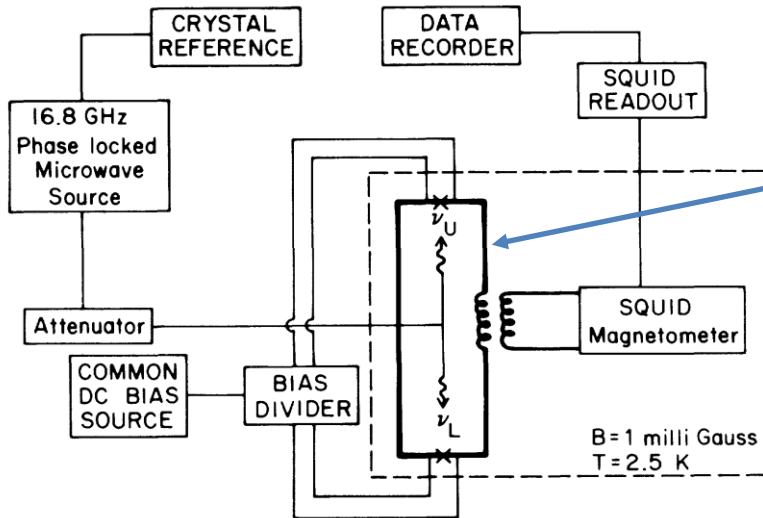
EMF @loop <  $1 \times 10^{-22}$  V

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

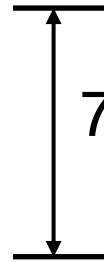




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EMF @loop <  $1 \times 10^{-22}$  V



7.2 cm

Red shift of electrons



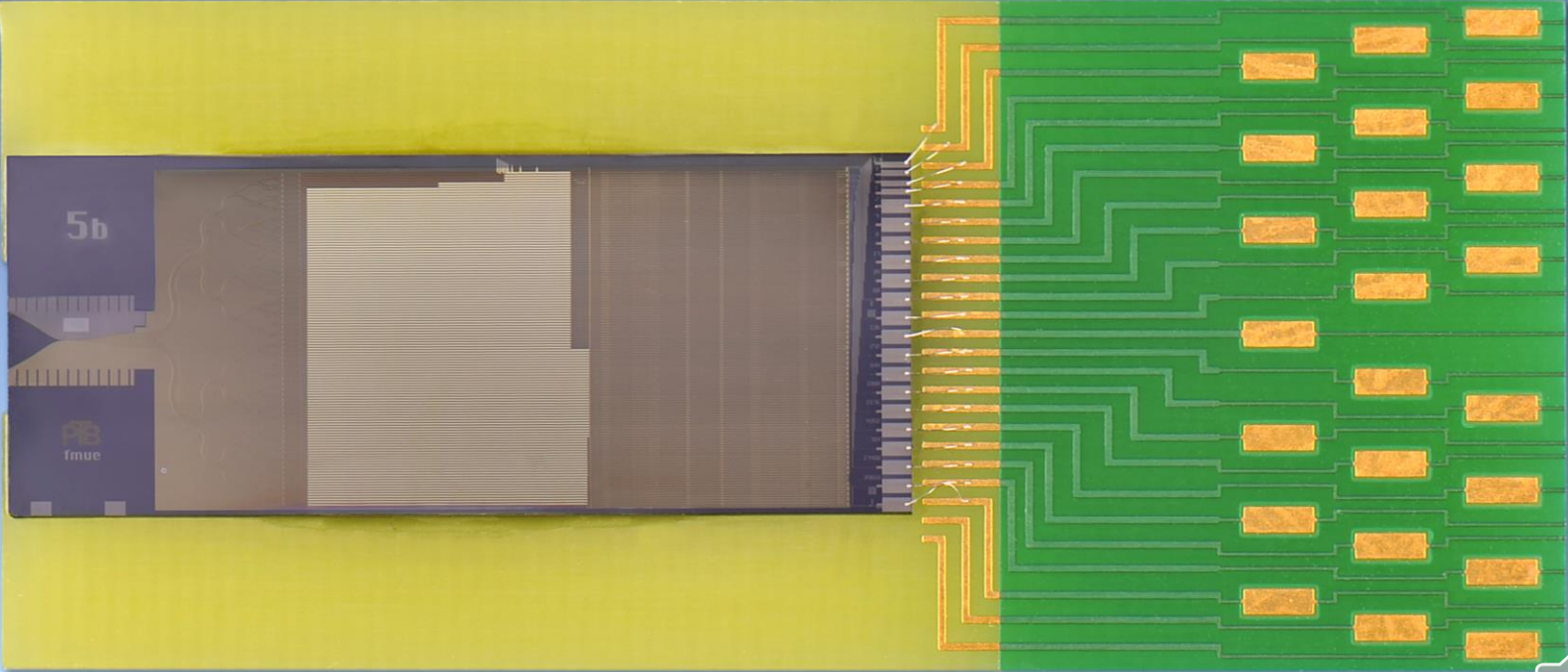
$$\Delta V = 2.35 \times 10^{-21} \text{ V}$$

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

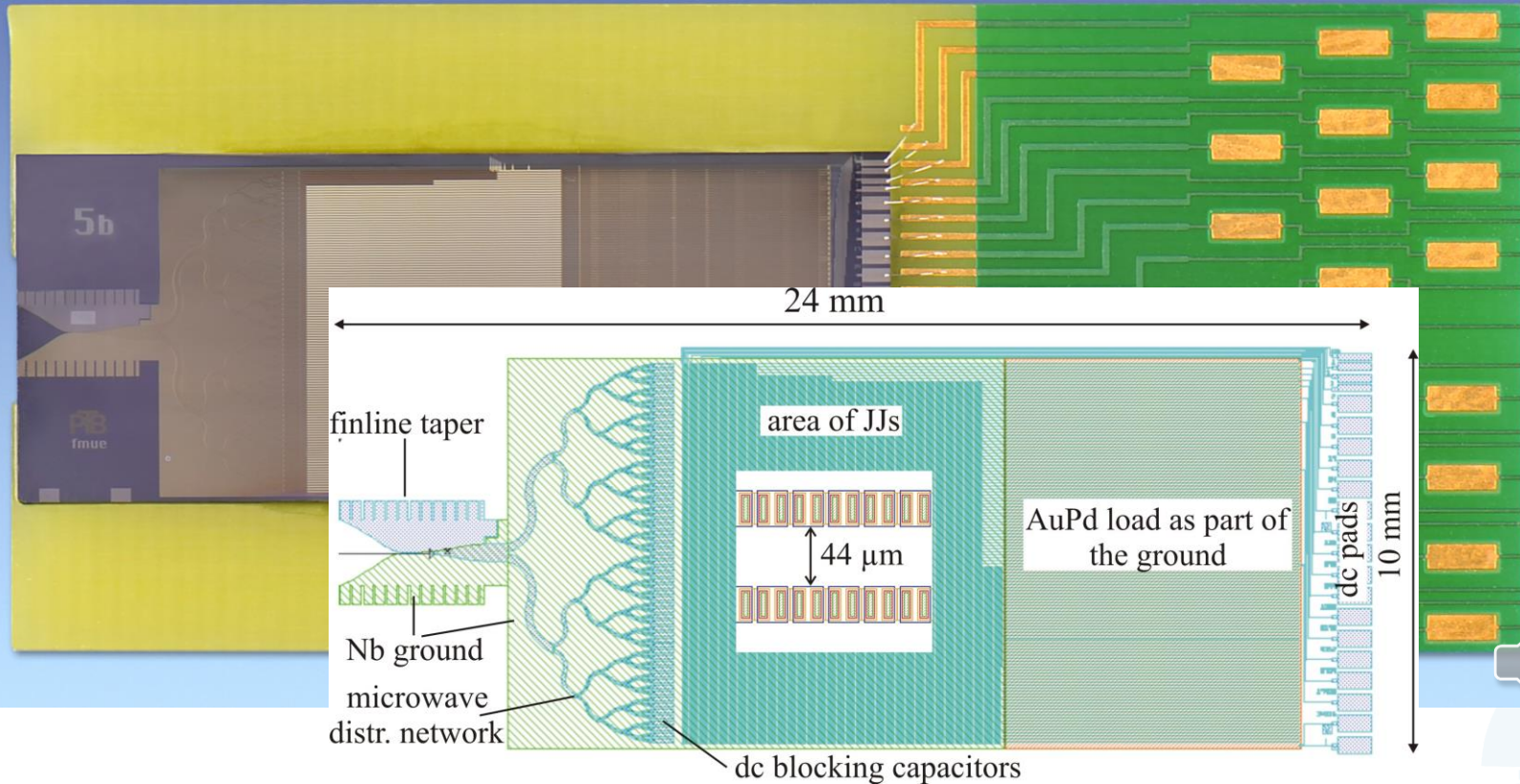




# Josephson Voltage Standard



# Josephson Voltage Standard



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



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

Uses superconductors, so needs low temperatures

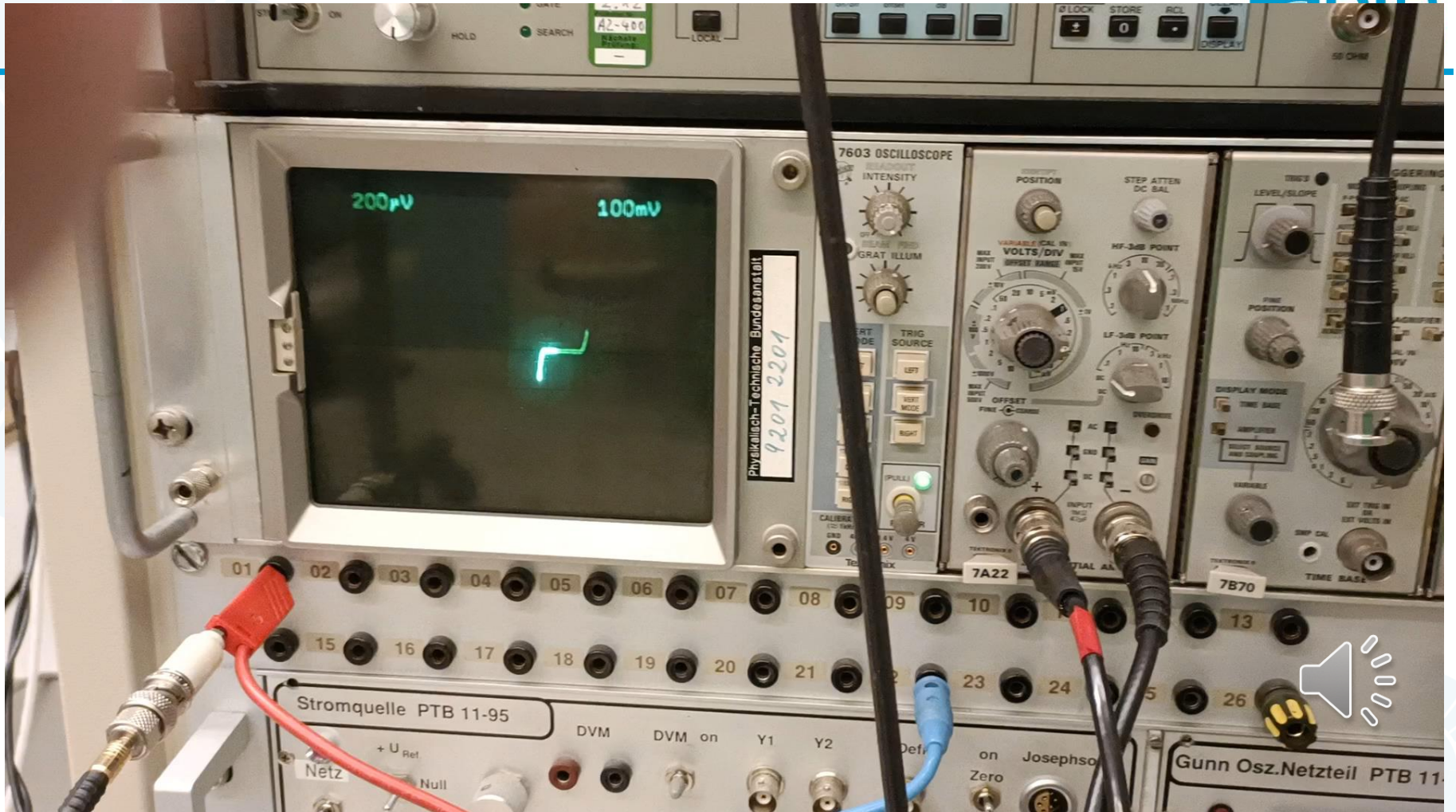


Based on a quantum effect, so independent from materials in the JJ, time, temperature, pressure, ...

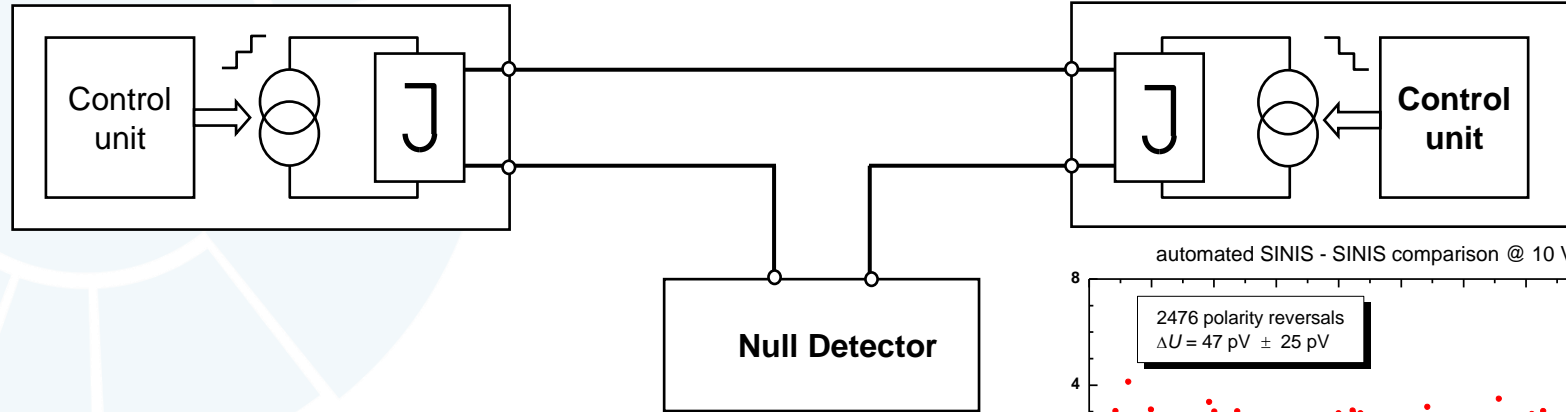
Uses superconductors, so needs low temperatures  
So far needs 4.2 K or 10 K



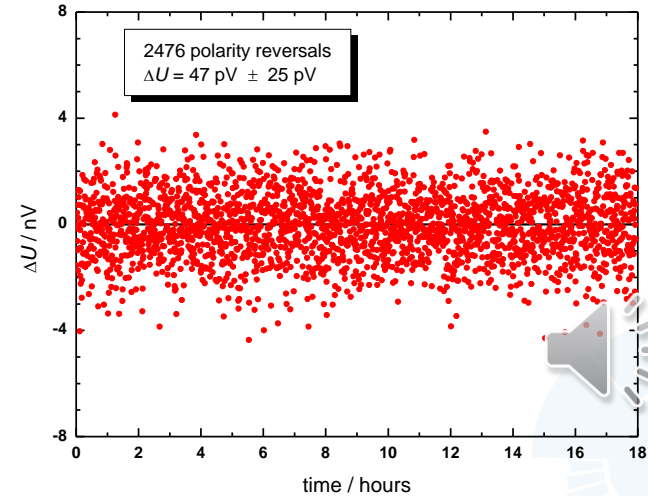




## Compared instead of calibrated

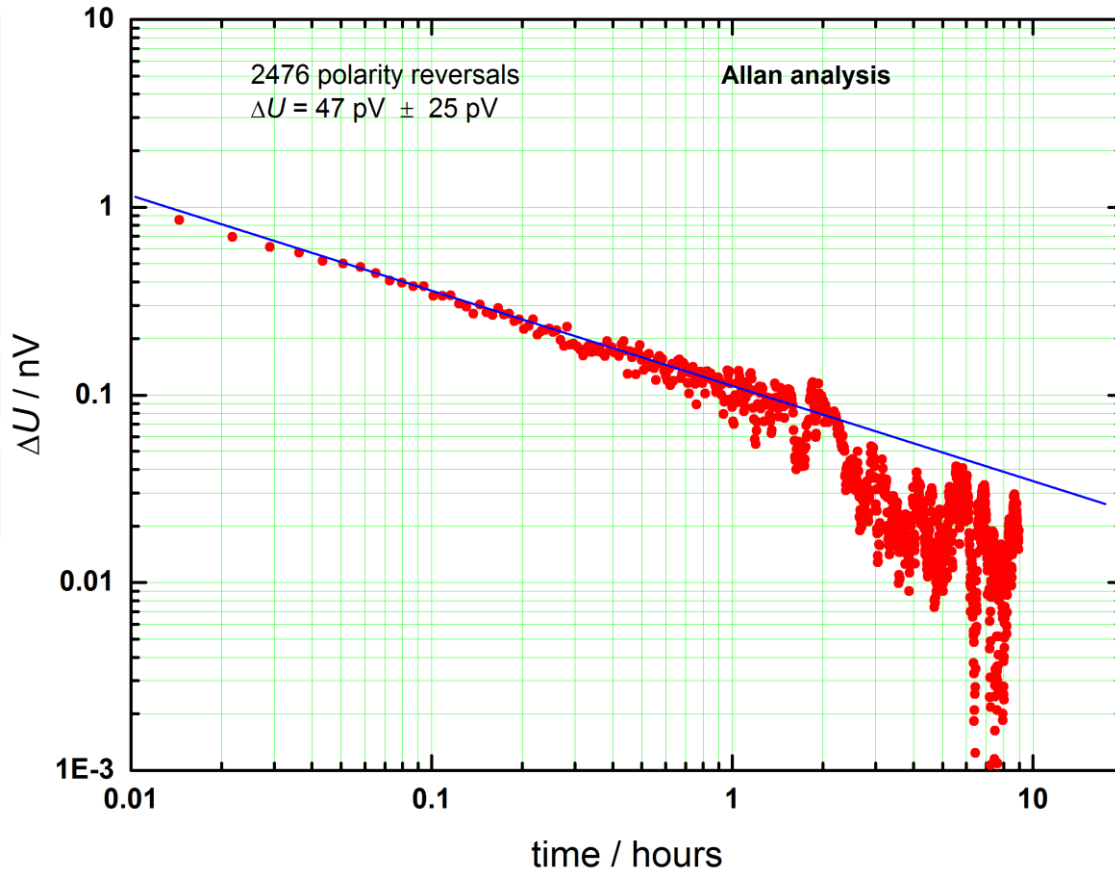


automated SINIS - SINIS comparison @ 10 V



# Josephson Voltage Standard

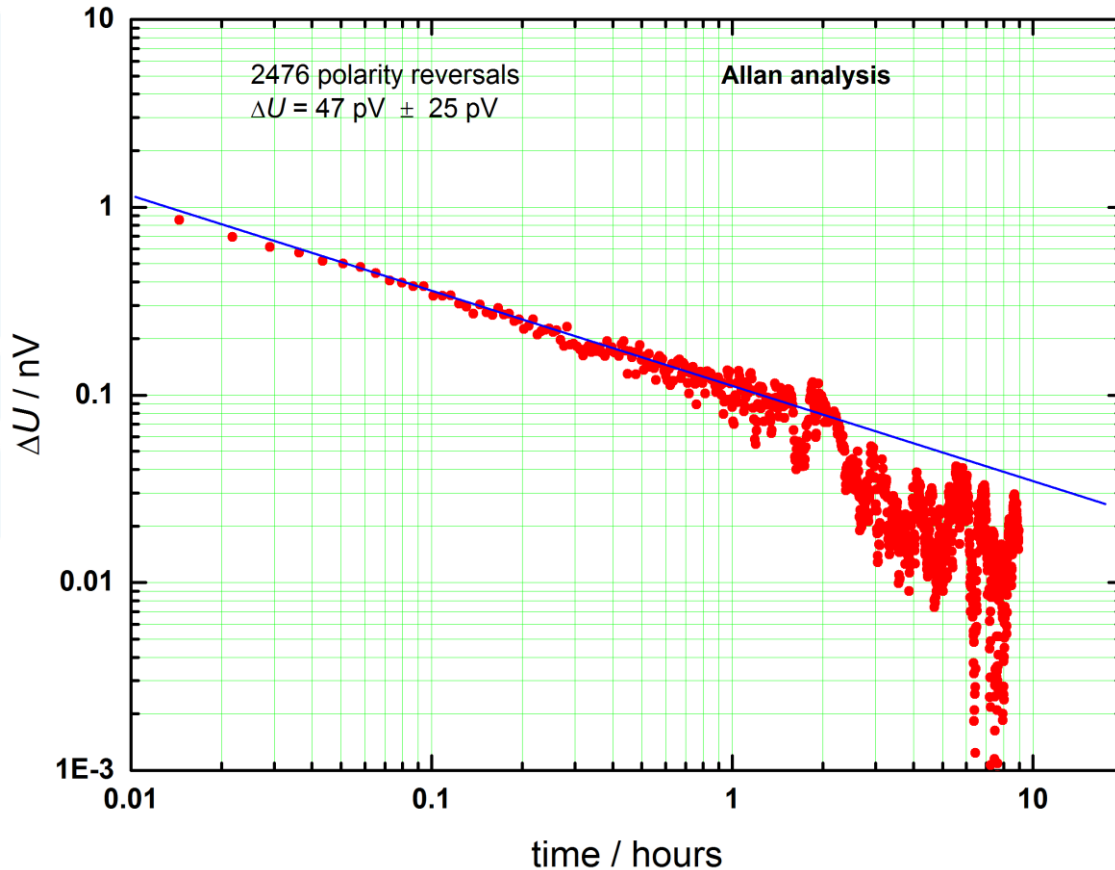
automated SINIS - SINIS comparison @ 10 V





# Josephson Voltage Standard

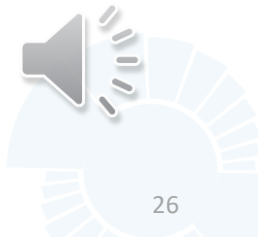
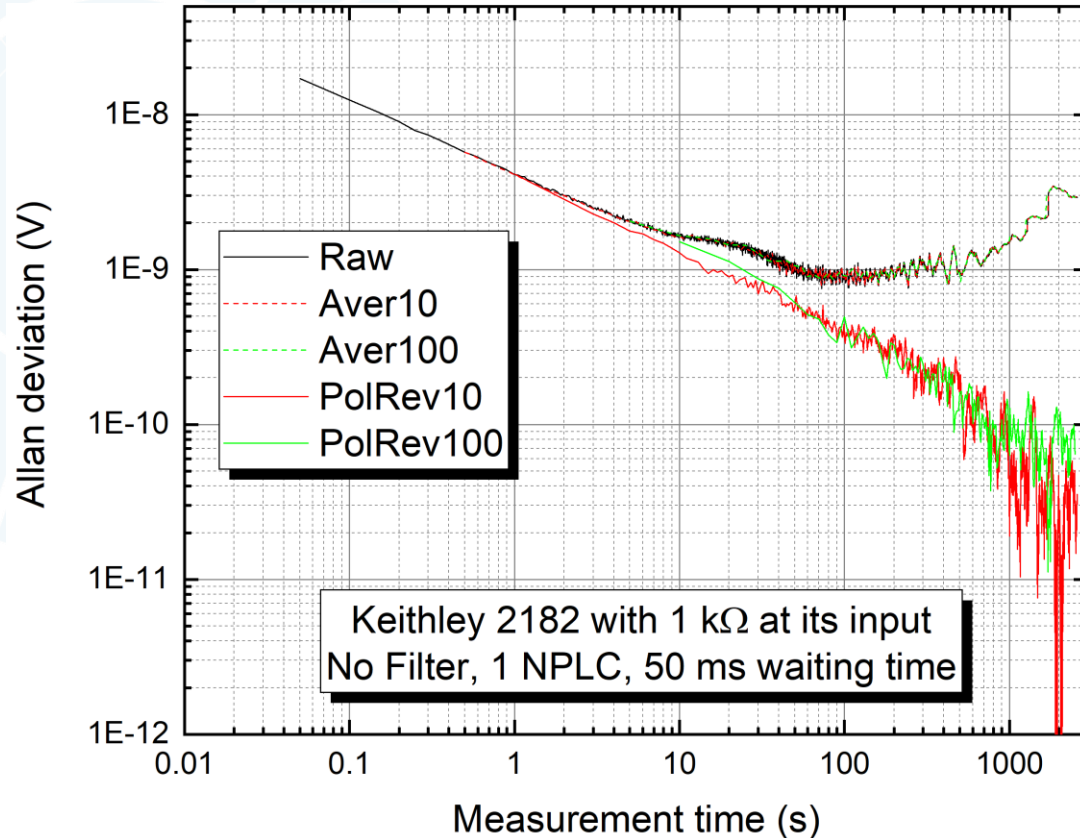
automated SINIS - SINIS comparison @ 10 V



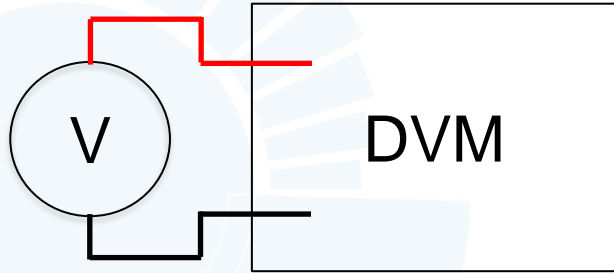
Noise of  
Null Detector  
removed!

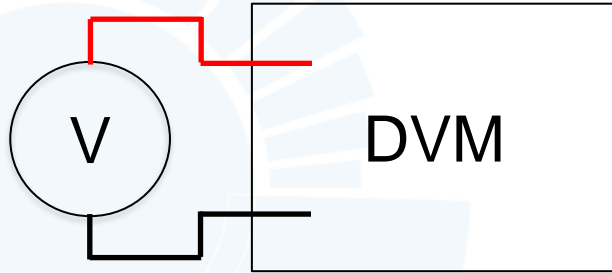


# Why do we prefer polarity reversals in metrology?

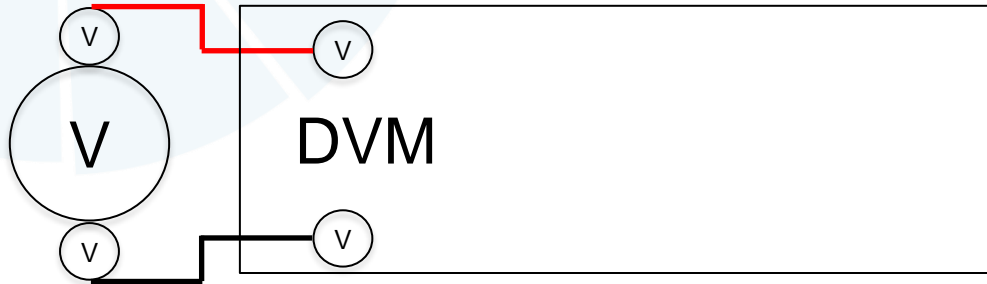


# Voltage measurements

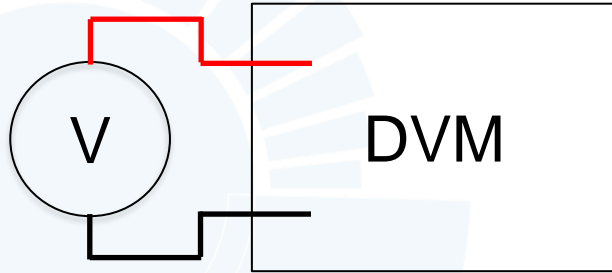




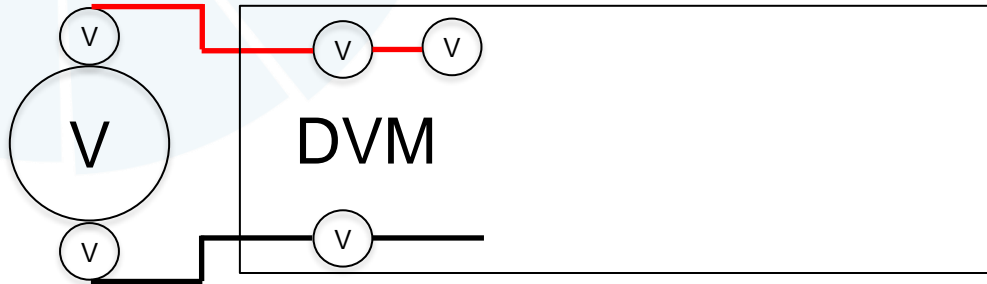
Terminals have EMF's,



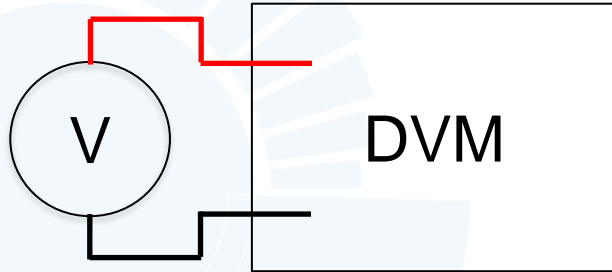
# Voltage measurements



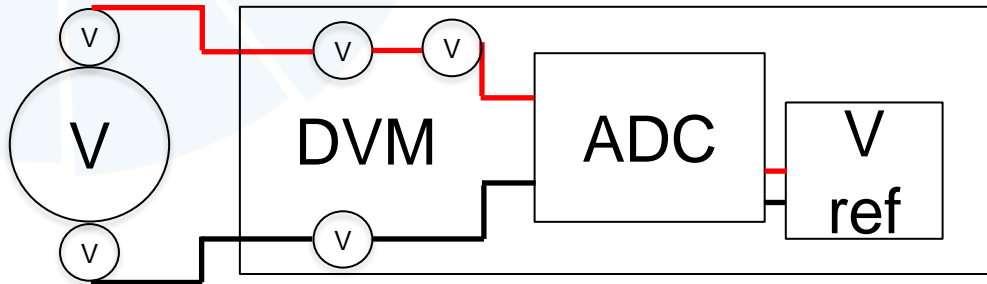
Terminals have EMF's,  
DVM input stages have  
an offset voltage,



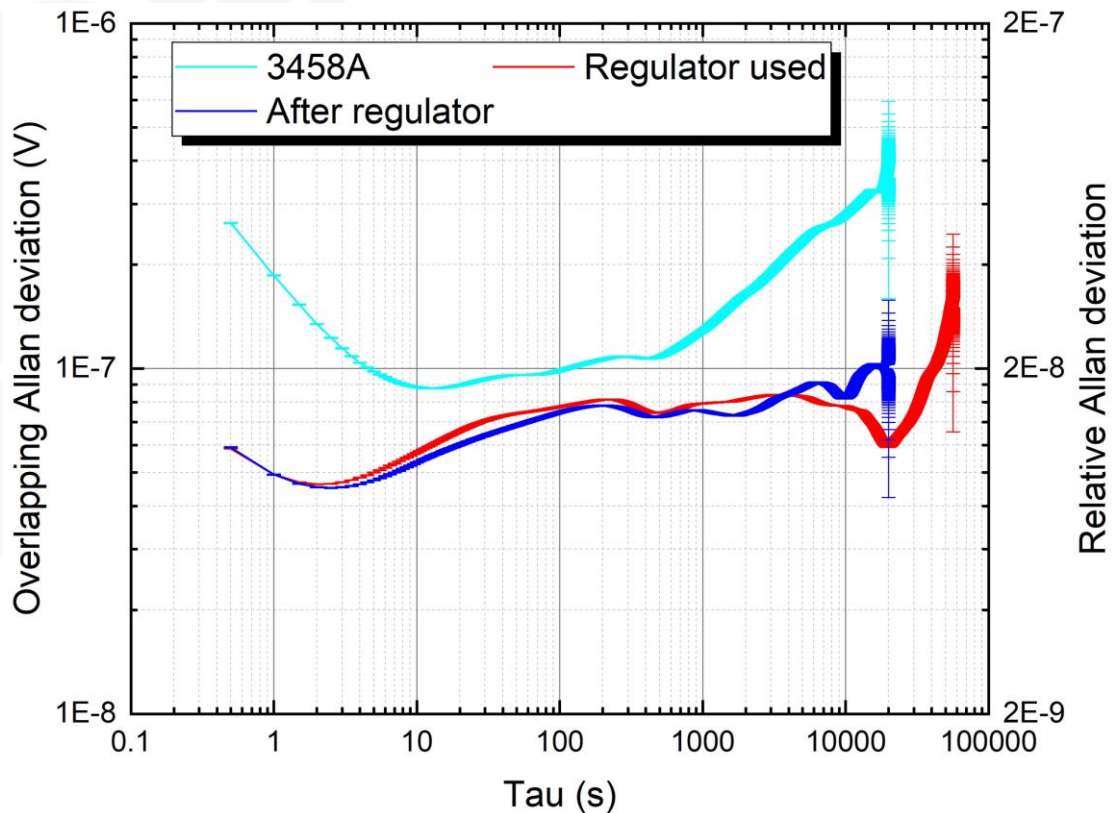
# Voltage measurements



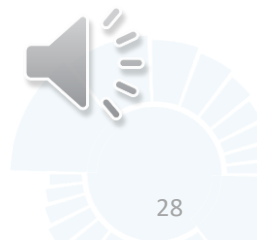
Terminals have EMF's,  
DVM input stages have  
an offset voltage,  
what about the  
voltage reference?



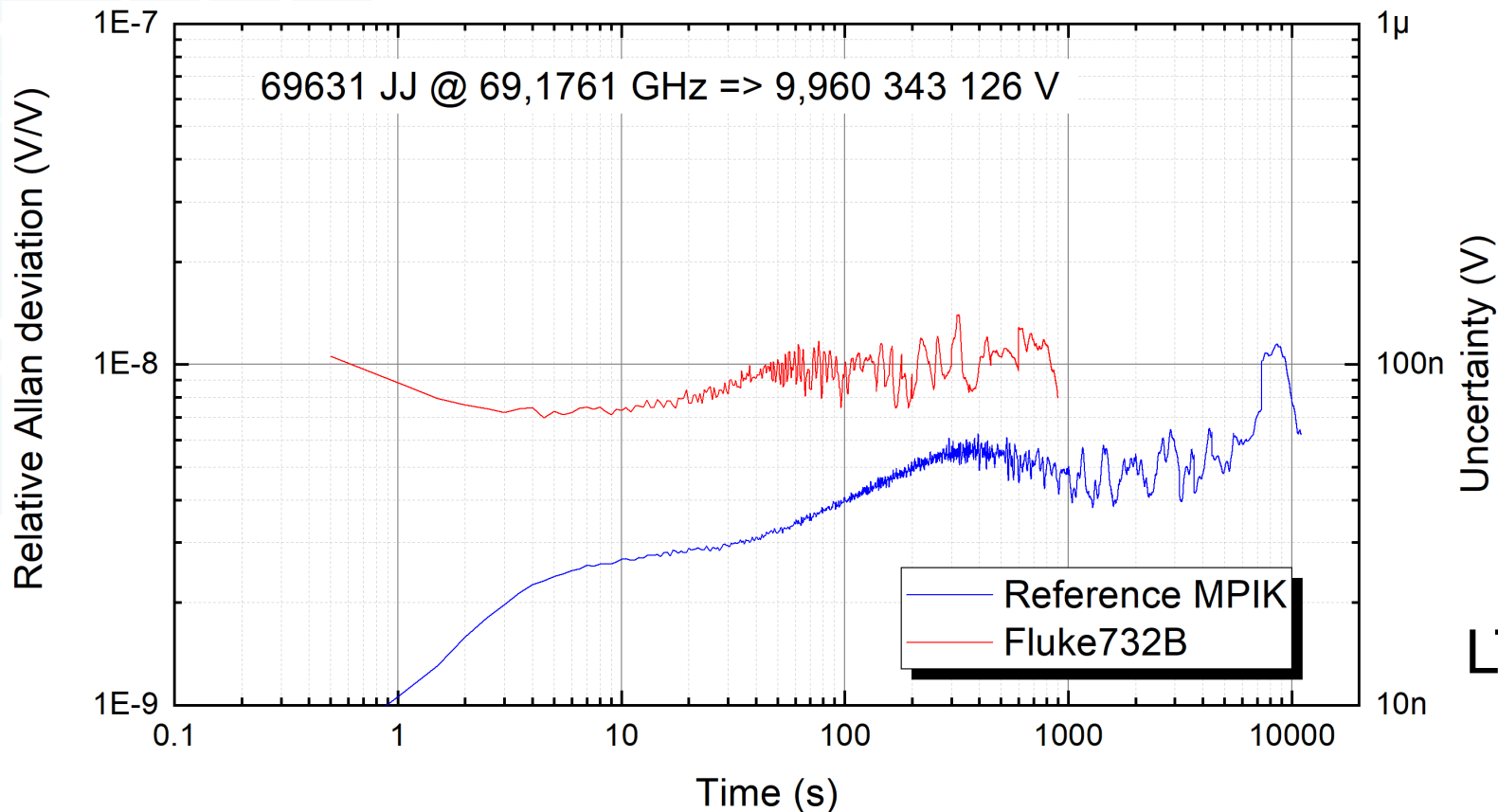
# Voltage measurements



ADR1001  
5 V



# Voltage measurements

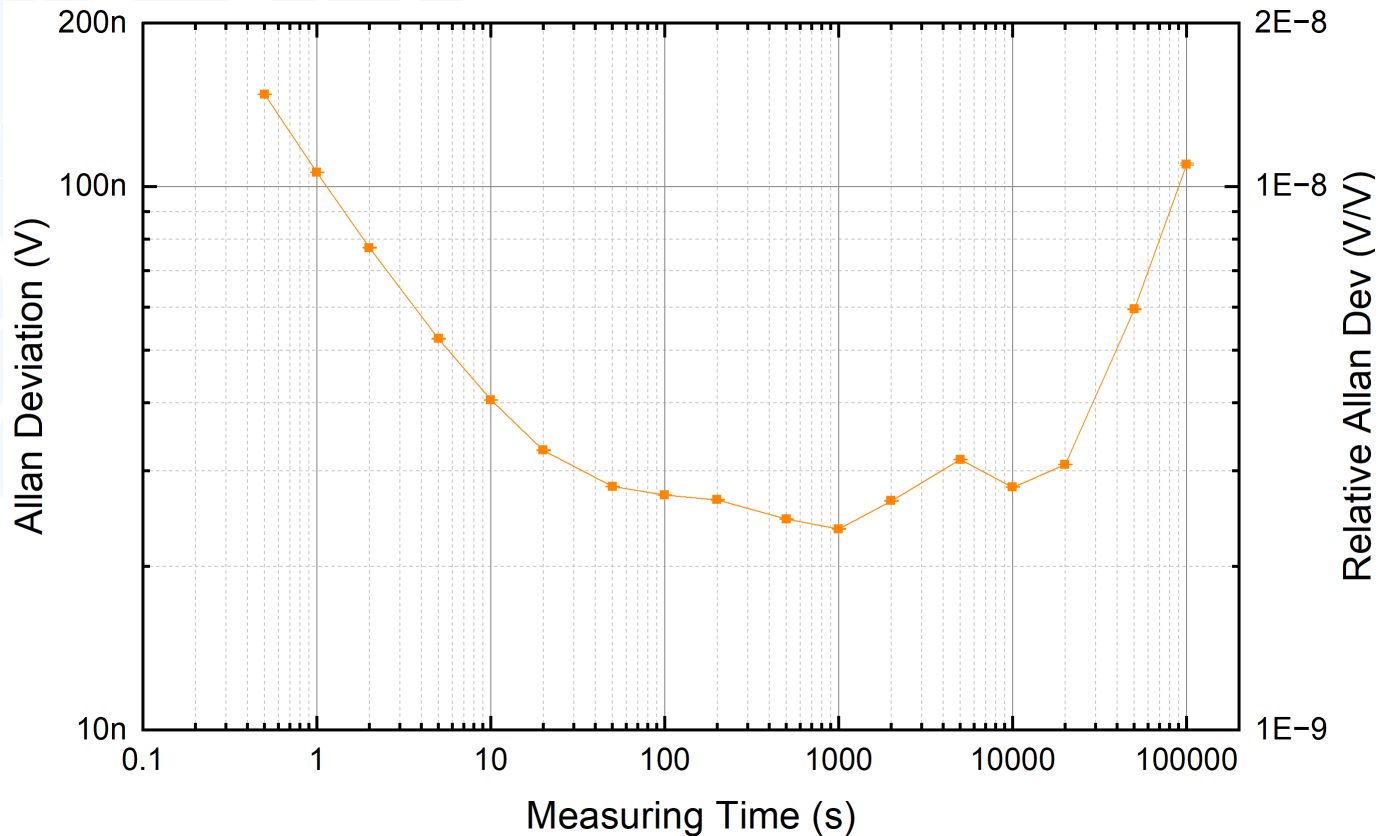


16x  
LTZ1000



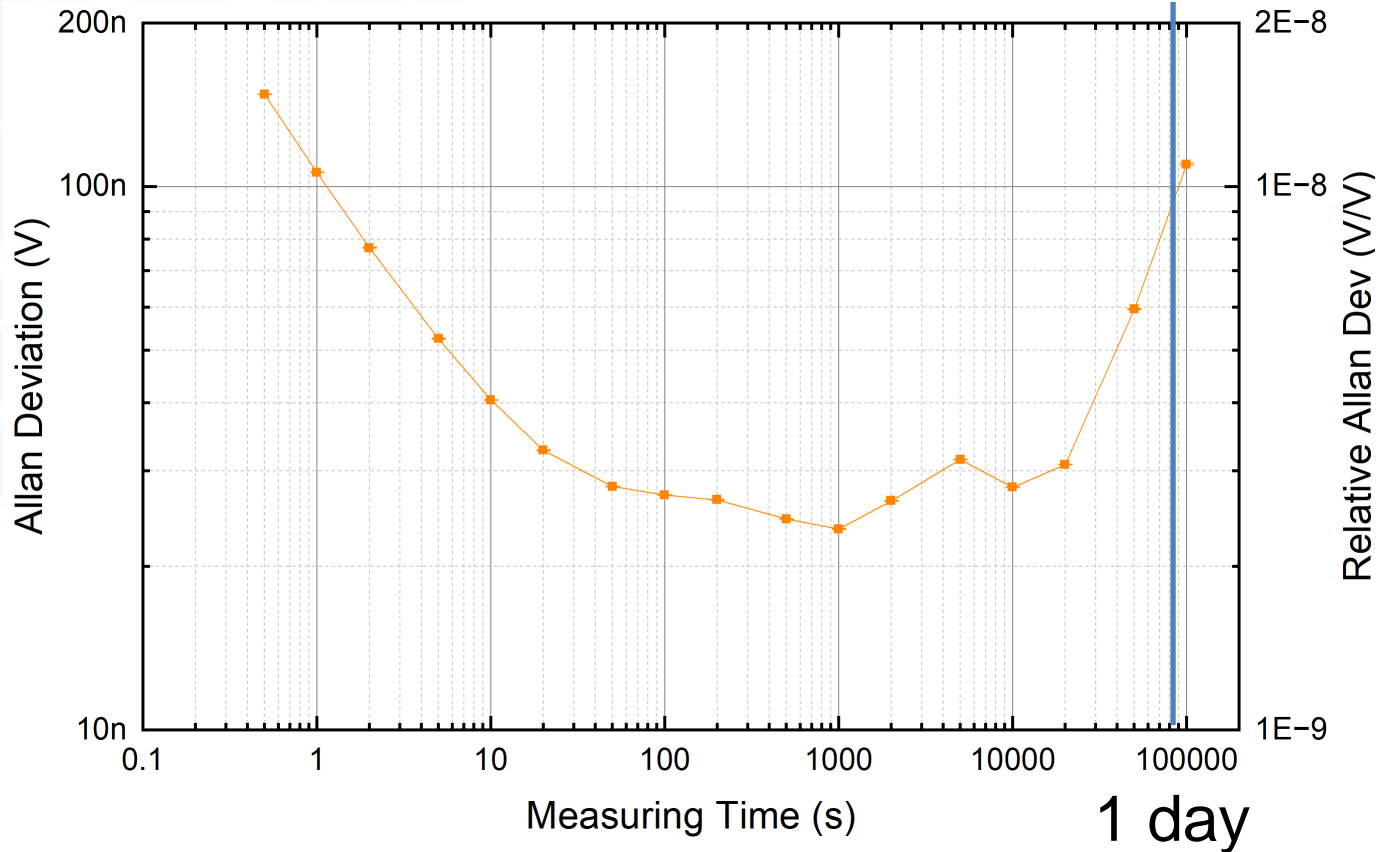


# Voltage measurements



1xADR1000

# Voltage measurements



1xADR1000

- 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



# Acknowledgment



Ralf Behr  
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John Pickering







Genauigkeit

Objektivität

Leidenschaft



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