Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

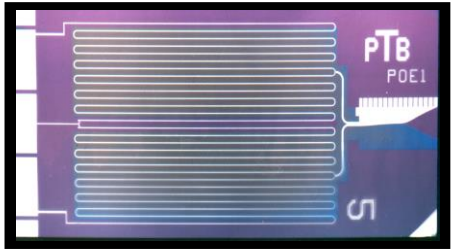
Overview on Josephson based applications

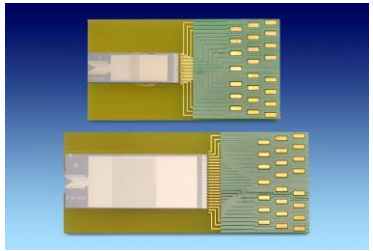
Ralf Behr

EURAMET DC&QM Meeting, on-line, 2-3 June 2021

Outline

1. Introduction
2. Josephson based applications
3. PJVS frequency range extension
4. Evaluation of Josephson based AC voltage standards

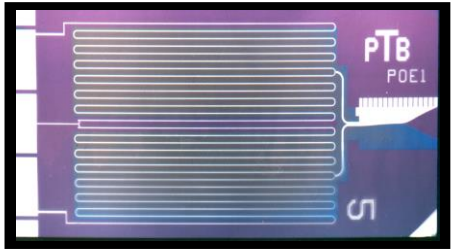




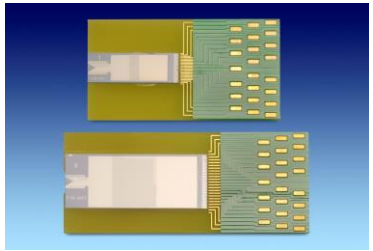
Josephson voltage standards

1. Conventional Josephson Voltage Standards - JVS
2. Programmable Josephson Voltage Standards - PJVS
3. Pulse-driven JVS = JAWS (Josephson Arbitrary Waveform Synthesizer)

JVS



PJVS



JAWS

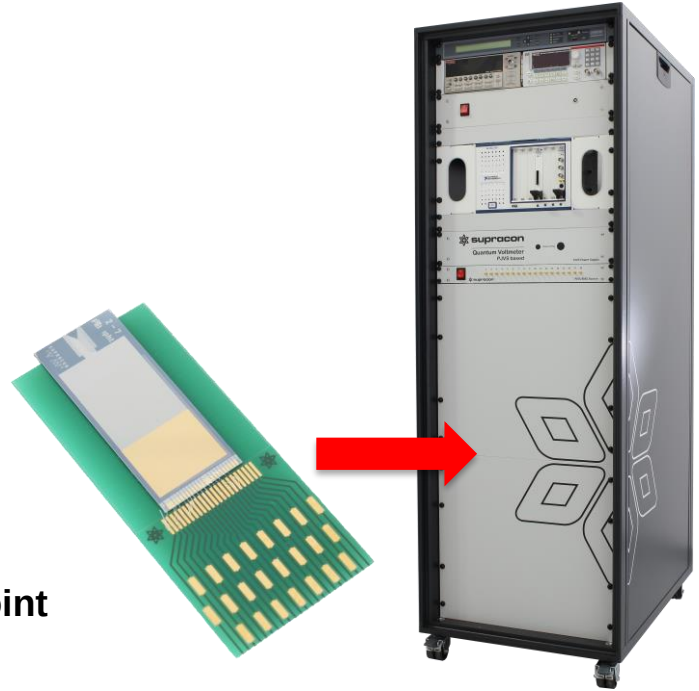
Josephson voltage standards

Frequency-Voltage-Converter: $V = N \cdot (h/2e) \cdot f$

10 V DC: worldwide > 100 systems
3 in European calibration labs!

Quantum voltage effect commercially available!
Hypres Inc., Supracon AG, NIST

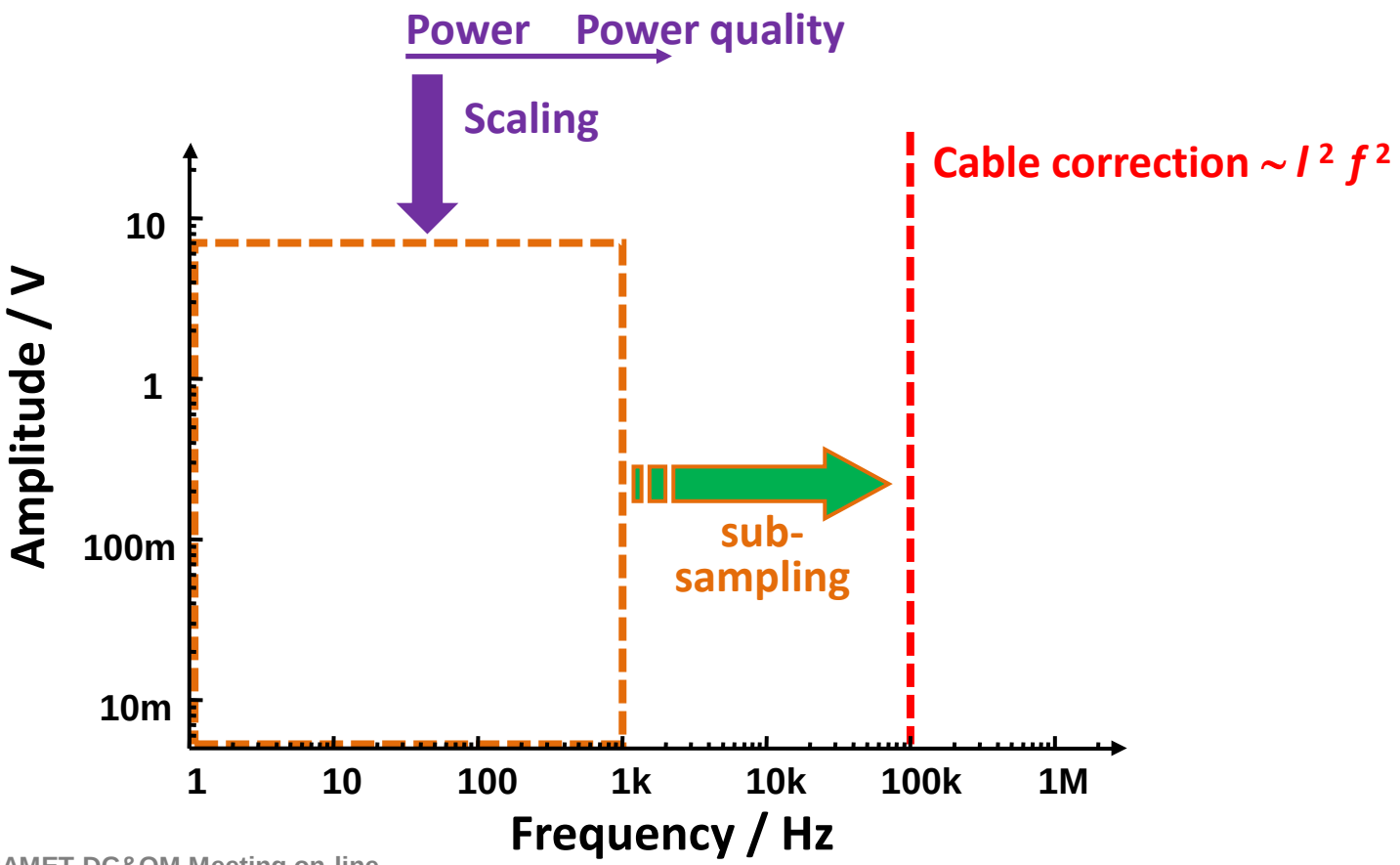
- **fully automated including internal test routines**
- **directly traceable to SI**
- **very low uncertainties:**
  DC 0.1 nV/V
  AC < 10 nV/V up to 500 Hz
- **highly efficient - measurement time is 1 minute per point**
- **versatile**



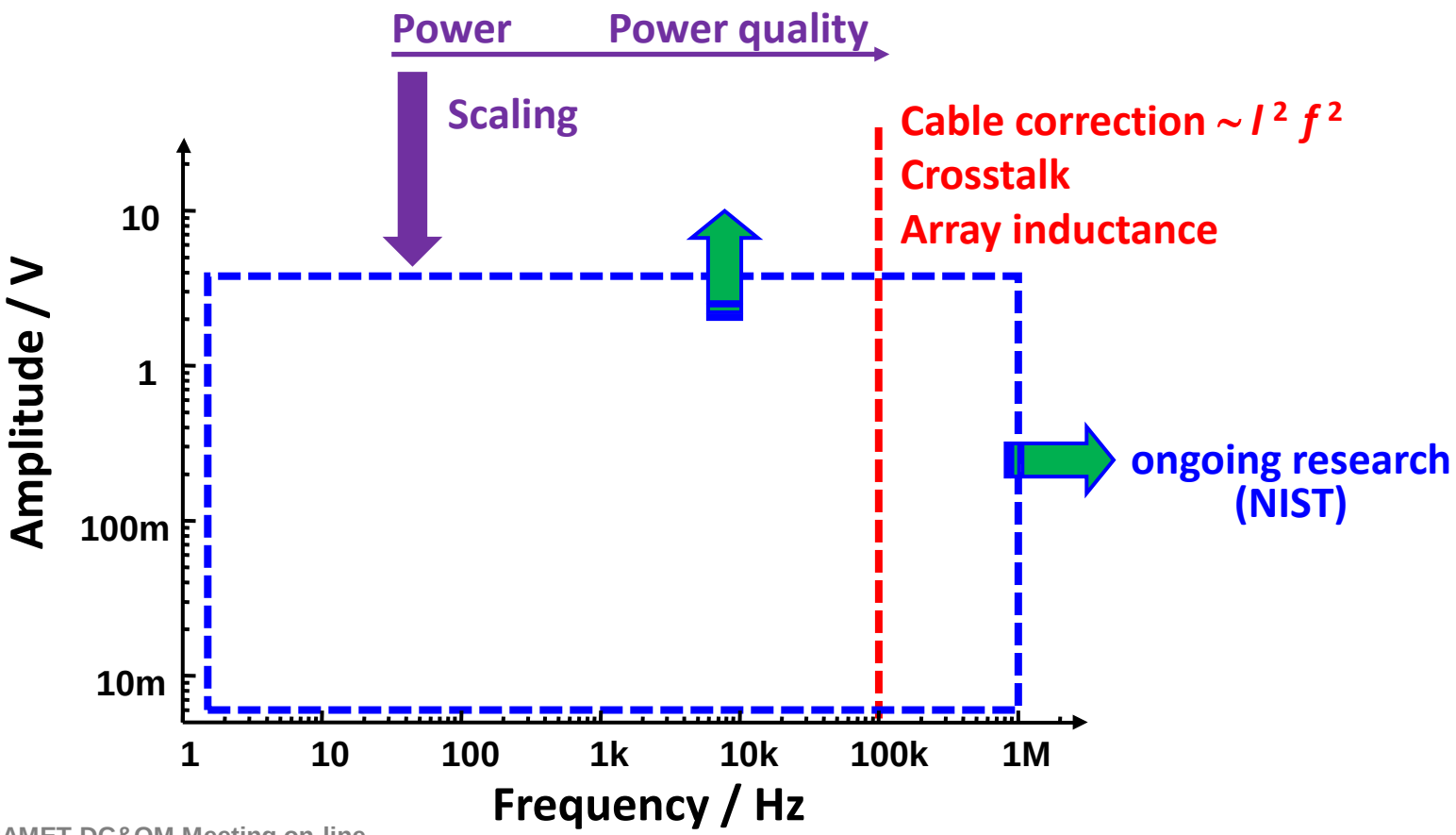
DC voltage calibration: Zener, voltmeter, Kibble balances, …

AC voltage application

PJVS – state of the art / challenges



JAWS – state of the art / challenges



Metrological applications

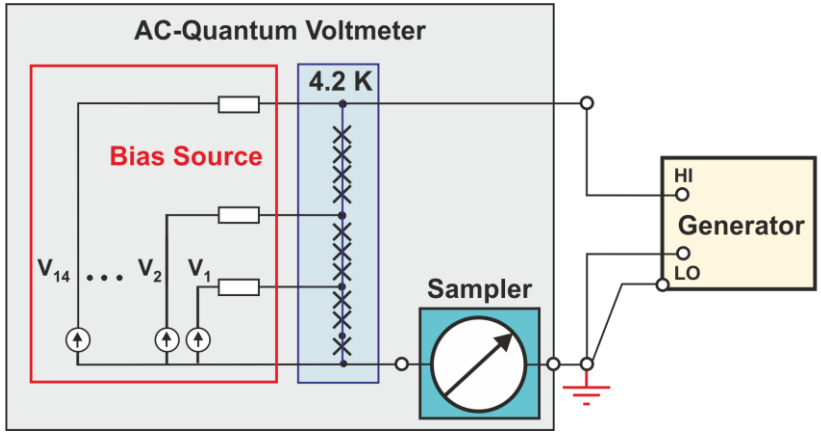
	JVS	PJVS	JAWS	Talks
+ DC voltage calibration (10 V)	✓	✓	(✓)	
+ DC voltmeter linearity (10 V)	✓	✓	✓ (nV)	
+ Quantum reference	(✓)	✓	✓	
+ AC voltage calibration (Power)	-	✓	✓	Helge Malmbekk
+ AC-DC transfer	-	(✓)	✓	
+ Impedances bridges	-	(✓)	✓	Stephan Bauer
+ Phase standard	-	-	✓	Stephan Bauer
+ Divider calibration / combination	-	(✓)	✓	Ilya Budovsky
+ JNT	-	-	✓	Marco Kraus
+ new quantum applictions …	-	-	✓	Jaani Nissilä

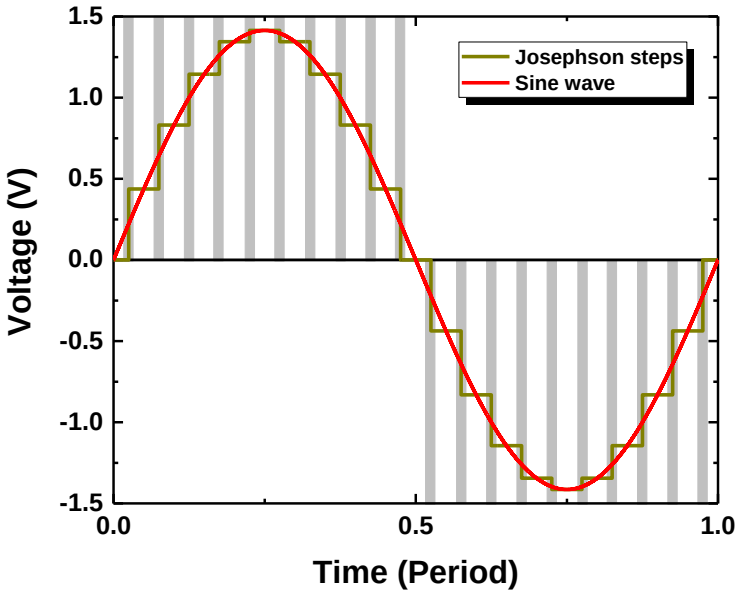
JAWS is the most flexible Josephson Voltage Standard.

Finally JAWS will be able to replace all other Josephson systems !

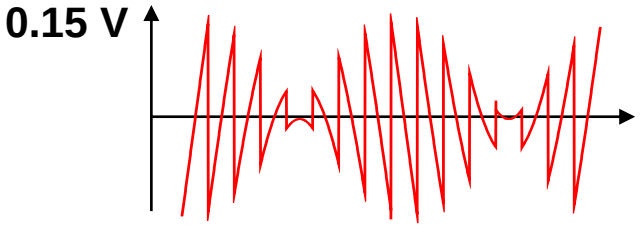
PJVS differential sampling

Set-up



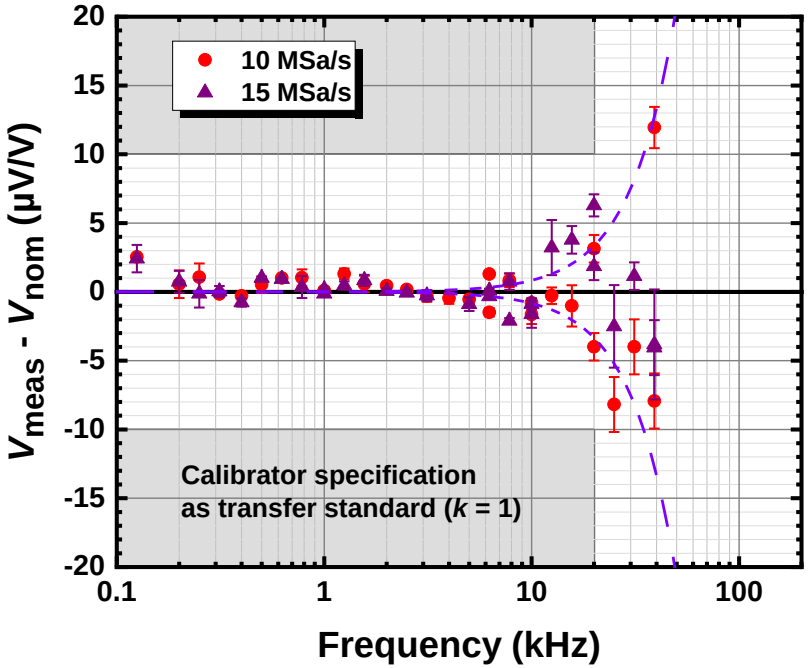


- Synchronization is crucial
- Sampler to measure differential signal →

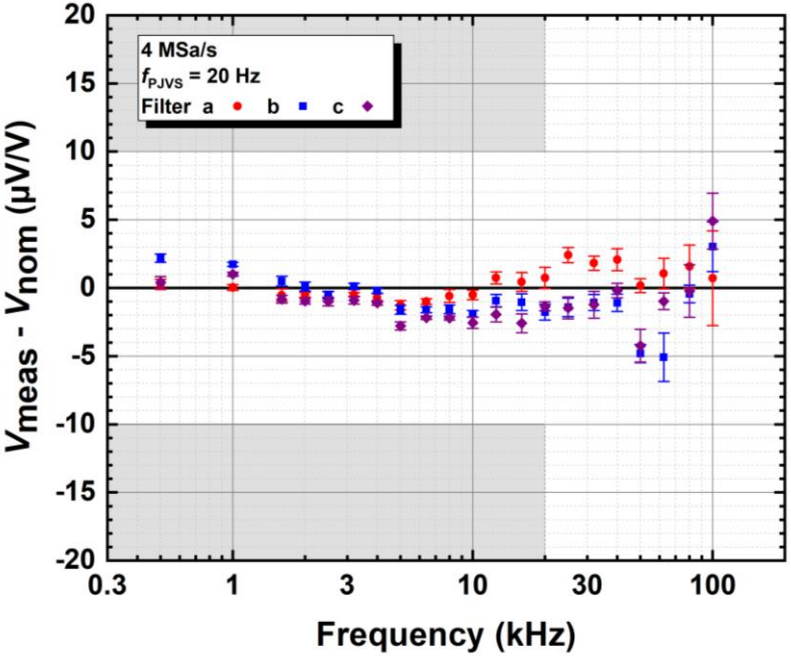


PJVS sampling up to 100 kHz

Differential sampling



Differential sub-sampling

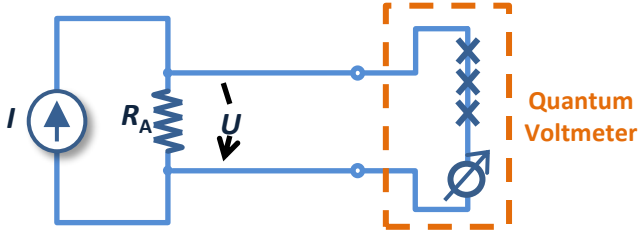


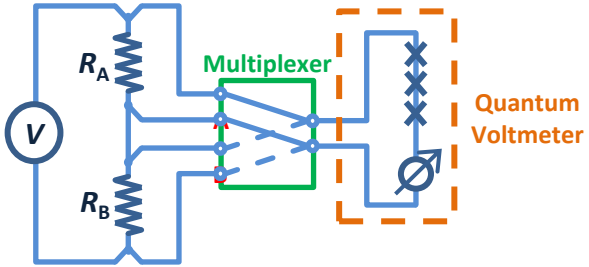
- **All data up to 100 kHz are within ±5 µV/V**

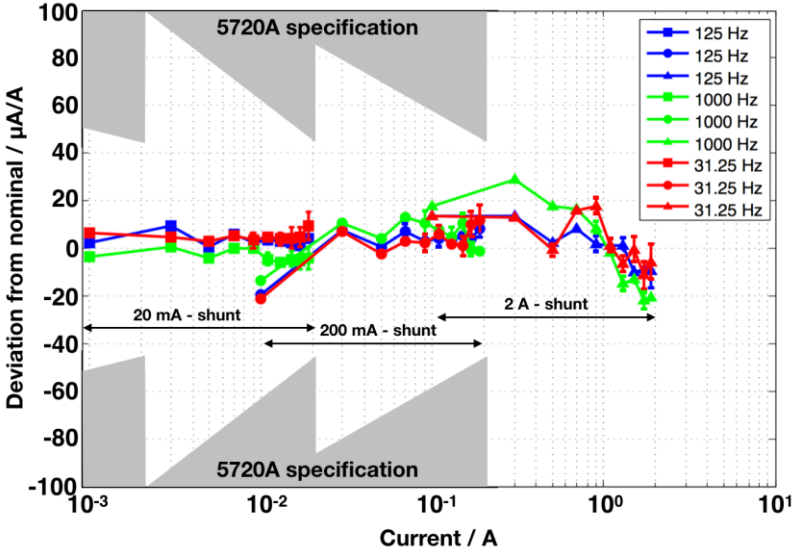
R. Behr und L. Palafox, Metrologia 2021

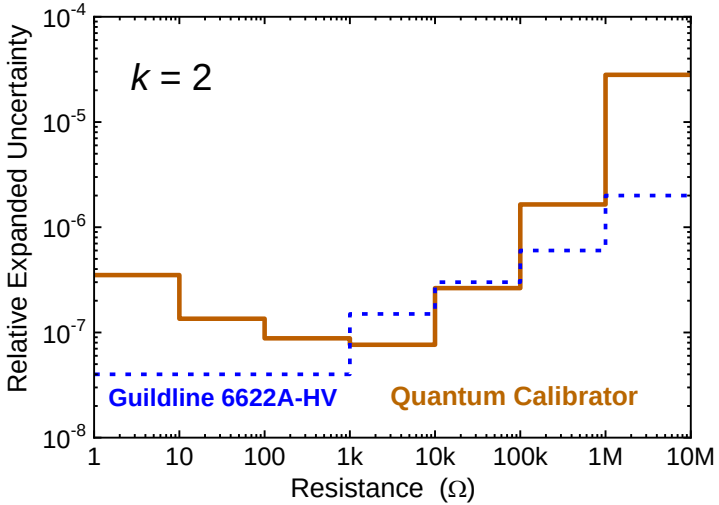
AC quantum voltmeter

+ calibrated resistor → extends application range









How to evaluate your JVS?

Evaluation by comparisons

DC

Indirect with Zener references → **limited uncertainty due to transfer standard, typically 50 nV/V**

Direct by BIPM on-site comparison → **see BIPM website, typically < nV/V**

How to do it for AC?

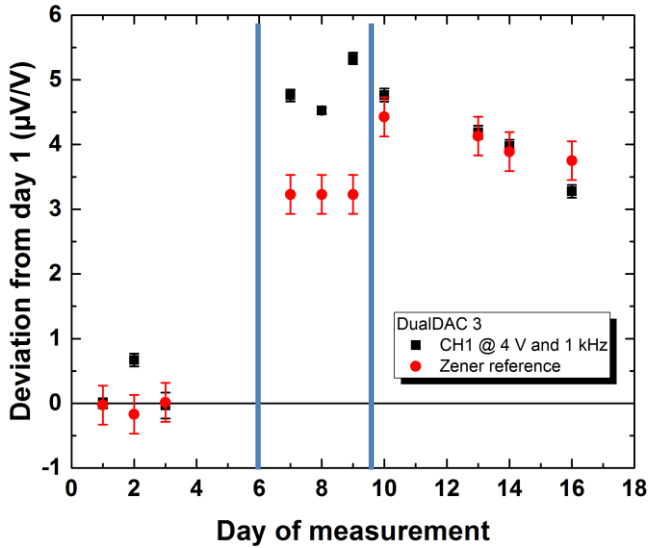
Indirect or direct?

By an on-site comparison?

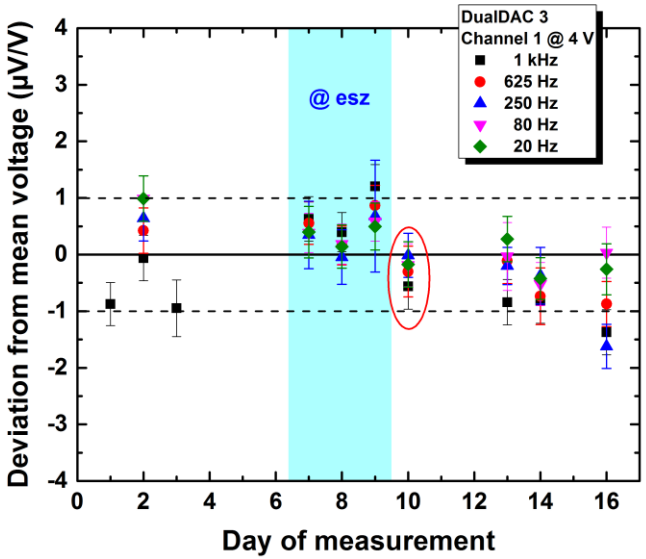
What uncertainty would you expect?

Indirect with transfer standard

Calibration Data for Aivon Oy DualDAC 3:



Correction of Zener reference drift



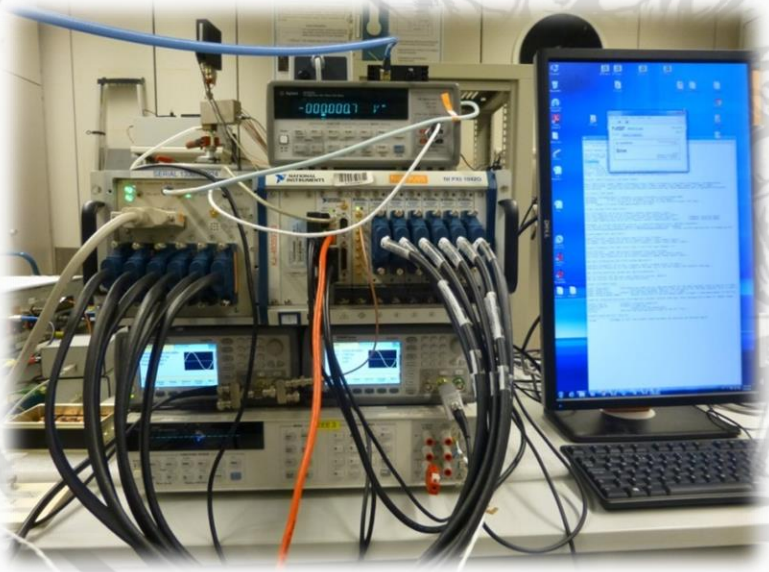
- Correlation between drift of Zener reference and output voltage
- Nearly all data within a band of 1 µV/V

Progress on the future BIPM on-site comparison program for Josephson ac voltage standards

Report to the CCEM-WGLF - 8 April 2021 and CPEM 2020 talk

Stephane Solve (BIPM)

Mun Seog Kim (KRISS)
Luis Palafox (PTB)
Ralf Behr (PTB)
Ilya Budovsky (NMIA)
Gleb Gubler (VNIIM)
Paul Dresselhaus (NIST)
Alain Rüfenacht (NIST)



BIPM – Transportable PJVS

Bureau International des Poids et Mesures

BIPM comparisons: Pilot Studies (2015-2019)

NMI PJVS Differential Sampling ⟷ **AC Source Transfer Standard** ⟷ **BIPM PJVS Differential Sampling**

Evaluation

- **Hardware**
- **Software**

7 V RMS at 62.5 Hz

NMIJ – 2015 (failed)

CENAM – 2016

PTB – 2017

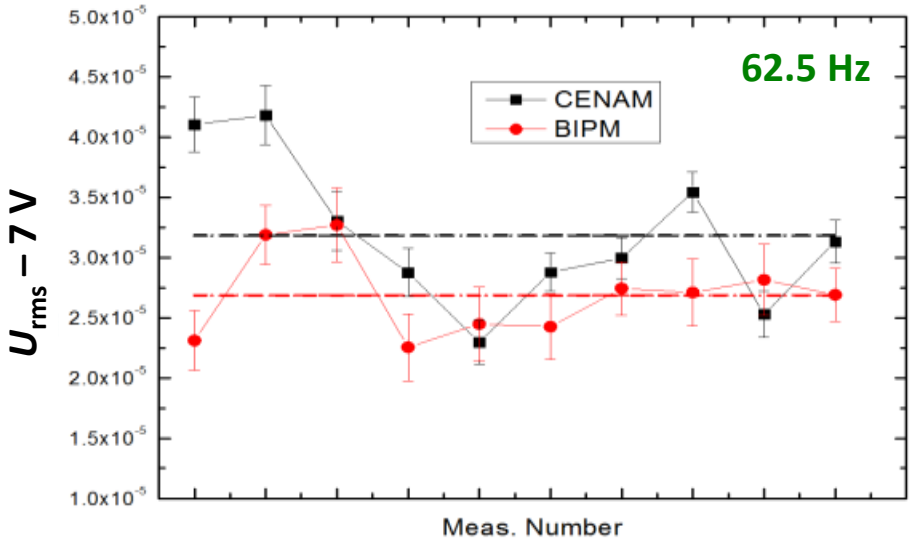
NMIA, VNIIM, KRISS – 2018

NMIA, VNIIM, PTB, KRISS – 2019

What uncertainties can be achieved?

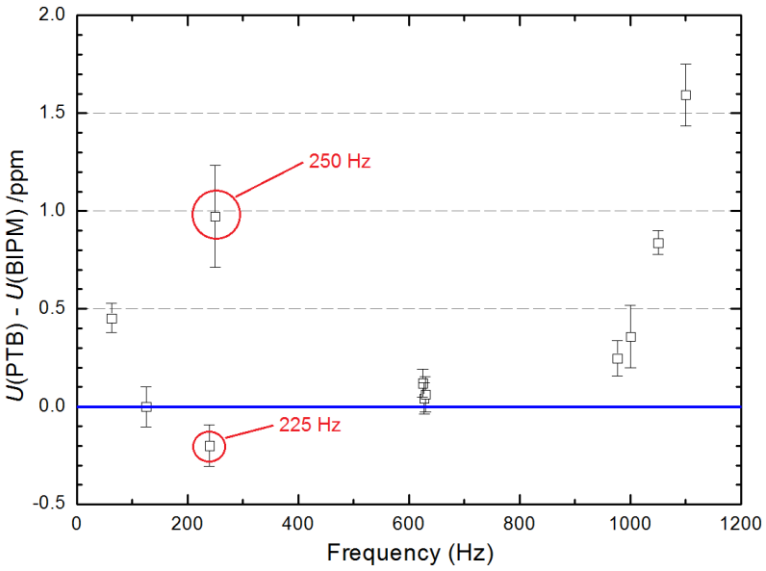
BIPM comparisons: Pilot Studies (2015-2019)

CENAM - 2016



Commercial calibrator typical results: a few 10^{-7} (with a Type A uncertainty of the same order)

PTB - 2017

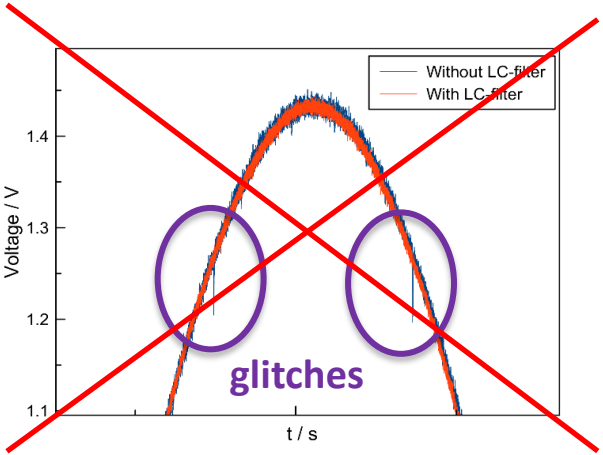


Can we do better with other transfer standards?

Transfer standard requirements

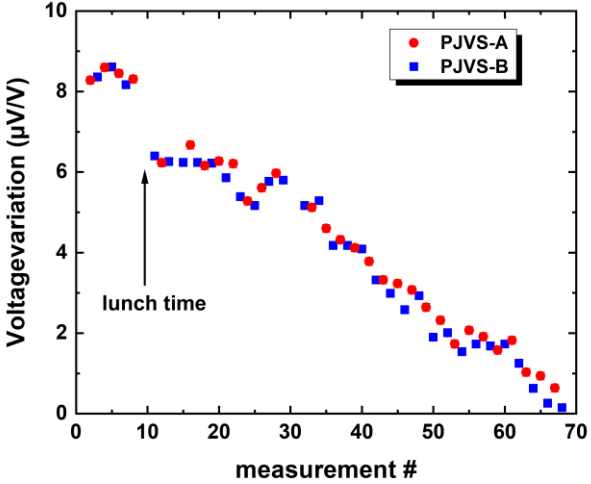
- Pure sinewaves
- Good stability

Filter → drift of transfer standard?
how to trace the drift?

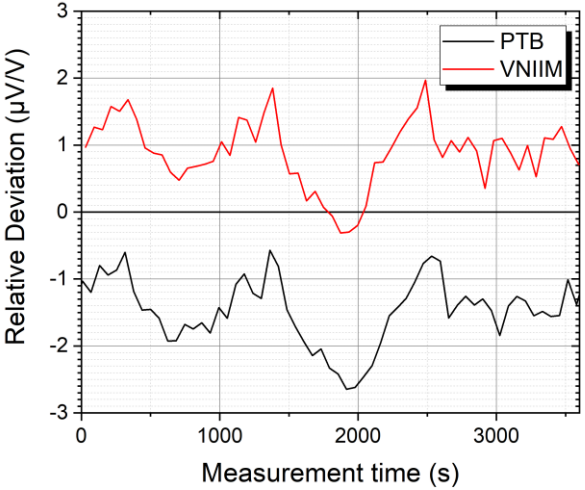


No chance!

…between the 2 systems

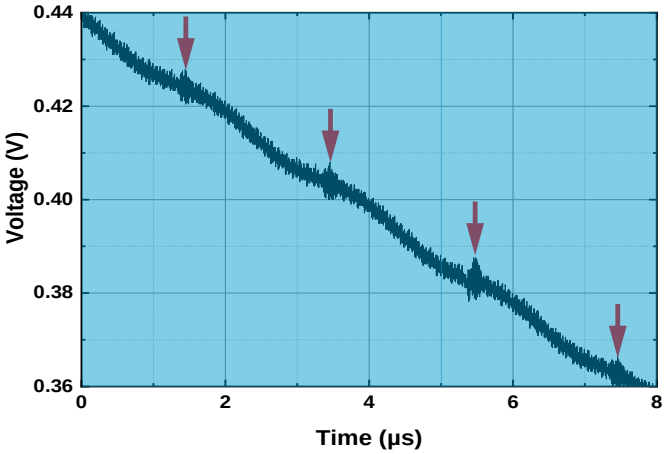


…with an extra sampler

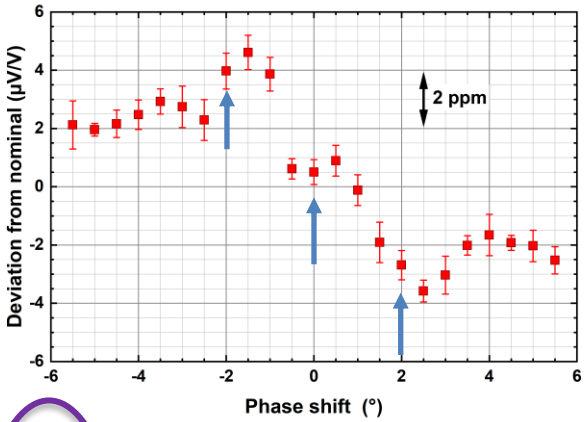


Transfer standard requirements

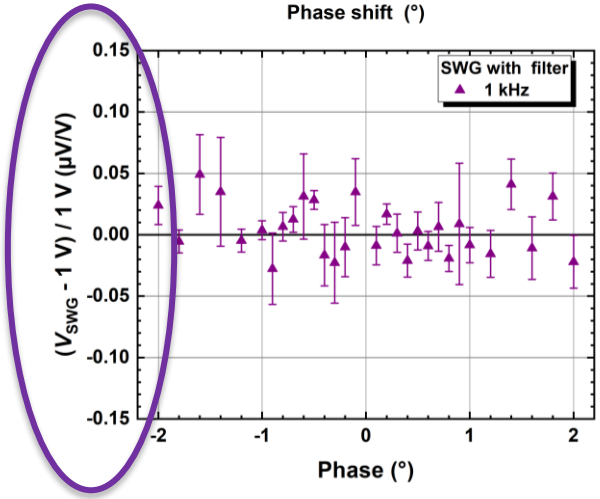
- Digital sources



Phase shift of the measurement



unsatisfying



perfect !

Suggestions for an on-site BIPM ac voltage comparison protocol

4 different frequencies: 62.5 Hz, 125 Hz, 625 Hz, 1020 Hz

2 amplitudes: 0.707 V_{RMS} and 7 V_{RMS}

Flexible BIPM PJVS system: **master/slave option**
two different samplers
different transfer standards

To be discussed in a CCEM task group

Conclusions

- **Increasing number of Josephson-based applications**
- **Finally, JAWS will be able to replace all other Josephson voltage standards – but will not always be required**
- **Sub-sampling with PJVS works up to 100 kHz within ± 5 µV/V (1 minute) - cable errors limit the uncertainty**
- **CCEM task group is working on an on-site BIPM ac voltage comparison protocol**

Acknowledgement

Thank you !

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

This work has received funding from the iMERA/EMRP/EMPIR programmes co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

Acknowledgement

Stephan Solve

Paolo Durandetto

Jaani Nissilä

Ilya Budovsky

Jan Kucera

Philip Fleischmann
Ludwig Schaidhammer

Marco Schubert
Michael Starkloff

PTB Technology

O. Kieler, F. Müller,
R. Wendisch, T. Weimann, H. Tian
P. Duda, R. Gerdau, K. Störr,
J. Felgner, J. Kohlmann,…

PTB Applications

L. Palafox, J. Lee, M. Bauer, S. Bauer, J. Herick, M. Kraus, H. Preißler, S. Gruber, V. Bürkel, G. Muchow, J. Schurr, T. Funck, E. Mohns, F. Ahlers, …and others

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
Bundesallee 100
38116 Braunschweig

Dr. Ralf Behr
Telefon: 0531 592-2630
E-Mail: ralf.behr@ptb.de
www.ptb.de

Stand: 06/21