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# Characterisation of the Effects of Time and Pressure on a Group of Electronic Voltage Standards

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# Characterisation of the Effects of Time and Pressure on a Group of Electronic Voltage Standards

By

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## Abstract

Although primary metrology laboratories use standards based on the Josephson effect to maintain a local reference standard for dc voltage, artefact standards are still the standard of choice in many secondary laboratories. The National Metrology Laboratory, Dublin maintains a local reference standard for dc voltage by means of an ensemble of Zener-diode based electronic voltage standard units. Electronic voltage standards have a number of shortcomings over Josephson standards for use as a local reference standard. In particular their output voltages are influenced by several external factors. In order to make optimum use of the NML reference standard it is important that the output voltage of individual units be characterised for the effects of these influence factors so that appropriate corrections can be applied. This thesis describes techniques and procedures used to characterise the effects of time and pressure on electronic voltage standards and reports the results obtained for the devices used at NML.

The methods of analysis, which can be applied to the results of interlaboratory comparisons in order to quantify the temporal characteristics of electronic voltage standards, are discussed. The temporal regression parameters and associated uncertainties, which were estimated for all the NML units, are presented and the use of within-group comparisons as a means of surveying the behaviour of individual units is illustrated.

An experimental set-up suitable for the measurement of the pressure coefficients of electronic voltage standards is described. The design and development of important aspects of this set-up, including the test chamber, the systems used to control and monitor temperature and pressure, and the data acquisition and analysis program are described. The results of the measurements of the pressure coefficients of five types of commercially available electronic voltage standards are presented.

# 1. Introduction to Electrical Units (SI) and dc Voltage Standards

## 1. Introduction

The Système International (SI) system is introduced and the notion of units, their definitions, realisations and representations are developed. Following from this the SI electrical units are introduced leading to a description of the methods employed by laboratories to maintain representations of the volt using Josephson standards, saturated standard cells and electronic voltage standards (EVS). The principles of operation of each are described and their advantages and disadvantages for use as local reference standards are discussed. Finally a brief description is given of the dc voltage reference standard maintained at the National Metrology Laboratory (NML), Dublin.

## 1.1 Metrology and the SI system

Metrology, defined as the science of measurement, is an essential element of today's industrialised societies. Accurate and precise measurements play an important role in international trade, science, industrial production, medicine, agriculture and environmental protection[1-3]. Even from ancient times, the importance of measurement for the essential purposes of civilisation had been recognised[1,2].

However, the need for a universally agreed measurement system for the development of scientific collaboration and international trade wasn't recognised until the 1800s[2]. This need was acknowledged in a formal sense, with the signing of the Convention du Mètre in Paris in 1875, which established agreement on a system of measurement units based on the decimal metric system, created almost a century earlier, at the time of the French revolution[2]. The convention also provided a forum to develop international co-operation on various aspects of metrology. The Bureau International des Poids et Mesures (BIPM) was also established whose role is to ensure world-wide uniformity of measurements through its activities as outlined under the Convention[4]. The Convention, an intergovernmental treaty, initially signed by seventeen nations now has forty-eight members, essentially comprising the industrialised nations of the world[4].

Originally the measurement system comprised three base units, but this was eventually extended to seven, giving the present day SI system[2]. The seven base units of the SI are; the kilogram (kg), the metre (m), the second (s), the ampere (A), the kelvin (K), the candela (cd) and the mole (mol)[4]. The system also includes two supplementary units, the radian and steradian, together with a set of derived units[4]. The SI system is coherent, characterised by expressions for the derived units in terms of the base units, which contain no factor other than unity. Along with prefixes for denoting multiples and submultiples of the units, the system provides for uniformity across the entire measurement spectrum of physical quantities.

It should be noted that the idea of physical quantities and units is somewhat abstract, and the number and choice of base units in a system is somewhat arbitrary. The base units of the SI system were chosen partly for convenience and partly because of tradition with no reason to suggest that any other system of units would be in any way inferior. Originally the system had three base units, for measurements of length, mass and time, which provided for the basic measurement needs at that time, but as these needs became more diverse additional units were required. For example, developments in electromagnetism led to the inclusion of the ampere as the base electrical unit. A unit for electric current had been developed in the earlier centimetre, gram, second system as, $cm^{½}\cdot g^{½}\cdot s^{-1}$, but the use of fractional exponents were considered inconvenient, and the inclusion of an additional unit was preferred[2]. The kelvin and the mole were added under somewhat similar circumstances to the ampere, with the inclusion of the candela purely for traditional reasons.

The base units of the SI are unambiguously defined and most have evolved from earlier definitions, to meet the measurement needs of the time[2]. In previous times the units were defined in terms of artefact standards. However, recently, attempts have been made to define the base units in terms of atomic or quantum phenomena or fundamental physical constants of nature. The presently adopted definitions of the metre and the second are typical of this trend[4]. Units defined in terms of atomic or quantum phenomena or fundamental constants ensure long term stability and reproducibility whereas artefact standards are not constant, an undesirable characteristic when defining a unit by such a method.

Once a unit has been defined a practical realisation is required using an experimental set-up in the laboratory. Many of the SI base units as presently defined are realised using rather complex experimental set-ups, which require a great deal of time and effort. Essentially the experimental set-ups can be of any nature providing they are consistent with the definition. Ideally the definitions are linked to quantum or atomic phenomena which allow practical realisations that are feasible. Quinn[2] gives details of experimental set-ups currently used to realise the base units together with their associated accuracy.

Because of the complexity of the experimental set-ups used to realise the definitions, methods have been developed to maintain representations of the unit using reference standards, which can be more stable and reproducible. For example a set of 1 kg masses used in a calibration laboratory maintain a representation of the SI definition of the kilogram. It should be noted at this stage however that as one moves further from the definition of the unit, through its realisation and representation there is a corresponding increase in uncertainty, which depends on the methods employed.

## 1.2 The SI electrical units

The ampere, the volt, the ohm, and the watt to a lesser extent, are the most widely used units in electrical dc metrology. The ampere is the base electrical unit of the SI and the volt, the ohm and the watt are SI derived units[4].

The ampere is defined as *....that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in a vacum, would produce between these conductors a force equal to 2 x $10^{-7}$ newton per metre of length* [4]. Most early attempts to realise this definition were based on a current balance but the accuracy was limited to a few parts in $10^6$ by uncertainties in the geometry of the current carrying wires[2]. Today, best realisations of the ampere, with an accuracy of about 4 parts in $10^7$ are made by combinations of realisations of the watt, the ohm and the volt[2].

The volt is the SI derived unit of electromotive force or electric potential difference. It is defined as *....the potential difference between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt*[4].

The definition can be realised using a voltage balance, which compares an electrostatic force (between the electrodes of a cylindrical capacitor) on one arm of the balance, to a mechanical force (the force of gravity acting on a mass) on the other arm. Such a device is maintained at the German national metrology institute, Physikalisch-Technische Bundesanstalt (PTB)[5]. Pöpel[5] describes how the balance is used to realise a voltage $V$, in terms of a mechanical force $mg$, and the capacitor geometry, with an accuracy of the order of a few parts in $10^7$.

The ohm is the SI derived unit of electrical resistance and is defined as *....the electric resistance between two points of a conductor when a constant potential difference of 1 volt, applied to these points, produces in the conductor a current of 1 ampere, the conductor not being the seat of any electromotive force*[4].

The definition can be realised with an accuracy of less than one part in $10^7$ by the calculable capacitor method developed by Thompson and Lampard[6].

The watt is the SI unit of power, and using the moving coil experiment as described by Robinson and Kibble[7], the electrically realised watt, can be compared to the mechanically realised watt. In fact, it is hoped that with improved design of this experiment, it will be possible to monitor the stability of the SI kilogram, eventually leading to a new definition of the kilogram; the only remaining SI base unit defined in terms of a material artefact [7,8].

### 1.3 Representations of the SI volt

Because of the complexity of the experimental set-ups used to realise definitions of the units most laboratories maintain representations of the units, using experimental set-ups which are in general more stable and reproducible. For example the realisation of the ohm using the calculable capacitor method has only been carried out on a continuous basis in one laboratory since its inception some 40 years ago whereas maintenance of a representation of the ohm using a group of precision wire-wound resistors is more readily attainable[6].

In the case of dc voltage, the voltage balance mentioned earlier is used to realise the definition whereas Josephson voltage standards, saturated standard cells and EVSs are used to maintain representations of the unit.

#### 1.3.1 Josephson Voltage Standards

Most of the major national metrology institutes maintain local representations of the volt using Josephson voltage standards. Josephson voltage standards are primary standards and provide a method of maintaining a representation of the volt based on quantum phenomena which is much more reproducible than its realisation[2].

Josephson voltage standards are based on an effect, known as the ac Josephson effect, predicted by Brian Josephson in the early 1960s[9]. The Josephson effect is observed as a result of the tunnelling behaviour of electron pairs through a very thin dielectric junction between two superconductors. Figure 1.3.1 shows a schematic representation of a Josephson junction comprising two superconductors A and B separated by an insulating dielectric.

A number of publications describing the principles of operation of Josephson standards are given in the literature[5,10-14].

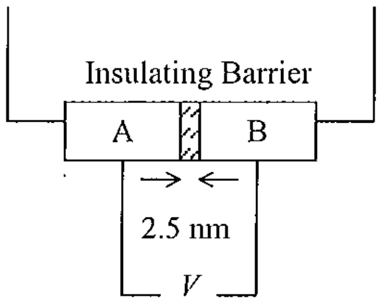


Figure 1.3.1: Schematic of Josephson junction.

Essentially a Josephson junction can be considered an ideal frequency-to-voltage converter. If microwave radiation of an appropriate frequency, is coupled to a dc current biased junction, cooled to about 4.2 K, constant-voltage steps appear at voltage levels given by;

$$V_J = \frac{nf}{K_J} \tag{1.3.1}$$

where n is an integer and $K_J$ is the Josephson frequency-to-voltage quotient, equal to $2e/h$, and referred to as the Josephson constant. Typically for a frequency $f$ = 70 GHz the first voltage step (for $n$=1) appears at around 145 μV and a single junction can generate up to seven steps giving a voltage of around 1 mV[11]. Such a reference value is inconveniently small, and potentiometers with well defined ratios are required to transform it to 1 V or 10 V, the level at which material reference standards are used to maintain the unit (see sections 1.3.2 and 1.3.3). However, a method which generates constant-voltage steps that cross the zero-current axis allows precise Josephson voltages to be generated, by connecting junctions in large series arrays[12-14]. Today arrays containing up to 20 000 junctions, irradiated with an appropriate microwave frequency allow voltages up to 10 V to be generated in steps of approximately 145 μV. The junctions are fabricated on chips and are typically comprised of an aluminium oxide layer between two Niobium superconducting layers.

During the 1970s many national metrology institutes began using Josephson standards to maintain a local representation of the volt. However, non-uniformity between laboratories regarding the value of the Josephson constant, $K_J$ meant that there were differences in the unit as maintained at different locations. Following an earlier attempt in 1972 to adopt an agreed value for $K_J$, the Comité Consultatif d'Électricité CCE, an appendage of the Convention du Mètre, recommended that all laboratories adopt a conventional value for $K_J$ from January 1st 1990. The value chosen, denoted $K_{J\text{-}90}$ is exactly 483 597.9 GHz/V by definition[6,15]. The value does not endeavour to ascribe a value to the quotient $2e/h$, but merely ensures agreement on a value for $K_J$ therefore guaranteeing uniformity between voltage representations based on the Josephson effect. The relative standard uncertainty of $K_{J\text{-}90}$ is 4 parts in $10^7$, which ultimately limits the uncertainty within which Josephson standards can maintain a representation of the volt with respect to the SI definition. However, reproducibilities of the order of a few parts in $10^{10}$ are possible using such standards[6,9]. Comparisons of Josephson reference standards maintained at the various national metrology institutes are carried out on a continuous basis to ensure confidence in the systems responsible for transferring the voltage from the junctions on a chip in a helium dewar at 4.2 K to a reference voltage for use at room temperature[2,9].

Josephson standards have provided laboratories with an almost ideal method of maintaining a local reference standard for dc voltage. However, in view of the high capital and operational costs of such systems many secondary laboratories continue to use artefact standards for this purpose. In the case of dc voltage, electrochemical standard cells and zener-diode based electronic voltage standards are used, both of which are discussed now.

### 1.3.2 Electrochemical standard cells

Until the development of Josephson voltage systems during the 1970s electrochemical standard cells were used to maintain a local dc voltage reference standard. The most widely used electrochemical cell was the saturated standard cell often referred to as the Weston cell developed in 1892 by Edward Weston[16]. The Weston cell consists of two electrodes, one comprised of cadmium amalgam and the other of mercurous sulphate immersed in a saturated solution of cadmium sulphate as shown in figure 1.3.2.

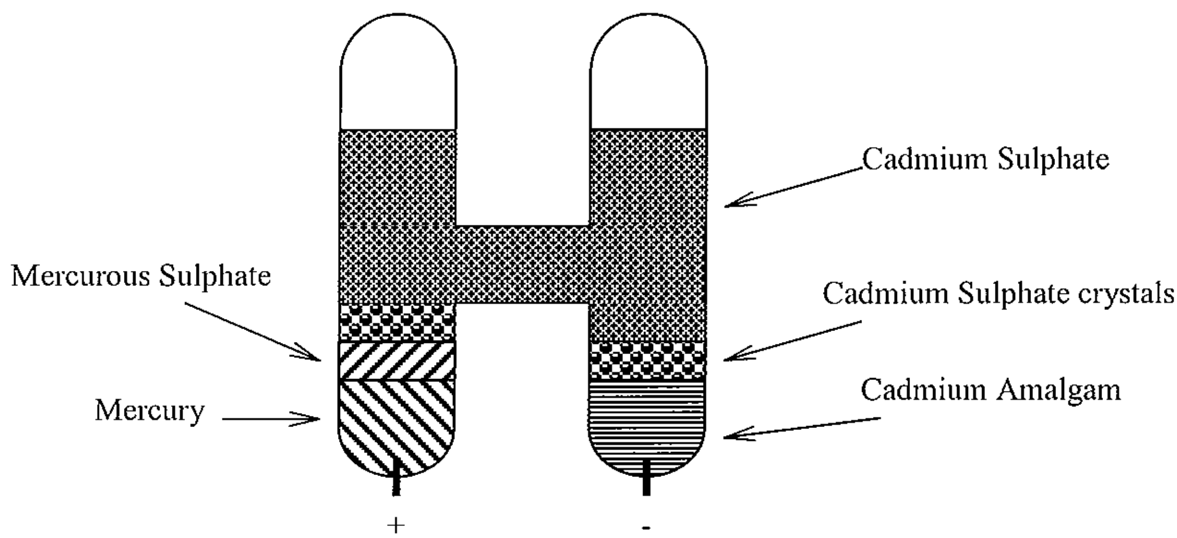


Figure 1.3.2: Schematic representation of a saturated electrochemical cell[16].

The characteristic output voltage of the Weston cells is 1.018 V at 20 °C and the mean voltage of a group of cells is used to maintain a local voltage standard. The individual cells are intercompared on a regular basis with each other to obtain difference measurements from the mean voltage of the group. These intercomparison measurements however, require a certain level of skill since current flow to or from the cells can result in significant shifts in their output voltages. Also thermoelectric voltages can be a significant problem when measuring at 1.018 V.

For use as reference standards, saturated standard cells have a number of shortcomings. Their output voltages have large temperature coefficients, with typical values of the order of – 40 parts per million (ppm) / °C at 20 °C. Therefore they must be housed in temperature controlled, oil or air baths with temperature stability of the order of 25 mK required to ensure the output voltage of the cells remain stable to within 1 ppm. Their output voltages also exhibit large temperature hysteresis, which means a malfunction in the temperature control of the bath can result in significant permanent shifts in their output voltages.

In addition to their sensitivity to temperature change any one of the following may also cause shifts in their output voltages:

- Shock or vibration
- Tilting
- Gas bubbles on the electrodes
- Current flow into or out of the cells

Because of these effects, local standards need to be compared with reference standards at other locations in order to establish traceability. This requires the use of one or more of the cells as a transfer standard. However, such a process is time consuming because of the recovery times required by the cells for the effects of transportation, and temperature differences between locations can increase the recovery time even more.

Due to these many shortcomings saturated standard cells are only used in limited applications nowadays mainly in situations where low noise levels and good stability are required. For use as artefact reference standards they have largely been replaced by EVSs.

### 1.3.3 Electronic Voltage Standards

Commercially available EVSs, based on Zener-diode reference elements have provided many secondary laboratories with an alternative to saturated standard cells as a means of maintaining a reference standard of dc voltage.

Based on developments in the design and manufacture of Zener-diodes in the early 1970s, essentially one of two types is used in today's EVS units depending on the type of temperature coefficient control employed[16,17]. The first type uses a compensated element, where the Zener-diode is placed in series opposition with a p-n junction so that the temperature coefficients of both diodes essentially cancel each other out. The second type is based on a reference amplifier element and is the type used in all EVS units studied in this thesis[18-22]. The temperature coefficient of such devices is controlled by the amplification provided by a transistor, which is placed in series with the Zener.

A simplified schematic of an EVS unit based on a reference amplifier element is shown in figure 1.3.3. The reference circuit is essentially a highly stable voltage regulator, consisting of a NPN transistor and a Zener-diode, both of which are mounted on a single chip. The reference circuit is supplied with a highly stable dc voltage from which it generates a voltage in the region of 7 V to 8 V, depending on the reference circuit design. Using a set of gain resistors this voltage is amplified up to give a voltage output of 10 V. By careful attention to the amplifier it is possible to obtain stability at the 10 V level approaching that of the reference[23]. Together with the 10 V output a 1.018 V output, and in some cases a 1 V output, are derived from the 10 V output by dividing down using an output divider. The 10 V output is the preferred output for use since it is less effected by thermoelectric voltages than the 1.018 V or 1 V outputs and is also more stable. The 1.018 V output is made available as this was the traditional nominal voltage maintained by saturated standard cells.

The entire reference element is housed in a temperature controlled oven which is maintained at a temperature of the order of 10 °C to 20 °C above ambient, depending on EVS manufacturers' design so that the effects of changes in ambient temperature on the reference element is reduced. The oven of most units is also fitted with a thermistor to monitor the oven temperature.

As with standard cells, laboratories maintain a local standard using the mean of a group of EVS units. The units are intercompared with each other on a regular basis so that the stability of individual units can be monitored. Intercomparisons of this type are typically carried out using the procedures and measurement system described in section 3.1. Measurements on EVSs are much less sensitive than standard cell measurements since EVSs can deliver significant output current without introducing error in the reference voltage.

EVSs have a number of advantages over standard cells. They are much more robust which means they are much more suitable for use as travelling standards in providing traceability to reference laboratories. They have significantly smaller temperature coefficients than standard cells also with typical values of the order of 0.05 ppm/K[18-22].

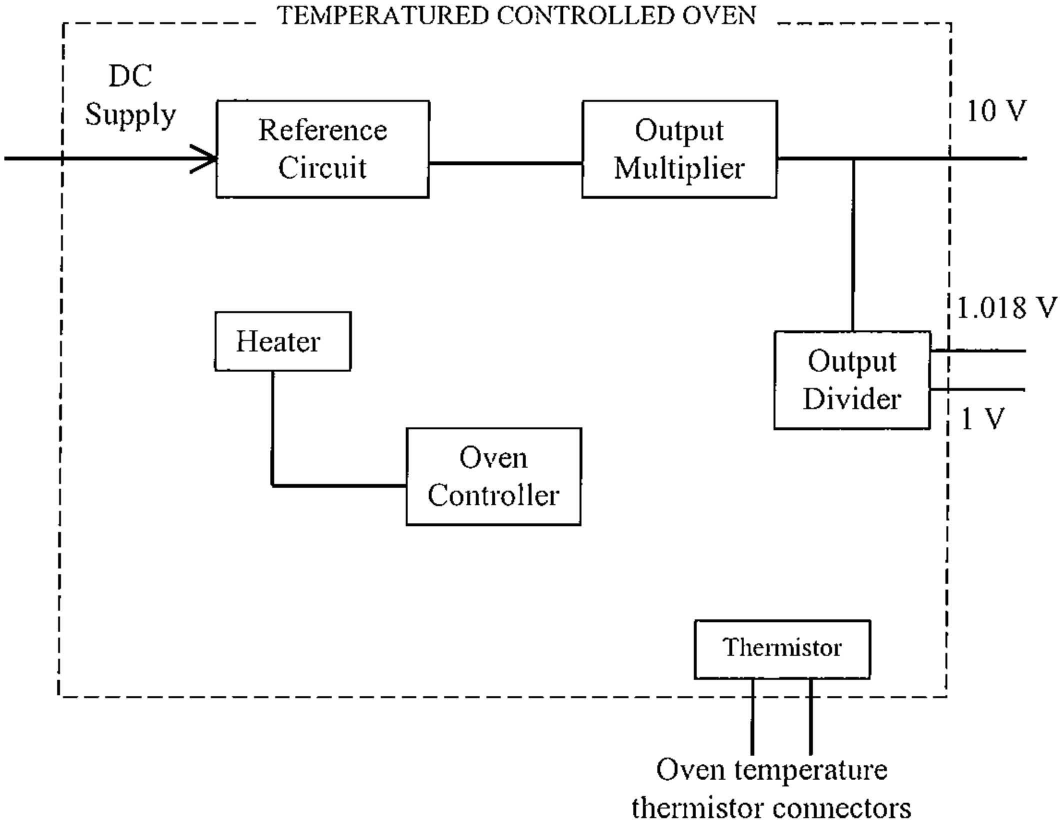


Figure 1.3.3: Schematic representation of EVS reference elements.

Having said this, EVS are far from ideal and they too have a number of shortcomings for use as laboratory reference standards. Their output voltages drift with time,[24] some have significant temperature and pressure coefficients[25,26] and in some cases are susceptible to changes in relative humidity[27]. Their output voltages also exhibit short to medium term noise at a much higher level than Weston cells[27,28].

EVS also have the problem of requiring a continuous power supply in order to maintain their oven at a constant temperature. If power supply failure occurs EVSs can exhibit a hysteresis effect which can result in a significant deterioration in the metrological characteristics of the unit[29]. Under normal operating conditions the EVS unit is supplied with continuous power from ac mains in the laboratory and power supply failure is not a real issue. However when used as a travelling standards for interlaboratory comparisons as described in section 3.2, the units are powered from a dc supply, the reliability of which is therefore very important. A more detailed description of the characteristics of EVS units follows in chapter 2.

## 1.4 The NML Voltage Reference Standard

The NML is the Irish national metrology institute. Amongst its responsibilities is the maintenance of national measurement standards and their dissemination to end users[30]. The NML reference voltage standard is maintained by an ensemble of EVSs of the type described in section 1.3.3. The value of the standard is the mean of the output voltages of the individual units, which comprise the standard. The reference standard also constitutes the Irish national measurement standard for dc voltage. In all, 13 commercially available EVS units are maintained at the NML. The units are maintained in a temperature and humidity controlled laboratory, nominally 23 °C, ± 0.5 °C and 40% relative humidity.

The ensemble includes commercial units of the following type: Fluke 732A, Fluke 732B, Datron 4910, Guildline 4410 and Wavetek 7001. A picture of the group is shown in figure 1.4.1. In general not all 13 units are used to maintain the standard, with a number of selected units being used at any given time. Their selection is based on an assessment of their output voltage characteristics such as temporal predictability, low noise output and insensitivity to environmental factors as detailed in chapter 2.

The standard is maintained at 10 V and traceability of the value assigned to the ensemble standard is assured through annual interlaboratory comparisons with the BIPM, as described in section 3.2. Within-group comparisons are carried out on a weekly basis as a means of continuously monitoring the output performance of the individual EVS units, as described in section 3.6. Measurements in the range 0 V to 10 V are made using a potentiometer which operates on the binary divider principle and which is standardised against the 10 V reference group. These facilities are used to support a dc voltage calibration workload consisting of voltage reference devices, high accuracy calibrators and voltmeters.

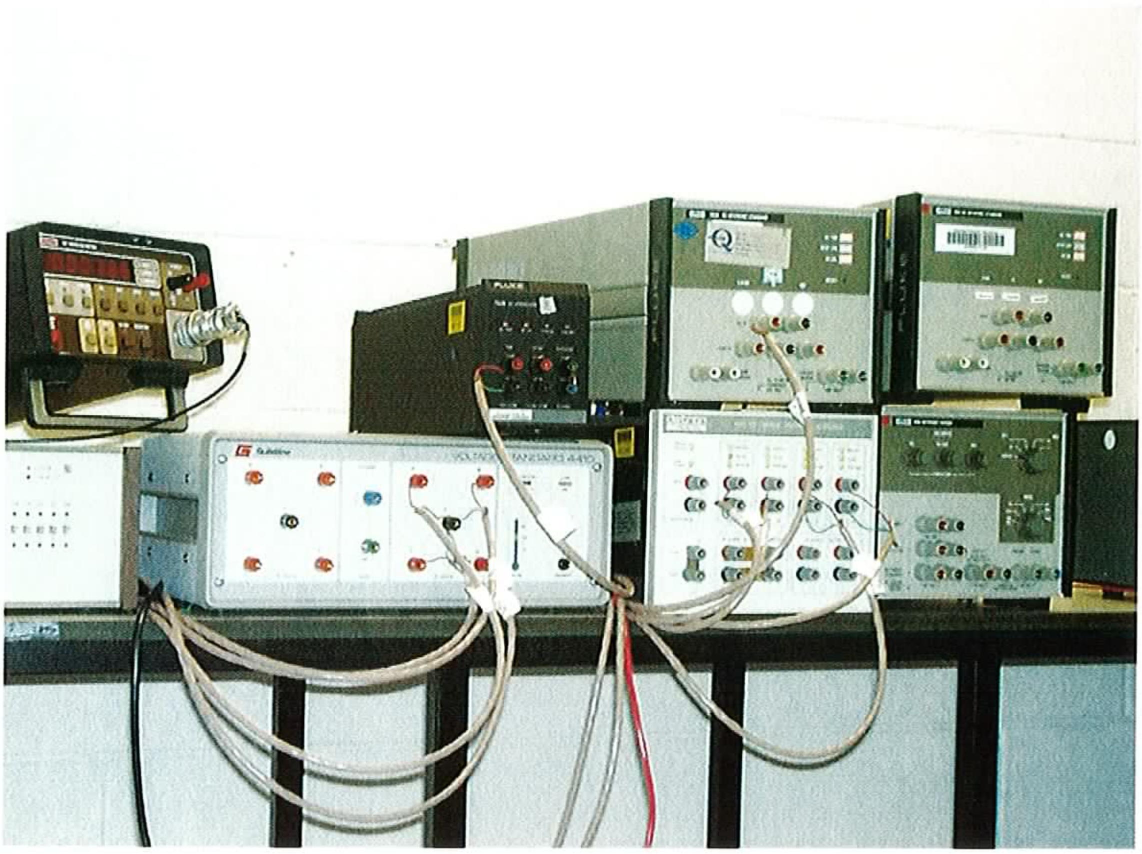

Figure 1.4.1: Picture of NML EVS group with auxiliary measuring equipment.

The use of the NML ensemble in maintaining a local voltage reference standard at 10 V is the basis of this thesis. The following chapters discuss techniques and present results of procedures and experiments used to quantify the temporal and pressure characteristics of the standard.

# 2. The Effect of Influence Factors on the Output of Electronic Voltage Standards.

## 2. Introduction

Having introduced EVSs and their use in maintaining a local reference standard for dc voltage in chapter 1, the effects of a number of influence factors on their output voltage is discussed. A characteristic model is proposed which can be used to describe the output voltage behaviour of any EVS unit.

Techniques are developed which can be used to estimate temporal regression parameters and their associated standard uncertainties for individual units, through the analysis of the results of a series of interlaboratory comparisons. The use of these parameters in predicting estimates of the value of the output of individual units and the ensemble standard is also discussed. The importance of within-group comparisons for monitoring the stability of individual units which comprise an ensemble standard are also highlighted. Finally, a technique is proposed which can be used to estimate pressure coefficients of EVS units.

## 2.1 Electronic Voltage Standards: influence factors

In section 1.3.3 EVS output voltages were shown to exhibit a number of characteristics which ultimately limit their performance as a laboratory reference standard. The effect of each of these factors on the output voltage of EVS units is discussed below.

### 2.1.1 Temporal drift

By far the most significant influence factor on the output of an EVS unit is time. All EVSs drift with time to a greater or lesser extent, with typical temporal drift coefficients $\alpha_t$, of the NML EVSs estimated to be between 0.1 ppm/year and 0.6 ppm/year, relative to their 10 V outputs. However, this temporal effect is not considered a major problem for metrologists since in most cases it is predictable and therefore can be readily characterised. A major part of the work reported in this thesis relates to the characterisation of the temporal behaviour of the EVS units, which comprise the NML laboratory reference standard and is discussed further in section 2.3.

### 2.1.2 Temperature

It is assumed that all the NML EVS units have finite temperature coefficients, $\alpha_T$. The manufacturers recognise the existence of temperature coefficients by quoting limits within which $\alpha_T$ lies and these limits are quoted in the relevant literature[18-21,31].
The coefficients associated with the NML EVS units are listed in table 2.1.1. Since all the units are maintained in a temperature-controlled environment with typical stability of ± 0.5 °C the associated variation in the output voltage of the EVSs in question, based on the coefficients listed in table 2.1, is of the order of 0.02 ppm.
However, the temperature coefficients as quoted by the manufacturer, can only be considered as limits of the temperature coefficient of an individual EVS unit of that particular model, and ideally the coefficient would need to be determined for each individual unit[25]. For example, Witt[25] found the temperature coefficients of 15 Fluke 732B units at 10 V to range between + 0.016 ppm/°C and – 0.015 ppm/°C, illustrating

the need to determine coefficients for individual units where the highest measurement accuracies are sought.

| EVS Model | Temperature Coefficient $\alpha_T$ (ppm/°C) |
|---|---|
| Fluke 732 A | ± 0.05 |
| Fluke 732 B | ≤0.04 |
| Guildline 4410 | ± 0.04 |
| Datron 4910 | ≤ 0.05 |
| Wavetek 7001 | ≤ 0.03 |

Table 2.1.1: NML EVS Temperature Coefficients as quoted by manufacturers.

Since the temperature coefficients of individual NML EVS units have not been measured directly the need for corrections due to temperature were evaluated based on the coefficients quoted by the manufacturers.

### 2.1.3 Pressure

The dependence of EVS output voltage with pressure is a relatively recent discovery. In fact, most manufacturers of commercially available EVS units do not quote any pressure coefficients for their units[18-21,31].

However, in April 1998 the effects of atmospheric low pressure (~965hPa) in the vicinity of the NML laboratories caused a detectable change in the output voltage of one of the EVS units in particular. This eventually led to an investigation of the effect, although work had already been carried out at the BIPM in determining the pressure coefficients of a number of EVS units[26]. The pressure coefficients $\alpha_p$, reported range from + 2.08 ppb/hPa to – 0.14 ppb/hPa, and indicate that pressure variations would be a significant source of error, in situations where the highest measurement accuracies are sought[26].

This thesis reports in part on the development of a system, used to determine the pressure coefficients of the individual EVS units, used to maintain the voltage reference standard at the NML. The coefficients determined for a number of EVS units are also reported.

### 2.1.4 Humidity Effects

Most electrical standards laboratories such as the NML, have air-conditioning systems, which maintain the laboratory at a specified temperature and relative humidity, ideally 23 °C and 40% relative humidity respectively, nominal values.

However, in the case of NML, the relative humidity has been found to fluctuate between about 35% and 50% throughout the course of a year. Because of this it is important to consider the possible implications of this on the EVS outputs, since like pressure, no literature is available from the manufacturers relating to the sensitivities of EVSs to changes in ambient humidity[18-21,31].

Work by Witt et al has illustrated the direct influence of changes in relative humidity on EVS output voltage[27]. The work detailed relates mainly to measurements on the 1.018 V output of just three Fluke 732A EVSs and therefore is not directly relevant to the work presented here since all voltage measurements are at the 10 V level. In fact, the work reported no discernible effect on the 10 V outputs of the units studied[27].

It is our opinion though, that one Fluke 732A EVS maintained at NML may be influenced by changes in relative humidity at the 10 V level. The output voltage of this particular unit over a number of years is shown in figure 2.1.1. The cyclic behaviour, with a period of approximately 1 year, may suggest a variation in EVS output with seasonal variations in relative humidity.

Work by Cobbe[32] as part of an undergraduate project found that this might in fact be true. The work described by Cobbe however was based purely on a history of humidity readings taken by a hygrometer in the laboratory and a more rigorous experiment using a humidity controllable chamber would be required in order to properly verify the findings. However, because of these suspicions, the unit in question, is not used to maintain the NML reference standard.

None of the other NML EVS units studied show any detectable sensitivity to humidity changes.

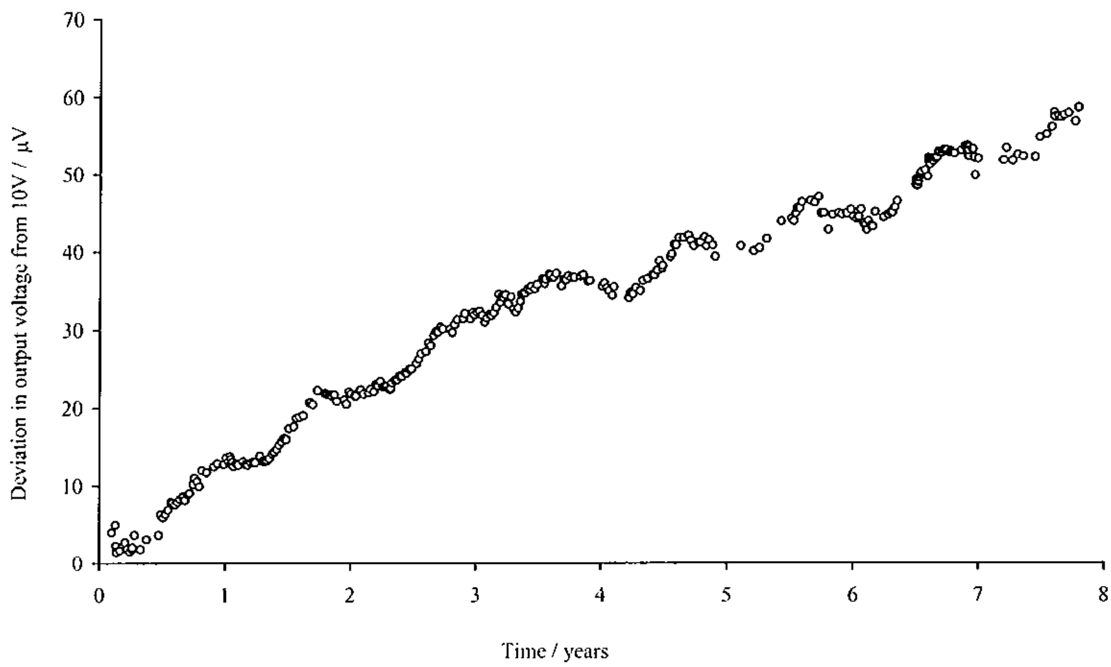


Figure 2.1.1: Deviation in output of an NML Fluke 732A with time.

### 2.1.5. Intrinsic Noise

One important intrinsic characteristic of the output voltage of EVS units is noise. Any measurement made on the output of an EVS unit will clearly illustrate this. Apart from the noise associated with the EVS unit itself, noise will also be introduced by the measuring system, e.g. voltmeter, measurement leads, thermoelectric voltages etc. Therefore, it is important that any reported measurements, on the output of an EVS unit, take noise into account.

The classical and probably simplest method of dealing with noise, is to make a number of measurements $n$ of the quantity $y$, and determine the associated sample mean $\bar{y}$ and standard deviation $s$. The sample standard deviation of the mean, often referred to as the standard uncertainty of $\bar{y}$, given by $s{\cdot}n^{-\frac{1}{2}}$ is used to characterise the noise or scatter of the measurements.

It would appear that the standard uncertainty $\bar{y}$ decreases with increasing $n$ and can be made arbitrarily small by making $n$ large enough. However, recent work suggests that quantifying the scatter of a series of EVS voltage measurements using these classical methods may have limited applications, particularly over extended measurement periods[27,28,33].

Spectral analysis techniques show the output voltage noise of EVSs to be comprised of white noise together with a strong low-frequency $1/f$ component, which ultimately limits the short-term stability of the EVS output voltage to between 3 and 10 parts in $10^9$. This point is further illustrated using Allan variance techniques, which also show the presence of a $1/f$ noise component implying that measurements on the voltage outputs of EVSs are serially correlated[33].

Clearly this draws into question the validity of the classical analysis techniques mentioned above, as they are only applicable when the associated measurements are independent and identically distributed i.e. when the noise is purely white.

Thus, the presence of $1/f$ noise, which becomes significant with increasing measurement periods, limits the use of classical statistical techniques. It can be shown how the classical variance can indeed underestimate the scatter in a series of measurements as the measurement period increases[33]. Using the Allan variance provides a better estimate of the scatter of EVS measurements, which does not descend below some $1/f$ floor value regardless of the number of measurements $n$.

The measurement period over which the $1/f$ floor value is reached depends on the voltmeter used to carry out the measurements, which is usually of the order of one to two minutes[27,28]. Therefore, it is important that all measurement periods of EVS outputs be of this order so that the use of classical statistical techniques are justified. In as far as possible measurement periods of this order were implemented when making voltage measurements during this project.

However in order to optimise the voltage measurement procedures such as voltmeter filter settings, sampling periods etc., the overall measurement system, would need to be characterised using some frequency-domain analysis technique such as those mentioned above.

## 2.2 Characteristic model

In order to make optimum use of a group of EVSs as a laboratory reference standard, a model is required which can be used to define the output voltage of any of the individual EVSs comprising the standard. It is proposed therefore, that the output voltage **V**, of any EVS at any time t, temperature T, pressure p, and relative humidity H, can be represented using the following model:

$$\mathbf{V}\,(t,p,T,H) = \mathbf{V}_0 + \alpha_t\cdot(t-t_0) + \alpha_p\cdot(p-p_0) + \alpha_T\cdot(T-T_0) + \Psi_H + \Phi \qquad (2.2.1)$$

where, $\mathbf{V}_0$ is the value of the EVS output at some set of reference conditions,

$\alpha_t$, is the temporal coefficient of the EVS,

$\alpha_p$ is the pressure coefficient of the EVS,

$\alpha_T$ is the temperature coefficient of the EVS,

$\Psi_H$ is a correction term for changes with ambient humidity,

$\Phi$ is a correction term due to the intrinsic noise characteristics of the EVS, and

$t_0$, $p_0$, and $T_0$ are reference values of time, pressure and temperature respectively.

This is a simplified model, which assumes that the EVS output behaves in a linear fashion with time, pressure, and temperature; the correction terms for relative humidity $\Psi_H$, and intrinsic noise $\Phi$, are assumed to be non-linear functions.

The model given can be used to determine the output voltage of an EVS for any given set of conditions once the constituent parameters are known.

The work, which follows describe techniques used to determine $\mathbf{V}_0$, $\alpha_t$ and $\alpha_p$ for a number of the EVS units that are presently maintained at the NML.

## 2.3 Quantifying temporal drift of an Electronic Voltage Standard

As mentioned in section 2.1 the output voltage of all EVS units drift with time, to a greater or lesser extent. Figure 2.3.1 shows typical temporal behaviour of an EVS unit over a number of years. In fact, of all the factors which influence EVS voltage outputs, time can be considered the most significant, with temporal drift coefficient magnitudes of the NML EVS units estimated to range from 0.1 ppm/year to 0.6 ppm/year.

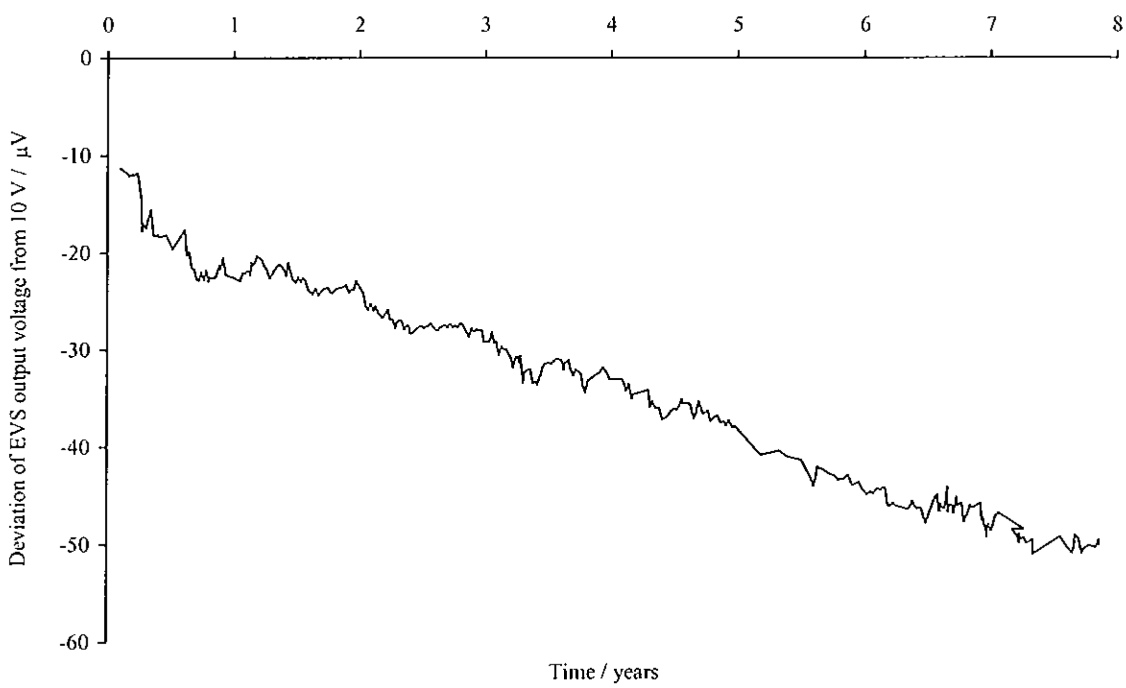


Figure 2.3.1: Typical temporal behaviour of an EVS unit (Datron 4910 unit).

Despite their magnitude, temporal effects are not considered a serious problem, since in most cases, the behaviour is predictable and can be characterised and corrected for using appropriate mathematical relationships. Also, the behaviour can usually be considered linear over the time periods of interest, which means a simple linear relationship suffices to characterise the effect. Even in cases where the EVS output voltage behaves in a non-linear manner, it is often possible to express the relationship in a linear form by a mathematical transformation of one or either variable[34]. The treatments discussed here apply only to cases where the EVS output voltage behaves in a linear fashion with time.

As detailed in section 1.4 the NML voltage reference standard is maintained as the mean of an ensemble of $n$ EVS units. The value ascribed to the reference standard is the arithmetic mean of the values of the individual EVS units as defined by:

$$\mathbf{V}_{\mathrm{NML}} = \frac{1}{n}\sum_{i=1}^{n}\mathbf{V}_i \tag{2.3.1}$$

where, $\mathbf{V}_{\mathrm{NML}}$ is the value of the NML reference standard,

and $\mathbf{V}_i$ is the value of the output voltage of the $i^{\mathrm{th}}$ EVS unit which comprise the reference standard.

However, the output voltage value, $\mathbf{V}_i$, of the EVS units which comprise $\mathbf{V}_{\mathrm{NML}}$, are not constant, but drift with time. Therefore, in order that $\mathbf{V}_{\mathrm{NML}}$ be determinable at any time we need to quantify the temporal characteristics of the constituent $\mathbf{V}_i$.

To do this, we refer to the EVS output characteristic model defined by equation 2.2.1. Ignoring the effects of humidity and intrinsic noise and considering the characteristic model at constant pressure, $p = p_0$ and constant temperature, $T = T_0$, the output voltage $\mathbf{V}_{ij}$ of the $i^{\mathrm{th}}$ unit at time $\mathbf{t}_j$ is defined as:

$$\mathbf{V}_{ij} = \mathbf{V}_{0i} + \alpha_{ti}\cdot(\mathbf{t}_j - \mathbf{t}_{0i}) \tag{2.3.2}$$

where, $\mathbf{V}_{ij}$ is the value of the output voltage of the EVS at time $\mathbf{t}_j$,

$\mathbf{V}_{0i}$ and $\alpha_{ti}$ are temporal regression parameters, that is, slope and intercept,

$\mathbf{t}_j$ is time and $\mathbf{t}_{0i}$ is an arbitrary reference time.

If $\alpha_{ti}$ and $\mathbf{V}_{0i}$ are known the output voltage $\mathbf{V}_i$ can be determined at any time $\mathbf{t}$ and from equation 2.3.1 $\mathbf{V}_{\mathrm{NML}}$ can be determined at $\mathbf{t}$. However, the output voltage $\mathbf{V}_{ij}$, of the EVS, cannot be determined exactly at any time $\mathbf{t}_j$, but may only be estimated from sample observations of the EVS output voltage, it follows therefore that the parameters, $\alpha_{ti}$ and $\mathbf{V}_{0i}$ cannot be determined exactly but may only be estimated also. The analysis of the sample observations follow the treatments developed in the literature, where time, $\mathbf{t}$ will be defined as the independent variable and the EVS output voltage, $\mathbf{V}_i$ defined as the dependent variable[35]. The independent variable, $\mathbf{t}$, is considered to be accurately known, and the only reason that observations of the dependent variable, $\mathbf{V}_i$, do not fit the equation exactly is because of disturbances or errors of measurement in the observations[35].

It is also assumed that the distributions of the observations of $\mathbf{V}_{ij}$, at $\mathbf{t}_j$, are normal, (or at least symmetrical and all of the same form), have the same variance $\sigma^2$, are uncorrelated and that the mean of the distribution of the observations at $\mathbf{t}_j$ coincides with the value, $\mathbf{V}_{ij}$, as defined by equation 2.3.2.

The appropriate sample observations of the output voltage of the EVS units with time are extracted from the results of interlaboratory comparisons as detailed in section 2.3.1. The observational sample data obtained from the interlaboratory comparison results, allow best estimates of $\alpha_{ti}$ and $\mathbf{V}_{0i}$ to be determined, denoted $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$ respectively, see section 2.3.4. These estimated values can be used, in turn, to predict an estimate of the value $\mathbf{V}_i$, at any time $\mathbf{t}$, which likewise is denoted $\hat{V}_i$, and following from equation 2.3.1 a best estimate of the value of the voltage reference standard $\mathbf{V}_{NML}$ can be determined, denoted $\hat{V}_{NML}$.

Note: Hat notation will be used throughout to denote estimates of the true value of a parameter. For example $\hat{V}_i$ denotes an estimate of the true value $\mathbf{V}_i$.

### 2.3.1 Interlaboratory comparisons

The primary aim of interlaboratory comparisons is to compare the measurement results produced by two or more laboratories. In the case where one of the laboratories in the intercomparison can achieve significantly lower uncertainties than the other participants, this laboratory can be considered the reference laboratory. The other laboratories may then determine the validity of their measurement results by comparison with the results of the reference laboratory.

As part of its voltage maintenance program, NML participates annually in interlaboratory comparisons of dc voltage measurements, with BIPM as the reference laboratory. Since only two laboratories are involved, comparisons of this type are often referred to as bilateral comparisons. Similar comparisons with other higher echelon laboratories such as the National Physical Laboratory are also carried out on occasion.

Bilateral comparisons between NML and BIPM are carried out using a group of well-characterised travelling standards, which are sent, from one laboratory to the other. The travelling standards are EVS units, which are powered by battery supply during transportation between locations. In fact Fluke 732B EVS units of the type mentioned in section 1.4 have been used for this purpose during most recent comparisons[36,37].

The comparison technique is essentially a three-step measurement process as illustrated in figure 2.3.2. Firstly, BIPM carry out a series of measurements on the output voltage of the travelling standards either directly or indirectly against their Josephson voltage reference standard $V_{BIPM}$. Secondly, the travelling standards are shipped to NML where measurements are carried out against the NML voltage reference standard, $V_{NML}$, using the NML measurement system as detailed in section 3.1.2. Finally, the standards return to BIPM where further measurements are carried out against the BIPM reference standard.

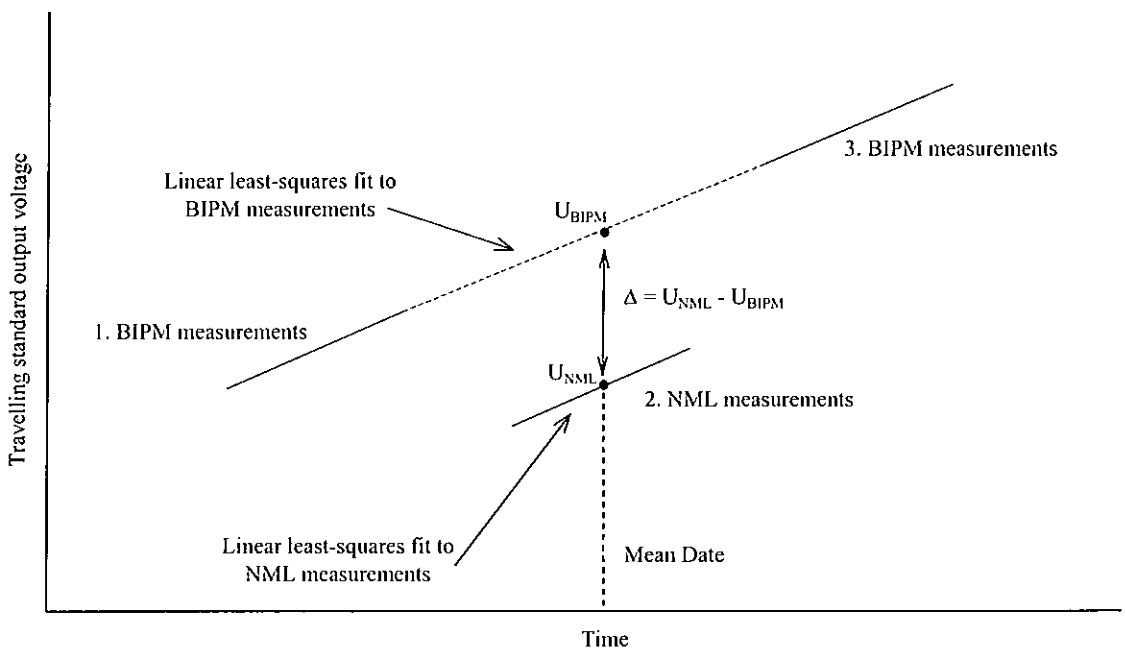


Figure 2.3.2: Illustration of interlaboratory measurement technique.

Values, $U_{BIPM}$ and $U_{NML}$ are ascribed to the output voltage of each travelling standard on the mean date of the comparison, based on a linear least-squares fit to the measurements made at BIPM and NML respectively.

Type A and type B standard uncertainties associated with $U_{NML}$ and $U_{BIPM}$ are also determined in accordance with the International Standards Organisation (ISO) *Guide to the expression of uncertainty in measurement*[38].

The final important result of the bilateral comparison is the difference $\Delta = U_{NML} - U_{BIPM}$ together with its associated standard uncertainty $u(\Delta)$ which is derived through a combination of the type A and type B uncertainties. The result of the comparison is deemed acceptable providing the difference $\Delta$ is less than its associated expanded uncertainty $k \cdot u(\Delta)$, where $k = 2$ for 95% coverage probability.

On the other hand if $\Delta$ exceeds $k \cdot u(\Delta)$ the measurement results of both laboratories are not consistent. This may be due to a number of factors, such as anomalies in the behaviour of the travelling standards, biases in the voltage measurement systems, or deviations of the NML laboratory reference standard $\mathbf{V}_{NML}$ from its expected value.

### 2.3.2 Acquisition of sample observations of $\mathbf{V}_{ij}$ at $\mathbf{t}_j$

In addition to its primary function of evaluating the status of NML's 10 V measurement capabilities, the results of a bilateral comparison allow sample observations $V_{ij}$ of the output voltage value, $\mathbf{V}_{ij}$ to be obtained for each of the $n$ NML units on the mean date of the comparison.

Note: Italic-face notation will be used throughout to denote observations of the true value. For example $V_{ij}$ is used to denote an observation of $\mathbf{V}_{ij}$.

The value $U_{NML}$, ascribed to the output voltage of each travelling standard on the mean date of a comparison is based in part on a series of difference measurements made between the output voltage of the travelling standards and the NML EVS units during the comparison.

On the mean date of the comparison the difference between any NML EVS unit and travelling standard is:

$$\delta_i = \mathbf{V}_{TS} - \mathbf{V}_i \qquad (2.3.3)$$

where, $V_{TS}$ is the output voltage of the travelling standard.

The best available estimate of $V_{TS}$ is $U_{BIPM}$, the value ascribed by BIPM to the output voltage of the travelling standard on the mean date and the best available estimate of $\delta_i$ is $\overline{\delta}_i$, the mean value of the observed voltage differences at NML, which are obtained using a digital nanovoltmeter.

Hence by substitution and rearrangement equation 2.3.3 yields,

$$V_i = U_{BIPM} - \overline{\delta}_i \tag{2.3.4}$$

This allows $V_i$, a value of the output voltage of the $i^{th}$ unit as observed on the mean date of the intercomparison $t_j$, to be determined which is directly traceable to the BIPM voltage reference standard.

From a similar treatment of a series of bilateral comparison results it is possible to obtain a series of $(t_j, V_{ij})$ data for each member of the NML ensemble voltage standard, where $V_{ij}$ is the observed value of the output voltage of the $i^{th}$ unit and $t_j$ is the mean date of the $j^{th}$ bilateral comparison.

This series of $(t_j, V_{ij})$ data can then be used to determine the estimates $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$.

### 2.3.3 Standard Uncertainty of $V_{ij}$

$V_{ij}$ as defined in equation 2.3.4 will have an associated standard uncertainty $u(V_{ij})$, comprising contributions from the standard uncertainties of $U_{BIPM}$ and $\overline{\delta}_i$. The standard uncertainty $u(U_{BIPM})$ is obtained from the BIPM bilateral comparison results and the standard uncertainty $u(\overline{\delta}_i)$ is obtained from the NML difference measurements.

Hence, in keeping with the guidelines of the ISO *Guide to the expression of uncertainty in measurement*[38], $u(V_{ij})$ is defined by equation 2.3.5 as:

$$u(V_{ij}) = \sqrt{u^2(U_{BIPM}) + u^2(\overline{\delta}_i)} \tag{2.3.5}$$

Appropriate coverage factors can also be applied to this estimate giving desired confidence intervals for the estimate $u(V_{ij})$.

### 2.3.4 Determination of $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$

The temporal regression parameters $\mathbf{V}_{0i}$ and $\alpha_{ti}$ introduced in equation 2.3.2 are simply the slope and intercept of the linear temporal drift characteristic equation. Ordinarily we do not know what $\mathbf{V}_{0i}$ and $\alpha_{ti}$ are and therefore we estimate them, from the observational sample data obtained as described in section 2.3.3.

A number of estimation techniques can be employed to determine estimators of $\mathbf{V}_{0i}$ and $\alpha_{ti}$ with the method of least-squares being used here. For each of the observations $(t_j, V_{ij})$ the method of least-squares considers the deviation $D$, of $V_{ij}$ from its expected value $\mathbf{V}_{ij}$ as defined by equation 2.3.2, i.e.

$$D = V_{ij} - (\mathbf{V}_{0i} + \alpha_{ti} \cdot (\mathbf{t}_j - \mathbf{t}_{0i})) \tag{2.3.6}$$

In particular the method of least-squares requires that we consider the sum of the $m$ squared deviations. This criterion is denoted by $Q$:

$$Q = \sum_{j=1}^{m} (V_{ij} - \mathbf{V}_{0i} - \alpha_{ti}(\mathbf{t}_j - \mathbf{t}_{0i}))^2 \tag{2.3.7}$$

According to the method of least-squares, the estimates of $\mathbf{V}_{0i}$ and $\alpha_{ti}$ are those values $\hat{V}_{0i}$ and $\hat{\alpha}_{ti}$, respectively, that minimise the criterion $Q$ for the given observations $(t_j, V_{ij})$. The estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$ are obtained directly as:

$$\hat{\alpha}_{ti} = \frac{\sum_{j=1}^{m} (t_j - \bar{t})(V_{ij} - \bar{V}_i)}{\sum_{j=1}^{m} (t_j - \bar{t})^2} \tag{2.3.8}$$

$$\hat{V}_{0i} = \overline{V_i} - \hat{\alpha}_{ti}\bar{t} \qquad (2.3.9)$$

where, $\bar{t}$ and $\overline{V_i}$ are the mean values of the $m$ sample observations ($t_j$,$V_{ij}$). Further details of how equations 2.3.8 and 2.3.9 are derived are given in the literature[35].

The number of degrees of freedom associated with each estimator should also be quoted. Since two estimators $\hat{V}_{0i}$ and $\hat{\alpha}_{ti}$ are determined from a sample of $m$ observations the number of degrees of freedom associated with each estimator is $m$-2.

Once the least-squares estimators $\hat{V}_{0i}$ and $\hat{\alpha}_{ti}$ have been determined we can use them to estimate the output voltage value, $\mathbf{V}_i$ at any time t, from equation 2.3.10.

$$\hat{V}_i = \hat{V}_{0i} + \hat{\alpha}_{ti}(t - t_{0i}) \qquad (2.3.10)$$

$\hat{V}_i$ is therefore an estimate of the mean value of the output voltage of the EVS unit at any time, t. Again, following from equation 2.3.1 we can also estimate the value assigned to the NML voltage reference standard as:

$$\hat{V}_{NML} = \frac{1}{n}\sum_{i=1}^{n}\hat{V}_i \qquad (2.3.11)$$

### 2.3.5 Standard uncertainties of $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$

In order to estimate the standard uncertainties of $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$ let us firstly discuss the notion of residuals. We define the $j^{th}$ residual as the difference between the observed value $V_{ij}$ at $t_j$ and the corresponding fitted or estimated value $\hat{V}_{ij}$. Denoting the residual by $e_j$, we can write:

$$e_j = V_{ij} - \hat{V}_{ij} = V_{ij} - \hat{V}_{0i} - \hat{\alpha}_{ti}(t_j - t_{0i}) \qquad (2.3.12)$$

Referring to figure 2.3.3 the residuals $e_j$ are the vertical deviations of $V_{ij}$ from the values $\hat{V}_{ij}$ on the fitted line. Hence, the residuals are useful for studying whether a given linear model is an appropriate description of the data at hand.

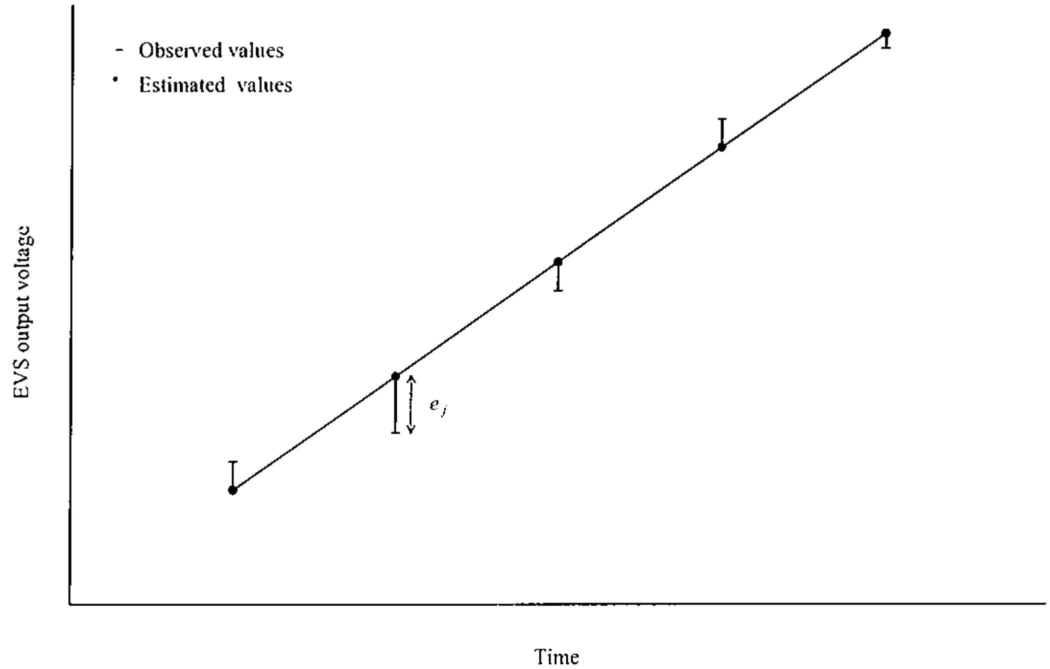


Figure 2.3.3: Residuals $e_j$, deviation of observed values from predicted values.

Further analysis of residuals, as discussed in the literature, leads to the result that the *mean square error* or *residual mean square*, MSE, defined in equation 2.3.13 is an unbiased estimator of the variance $\sigma^2$, for the linear temporal drift model as given in equation 2.3.2[35].

$$\text{MSE} = \frac{\sum e_j^2}{m-2} \qquad (2.3.13)$$

An estimator of the corresponding standard deviation $\sigma$ is simply the square root of MSE. Having obtained an estimator for $\sigma^2$ it will now be used to derive the standard uncertainties, associated with the estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$.

Firstly taking $\hat{\alpha}_{ti}$, and following the treatments of Neter et al[35], we obtain an estimator for $\sigma^2(\hat{\alpha}_{ti})$, the variance of $\hat{\alpha}_{ti}$ defined as:

$$s^2(\hat{\alpha}_{ti}) = \frac{\text{MSE}}{\sum (t_j - \bar{t})^2} \tag{2.3.14}$$

Likewise, an estimator of $\sigma^2(\hat{V}_{0i})$, the variance of $\hat{V}_{0i}$ is defined as:

$$s^2(\hat{V}_{0i}) = \text{MSE}\left[\frac{1}{m} + \frac{\bar{t}^2}{\sum (t_j - \bar{t}^2)}\right] \tag{2.3.15}$$

Following from this the positive square roots of $s^2(\hat{\alpha}_{ti})$ and $s^2(\hat{V}_{0i})$ give $s(\hat{\alpha}_{ti})$ and $s(\hat{V}_{0i})$ respectively, estimators of the standard deviations of $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$. In keeping with the notation of the ISO *Guide to the expression of uncertainty in measurement*, the estimators $s(\hat{\alpha}_{ti})$ and $s(\hat{V}_{0i})$, are written as $u(\hat{\alpha}_{ti})$ and $u(\hat{V}_{0i})$ respectively, and referred to as the standard uncertainties of $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$[38].

Appropriate coverage factors, based on the number of degrees of freedom, $m$-2, associated with the estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$ can be applied to the standard uncertainties to give desired confidence intervals.

### 2.3.6 Standard uncertainties of $\hat{V}_i$ and $\hat{V}_{NML}$

The estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$ are used to predict the output voltage of the NML EVS units at any time t, using equation 2.3.10. A predicted value $\hat{V}_i$ has an associated variance which following the techniques developed by Neter et al[35] is given as:

$$s^2(\hat{V}_i) = \text{MSE}\left[1 + \frac{1}{m} + \frac{(t - \bar{t})^2}{\sum (t_j - \bar{t})^2}\right] \tag{2.3.16}$$

where, $t_j$, $\bar{t}, m$ and MSE have been defined earlier.

The positive square root of equation 2.3.16 gives an estimate of the standard uncertainty of $\hat{V}_i$ denoted $u(\hat{V}_i)$.

The standard uncertainty is a quadratic function having the property that as one predicts further from the mean value $\bar{t}$ the greater the value of $u(\hat{V}_i)$ as illustrated by the dashed lines in figure 2.3.4 which are often referred to as prediction bands.

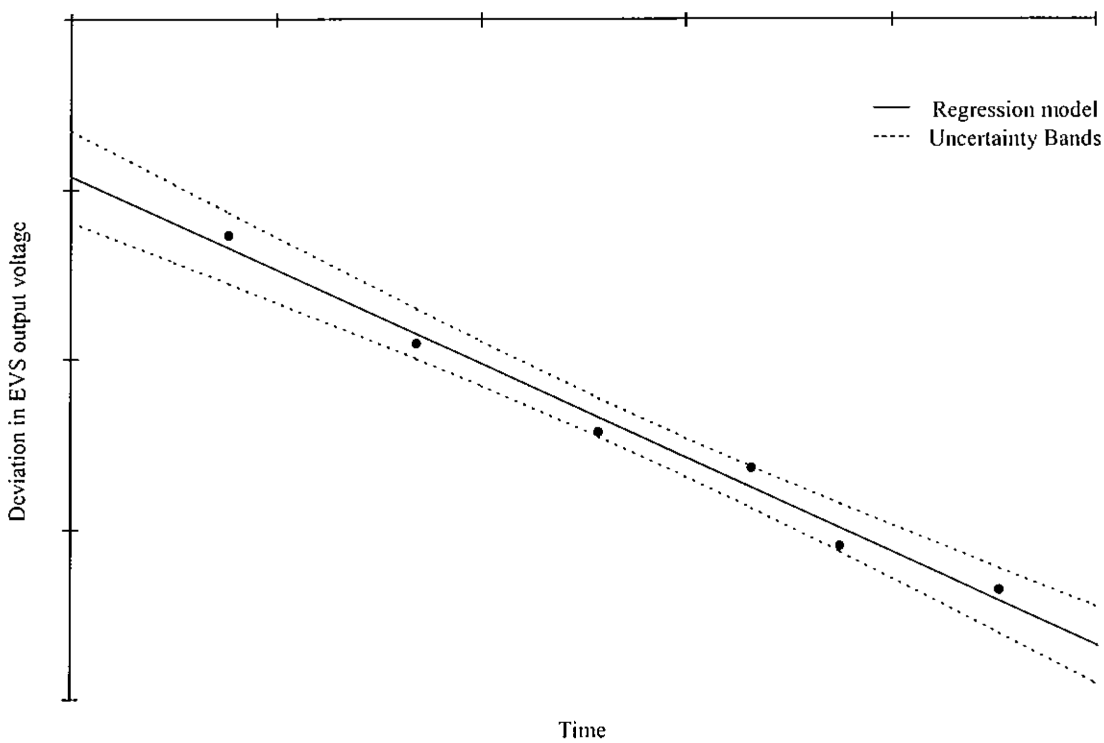


Figure 2.3.4: Characteristics of the uncertainty, $u(\hat{V}_i)$.

The estimators $\hat{\alpha}_{1i}$ and $\hat{V}_{0i}$ which are used to predict the value $\hat{V}_i$, were estimated from analysis of a series of time sampled data $V_{ij}$. This sample data has an associated standard uncertainty $u(V_{ij})$ defined by equation 2.3.5 which also makes a contribution to the standard uncertainty of $\hat{V}_i$. To account for this the total standard uncertainty $u_{tot}$ of the predicted value is determined from the root-sum-square of contributions derived from equations 2.3.5 and 2.3.16. given as:

$$u_{\text{tot}}(\hat{V}_i) = \sqrt{u^2(V_{ij}) + u^2(\hat{V}_i)} \qquad (2.3.17)$$

Appropriate coverage factors can be applied to the standard uncertainty to give prediction bands for $\hat{V}_i$ at the desired confidence level.

Hence, equations 2.3.10 and 2.3.17 can be used to ascribe a value and associated standard uncertainty to the output voltage of the NML EVS units at any time. The $\hat{V}_i$ values once determined are used to estimate the value of the NML reference $\hat{V}_{\text{NML}}$ using equation 2.3.11. The corresponding standard uncertainty $u(\hat{V}_{\text{NML}})$, is obtained as the root-mean-square of the standard uncertainties $u_{\text{tot}}(\hat{V}_i)$ as follows:

$$u(\hat{V}_{\text{NML}}) = \frac{1}{n}\sqrt{\sum_{i=1}^{n} u^2(\hat{V}_i)} \qquad (2.3.18)$$

This completes the discussion on the determination of the temporal regression parameters of the EVS units together with their associated standard uncertainties. Alternatively, a matrix approach to linear regression analysis can be applied which allows the regression parameters together with their associated uncertainties to be determined using matrix algebra. The matrix approach has the advantage that it permits extensive systems of equations and large arrays of data to be denoted and operated upon efficiently. The matrix techniques are not discussed here but methods discussed in the literature are readily applicable in quantifying the temporal behaviour of EVS units[35,39].

### 2.3.7 Monitoring temporal stability of EVS units

In sections 2.3.1 through section 2.3.6 the methods employed to characterise the temporal behaviour of EVS units, in particular the determination of the estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$, were discussed. The estimators are used to determine best estimates, $\hat{V}_i$, of the output voltage of the NML EVS units at any time, which in turn are used to determine an estimate, $\hat{V}_{NML}$, of the value of the NML voltage reference standard.

Once determined, the estimators $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$, for any particular unit remain unchanged during the time period between interlaboratory comparisons. Each subsequent comparison provides an additional pair of data, $(t_j, V_{ij})$, for each unit and this additional data is used to re-determine $\hat{\alpha}_{ti}$ and $\hat{V}_{0i}$, as described in section 2.3.3. The inclusion of additional data will, in general, result in some change in the estimates of the temporal regression parameters.

Since bilateral comparisons are carried out annually, it follows that the temporal regression parameter estimators are only re-determined at similar intervals. Some means are required to ensure that the output voltage of the EVS units are behaving in a manner predicted by their temporal regression models in the intervening time period. This is done by carrying out within-group comparisons on a regular basis.

### 2.3.8 Within-group comparisons

Within-group comparisons consist of a series of measurements which allow estimates, $\hat{W}_i$, to be ascribed to the output voltage of the EVS units, which is compared to the temporal regression estimates, $\hat{V}_i$, at the time in question. It should be noted that the symbols V and U are conventionally used to denote voltage or emf. However, to avoid confusion with earlier notation, $\hat{W}$ is used to denote the estimators determined here.

If the difference $\hat{W}_i - \hat{V}_i$, falls within certain limits, details of which are given below, there is a high probability that the output of the EVS in question is behaving as predicted by its temporal drift model. If, on the other hand, $\hat{W}_i - \hat{V}_i$, falls outside these limits, the output voltage of the unit disagrees with its predicted value, and the unit may be considered to be behaving in an erratic or anomalous fashion. If this anomalous behaviour persists then the unit is removed from the ensemble reference standard.

Although removal of the unit means that it is no longer used to maintain the reference standard it will nonetheless still be included in the within-group comparisons as an unknown unit as described in section 3.1.2. In this way, its output continues to be monitored and its anomalous behaviour can be confirmed using the results of the next interlaboratory comparison. It is only when the unit has demonstrated predictable behaviour for an extended period that its re-inclusion in the ensemble group can be considered.

A useful action limit on the difference, $\hat{W}_i - \hat{V}_i$, is the 95% prediction limits associated with the estimator, $\hat{V}_i$, which is determined by applying an appropriate coverage factor to the standard uncertainty, $u(\hat{V}_i)$, as defined by equation 2.3.17. This overall monitoring process is illustrated in figure 2.3.5.

The actual within-group measurements consist of a series of voltage difference measurements between the output voltages of pairs of EVSs which comprise the reference standard. The number of difference measurements, $l$, depends on the number of units, $n$, and $l \geq n$.

The difference in output voltage between the, $i$ and the $j$ unit is defined as:

$$\mathbf{Y}_{ij} = \mathbf{V}_i - \mathbf{V}_j \qquad (2.3.19)$$

where, $\mathbf{V}_i$ and $\mathbf{V}_j$ are the output voltage of the $i$ and $j$ units respectively.

As with the determination of the estimators $\hat{\alpha}_{ui}$ and $\hat{V}_{0i}$, in section 2.3.4, the method of least-squares is also used here to determine the estimators, $\hat{W}_i$, based on the voltage difference observations, $Y_{ij}$ obtained using a nanovoltmeter. A simplified description of the method is given here.

Since the number of difference measurements, $l$, varies with $n$, and can also be quite large, for generality and conciseness, matrix algebra will be used to describe the least-squares estimation technique employed. Using underscore notation to denote matrices a series of difference measurements $l$, between the $n$ units can be expressed in matrix form as:

$$\underline{\mathbf{Y}} = \underline{\mathrm{X}}\,\underline{\mathbf{V}} \qquad (2.3.20)$$

where, $\underline{\mathbf{Y}}$ is a matrix of difference data i.e. voltage differences,

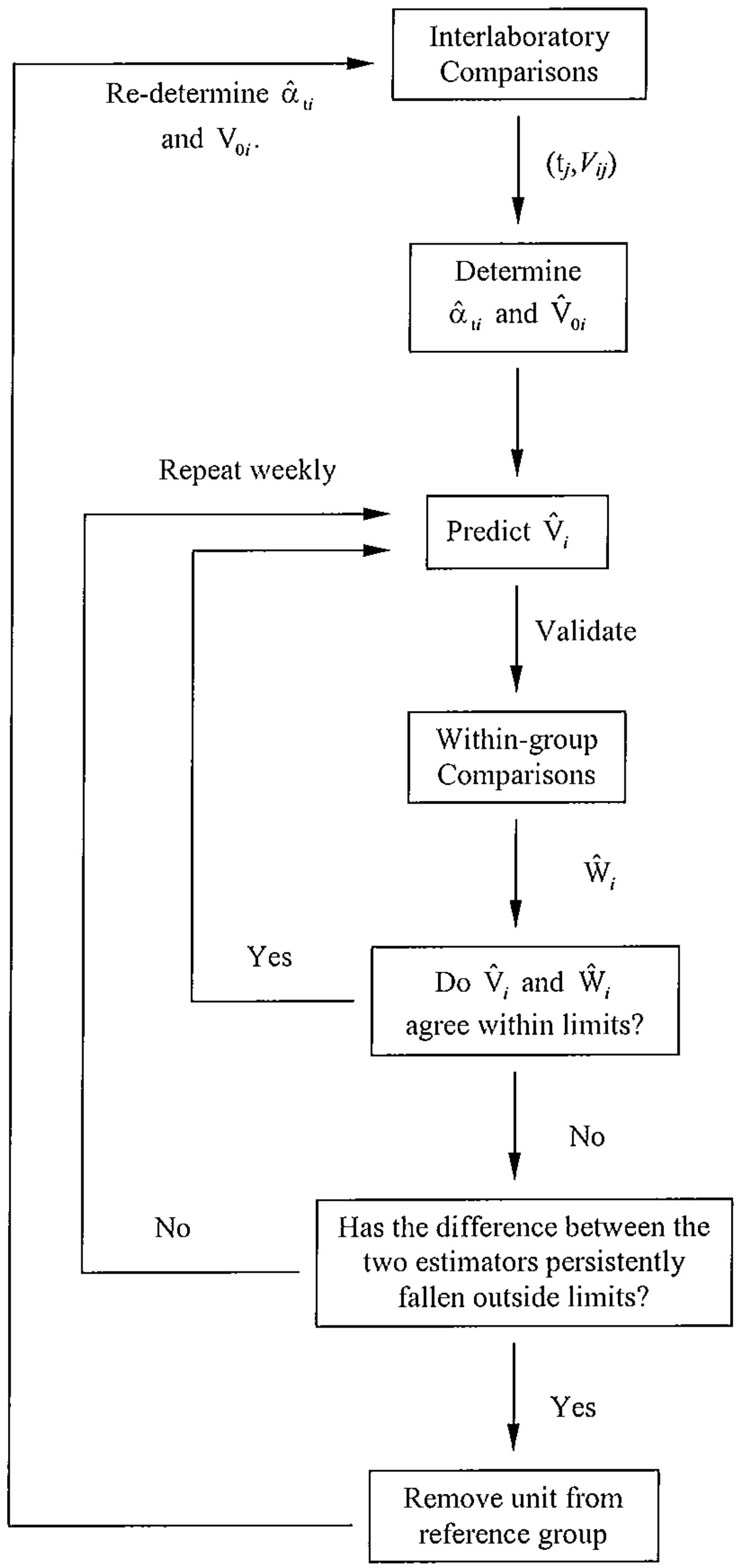


Figure 2.3.5: Representation of EVS monitoring process.

$\underline{V}$ is the matrix of the EVS voltage outputs,

$\underline{X}$ is a design matrix containing 1's, 0's or −1's.

For example the comparison of three EVSs using matrix notation would take the form:

$$\begin{bmatrix} Y_{12} \\ Y_{13} \\ Y_{23} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{2.3.21}$$

$$\underline{Y} \quad = \quad \underline{X} \quad \underline{V}$$

In general the matrix $\underline{Y}$ is a $l \times 1$ matrix, $\underline{X}$ is a $l \times n$ matrix and $\underline{V}$ is a $n \times 1$ matrix. However, when only differences are measured the system is said not to be of full rank and therefore it is not possible to get a unique least-squares solution. There will be an infinite number of possible estimators $\hat{W}_i$, all of which would yield the differences observed experimentally. In order to obtain a unique least-squares solution a constraint is required. In the analysis discussed here, the estimated mean value of the group of $n$ units $\hat{V}_M$, which in our case is $\hat{V}_{NML}$ is used as the constraint.

Similar methods are employed in the mass metrology field for comparing masses of nominally equal value against a known reference mass[40-43]. Using the mean of the group as a constraint results in the inclusion of an additional row in the matrices, $\underline{X}$ and $\underline{Y}$, which are now denoted $\underline{X}_c$ and $\underline{Y}_c$ respectively. For example, in the comparison of the three units illustrated in equation 2.3.21 the use of a constraint yields:

$$\begin{bmatrix} \hat{V}_M \\ Y_{12} \\ Y_{13} \\ Y_{23} \end{bmatrix} = \begin{bmatrix} 1/3 & 1/3 & 1/3 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{2.3.22}$$

$$\underline{Y}_c \quad = \quad \underline{X}_c \quad \underline{V}$$

In general all the elements of the additional row in the design matrix will equal $1/n$ and the additional row in $\underline{Y}_c$ will be the estimate of the mean of the reference standard.

With the inclusion of a constraint and following the methods of Beck and Arnold[44], it is possible to obtain a solution for the estimators using Restrained Least-Squares or Least-Squares with Constraints as:

$$\underline{\hat{\mathrm{W}}} = (\underline{\mathrm{X}}_c{}^{\mathrm{T}} . \underline{\mathrm{X}}_c)^{-1} . \underline{\mathrm{X}}_c^{\mathrm{T}} . \underline{Y}_c \qquad (2.3.23)$$

where, $\underline{\hat{\mathrm{W}}}$ is a column matrix of best-fit estimators $\hat{\mathrm{W}}_i$

and, $\underline{Y}_c$ is the matrix of observed differences replacing $\underline{\mathbf{Y}}_c$ in earlier notation.

The value of the constraint, $\hat{\mathrm{V}}_{\mathrm{NML}}$, is independent of the difference observations and its inclusion fixes the value of the mean of the estimators, $\hat{\mathrm{W}}_i$, so that:

$$\frac{1}{n}\sum_{i=1}^{n} \hat{\mathrm{W}}_i = \hat{\mathrm{V}}_{\mathrm{NML}} \qquad (2.3.24)$$

Therefore, although

$$\hat{\mathrm{V}}_{\mathrm{NML}} = \frac{1}{n}\sum_{i=1}^{n} \hat{\mathrm{W}}_i = \frac{1}{n}\sum_{i=1}^{n} \hat{\mathrm{V}}_i \qquad (2.3.25)$$

the value $\hat{\mathrm{W}}_i$, ascribed to any particular unit may differ from the value, $\hat{\mathrm{V}}_i$ as a result of the difference observations. The only stipulation placed on the estimators, $\hat{\mathrm{W}}_i$, by the restrained least-squares is that of equation 2.3.24.

The within-group comparisons carried out at NML are implemented using a commercially available software package called the Voltage Reference Maintenance Program (VRMP), discussed in section 3.1.

## 2.4 Quantifying the pressure dependence of an Electronic Voltage Standard

As mentioned in section in 2.1 the output voltage of certain EVS units have been found to be pressure dependent. The effects of variations in atmospheric pressure on EVS output voltage became apparent at NML as a result of a low-pressure area passing over the region in April 1998. As the low pressure passed the output voltage of one of the Fluke 732B EVS units exhibited anomalous behaviour as suggested by the results of routine within-group comparisons. A series of within-group comparisons over a two-week period showed a correlation between EVS output voltage and ambient pressure as illustrated in figure 2.4.1. This graph illustrates the need to determine pressure coefficients of individual units so that corrections can be applied where appropriate.

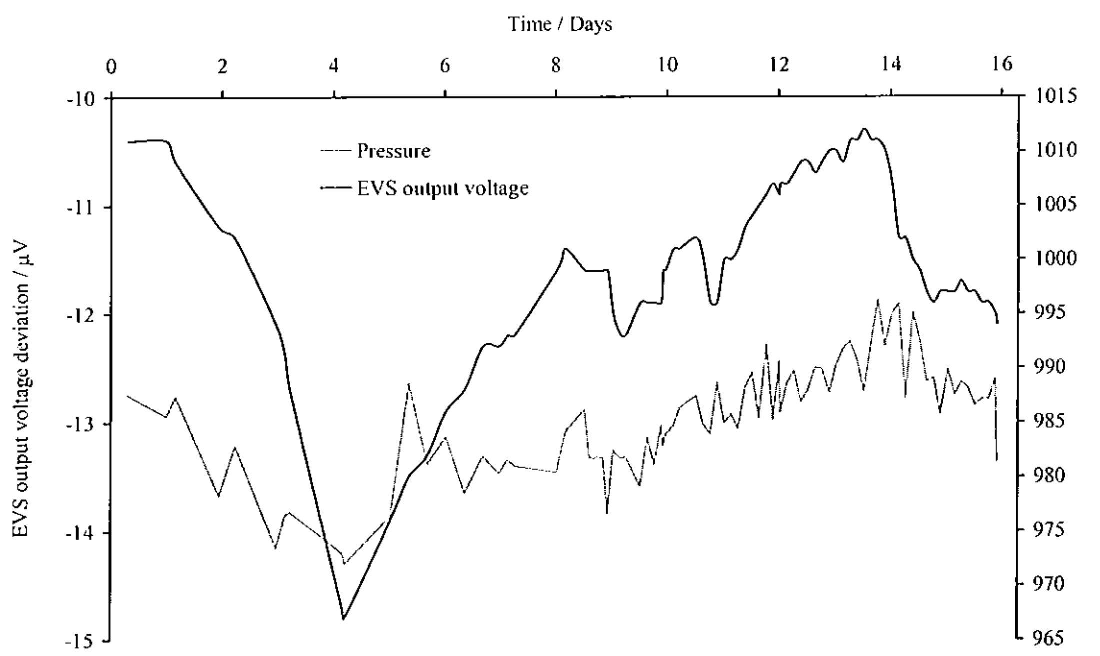


Figure 2.4.1: Variation of Fluke 732B output voltage with ambient pressure.

From the characteristic model given by equation 2.2.1, if time, temperature and humidity are assumed constant at some arbitrary reference values, we can define the pressure coefficient of the $i^{th}$ EVS unit as;

$$\alpha_{pi} = \frac{d\,V_i}{dp} \tag{2.4.1}$$

where, $\mathbf{V}_i$ is the output of the $i^{th}$ unit and $\mathbf{p}$ is pressure.

As with the determination of the temporal coefficient described in section 2.3.4 we can determine an estimate of the pressure coefficient, denoted $\hat{\alpha}_p$ by measuring changes in the output voltage of the EVS as a function of pressure. A comparison technique is used to measure changes in the output voltage of the EVS unit with pressure. In keeping with earlier notation a voltage difference $\Delta V$ is measured between the test EVS unit and a reference EVS maintained at standard laboratory conditions.

The change in the difference $\Delta\mathbf{V}$ at any pressure $\mathbf{p}$ with respect to the difference $\Delta\mathbf{V}_r$ at some arbitrary reference pressure $\mathbf{p}_r$ can be attributed to the pressure coefficient of the test EVS unit. By substitution in equation 2.4.1 the pressure coefficient of the unit can be given as;

$$\alpha_{pi} = \frac{d(\Delta V - \Delta V_r)}{dp} \tag{2.4.2}$$

If a series of observational data points $((\Delta V\text{-}\Delta V_r),p)$ are obtained an estimate of the pressure coefficient $\hat{\alpha}_{pi}$, can be determined from a linear-least squares fit to the data using the techniques described in section 2.3.4. Here $p$ is defined as the independent variable and $(\Delta V\text{-}\Delta V_r)$ as the dependent variable. The associated standard uncertainty $u(\hat{\alpha}_p)$ can also be determined using the techniques described in section 2.3.5.

In order to estimate the coefficient, an environmentally controllable chamber is required where the pressure environment of the test EVS can be varied whilst changes in all other parameters are assumed negligible. A description of such a chamber is given in section 4.1.

# 3. Determination of temporal regression parameters of Electronic Voltage Standards.

## 3. Introduction

Chapter 3 begins with a description the Voltage Reference Maintenance Program, which plays an important role in the collection of data for temporal regression analysis of the NML EVS units. A general description of interlaboratory comparisons is given and the results of two comparisons carried out during the course of this project are presented. The method, which is used to acquire the sample data upon which the temporal regression models for the individual units are based, is described. The temporal regression parameters estimated for each unit based on the techniques described in chapter 2 is then presented. Finally, the importance of regular monitoring of the NML voltage standard is illustrated through the use of within-group comparisons.

### 3.1 The Voltage Reference Maintenance Program

The Voltage Reference Maintenance Program is a commercially available software package. It is used at NML to carry out measurements and data analysis during interlaboratory comparisons and within group comparisons. VRMP reports also provide difference data, which is used to obtain the observational sample data, $V_{ij}$, upon which the temporal regression models of the EVSs are based.

A brief description of the use of the VRMP in within-group comparisons and interlaboratory comparisons is given below.

#### 3.1.1 Use of the VRMP for within-group comparisons

The VRMP handles all aspects of the within-group comparison measurement process, from the gathering of difference observations to determining the least-squares estimators, $\hat{W}_i$. General information on use of the VRMP can be found in its Operating Instructions manual[45]. The difference measurements between EVSs are made using a calibrated Keithly 181 digital nanovoltmeter via a Data Proof 32 channel low-thermal scanner, both of which are controlled by the PC over a GPIB.

All EVS units are connected to the scanner using shielded signal cable and the general measurement system is shown in figure 3.1.1.

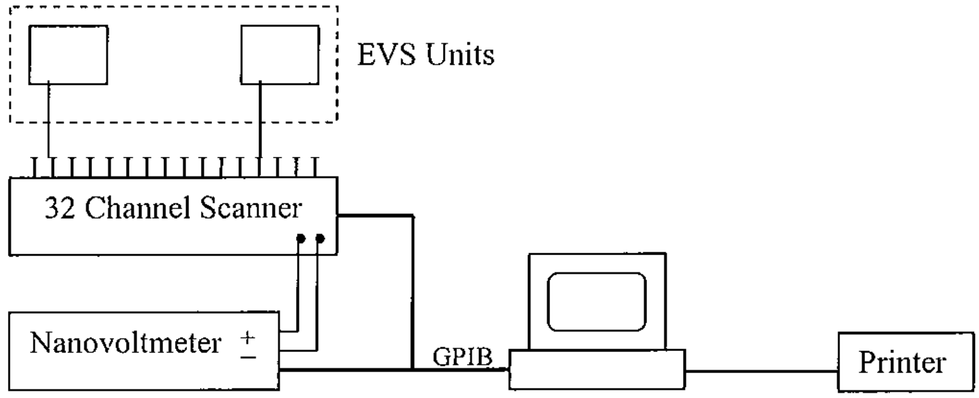


Figure 3.1.1: Voltage Reference Maintenance Program measurement system.

Before running the VRMP, it is supplied with the estimators, $\hat{V}_i$, from the temporal regression models and it determines an estimate of the mean value of the group, $\hat{V}_{NML}$, which is used as the constraint in the determination of the least-squares estimators, $\hat{W}_i$.

When the program begins it chooses an appropriate design matrix, $\underline{X}_c$, to make the difference measurements. The VRMP was written in collaboration with statisticians from the National Institute of Standards and Technology (NIST) who aided in the formulation of the appropriate design matrices[45]. The VRMP chooses an appropriate design matrix whose dimensions depend in part on the number of units $n$, involved in the within-group comparison. The design matrices formulated also attempt to minimise the number of difference observations, $l$, and on the other hand to give estimates, $\hat{W}_i$, with relatively high precision.

The program then initiates the difference measurement process using the nanovoltmeter and low-thermal scanner, both of which are controlled by the PC over the GPIB. The low-thermal scanner is used to reverse the measurement, $(\mathbf{V}_i - \mathbf{V}_j)$, so that any unwanted parasitic or thermal voltages can be eliminated. In practice the VRMP takes 10 forward and 10 reverse measurements and estimates their mean.

Once the difference measurements are complete the program carries out the least-squares analysis as described in section 2.3, and a printed report is produced. A typical report is shown in figure 3.1.2 for a within-group comparison of three units denoted "EVS 1", "EVS 2" and "EVS 3". The names assigned to the units are irrelevant and are chosen by the user.

The first section of the report gives details of the voltage difference measurements, with the "READING" column listing the mean of the difference measurements between the respective units. The remainder of the report gives the results of the least-squares analysis. The "CORRECTED MICROVOLTS" column lists the estimators, $\hat{W}_i$, the "REFERENCE MICROVOLTS" column lists the temporal regression estimators, $\hat{V}_i$, and the "DEVIATION" column lists the corresponding differences, $\hat{W}_i - \hat{V}_i$. The nominal value of the reference standard and the estimated value of the reference standard, $\hat{V}_{NML}$, used as the constraint are listed under the "NOMINAL MICROVOLTS" and "GROUP MEAN" headings respectively.

The VRMP also allows the user to store the results of the comparison on disk.

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A – B COMPONENT: -0.02 — TIME: 20 : 30 : 26

OBSERVATIONS OF EMF STANDARD PAIR DIFFERENCES IN MICROVOLTS

| OBS | A-LINE | B-LINE | READING | DEV |
|---|---|---|---|---|
| 1 | 10EVS 1 | 10EVS 2 | 37.12 | -0.14 |
| 2 | 10EVS 1 | 10EVS 3 | 16.30 | 0.19 |
| 3 | 10EVS 2 | 10EVS 3 | -21.28 | -0.11 |
| 4 | 10EVS 2 | 10EVS 1 | -37.32 | -0.01 |
| 5 | 10EVS 3 | 10EVS 1 | -16.11 | 0.05 |
| 6 | 10EVS 3 | 10EVS 2 | 21.15 | 0.03 |

LEAST SQUARES ANALYSIS OF EMF STANDARD DATA

| GROUP | NOMINAL MICROVOLTS | GROUP MEAN |
|---|---|---|
| EVS | 10 000 000 . 00 | 9 999 985 . 96 |

| NO | SCAN | UNIT | REFERENCE MICROVOLTS | DEVIATION | CORRECTED MICROVOLTS |
|---|---|---|---|---|---|
| 1 | 3 | EVS 1 | 10 000 003.63 | 0.14 | 10 000 003.77 |
| 2 | 1 | EVS 2 | 9 999 967.35 | - 0.87 | 9 999 966.48 |
| 3 | 12 | EVS 3 | 9 999 986.89 | 0.74 | 9 999 987.63 |

Figure 3.1.2: Sample printout of a within-group comparison of 3 units.

### 3.1.2 Use of the VRMP for measurements of unknown units

As well as being used for within-group comparisons the VRMP is also used for carrying out measurements and data analysis on what are termed unknown EVS units. By unknown we mean that no estimate of their output voltage is available. Unknown EVS units could be travelling standards used during interlaboratory comparisons, NML client laboratories' EVSs sent to NML for calibration or NML EVS units whose output voltages are considered unknown because they have deviated outside the confidence limits associated with their temporal regression estimates, $\hat{V}_i$. In either case the VRMP is used to determine an estimate of their unknown output voltage, $\mathbf{V}_x$.

This estimator denoted, $\hat{W}_x$, is determined by the VRMP in essentially the same manner as it determines the estimators, $\hat{W}_i$, for within-group comparisons. The estimate of the NML reference, $\hat{V}_{NML}$, is used as the constraint and the estimate of the unknown is determined with respect to this.

The rest of the method and analysis follows that of a within-group comparison, and a printed report is produced by the VRMP upon completion of the least-squares analysis. A typical report is shown in figure 3.1.3. The report is similar to that produced for within-group comparisons. Here a single unknown unit denoted "10VRF 1" is measured against two NML reference units denoted "10VRF 2" and "10VRF 3" respectively. Again the names are irrelevant and are chosen by the user.

The first part of the report contains the results of the difference measurements, which are listed in the "READING" column. The difference measurements listed are used to obtain the observational sample data, $V_{ij}$, when the unknown unit is a travelling standard, as described in section 3.3

The second half of the report presents the least-squares analysis results. The "CORRECTED MICROVOLTS" column lists the estimators, $\hat{W}_i$, for the NML units and the estimator, $\hat{W}_x$, for the unknown unit. The "REFERENCE MICROVOLTS" column lists the corresponding temporal regression estimators, $\hat{V}_i$, for the NML units whose mean value is used as the constraint for the least-squares estimation and is listed under the "GROUP MEAN" heading. There is no entry for the unknown unit in the "REFERENCE MICROVOLTS" column.

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|---|---|
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| A – B COMPONENT: -0.10 | TIME: 20 : 30 : 26 |

OBSERVATIONS OF EMF STANDARD PAIR DIFFERENCES IN MICROVOLTS

| OBS | A-LINE | B-LINE | READING | DEV |
|---|---|---|---|---|
| 1 | 10VRF1 | 10VRF2 | 23.89 | -0.04 |
| 2 | 10VRF1 | 10VRF3 | 44.99 | 0.09 |
| 3 | 10VRF2 | 10VRF3 | 20.77 | -0.11 |
| 4 | 10VRF2 | 10VRF1 | -24.04 | 0.08 |
| 5 | 10VRF3 | 10VRF1 | -45.14 | -0.04 |
| 6 | 10VRF3 | 10VRF2 | -21.06 | 0.01 |

LEAST SQUARES ANALYSIS OF EMF STANDARD DATA

| GROUP | NOMINAL MICROVOLTS | GROUP MEAN |
|---|---|---|
| 10VRF | 10 000 000 . 00 | 9 999 977 . 28 |

| NO | SCAN | UNIT | REFERENCE MICROVOLTS | DEVIATION | CORRECTED MICROVOLTS |
|---|---|---|---|---|---|
| 1 | 11 | 10VRF 1 | | | 9 999 932.18 |
| 2 | 12 | 10VRF 2 | 9 999 987.58 | 0.23 | 9 999 987.81 |
| 3 | 1 | 10VRF 3 | 9 999 966.97 | -0.23 | 9 999 966.84 |

Figure 3.1.3: Sample VRMP printed report for measurement of an unknown EVS unit against two reference units.

The use of the VRMP in either application as described above will be referred to in sections 3.2 through 3.6 that follow.

### 3.2 Procedure of an Interlaboratory Comparison

During the course of this project two interlaboratory comparisons were carried out, in April 1998 and June 1999. For the 1998 comparison three Fluke 732B EVSs were used as travelling standards while only two such units were used for the 1999 comparison (the performance characteristics of EVS units as transfer devices was presented at an IEE seminar in May of 1999, listed in appendix A of this thesis). The standards are shipped from BIPM as air freight in special padded cases so as to avoid any damage due to mechanical shock. Prior to 1998, the standards were carried as hand luggage by laboratory personnel, but this was deemed no longer necessary providing the consignor took due care whilst handling the units.

Special care is also taken to ensure the travelling standards are continuously powered during the transport to avoid temperature hysteresis effects[29]. External battery supplies are used to power the units and the transportation time is limited to less than 48 hours.

Upon arrival at NML the units are connected to the ac mains supply and the battery supplies recharged. The units are left settle in the laboratory for a few days to allow them recover from any transit effects and to acclimate to the NML laboratory environment conditions.

Each travelling standard is connected to the NML VRMP measurement system, as shown in figure 3.1.1, and using the VRMP as discussed in section 3.1.2 a value $\hat{W}_x$ is ascribed to the output voltage of each travelling standard.

In order to eliminate common mode problems the travelling standards are powered by their internal battery supplies during the measurements. The front panel "GUARD" binding post of each travelling standard is connected to the standard's "CHASIS" binding posts, and to the guard of the NML measuring system[19]. At one point the guard of the entire measurement system is connected to ground.

The VRMP is run four to five times daily over a two-week period and a series of values $\hat{W}_x$ are obtained for each travelling standard.

Ambient humidity, ambient temperature, ambient pressure and EVS internal oven thermistor resistances of the EVSs are also recorded. The internal oven thermistor is measured using a multimeter via a 9-pin D connector at the rear of the travelling standard[19]. The sensitivities of the output voltage of the travelling standards to temperature and pressure have been determined at BIPM so as appropriate corrections can be applied to the measurement results.

The NML measurement results for each travelling standard are sent to BIPM. A sample of such measurement results is shown in table 3.2.2.

Upon completion of the NML measurements the travelling standards are returned to BIPM.

| Date/Time | $\hat{W}_{x(BIPM4)}$ - 9 999 900 μV | T / °C | Pressure / hPa | % RH | BIPM4 R / kΩ |
|---|---|---|---|---|---|
| 6/16/99 12:00 | 68.22 | 22.47 | 1016 | 43 | 38.846 |
| 6/16/99 13:00 | 68.15 | 22.59 | 1016 | 43 | 38.858 |
| 6/16/99 14:00 | 68.83 | 22.64 | 1016 | 44 | 38.863 |
| 6/16/99 15:00 | 68.57 | 22.65 | 1016 | 44 | 38.866 |
| 6/16/99 16:00 | 68.31 | 22.56 | 1015 | 45 | 38.866 |
| 6/17/99 12:00 | 67.95 | 22.77 | 1020 | 35 | 38.813 |
| 6/17/99 13:00 | 67.85 | 22.76 | 1020 | 35 | 38.841 |
| 6/17/99 14:00 | 68.31 | 22.75 | 1020 | 35 | 38.854 |
| 6/17/99 15:00 | 68.05 | 22.66 | 1021 | 36 | 38.860 |
| 6/17/99 16:00 | 67.97 | 22.61 | 1021 | 37 | 38.862 |

Table 3.2.1: Sample of 1999 NML interlaboratory comparison measurement results, on BIPM4 travelling standard.

A similar set of measurements is carried out on the standards at BIPM against their Josephson reference standard prior to shipment to NML, and on their return. A linear least-squares fit to the NML measurements, $\hat{W}_x$, and to the BIPM measurements is used to ascribe values $U_{NML}$ and $U_{BIPM}$ respectively, to the output voltage of each travelling standard on the mean date of the comparison. This analysis process is illustrated graphically in figure 3.2.1 for a typical set of measurement results.

Type A and type B standard uncertainties for $U_{NML}$ and $U_{BIPM}$ are also determined. The type A standard uncertainties, $u_A(U_{NML})$ and $u_A(U_{BIPM})$ are determined from the linear least-squares fit to the measurement data.

The type B standard uncertainty associated with the BIPM result, $u_B(U_{BIPM})$ comprise contributions from its voltage measurement system such as thermoelectric voltages, frequency stability of Josephson microwave source, leakage resistances and offsets in the voltage detector[37].

For the NML result the type B standard uncertainty $u_B(U_{NML})$ is comprised of contributions due to the instability of the voltage reference standard $V_{NML}$, uncorrected parasitic voltages and offsets in the voltage detector.

The final result of the comparison, is the mean difference $U_{NML}$-$U_{BIPM}$ for each of the travelling standards on the mean date, together with its associated standard uncertainty $u(U_{NML}-U_{BIPM})$.

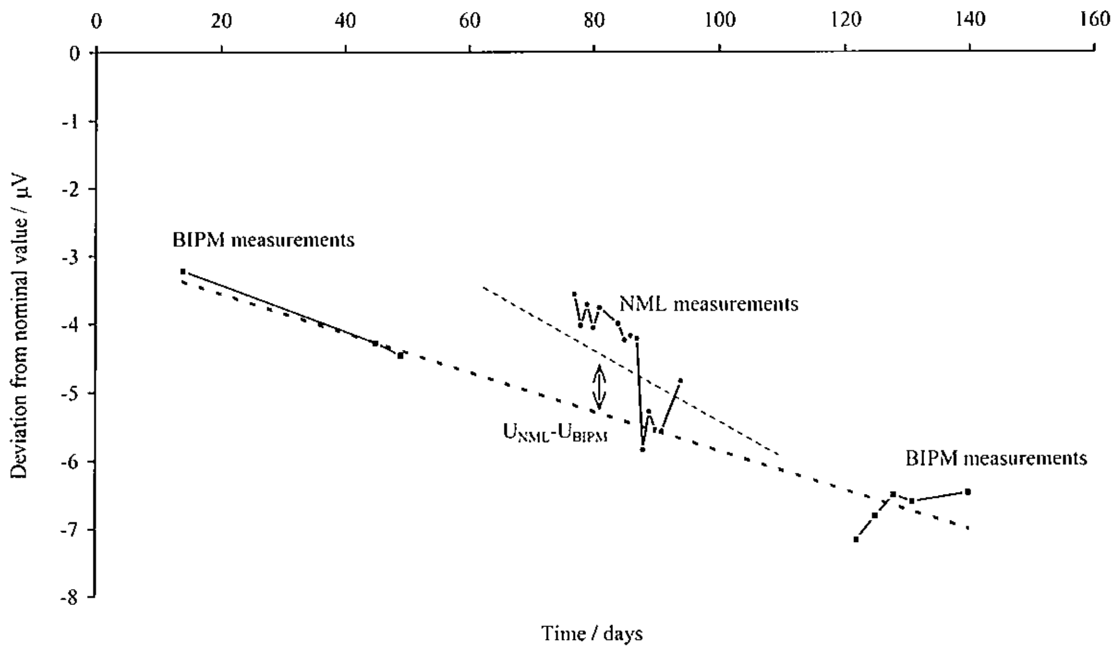


Figure 3.2.1: Graphical illustration of interlaboratory comparison data analysis.

### 3.3 Interlaboratory Comparisons: Results and Discussion

The results of the bilateral comparisons carried out between NML and BIPM in April 1998 and June 1999 are reported in official BIPM reports[36,37].

For the 1998 comparison the result was;

| $U_{NML} - U_{BIPM} = -2.5\ \mu V$; | $u_c = 2.5\ \mu V$ |
|---|---|

where $u_c$ is the combined type A and type B standard uncertainties from both laboratories.

The raw NML measurement results are not reported here. However, they have been filed in the electrical standards laboratory at NML. The individual measurement results from both laboratories for this comparison are summarised in table 3.3.1.

| | | **BIPM 4** | **BIPM 5** | **BIPM 7** |
|---|---|---|---|---|
| 1 | NML value linear fit | 9 999 972.29 | 9 999 987.06 | 9 999 991.99 |
| 2 | NML unc (A) linear fit | 0.03 | 0.03 | 0.04 |
| 3 | NML unc (B) | 2.5 | 2.5 | 2.5 |
| 4 | BIPM value linear fit | 9 999 974.65 | 9 999 989.54 | 9 999 994.61 |
| 5 | BIPM unc (A) linear fit | 0.27 | 0.15 | 0.16 |
| 6 | BIPM unc (B) | 0.01 | 0.01 | 0.01 |
| 7 | $U_{NML}$-$U_{BIPM}$ | -2.36 | -2.48 | -2.62 |
| 8 | Unc (A) $U_{NML}$-$U_{BIPM}$ | 0.06 | 0.06 | 0.08 |
| 9 | **mean $U_{NML}$-$U_{BIPM}$** | **-2.49** | | |
| 10 | unc of transfer | 0.08 | | |
| 11 | **Total unc of comparison** | **2.5** | | |
| 12 | mean date dd/mm/yy | 09/04/98 | | |

Table 3.3.1: Summary of 1998 interlaboratory comparison results.

The references to table 3.3.1 are as follows:

1. Results from the linear least-squares fit to the NML data.
2. Type A standard uncertainty from least-squares fit to NML data.
3. Type B standard uncertainty estimated by NML.
4. Results from the linear least-squares fit to the BIPM data.
5. Type A standard uncertainty from least-squares fit to BIPM data.
6. Type B standard uncertainty estimated by BIPM.
7. The difference between the values ascribed by both laboratories.
8. The root-sum-square of the type A contributions from both laboratories.
9. The mean of the values on row 7.
10. The standard deviation of the mean value reported on row 8.
11. The root-sum-square of values on rows 3, 6, 8 and 10.
12. The mean date of the comparison.

For the 1999 comparison the result was;

| | |
|---|---|
| $U_{NML} - U_{BIPM} = 0.29\ \mu V$; | $u_c = 2.31\ \mu V$ |

with the individual measurement results from both laboratories are summarised in table 3.3.2.

The result of the 1999 comparison shows a significant improvement in the agreement between the two laboratories from the '98 comparison. The disagreement in the '98 results was found to be due to deviations in the NML reference standard from its estimated value $\hat{V}_{NML}$, since the value ascribed to the travelling standards, $U_{NML}$ is dependent in part on $\hat{V}_{NML}$.

The improvement in agreement of the 1999 results is due in part to the continuous development of temporal regression models for the NML units following the '98 comparison.

| | | BIPM 4 | BIPM 5 |
|---|---|---|---|
| 1 | NML value linear fit | 9 999 967.64 | 9 999 980.46 |
| 2 | NML unc (A) linear fit | 0.10 | 0.12 |
| 3 | NML unc (B) | 2.30 | 2.30 |
| 4 | BIPM value linear fit | 9 999 967.39 | 9 999 980.13 |
| 5 | BIPM unc (A) linear fit | 0.10 | 0.10 |
| 6 | BIPM unc (B) | 0.10 | 0.10 |
| 7 | $U_{NML}$-$U_{BIPM}$ | 0.25 | 0.33 |
| 8 | Unc (A) $U_{NML}$-$U_{BIPM}$ | 0.18 | 0.20 |
| 9 | **mean $U_{NML}$-$U_{BIPM}$** | **0.29** | |
| 10 | unc of transfer | 0.13 | |
| 11 | **Total unc of comparison** | **2.31** | |
| 12 | mean date dd/mm/yy | 20/06/98 | |

Table 3.3.2: Summary of 1999 interlaboratory comparison results.

The references in table 3.3.2 are similar to those in table 3.3.1.

The NML type B standard uncertainty reported in table 3.3.1 for the '98 comparison, is the root-sum-square of contributions from a number of sources listed in table 3.3.3. The NML type B standard uncertainty for the '99 comparison, quoted in table 3.3.2, is similar except the reference group stability uncertainty is 2.2 μV.

| Source | Contribution / μV |
|---|---|
| Reference group stability | 2.4 |
| Uncorrected parasitic voltages | 0.3 |
| Detector | 0.5 |
| NML unc. (B) | **2.5** |

Table 3.3.3: Composition of NML type B standard uncertainty.

### 3.4 Acquisition of Data for Temporal Regression Analysis

During a bilateral comparison the VRMP, is run approximately 4 times daily over a two-week period as described in section 3.1. As well as listing the estimates $\hat{W}_x$ the VRMP printed reports also list the difference measurements, $\delta_{ik}$, made between the travelling standards and the NML EVS units.

A typical VRMP report as obtained during a bilateral comparison is shown in figure 3.1.3, where the single travelling standard denoted "10 VRF1" is measured against two reference standards denoted "10 VRF2" and "10 VRF3" respectively. To simplify the analysis here only three units are considered, however all $n$ NML units are included in the actual comparisons, and up to three travelling standards.

The value, $\hat{W}_x$, ascribed to the travelling standard is reported in the first row of the "CORRECTED MICROVOLTS" column, and rows 1,2,4, and 5 of the "READING" column list the observed voltage differences, $\delta_{ik}$, made between the travelling standard and the NML EVS reference units.

A number of such reports are available over the course of a bilateral comparison allowing the mean difference, $\bar{\delta}_i$, to be determined on the mean date of the comparison.

The BIPM results of the comparison provide a best estimate, $U_{BIPM}$, of the output voltage of the travelling standard on the mean date of the comparison and hence, from equation 2.3.4 an observed value, $V_{ij}$, of the NML units is obtained.

This value, together with mean date of the comparison, provides the observational sample data upon which the temporal regression models are based. A pair of such sample data were obtained for each of the NML units following the comparisons of 1998 and 1999 and the measurement results of comparisons back to 1992 were analysed in a similar manner leading to a series of $(t_j, V_{ij})$ data.

It should be noted that the temporal drift model defined by equation 2.3.2 implies that the observations $V_{ij}$ be made at constant reference values of temperature and pressure. However, in practice this was not the case but the variations in temperature and pressure over the series of $V_{ij}$ are assumed negligible and therefore no corrections are made for their effects.

### 3.4.1 Uncertainty of $V_i$

The observed output voltage $V_i$, also has an associated standard uncertainty, $u(V_i)$, comprised of contributions from $U_{BIPM}$ and $\overline{\delta}_i$, and is defined by equation 2.3.5.

The standard uncertainty of $U_{BIPM}$ is obtained from the interlaboratory comparison results, see tables 3.3.1 and 3.3.2. The standard uncertainty $u(\overline{\delta}_i)$ is the sample standard deviation of the difference measurements, $\delta_{ik}$. For simplicity, the type B contributions to $u(\overline{\delta}_i)$ due to voltmeter offsets, uncorrected thermoelectric voltages etc. are considered negligible.

Hence, since there is no significant correlation between the quantities, $u(V_i)$, is determined using equation 2.3.5. As defined in section 2.3 the independent variable, $t$, can be considered to be accurately known and therefore its associated standard uncertainty can be ignored.

### 3.5 Temporal Regression Parameters: Results and Discussion

The observational sample data, $(t_j, V_{ij})$, obtained for each of the NML units following the bilateral comparison of 1998 and 1999 is presented in table 3.5.1. The second column lists the data obtained from the 1998 comparison and the third column lists the data obtained from the 1999 comparison. The data in column two is referenced to the mean date of the '98 comparison; April $4^{th}$ and the data in column three is referenced to the mean date of the '99 comparison; June $20^{th}$.

Data is presented in tables 3.5.2 through table 3.5.4 of the overall series of $(t_j, V_{ij})$ data obtained following the analysis of bilateral comparison results as far back as 1992.

| **NML EVS Unit** | $V_i$ / μV (1998) | $V_i$ / μV (1999) |
|---|---|---|
| Guildline 4410 (A) | 9 999 990.8 | 9 999 981.9 |
| Guildline 4410 (B) | 10 000 009.2 | 10 000 001.8 |
| Guildline 4410 (C) | 10 000 050.4 | 10 000 046.1 |
| Guildline 4410 (D) | 10 000 019.3 | 10 000 011.3 |
| Datron 4910 (#1) | 9 999 956.5 | 9 999 950.1 |
| Datron 4910 (#2) | 9 999 937.6 | 9 999 932.3 |
| Datron 4910 (#3) | 9 999 956.0 | 9 999 952.7 |
| Datron 4910 (#4) | 9 999 935.1 | 9 999 930.9 |
| Fluke 732A (#1) | 9 999 965.0 | 9 999 966.1 |
| Fluke 732A (#2) | 10 000 046.7 | 10 000 054.1 |
| Fluke 732B (#3) | 9 999 988.8 | 9 999 987.6 |

Table 3.5.1: $V_i$ values obtained from 1998 and 1999 bilateral comparison results.

| $t_j$ (dd/mm/yy) | $V_{ij}$ / μV (A) | $V_{ij}$ / μV (B) | $V_{ij}$ / μV (C) | $V_{ij}$ / μV (D) |
|---|---|---|---|---|
| 23/12/92 | 10 000 016.2 | 10 000 025.8 | 10 000 057.2 | 10 000 049.3 |
| 23/03/94 | 10 000 007.7 | 10 000 021.3 | 10 000 058.0 | 10 000 043.5 |
| 05/06/95 | 9 999 997.2 | 10 000 019.9 | 10 000 054.8 | 10 000 035.6 |
| 07/06/96 | 9 999 994.1 | 10 000 014.2 | 10 000 059.9 | 10 000 032.4 |
| 30/03/97 | 9 999 991.4 | 10 000 010.9 | 10 000 055.3 | 10 000 025.6 |
| 09/04/98 | 9 999 990.8 | 10 000 009.2 | 10 000 050.4 | 10 000 019.3 |
| 20/06/99 | 9 999 981.9 | 10 000 001.8 | 10 000 046.1 | 10 000 011.3 |

Table 3.5.2: Series of $(t_j, V_{ij})$ data for Guildline 4410 units A to D.

| $t_j$ (dd/mm/yy) | $V_{ij}$ / μV (#1) | $V_{ij}$ / μV (#2) | $V_{ij}$ / μV (#3) | $V_{ij}$ / μV (#4) |
|---|---|---|---|---|
| 23/12/92 | 9 999 978.4 | 9 999 967.9 | 9 999 979.2 | 9 999 964.7 |
| 23/03/94 | 9 999 972.6 | 9 999 957.1 | 9 999 971.9 | 9 999 956.2 |
| 05/06/95 | 9 999 967.8 | 9 999 955.2 | 9 999 965.1 | 9 999 951.4 |
| 07/06/96 | 9 999 964.1 | 9 999 947.9 | 9 999 961.7 | 9 999 943.6 |
| 30/03/97 | 9 999 959.1 | 9 999 941.5 | 9 999 957.1 | 9 999 937.8 |
| 09/04/98 | 9 999 956.5 | 9 999 937.6 | 9 999 956.0 | 9 999 935.1 |
| 20/06/99 | 9 999 950.8 | 9 999 932.3 | 9 999 952.7 | 9 999 930.9 |

Table 3.5.3: Series of $(t_j, V_{ij})$ data for Datron 4910 units (#1) to (#4).

| $t_j$ (dd/mm/yy) | $V_{ij}$ / μV Fluke 732A (#1) | $V_{ij}$ / μV Fluke 732A (#1) | $V_{ij}$ / μV Fluke 732B (#3) |
|---|---|---|---|
| 23/12/92 | | 10 000 011.0 | |
| 23/03/94 | | 10 000 021.6 | |
| 05/06/95 | | 10 000 032.1 | |
| 07/06/96 | | 10 000 033.6 | |
| 30/03/97 | | 10 000 041.0 | 9 999 992.0 |
| 25/05/97 | 9 999 963.9 | | |
| 09/04/98 | 9 999 965.0 | 10 000 046.7 | 9 999 989.7 |
| 20/06/99 | 9 999 966.1 | 10 000 054.1 | 9 999 987.18 |

Table 3.5.4: Series of ($t_j$, $V_{ij}$) data for Fluke units (#1) to (#3).

### 3.5.1 Uncertainty of $V_{ij}$

The associated standard uncertainty, $u(V_{ij})$, of the data, $V_{ij}$, for each NML unit was determined using equation 2.3.5 and is presented in table 3.5.5.

The uncertainties listed in table 3.5.5 are dominated by the $u(\overline{\delta}_i)$ term in equation 2.3.5. The uncertainty $u(\overline{\delta}_i)$ is the sample standard deviation of the mean of 10 difference measurements, $\delta_{ik}$, carried out over a 3-day period during the 1999 comparison. The spread in values is table 3.5.5 is therefore an indication of the scatter of the measurements due to the short-term noise characteristics of the particular EVS unit. However, recent studies have shown that the use of the sample standard deviation to quantify the scatter of a series of EVS voltage measurements should be used cautiously[33].

It is also assumed that $u(U_{BIPM})$ is the same for all $j$ and for all units, and that $u(\overline{\delta}_i)$ is the same for all $j$ for each individual unit. Hence, from equation 2.3.5 $u(V_{ij})$ is the same for all $j$ for each individual unit.

The consequence of these assumptions is that equation 2.3.17 for the uncertainty of $\hat{V}_i$, the estimate of the output voltage of the $i^{th}$ unit, as predicted by the temporal regression model is valid.

| **NML EVS Unit** | $u(V_{ij})$ / μV |
|---|---|
| Guildline 4410 (A) | 0.22 |
| Guildline 4410 (B) | 0.24 |
| Guildline 4410 (C) | 0.27 |
| Guildline 4410 (D) | 0.38 |
| Datron 4910 (#1) | 0.18 |
| Datron 4910 (#2) | 0.19 |
| Datron 4910 (#3) | 0.27 |
| Datron 4910 (#4) | 0.86 |
| Fluke 732A (#1) | 0.39 |
| Fluke 732A (#2) | 0.19 |
| Fluke 732B (#3) | 0.22 |

Table 3.5.5: Standard uncertainties of $V_{ij}$.

### 3.5.2 Temporal regression parameter estimates of the NML EVS units

The temporal regression parameters for each EVS unit, estimated from a linear least-squares fit to the observational sample data, listed in tables 3.5.2 through 3.5.4 is given in table 3.5.6. The assumption of linearity was appropriate for all units, over the time periods of interest.

The temporal regression offset term $\hat{V}_{0i}$ for each of the Datron units, the Guildline units and the Fluke 732A (#2) is referenced to $t_0$ defined as January 1st 1992. For the Fluke 732A (#1) and the Fluke 732B (#3) $t_0$ is defined as January 1st 1997.

The associated standard uncertainties $u(\hat{\alpha}_{ti})$ and $u(\hat{V}_{0i})$ are also listed in table 3.5.6.

| **NML EVS Unit** | $\hat{\alpha}_{ti}$ (nV/day) | $\hat{V}_{0i}$ (μV) | $u_A(\hat{\alpha}_{ti})$ (nV/day) | $u_A(\hat{V}_{0i})$ (μV) |
|---|---|---|---|---|
| Guildline 4410 (A) | -13.0 | 10 000 017.6 | 1.6 | 2.9 |
| Guildline 4410 (B) | -9.4 | 10 000 029.7 | 0.8 | 1.5 |
| Guildline 4410 (C) | -4.3 | 10 000 061.4 | 1.6 | 2.8 |
| Guildline 4410 (D) | -15.6 | 10 000 055.7 | 0.7 | 1.3 |
| Datron 4910 (#1) | -11.4 | 9 999 982.1 | 0.6 | 1.0 |
| Datron 4910 (#2) | -14.4 | 9 999 971.4 | 1.0 | 1.7 |
| Datron 4910 (#3) | -10.8 | 9 999 980.6 | 1.1 | 1.9 |
| Datron 4910 (#4) | -14.2 | 9 999 968.3 | 1.0 | 1.7 |
| Fluke 732A (#1) | +3.1 | 9 999 963.6 | 0.6 | 0.4 |
| Fluke 732A (#2) | +17.1 | 9 999 992.5 | 1.1 | 1.9 |
| Fluke 732B (#3) | -5.7 | 9 999 992.5 | 0.4 | 0.3 |

Table 3.5.6: Temporal regression parameters of NML EVS units.

Once determined, the temporal regression parameters can be used to estimate the output voltage $\hat{V}_i$ of the individual EVS units at any time, t, with reference to $t_0$ using equation 2.3.10, and the associated standard uncertainty $u(\hat{V}_i)$ can be derived from equation 2.3.17. Following from this an estimate of the value of the NML reference standard $\hat{V}_{NML}$ together with its associated standard uncertainty $u(\hat{V}_{NML})$ can be determined from equations 2.3.11 and 2.3.18 respectively.

The temporal regression parameters for the Guildline units, the Datron units and the Fluke 732A (#2) unit have been estimated with 5 degrees of freedom i.e. $m$-2, where $m$ is the number of observational sample data points, $(t_j, V_{ij})$, whereas the estimators for the Fluke 732A (#1) and Fluke 732B (#3) units have been determined with only one degree of freedom. The number of degrees of freedom need to be considered so as appropriate coverage factors can be applied to attain desired confidence levels for the temporal estimators $\hat{V}_i$.

The temporal behaviour of the EVS units are shown graphically in figures 3.5.1 through 3.5.3. Figure 3.5.1 illustrates the temporal behaviour of the Fluke units, figure 3.5.2 the Guildline 4410 units and figure 3.5.3 the Datron 4910 units. From the results presented it can be clearly seen that similar EVS models exhibit temporal coefficients of the same sign, suggesting the temporal behaviour is dependent on the particular Zener reference elements of the unit. In fact for the Datron 4910 unit the estimated temporal coefficients are of the same order of magnitude for all 4 units and the coefficients of Datrons (#1) and (#3) like Datrons (#2) and (#4) have been estimated to be equal.

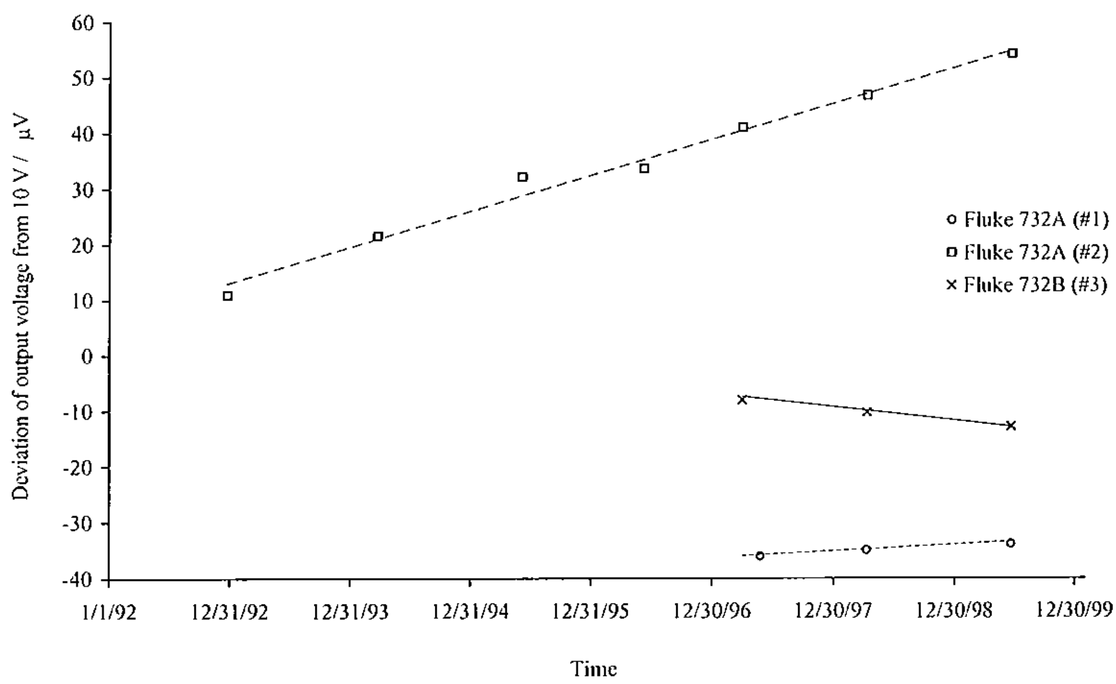


Figure 3.5.1: Graphical illustration of temporal behaviour of Fluke EVS units.

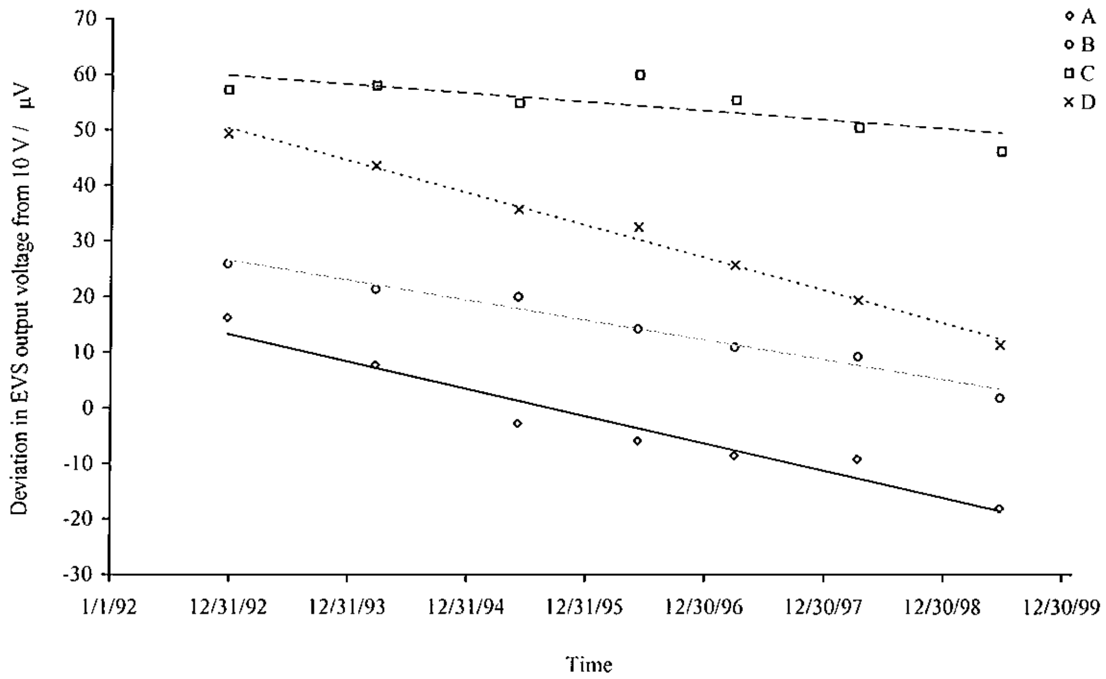


Figure 3.5.2: Graphical illustration of temporal behaviour of Guildline 4410 units.

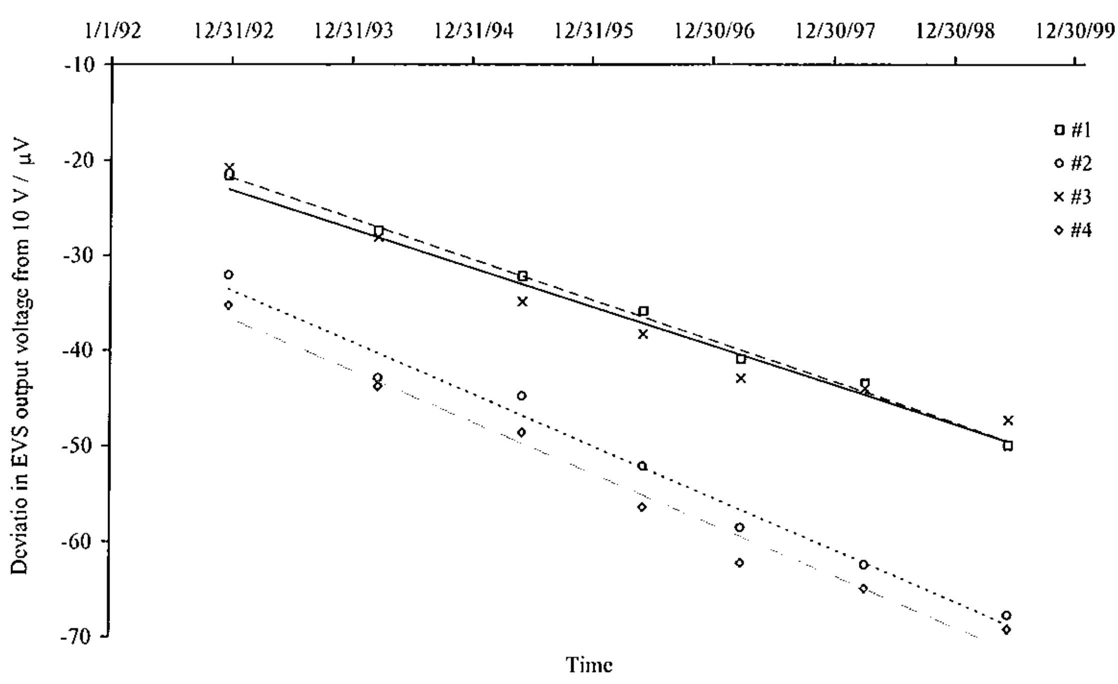


Figure 3.5.3: Graphical illustration of temporal behaviour of Datron 4910 EVS units.

### 3.6 Procedure for within-group comparisons

Within-group comparisons provide an estimate, $\hat{W}_i$, of the output voltage of the NML EVS units, which is compared to the value, $\hat{V}_i$, obtained from the temporal regression models at the time in question.

Within-group comparisons are carried out on a weekly basis at NML using the VRMP. The VRMP is supplied with values $\hat{V}_i$, for each of the $n$ NML EVS units, obtained from the temporal regression models. The program is run and a series of difference measurements are made between the various EVS units using the measurement set-up shown in figure 2.4.1.

Once the measurement sequence and least-squares analysis is complete a printed report is produced by the VRMP. A typical VRMP within-group comparison report is shown in figure 3.1.2 for three EVS units, denoted "EVS 1", "EVS 2" and "EVS 3".

The first half of the report gives details of the voltage difference measurements and the remainder of the report gives the results of the least-squares analysis. The "CORRECTED MICROVOLTS" column lists the $\hat{W}_i$ values ascribed to each unit, the "REFERENCE MICROVOLTS" column lists the corresponding $\hat{V}_i$ values, and the "DEVIATION" column lists the corresponding difference $\hat{W}_i - \hat{V}_i$.

The $\hat{W}_i$ values are also stored on disk, allowing them to be displayed graphically which helps in detecting emerging anomalies in the EVS output voltage.

### 3.7 Results and Discussion of Typical Within-Group Comparisons

Within-group comparisons are carried out using the VRMP as described in section 3.1. Each time the VRMP is run an estimator of the output voltage $\hat{W}_i$, is obtained, for each of the units and compared to the value $\hat{V}_i$ as determined by the particular regression model. The agreement between the two values is examined each time the within-group comparisons are carried out, and gives an indication of the suitability of a particular EVS for inclusion in the ensemble voltage reference standard.

As a general action limit, if the difference between the two estimators $\hat{W}_i$ and $\hat{V}_i$ exceeds the 95% prediction interval for $\hat{V}_i$ over a time period of approximately one month, the unit is considered to be behaving erratically and is removed from the ensemble reference standard.

Figure 3.7.1 shows the results of the within group comparisons for the Fluke 732B. Also shown is the temporal regression line together with the 95% prediction bands either side, which are derived from equation 2.3.17. As can be seen, the results of the within-group comparisons, in general, fall within these bands and consequently this unit is part of the ensemble reference standard. Similar data is available for the other units used to maintain the laboratory reference.

Figure 3.7.2 shows the results of the within group comparisons for the Datron 4910 unit #3 over the same time periods as the Fluke. This unit had been used to maintain the reference standard but as the data clearly shows its output voltage began to deviate significantly from its expected value and consequently the unit was deemed to be no longer suitable for use as a reference unit and was removed from the group. The unit however was still included in the within-group comparisons as an unknown unit, see section 3.1.2, so its behaviour could still be monitored. After a period of approximately 6 months it appeared to behave as expected again. To date no explanation for this behaviour is known. The most likely reason is due to a temperature control problem with the internal oven of the unit however this is difficult to verify since the Datron 4910 model, unlike others, has no internal oven thermistors.

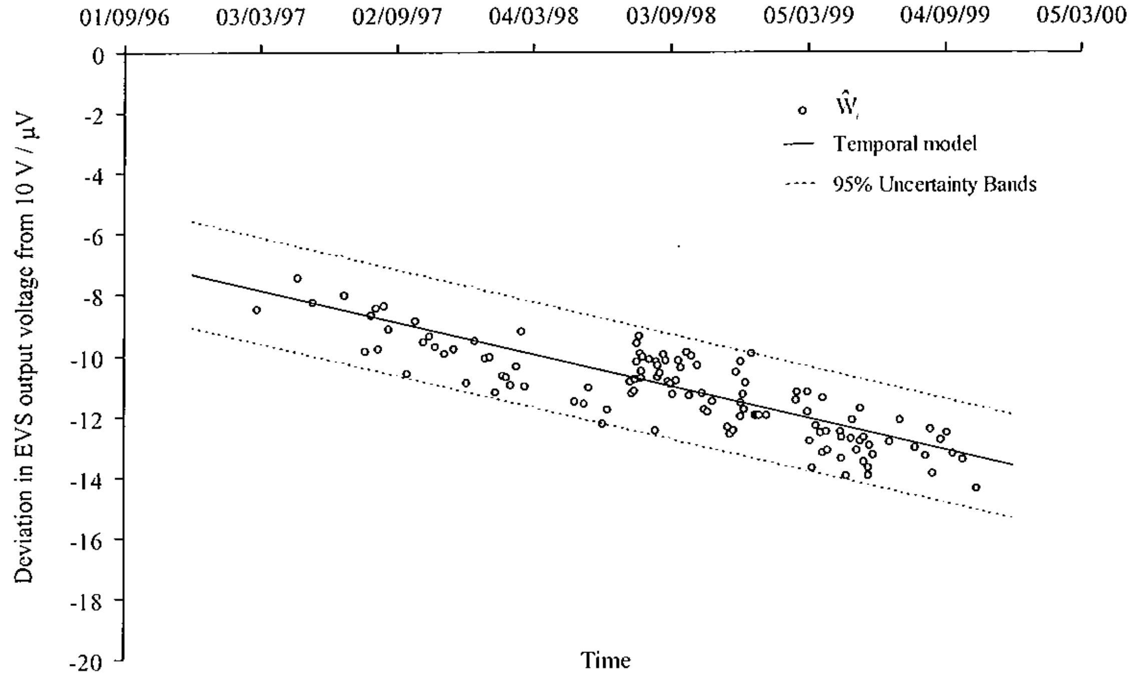


Figure 3.7.1: Within-group comparison results for Fluke 732B EVS including temporal regression model and 95% confidence bands.

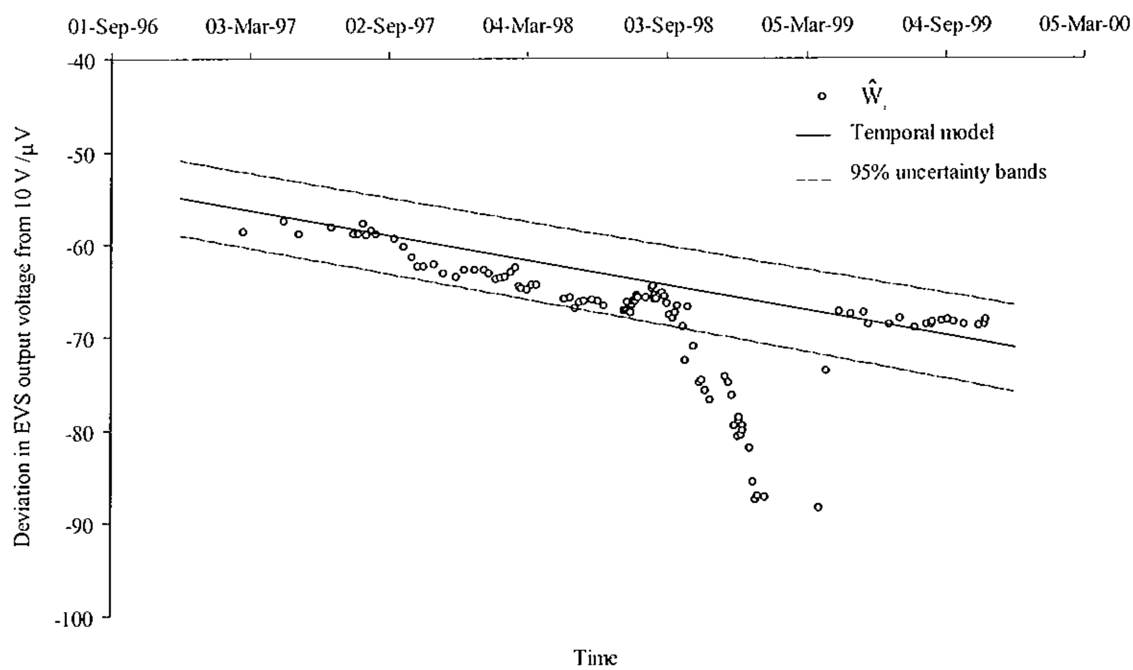


Figure 3.7.2: Within-group comparison results for Datron 4910 (#2) EVS including temporal regression model and 95% confidence bands.

Figure 3.7.2 clearly illustrates the importance of carrying out regular within-group comparisons since if this type of behaviour were to go undetected it would lead to serious inaccuracies in the maintenance of the reference standard.

The within-group comparisons also allow the detection of other anomalies in the EVS output behaviour such as the suspected humidity effects on the Fluke 732A (#2) unit as shown in figure 2.1.

Similar data is available for the other NML units and based on a continuous analysis of the within-group comparison results, 7 units are deemed suitable for use in maintaining the reference standard at present.

# 4. Determination of Pressure Coefficients of Electronic Voltage Standards.

## 4. Introduction

The chapter begins with a description of an experimental set-up, which was developed to measure pressure coefficients of EVSs. All aspects of the set-up are detailed, from the design of the chamber through the development of systems to control and monitor temperature and pressure. A detailed description is then given of the development of data acquisition software, which was implemented using LabVIEW®. A typical description of how the system is used to measure a pressure coefficient is then presented. Finally, the chapter concludes with a presentation of the pressure coefficients estimated for a number of EVSs.

## 4.1 Experimental set-up

In order to test the effects of pressure on the output voltage of EVS units while controlling other variables, which may effect it, an atmospheric control system is designed and tested. Details of the components of this system are given below.

### 4.1.1 Overview

A schematic diagram of the overall experimental set-up used to determine the pressure coefficients of the EVSs is shown in figure 4.1.1. It is based on a similar set-up, used by Witt, in determining the pressure and temperature coefficients of EVSs at the BIPM[25,26].

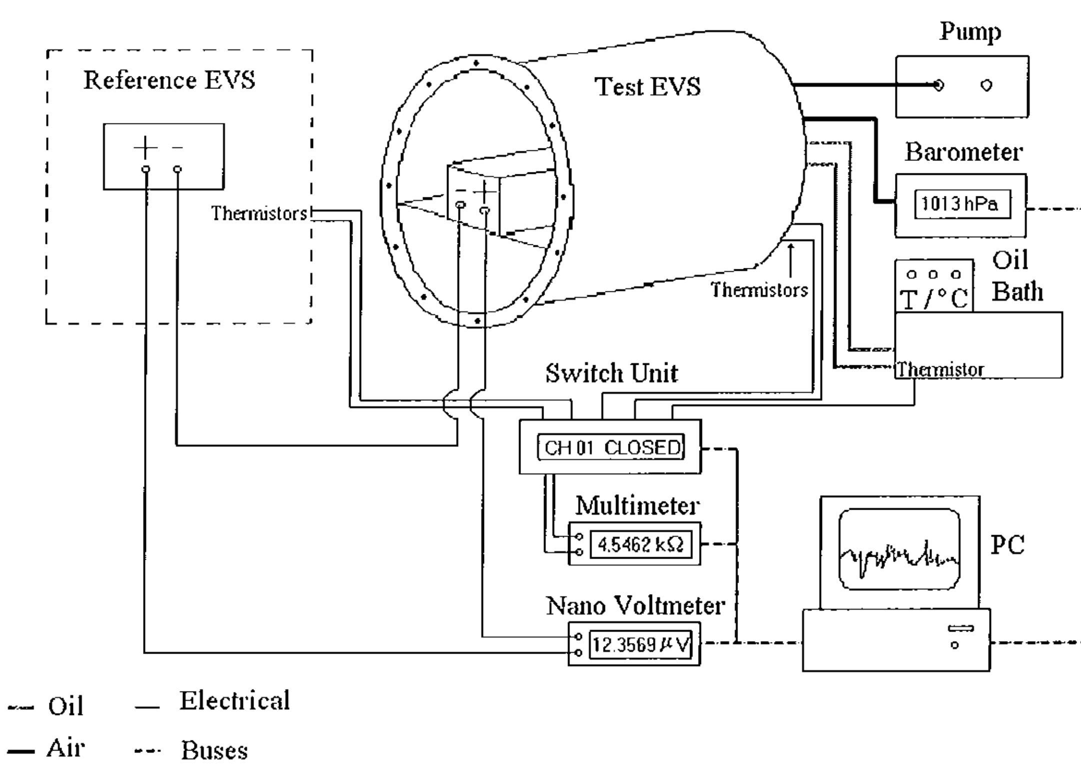


Figure 4.1.1: Schematic of overall experimental set-up.

The overall principle of the system is that the test EVS is housed in a pressure tight chamber within which the pressure can be varied in a controlled manner. Pressure is controlled using a combination of valves and a pump, and is measured using a digital barometer.

For temperature control inside the chamber temperature controlled oil is circulated through a coil of stainless steel tubing, and the chamber is also thermally insulated using a domestic lagging jacket. Temperature is monitored using a series of thermistors measured using a multimeter, in conjunction with a switch box.

The variation of the output voltage of the test EVS due to changes in pressure is measured by comparison with a reference EVS (itself maintained at the approximately constant pressure of the laboratory), using a digital nanovoltmeter to measure the voltage difference. All data acquisition is done using a PC and a detailed description of each element of the set-up is given below.

### 4.1.2 Test Chamber

The size of the test chamber is determined by the sizes of the various NML EVS units. A cylindrical chamber 45 cm in diameter and 80 cm long is chosen as shown in figure 4.1.2, which is fabricated in a workshop from stainless steel.

Although we were only concerned with variations in pressure of the order of those associated with typical meteorological and altitude changes, for safety purposes, and to make the chamber more adaptable for further use, it is designed to withstand pressure differentials well in excess of this.

For convenience, one end of the chamber referred to hereafter as the rear is permanently sealed with a stainless steel plate, since it eliminated the likelihood of leakage around seals etc. It also provided a convenient base on which various fittings and feedthroughs could be mounted. The other end, referred to hereafter as the front, consisted of a removable perspex cover, with an o-ring seal, held in position with a series of bolts around the circumference of a flange which is welded to the chamber.

Tracks for a sliding floor (made of mesh metal which improves heat exchange with the coil underneath), were fixed near the base of the chamber so that the test EVS units could be slid in and out more easily as some of the units have a mass of 20kg[20].

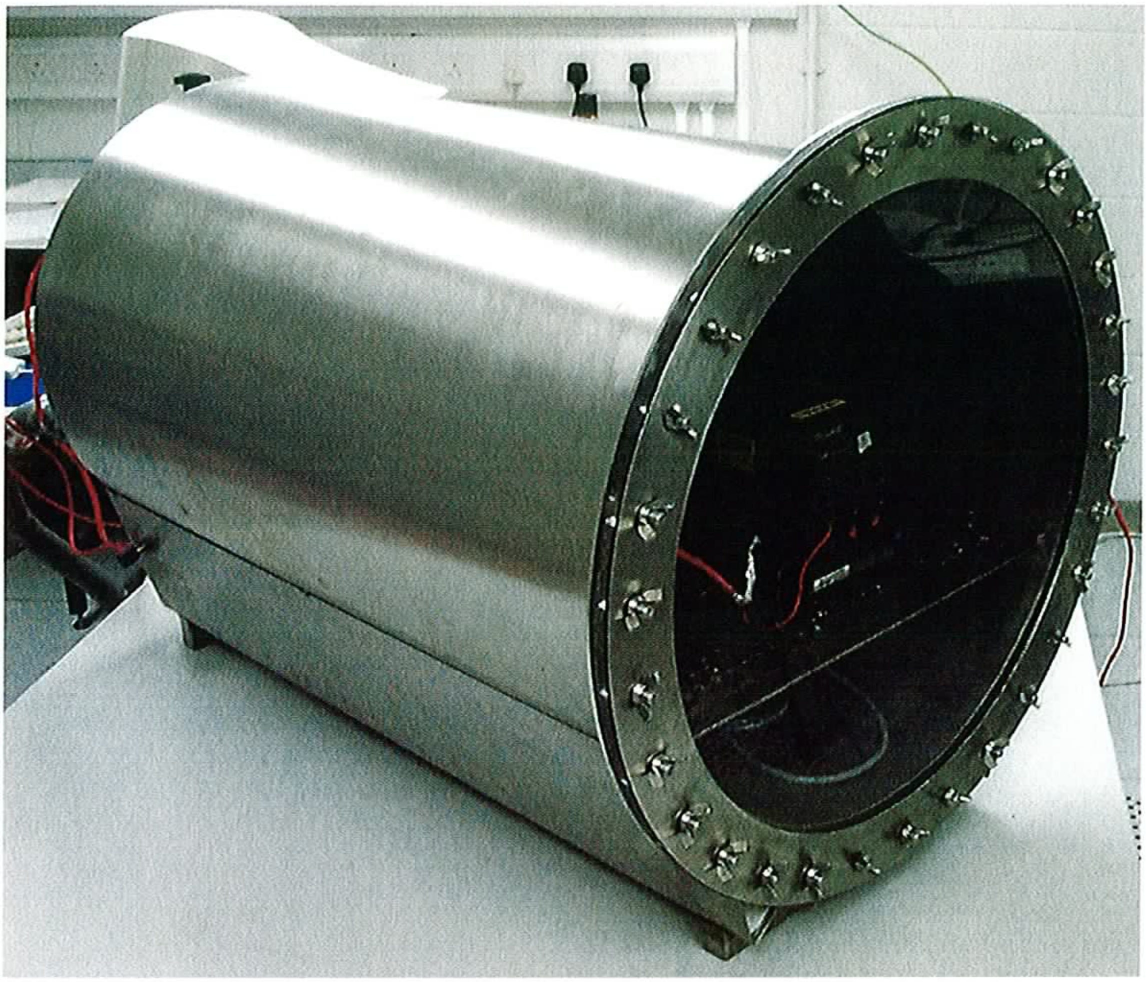

Figure 4.1.2: Picture of test chamber.

A number of electrical feedthroughs were required, to allow power leads and signal leads into the chamber. Conventional vacuum electrical feedthroughs proved expensive, so an alternative is required.

The feedthroughs used were fabricated in the laboratory and consisted of a length of threaded piping approximately 5cm long and 3cm diameter, within which lengths of wire were positioned, and sealed around using silicone sealant as shown in figure 4.1.3. Thermistor leads, IEC leads, power leads were then soldered to both ends of the feedthrough wires.

The feedthrough for the signal lead which measures the test EVS output voltage, is fabricated by threading the entire lead through the piping, stripping back its insulation along the length of piping, and sealing around using the silicone sealant as before. The continuous length is required in this case as soldered connections on this lead might introduce unwanted thermoelectric voltages, which could adversely affect the voltage measurements.

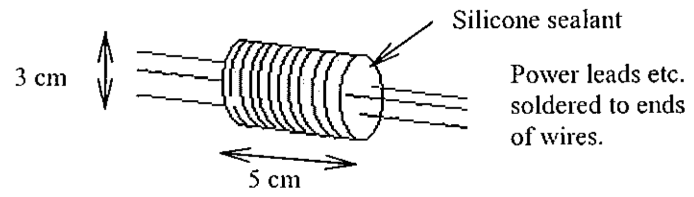


Figure 4.1.3: Design of electrical feedthroughs.

The feedthroughs were inserted in holes at the rear of the chamber and held in position using nuts on the piping, which were then tightened against plastic washers on both sides of the chamber wall. For safety purposes, electrical leakage and insulation tests were carried out on the feedthroughs prior to fitting them on the chamber and the chamber itself is electrically grounded.

### 4.1.3 Pressure control and measurement system

The pressure inside the chamber is controlled using a small diaphragm pump and two needle valves. Both needle valves were connected to ports on the rear of the chamber. The pump is connected to the chamber via one of the valves, which acts as a flow controller for the pump. The other valve is used to bleed the pressure inside the chamber back to the ambient external pressure.

The pump used is a KNF Neuberger VP1 series, which allowed us pump both above and below ambient pressure. It has a flow rate of 5 litres min$^{-1}$ allowing pressure changes in the region of interest to be achieved quite readily.

As the chamber is not entirely pressure tight the pressure inside is maintained at the required level by leaving the pump running, and adjusting the vent on one or either valve. This technique allowed pressure stabilities of 1hPa to be achieved for periods of up to one hour.

The pressure inside the chamber is measured using a Druck DPI 141 digital barometer with 0.1 hPa resolution. The barometer is connected to the rear of the chamber using plastic tubing and pneumatic fittings.

### 4.1.4 Temperature control system

EVSs are conventionally maintained in temperature controlled laboratories at 23 °C however, since EVSs are sources of heat, when placed in a closed chamber such as that described heating can be a significant problem.
The determination of the pressure coefficient of an EVS necessitates the measurement of voltage changes of the order of 1 μV. With typical temperature coefficients of EVSs of the order of 0.05 ppm·K$^{-1}$, temperature fluctuations of 1 K would result in changes in EVS output of the same order as that produced by the pressure variations[18-21,31]. It is therefore important to achieve adequate temperature stability within the chamber.
For this reason, a coil of ¼" stainless steel tubing was fitted underneath the floor of the chamber with both ends protruding through the rear chamber wall so that connections could be made to circulate temperature controlled oil. By setting the oil temperature, the various heating loads produced by different models of EVS can be accommodated. Figures 4.4.8 and 4.4.9 show typical temperature control and stability obtained with the system.
The oil bath used is a Haake C with a Haake F3 control unit, which is stable to within 0.1 K. A thermistor is also placed in the oil bath so as its temperature can be measured.
To improve the efficiency of the heat exchange within the chamber a small fan, powered by an external dc supply is suspended underneath the stainless steel tubing.

### 4.1.5 Temperature monitoring system

Although no temperature corrections were applied to the measurement data, it is nonetheless necessary to monitor several temperatures in order to confirm that the temperature stability is adequate.
The ambient air temperature where the units are maintained is measured by means of thermistors, fitted in the test chamber and reference enclosure. As well as this, the

internal oven temperature of the EVSs is measured by means of thermistors, which have been fitted by the particular EVS manufacturer as described in section 1.3.3. A thermistor is also fitted in the oil bath giving a total of five resistance measurements.

Employing a multimeter for each measurement would be impractical so a switch box is used, connected to a single multimeter as shown in figure 4.1.1. Using this technique allowed each resistance to be measured in sequence using one multimeter. The switch box used is a Hewlett-Packard 34970A with 20 channel multiplexer, which is connected to a Hewlett-Packard 34401A multimeter. The five thermistors are connected to channels one through five on the switch box as shown in table 4.1.1.

| **Entity measured** | **Channel number** |
|---|---|
| Test EVS oven thermistor | 1 |
| Oil bath thermistor | 2 |
| Reference EVS air thermistor | 3 |
| Test EVS air thermistor | 4 |
| Reference EVS oven thermistor | 5 |

Table 4.1.1: Thermistor connections to the Hewlett-Packard 34970 A switch box.

### 4.1.6 Voltage measuring system

The variation of the output voltage of the test EVS, over the course of an experiment to determine its pressure coefficient, is expected to be no more than a few microvolts. Since this is a few parts in $10^7$ at the 10V level it is necessary to devise a method for reliably measuring such small variations.

Direct measurement of the output voltage of the test unit using a high-resolution voltmeter would be inadequate, since the best attainable resolution with most modern meters is around 1μV on the 10V range.

The solution is to use a comparison method, where the voltage difference between the test EVS output and reference EVS output is measured using a nanovoltmeter. The principle of this technique is illustrated in figure 4.1.4. The LO outputs of both EVSs are tied at a common potential, and the voltage difference between the HI outputs is measured using a nanovoltmeter.

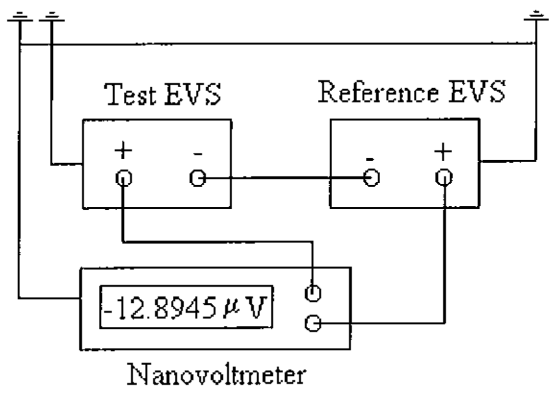


Figure 4.1.4: Voltage measurement system using a comparison technique.

The advantage of this technique is that the measured difference is usually in the microvolt region and using a nanovoltmeter we can achieve resolutions of (1 to 0.1) nV on the lower millivolt ranges, allowing the measurement of voltage variations of the order mentioned earlier.

The voltage measurements are made using a Hewlett Packard 34420A nanovoltmeter fitted with an input connector having low thermal electromotive forces, which has a resolution of 0.1 nV on its 1 mV range.

A number of other factors also needed to be considered when carrying out voltage measurements at this level. The inherent noise on the EVS output, which is ever present, is dealt with by averaging the voltage measurement. This is done using the nanovoltmeter by setting an appropriate integration time, and by the software used in the data acquisition as discussed in section 4.2.

Thermoelectric voltages are also an undesirable influence at these measurement levels, and copper to copper connections, were used throughout to eliminate their effects.

Common mode effects, which may result in the introduction of unwanted offsets and bias, needed consideration and all measuring instrumentation is tied to a common "clean" earth to overcome this as shown in figure 4.1.4.

Finally, pickup between the measurement leads meant that they had to be isolated from each other in the experimental area.

## 4.2 Data acquisition

For an experiment of this nature the data acquisition process needed to be automated. Using a PC to control the instrumentation and record the data is more efficient and dependable than an analog or manual method. It is also much faster and time saving and allows the data be recorded in a format that can be read directly by a spreadsheet or similar software application so it can be easily analysed and manipulated. In fact, an experiment of this nature would be almost impossible without automation of the data acquisition process due to the large amount of data being recorded.

In order to automate the process all instruments needed to be equipped with interfaces, which facilitated communication with the PC. The nanovoltmeter, multimeter and switch box had GPIB interfaces as standard and the PC is fitted with a GPIB card, which allowed for connection to these instruments. The barometer had an RS-232 interface allowing communication be established via the PC serial or COM port.

Together with the hardware, software is also required for the data acquisition. For the purposes of these experiments the programs required were constructed in LabVIEW®.

### 4.2.1 LabVIEW®

Use of the LabVIEW environment was one of the main tasks required to carry out the experiments on pressure coefficients reported in this thesis. LabVIEW is a program development environment based on a graphical programming concept. Unlike other development systems such as C or BASIC, LabVIEW relies on graphical symbols and icons rather than textual language to describe programming actions. LabVIEW is a general-purpose programming system, with extensive libraries of functions for any programming task. It includes libraries for data acquisition, GPIB and serial instrument control, data analysis, data presentation and data storage[46,47].

LabVIEW programs are called Virtual Instruments (VIs) because their appearance and operation can imitate actual instruments. A VI consists of essentially three parts, an interactive user interface, a dataflow diagram that serves as the source code and icon connections that allow the VI to be called from higher level VIs.

The interactive user interface of the VI is called the front panel because it simulates that of a physical instrument. Figure 4.2.1 shows a screen-shot of the front panel of a VI used to control a Hewlett Packard 34401A multimeter. The front panel consists of controls and indicators as would probably appear on the front panel of the actual instrument.

Controls such as knobs, push buttons scroll menus allow the user simulate instrument input devices, such as resistance or voltage range, and indicators such as digital displays, graphs and charts simulate instrument output devices or displays.

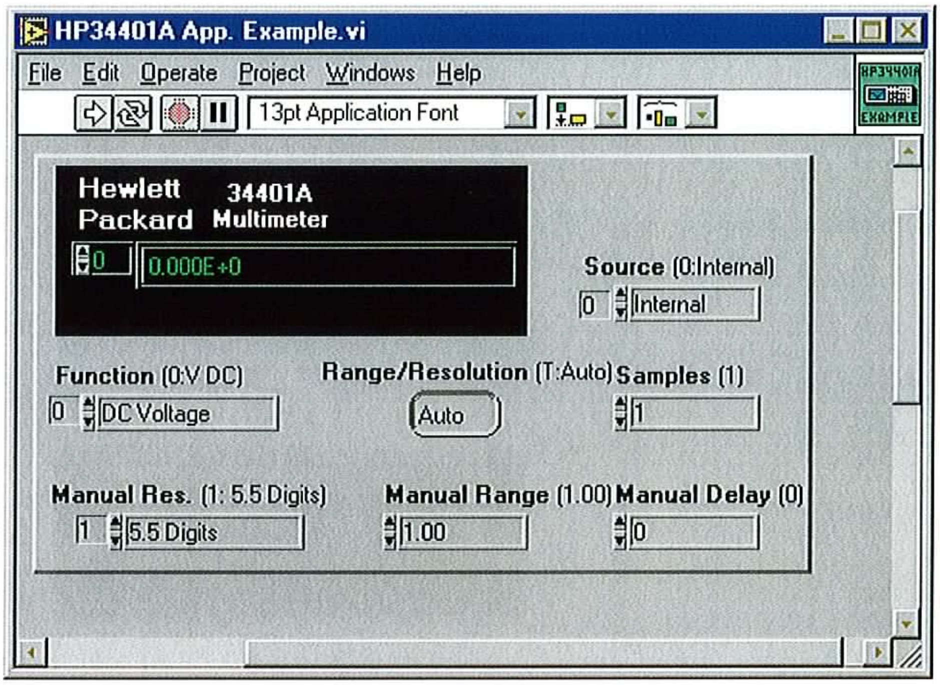


Figure 4.2.1: Screen-Shot of front panel of Hewlett Packard 34401A multimeter VI.

The VI receives instructions from a block diagram. Figure 4.2.2 shows a screen-shot of the block diagram associated with the front panel shown in figure 4.2.1. The block diagram is constructed in G, which basically involves virtual wiring together of objects that send or receive data, perform specific functions and control the flow of execution. Controls and indicators from the front panel are linked to corresponding terminals on the block diagram, as indicated by the icons in the block diagram, which have the same labels as the controls and indicators on the front panel.

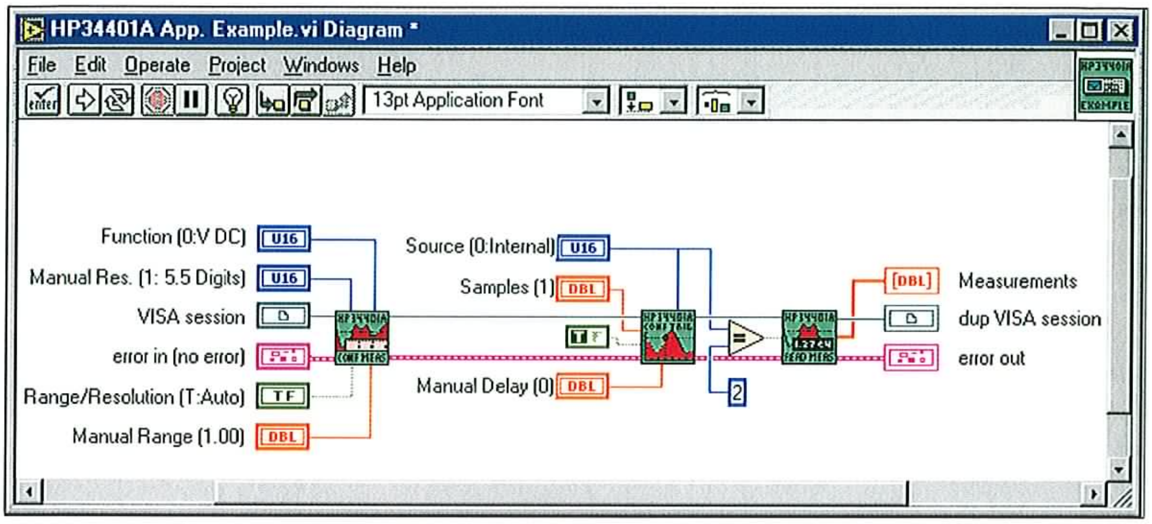


Figure 4.2.2: Screen-Shot of block diagram of Hewlett Packard 34401A multimeter VI.

VIs are hierarchical and modular, they can be used as top-level programs or as subprograms within other programs, a VI within another VI is called a subVI.

LabVIEW adheres to the concept of modular programming, which allows the programming problem be broken down into a series of simple subtasks. This feature of LabVIEW is most beneficial to us, as it allowed the data acquisition of voltage, pressure and temperature, from the various instruments to be broken down into single tasks that were combined to give the overall top-level VI.

### 4.2.2 Data acquisition sequence.

To determine the pressure coefficient of the test EVS, voltage differences between it and the reference EVS outside the chamber are recorded as a function of pressure. The temperature stability of both units is also monitored to ensure no corrections for temperature effects need to be applied.

Therefore, the focus of the LabVIEW program used to acquire the data is the recording of pairs of voltage and pressure data, together with the periodic recording of temperature via the thermistors. For completeness, and convenience in carrying out the data analysis, the acquired data is also time-stamped.

With these requirements in mind the overall measurement sequence to be implemented is given in figure 4.2.3.

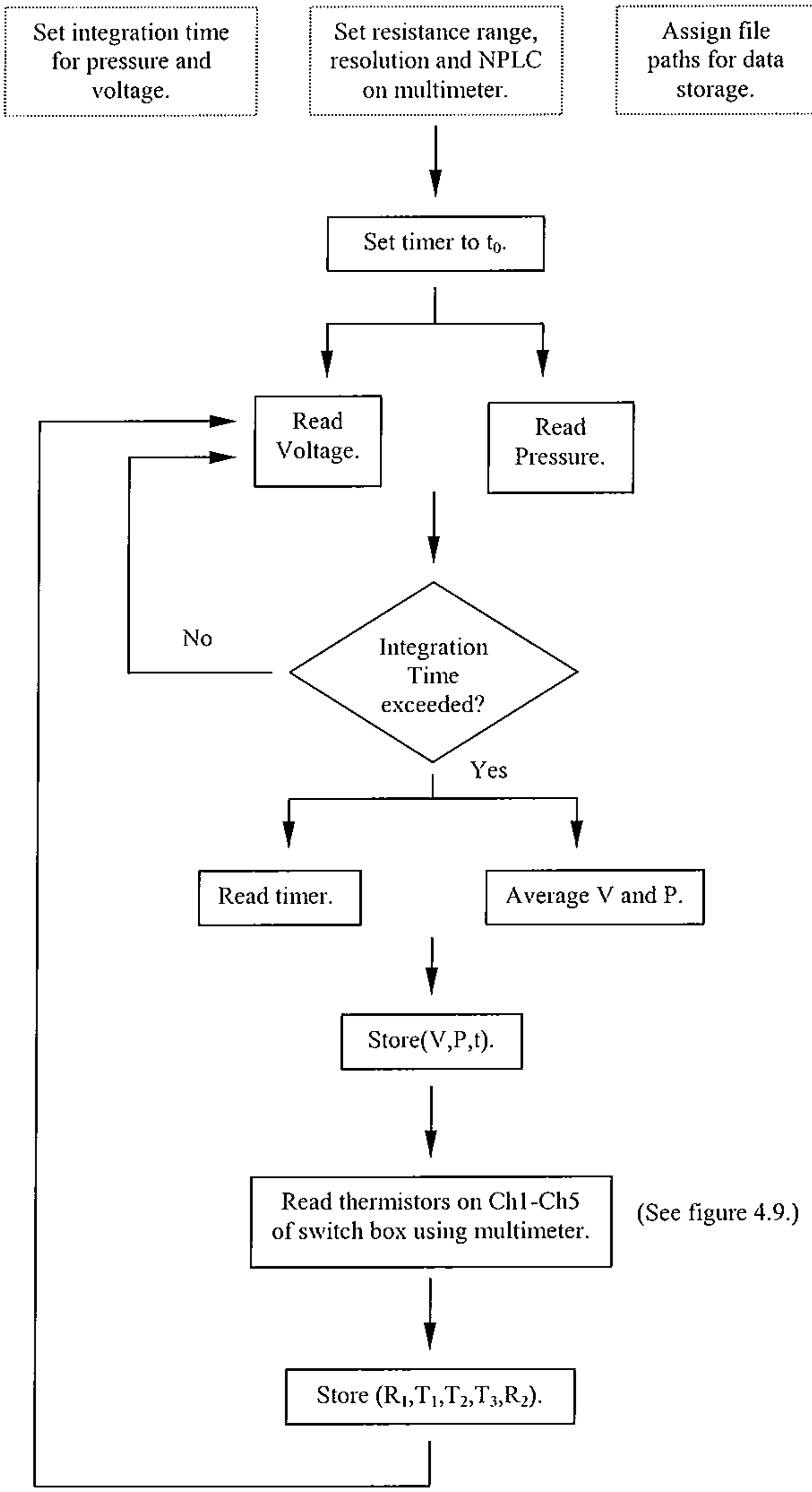


Figure 4.2.3: Data Acquisition Sequence.

The first step of the sequence, which is carried out before any data is actually acquired, is the configuration of the instrumentation. Here the relevant settings on the nanovoltmeter and multimeter are made, the integration time is set and file paths for data storage are assigned.

The next step is the acquisition of a pair of pressure and voltage readings from the barometer and nanovoltmeter.

When this is complete a subroutine, checks the elapsed time and compares it with the integration time, which was set, in step one. If the elapsed time equals or exceeds the integration time the program proceeds to the next step, otherwise it repeats the pressure and voltage readings.

When the integration time is exceeded the pressure and voltage readings taken over the time period are averaged, time-stamped and stored.

Following storage of the mean pressure and voltage the thermistor resistances, which are connected to the monitoring multimeter through channels one through five of the switch box (see table 4.1.1) are measured following the sequences outlined in figure 4.2.4.

The resistance readings of the thermistors, used for measuring air temperatures and oil temperature are converted to corresponding temperature values using appropriate conversion formulae.

Once the measurement sequence of figure 4.2.4 is complete the readings are sent to an array for storage comprising two resistance values, from EVS internal oven thermistors and three temperature values.

This sequence of pressure and voltage measurements followed by thermistor measurements is repeated until the experiment is complete and the program stopped.

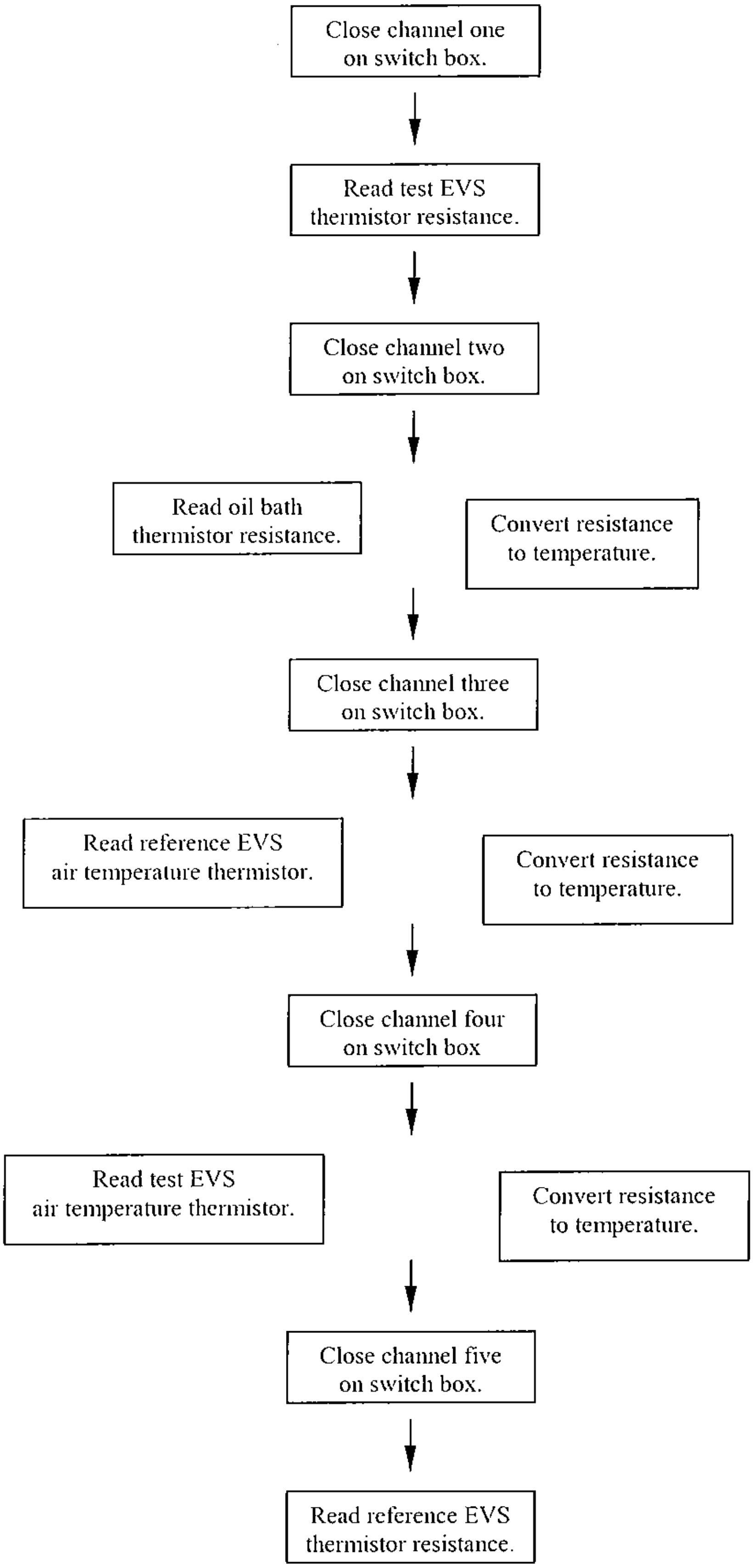


Figure 4.2.4: Thermistor measurement sequence.

### 4.2.3 Implementation of Data acquisition sequence using LabVIEW

A screen-shot of the front panel of the LabVIEW VI constructed specifically to acquire the data using the measurement sequences of figures 4.2.3 and 4.2.4 is shown in figure 4.2.5.

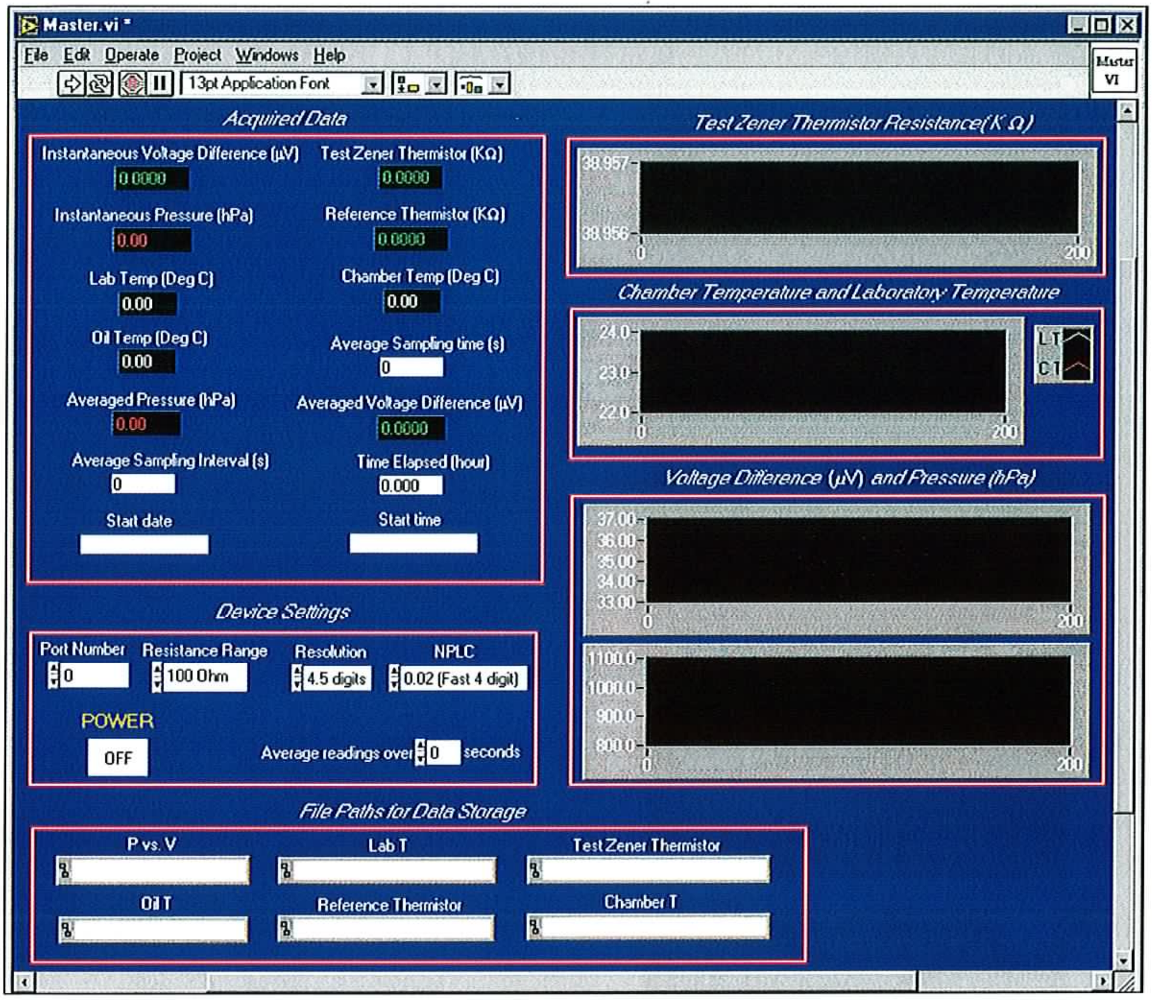


Figure 4.2.5: Screen-shot of overall data acquisition VI front panel.

The first step of the measurement sequence described in section 4.2.2 is a preliminary step, carried out to configure the instruments, set integration times and assign file paths for data storage. The settings are made using the function controls of the front panel of the VI, under the "*Device Settings*" and "*File paths for Storage*" headings as shown in figure 4.2.5.

Whilst the measurement sequences are in progress the data is displayed by the digital indicators under the "*Acquired Data*" heading. The data is also displayed on the front panel graphs, which is useful for monitoring test EVS response as well as allowing any developing problems or abnormalities to be detected and remedied. Finally, when the experiment is complete the VI is stopped using the "POWER" button.

The front panel of figure 4.2.5 is controlled from the block diagram shown in figures 4.2.7a and 4.2.7b. Using LabVIEW's modular programming concept the measurement sequences of figures' 4.2.2 and 4.2.3, for any instrument, can be broken down into essentially three steps as shown in figure 4.2.6.

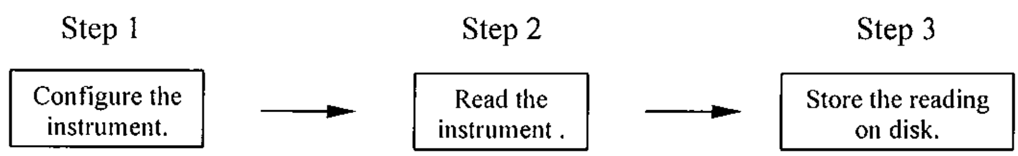


Figure 4.2.6 Data acquisition sequence.

In the first step the instrument is configured, communication is established with the PC and various function settings are made. Individual VIs were written to configure each instrument and are included as sub VIs in the overall data acquisition VI.

The subVIs which were constructed to configure the nanovoltmeter, multimeter and switch box are represented by the icons "34420 Config", "34401 Config" and "34970 Config" respectively, shown to the left of the screen-shots in figures 4.2.7a and 4.2.7b.

The barometer is controlled over the RS-232 interface, and is configured by setting baud rate, number of data bits etc. The VI used is a standard one, taken from a LabVIEW data acquisition library. This sub VI is labelled "SERIAL PORT" in figures 4.2.7a and 4.2.8b.

The multimeter settings are chosen from the front panel as described above and are linked directly to its configuration VI in the block diagram. The nanovoltmeter is configured to read dc volts, on its lowest 1mV range, at maximum resolution of 7½ digits. These settings are fixed in its configuration VI, as minimum range, maximum resolution, were required for all voltage measurements. Configuration of the scanner involved establishing communication with the PC.

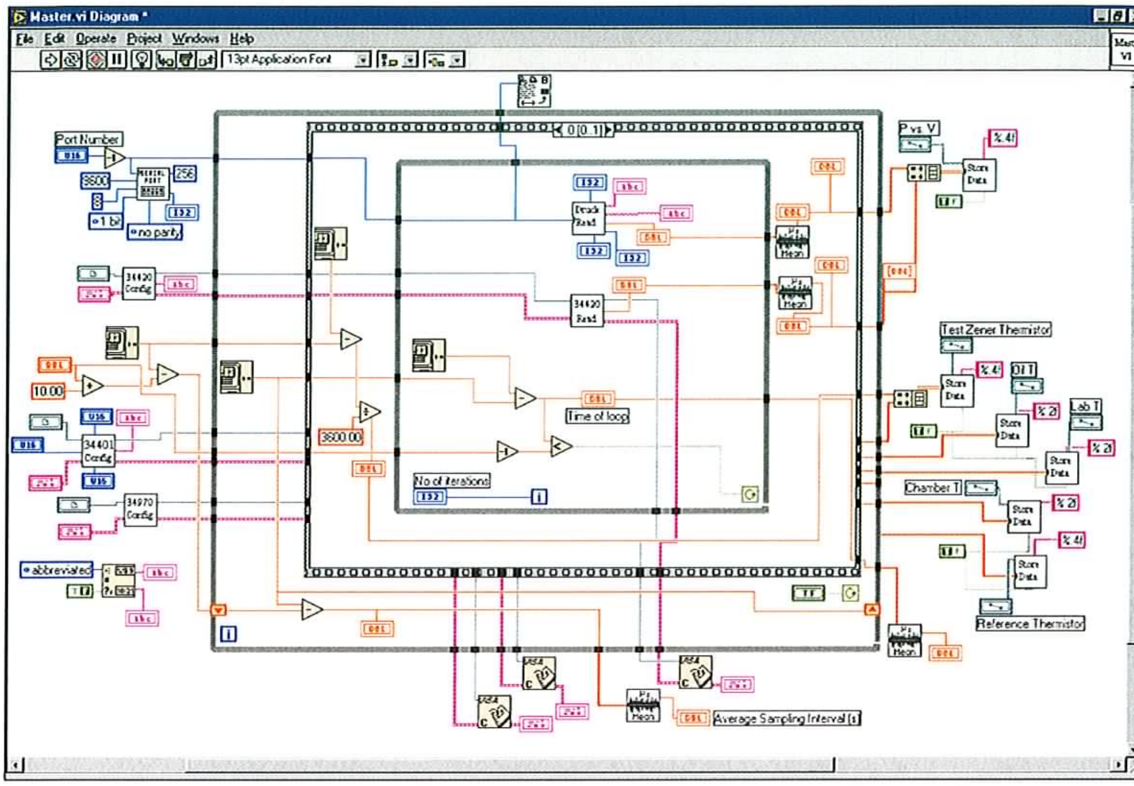


Figure 4.2.7a: Screen-shot of overall data acquisition VI block diagram.

In step two the instrument is requested to send a reading to the PC. Again separate VIs for each instrument were written for this task and are included as sub VIs in the overall data acquisition VI. In the centre of figures 4.2.7a and 4.2.7b the "Druck Read" and "34420 Read" icons represent the sub VIs used to measure pressure and voltage differences from the barometer and nanovoltmeter respectively. The "34401 Read" icon in figure 4.11b represents the sub VI of the multimeter used for measuring the thermistor resistances. Also shown in figure 4.11b under the "Oil bath temperature" heading is a conversion formula, which is used to convert the measured resistance of the oil bath thermistor to a corresponding temperature in degrees celsius. Similar formulae were developed for converting the resistance of the ambient air temperature monitoring thermistors in to a corresponding temperature, but these are not shown here.

Icons for the sub VI that controls the opening and closing of the various channels on the switch box described in figure 4.2.4 are not shown here but they are called up by the overall VI between each resistance measurement by the multimeter.

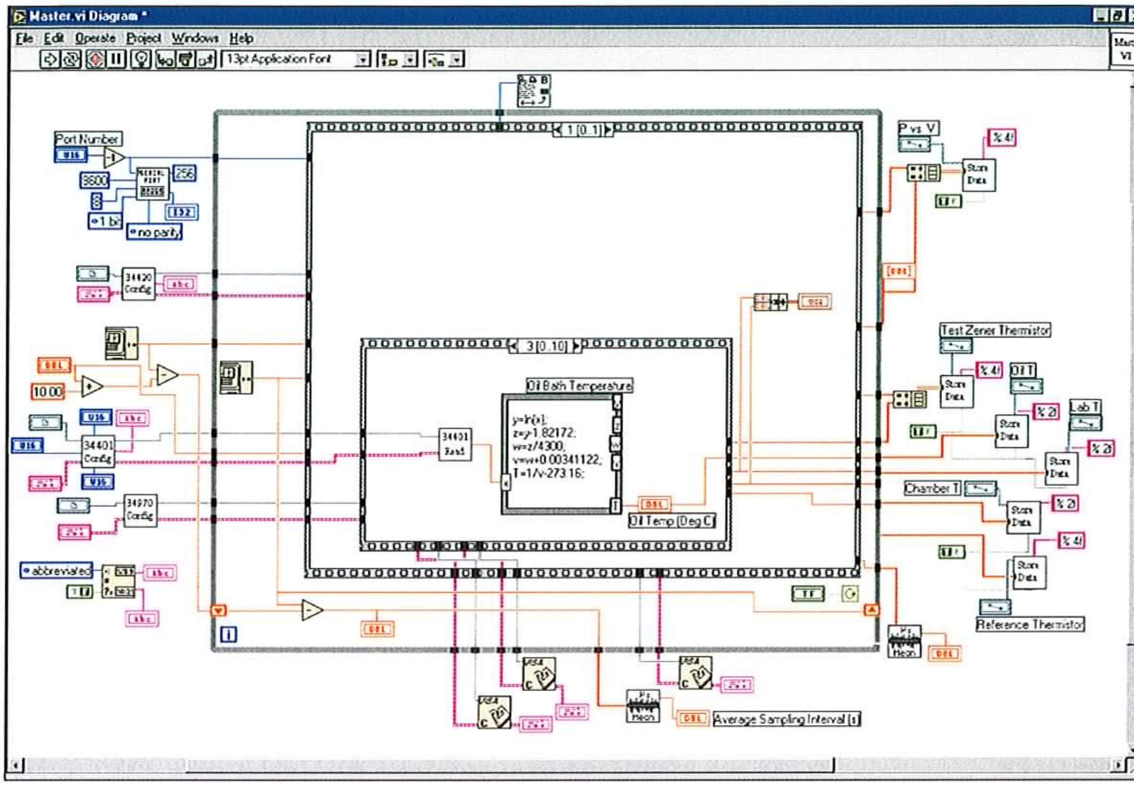


Figure 4.2.7b: Screen-shot of overall data acquisition VI block diagram.

The third step in the data acquisition process stores the results on disk. The VIs employed for this task are taken from a LabVIEW functions library and are represented by the Store Data icons to the right of figures 4.11a and 4.11b.

### 4.3 Experimental procedure

A series of identical experiments were carried out to determine the pressure coefficients of a number of EVS units. The test EVS is placed inside the chamber and the reference EVS is maintained in standard laboratory conditions. Throughout the course of the experiments both test and reference units were powered by the mains supply.

#### 4.3.1 Initial temperature monitoring

The temperature stability of both test and reference units is monitored using the methods detailed in section 4.1.5. This is necessary to ensure the temperature stability is adequate prior to carrying out the pressure experiments. Once the temperature stability is deemed sufficient its effects on the subsequent pressure experiment could be neglected.

The oil is circulated from the bath, the fan switched on and the temperature stability of both units is monitored via the VI front panel graphs illustrated in figure 4.2.5.

The oil temperature is adjusted until the air temperature inside the chamber approached 23 $^{o}$C. At this stage the system is allowed stabilise overnight.

#### 4.3.2 Pressure coefficient measurements

Once the system had stabilised the pressure inside the chamber is varied to determine the pressure coefficient of the test EVS. Pressure is varied in a stepwise fashion, illustrated in figure 4.3.1 while the voltage difference between the test and reference units is measured using the nanovoltmeter.

Starting at an initial pressure of 1050 hPa the pressure is stepped down to 850 hPa in 50 hPa intervals. It is then stepped back up in a similar manner to avoid any linear correlation, which may exist between time and pressure.

The pressure is maintained at each plateau for about 30 minutes by adjusting the needle valves described in section 4.1.3. and the data acquisition is carried out using the LabVIEW VI described in section 4.2. The various instrument settings, file paths for data storage and an integration time of 30 seconds were made from the front panel.

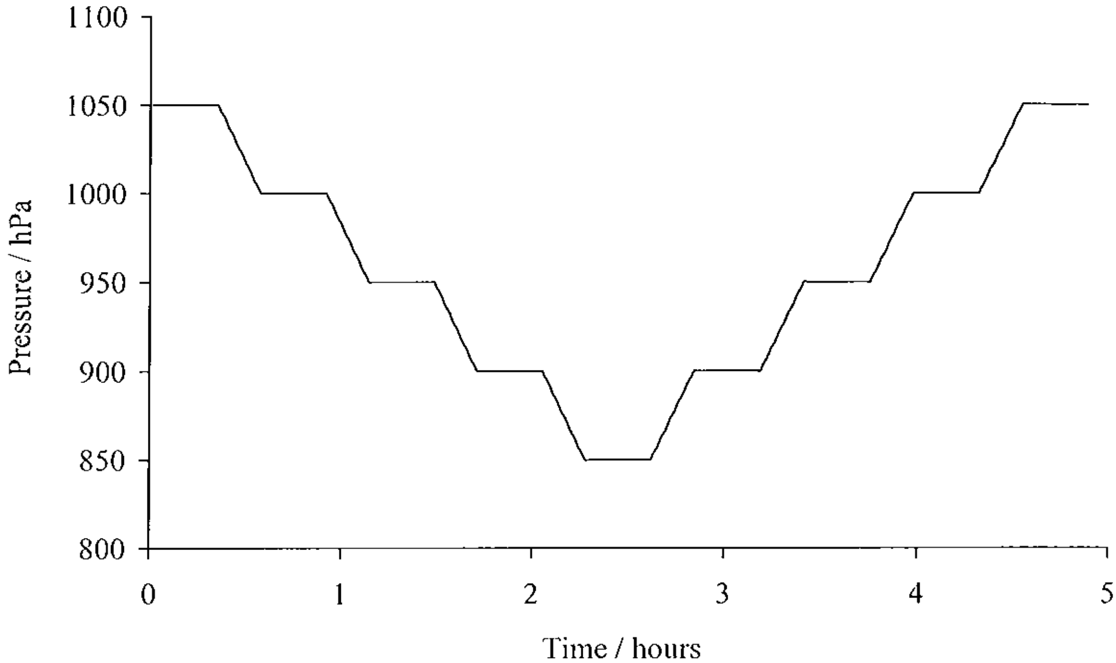


Figure 4.3.1: Pressure variation during experiment.

The entire experiment takes approximately five hours and upon completion the data is available on disk for analysis.

## 4.4 Pressure coefficients: Results and Discussion

The results of experiments carried out to determine the pressure coefficients of 6 of the NML EVS units are now presented here.

Figures 4.4.1 through figure 4.4.6 are plots of the measurement results. The upper plot shows how the pressure inside the chamber was varied throughout the course of the experiment and it is scaled on the left ordinate. The lower plot shows the corresponding change in the measured output voltage difference ($\Delta V$) between the test and reference EVSs.

The output of the reference EVS can be considered constant throughout, and the change in ($\Delta V$-$\Delta V_r$) as defined in section 2.4 can be attributed to the pressure coefficient of the test EVS unit. Identical scales are used on all the graphs and the relative size and sign of the pressure effect from unit to unit can clearly be seen.

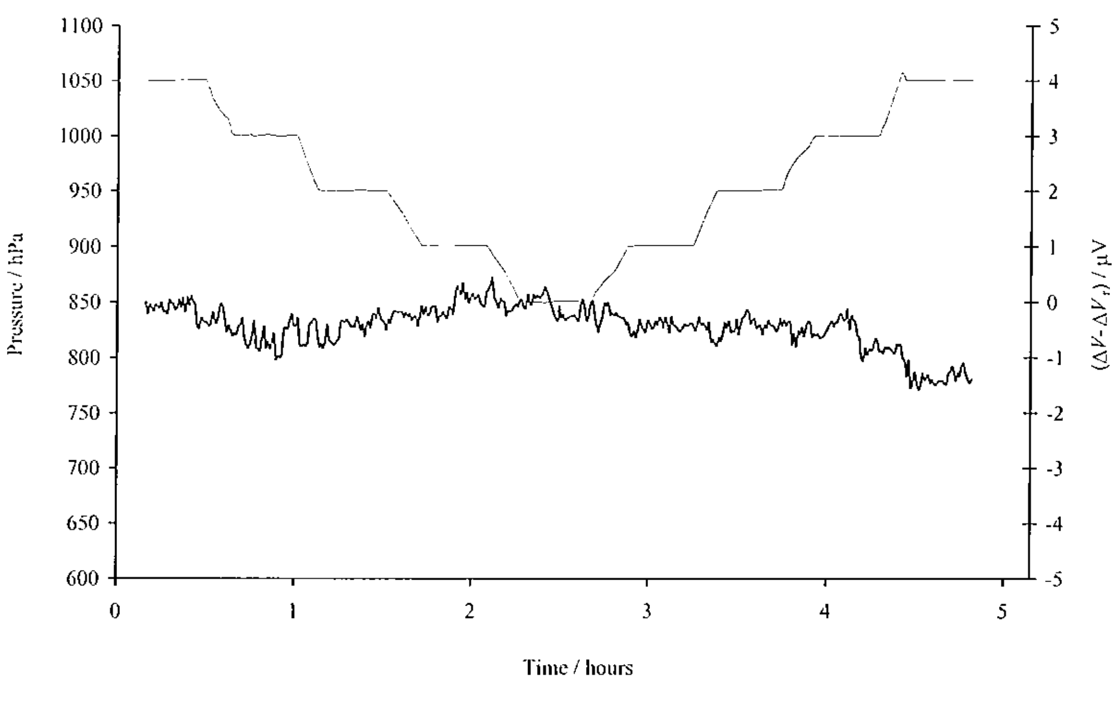


Figure 4.4.1: Deviation in output voltage of Fluke 732A (#1) EVS with pressure.

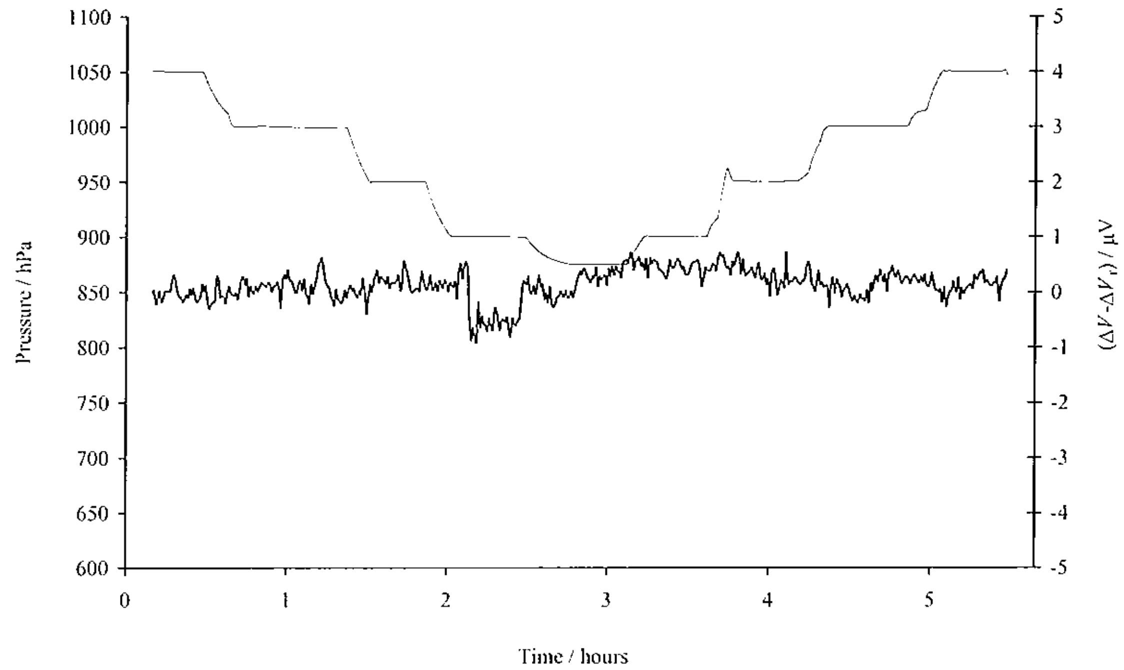


Figure 4.4.2: Deviation in output voltage of Fluke 732A (#2) EVS with pressure.

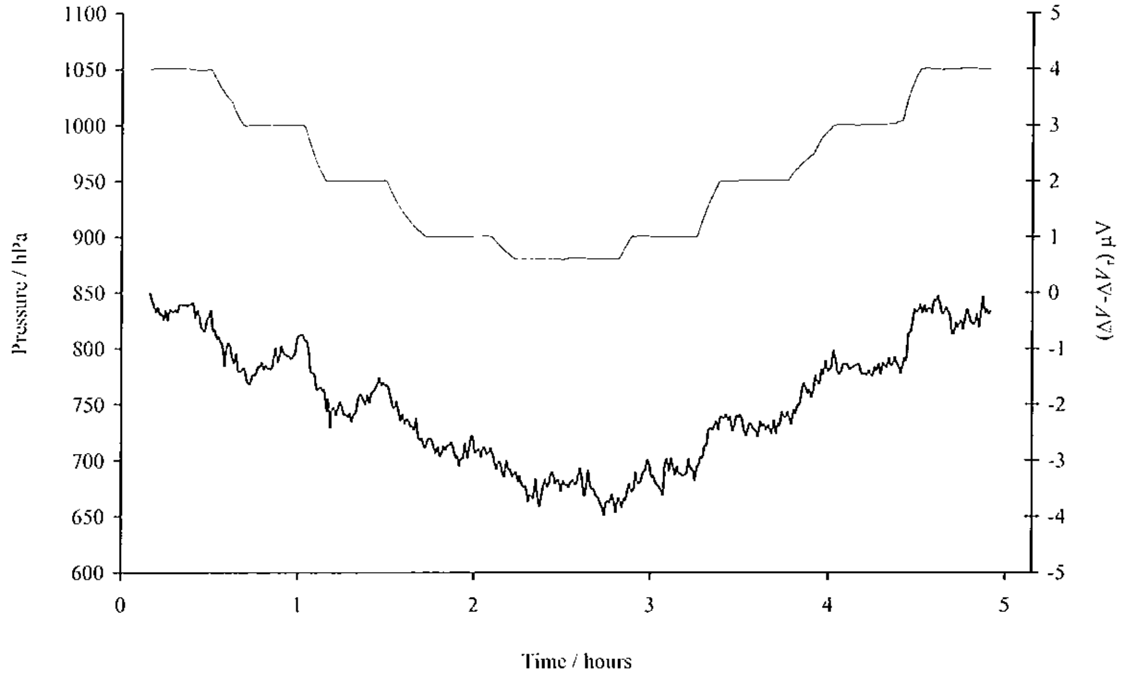


Figure 4.4.3: Deviation in output voltage of Fluke 732B (#3) EVS with pressure.

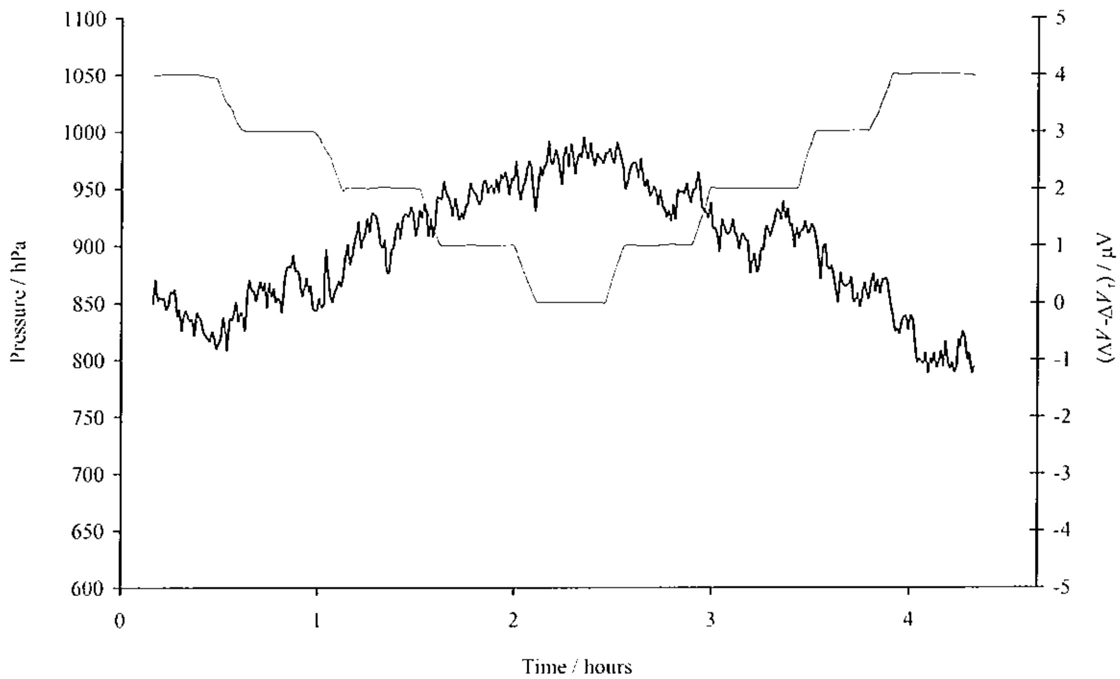


Figure 4.4.4: Deviation in output voltage of Guildline 4410 (B) EVS with pressure.

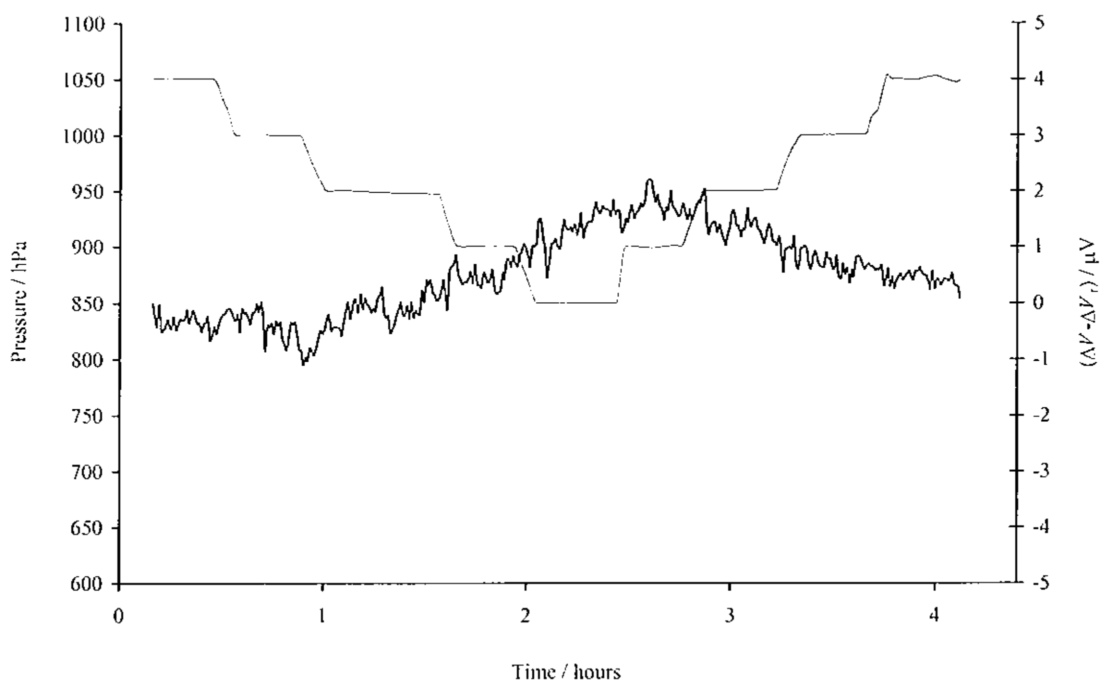


Figure 4.4.5: Deviation in output voltage of Datron 4910 (#3) EVS with pressure.

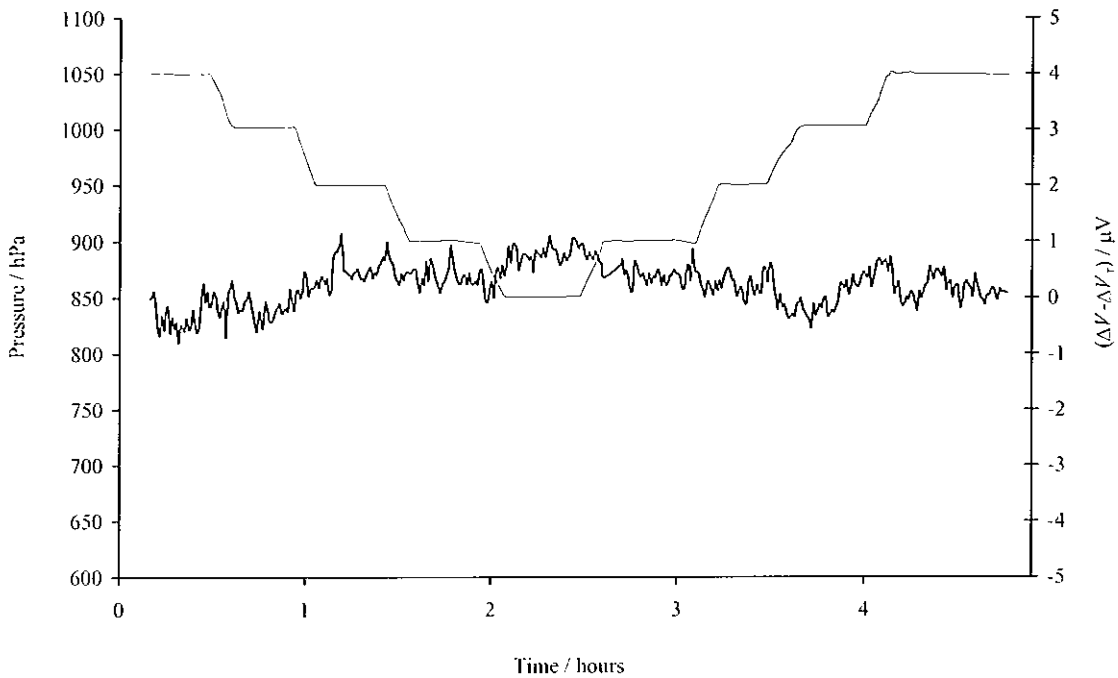


Figure 4.4.6: Deviation in output voltage of Wavetek 7001 EVS with pressure.

Figures 4.4.1 through 4.4.6 show the general behaviour of the EVS output voltages with pressure. From the plots all the units have observable pressure coefficients, with all except the Fluke 732B (#3) exhibiting negative coefficients. In general only one set of pressure measurements were carried out on each unit, due mainly to the time restrictions of the project. However, measurements were repeated for some of the Fluke units and in such instances the repeatability was found to be satisfactory, to within typical experimental uncertainties.

In figure 4.4.2 the output voltage of the Fluke 732A (#2) appears to behave in an anomalous manner as the pressure approaches 900 hPa. This may be due to any number of factors, such as an offset voltage introduced by some component of the measuring system or by signal switching on the GPIB or serial buses by the PC.

In figure 4.4.5, which shows the Datron 4910 (#3) measurements, it can be seen that the final measured voltage differences do not correspond with the initial measured differences. It is suspected that this may be due to a temperature effect on the output voltage of the Datron 4910 (#3). The overall Datron 4910 unit is a significant heat source since it comprises of 4 independent EVS units in one housing and when placed in an enclosed chamber heating can prove to be a considerable problem. The added problem with the Datron 4910 unit is that unlike other EVS units it has no thermistor in its internal oven. This makes it difficult to accurately quantify the temperature stability of the Zener reference element.

The graphs in figures 4.4.1 through 4.4.6 show clearly visible pressure plateaux. However, corresponding voltage difference plateaux are not as clearly visible. The pressure inside the chamber was held constant at each plateau for approximately 20 minutes which may not have been sufficiently long enough for the output voltage of the EVS to respond fully. This may also explain why the repeatability in voltage measurements at 1050 hPa is not as expected, particularly in figures 4.4.1, 4.4.2 and 4.4.5. Since the pressure was controlled manually using needle valves it was not feasible to maintain the pressure at each plateau for longer than 20 minutes as the overall experimental time becomes too long to carry out within an average working day. The use of electronic valves controlled by the PC, in conjunction with the pump would provide a means of automatic control allowing the pressure to be set at any value for any period of time, however the use of this method was beyond the budget of this project.

By averaging the change ($\Delta V$-$\Delta V_r$), and pressure for each plateau, a set of data pairs consisting of the pressure and corresponding change in test EVS output voltage is obtained. The pressure coefficients of the units are determined from a linear-least-squares fit to the data as shown in figure 4.4.7.

The estimated pressure coefficients $\hat{\alpha}_{pi}$ together with their associated type A standard uncertainties, determined from the linear-least-squares fit are listed in table 4.4.1.

The results presented in table 4.4.1 show all the units studied to have statistically significant pressure coefficients. This is also illustrated in figure 4.4.7 with the dashed line representing a zero coefficient.

The pressure coefficients determined for the Fluke 732A and 732B units are in very good agreement with coefficients determined by Witt for a number of similar EVS models at the BIPM[26]. The difference in value for the two models was found to be due to two different Zener-diode suppliers. The Zener-diode used in the 732A is supplied by Motorola whereas the Zener-diode used in the 732B is supplied by Linear Technology[26]. Communications with Guildline, Datron and Wavetek revealed that the

Zener-diodes used in each of these units were also supplied by Linear Technology. The spread of values for these three units and the Fluke 732B whose Zener-diode is also supplied by Linear Technology suggests that the pressure coefficient of EVS units may also be dependent on other circuit elements or the Zener-diode manufacturing process.

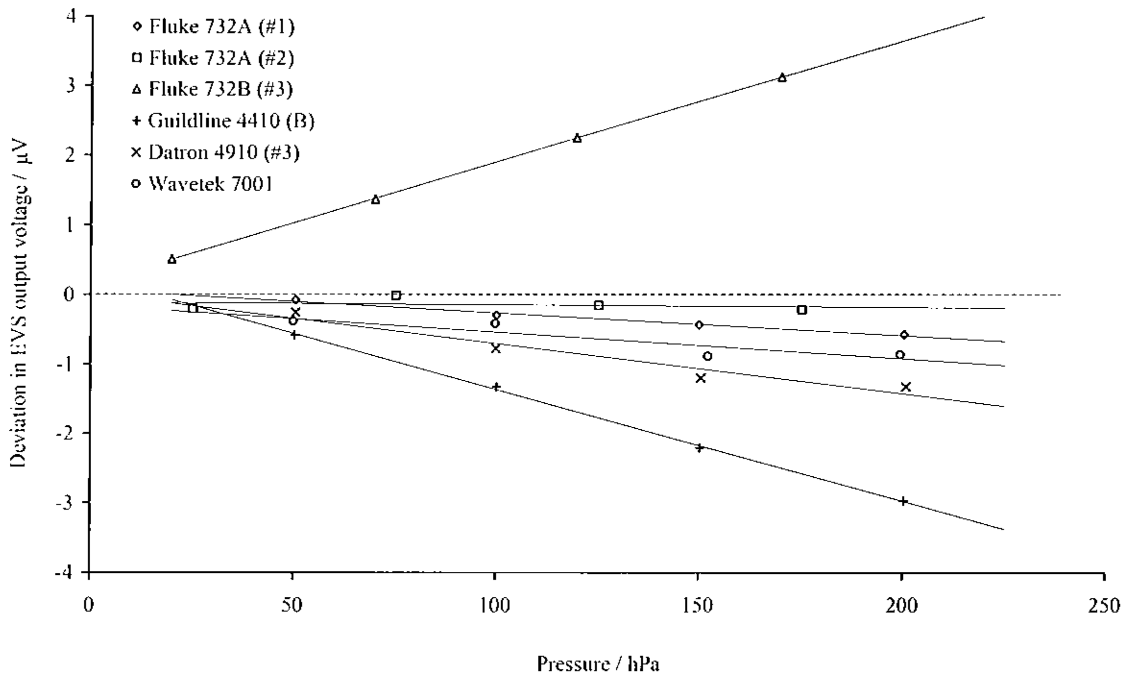


Figure 4.4.7: Graphical representation of NML EVS units' pressure coefficients.

| EVS Type. | Pressure coefficient. (x $10^{-9}$/hPa) | Type A standard uncertainty. (x $10^{-9}$/hPa) |
|---|---|---|
| Fluke 732A (#1) | -0.30 | 0.023 |
| Fluke 732A (#2) | -0.07 | 0.060 |
| Fluke 732B (#3) | +1.81 | 0.045 |
| Guildline 4410 (B) | -1.51 | 0.061 |
| Datron 4910 (#3) | -0.71 | 0.074 |
| Wavetek 7001 | -0.44 | 0.082 |

Table 4.4.1: Relative pressure coefficients of EVS units including type A standard uncertainty.

The results listed above were published in the 1999 National Conference of Standards Laboratories (NCSL) Workshop and Symposium conference proceedings and the 1999 British Electromagnetic Measurements Conference (BEMC) conference proceedings, both of which are listed in Appendix A.

Corrections were not applied to the voltage measurements for the effects of time temperature, or relative humidity. The measurements were carried out over a 4-5 hour period and therefore the effects of temporal drift and changes in relative humidity on both test and reference were assumed to be negligible. Temperature stability of both test and reference units were monitored throughout the experiments by means of EVS internal oven thermistors, and the ambient temperature was also monitored. The internal oven thermistors were used to quantify the temperature stability of the EVS units and typical temperature stability of the reference unit was of the order of 5 mK. Figure 4.4.8 shows typical stability of test EVS internal oven temperature and chamber air temperature. The air temperature inside the chamber cycles by ± 150 mK whereas the corresponding change in the EVS oven temperature is almost undetectable. It was found that cycling of the chamber air temperature was due to the corresponding cycling of external laboratory air temperature, caused by the air conditioning system.

Figure 4.4.9 shows the temperature stability of the EVS oven temperature using a higher resolution scale and by comparison with the air temperature stability plot of figure 4.4.8 it can be clearly seen that the EVS oven temperature follows the chamber air temperature. However the cyclic behaviour of the chamber air temperature is attenuated by a factor of forty in the internal oven of the EVS with typical fluctuations of ± 5 mK.

Corrections were not applied to the voltage measurements for the effects of pressure changes on the reference unit either. Although pressure in the reference enclosure was not monitored continuously throughout the experiment it was recorded at the beginning and end of each experiment. Changes of 1 hPa were typical and based on the coefficients listed in table 4.4.1 no corrections were applied.

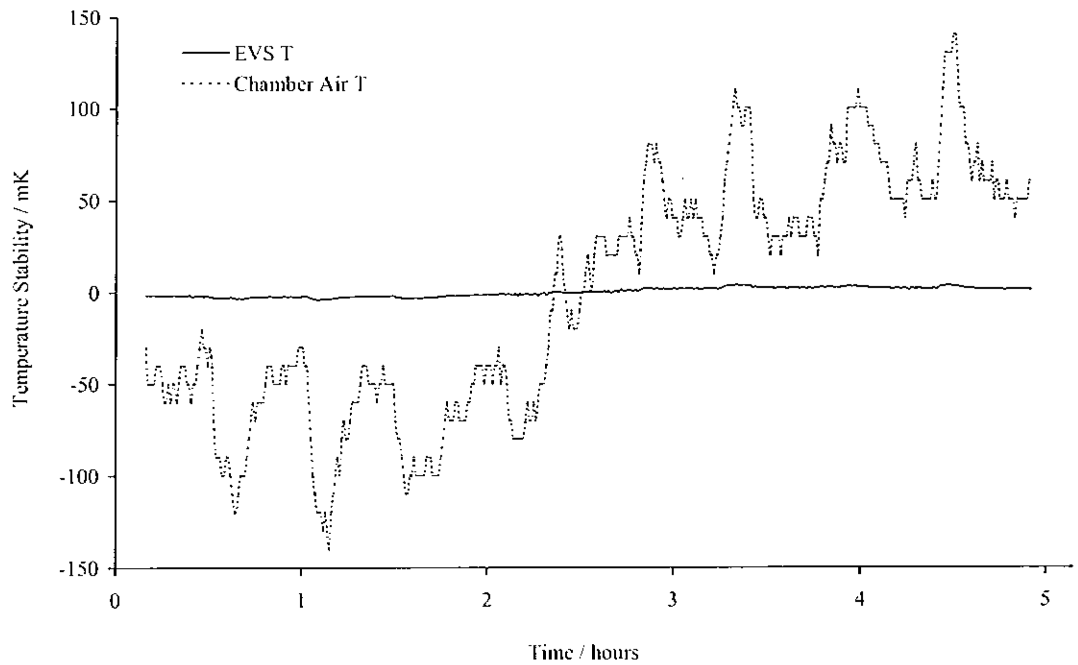


Figure 4.4.8: Typical temperature stability of EVS internal oven temperature and test chamber temperature.

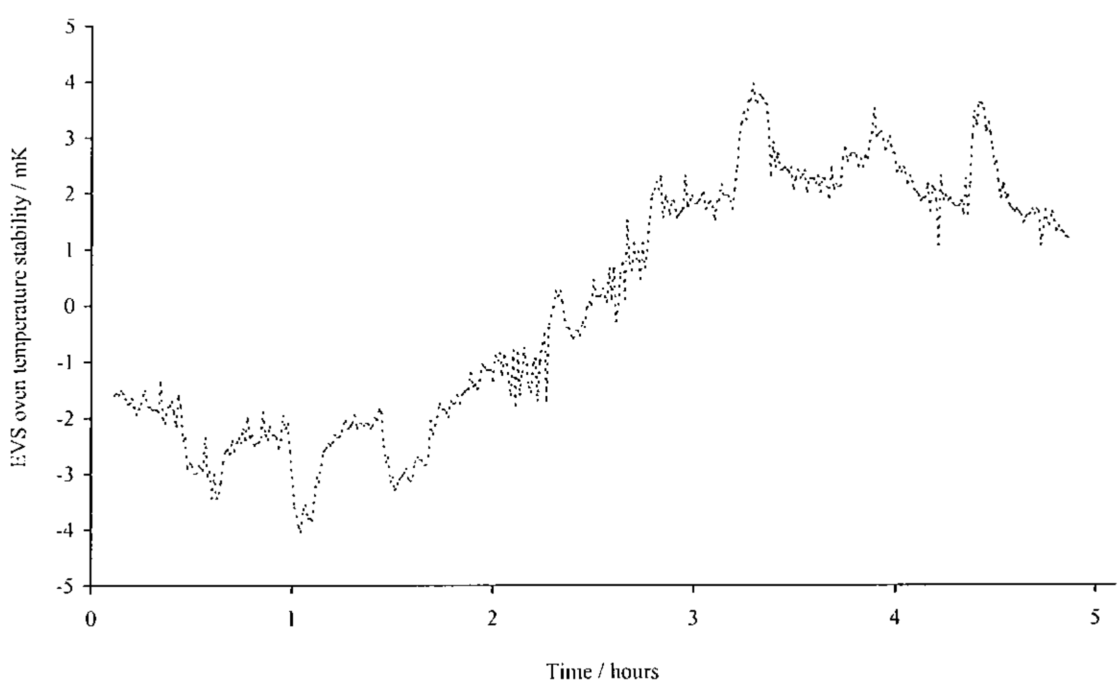


Figure 4.4.9: Temperature stability of EVS internal oven.

# 5. Conclusions

The background to the work reported in this thesis, is the need to maintain a local representation of the SI unit for dc voltage in Ireland. The hierarchy of measurement standards for dc voltage has been described, and the distinction between realisation of the definition of the voltage unit and its practical representation pointed out. EVSs offer a practical and economic means of maintaining a local voltage reference standard. The ensemble standard maintained at the NML, Dublin has been described.

Based on a literature survey and on the analysis of observations made at NML it was suggested that the behaviour of the output voltage of an EVS is influenced by a number of factors, both internal and external. A model, which describes the behaviour of an EVS output has been proposed, which allows corrections to be made for external influences, provided the corresponding sensitivity coefficients are known. The effects of time and ambient pressure on the output voltage of a number of EVS units was studied and temporal regression parameters and pressure coefficients were determined.

Estimates of the temporal regression parameters were determined through a systematic and logical analysis of the results of a number of interlaboratory comparisons with the BIPM. Results of comparisons dating back to 1992, together with the results of two comparisons carried out during the course of this project, in 1998 and 1999, were used to provide data for the analysis. All of the EVS units studied showed a linear drift, with drift rates ranging from + 17 nV/day to –16 nV/day. The uncertainty associated with the drift rates ranged from 0.4 nV/day to 1.6 nV/day. By means of the temporal drift models for individual EVS units, the mean value of the NML ensemble standard and its associated uncertainty can be predicted. The relative standard uncertainty of the predicted value during the time between interlaboratory comparisons (1 year) is typically 2 parts in $10^7$. The validity of the temporal models and associated uncertainty was confirmed by the results of the 1999 interlaboratory comparison with the BIPM which showed agreement to within 0.3 μV or 3 parts in $10^8$. Future bilateral comparisons with the BIPM will provide further data to refine the temporal models using the method described.

Within-group comparisons have been shown to play an important role in the surveillance of an ensemble standard of EVS units in the period between validation of temporal regression models through comparisons with higher echelon laboratory. Some improvements of the procedure used at NML to carry out within-group comparisons have been suggested as well as criteria for the selection of individual EVS units for inclusion in the ensemble standard.

An experimental set-up used to measure the pressure coefficients of the output voltage of an EVS has been described. This included a pressure chamber and auxiliary systems for monitoring and controlling the temperature and pressure. A specialised LabVIEW program was developed for data acquisition and analysis.

The present system could be improved further by developing an automated pressure control system using PC controlled valves, as the present system requires continuous attention to ensure the chamber pressure remains constant at the desired level. With some small modifications, the experimental set-up described can be used to determine temperature and perhaps humidity coefficients for EVS units.

A drawback with the present system is the control of the reference EVS environment. The reference EVS is maintained in an enclosure in the laboratory whose environmental stability and in particular temperature stability, is dependent on the stability of the laboratory environment as maintained by the air conditioning system. Ideally the reference should be maintained in a chamber similar to the test chamber but due to budget restrictions only one chamber was made available for the purposes of this project. The temperature stability of the reference enclosure was monitored continuously before and during the experiment so that any anomalous behaviour could be detected. Also, since typical experiment times were of the order of 4-5 hours the long-term stability of the reference environment was not crucial.

The pressure coefficients of five types of commercially available EVS units, which comprise part of the NML ensemble standard, were determined. All units studied showed statistically significant linear pressure coefficients ranging from + 18 nV/hPa and –15 nV/hPa for the 10 V output. The standard uncertainty of the measured pressure coefficients, which was dominated by the type A uncertainty component, was of the order of 0.6 nV/hPa. For the EVS units whose pressure coefficients have been determined elsewhere, the values determined here agree well with the other values as reported in the literature[28].

The variation of the pressure coefficient between different EVS models together with its consistency between EVS units of the same model suggest that the pressure effect is determined by the characteristic of the EVS unit's reference elements. However, further work is required to discover which characteristics determine the pressure coefficient.

# REFERENCES


1. Kose V., (1994/95) *Dissemination of Units in Europe (Traceability and its assurance in a National and Regional Context)*, Metrologia, **31**, pp 457-466.

2. Quinn T.J., (1994/95) *Base Units of the Système International d'Unités, their Accuracy, Dissemination and International Traceability*, Metrologia, **31**, 515-527.

3. Petley B.W., (1990), *Metrology, the key to Progress: in the Past and in the Future.* Physica Scripta, **41**, pp 701-711.

4. *Le Système International d'Unités (SI)*, (1998), 7th Ed., Sèvres, BIPM.

5. Pöpel R., (1992), *The Josephson effect and voltage standards*, Metrologia, **29**, pp 153-174.

6. Taylor B.N., Witt T.J., (1989), *New International Electrical Reference Standards based on the Josephson and Quantum Hall effects*, Metrologia, **26**, pp 47-62.

7. Robinson I.A., Kibble B.P., (1999), *The NPL moving coil balance: Progress towards monitoring the kilogram*, Proceedings of the 1999 NCSL workshop and symposium, pp 333-335.

8. Taylor B.N., Mohr P.J., (1999), *On the redefinition of the kilogram*, Metrologia, **36**, pp 63-64.

9. Petley B.W., (1994/95) *Electrical Units -- the last thirty years.*, Metrologia, **32**, pp 495-502.

10. *Array Josephson Junction*, (1991) Recommended Intrinsic/Derived Standards Practice, RISP-1, National Conference of Standards Laboratories, Boulder, CO.

11. Pöpel R., Niemeyer J., Fromknecht R., Meier W., Grimm L., (1990), *1- and 10-V series array Josephson voltages standards in Nb/$Al_2O_3$/Nb technology*, J. Appl. Phys., **68**, pp 4294-4303.

12. Niemeyer J., Grimm L., (1998), *Present status of Josephson Voltage Metrology*, Metrologia, **25**, pp 135-140.

13. Hartland A., (1998), *Quantum standards for electrical units*, Contemp. Phys., **29**, pp 477-498.

14. Hamilton C.A., Kautz R.L., Steiner R.L., Lloyd Frances L., (1985), *A practical Josephson voltage standard at 1 V*, IEEE Electron Device Letters, **EDL-6**, pp 623-625.

15. Quinn T.J., (1989), *News from the BIPM*, Metrologia, **26**, pp 69-74.

16. Hineman Ernest, Roberson John, (1971), *Solid State Voltage References*, Instruments and Control Systems, pp 133-135.

17. Spreadbury, P.J., *Electronic voltage standards*, (1981), Electronics and Power, February 1981, pp 140-142.

18. *Fluke 732A DC Reference Standard Instruction Manual*, (1986), Fluke Corporation, Everett, WA.

19. *Fluke 732B DC Reference Standards Instruction Manual*, (1992), Fluke Corporation, Everett, WA.

20. *4910 and 4911 DC voltage Reference Standards User's Handbook*, (1990), Datron Wavetek Ltd., Norwich, England.

21. *Guildline 4410 Technical Manual*, (1990), Guildline Instruments Limited, Ontario, Canada.

22. Pickering John R, (1995) Design details and *Measurements of a sub ppm Zener based reference System*, BEMC 1995 conference digest, pp 23/1-23/4.

23. *Calibration: Philosophy in Practice*, (1994), 2nd ed. Fluke Corporation, Everett, WA.

24. Kletke Raymond D., (1998), *Predicting 10 V DC Reference Standard output voltage*, Proceedings of the 1998 NCSL workshop and symposium, pp 615-621.

25. Witt T.J., (1998), *Measurements of the Temperature Dependence of the Output voltages of some Zener Diode Based voltage Standards*, IEE Proc.-Sci. Meas. Technol., **145**, pp 154-158.

26. Witt Thomas J., (1999), *Pressure Coefficients of some Zener Diode-Based electronic voltage standards*, IEEE Transactions on Instrumentation and Measurement, **48**, pp 329-332.

27. Witt T.J., Reymann D., Avrons D, (1995), *The stability of some Zener-diode-based voltage* standards. IEEE Transactions on Instrumentation and Measurement, **44**, pp 226-229.

28. Witt T.J., (1997), *Low-frequency spectral analysis of dc nanovoltmeters and voltage reference standards*. IEEE Transactions on Instrumentation and Measurement, **46**, pp 318-321.

29. Aprelev A.V., (1996), *Effects of power supply failure on the metrological characteristics of solid-state voltage standards*, Measurement Techniques, **39**, pp 1221-1224.

30. *National Metrology Services Annual Report for Year ended 1997*, Forbairt Technology Services Directorate, Glasnevin, Dublin.

31. *7000-Series Volt Maintenance System Operation and Performance User's Handbook*, (1998), Wavetek Ltd., Norwich, England

32. Cobbe Derek, (1998), *Investigation of the influence of environmental humidity on the anomalous behaviour of Voltage Standards*, DIT School of Physics undergraduate project report.

33. Witt T.J., Reymann D., (1999), *Characterizing the Noise of Zener-diode Voltage Standards*, BEMC 1999 conference digest, pp 6/1-6/4.

34. Kletke Raymond D., (1998), *Predicting 10 VDC Reference Standard Output Voltage*, Proceedings of 1998 NCSL Workshop and Symposium, pp 615-621.

35. Neter John, Wasserman William, Kutner Michael H., (1985), *Applied Linear Statistical Models*, 2nd Ed., Irwin, Illinois.

36. Rapport BIPM-98/14, *Bilateral Comparison of 10 V and 1.018 V Standards between the NML (Forbairt) and the BIPM, April 1998.*

37. Rapports-99/ , in preparation, *Bilateral Comparison of 10 V Standards between the NML (Forbairt), Ireland and the BIPM, June 1999.*

38. ISO (1993), *Guide to the Expression of Uncertainty in Measurement*, Geneva: International Standards Organisation.

39. Natrella M., (1966), *Experimental Statistics*, National Bureau of Standards Handbook 91, US Government Printing Office, Washington.

40. Grabe M., (1978), *Note on the Application of the Method of Least Squares*, Metrologia, **14**, pp 143-146.

41. Hughes C.G., Musk H.A., (1972), *A Least Squares Method for Analysis of Pair Comparison Measurement*, Metrologia, **8**, pp 109-113.

42. Prowse D.B., Anderson A.R., (1974), *Calibration of a Set of Masses in Terms of One Mass Standard*, Metrologia, **10**, pp 123-128.

43. Sutton C.M., Clarkson M.T., (1993/94), *A General Approach to Comparison in the Presence of Drift*, Metrologia, **30**, pp 487-493.

44. Beck J.V., Arnold K.J., (1977), *Parameter Estimation in Science and Engineering*, Wiley, New York.

45. VoltRef, (1984), *Operating Instructions for Voltage Reference Maintenance Program*, DATA PROOF, 1177S De Anza Blvd., San Jose, CA 95129.

46. LabVIEW®, *Function and VI Reference Manual*, (1997) National Instruments, Austin, TX.

47. LabVIEW®, *User Manual*, (1997) National Instruments, Austin, TX.

# Appendix A. Publications

In: Institute of Electrical Engineers, Science, Education and Technology Seminar Proceedings on Measurement dissemination by transfer methods, 12 May 1999, pp 1/3-1/4.

THE PERFORMANCE OF ZENER-DIODE-BASED ELECTRONIC VOLTAGE STANDARDS AS TRANSFER DEVICES

Kevin Armstrong, Oliver Power, James Walsh.

**Introduction.**

Throughout the most part of this century electrical, in common with many other measurement standards, have been maintained by means of artefacts. Up until recently the volt was realised locally using a group of electrochemical (Weston) cells and the ohm by means of a group of wire wound resistors stored in temperature controlled oil baths. These standards, for the purposes of scientific collaboration and international trade, needed to be compared with similar artefact standards in other national laboratories, and this was carried out through the auspices of the Bureau International des Poids et Mesures (BIPM). However, in the intervening time period between comparisons significant differences between standards could arise (several parts in $10^6$ in the case of the volt) due to undetected drift in the local standard.[1]

The recent availability of electrical standards based on quantum phenomena has provided (upper echelon) laboratories with an almost ideal means of maintaining local representation of the electrical units. In the case of dc voltage, measurement standards based on the Josephson effect have shown agreement to within a few parts in $10^9$ between laboratories in different countries.[2] However, in view of the high capital and maintenance cost of Josephson Voltage Array Standards (JVAS), many advanced industrial laboratories as well as some national metrology institutes continue to maintain their voltage standards by means of artefacts. Nowadays, Weston cells have largely been replaced by electronic voltage standards (EVSs) based on zener-diode reference elements.

The Irish National Metrology Laboratory (NML) maintains its reference voltage standard by means of an ensemble standard comprising a group of EVSs. The maintenance of this standard comprises two parts. The establishment of the traceability to the SI unit of the value assigned to the reference standard which is accomplished by regular bilateral comparison with a higher echelon laboratory, and the surveillance of the NML standard between such comparisons which is accomplished by internal intercomparison. One or more EVSs, of identical construction to those used for the maintenance of the local standard, are used as travelling standards for the bilateral comparison.

**Factors which influence the performance of EVS.**

The influence factors which affect the performance of an EVS as a laboratory standard must also be considered when it is used as a travelling standard. The main factors which influence the output e.m.f. of an EVS are :

time
ambient temperature
ambient pressure
ambient humidity
internal noise
external EM fields.

All EVSs drift with time to a greater or lesser extent, with typical drift rates of 0.5 to 2 parts in $10^6$ per year. Figure 1 shows the temporal behaviour of a member of the NML ensemble over a period of several years. This drift does not present a problem to the user provided that it is predictable. By means of regression analysis of external calibration data it is usually possible to produce a drift model for an individual EVS which allows sufficiently accurate prediction of its output at any date between calibrations.[3]
Since the typical duration of a bilateral comparison is of the of the order of 1 month, it may appear that the temporal behaviour of an EVS used as a transfer standard is not a major concern. However, the effect of the transport can produce short-term drift effects of the EVS which are different from the long-term behaviour. Consequently, it is necessary to carefully monitor the drift characteristics of the EVS throughout the transfer process.

The EVS output is also dependent upon ambient temperature and pressure with typical sensitivity coefficients at the 10V level of up to100 ppb $K^{-1}$ and 2 ppb $hPa^{-1}$ respectively for some commercial devices.[4] [5] When using an EVS as a transfer standard both its temperature and pressure coefficients should be known. This allows all measurement data taken during the comparison to be reduced to standard temperature and pressure values. Another important temperature effect is the response of the EVS output to thermal shock which occurs when power is lost to the oven which house the EVS reference element.[6] Most EVSs exhibit an hysteresis effect whereby the EVS output does not recover to its previous value after a thermal shock (see step change in EVS output in Fig.1). Indeed, not only the mean output value but even the drift rate may be affected. As a consequence, care should be taken to ensure that the transfer standard EVS is continuously powered (by internal or external batteries) and is not subjected to extremes of temperature during its transport.

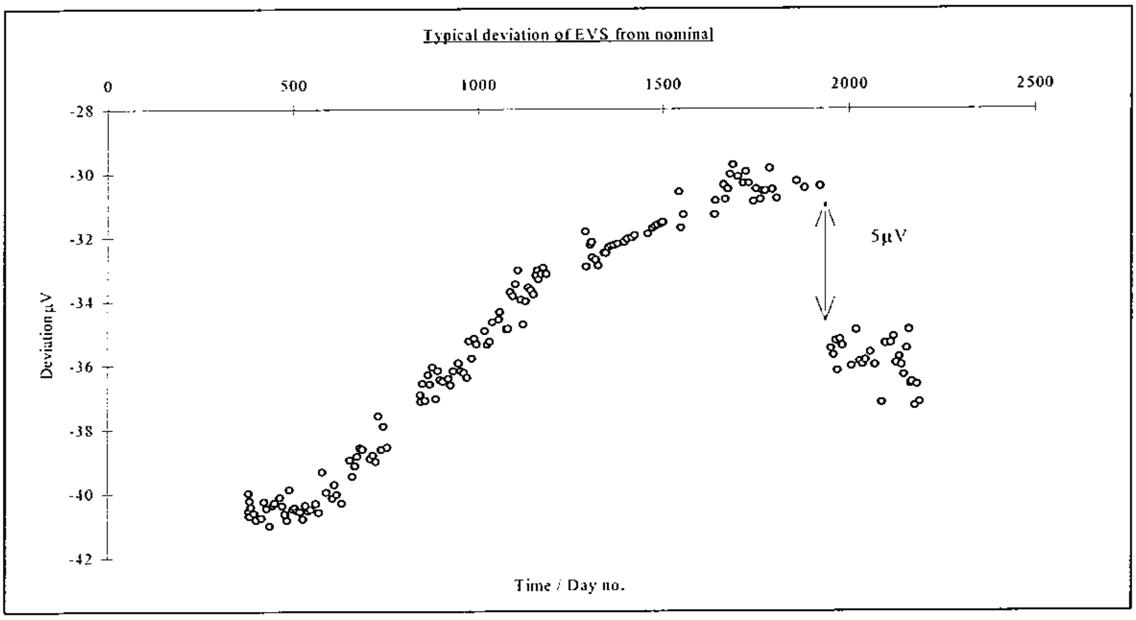


**Fig.1 Long-term behaviour of EVS Output (at 10V level)**

Some EVSs are sensitive to ambient humidity and studies suggest that there is a considerable lag (several weeks) between the humidity variation and the corresponding change in the EVS output. For this reason, and since travelling standards are likely to be subjected to significant changes in ambient humidity during transport, the use of EVSs showing a sensitivity to humidity as travelling standards should be avoided.

Perhaps the most intractable problem associated with using an EVS as a transfer standard is its output noise. Low frequency spectral analysis may be used to characterise this noise[7]. Short-term noise effects (over typical measurement intervals) can be reduced by filtering and averaging. It is the fluctuations with longer periods, up to about 1 week, which are most important when using an EVS as a transfer standard. These random variations, which may have magnitudes of a few parts in $10^7$, cannot be corrected for but must be included in the uncertainty analysis. One approach is to characterise, over a long period, the fluctuations of the EVS output assuming that the variations are normally distributed about a mean regression line.

## Typical Comparison using EVSs as travelling standard.

The aim of an intercomparison between two laboratories is to determine the difference between the local representations of maintained the unit. For almost a decade now, the reference voltage standard of the NML has been compared with the BIPM reference standard on an annual basis. A group of EVSs belonging to BIPM is used as a travelling standard for the bilateral comparison. Prior to shipping these standards to NML, the output of each EVS is characterised for temporal drift by the BIPM against its JAVS. The pressure and temperature coefficients of each member of the travelling standard group are also known. Upon receipt, and after stabilisation NML carries out a series of measurements on the travelling group. After completion of the NML (typically 2-3 weeks) the travelling group is shipped back to BIPM where further measurements are carried out against the JAVS. Both laboratories assign values to the outputs of the travelling standards on the mean date (fig.2). In this way the difference between NML's representation of the volt and that of the BIPM is determined and published in an official BIPM report[8]. Depending upon the result NML may reassign the value of its reference standard by appropriate adjustment of the prediction models of individual members of the ensemble.

The uncertainty associated with the measured difference is evaluated based on the uncertainties of the input quantities, including temperature and pressure corrections, the parameters associated with the curve fitting, and low frequency noise. A standard uncertainty of the order of 1 part in $10^7$ is typical for a comparison using three EVSs as transfer standards. This uncertainty is subsequently used as a component in the NML uncertainty budget for the value assigned to its reference voltage standard on any date between comparisons.

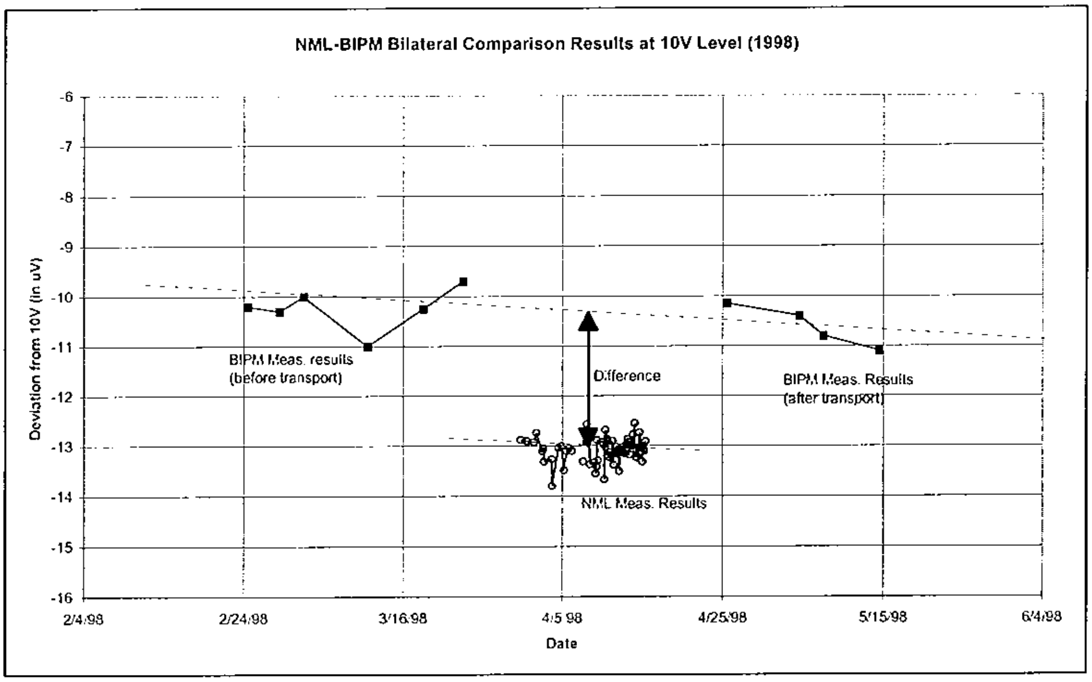


**Fig 2 Typical Bilateral Comparison Results at 10V Level**

## Conclusions

Although far from ideal for use as travelling standards for interlaboratory comparisons EVSs offer the best practical and economic solution. Provided the EVS transfer standards are well characterised for all influence factors and sufficient care is taken with the transport, the difference between the e.m.f. value assigned to the local standard and that of the reference standard can be determined with a standard uncertainty of the order of 1 part in $10^7$. This uncertainty is acceptable in most cases, particularly in view of the magnitude of other uncertainty components associated with the maintenance and surveillance of a local voltage standard between comparisons.

## References


[1] Hartland, A *Quantum standards for electrical units* Contemp. Phys, 1988, **29**, Pt 5, 477-498.

[2] Quinn, T.J. *Base Units of the SI, their Accuracy, Dissemination and International Traceability.* Metrologia. 1994/5, **31**, 515-527.

[3] Kletke, R., *Predicting 10Vdc Reference Standard Output Voltage,* Proc. 1998 NCSL Workshop & Symposium, 615-622.

[4] Witt, T.J. *Measurements of the temperature dependence of the output voltages of some Zener diode based voltage standards.*, IEE Proc.-Sci. Meas. Technol., **145**, No.4, July 1998.

[5] Witt, T. J. *Pressure Coefficients of some zener-diode based electronic voltage standards.* Bureau International des Poids et Measures

[6] Aprelev A.V., *Effect of Power Supply Failure on the Metrological Characteristics of Solid-State Voltage Standards.*. Measurement Techniques, **39**, No.12, 1996 , 1221-1224

[7] Witt, T.J. (1997) *Low-frequency spectral analysis of dc nanovoltmeters and voltage reference standards.* IEEE Trans. on Instru. and Measurement, **46**, pp 318-321.In: 1999 National Conference of Standards Laboratories conference digest pp 111-118.

In: National Conference of Standards Laboratories 1999 workshop and symposium conference proceedings, July 11-15 pp 111-118.

# Characterisation of Zener-diode-based electronic voltage standards.

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## Abstract

In order to make optimum use of a group of Zener-diode-based electronic voltage standards as a laboratory standard for emf, it is necessary to characterise the individual standards in terms of temporal drift and the effects of environmental influences. An experimental set-up for the measurement of the temperature and pressure coefficients of electronic voltage standards is described and the results obtained for a number of commercial electronic voltage standards presented. The improvement in the overall accuracy of the group standard resulting from applying temperature and pressure corrections using derived coefficients is given.

## 1. Introduction

Nowadays most national metrology institutes of the industrialised world employ Josephson Array Voltage Standards (JAVSs) as their primary reference standard for dc voltage. Secondary, electronic voltage standards (EVS), based on Zener-diodes are used mainly as travelling standards for interlaboratory calibrations and as transfer standards for Josephson comparisons. However, some national metrology institutes as well as advanced industrial laboratories use EVSs as a reference standard to maintain their local representation of the volt for periods of up to one year between comparisons with external primary standards. The National Metrology Laboratory (hereafter referred to as NML) in Dublin, Ireland, is one such national metrology institute.

The NML maintains the Irish national measurement standard for emf using the mean of an ensemble of commercially available EVSs comprising the following : Fluke (732A/B), Datron/Wavetek (4910) and Guildline (4410). The national standard is maintained at 10V and the validity of the ensemble mean is assured through regular bilateral comparisons with the Bureau International des Poids et Mesures (BIPM). Measurements in the range 0-10V are carried out using a potentiometer which operates on the binary divider principle and which is standardised against the 10V reference group. These facilities are used to support a dc V calibration workload consisting of voltage reference devices, high accuracy calibrators and voltmeters.

One significant feature of EVSs is that unlike JAVSs they exhibit temporal drift, short and medium-term noise and are susceptible to environmental influences such as temperature, pressure and humidity.[1] In order for the NML to achieve the lowest possible uncertainties, corrections must be made, where possible, to the output values of each of its references to account for these influences. Consequently the relevant sensitivities of each of the individual EVSs comprising the ensemble standard needs to be determined.

## 2. EVS Output Characteristic Model

A functional relationship describing the output of any of the EVSs is required, and a simple expression of the form given in equation (1) has been found to suffice:

$$U_{ref} = a + \alpha_t (t-t_0) + \alpha_p(p-p_0) + \alpha_T(T-T_0) + \alpha_H + \Phi \text{ - (1)}$$

where;

$U_{ref}$ is the value assigned to the output of a reference EVS at any time t, pressure p, and ambient temperature T,
a is the regression offset term,
$\alpha_t$ is the temporal coefficient of the EVS,
$\alpha_p$ is the pressure coefficient of the EVS,
$\alpha_T$ is the temperature coefficient of the EVS, and
$t_0$, $p_0$ and $T_0$ are reference values of time, temperature and pressure.
$K_H$ is a correction term due to changes in ambient humidity, and
$\Phi$ is a correction term to allow for random changes in the EVS output not attributable to any outside influence.

$K_H$, the effect due to changes in relative humidity is not considered here as all EVSs studied have been maintained in laboratories with relative humidity control and none of the NML reference EVSs show any detectable correlation with variations in relative humidity. Where humidity effects are found to exist, it has been suggested that the response of the EVS to changes in relative humidity is exponential, with time constants of the order of 3 weeks.[1] The correction term to be applied is therefore not a simple function of the prevalent relative humidity.

The results of measurements made on the temperature sensitivities of the NML group were not available at the time of writing this paper and will be made available at a later date. The methods used to establish temporal and pressure sensitivities for the NML ensemble are outlined below.

### 3. Temporal Behaviour

The temporal drift of the NML ensemble is accounted for by regression analysis of calibration points obtained for each of the EVSs over a number of years through bilateral comparisons with the BIPM A group (up to three) EVSs belonging to the BIPM is used as a travelling standard for a bilateral comparison. Prior to shipping these standards to NML, the output of each EVS is characterised for temporal drift by the BIPM against its JAVS. The pressure and temperature coefficients of each member of the travelling standard group are also known. On arrival at the N.M..L. and after a suitable settling period NML carries out a series of measurements on the travelling group against its own EVS ensemble whose mean value at the time has been obtained by applying equation (1) to each member of the ensemble. After the NML measurements have been completed (typically 2-3 weeks) the travelling group is shipped back to BIPM where further measurements are carried out against the JAVS. BIPM then assigns values to the travelling standards on the mean date of the intercomparison schedule based on the measurements made pre- and post-shipment. NML also assigns values to the travelling standards on the mean date based on its measurements. The comparison is illustrated graphically in Fig. 1. Typically the total standard uncertainty associated with the measured difference $\Delta V$ is 0.25ppm.[2]

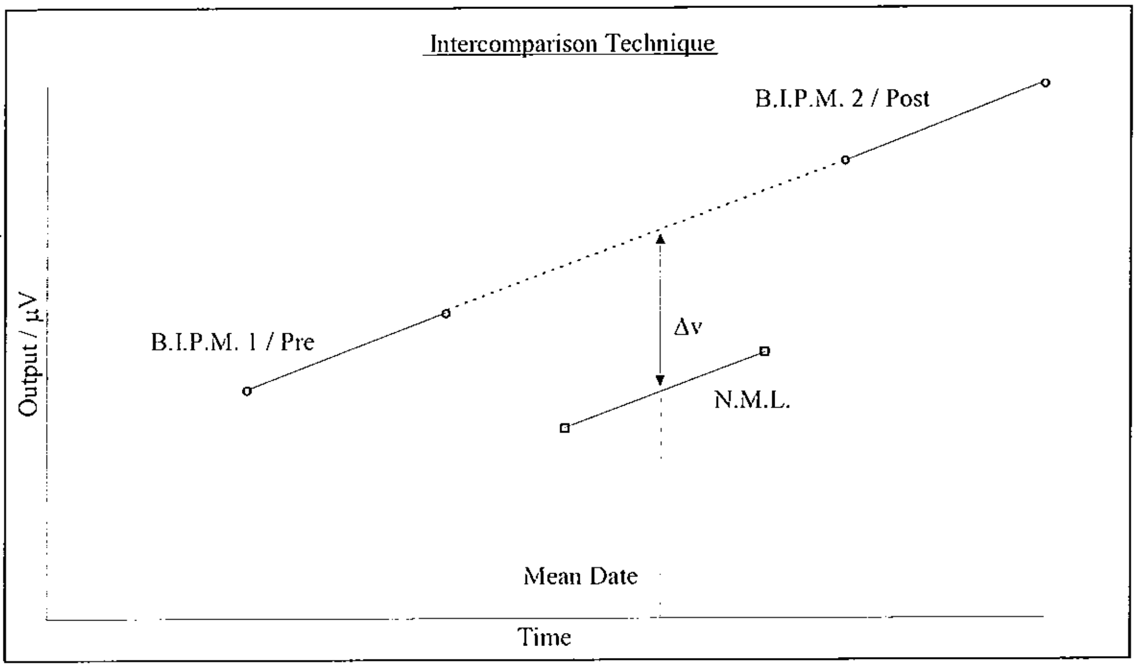


Fig. 1. Bilateral Comparison of DC Voltage (BIPM - NML)

The difference between the two values on the mean date (ΔV), is an indication of how well the NML ensemble is maintained w.r.t. the BIPM primary standard. This difference, together with its associated uncertainty is reported in the literature [3], and is a public statement of the equivalence of the N.M.L reference standard for emf to an international standard. The magnitude of ΔV is an indication of the validity of the models used to predict the output of the individual NML EVSs. Based on the results of the bilateral comparison the output models for the individual NML reference EVSs are adjusted as necessary. The bilateral comparison also allows the assignment of an additional value to the regression models of the individual EVSs which is directly traceable to the BIPM JAVS.

Least-squares parameter estimation techniques based on the bilateral comparison results are used to obtain values for the regression offset term (a) and the temporal coefficient ($\alpha_t$) for the individual EVSs of the ensemble. These are then used to predict values for the ensemble mean in the intervening time period and techniques similar to those described in [3] are used in the uncertainty estimation.

Since, for practical reasons, bilateral comparisons are only carried out annually, NML requires some other method of assuring the validity of the value assigned to the mean emf of its reference group at intermediate times. This is achieved through internal intercomparison of the individual EVSs, which is carried out on a regular basis. This method allows the detection of abnormal deviations (from regression predictions), of individual group members and may even lead to certain EVSs being removed from the ensemble altogether if the behaviour so warrants. The agreement obtainable for some EVSs of the ensemble, between that observed (through group intercomparisons), and that predicted (through regression analysis) can be of the order of 0.1ppm over a 12 month period. Fig. 2 shows the behaviour of the 10V output of one of the NML EVSs (Datron 4910) over approximately 5 years with values assigned from bilateral comparisons and the NML intercomparisons showing satisfactory agreement. The graph also indicates the medium term stability of this device, in other words, the variation of the correction term Φ in equation (1).

Work is currently underway at NML to determine the uncertainty associated with the observed value of the references at intermediate dates between bilateral comparisons by applying the principles of the ISO Guide to the Expression of Uncertainty in Measurements to the available data.

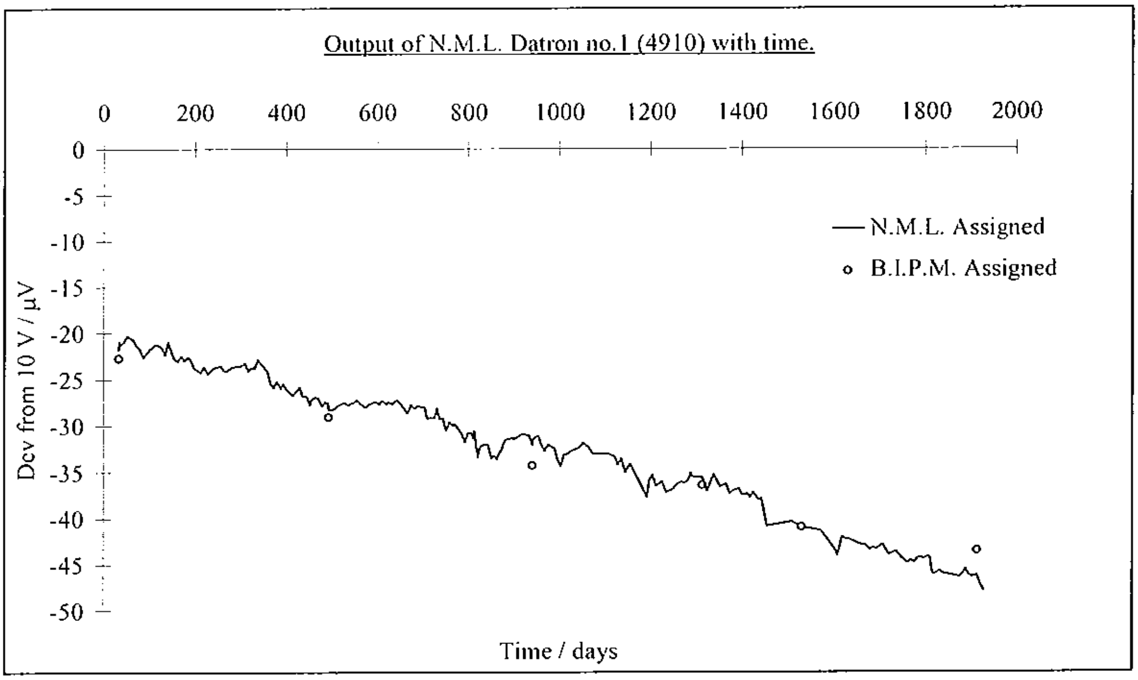


Fig.2 Typical temporal behaviour of EVSs (Datron 4910)

## 4. Pressure Sensitivity of EVS

Pressure sensitivities of certain EVSs first came to our attention at NML following a series of measurements which coincided with a natural change in atmospheric pressure of the order of 50 hPa during a 48 hour period. This effect had, of course, already been reported in the literature [5].

In order to investigate the effect experimentally a sealed cylindrical chamber 50cm in diameter and 80 cm long has been constructed.. The temperature within the chamber is maintained constant by means of a coil through which temperature controlled oil is circulated and a small fan to ensure sufficient air circulation. The chamber is also fitted with electrical feedthroughs to allow signal leads, power leads etc. inside the chamber and provisions are also made to connect a pump and barometer. A schematic representation of the experimental set-up is shown in Fig. 3.

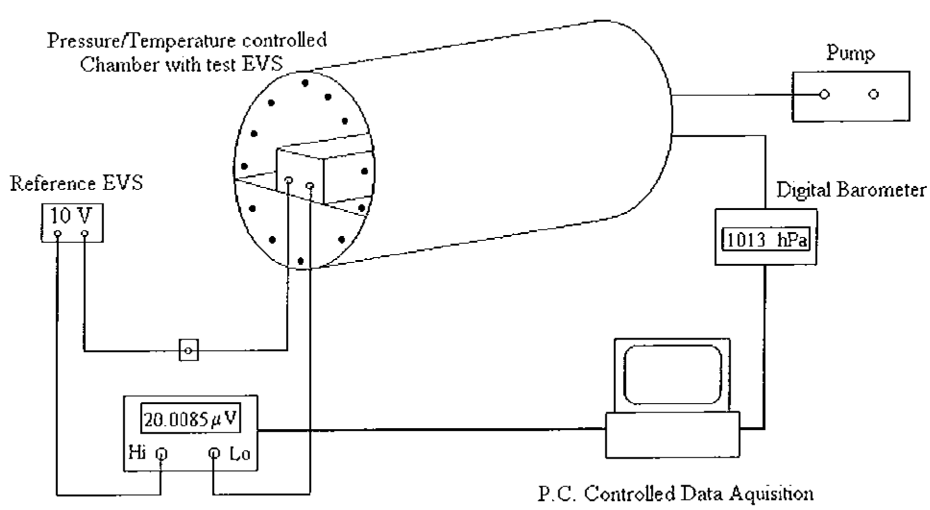


Fig. 3 Schematic of set-up used for determining pressure/temperature coefficients of EVSs.

In a typical measurement run the pressure inside the chamber is changed in a stepwise fashion in steps of 50 hPa and the corresponding difference in emf between the EVS under test and the reference EVS is measured. The pressure is stepped down and then back up to eliminate correlation between EVS output and time. The voltage difference and pressure data from a typical run for a Fluke 732B dc reference standard is illustrated in Fig. 4. Differences in emf were measured using a HP-34420A nano-voltmeter and pressure was recorded using a Druck digital barometer. All data acquisition was done using LabVIEW® data acquisition software. The reference EVS is kept in a temperature/humidity controlled enclosure and zener temperature of both test and reference units are monitored using their own oven thermistors. Temperature stability for both reference and test units during a test run is of the order of 10mK as measured by the oven thermistors and using the temperature sensitivities of the thermistors given by the manufacturer[6] [7]. This same experimental set-up will be used to determine the temperature coefficients of the EVSs by varying temperature inside the chamber while keeping the pressure constant and recording the corresponding change in EVS output.

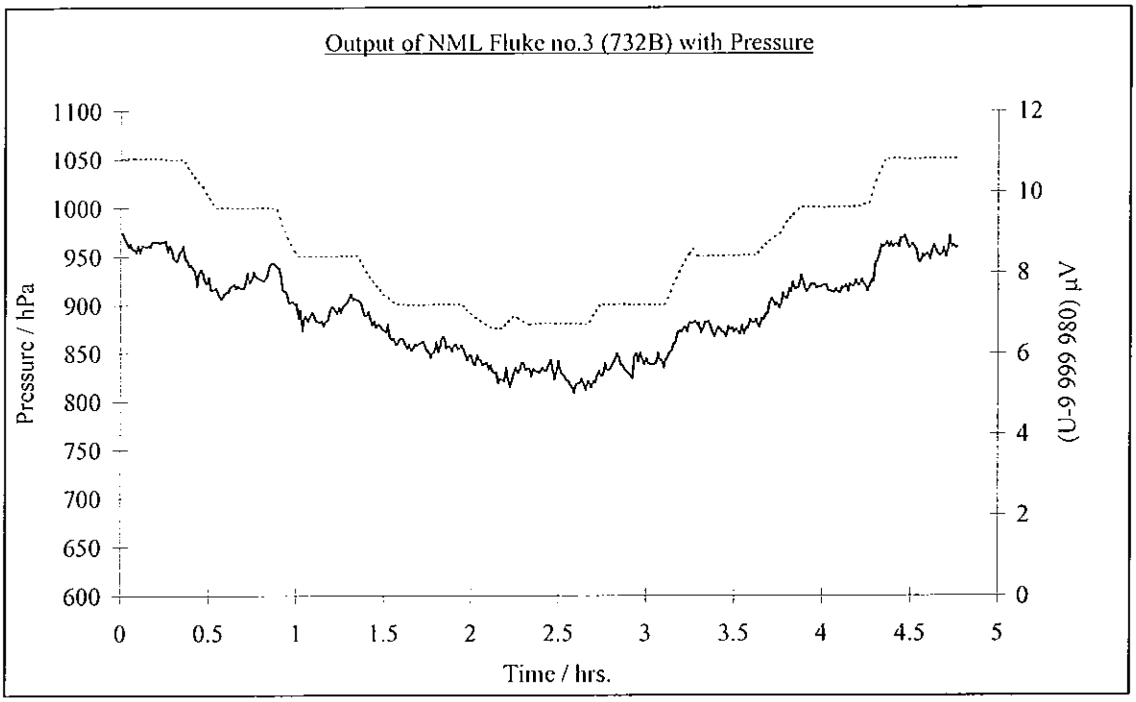


Fig. 4. Output of NML Fluke no.1 (732B) as a function of pressure

The EVS output shown in Fig.4 has a pressure coefficient dU/dP of 18nV/hPa equivalent to 1.8ppb at the 10V level with a type A standard uncertainty of 0.5nV/hPa. This 732B unit contains a L-type zener reference which has a more significant pressure coefficient than the M-type zener references used in earlier Fluke reference devices.[5] The relevant Fluke literature on the pressure dependence of the 732B reference EVS is given in terms of an altitude effect but the advantages of pressure coefficients instead has been outlined in [5]. Other EVSs studied thus far have shown smaller pressure coefficients ranging from zero to to -2.9nV/hPa.

## Conclusions

The importance of applying all known corrections to the output of an EVS in order to obtain the best possible accuracy has been demonstrated. In the case of the EVSs which form the ensemble standard of NML the methods used to determine the corrections due to temporal drift and ambient pressure have been outlined. Some EVSs have been found to drift in a predictable fashion and the results of regular bilateral comparisons with BIPM have demonstrated the validity of the prediction models used. However, short-term unpredictable behaviour of the EVS output needs to be accounted for by means of regular internal intercomparisons of the members of the ensemble. The effect of ambient pressure variations, though small, is still significant at the level of accuracy sought. Of the EVSs studied thus far the Fluke 732B reference unit has been found to have the largest pressure coefficient. Once the temperature coefficient data for the EVSs become available a complete and individual model for the output of each EVS of the ensemble will be available and the accuracy of the realisation of the local voltage standard will be considerable improved.

## References


1. Witt, T.J. *The stability of some Zener-Diode-Based Voltage Standards*, IEEE Transactions on Measurement and Instrumentation, 44 April '95 pp 226-229.

2. Witt et al, *Bilateral Comparison of 10V and 1.018V Standards between the NML and the BIPM*, April 1998. Rapport BIPM-98/14.

3. Quinn T.J., Metrologia, 1996 33 p278.

4. Ketke, Raymond, D. Predicting 10VDC Reference Standard Output Voltage, 1998 NCSL Workshop and Symposium. pp 615-621.

5. Witt, T.J. Pressure Coefficients of some Zener-Diode-Based Electronic Voltage Standards, Conference on Precision Electromagnetic Measurements (CPEM) 1998.

6. Fluke 732B DC Reference Standard, Instruction Manual, Fluke Corporation.

7. Fluke 732A DC Reference Standard, Instruction Manual, Fluke Corporation.

In: 1999 British Electromagnetic Measurement Conference, Conference Digest, pp 7/1-7/4. Also submitted to Institute of Electrical Engineers, Proceedings-Science, Measurement, Technology Journal.

# Determination of the Pressure Coefficients of Electronic Voltage Standards

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Oliver Power (National Metrology Laboratory)
James Walsh (Dublin Institute of Technology)

## Abstract

Electronic voltage standards, based on zener diode reference elements, are widely used as standards to maintain a local representation of the voltage unit and as transfer standards for comparisons between local voltage reference standards at different locations. In order to make optimum use of such standards, it is important that individual units be characterised for the effects of external influence factors so that the appropriate corrections can be applied. Ambient atmospheric pressure affects the outputs of some EVSs. An experimental set-up to measure the pressure coefficient of an EVS is described and the results obtained for a range of commercial electronic voltage standards presented.

## Introduction

Although the availability of electrical measurement standards based on quantum phenomena has provided metrology laboratories with an almost ideal method of maintaining a local representation of the electrical units, many secondary laboratories continue to use artefact standards for this purpose. In the case of dc voltage, electronic voltage standards based on a zener-diode reference element are the artefact of choice. An ensemble standard, comprising a group of such electronic voltage standards, is widely used to maintain a local dc voltage standard.

Such, modern electronic voltage standards, being both portable and rugged, are also ideal for use as travelling standards when transferring traceability from a higher echelon laboratory or when comparing local voltage reference standards at different locations.

Although not nearly as sensitive to external influence factors as its predecessor, the electrochemical standard cell, the output e.m.f. of an EVS is nonetheless sensitive to several external factors. Whether used as a local reference standard or as a transfer device the effect of these influence factors on an EVS must be taken into account by measuring the influence factor and applying the appropriate correction to the EVS output. The correction will only be accurate provided the sensitivity coefficient of the EVS output to the influence factor is known for the individual EVS.

The main factors which influence the output e.m.f. of an EVS are time[1], ambient temperature[2,3], ambient humidity[4], ambient pressure[5], internal noise[2,4] and external electromagnetic fields. This paper describes the determination of the sensitivity coefficients of a number of commercial EVSs to ambient pressure.

## Measurement Set-up

A pictorial of the measurement set-up is shown in figure 1.

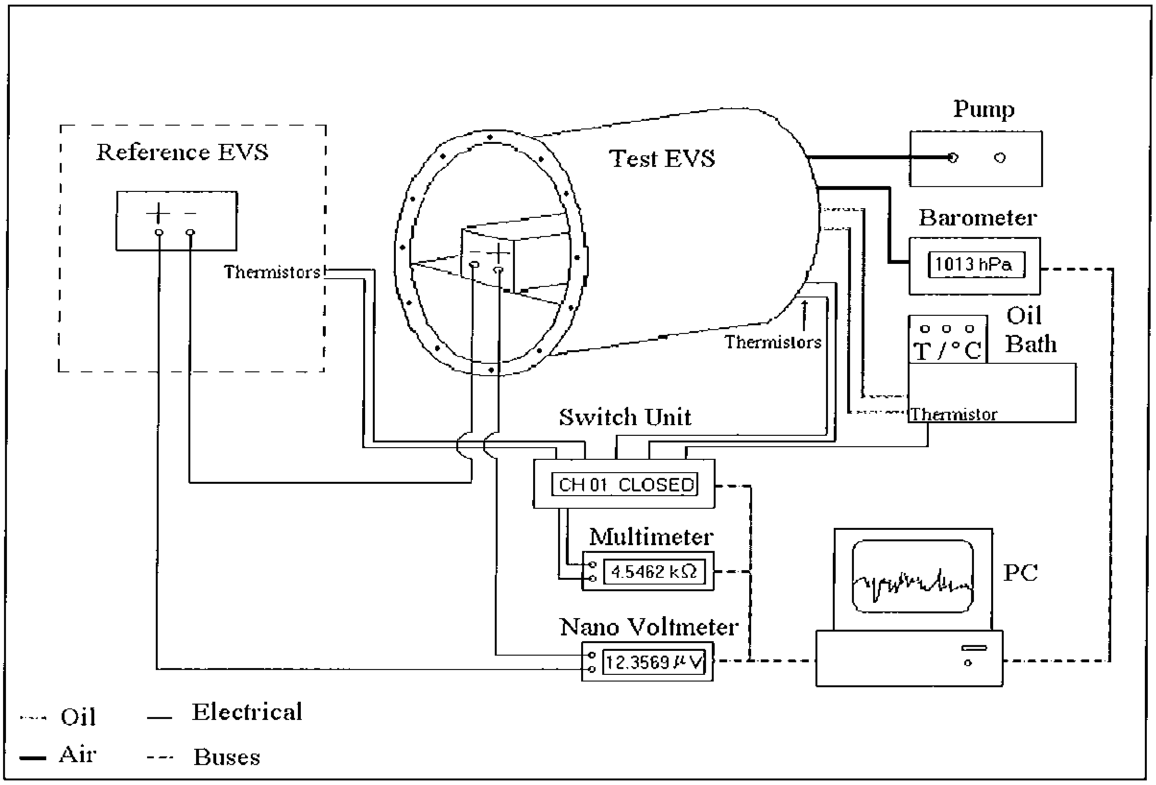


Figure 1: Pictorial of experimental set-up.

A sealed cylindrical chamber, 50cm in diameter and 80cm long, is used as the test vessel to house the EVS under test. The pressure within the chamber is set and maintained by means of manual valves and a small diaphragm pump and is measured by a digital barometer. With this set-up it is possible to maintain the pressure within the chamber constant to within 1hPa over several hours .

The temperature within the chamber is maintained constant by means of a heat exchanger through which temperature controlled oil is circulated. A small internal fan is used to ensure adequate air circulation. The air temperature within the chamber is monitored using a thermistor and when the EVS under test is fitted with an internal thermistor, this is also monitored. For various loads (depending on EVS unit), typical temperature stability during measurements was 10mK.

The chamber is fitted with electrical feedthroughs to allow signal leads, power leads etc. inside the chamber. The change in the output e.m.f. of the EVS under test was measured by comparing it to the output of a reference e.m.f. maintained in controlled conditions outside the chamber. The voltage difference ($\Delta U$), was measured using a digital nanovoltmeter. All data acquisition was done using LabVIEW®.

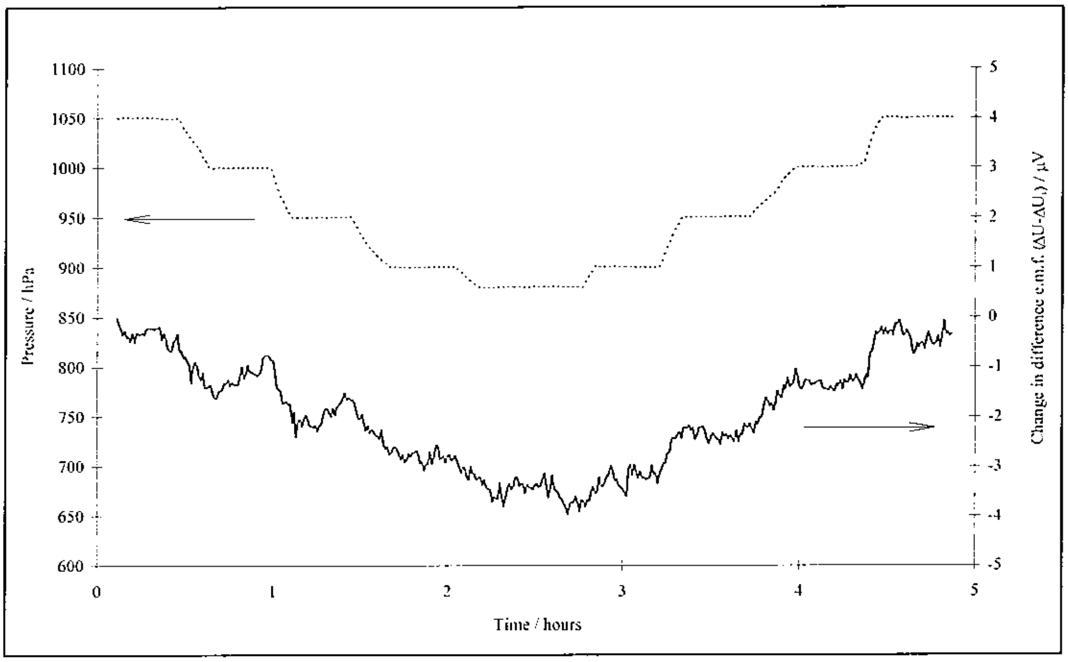


Figure 2: Typical pressure coefficient measurements on Fluke 732B EVS.

For a typical measurement run, the pressure inside the chamber is changed in a stepwise fashion in steps of 50hPa. At any pressure $p$, the e.m.f. difference between the test and reference EVS outputs ($\Delta U$), is determined with respect to the difference e.m.f. at an arbitrary initial pressure $p_i$, ($\Delta U_i$). Therefore, the change in ($\Delta U$-$\Delta U_i$) can be attributed to the effect of pressure variation on the EVS under test. The pressure is stepped down and then back up so as to allow the detection and elimination of the effects of any significant temporal drift of the e.m.f.s. The total measurement cycle time of some 5 hours is short enough however, so that no temporal drift effect was detected. Figure 2 shows the pressure and e.m.f. data for a typical measurement run. By averaging the change in difference e.m.f. and pressure for each plateau, a set of data pairs consisting of the pressure and the corresponding EVS output e.m.f. are obtained, which can be used to determine the pressure coefficient of the EVS output by fitting a line to the data.

## Measurement Results

The pressure coefficients of the 10V output of five types of commercially available EVSs were measured. The results obtained are given in Table 1 together with their type A standard uncertainties.

| EVS Type | Zener Type | Pressure Coefficient $\alpha_p$ (nV/hPa) | $U_A$ (nV/hPa) |
|---|---|---|---|
| Fluke 732A | Motorola | -3.0 | 0.23 |
| Fluke 732B | Linear Technology | +18.1 | 0.45 |
| Datron 4910 | LTZ1000 | -7.1 | 0.74 |
| Guildline 4410 | LM329AII (LT) | -15.1 | 0.61 |
| Datron 7001 | LTZ1000 | -4.4 | 0.82 |

Table 1: Pressure coefficients of EVS units studied.

The uncertainty associated with the pressure coefficients is dominated by the scatter of the data points about the best-fit line and is quantified by the type A standard uncertainty listed in table 1. Since all quantities used in the evaluation of the pressure coefficients ($\alpha_p$), are obtained from difference measurements, uncertainty components arising from systematic effects in the voltage and pressure measurements can be neglected because of negative correlations.

All units studied were found to have statistically significant pressure coefficients. The Fluke 732A unit showed the smallest pressure coefficient of all the units studied. The 732A uses a zener reference supplied by Motorola, whereas the zener references for the other units were supplied by Linear Technology[6]. There are however significant differences in the pressure coefficients determined for these latter units (from +18 nV/hPa to -15nV/hPa). This suggests that the pressure coefficient of an EVS may be dependent on circuit elements other than the zener itself or may be sensitive to the manufacturing process of the zener.

## Conclusion

An experimental set-up to measure the pressure coefficient of the output e.m.f. of electronic voltage standards has been described. Five types of commercially available EVSs have been tested and have been found to have pressure coefficients ranging from +18 nV/hPa to -15 nV/hPa for the 10 V output. The standard uncertainty of the measured pressure coefficients, which is dominated by the type A uncertainty component, is of the order of 0.6 nV/hPa. The corresponding pressure correction to be applied to an EVS output would be of the order of 0.05ppm for typical local atmospheric pressure variations. A correction due to pressure changes with altitude would be of the order of 0.2 ppm in the case of the Guildline 4410 and Fluke 732B, for altitude changes of 1000m. The results detailed above illustrate the need to determine pressure coefficients of EVSs where the highest measuring accuracy is sought.

**References**


1. Kletke Raymond D, 'Predicting 10 V DC Reference Standard Output', 1998 NCSL Workshop and symposium, pp 615-621.
2. Witt T.J., 'Low-Frequency Spectral Analysis of DC nanovoltmeters and voltage Reference Standards', IEEE Transactions on Instrumentation and Measurement, **46** (2), pp 318-321.
3. Witt T.J., 'Measurement of the temperature dependence of the output voltages of some Zener diode based voltage standards', IEE Proc.-Sci. Meas. Technol., **145** (4), pp 154-158.
4. Witt T.J. et al, 'The stability of Zener-Diode Based Voltage Standards', IEEE Transactions on Instrumentation and Measurement, **44** (2), pp 226-229.
5. Witt Thomas J., 'Pressure Coefficients of some Zener-Diode Based electronic voltage standards', presented at CPEM 1998.
6. Private communications with Guildline, Fluke and Wavetek (Datron).

# Appendix B. Glossary of selected terms

**BIPM: Bureau International des poids et Mesures:** International metrology institute located in Sèvres, France, established under the Convention du Mètre, whose role is to ensure world-wide uniformity of measurements through its various activities.

**Bilateral Comparison:** An interlaboratory comparison where the number of participating laboratories is two.

**Block Diagram:** Source code for LabVIEW® virtual instruments, constructed using graphical programming concepts.

**Electrochemical Standard Cell:** An electrochemical cell devised to produce a stable e.m.f. The most common type is the Weston saturated cell, which contains an electrode of mercury in contact with a paste of mercurous sulphate, and an electrode of cadmium amalgam in contact with a solution of cadmium sulphate.

**EVS: Electronic Voltage Standard:** DC voltage standard based on Zener-diode reference elements, used primarily for maintaining a local representation of the SI volt in secondary laboratories and as travelling standards for interlaboratory comparisons.

**Expanded Uncertainty:** A measure of uncertainty that defines an interval about a measurement result that can be expected to encompass a large fraction of the values that could reasonably be attributed to the entity being measured. It is denoted by $U$ and is obtained by multiplying the standard uncertainty by an appropriate *coverage factor*, $k$.

**Front Panel:** Graphical user interface of virtual instrument written in the LabVIEW® environment with control knobs, displays etc.

**Interlaboratory Comparison:** A comparison process between at least two laboratories, where the measurement capabilities of the laboratories are compared by the analysis of measurements made by each laboratory on one or more travelling standards.

**ISO: International Organization for Standardization:** Worldwide federation of national standards bodies from some 130 countries, whose mission is to promote the development of standardization and related activities. Publishers of the *Guide to the expression of uncertainty in measurement*, which establishes general rules for evaluating and expressing uncertainty in measurement that are intended to be applicable to a broad spectrum of measurements.

**Josephson Voltage Standard:** DC voltage reference standard based on the quantum ac Josephson effect, used in many primary laboratories to maintain a local representation of the SI volt.

**LabVIEW®:** Program development environment based on a graphical programming concept used for instrument control, data acquisition, data analysis, data presentation and data storage.

**NML: National Metrology Laboratory:** Irish national metrology institute, responsible for the maintenance, development and dissemination of the national measurement standards for Ireland.

**ppm: Parts per Million:** Expression widely used in the metrology field to express stabilities, changes and uncertainties relative to some nominal value, 1 ppm = 1 part in $10^6$.

**Standard Laboratory Conditions:** Specified temperature and humidity values at which electrical standards laboratories are maintained, usually 23 °C and 40% relative humidity.

**Standard Uncertainty:** A statistical expression used to quantify the uncertainty of the results of a measurement expressed as a standard uncertainty.

**SI: Système International:** Internationally agreed unit system, established under the Convention du Mètre, comprising 7 base units and a set of derived units for measurement of physical quantities.

**Temporal Regression Parameters:** The slope and intercept of the linear temporal drift equation, used to characterise and predict the temporal behaviour of individual EVS units, of the NML ensemble reference standard.

**Travelling Standards:** EVS units, which are used as, transfer devices during interlaboratory comparisons.

**Type A evaluation:** Method of evaluation of uncertainty by means of statistical analysis of experimental data. The result is sometimes referred to as the type A standard uncertainty.

**Type B evaluation:** Method of evaluation of uncertainty using other available knowledge other than the statistical analysis of experimental data.

$U_{BIPM}$: The value ascribed by the BIPM to the output voltage of a travelling standard on the mean date of a bilateral comparison.

$U_{NML}$: The value ascribed by the NML to the output voltage of a travelling standard on the mean date of a bilateral comparison.

**Unknown EVS:** An EVS unit whose output voltage value is not known and is estimated by comparison with the EVS units of the NML ensemble reference standard. Examples of unknown units are travelling standards used in interlaboratory comparisons, NML client laboratories' EVS units or NML EVS units no longer used to maintain the reference standard.

$V_{BIPM}$: The true, but indeterminable value of the BIPM laboratory reference voltage standard.

$V_i$: The true, but indeterminable value of the output voltage of the $i^{th}$ unit, of the NML ensemble reference standard.

$\hat{V}_i$: The value of the output voltage of the $i^{th}$ unit, of the NML ensemble reference standard estimated using its temporal regression parameters.

$V_i$: The observed or measured value of the output voltage of the $i^{th}$ unit, of the NML ensemble reference standard.

**VI: Virtual Instrument:** Program written in the LabVIEW® environment whose appearance mimics that of a physical measuring instrument.

$V_{NML}$: The true, but indeterminable value of the NML laboratory reference voltage standard. This is equal to the mean voltage of the ensemble of EVSs, which comprise the standard.

$\hat{V}_{NML}$: The estimated value of the NML laboratory reference voltage standard.

**VRMP: Voltage Reference Maintenance Program:** Commercially available software package used at NML to carry out measurements during interlaboratory comparisons and within-group comparisons.

$\hat{W}_i$: The value of the output voltage of the $i^{th}$ unit, of the NML ensemble reference standard, as estimated from within-group comparison results.

**Within-Group Comparison:** Measurement process carried out between individual units of the NML ensemble reference standard in order to estimate the output voltage of each unit with respect to the mean of the group.

$\hat{W}_x$: The estimated value of the output voltage of an unknown EVS unit, determined from measurements against the NML reference standard using the VRMP.

**Zener-Diode:** Discrete electronic component, based on a reverse biased p-n junction used to provide a constant output voltage in commercially available electronic voltage standards.