An Overview of the Josephson Voltage Standard Interlaboratory Comparison

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Abstract

A majority of Josephson Voltage Standard (JVS) interlaboratory comparisons have been performed by using Zener voltage transfer standards and a protocol based on the Measurement Assurance Program (MAP) with uncertainties in the range of a few parts in 10^8 at 10 V that are limited by the Zener characteristics. In order to improve the uncertainty of the comparison, protocols using a compact Josephson voltage standard (CJVS) as the transfer standard have been developed. The uncertainty using the CJVS in the comparison can be in the range of a few parts in 10^9 at 10 V. The array to array direct comparison using the conventional JVS or programmable JVS (PJVS) can further improve the uncertainty of the comparison.

1. Introduction

The Josephson Voltage Standard (JVS) system is widely used as the primary voltage standard in many national metrology institutes (NMIs). A traditional "traceability path" of an unbroken chain of comparisons with stated references does not apply to the case of the JVS operating in different locations. However, the equivalence of the JVS used by different laboratories must be demonstrated through comparisons.

This paper reviews the protocols for the JVS comparison that was developed in the last decade. The majority of the JVS comparisons, the Bureau International des Poids et Mesures (BIPM) Key Comparison and the National Conference of Standards Laboratories International Josephson Voltage Standard Interlaboratory Comparison (NCSLI JVS ILC), have been performed by using Zener voltage transfer standards and a protocol based on the Measurement Assurance Program (MAP). The uncertainty of such a comparison is in the range of a few parts in 10^8 at 10 V and limited by the Zener characteristics. In order to improve the uncertainty of the comparison, a protocol using the compact Josephson voltage standard (CJVS) as the transfer standard has been developed. The uncertainty using the CJVS in the comparison can be in the range of a few parts in 10^9 at 10 V, so that the JVS system errors at the level of a few parts in 10^9 can be detected and corrected. The BIPM has also sponsored many direct array comparisons with other NMIs. This is the ultimate

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comparison with an uncertainty of a few parts in 10^{10} at the 10 V level. Because the Josephson junction array, developed during 1980's, used the intrinsically non-stable voltage steps, the direct comparisons used by BIPM were difficult to carry out. In 1997, a new type of Josephson junction array using non-zero current bias voltage steps was developed. The new device can be implemented quicker and easier in the direct array comparison and the uncertainties can be improved by at least an order of magnitude compared to the Zener MAP.

This paper will use examples to illustrate the various protocols of JVS comparisons. The uncertainty results using actual JVS comparison data will be demonstrated. New developments and the future perspective concerning the JVS comparison will also be discussed.

2. JVS Intercomparison using Measurement Assurance Program

A Measurement Assurance Program (MAP) is commonly used to establish the difference between the measurement units realized at the National Institute of Standards and Technology (NIST) and a customer laboratory. In a voltage MAP, a set of transfer Zener standards is measured at NIST and then sent to a customer for measurement, for example using a JVS. After a certain number of measurements have been taken, the transfer Zener standards are returned to NIST for further measurements. The data are then analyzed to determine the difference between NIST and the customer measurements and the total uncertainty that includes all known uncertainty contributions. In the case of JVS systems, when the offset between the NIST and customer measurements can not be explained by the uncertainty analysis, a further investigation should be conducted to find the source of the difference.

Figure 1 shows an example of a JVS comparison between NIST and Lockheed Martin Astronautics (LMA) [1]. It was assumed that the transfer Zener standards drift with the same rate at LMA as at NIST. An offset between LMA and NIST for the Zener standard was calculated based on LMA's measurements and on the drift rate from the NIST data. The difference between the LMA and NIST measurements can be obtained by averaging the differences of the four transfer Zener standards. A corresponding uncertainty can also be calculated based on the *Guide to the Expression of Uncertainty in Measurement* [2].

The MAP protocol and its variation have been widely used in JVS intercomparisons that are sponsored by the National Conference of Standards Laboratories International (NCSLI) every 2 or 3 years since 1991. A pivot lab is selected for the NCSLI JVS intercomparison. Four transfer Zener standards were circulated in a "daisy" pattern to minimize the time difference between the pivot lab and the participant laboratories, thus minimizing the effects of long-term Zener standards noise. There were several NCSLI JVS intercomparisons where the transfer Zeners returned to the pivot lab after measurements by 2 or 3 participating labs in order to reduce the workload of the pivot lab and the operational cost. Most key comparisons conducted by the BIPM with other NMIs also use Zener standards as the transfer standards. The uncertainty of this type of comparison is also in the range of a few parts in 10^8 at 10 V. Table 1 lists the results from a NCSLI JVS ILC. Table 2 lists several examples from the BIPM Key Comparison Data Base (KCDB) BIPM.EM-K11.b [3]. The expanded uncertainty (k = 2) is used in the tables.

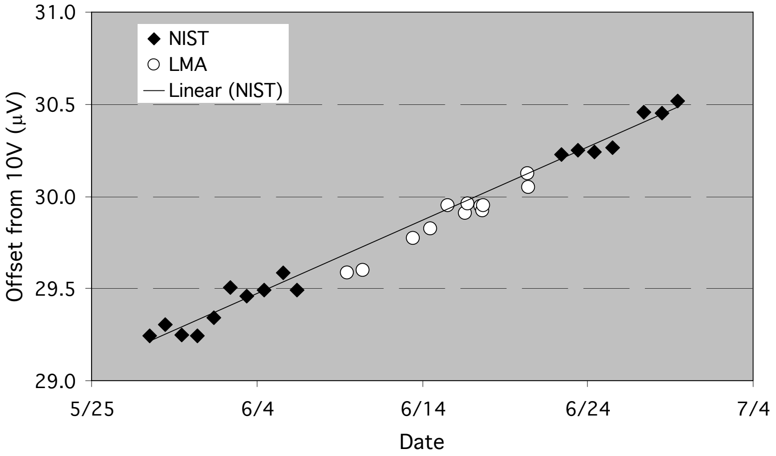

Figure 1. Measurements of a transfer Zener standard at NIST and LMA. The data have been adjusted to the standard atmospheric pressure of 1013.25 hPa. A least squares fit line is obtained using NIST data only.

The advantage of using the MAP protocol is the cost to the participants is minimal, usually just the shipping expense. The drawback of such a comparison is the uncertainty is in the range of a few parts in 10^8 at 10 V, limited by the characteristics of the transfer Zener standards. The type B uncertainty of a JVS system is normally a few parts in 10^{10} at 10 V. A small system error may not be detected in the comparison using the MAP protocol.

Table 1. Results of the NCSLI JVS comparisons at 10 V using MAP protocol

Year	Pivot	Lab	Uncertainty k = 2 (Parts in 10^8)	Notes
1991	NIST	8	5	First JVS ILC in North America
1993	Fluke	10	2.5	Daisy pattern implemented
1995	Fluke	12	3.5	Same protocol as JVS ILC 1993 implemented
1997	None	15	1.7[1]	No pivot lab
1999	LMA	17	2.3	Pressure effect correction for transfer standards
2002	SNL	16	2.4	CJVS introduced to improve link between pivot lab and NIST
2005	NIST	17	0.2[2] – 3.3	CJVS used as transfer standard between subset pivot lab and NIST

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[1] The listed uncertainty excluded two participants.

[2] Small uncertainty of 0.2 parts in 10^8 was from comparisons between CJVS and sub-pivot labs.

Table 2. Selected results of JVS comparison at 10 V of BIPM Key Comparison using transfer Zeners (full name of NMIs listed in Appendix)

Year	Pivot	NMI	Uncertainty $k = 2$ (Parts in 10^8)	Country
1998	BIPM	SPRING	2.2	Singapore
1998	BIPM	SMU	6.4	Slovakia Republic
1998	BIPM	NIST	2.8	USA
1999	BIPM	METAS	2.8	Switzerland
2001	BIPM	BEV	2.0	Austria
2001	BIPM	GUM	2.6	Poland
2003	BIPM	CSIR-NML	6.6	South Africa
2003	BIPM	NMIA	2.8	Australia

3. JVS Comparison Using the Compact JVS as Transfer Standard

It is a presumption that transfer Zener standards drift linearly during the comparison. The time period of the comparison varies from a few weeks to a few months, depending on how the pivot lab controls the process. The non-linear drift of transfer Zener standards can increase the uncertainty of the comparison. Non-ideal responses of Zener standards to environmental conditions can also affect the results of the comparison. Non–ideal transportability is often the largest component of the uncertainty of the comparison using the MAP protocol. To reduce the uncertainty contribution from the non-ideal behavior of transfer Zener standards, the use of a compact JVS (CJVS) as a transfer standard was introduced in the NCSLI JVS ILC 2002 to link the pivot lab, Sandia National Laboratories (SNL) and NIST [4].

As a further development, NIST implemented its CJVS for comparisons with 5 sub-pivot labs in the NCLSLI ILC 2005. The same set of four Zener standards were used as transfer standards during the comparison between the sub-pivot lab's JVS and the CJVS. A low thermal switch system was implemented to change the Zener polarity. Because the comparison was carried out by measuring the same Zener set in the sub-pivot lab, the environmental effects due to atmospheric pressure, temperature and relative humidity were largely eliminated. The possible shipping impact on the Zeners was also excluded. The measurements performed by the two JVS systems were made in an interlaced pattern within a few hours so that the Zener drift during the measurement period was insignificant. The uncertainty of such a comparison is mostly determined by the *1/f* noise floor of the transfer Zeners used in the comparison [5]. The lower the *1/f* noise floor from the Zeners, the better results obtained for the comparison. Figure 2 shows the comparison results from the NIST CJVS and a sub-pivot lab JVS during the NCSLI JVS ILC 2005.

The use of the CJVS in NCSLI JVS ILC 2005 has improved the uncertainty of the sub-pivot comparisons by about an order of magnitude to a few parts in 10^9 [6]. The cost of performing a comparison using the CJVS is higher than a comparison using the MAP protocol. Normally, NIST sends the CJVS with a staff personnel to perform the measurements at the customer's site. Training the customer to make measurements using the CJVS can reduce the cost of such a comparison in the future.

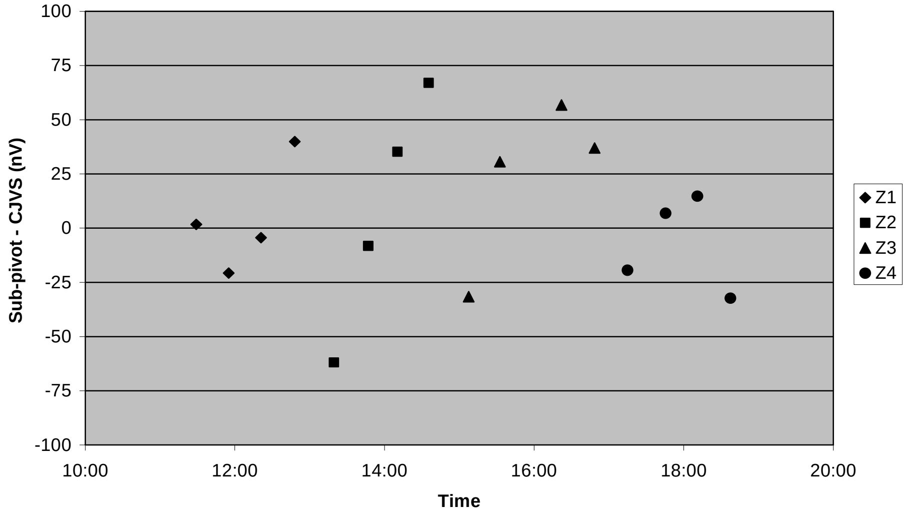


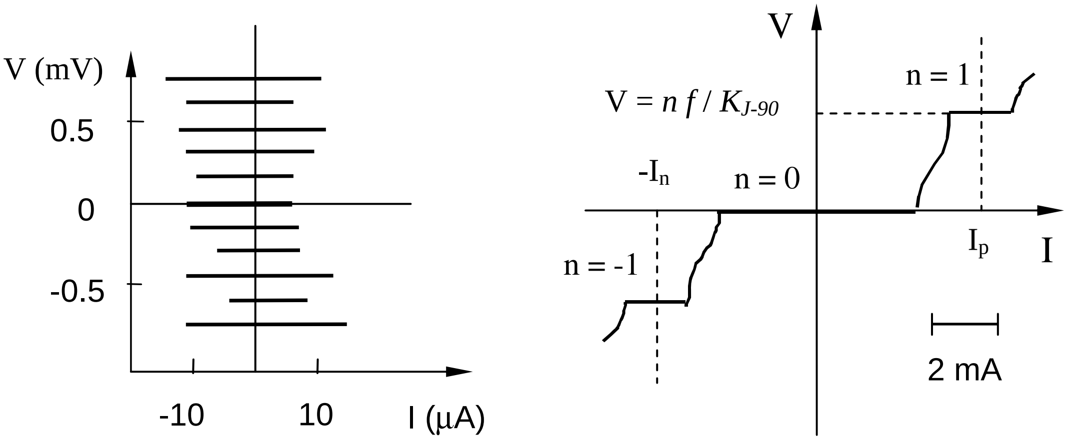
Figure 2. The differences between a sub-pivot lab JVS and the NIST CJVS for a set of 4 transfer Zeners over a time period of 7 hours. The mean difference between the two JVS systems at 10 V was 7 nV with an expanded uncertainty of 19 nV at the 95% confidence level or 1.9 x 10^{-9}.

4. Direct Array Comparison

To further improve the JVS comparison, a direct array comparison is necessary. In a direct array comparison, two arrays are connected in series opposition polarity through a null detector. The sources of uncertainty in a direct array comparison are frequency stability, frequency measurement, leakage error from the cryoprobe and the null detector. If both arrays are operated correctly, the uncertainty of such a comparison is mainly limited by the noise performance of the null detector. A digital nanovoltmeter is often used in a direct array comparison. The uncertainty of such a comparison is usually a few nanovolts which is equivalent to an uncertainty of a few parts in 10^{10} for a 10 V JVS comparison. An ultra low noise analog null detector can also be used to measure the difference between the two array voltages. The uncertainty using an analog null detector can be lower.

4.1 Direct Array Comparison with the Zero Bias Current Josephson Junction Array

BIPM has pioneered the array to array direct comparisons since the early 1990s. The successful development of the Josephson junction array in the mid 1980s delivering up to 10 V was based on the technology of the zero bias current Josephson junction with high intrinsic capacitance shown in Figure 3(a). Since all the voltage steps are biased at zero current, the array is intrinsically non-stable. A voltage step can jump to nearby voltage steps during the measurement due to electromagnetic interference in the measurement circuit. The step transition makes a direct array comparison difficult to perform. Only a small portion of the JVS comparisons are carried out directly. Table 3 lists some direct array comparison performed by BIPM in the Key Comparison Data Base BIPM.EM-K10.b [3].



(a) (b)

Figure 3. Voltage steps of (a) zero bias current Josephson junction array, (b) programmable Josephson junction array. K_{J-90} is the Josephson constant adopted by the Consultative Committee for Electricity and Magnetism (CCEM) since January 1, 1990.

Table 3. Direct array comparison at 10 V carried out by BIPM (full name of NMIs listed in Appendix)

Year	NMI	NMI – BIPM (nV)	Uncertainty $k = 2$ (Parts in 10^{10})	Country
1994	LNE	1.2	2.4	France
1998	PTB	-0.3	1.0	Germany
1998	SP	1.4	2.4	Sweden
1999	SMU	14	22	Slovakia
2004	NPL	-1.5	4.4	United Kingdom
2004	NRC	2.8	6.2	Canada
2005	CEM	0.4	3.0	Spain
2005	NMIJ	-1.2	2.6	Japan
2005	BEV	1.1	7.0	Austria

During the NCSLI JVS ILC 2005, a protocol for a conventional array direct comparison was developed and implemented in a direct array comparison between the NRC JVS and the NIST CJVS [7]. The difference between the two JVS systems at 10 V was found to be 0.3 nV with an expanded uncertainty 1.6 nV or a relative uncertainty of 1.6 x 10^{-10}. A common problem encountered in an array direct comparison is the grounding loop caused by the two JVS systems. To make a successful direct array comparison, at least one of the array outputs must be floating from the ground. In the NRC-NIST CJVS comparison, the NRC JVS was floated by using a bias source powered by a battery. Further development of a dual JVS bias source that is powered by a battery is in progress for future JVS direct comparisons.

A direct array comparison does not test the offset and repeatability of the low potential reversing switches that are normally part of a JVS measurement system, because the polarity of each array can be reversed electronically without using a reversing switch. Reversing switch offset and repeatability embedded in an indirect comparison using MAP protocol can be evaluated by short circuit measurements and is a source of measurement uncertainty.

4.2 Direct Array Comparison using the Programmable JVS

A new type array, the Programmable Josephson voltage standard (PJVS), was developed in 1997 at NIST [8]. The PJVS, biased at non-zero current, has distinct voltage values depending on the bias current, as shown in Figure 3 (b). Unless the bias current changes, the voltage output of a junction is set to be stable for an infinitely long time. The programmable array has a superior stability due to its higher current step amplitude (a.k.a. current margin), as much as 100 times compared to that of the conventional array with zero bias current. This property makes it convenient to perform a direct array comparison between a PJVS and a conventional JVS.

Two types of programmable array were developed in recent years by NIST and PTB. NIST has developed a programmable array based on the Superconductor-Normal metal-Superconductor (SNS) junction working at 16 GHz while PTB has designed a programmable array based on the Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) working at 75 GHz, similar to the frequency used by a conventional array. The voltage generated by the NIST PJVS is reported to reach 2.6 V [9]. A continuous effort to raise the voltage output to 10 V is in progress.

The NIST PJVS has been used in three critical projects: the electronic mass experiment, the voltage dissemination chain to replace the standard cell groups, and the direct array comparison to assure the proper operation of all NIST JVS systems.

Figure 4 shows an example of a direct comparison between NIST10, a conventional 10 V JVS system, and the PJVS at 1.018 V over a 3 week period to monitor the long-term performance of the NIST10 JVS system. The difference between the two systems was found to be 0.5 nV with an expanded uncertainty of 0.58 nV at the 95 % confidence level or a relative uncertainty of 5.6 x 10^{-10}. Figure 5 is the histogram of all the data points collected during the 3 weeks. The NIST PJVS was also used for making direct comparisons with the CJVS during the NCSLI JVS ILC 2005 before the CJVS was shipped to a sub-pivot lab. The comparisons were carried out at the highest voltage output of 2.5 V from the PJVS. The uncertainty of such comparisons was in a vicinity of 1 x 10^{-9} based on about a dozen measurements.

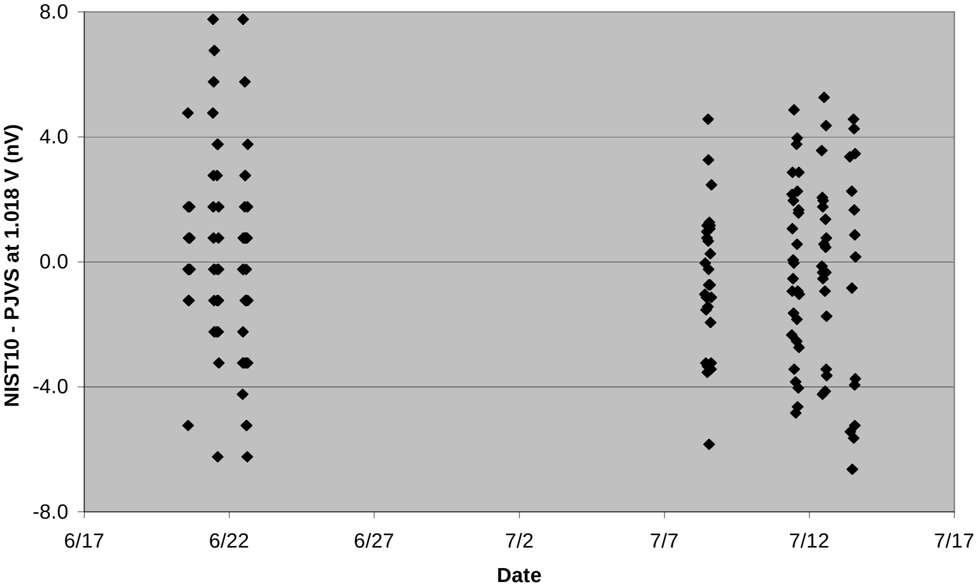


Figure 4 Direct comparison between NIST10, a 10 V conventional JVS system, and PJVS at 1.018 V over 3 weeks to monitor the long-term performance of NIST10 JVS system.

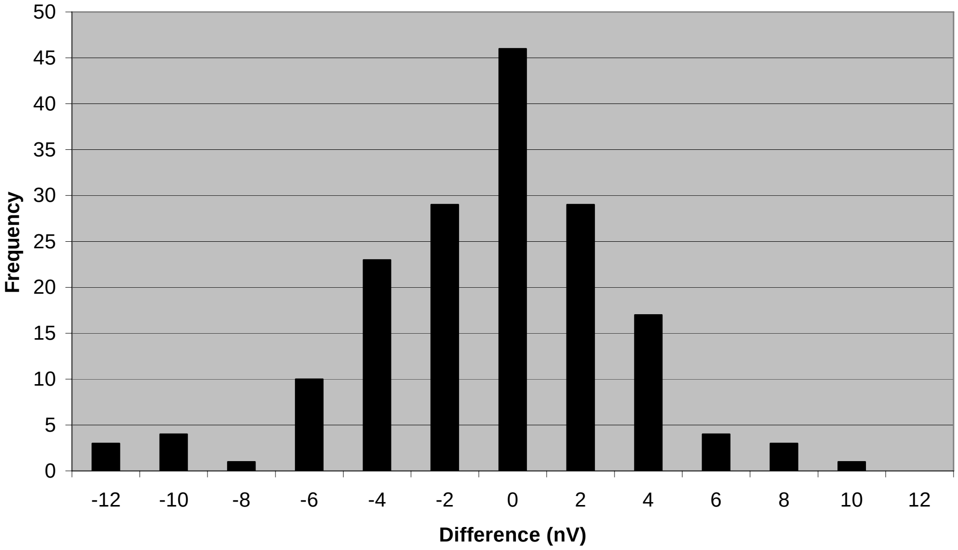


Figure 5 A histogram based on the data from the direct comparison between NIST10 and PJVS at 1.018 V in Figure 4.

EUROMET carried out a regional JVS intercomparison at a nominal voltage of 1.09 V using a PJVS designed by PTB [10, 11]. Twelve NMIs and BIPM participated in the intercomparison from September 2003 to May 2004. The uncertainty of the direct comparisons between the PJVS and the participating NMIs was in the range from 5.2 x 10^{-10} to 1.2 x 10^{-8} at the 95 % confidence level.

5. Summary

Table 4 summaries the different protocols used for JVS comparisons.

Table 4 Summary of different protocols for JVS comparison

	MAP	CJVS	JVS vs. JVS	JVS vs. PJVS
Voltage range	Up to 10 V	Up to 10 V	Up to 10 V	Up to 2.5 V
Uncertainty	2 x 10^{-8}	2 x 10^{-9}	1 - 7 x 10^{-10}	5 x 10^{-10}
Time needed	Weeks	Days	Hours	Hours
Expense	Low	High	High	Potentially low

Since the JVS became the primary voltage standard in the late 1980s, different protocols have been developed to make comparisons between JVS systems. The uncertainty of a JVS comparison has been improved over the last two decades. By implementing a CJVS or PJVS, the uncertainty of a JVS comparison can be reduced by an order of magnitude or better compared to a comparison using the MAP protocol. The effort to develop a 10 V PJVS is in progress. Using a PJVS working at a higher voltage up to 10 V will make the future JVS comparison more efficient, convenient, and with lower uncertainty.

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Appendix List of selected NMIs

Institute	Name	Country
BEV	Bundesamt für Eich-und Vermessungswesen	Austria
CEM	Centro Español de Metrologia	Spain
CSIR-NML	The Council for Scientific and Industrial Research – National Metrology Laboratory	South Africa
GUM	Central Office of Measures	Poland
LNE	Laboratoire National de Métrologie et d'Essais	France
METAS	Swiss Federal Office of Metrology and Accreditation	Switzerland
NIST	National Institute of Standards and Technology	USA
NMIA	National Measurement Institute of Australia	Australia
NMIJ	National Metrology Institute of Japan	Japan
NPL	National Physical Laboratory	United Kingdom
NRC	National Research Council	Canada
PTB	Physikalisch-Technische Bundesanstalt	Germany
SMU	Slovakia Institute of Metrology	Slovakia
SP	Swedish National Testing and Research Institute	Sweden
SPRING	Standards, Productivity and Innovation Board	Singapore