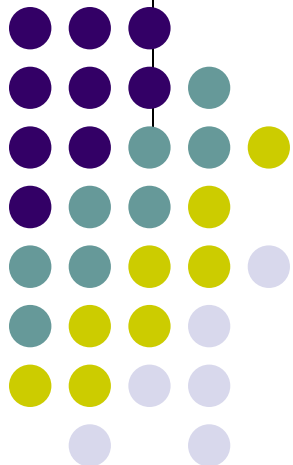


# Towards Uniformity of DC Voltage Metrology within SIM

Yi-hua Tang

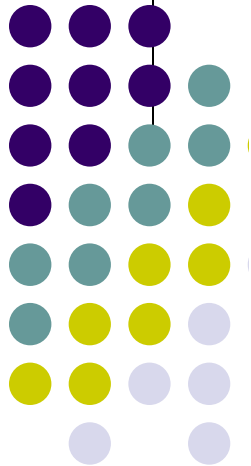
Quantum Electrical Metrology Division  
National Institute of Standards and Technology  
Gaithersburg, MD 20899





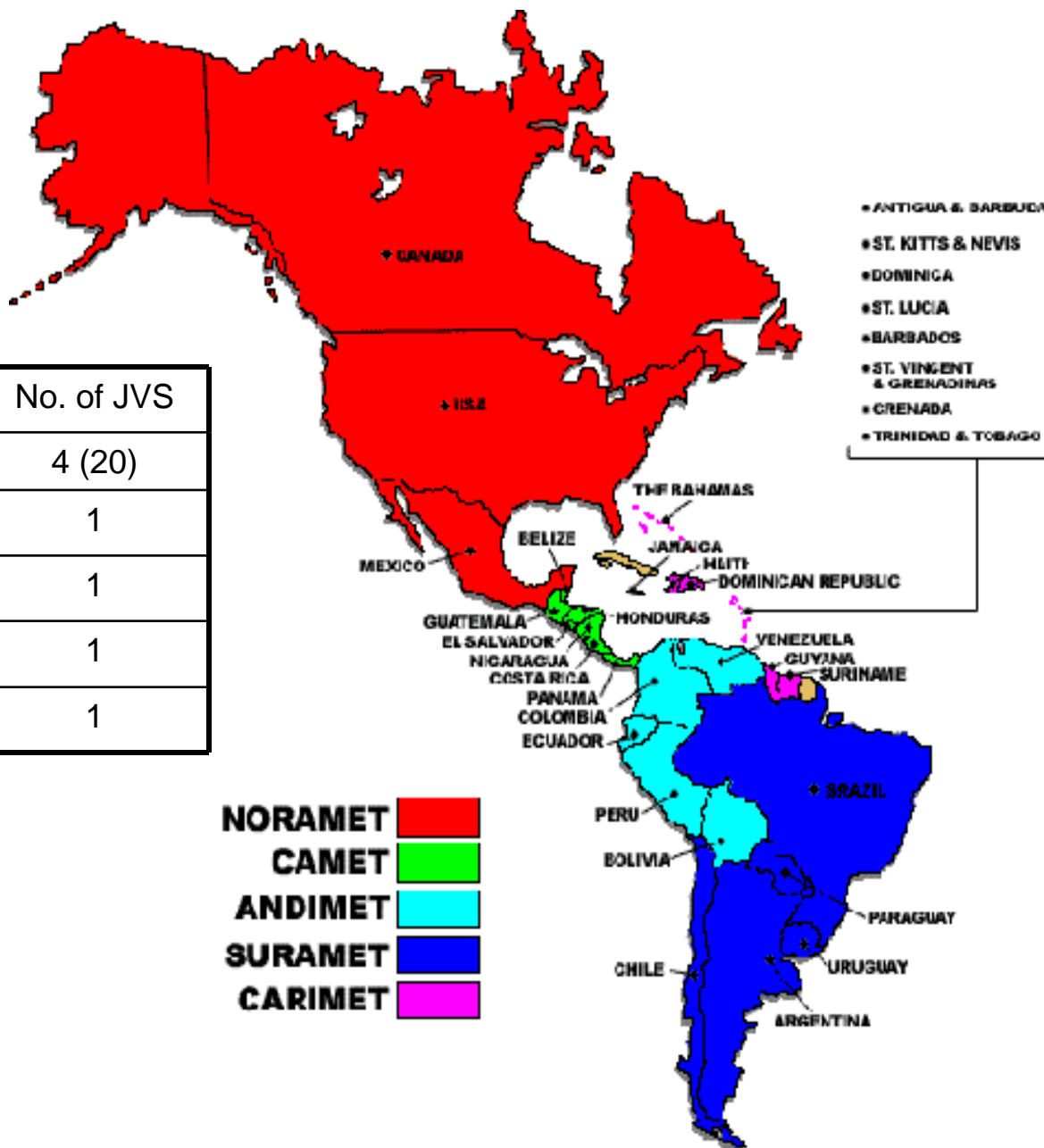
# Outline

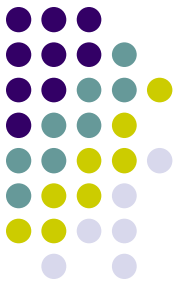
- DC voltage metrology status within SIM
- JVS Comparison
  - MAP
  - Indirect comparison
  - Direct comparison
- Summary
- Future perspective





Lab / Country	No. of JVS
NIST / USA	4 (20)
NRC / Canada	1
CENAM / Mexico	1
INMETRO / Brazil	1
INTI / Argentina	1





## Principle of JVS

$$V = nf / K_{J-90}$$

$f$ : frequency

$K_{J-90} = 2e/h = 483\,597.9 \text{ GHz/V}$  Josephson constant

$n$ : integer

BIPM.EM-K10.a

BIPM.EM-K10.b

BIPM.EM-K11.b

SIM.EM.BIPM-K11.a

SIM.EM.BIPM-K11.b

SIM.EM.BIPM-K10.b

JVS at 1.018V

JVS at 10 V

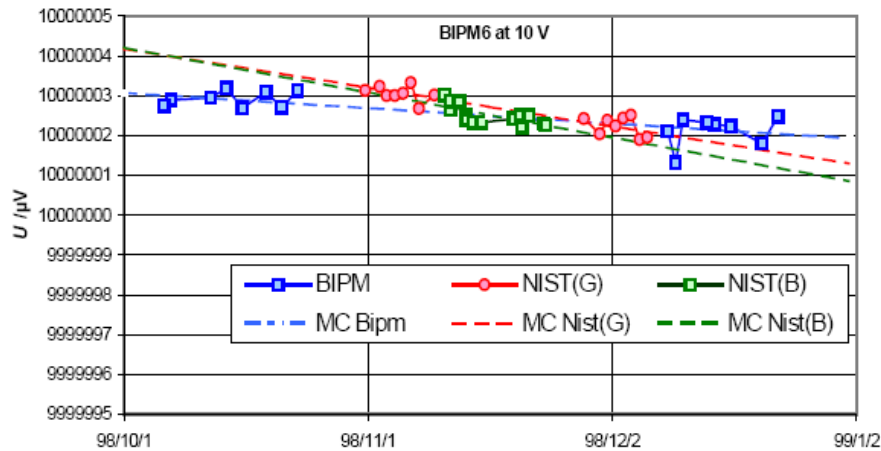
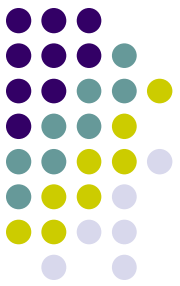
Zener at 10 V

Zener at 1.018 V

Zener at 10 V

JVS at 10V

# MAP Example 1: NIST-BIPM JVS comparison at 10 V



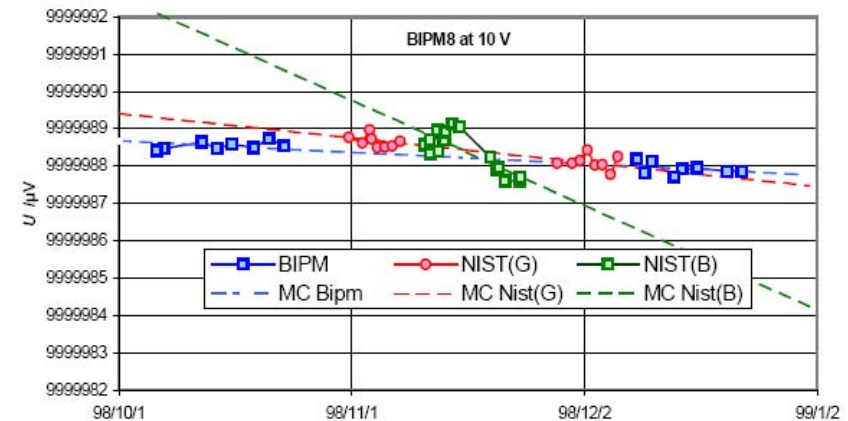
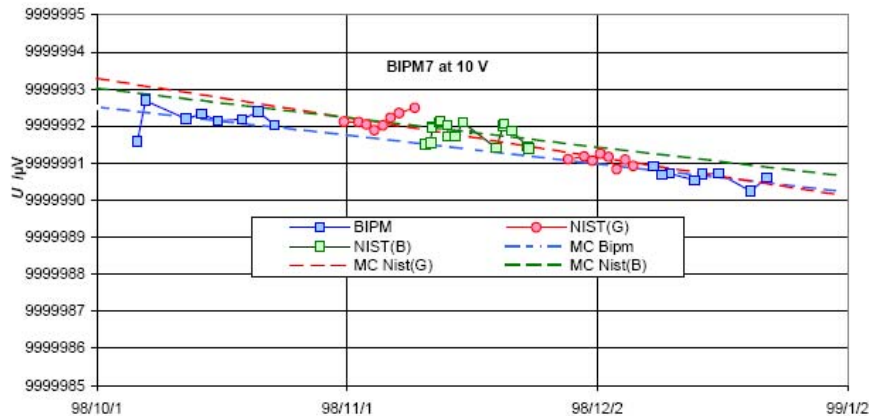
**3 system comparison:**  
*BIPM*

*NIST-Gaithersburg*

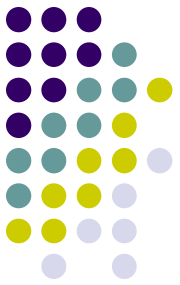
*NIST-Boulder*

*Oct. 1998 – Jan. 1999*

*BIPM.EM-K11.b*



Pressure corrections applied.



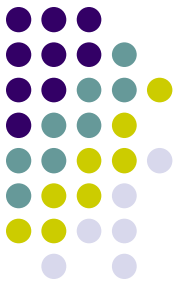
## Results of *BIPM.EM-K11.b*

	$d$ ( $\mu\text{V}$ )	$u_c$ ( $\mu\text{V}$ ) ( $k = 1$ )
NIST(G) - BIPM	0.26	0.14
NIST(B) - BIPM	0.22	0.17
NIST(G) – NIST(B)	0.04	0.13

Uncertainty: 1 - 2 parts in  $10^8$

# INMETRO JVS system

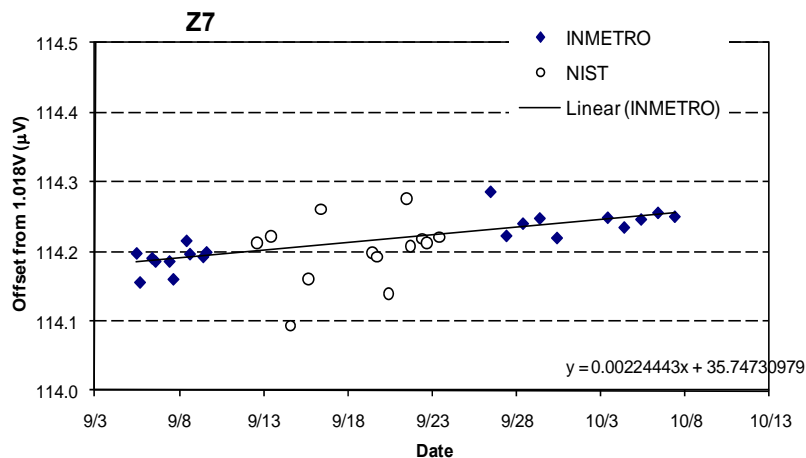
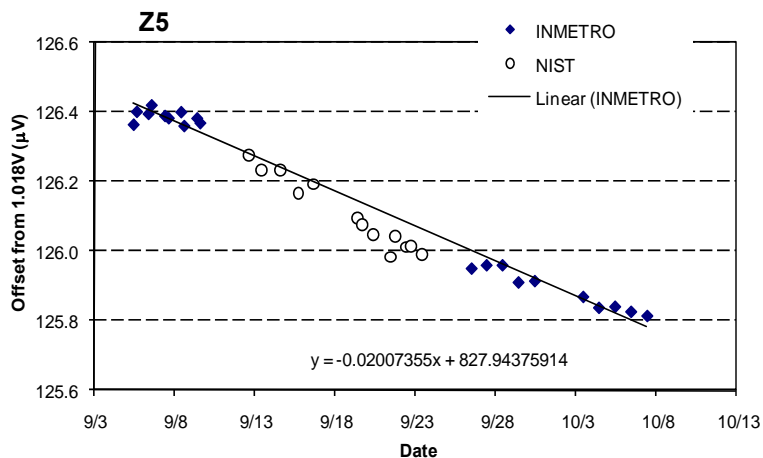
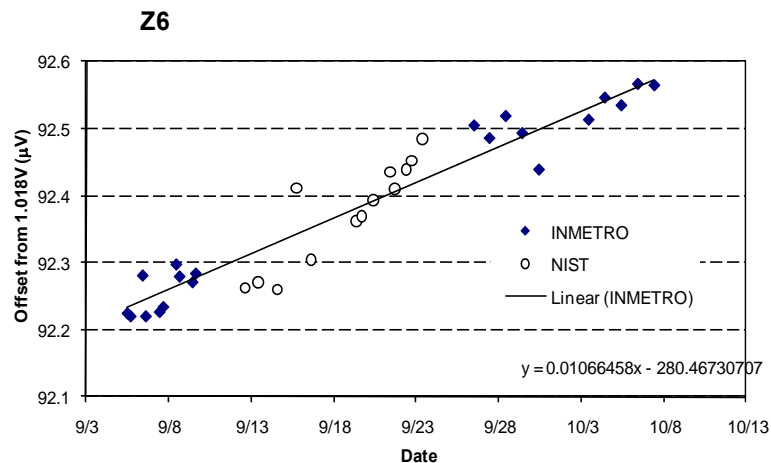
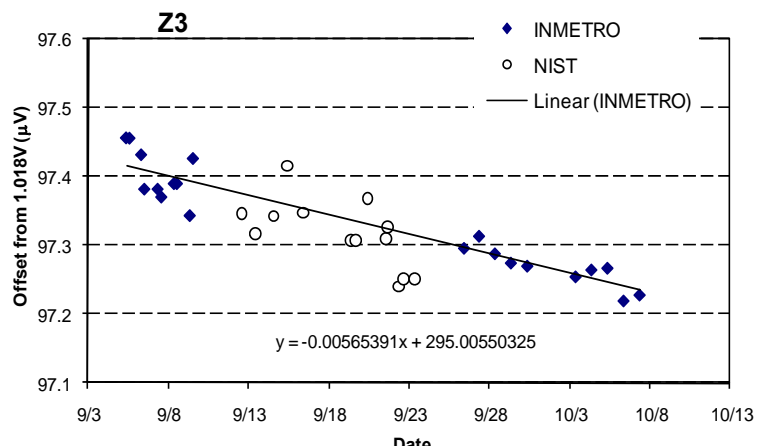
Established in 1998



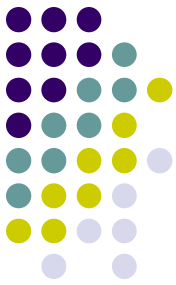
# INMETRO-NIST JVS Comparison at 1.018V

Sept. to Oct. 1999  
Protocol: MAP

SIM.EM.BIPM-K11.a







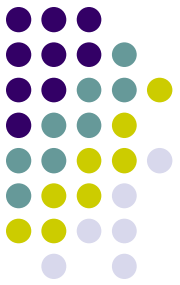
$$\Delta(INMETRO - NIST) = \frac{\sum_{i=1}^{13} [V_i(predict) - V_i(NIST)]}{13}$$

	Z3	Z5	Z6	Z7
INMETRO - NIST	0.023	0.052	0.001	0.013

$$Mean(INMETRO - NIST) = 0.022 \mu V$$

$$u_c = 2 \sqrt{(u_A^{INMETRO})^2 + (u_A^{NIST})^2 + \left(\frac{3.18}{2} u_B^{INMETRO - NIST}\right)^2 + (u_B^{INMETRO, NIST})^2}$$

Source	Uncertainty ( $\mu V$ )
Pooled Type A of INMETRO, $u_A^{INMETRO}$	0.003
Pooled Type A of NIST, $u_A^{NIST}$	0.006
Standard deviation of mean of four Zener differences $u_B^{INMETRO - NIST}$	0.011
Type B uncertainty from INMETRO and NIST JVS systems, $u_B^{INMETRO, NIST}$	0.016
Expanded uncertainty ( $k = 2$ )	0.049

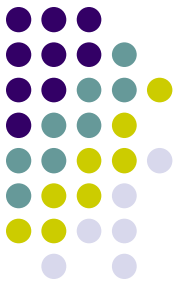


**Question:** Is MAP good enough for JVS comparison?

**Answer:** No

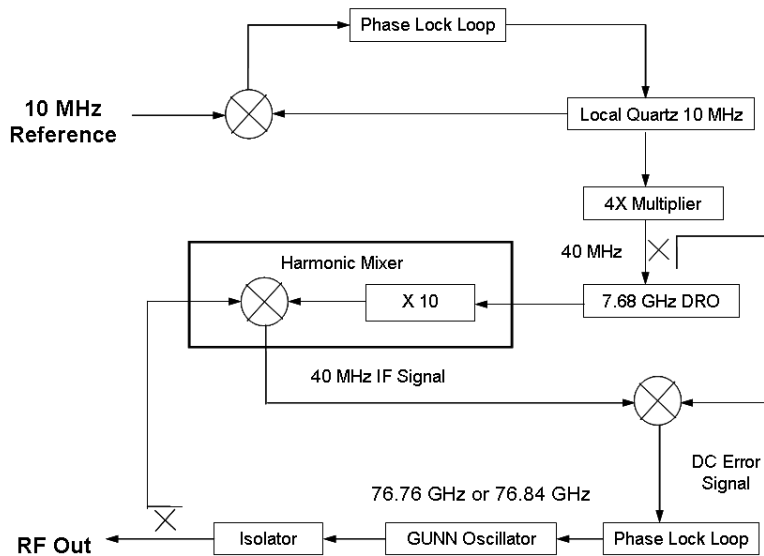
**Why?**

1. JVS uncertainty: few parts in  $10^{10}$   
MAP uncertainty: few parts in  $10^8$
2. Uncertainty using MAP limited by **Zener characteristics**
  - Environmental effects
    - Pressure
    - Temperature
    - Relative humidity
  - Zener intrinsic noise
  - Shipping impact



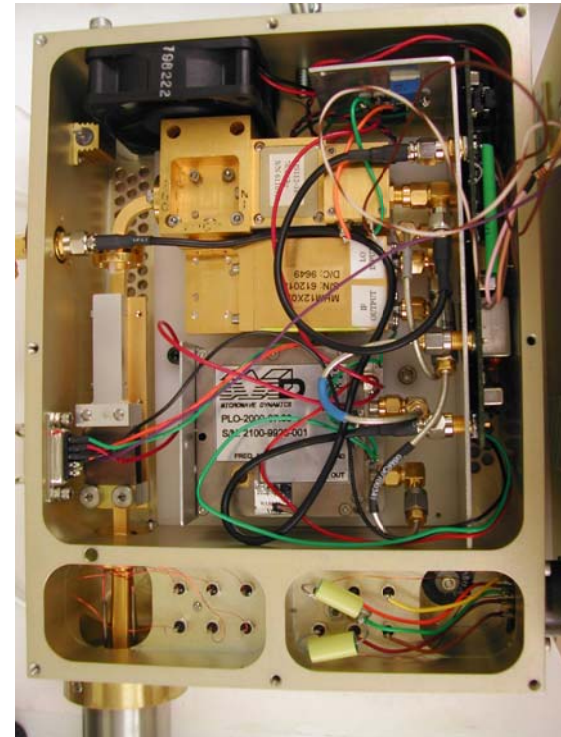
**Question:** How can we improve the situation?

**Answer:** Develop a transportable JVS



Net weight: 50 lb

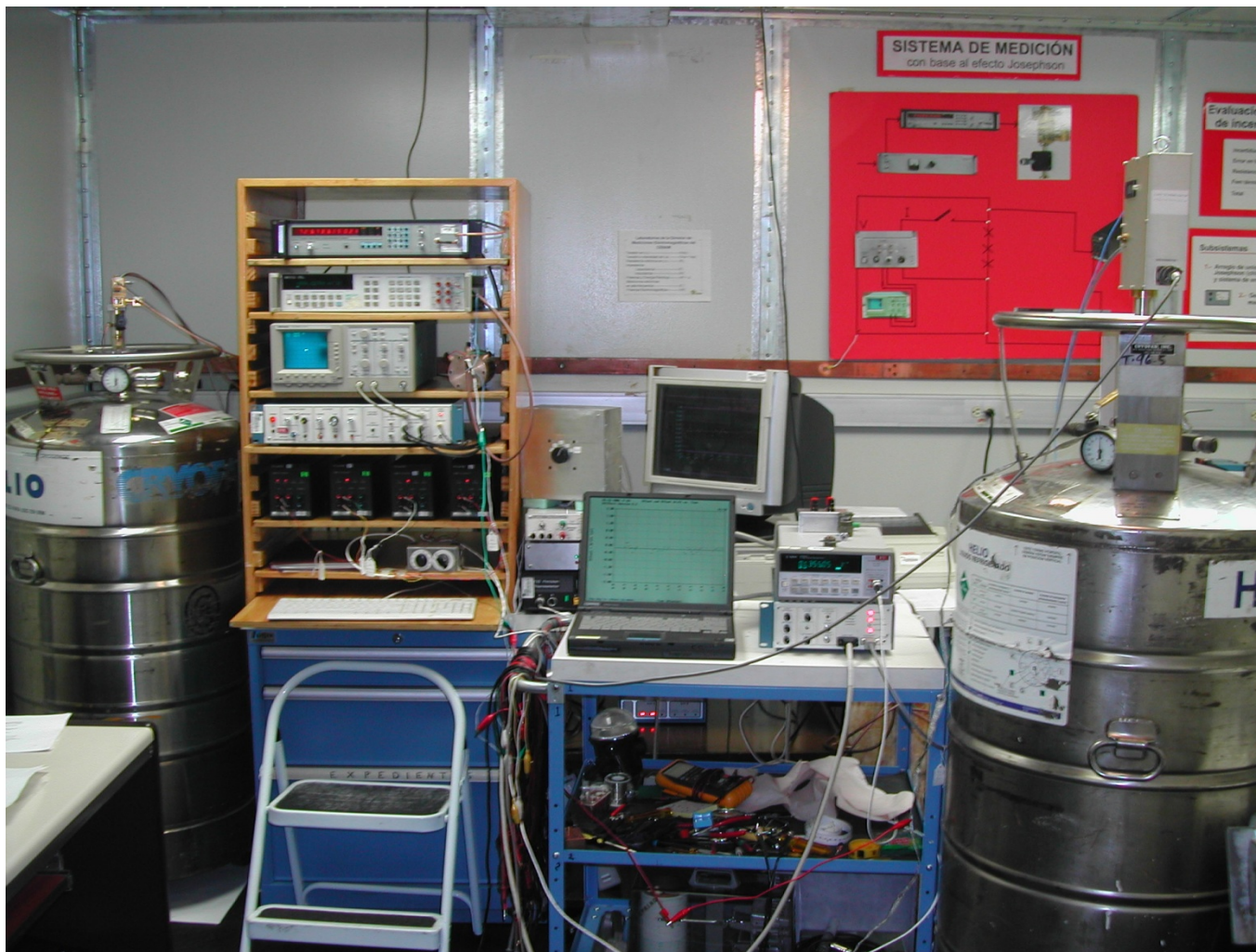
Gross weight: 120 lb



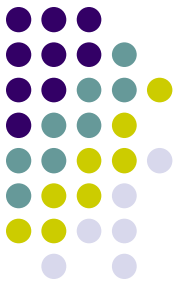
8.5"

# NIST-CENAM SIM.EM.BIPM-K11.b

NIST CJVS in CEMETRO, March 2006







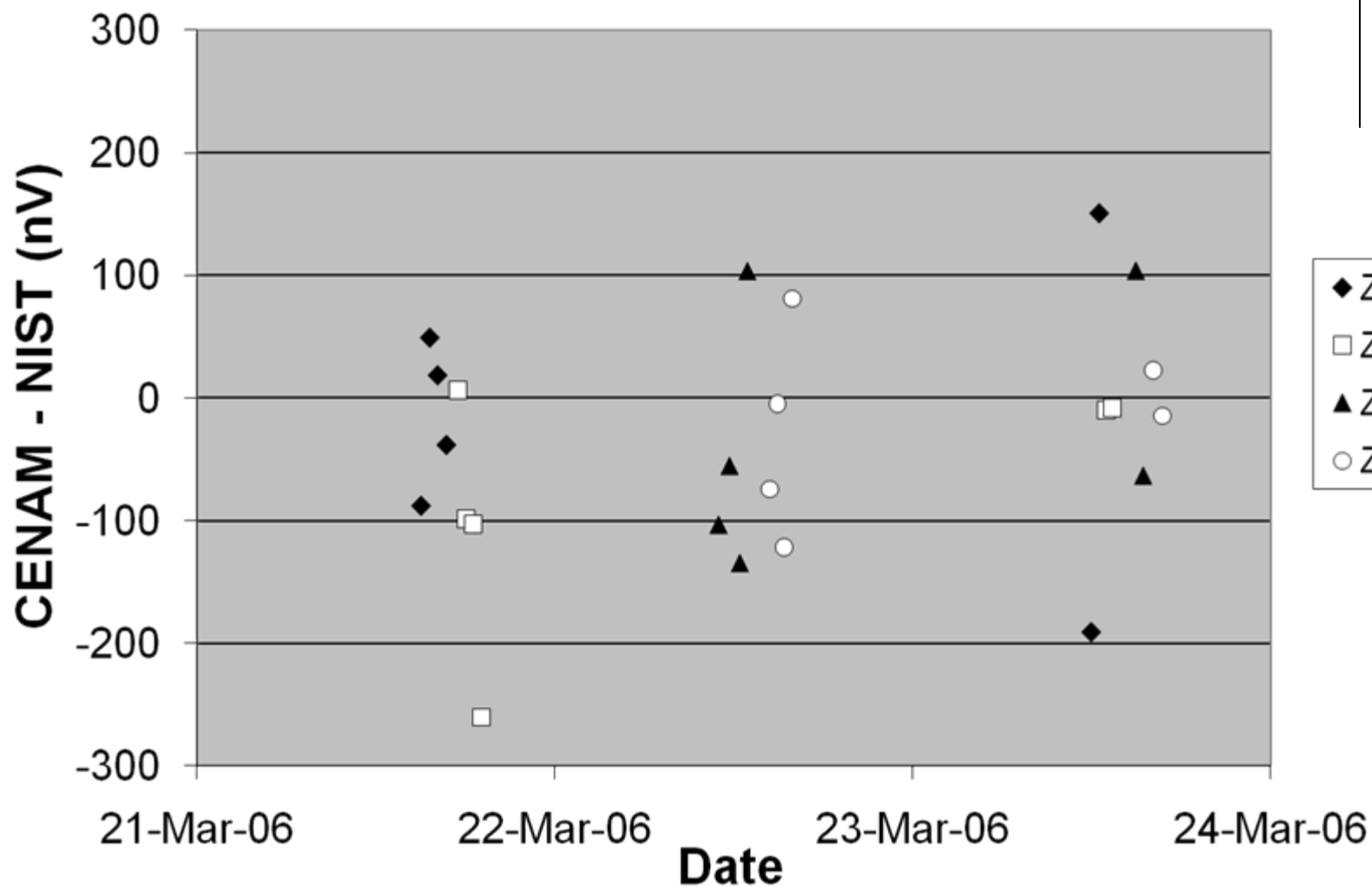
Yi-hua Tang

Enrique Navarrete

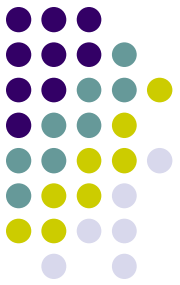
Dionisio Hernández

David Avilés

# Results of NIST-CENAM SIM.EM.BIPM-K11.b



No pressure correction needed.

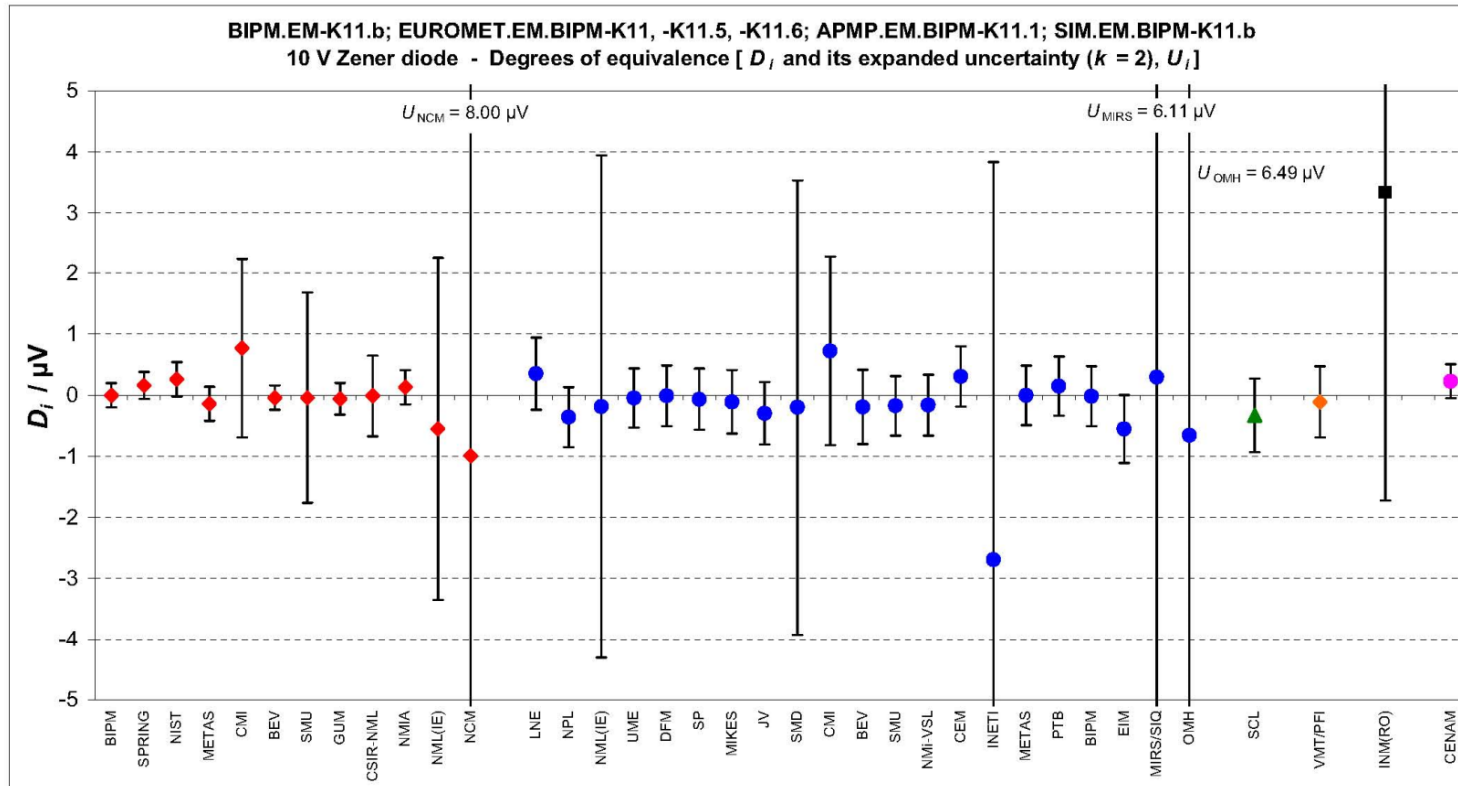
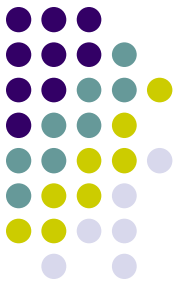


## To establish a link between CENAM and BIPM

$$D_{\text{CENAM-BIPM}} = (d_{\text{NIST-BIPM}} + d_{\text{CENAM-NIST}})$$

$$U_{\text{CENAM-BIPM}} = (U_{\text{NIST-BIPM}}^2 + U_{\text{CENAM-NIST}}^2)^{1/2}$$

	$d$ ( $\mu\text{V}$ )	$u_c$ ( $\mu\text{V}$ )
CENAM - NIST	-0.035	0.043
NIST - BIPM	0.26	0.28
CENAM - BIPM	0.23	0.28



Red diamonds: participants in BIPM.EM-K11.b

Blue circles: participants in EUROMET.EM.BIPM-K11

Black square: participant in EUROMET.EM.BIPM-K11.6 only

Green triangle: participant in APMP.EM.BIPM-K11.1 only

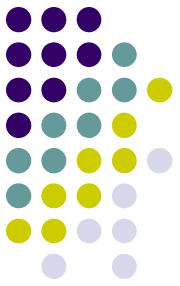
Orange diamond: participant in EUROMET.EM.BIPM-K11.5 only

Pink circle: participant in SIM.EM.BIPM-K11.b only

The BIPM key comparison database, August 2007

13/13





**Question:** Is indirect JVS comparison good enough?

**Answer:** No

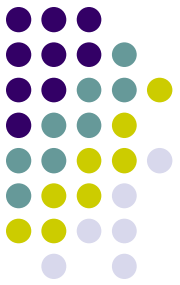
**Why?**

JVS uncertainty: few parts in  $10^{10}$

Indirect JVS comparison uncertainty: few parts in  $10^9$

Uncertainty limited by **Zener noise**

- ~~Environmental effects~~
  - ~~Pressure~~
  - ~~Temperature~~
  - ~~Relative humidity~~
- **Zener intrinsic noise**
- ~~Shipping impact~~

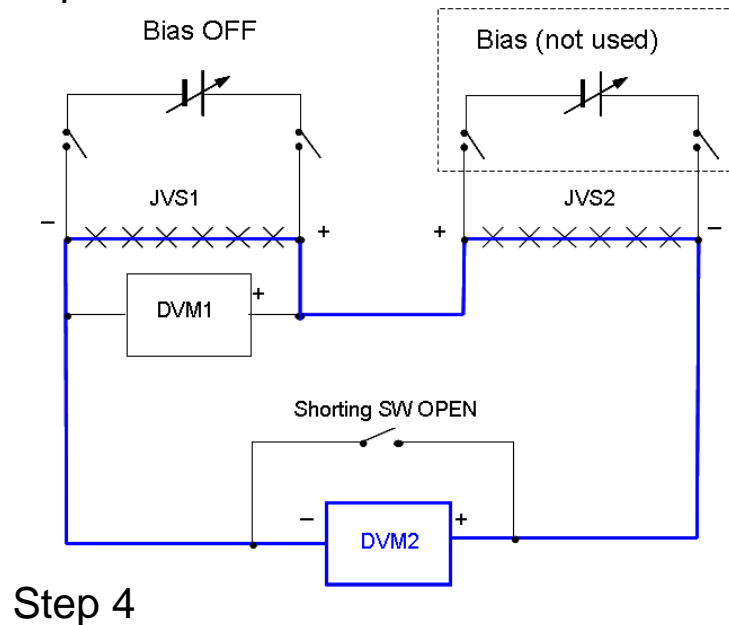
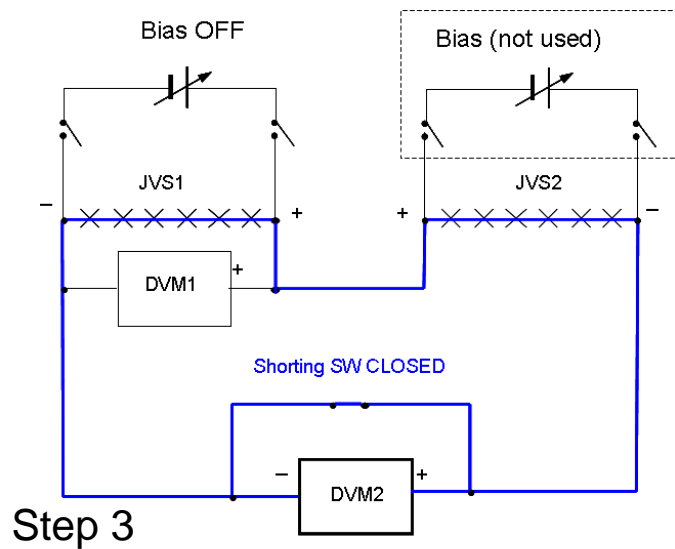
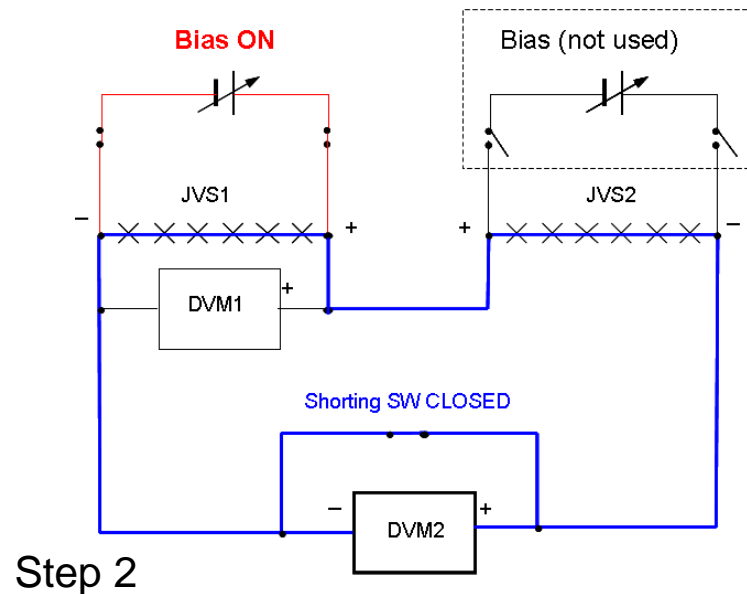
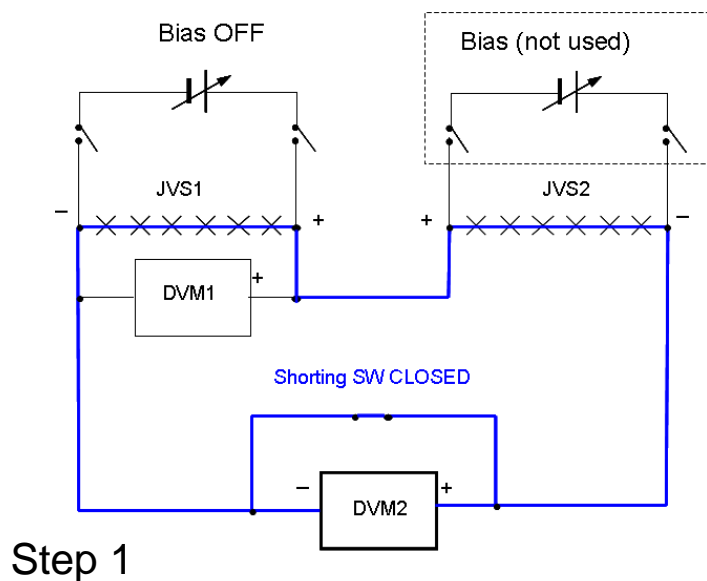


**Question:** How can we improve the situation?

**Answer:** Do not use Zener as transfer standards.  
Make direct JVS comparison.

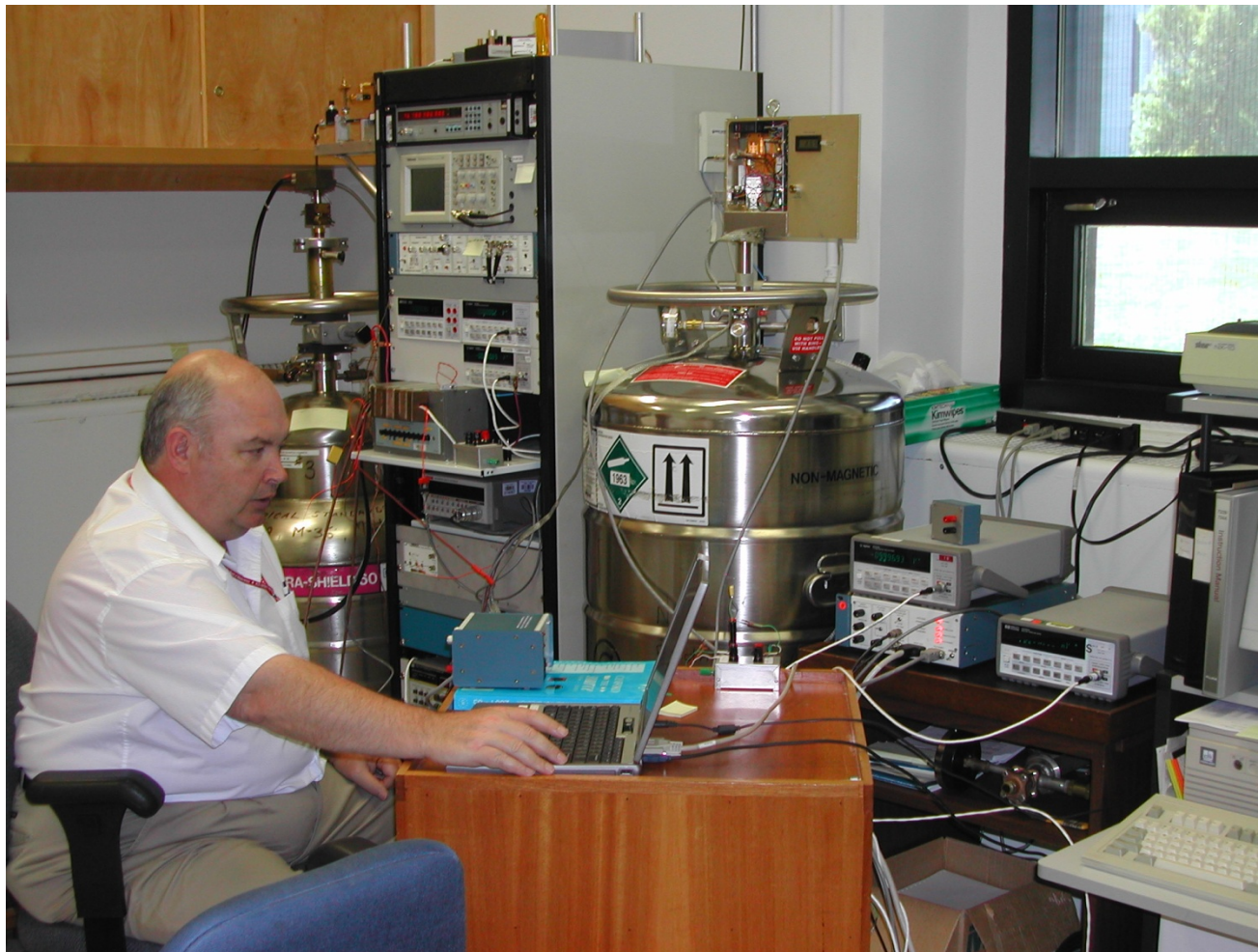
**Protocol:** BIPM JVS comparison Option a;  
BIPM JVS comparison Option b;  
Alternative protocols

# An alternative protocol



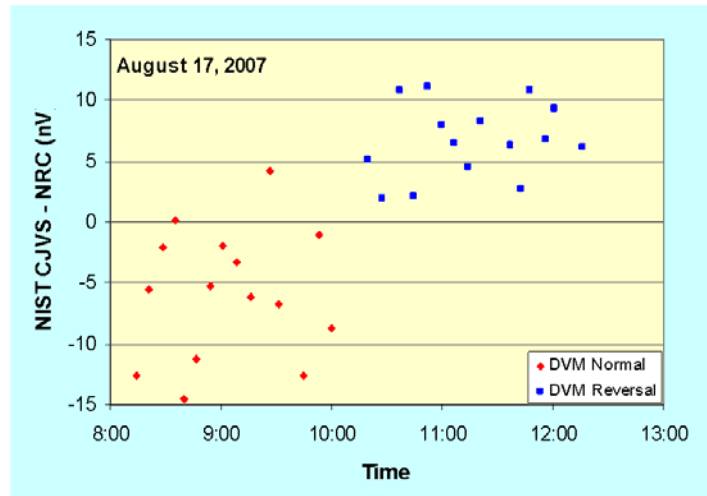
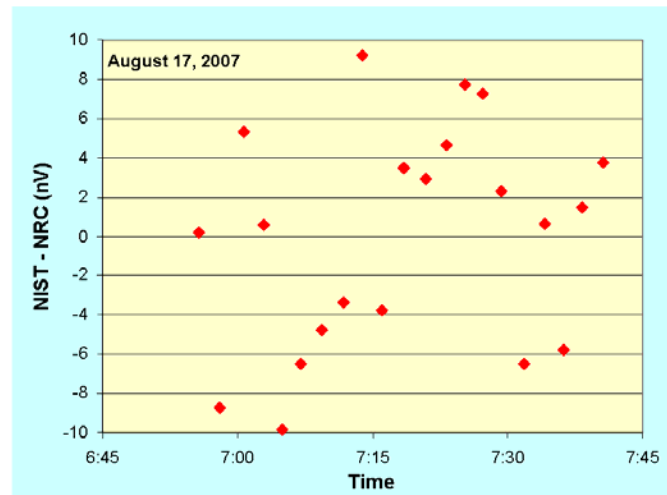
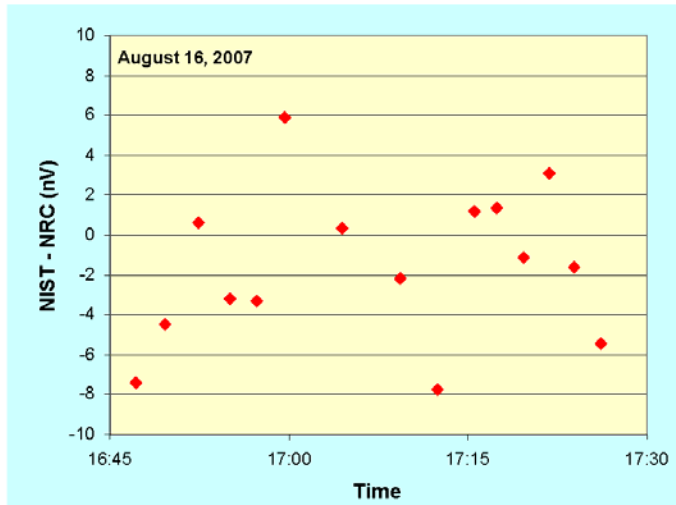
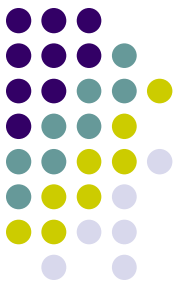
# NIST-NRC SIM.EM.BIPM-K10.b

NIST CJVS at NRC August 2007



Barry Wood of NRC



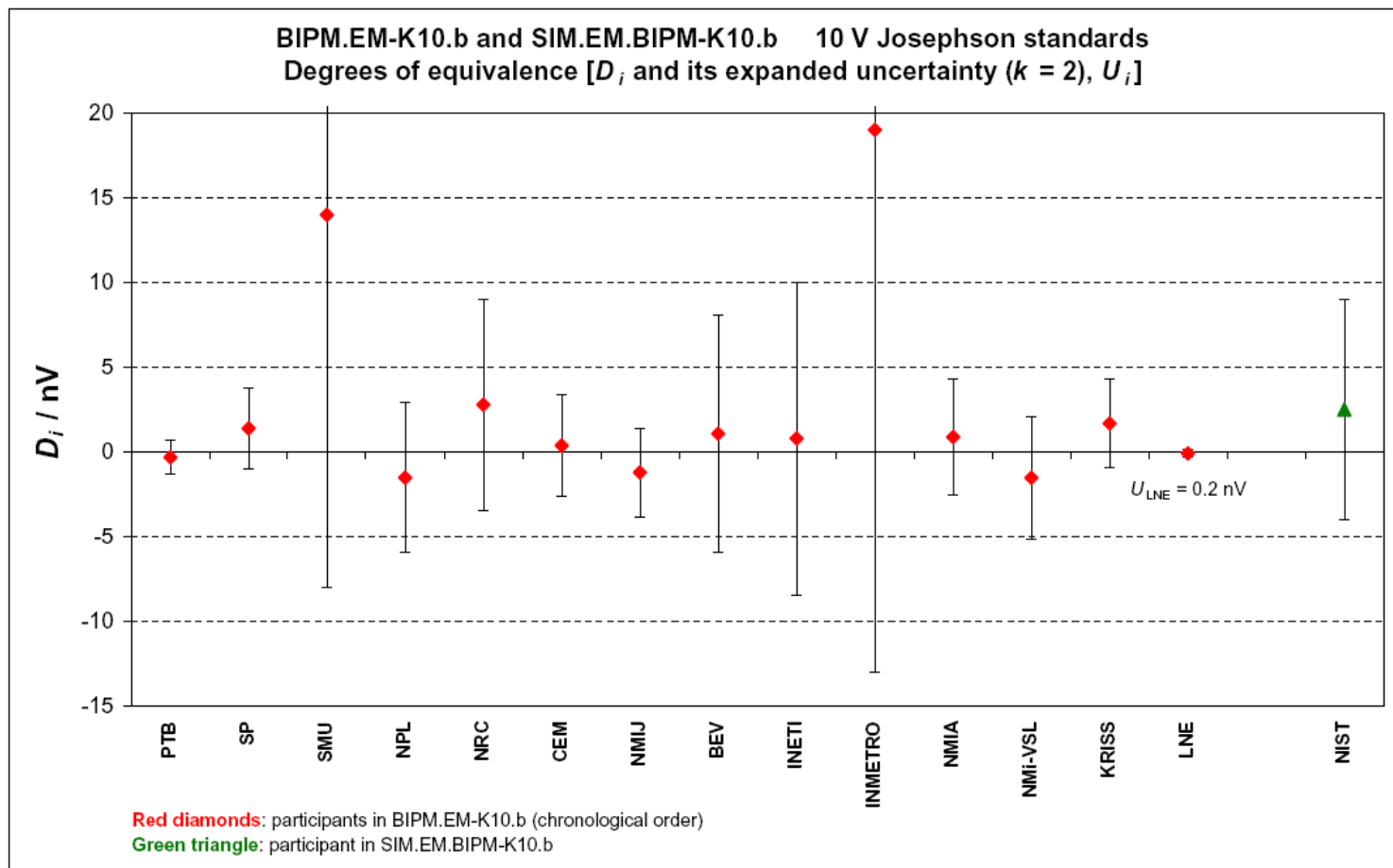


	Made by NRC	Made by NIST
NIST - NRC (nV)	-0.66	0.10
Type A uncertainty $u_A$ (nV)	0.82	0.80
Type B uncertainty $u_B$ (nV)	0.86	0.87
Combined uncertainty (nV)	1.19	1.18

NIST - NRC (nV)	-0.28
Pooled Combined uncertainty $u_c$ (nV)	1.04
Expanded uncertainty (nV) $k = 2$	2.07

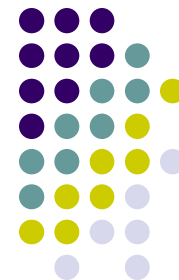
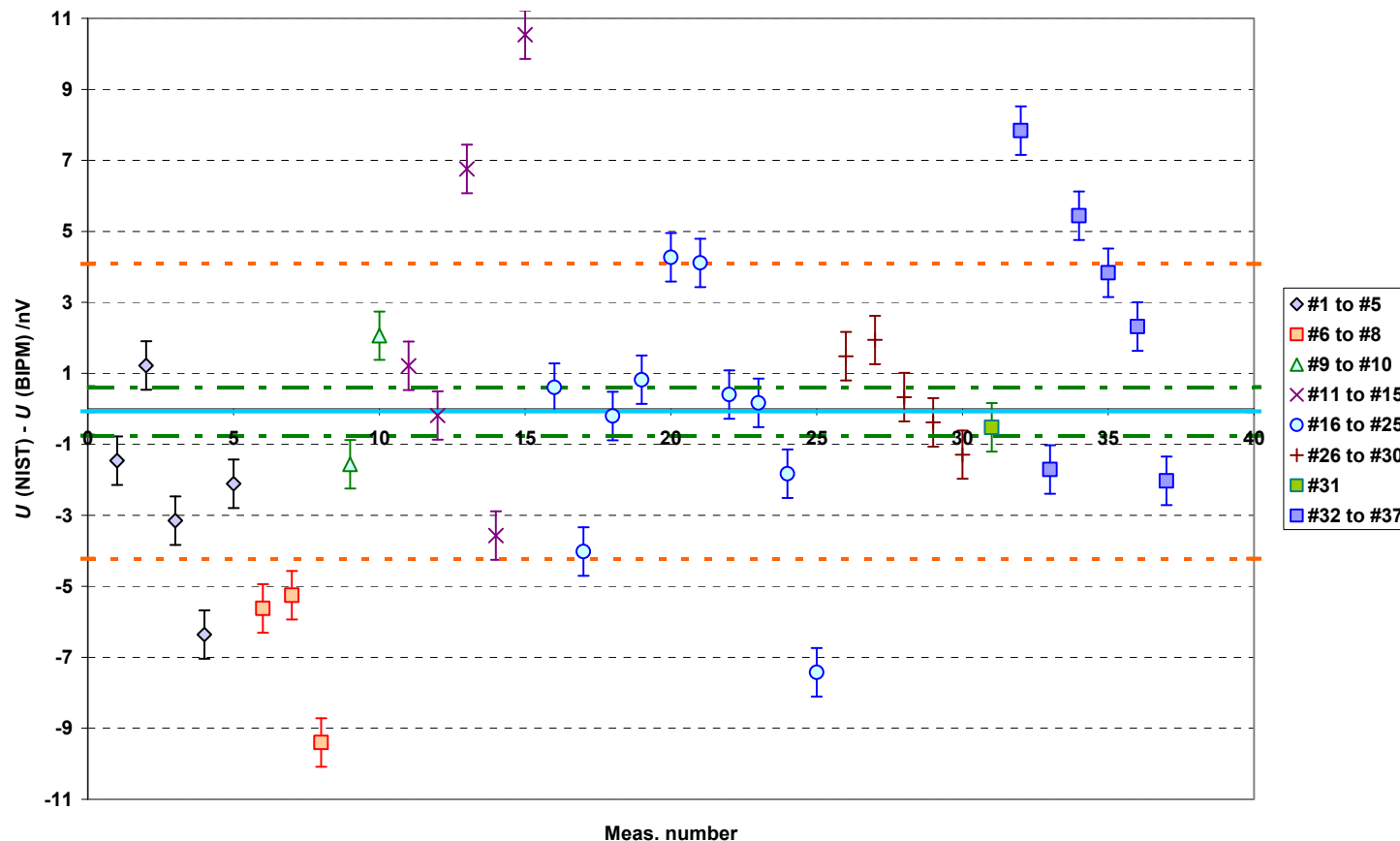
	NIST - NRC	NRC - BIPM	NIST - BIPM
Difference (nV)	-0.28	2.8	2.52
Combined standard uncertainty (nV)	1.04	3.1	3.27

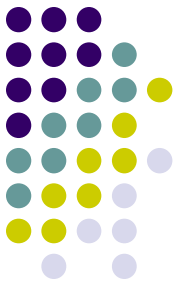
# Link between NIST and BIPM via NRC



# NIST-BIPM JVS comparison BIPM.EM-K10.b

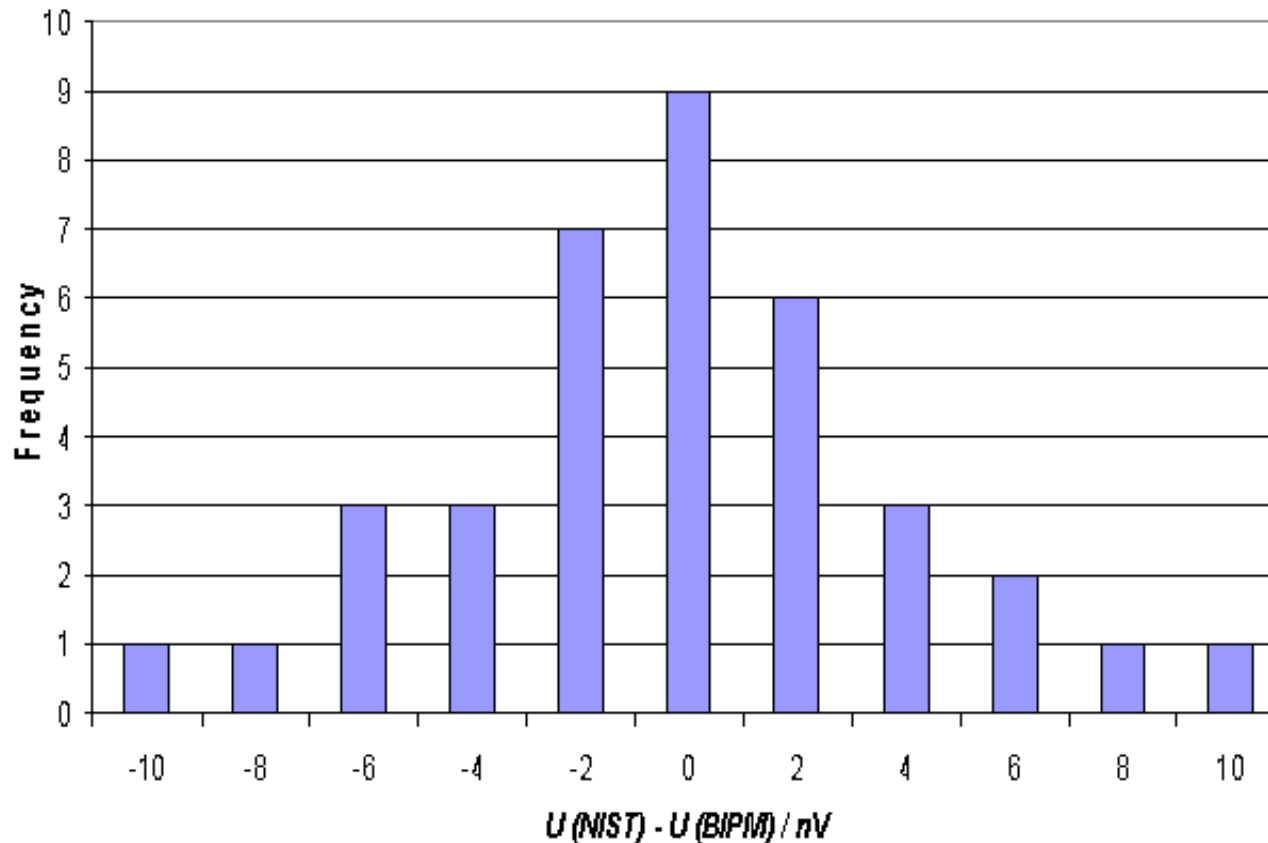
## BIPM protocol Option B





# Histogram of the JVS comparison

BIPM protocol Option B

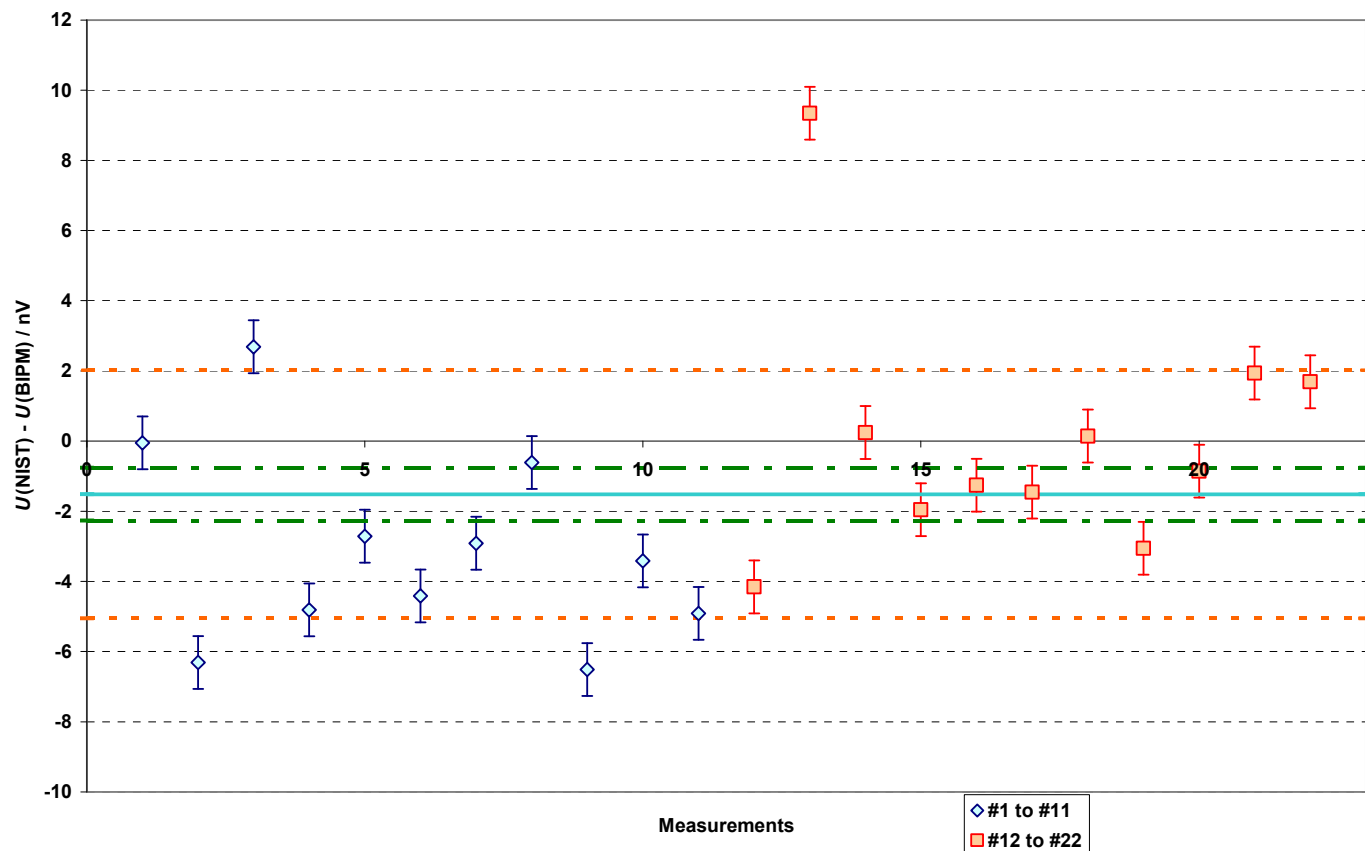


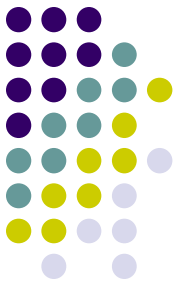


# NIST-BIPM JVS comparison BIPM.EM-K10.b



## BIPM protocol Option A

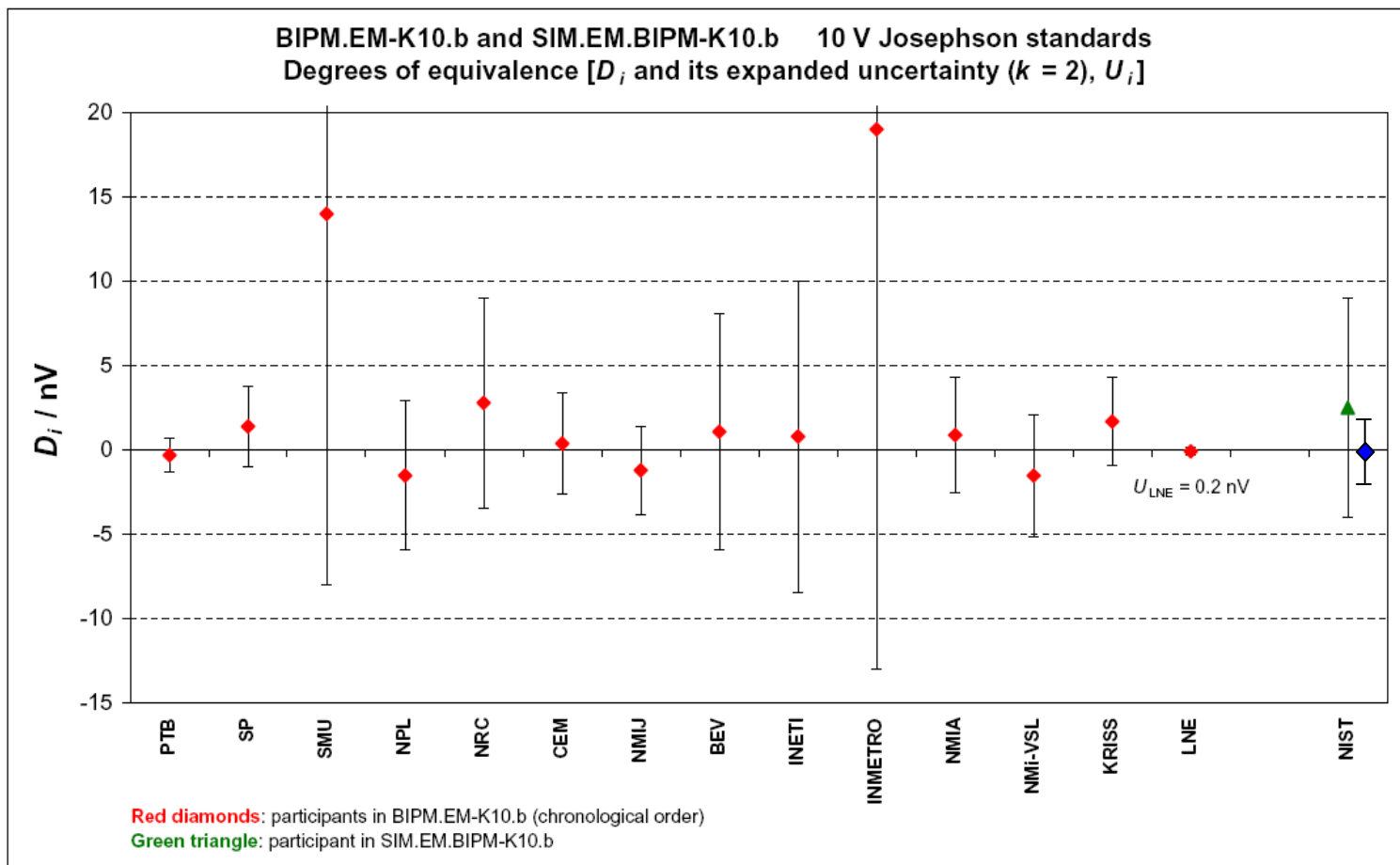




$$U(NIST) - U(BIPM) / nV$$

	Option B Measured by NIST	Option A Measured by BIPM
Difference (nV)	-0.074	-1.53
Type A (nV)	0.68	0.75
Type B (nV)	0.93	0.77
Combined uncertainty (nV)	1.15	1.07

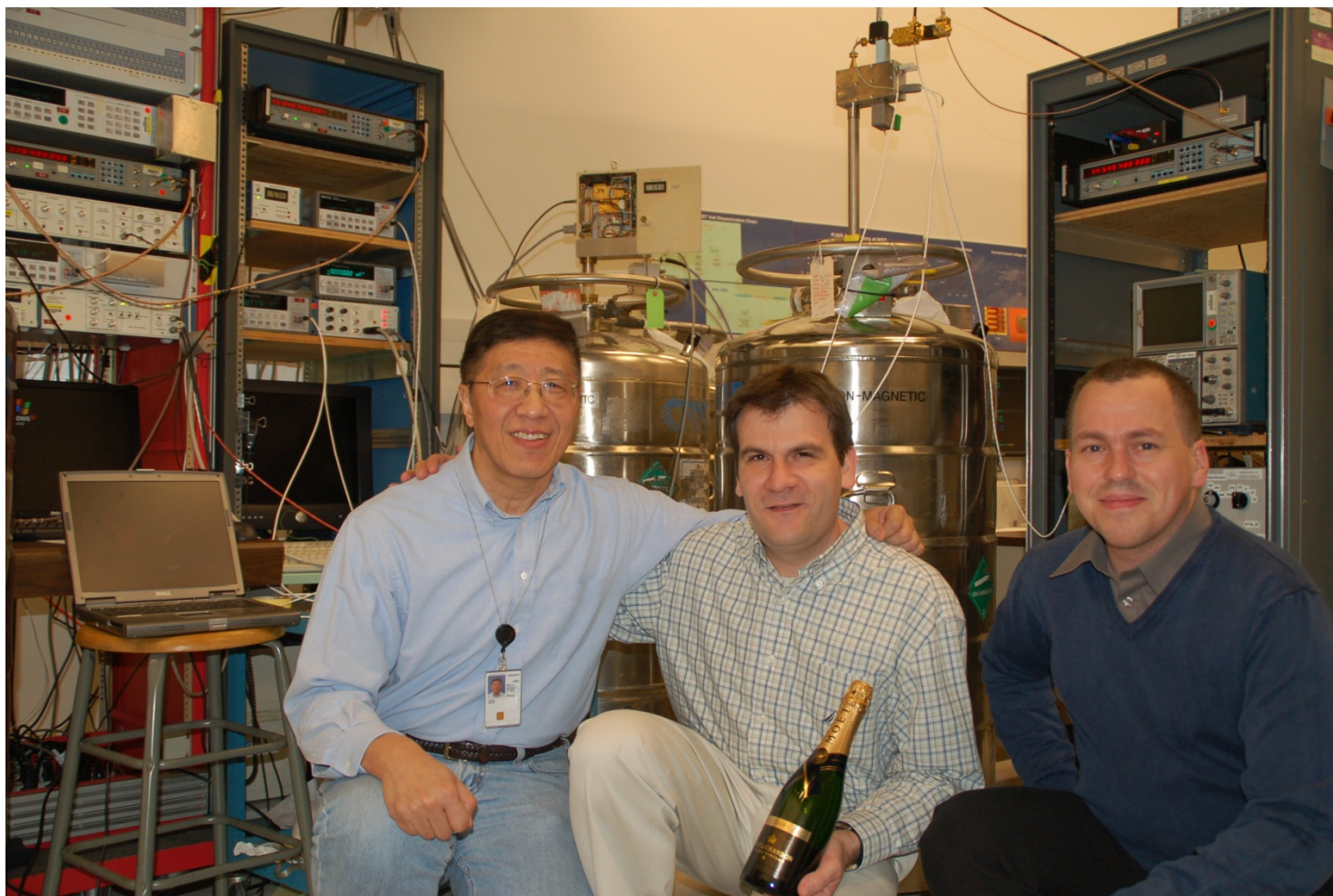
# Direct link between NIST and BIPM



# BIPM JVS in NIST March 2009





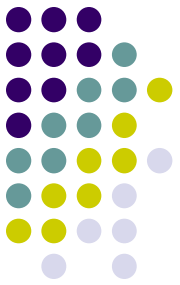


Yi-hua Tang

Stephane Solve

Regis Chayramy

# Automatic JVS direct comparison

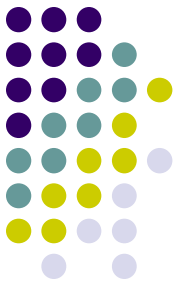


Model of NIST protocol

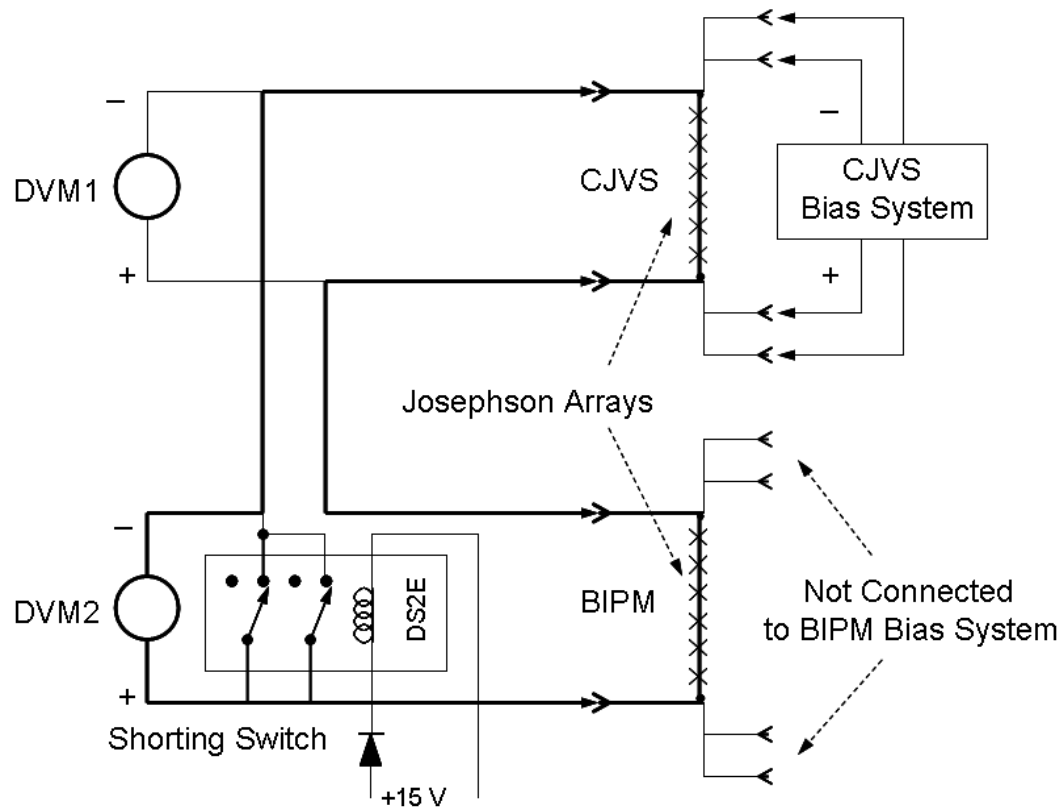
$$V_d = V_{a1} - V_{a2} = (N_1 f_1 - N_2 f_2) / K_{J-90}$$

$$V_d - V_m = V_o + mt + V_n + \delta$$

$$\delta = V_d - V_m - V_o - mt - V_n$$

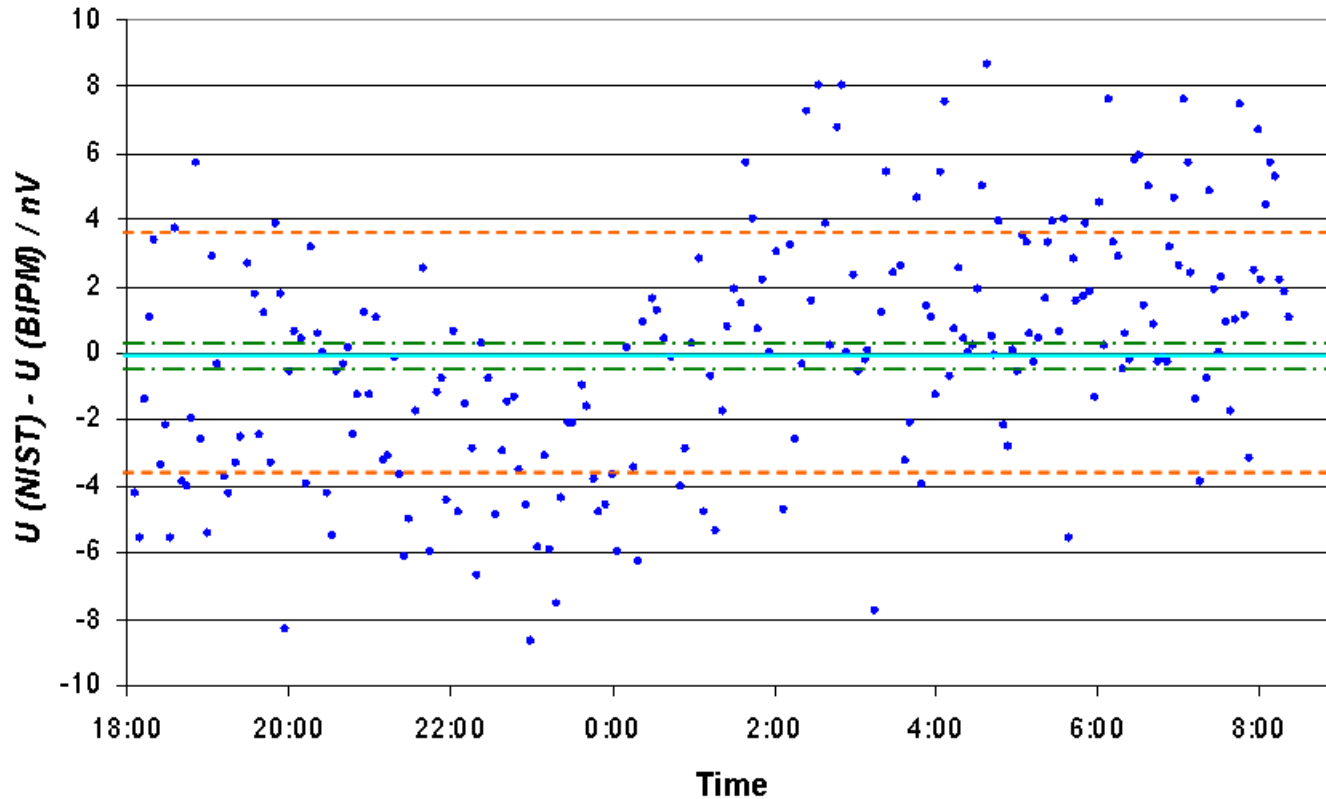


## Automatic JVS direct comparison



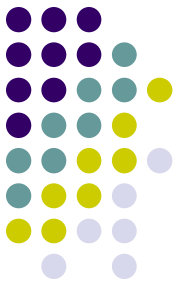
## Example: automatic comparison

nominal voltage: 9.997 V

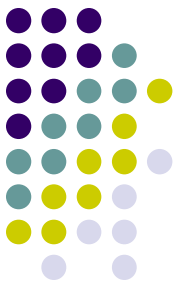


217 points in 14 h.

$U(NIST) - U(BIPM) / nV$	$u_a / nV$
0.02	0.24

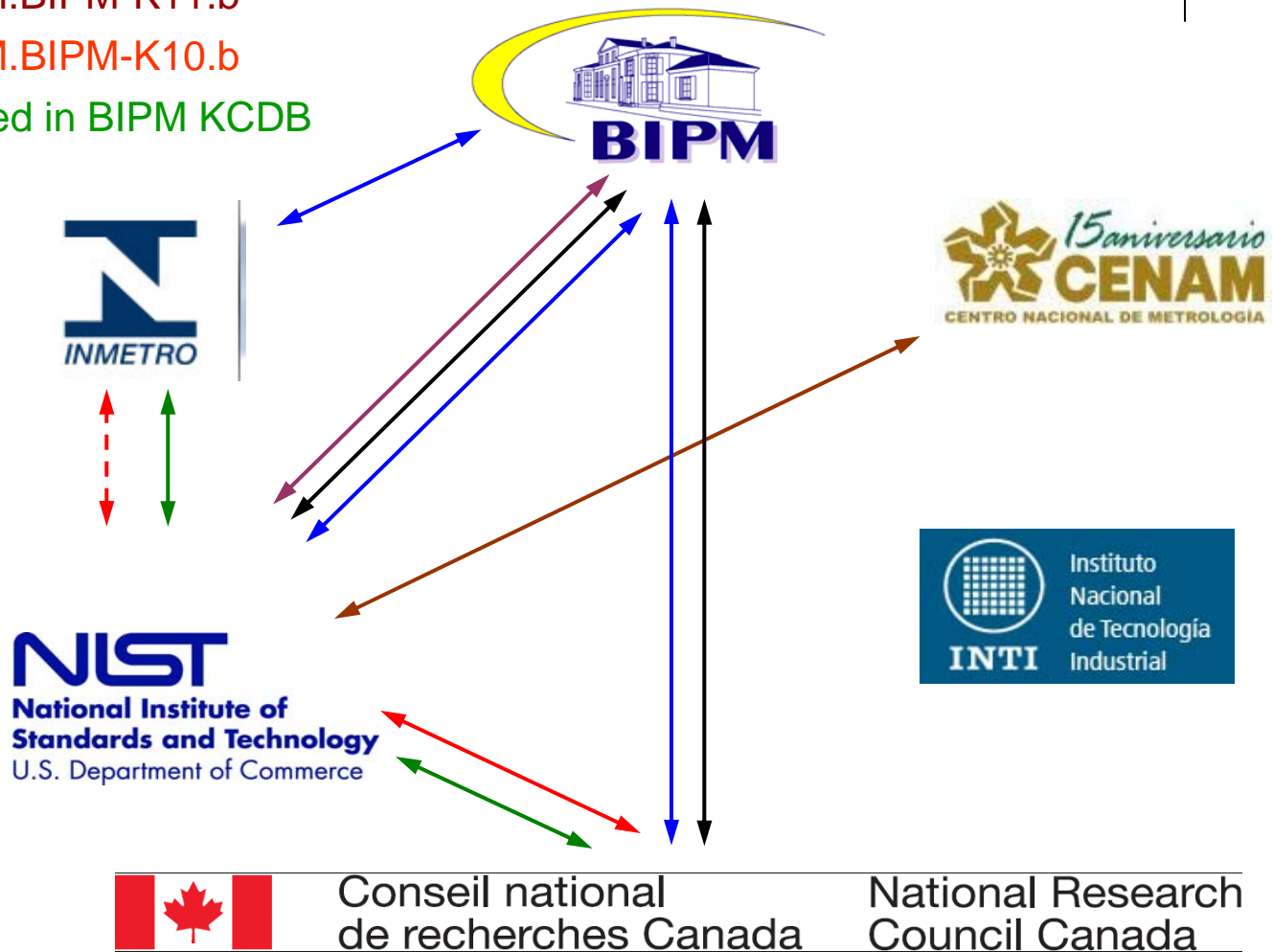


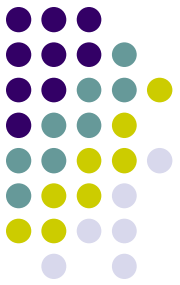




# Summary

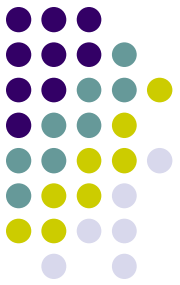
- ↔ BIPM.EM-K10.a
- ↔ BIPM.EM-K10.b
- ↔ BIPM.EM-K11.b
- ↔ SIM.EM.BIPM-K11.b
- ↔ SIM.EM.BIPM-K10.b
- ↔ Not listed in BIPM KCDB





# Comparison of various protocols

	MAP (Indirect)	CJVS (Indirect)	JVS vs. JVS (Direct)	PJVS vs. PJVS (Future)
Voltage range	Up to 10 V	Up to 10 V	Up to 10 V	Up to 10 V
Uncertainty	$2 \times 10^{-8}$	$2 \times 10^{-9}$	$1 - 7 \times 10^{-10}$	parts $\times 10^{-11}$
Limiting factor	Zener	Zener (1/f noise)	Null detector	Null detector
Time needed	Weeks	Days	Hours	Hours
Expense	Low	High	High	Potentially low



## Future perspective

**Coming soon: new 10 V PJVS**

**Expected uncertainty: few parts in  $10^{11}$  at 10 V**

**Detection of small system error is possible**