# THE NBS OHM
# PAST - PRESENT - FUTURE

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## ABSTRACT

A brief history is given of the NBS Ohm commencing from the establishment of the NBS in 1901 to the present. It includes a description of the resistance standards and measurement methods used to maintain the NBS Ohm during its 85-year history. Indications of the drift of the NBS Ohm based on absolute-ohm determinations and quantized-Hall effect measurements are presented. The results of these measurements may lead to an adjustment of the value of the NBS Ohm in 1990.

## INTRODUCTION

The establishment and maintenance of the unit of resistance for the United States is the responsibility of the National Bureau of Standards (NBS). This legal unit as maintained at NBS will be referred to as the NBS Ohm. Since the establishment of the NBS in 1901, the value of the NBS Ohm has been adjusted only once, and that was in 1948 when the NBS Ohm was reassigned using a conversion factor relating the international ohm to the best experimentally realized value for the defined "absolute" ohm. The practical metric system of defined units that has been adopted internationally is the Systeme International (SI), and the derived absolute unit of resistance in this system will be referred to as the SI ohm. The NBS Ohm is the U.S. representation of the SI Ohm. A second adjustment in the value of the NBS Ohm is planned for 1990 as a result of improved realizations of the SI ohm by NBS and other national standards laboratories.

Since 1901, the NBS Ohm has been maintained at the 1-Ω level by a select group of manganin resistance standards. Four different types of resistance standards have represented the reference group. The size of the group has varied from 5 to 17 resistors. The mean value of the reference group was in each case assumed to remain constant. Recent absolute-ohm determinations and quantized-Hall effect (QHE) measurements indicate that this is not true. Although the NBS Ohm is not constant, it has been remarkably stable throughout its 85 years of existence. During this period, the NBS Ohm has changed less than 10 ppm, neglecting the conversion factor of 1948.

## HISTORICAL DEVELOPMENT

When the National Bureau of Standards was established in 1901, the legal unit of resistance for the United States was based on the mercury ohm as defined in Public Law #105 enacted by the US Congress in 1894. This action was taken in accordance with the recommendation of the 1893 International Electrical Congress held in Chicago. At the time precise realizations of the mercury ohm were being carried out in Germany and England. It was not until 1911 that the first NBS determination of the mercury ohm was completed [1]. Consequently, during the early years of NBS, the unit of resistance was maintained by a group of Reichsanstalt-type resistance standards whose values were based on mercury-ohm determinations at the Physikalisch-Technische Reichsanstalt (PTR) and the National Physical Laboratory (NPL).

An International Conference on Electrical Units and Standards was held in London in 1908 for the purpose of adopting a system of international electrical units that was the best approximation of the state-of-the-art realization of the electrical units in absolute measure. The London conference also set up a Technical Committee of representatives from NBS, PTR, NPL, and LCE (France) that met at NBS-Washington in 1910 for an international comparison of the ohm. The measurements by the Technical Committee were based on the average of mercury-ohm determinations at PTR and NPL, and the results indicated that the NBS Ohm was less than the accepted value for the International Ohm by 7 ppm. This difference was small in comparison to the uncertainties associated with the absolute-ohm experiments of the time, and therefore, no adjustment to the NBS Ohm was made. At this time the NBS Ohm was maintained by a group of sealed resistance standards developed by Rosa in 1908 [2]. Beginning in 1928, Thomas constructed a number of 1-Ω resistance standards of the "double-walled" type. In 1932 the Rosa-type standards in the primary group were replaced by the Thomas type made with a coil diameter of 6 cm [3]. Subsequently, these were replaced in 1939 by a group of larger Thomas-type standards constructed in 1933 with a resistance coil diameter of 8 cm [4]. At present, five of the original Thomas-type resistance standards constructed in 1933 are still being used to maintain and disseminate the NBS Ohm.

Good agreement between absolute-ohm experiments at NPL in 1914 and at PTR in 1920 indicated that the absolute ohm was less than the international ohm by about 500 ppm [5]. Improved absolute-ohm determinations during the period from 1936 to 1939 by NBS, NPL, PTR, LCE, and ETL (Japan) substantiated this finding [6]. The weighted mean of the results of these experiments indicated that the absolute ohm was 490 ppm smaller than the international ohm. An international committee recommended the abandonment of the mercury ohm and the return to the absolute ohm as the basic unit as of January 1, 1940. Because of the war the change was not made until January 1, 1948. During 1946, international ohm comparisons indicated that the NBS Ohm at that time was 2 ppm less than the mean international unit as maintained at BIPM, the International Bureau of Weights and Measures. Since no adjustment was made in 1910, this meant that the as-maintained NBS Ohm was decreased by 495 ppm in order to conform to the agreed upon international value for the absolute ohm. In other words, the value of all NBS resistance standards was increased by 495 ppm on January 1,1948. This has been the only adjustment to the NBS Ohm since the establishment of the NBS in 1901. Public Law #617 enacted by the US Congress in 1950 redefined the unit of resistance in terms of absolute units, eliminating the reference to the mercury ohm.

## RESISTANCE STANDARDS

Until 1948, the international ohm was defined in terms of the reproducible mercury ohm. However, wire-wound standards were and still are used to maintain the unit of resistance at NBS. The different types of wire-wound resistance standards used to maintain the NBS Ohm from 1901 to the present day were developed to have improved stability with time and temperature.

### Mercury Ohm

The mercury ohm was proposed by Siemens in 1860 and soon became adopted internationally. Mercury was chosen because it could easily be purified, and compared to other suitable pure metals it had a much higher resistivity (94 $\mu\Omega$-cm) and a lower temperature coefficient of resistance or TCR (880 ppm/K). As a reproducible standard of resistance, it was defined as a column of pure mercury of specified mechanical dimensions at a specified temperature. The dimensions of the mercury column were twice modified (1881 and 1893) to bring the mercury ohm into closer agreement with the absolute ohm. The US Public Law of 1894 stated that "the unit of resistance is represented by the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 g in mass, of a constant cross-sectional area of a length of 106.300 cm." Realization of the mercury ohm was a difficult two-part experiment. The first consisted of filling a tube with mercury for the resistance measurements, and the second of refilling the tube under the same conditions for the determination of the mass. Uncertainties associated with the non-uniformity of the bore, temperature of the mercury, and the end lead effects, limited the accuracy of the realization of the international ohm in terms of the mercury ohm to about 20 ppm. The values of resistance originally assigned to the first NBS wire-wound resistance standards were in terms of mercury-ohm determinations made at PTR and NPL. The only mercury-ohm determinations at NBS were done in 1911 and 1912 and the results agreed with the PTR-NPL results to within 20 ppm [1]. This was considered to be a check within the limits of uncertainty of the mercury ohm, and the values to the NBS wire-wound resistance standards were not changed. Agreement to within 10 ppm of absolute-ohm determinations at NPL in 1914 and at PTR in 1920 by entirely different methods led to the abandonment of the use of the mercury ohm.

### Manganin Standards

The early research on zero TCR resistance alloys during the 1880's by Weston of the US and Feussner of Germany led to the development of manganin by 1890 [7]. Its modern composition is approximately 84% Cu, 12% Mn, and 4% Ni. Manganin has a resistivity of about 48 $\mu\Omega$-cm and a thermal emf to copper of < 3 $\mu$V/K. Its TCR can be reduced to zero at room temperature by proper heat treatment; however, the curvature of its resistance/temperature curve at room temperature is approximately -0.5 ppm/$K^2$. It is subject to surface oxidation and has a significant pressure coefficient of resistance.

Manganin was used in the construction of the Reichsanstalt, Rosa, and Thomas types of resistance standards that have maintained the NBS Ohm since 1901.

Reichsanstalt Type - This type of resistance standard using manganin material was first described by Feussner in 1890 [8]. It is constructed with silk-covered manganin wire wound bifilarly on a brass cylinder that previously was covered with silk, and coated with shellac varnish in order to obtain good insulation. The unit is then baked at 140 °C for 24 hours. After the baking, copper wires are silver-soldered to the manganin, and these copper wires are soft-soldered to heavy copper terminals. This assembly is mounted on a hard-rubber top, to which is attached a perforated metal can for protecting the winding, yet permitting air or oil to circulate over the shellacked surface.

From 1901 to 1909, the NBS Ohm was maintained by a group of Reichsanstalt-type resistance standards made in Berlin by the firm of Otto Wolff. The values of these standards were based on measurements made at PTR; hence, the unit of resistance for NBS during this period was that of PTR. As best as it can be discerned, up to 1907 the mean of five 1-Ω Reichsanstalt-type resistors constituted the NBS Ohm. From 1907 until May 1909, the mean of ten 1-Ω and seven 0.1-Ω Reichsanstalt-type resistors carried the unit forward.

Rosa Type - Measurements at NBS indicated that the Reichsanstalt type of resistor underwent changes in resistance as a function of seasonal variations in atmospheric humidity. To cure the problem, Rosa developed a sealed resistance standard in 1907 [2]. The materials, construction, and heat treatment of the coil assembly of the Rosa-type resistor were the same as in the Reichsansalt type, except the Rosa type was much smaller. The coil assembly is enclosed in a hermetically-sealed metal can which is nearly filled with mineral oil.

In 1908, Rosa took a number of these standards to Europe and had them compared at NPL and PTR. The results at the 1-Ω level indicated that the difference between the NBS Ohm and the NPL and PTR units was -26 ppm and -11 ppm, respectively. From May 1909 to October 1930, the NBS Ohm consisted of the mean value of ten Rosa-type 1-Ω resistance standards. The group mean was assumed to be constant. In 1910, the International Committee met at NBS for an international comparison of the units of resistance. The difference between the NBS Ohm and the NPL and PTR units was -12 ppm and -2 ppm, respectively. The mean difference of -7 ppm represented the mean values of the NPL and PTR mercury ohms as compared to the NBS Ohm. The NBS Ohm was not adjusted for this difference.

Thomas Type I - Over the years, measurements of the individual Rosa-type resistors indicated that the group mean was not constant. Thomas in 1930 reported on the development of a new design for a resistance standard having improved stability [3]. The major design change was to thoroughly anneal the resistance wire on a mandrel, the same size as the brass cylinder on which it is mounted. The first Thomas-type resistors were constructed of #16 AWG bare manganin wire wound on a 6-cm diameter metal form and then annealed at about 550 °C in a vacuum. The rigid coil was slipped onto a silk-insulated inner cylinder of a double-walled container, spaced and tied down with linen thread, shellacked and baked for an hour at about 80 °C. The resistance coil is sealed in dry air within the 1-cm annular space between two coaxial brass cylinders. The Thomas-type resistance standards were more stable immediately following construction than the other types. Two of them were used in the primary group in October 1930, and a third resistor was added in April 1932. From October 1932 until March 1939, the use of the Rosa-type resistors in the primary group was discontinued, and 10 resistors of the first Thomas type formed the primary group.

Thomas Type II - Apparently the first group of Thomas-type resistors exhibited a measureable load coefficient. In 1933, Thomas completed work on an additional group of 24 standards constructed of #12 AWG manganin wire mounted on 8-cm diameter brass cylinders. The same technique for annealing, mounting, and sealing was used as for the earlier Thomas design. The somewhat larger dimensions provided for a greater cooling surface. Also to facilitate cooling, the bottoms of the containers were left open and provisions were made for a series of holes along the top above the sealed joint between the inner and outer cylinders. This is the design of the Thomas-type standards that are available commercially.

From March 1939 until September 1969, ten of these Thomas-type resistance standards maintained the NBS Ohm. Again it was assumed that the mean value of the reference group of ten resistors was constant. In September 1969, the primary group was divided into two sub-groups of 5 each. At this time the Wenner bridge was replaced by a dc current comparator potentiometer for the 1-Ω measurements. The new measurement system using the dc current comparator was setup to accomodate only five of the primary standards during a test run. One of the subgroups of five standards was subjected to high temperatures of 34°C in 1970 and 45 °C in 1971, because of malfunctions in the controller circuit for the oil bath. Measurements indicated that these standards changed significantly from the group mean, and, subsequently, they were removed from the primary group. By 1972, only five Thomas-type resistance standards were designated as the primary group to maintain the NBS Ohm. This necessitated applying a small drift correction to the mean value of the group of five resistors. This drift correction was determined from the relative drift rates of the resistors based upon the assumed zero drift rate for the mean value of the original group of ten. From 1972 to the present, the same five Thomas-type resistance standards, constructed in 1933, have been used to maintain the NBS Ohm.

Evanohm Standards

Evanohm was developed by the Wilbur B. Driver Co. around 1948. Its nominal composition is 75% Ni, 20% Cr, 2.5% Al, and 2.5% Cu. It has a resistivity of 110 μΩ-cm and a thermal emf to copper of < 1 μV/K. The resistance/temperature curve for Evanohm is much flatter than that for manganin: its curvature term at room temperature is approximately -0.05 ppm/$K^2$. Heat treatment of Evanohm changes its temperature and time stability. A prolonged heat treatment process of temperature cycling and soaking time is necessary in order to condition the alloy for zero temperature coefficient and long-term stability [9].

Although the NBS Ohm is maintained at the 1-Ω level using manganin standards, Evanohm resistors are used at the higher resistance levels as primary standards. These Evanohm standards are either complete commercial units or constructed at NBS from commercial resistance elements. During the 1970's, the Australian national standards laboratory (NML) started development of a transportable, 1-Ω resistance standard. It consisted of a coil of Evanohm wire shock mounted in an unsealed can, the size of a Thomas-type resistor. These resistors appear to be superior in quality (TCR and stability) compared to the Thomas-type standards.

## MEASUREMENT SYSTEMS

Since the organization of NBS, various 1/1 ratio bridges have been used to compare the resistance standards that form the reference group for maintaining the NBS Ohm. In general, the method employed was the measurement of small differences of the nominally-equal resistance standards by the substitution technique. The advantage of this method is that errors resulting from ratio inequality, leakage currents, lead resistances, and contact resistances tend to cancel out using the direct substitution procedure. Series-parallel buildup resistors that provided accurate ratios of 10/1 or 100/1 were used to extend the NBS Ohm to higher resistance levels.

Wheatstone Bridge - The best evidence indicates that a Wheatstone bridge manufactured by the firm of Otto Wolff in Berlin was used to compare resistance standards during the early years of NBS.

Rosa Bridge - In Rosa's resistance standard paper of 1909 is contained a description of a novel mercury stand that is used to set up a Wheatstone bridge for comparing resistors [2]. The circular stand contained the four main resistors of the bridge along with two other resistors that were shunted by external variable resistors for balancing the circuit. The circular frame was hinged so that it could accomodate a larger size resistor such as the Reichsanstalt type. Rosa also described a series-parallel method for extending the resistance range in steps of 10/1. The sum of five series-connected resistors were compared to two parallel-connected resistors of the next higher decade level by the substitution method. Thus the mean of two 10-Ω resistors can be determined based on the values of five 1-Ω resistors in the primary group.

Wenner Bridge - The first Wenner bridge was built at the NBS in 1918 and continued in service for over 50 years [10]. It was a combination bridge that could be used as a simple Wheatstone bridge or a Kelvin double bridge with a 1/1 or 10/1 ratio. The important resistance sections were sealed and the entire bridge operated in a temperature-controlled oil bath. The 10/1 ratio was established using six 150-Ω resistors and one 50-Ω resistor. The resistors are connected in series with the 50-Ω resistor in the center so that a 500 Ω/50 Ω or 10/1 ratio could be established with one set of three 150-Ω resistors in parallel. The ratio was calibrated by comparing the 50-Ω resistor to the two sets of three 150-Ω resistors in parallel by successive substitution in the bridge. In the early 1960's, NBS constructed several series-parallel buildup resistors of the Hamon design for resistance scaling [11]. These units contained ten series-connected resistors and could be configured as a 10R or 100R transfer standard, where R is the nominal value of the unit with all ten resistors connected in parallel.

Current Comparator - In 1969, a dc current comparator [12] replaced the Wenner bridge for the comparison of Thomas-type 1-Ω resistance standards. With the improved precision of this system, the change of resistance of a Thomas-type resistor with variations of barometric pressure could easily be measured. This led to the determination of the pressure coefficients of the individual resistors that maintain the NBS Ohm in order to correct for this effect. This dc current comparator measurement system for 1-Ω resistors was automated in 1982 [13].

## DRIFT OF THE NBS OHM

Throughout the history of the NBS Ohm, it was assumed that the mean value of the group of resistance standards, used to maintain the unit at the time, remained constant. An exception to this rule is the fact that a drift factor was applied to the NBS Ohm starting in 1971, when the number of standards in the reference bank was reduced from ten to five. However, this drift factor was based on the relative drift rates of the five resistors as compared to an assumed absolute drift rate of zero for the previous reference bank of ten resistors. Until the mid 1970's, the assumption of a constant NBS Ohm was an acceptable one, since there was no precise way of determining the slow drift of the Thomas-type resistance standards. Now, however, the drift of the NBS Ohm can be determined directly by NBS absolute-ohm and quantized-Hall experiments, and indirectly by international comparisons of the ohm.

Absolute-ohm Experiments - The NBS absolute-ohm experiments during 1936 to 1948 using inductors were not precise enough to determine the drift of the NBS Ohm [6]. The development of the computable cross capacitor by Thompson and Lampard in 1956 led to improved determinations of the absolute ohm [14]. An initial NBS determination of the ohm using the calculable capacitor was completed in 1960 [15]. Corrected for the newly adopted value for the speed of light, it indicated that the NBS Ohm was 0.3 ppm greater than the SI ohm. The estimated uncertainty of the experiment was about 2 ppm (1 $\sigma$) and was limited by the uncertainties associated with the capacitance measurements. It was not until new measurements in 1974 that the uncertainties of a NBS absolute-ohm determination were limited by the uncertainties associated with the comparison of dc resistors [16]. The results of this determination indicated that the NBS Ohm was 0.82 ppm less than the SI Ohm. The estimated uncertainty of this measurement was about 0.06 ppm (2 $\sigma$). A repeat determination is at present underway at NBS and should be completed within the next two years. This result should give the best value of the NBS Ohm in terms of the SI unit, and, along with the 1974 result, should indicate the drift rate of the NBS Ohm.

Quantum-Hall Effect Measurements - The discovery of the quantum-Hall effect by von Klitzing in 1980 has produced a more precise method of monitoring the stability of the NBS Ohm [17]. The quantized-Hall resistance depends only on the ratio of the fundamental constants $h/e^2$. The comparison of the NBS Ohm to the quantized-Hall resistance involves fewer critical measurements than those associated with the determination of the absolute ohm using the calculable capacitor. Hence, the quantum-Hall measurements can be done more frequently and a better characterization of the drift rate of the NBS Ohm is possible. Figure 1 gives evidence of the drift rate of the NBS Ohm based on the quantum-Hall measurements at NBS since 1983 [18]. It indicates that the NBS Ohm is drifting at a rate of -0.055 ppm/yr. The quantum-Hall results are not a direct measure of the NBS Ohm in absolute units, since $h/e^2$ must be determined by other experiments.

International Comparisons.- Another way of determining the drift rate of the NBS Ohm is through periodic comparisons of the unit with BIPM. The drift of the BIPM unit of resistance has been well-characterized based on comparisons with NML, whose unit is continuously monitored against the calculable capacitor. Unfortunately, these comparisons involve the transfer of resistance standards that during transit may shift in value by an amount that surpasses the uncertainty of the measurements. Figure 2 is a plot of some recent 1-Ω comparisons between NBS and BIPM showing large differences between resistors for some transfers. Three resistors were used for the comparisons in 1973, 1982, and 1984; while, only two resistors were involved in the 1970 and 1978 comparisons. Recent direct comparisons with NML in October 1985 and June 1986, using the improved NML 1-Ω resistors as transfer standards, indicate a drift of about -0.07 ppm/yr for the NBS Ohm. However, this result is based on only two determinations over a relatively short period of time.

## PRESENT STATUS OF THE NBS OHM

At present, the NBS Ohm is maintained by a group of five Thomas-type, 1-Ω resistors that were constructed in 1933. These resistors are compared to each other or against other 1-Ω standards in an automated measurement system using a dc current comparator. The standard deviation of this measurement system is on the order of 0.01 ppm. Table I lists the important characteristics of the five reference resistors. The best evidence indicates that the NBS Ohm is decreasing with respect to the SI ohm at a rate of $-0.06 \pm 0.02$ ppm/yr ($1\ \sigma$). The NBS Ohm is not constant.

The value of the NBS Ohm was last formally adjusted in 1948. The value was changed in 1948 to reflect the reassignment of the electrical units from the international system to the absolute system. The value of the NBS Ohm was based on the best absolute-ohm determinations at that time. The 1974 NBS absolute-ohm determination along with an assumed linear drift rate indicates that the NBS Ohm is $1.60 \pm 0.26$ ppm ($1\ \sigma$) less than the absolute or SI ohm. The NBS Ohm is not equal to the SI ohm.

## FUTURE OUTLOOK OF THE NBS OHM

The value of the NBS Ohm will probably be changed in 1990. The Consultative Committee on Electricity (CCE) of the International Committee of Weights and Measures decided at their 1986 meeting to meet in September 1988 to adopt a value for the quantized-Hall resistance for maintaining the SI ohm. The new value will be based on absolute-ohm experiments using the calculable capacitor and other determinations of fundamental constants. Based on present knowledge, the value of the NBS Ohm would increase about 1.8 ppm. Also a drift rate, periodically updated based on QHE measurements, will be assigned to the reference group in order to keep the NBS Ohm constant. This adjustment of the NBS Ohm is expected to be semi-permanent or until the ohm becomes a frequency measurement.

In the future, the improved realization of the NBS Ohm in SI units will demand improved resistance standards for maintaining the ohm on a day-to-day basis. Unless some other breakthrough occurs, there will still be a need for resistance standards. The NBS is hoping to develop the next generation of resistance standards. Various alloys and resistor construction techniques would be investigated in order to develop a transportable resistance standard having high temperature and time stability, and high immunity to vibration or shock. The final design is envisioned to be a resistor slightly larger in physical size than present-day standards in order to accomodate the latest thermal-lagging and shock-mounting materials. The resistor would have shielded four-terminal connectors and operate in a room-temperature environment. A low-power digital display would be mounted on the resistor case to indicate its correction or temperature as selected by the operator. The operator would also be able to select the readout of the maximum or minimum temperature that the resistor was subjected to during its recent travels. An EPROM chip would be re-programmed after each calibration to update the correction to the resistor.

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Table I

NBS 1-Ω REFERENCE GROUP

| S/N | Temperature Coefficients | | Pressure Coefficient | Drift Rate |
|---|---|---|---|---|
| | $\alpha$($\mu\Omega$/K) | $\beta$($\mu\Omega$/K*K) | (n$\Omega$/mmHg) | ($\mu\Omega$/yr) |
| 66 | +0.80 | -0.48 | +2.96 | -0.098 |
| 69 | +1.10 | -0.54 | +3.56 | +0.026 |
| 70 | +1.40 | -0.52 | +8.88 | +0.043 |
| 72 | +1.70 | -0.54 | +6.67 | +0.023 |
| 83 | 0.00 | -0.47 | +12.30 | +0.029 |

Mean Drift Rate = +0.0046

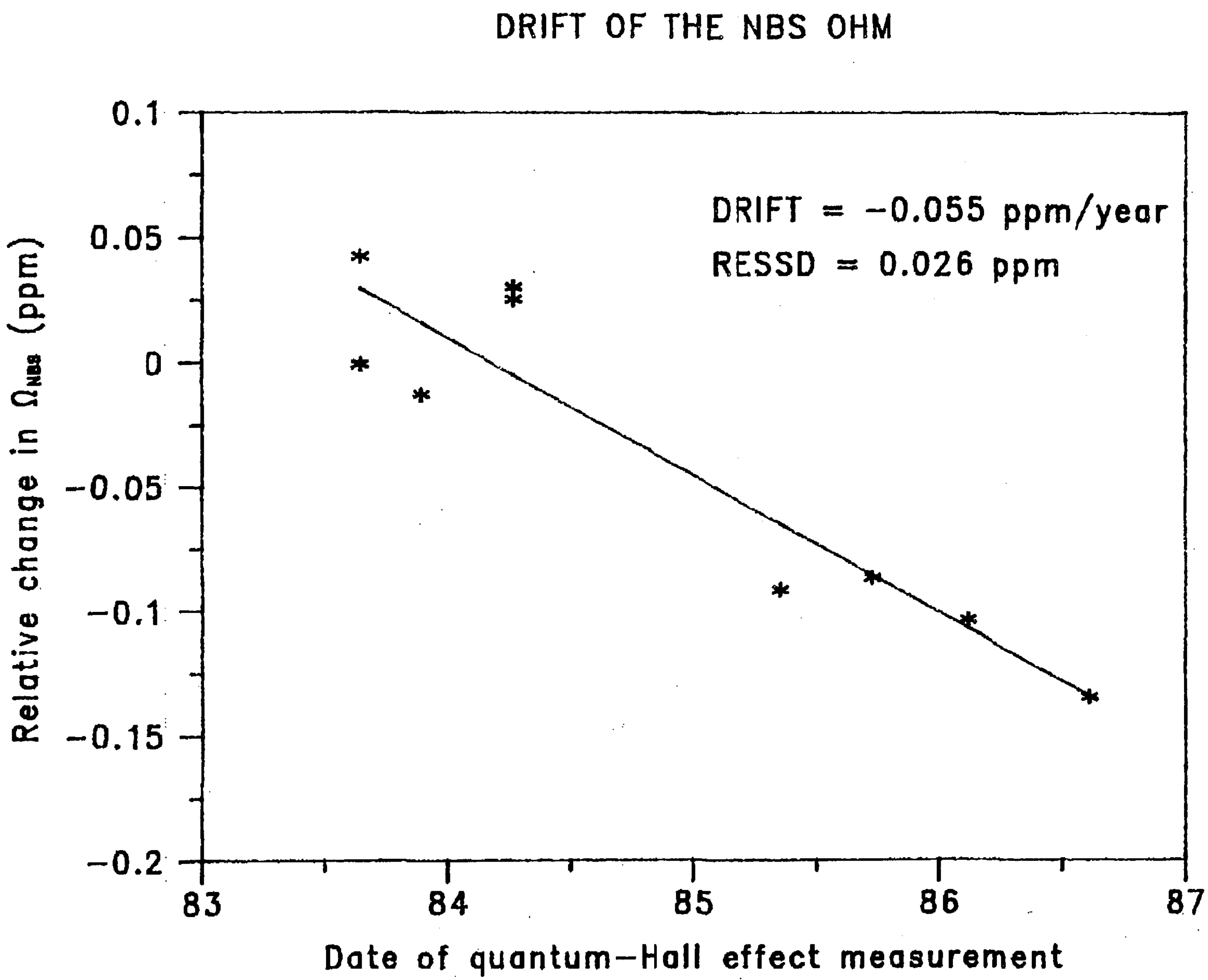


Fig. 1. NBS Ohm drift based on QHE measurements.

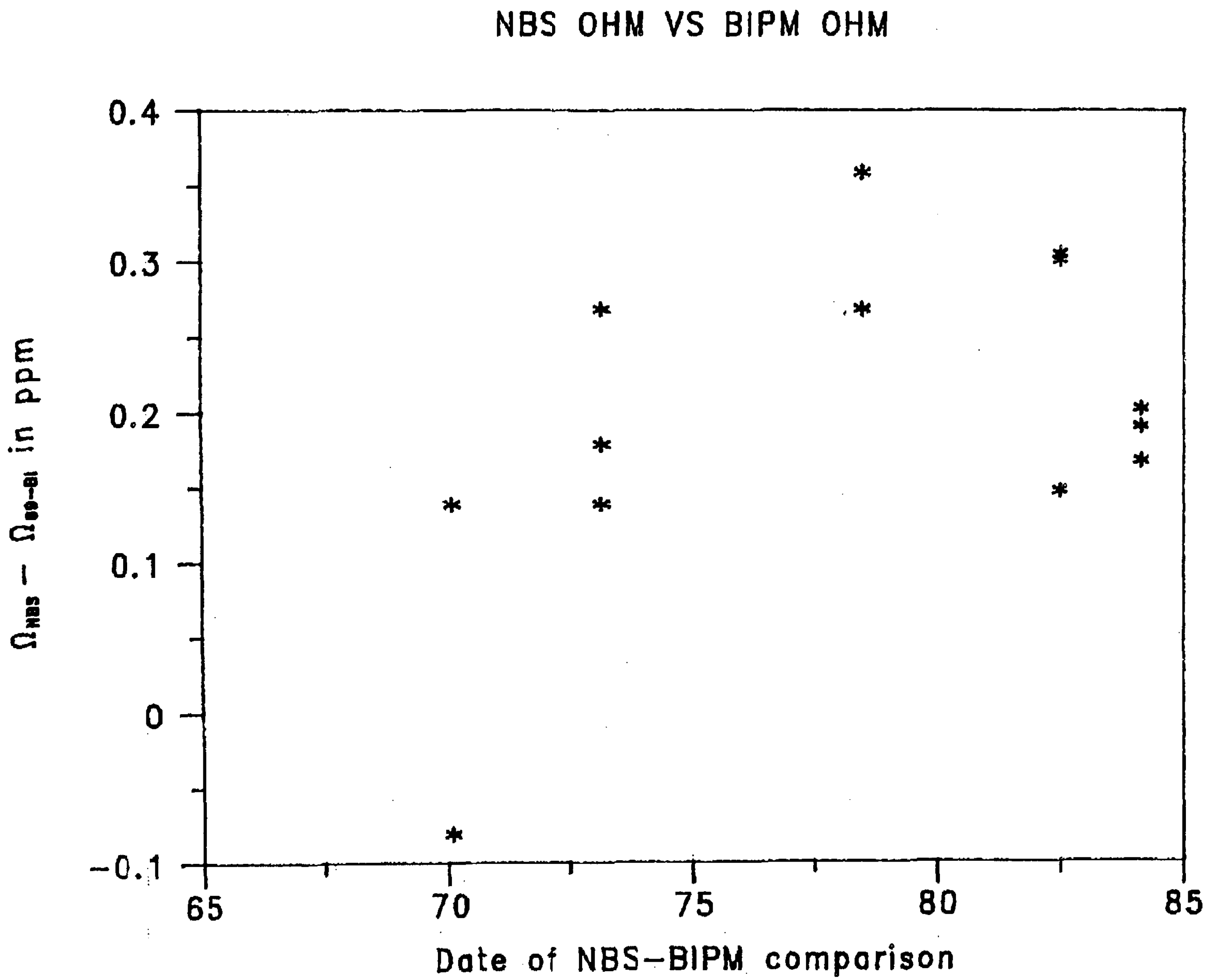


Fig. 2. NBS and BIPM 1−Ω comparisons. Note large differences between resistors for some transfers.