NOAA Technical Report NOS 94 NGS 23

Scribing, Graduation, and Calibration of U.S. Coast and Geodetic Survey Leveling Rods From 1877 to 1968

Rockville, Md.
August 1982

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Survey

NOAA Technical Publications

National Ocean Survey/National Geodetic Survey subseries

The National Geodetic Survey (NGS) of the National Ocean Survey (NOS), NOAA, establishes and maintains the basic national horizontal and vertical networks of geodetic control and provides Government-wide leadership in the improvement of geodetic surveying methods and instrumentation, coordinates operations to assure network development, and provides specifications and criteria for survey operations by Federal, State, and other agencies.

NGS engages in research and development for the improvement of knowledge of the figure of the Earth and its gravity field, and has the responsibility to procure geodetic data from all sources, process these data, and make them generally available to users through a central data base.

NOAA geodetic publications and relevant geodetic publications of the former U.S. Coast and Geodetic Survey are sold in paper form by the National Geodetic Information Center. To obtain a price list or to place an order contact:

National Geodetic Information Center
C18x2
National Ocean Survey, NOAA
Rockville, MD 20852

(301) 443-8316

When placing an order, make check or money order payable to: National Geodetic Survey. Do not send cash or stamps.

Publications can also be purchased over the counter at the National Geodetic Information Center, 11400 Rockville Pike, Room 14, Rockville, Md. (Do not send correspondence to this address.)

An excellent reference source for all Government publications is the National Depository Library Program, a network of about 1,300 designated libraries. Requests for borrowing Depository Library material may be made through your local library. A free listing of libraries in this system is available from the Library Division, U.S. Government Printing Office, 5236 Eisenhower Ave., Alexandria, VA 22304 (703-557-9013).

NOAA Technical Report NOS 94 NGS 23

Scribing, Graduation, and Calibration of U.S. Coast and Geodetic Survey Leveling Rods From 1877 to 1968

William E. Strange

National Geodetic Survey
Rockville, Md.
August 1982

U. S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

National Oceanic and Atmospheric Administration
John V. Byrne, Administrator

National Ocean Survey
R. Adm. H. R. Lippold, Jr., Director

For sale by the National Geodetic Information Center,
Rockville, MD 20852 Price $2.90

CONTENTS

TABLES

FIGURES

SCRIBING, GRADUATION, AND CALIBRATION OF U.S. COAST AND GEODETIC SURVEY LEVELING RODS FROM 1877 TO 1968

William E. Strange
National Geodetic Survey
National Ocean Survey, NOAA
Rockville, Md. 20852

ABSTRACT. Precise leveling by the U.S. Coast and Geodetic Survey (C&GS) began in 1877. Until the early 1970's most leveling surveys by C&GS and its successor organizations employed level rods that were designed, constructed, scribed, and graduated by C&GS. From 1877 through 1923, C&GS also calibrated the rods. From 1924 until 1968, calibrations were carried out by the National Bureau of Standards (NBS). This report describes the methods and results of scribing, graduating, and calibrating these rods from 1877 until 1968 when the last calibrations were made. Four types of rods are discussed: brass target rods used from 1877 through 1894, paraffin-saturated wooden target rods used from 1895 through 1898, paraffin-saturated wooden Fischer rods used from 1899 through 1915, and Fischer Invar-scale rods used from 1916 until the early 1970's.

Scribing and calibration of brass target rods are commensurate with accuracies of the order of ± 50 ppm. However, the coefficient of expansion of brass is about 18 ppm/°C, and inaccuracies resulting from rod temperature changes greatly reduced the accuracies obtained with these instruments. One pair of wooden target rods was manufactured. While the rod scribings were in error by 400 to 600 ppm, calibrations appeared to have been accurate to within ± 50 ppm, and were stable with time so the scribing errors could be adequately monitored. Calibration corrections for paraffin-soaked wooden Fischer rods were very large, exceeding 400 ppm and reaching a maximum of 770 ppm. Of more serious concern was the unstable nature of the calibration values which often varied as much as 370 ppm between pre- and post-survey calibrations with both slow and rapid calibration changes.

After the introduction of Fischer Invar-type rods in 1916, the accuracy of scribing, graduation, and calibration increased with time. Discussion of scribing and graduation is divided into four periods: 1916 to 1926, 1927 to mid-1928, mid-1928 to about 1951, and 1951 to 1968. Scribing was generally done with a standard meter bar. Graduation was carried out during the initial 1916-26 period by using a steel square to establish boundaries and by hand-painting the checkerboard pattern; from 1927 to about 1951 a graduating machine with a 4-centimeter painting mask was used. From about 1951, a 1-meter Invar painting mask was used. Calibrations of Fischer Invar-type rods were carried out between 1916 and 1929 with standard reference bars--by C&GS during 1916-23 and by NBS from 1924-27. Between 1930 and 1963, calibrations were carried out by NBS using standardized steel tape; from 1964 until 1968, a standard Invar bar was used. From 1930 onward, the root-mean-square differences between scribing and calibration were about ± 30 ppm. However, using the 1964-68 period as a standard, calibrations during 1949-63 showed a systematic offset of 20 ppm, while those in 1930-39 showed a systematic 50 ppm offset. (Almost no calibrations were made during 1940-48.) Calibrations prior to 1930 were less accurate than those after 1930.

INTRODUCTION

Although the U.S. Coast and Geodetic Survey (C&GS) began leveling as early as 1856, precision leveling was initiated in 1877. The 105 years of precision leveling performed by C&GS and its successors [now the National Ocean Survey (NOS)] can be divided into two distinct periods characterized by the type of leveling instrument used. During the period 1877-98 the leveling instruments used by C&GS were the "Vienna" or "Stampfer" instruments. These instruments are described in appendix 15 of the C&GS Annual Report for 1879 and appendix 8 of C&GS Annual Report for 1899. The instruments were characterized by a micrometer screw which was used to measure the angle between the orientation of the telescope when it was leveled with the striding level and the orientation when a line on the scale of a movable target on the rod was matched with the cross hair in the telescope of the level instrument. The movable target on the rod, graduated at millimeter intervals, was used to interpolate between calibrated graduations 1 or 2 cm apart on the rod scale.

In 1899, the Stampfer-type leveling instruments and target-type rods were replaced by direct-reading rods and leveling instruments. In this case, the leveling instrument was read only when level. The rods, known as Fischer rods, had scribe marks at 1-meter intervals with painted graduations at 1-centimeter intervals located along the entire rod. Reading lines associated with the telescopes of the leveling instrument were used to interpolate readings to 0.1 mm. Since 1899 both leveling instruments and rods have changed substantially in detail and improved in accuracy, but the basic theory remains the same.

C&GS constructed leveling rods from 1877 until the early 1960's. These rods continued to be calibrated until 1968, and were the primary leveling rods used by C&GS from 1877 to 1964 and by its successor, the Environmental Science Services Administration (ESSA), from 1965 until about 1970. In the 1960's leveling rods purchased from instrument manufacturers gradually replaced the C&GS rods until, in the mid-1970's, C&GS leveling rods no longer were used. This publication will consider only leveling rods constructed by C&GS. Thus it will encompass only the period from when the first rods were constructed in 1877 to the last calibration of these rods for ESSA by the National Bureau of Standards (NBS) in 1968.

In assuming the accuracy of the scribing, graduation, and calibration of C&GS leveling rods, six time periods--characterized by different rod types, different scribing and graduation accuracies, and different calibration procedures--will be considered. These periods are as follows:

- 1877 - 1894 Brass target rods.
- 1895 - 1898 Paraffin-saturated wooden target rods.
- 1899 - 1915 Paraffin-saturated wooden Fischer rods.
- 1916 - 1927 Fischer Invar-scale rods.
- 1928 - 1963 Fischer Invar-scale rods with improved scribing and graduation.
- 1964 - 1970 Fischer Invar-scale rods with improved calibration.

GENERAL CONCEPT OF ROD CALIBRATION

Reading lines were placed on target leveling rods by scribing lines on metal parts of the rod at 1- or 2-centimeter intervals. Reading lines were placed on Fischer rods by scribing lines on an Invar strip at 1-meter intervals and using these to control the painting of graduations on the Invar strips in the form of 1-centimeter-wide alternating black and white tessera. The scribed and graduated part of the leveling rods did not extend to the bottom of the rods but normally began 10 to 20 cm above the bottom.

Leveling rod calibration was performed by determining two quantities: rod excess and rod index error. The rod index error is the difference between the height value assigned to the bottom scribe mark on the rod and the distance between this bottom scribe mark and the bottom of the rod as determined during calibration. The rod excess is the value obtained from dividing the calibration-derived distance between the bottom and top scribe marks on the rod by the distance between the bottom and top scribe marks defined during scribing. Therefore, rod excess is the linear scale error for the rod. For Fischer rods, the normal procedure was to place the bottom scribe mark a nominal 0.2 m above the bottom of the rod, with additional scribe marks at nominal distances of 1.2, 2.2, and 3.2 m from the bottom of the rod. In this case, index error is the difference between the distance from the base of the rod to the bottom scribe mark obtained during calibration and the nominal value of 0.2 m. The rod excess is the distance between the 0.2- and 3.2-meter scribe marks obtained from calibration measurements, divided by 3.0 m.

In calibrating a rod, it was the usual practice to make measurements in a manner that allowed independent determinations of rod scale error from each 1.0-meter segment of the rod; e.g., measurements of the intervals 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m; or of the intervals 0.2 to 1.2, 0.2 to 2.2, and 0.2 to 3.2 m. However, the normal procedure has been to compute a single rod excess value from the measurements. To the extent that the scribing errors are different for the different rod intervals, an error is clearly introduced from use of a single rod excess value.

The index error is not a large source of error in leveling. If the index error remains constant for the two leveling rods used on a survey, the maximum error which can be introduced for the height difference between any two bench marks on the line of leveling, regardless of their horizontal separation or height difference, would be the difference between the index errors for the two rods, even if no correction were applied. By assuring that an even number of setups is used for each bench mark to bench mark interval, and, thus, that the same leveling rod is placed on each bench mark, index error is eliminated even if no correction is applied, provided it does not change with time. For Fischer Invar rods the index error is unlikely to change significantly during the time of a survey. For brass and wooden rods, some change may occur, as will be discussed later.

BRASS TARGET RODS (1877-94)

The overall characteristics of brass target rods used during the period 1877-94 are published in appendix 15 of the C&GS Annual Report for 1879 (pp. 203-205). The rods are described in that document as follows:

> The rods are made of well-seasoned white-pine wood, oiled and varnished, and are a little more than 3 meters long. Each rod

consists of a main strip of wood 7.5 cm wide and 2.5 cm thick, along the center of each broad face of which is screwed and glued another strip of the same length, and 2.5 cm wide and 2.5 cm thick. A target, provided with guide pieces, and friction spring, can be moved up and down one of the faces of the rod by means of an endless chain running over a fixed pulley at the bottom, and an adjustable one near the top of the rod. The chain passes through a clamp convenient to the rodman's hand. The target carries with it, at right angles to its face, a small ivory scale, graduated to millimeters, moving over a strip of brass set into the rod and extending its whole length. The brass is graduated to centimeters, and can be read to fractional parts of a millimeter by means of the ivory scale. The brass scale is fastened in the middle immovably to the rod, and is held in its groove by means of screws at the back passing through slots, so that the brass may freely expand towards the top and bottom, and it forms the scale proper on which all differences of heights are measured. The temperature is registered by means of a thermometer set into the rod. A handle screwed on that face of the rod opposite to the target, and a small circular level, enable the rodman to hold the rod vertical. That face of the rod which carries the target is graduated to centimeters, and serves the double purpose of a telemeter and of checking the reading of the brass scale, as will be explained further on. The foot of the rod is a rounded piece of brass, which is intended to rest in a corresponding depression in the foot plates.

The wooden parts of these rods were not paraffin-soaked (C&GS Annual Report for 1899, p. 416). The procedure of fastening the brass strip to the wooden backing at the center point and allowing it to expand and contract in both directions with changing temperature, as described in the previous excerpt, was found to be unsatisfactory (C&GS Annual Report for 1899, app. 8, p. 416).

In July 1889, the construction method changed. Thereafter the brass strip was fastened to the wood at the bottom of the rod so that the strip expanded only upward (C&GS Annual Report for 1892, part II, app. 3, p. 163; C&GS Annual Report for 1899, app. 8, p. 416). There were apparently 16 brass rods constructed, each identified by a letter designation. Rods with letters A through K and a rod designated A_1 (to replace rod A which was broken shortly after being manufactured) had the brass strip fastened at the center point. Rods L, M, N, and O had the brass strip fastened at the bottom.

The coefficient of thermal expansion of the brass strip was found to be 18 to 19 ppm per °C. Thus, accurate temperature measurements were necessary to make required corrections. Obtaining sufficiently accurate temperature measurements was one of the problems encountered with brass rods. Initially neither the brass strip nor the thermometer bulb was protected from the direct rays of the Sun. As time went on, gradual improvements were made in protecting the strip and the thermometer. On the last brass rod constructed, a felt strip was used to protect the brass strip from the direct rays of the Sun, and the thermometer was sunk into the rod and protected by a metal cover (C&GS Annual Report for 1899, app. 8, p. 416). However, the determination of temperatures and the application of corrections when using brass rods were never considered satisfactory, even with the improvements incorporated in later rods (C&GS Annual Report for 1895, app. 8, p. 381).

The only information found in the C&GS files concerning exact procedures for either scribing the 1-centimeter intervals on the brass rods or calibrating the rods was a statement in appendix 9 of the C&GS Annual Report for 1887. The report stated that calibration of 1-meter intervals was carried out through comparisons with a standard using "Saxton's dividing and comparing machine." It must be remembered that during this period the C&GS Office of Standard Weights and Measures performed many of the functions of the present National Bureau of Standards. Therefore, C&GS had standard length references of the highest available accuracy and used high-precision techniques to compare (i.e., calibrate) and transfer the scale from the standards.

For reduction of the survey data, single calibration constants were used for an entire rod. Table 1 summarizes all of the calibration data found for the brass rods used by C&GS. Rather than referencing the calibration constants to 0 °C, as was the common practice, table 1 references the constants to 20 °C. Referencing the values to 20 °C gives a clearer picture of the magnitude of the calibration correction which was actually applied during leveling, since 20 °C is nearer to the actual temperature at which the leveling was carried out. Because of the large coefficient of thermal expansion of brass (18 ppm/°C), every brass rod had one temperature in the range 10 °C to 30 °C, at which the calibration correction was zero. A common mode used to present the calibration results for brass rods was to specify the temperature at which the calibration correction would be zero. This "zero correction" temperature is also shown in table 1.

Table 1.--Average calibration values of C&GS brass rods
(Coefficient of thermal expansion = 18 ppm/°C)

Rod designation	Accepted calibration value		Calibration date	Source**
	ppm at 20° C*	zero corr. temp. (°C)		
A_1	+25	19.4	Sept. 1882	(1)
B	-37	22.1	Sept. 1882	(1)
C	-5	20.3	Sept. 1880	(2)
D	+101	14.4	Aug. 1882	(2)
E	+59	16.7	Dec. 1882	(1)
F	+20	18.9	Dec. 1882	(1)
I	-2	20.1	Nov. 1888	(3)
K	+42	17.7	Nov. 1888	(3)
L	-31	21.7	?	(4)
M	-31	21.7	?	(4)
N	-31	21.7	?	(4)
O	-31	21.7	?	(4)

*Positive calibration values indicate rods were too long.
**(1) C&GS Annual Report for 1887, appendix 9.
(2) C&GS Annual Report for 1893, appendix 2.
(3) C&GS Annual Report for 1896, part II, appendix 2.
(4) C&GS Annual Report for 1892, appendix 3.

It is not clear from the available records whether any of the brass rods were calibrated more than once. If they were, no changes in calibration values were noted. As shown in table 1, no calibration values were found for rods G, H, and J, and no evidence exists that they were used in leveling.

The calibration values given in table 1 are not large, which would give the impression that the brass rods were very accurately scribed. However, the numbers in the table are somewhat misleading. The C&GS Annual Report for 1887, appendix 9, gives measurements of the intervals 0 to 1, 1 to 2, and 2 to 3 m for four rods. In addition, the C&GS Annual Report for 1896, appendix 2, gives measurements for the intervals 0 to 1, 0 to 2, and 0 to 3 m for two rods. The interval calibration values for these six rods are shown in table 2.

The values in table 2 indicate the scribing errors for the brass rods are more nonlinear than might have been expected from the values listed in table 1. Even so, calibration corrections for an interval seldom exceeded ± 125 ppm.

As indicated in the C&GS Annual Report for 1887, appendix 9, the mean values used for data reduction, as given in table 1, were often derived from taking the mean of the three interval values, such as those shown in table 2, with the middle interval given double weight. The values in table 1 for rods A_1, B, E, and F were obtained in this way from the values in table 2.

Table 2.--Interval calibrations of brass rods

Rod designation	Temperature during calibration (°C)	Measured interval value			Source*
		0-1 m	1-2 m	2-3 m	
A_1	20.3	1.000244	0.999949	0.999949	(1)
B	20.3	1.000141	0.999876	0.999974	(1)
E	20.3	1.000052	1.000039	1.000121	(1)
F	20.3	1.000052	0.999959	1.000120	(1)
I	22.7	1.000007	1.000024	1.000013	(2)
K	22.7	1.000014	1.000110	1.000050	(2)

*(1) C&GS Annual Report for 1887, appendix 9.
(2) C&GS Annual Report for 1896, appendix 2. (Values for these intervals determined by differing observed data.)

For those rods having the brass strip fastened to the wooden part of the rod at the center, the zero scribe mark on the brass strip was well above the bottom of the rod (often more than 5 cm). This allowed for the downward expansion of the brass strip. Thus, these rods had an index error which was a function of the temperature of the brass strip. Also, expansion or contraction of the wooden rod could cause changes in the correction, since the distance from the bottom of the rod to the point of attachment of the brass strip changed. Of importance in this respect is the fact that the wooden part of the rod was not paraffin soaked. Thus, the wooden part of the rod would be expected to undergo humidity-induced changes in length. To keep these index errors in perspective, it must be noted that during a survey season the rods were unlikely to produce changes in the value of the index error greater than 5 mm.

From a vantage point almost 100 years after the fact, it is not possible to assess thoroughly the accuracy of scribing and calibrating brass target rods. Because totally different procedures were used for leveling at that time, it would be difficult to unambiguously assign to rod scribing or calibration any systematic errors which might be found from comparison with repeat levelings. It does seem clear that the results obtained with these rods should not be expected to be as accurate as those obtained in more recent times using Invar-type Fischer rods.

PARAFFIN-SATURATED, WOODEN, TARGET RODS (1895-98)

Because C&GS was not fully satisfied with the "brass" rods, the C&GS Superintendent appointed a special committee to design a better rod. The replacement designed by the committee was a wooden rod saturated with paraffin to minimize changes in length due to changes in humidity. Details concerning paraffin-saturated target rods are given in appendix 8 of the C&GS Annual Report for 1895. The following excerpts summarize the characteristics of this rod:

> The rod is made of well-seasoned white-pine wood, thoroughly saturated with paraffin and is a little more than 3 meters long. Each rod consists of a main strip of wood, 7 cm. wide and 2.1 cm. thick, along the center of each broad face of which is fastened by screws another strip of equal length and 2.5 cm. thick, thus forming a cross of symmetrical proportions.
>
> Holes were then bored in the face of the rod to receive the silver faced brass plugs, 5 mm. in diameter and 20 mm. long, which were inserted at intervals of 0.02 m. to receive the graduation. These plugs fit accurately in the holes made to receive them and are secured in position by a rivet passing through the wood and near the end of the plug. They project slightly above the face of the rod. A single line is cut across the silver end of each plug. The rods were again delivered to the Weights and Measures Office, and the length of each 0.1 m. division determined. The fittings were then placed upon the rod.
>
> The target, provided with guide pieces and friction springs, is moved up and down the face of the rod by means of an endless chain passing over a fixed pulley near the bottom of the rod and an adjustable one near the top.
>
> A similar endless chain is attached to a lever and eccentric carried by the target, by means of which the latter can be clamped in any position on the rod without loss of time. An opening is made in the target to permit the graduation to be seen, and it carries a millimeter scale 0.02 m. long, with a feather edge mounted on a spring which holds it slightly above the plugs and allows a reading to be easily made without parallax by pressing the scale against the plug while reading the rod. The zero of the graduation corresponds to the foot of the rod, and the zero of the scale to the center of the target. The rod is read directly to 0.001 m. and by estimation to 0.0001 m. A circular level is attached to the rod, by means of which it can be held in a vertical position, and a handle is screwed to its back for convenience in carrying it.

Only two paraffin-saturated target rods, denoted C&GS rods P and Q, were constructed. To make certain that they were essentially immune to humidity effects, these two rods were soaked in melted paraffin until they nearly doubled their weight. One rod absorbed 95 percent of its original weight in paraffin and the other 72 percent. In absorbing the paraffin, all void spaces were filled, making the rods impervious to water. As noted in appendix 8 of the C&GS Annual Report for 1895, the C&GS Office of Standard Weights and Measures carried out a number of tests on these rods to determine the effects of temperature and humidity. The coefficient of thermal expansion for both rods was found to be 4.2 ppm per °C. To test the paraffin-saturated rods against the effects of humidity, one of the rods was immersed in water for 19 hours and showed no measurable change in length.

Appendix 8 of the C&GS Annual Report for 1895 states that the Office of Standard Weights and Measures carefully calibrated each 10-centimeter interval on rods P and Q. No information was found on how these calibrations were carried out, nor were any results of these calibrations published. The only calibration data found were calibration values for the larger intervals 0.1 to 1.0, 1.0 to 2.0, and 2.0 to 3.0 m. Tables 3a and 3b summarize the available calibration data for the two rods. Table 3a shows errors in scribing of 445 to 610 ppm. However, reasonably good linearity appears in table 3b, with the calibration corrections varying over a range of no more than 60 ppm from interval to interval for a given rod during a given calibration.

Table 3.--Calibration values for paraffin-saturated rods P and Q. (Coefficient of thermal expansion used to reduce data to 0 °C = 0.000004 m per °C)

Table 3a

Calibration date	Temperature during calibration (°C)	Rod length: 0.1 to 3.0 m		Calibration corrections		Source*
		P	Q	P (ppm)	Q (ppm)	
June 1896	24	2.90161	2.90138	555	476	(1)
Oct. 1896	21.3	2.90149	2.90129	514	445	(1)
Mar. 1897	24	2.90159	2.90148	548	510	(2)
May 1899	24	2.90177	2.90142	610	490	(3)

*(1) C&GS Annual Report for 1897-98, appendix 1. (2) C&GS Annual Report for 1897-98, appendix 2. (3) C&GS Annual Report for 1899, appendix 5.

Table 3b

Rod designation	Calibration date	Temperature during calibration (°C)	Measured interval value			Source*
			0.1-1.0 m	1.0-2.0 m	2.0-3.0 m	
P	1896	24	0.90050	1.00051	1.00051	(1)
P	1897	24	0.90051	1.00054	1.00054	(2)
Q	1896	24	0.90047	1.00044	1.00041	(1)
Q	1897	24	0.90051	1.00050	1.00047	(2)

*(1) C&GS Annual Report for 1897-98, appendix 1. (2) C&GS Annual Report for 1897-98, appendix 2.

In using the calibration corrections in tables 3a and 3b to process observed leveling data, the normal procedure was to take the mean of pre- and post-survey calibrations of the total length of the rod. At times, only one calibration value, determined either before or after the survey, was available for reducing the data. The degree of agreement between pre- and post-survey calibrations and the total variability of all calibrations suggest calibration error did not exceed 50 ppm even when only one calibration value was available.

Paraffin-saturated, wooden, target rods P and Q were used during the period 1895-98. In 1899, they were replaced by paraffin-saturated, wooden, Fischer rods.

PARAFFIN-SATURATED, WOODEN, FISCHER RODS (1899-1915)

In 1899, C&GS introduced a new leveling instrument and changed its leveling procedures. Appendix 8 of C&GS Annual Report for 1899 (p. 418) briefly describes the new leveling instrument. Greater detail is presented in Parkhurst (1927). For use with this instrument, an entirely new type of "direct-reading" rod was designed by E. G. Fischer(C&GS Annual Report for 1899, app. 8, p. 418-419). The new rods were originally soaked in paraffin, similar to rods P and Q already described, but with the following important differences (C&GS Annual Report for 1899, app. 8, p. 419):

> They differ essentially from rods P and Q, as used in 1895-1898, in being direct-reading rods instead of target rods. The graduation, which is read directly from the telescope, is in black and white squares 1 centimeter on a side. Metal plugs are inserted at the 0.1, 1.1, 2.1, and 3.1 meter points. A fine graduation on these plugs is used to determine the exact length of the rods and to study their changes of length while in the field. The new rods contain less than 20 percent of their original weight of paraffin as contrasted with 72 to 95 percent in rods P and Q. This, together with the omission of the target and connected chains, reduces the weight of the rod from about 10 kilograms to about 4.5 kilograms.

No statement was found in the records as to how the graduations were placed on the metal plugs or how the familiar Fischer checkerboard graduations were painted on the rods.

During all but the final year of their use, calibrations of the paraffin-saturated Fischer rods were made in the following way: Careful measurements of the distance between the 0.1- and 3.1-meter scribe marks on the rod were made in the laboratory before and after each field season. Standard meter reference bars were used for this measurement. Measurements of the same interval were also made, generally once or twice a month in the field, using a calibrated steel tape (C&GS Annual Report for 1903, app. 3, pp. 214-215). The laboratory measurements provided the definitive calibration values used to reduce the data. The field measurements with the steel tape were used only to aid in determining how to apply the laboratory calibrations; e.g., the field measurements could be used to determine if an observed change between pre- and post-survey calibration had occurred linearly over a period of time or abruptly over a short time interval during the field season.

During the 1915 field season, a change in calibration procedure was made. A standard Invar meter bar was taken to the field and frequent calibrations of the leveling rods were carried out with this standard bar at the field site. These measurements provided calibration information for the reduction of the observed leveling data (Avers and Cowie 1916).

Tables 4 through 9 present calibration data for six pairs of wooden Fischer rods, carried out at various times during the period 1899-1915. These represent all the calibration values found in the records for wooden Fischer rods. Other calibration data may exist, but the bulk of the calibrations is believed to be included in these tables. The interval observed to obtain a calibration value was the distance between scribe lines on the brass plugs at the 0.1- and 3.1-meter points on the rods.

Table 4.--Calibration values for paraffin-saturated rods R_2 and S. (Coefficient of expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value		Correction	
	R_2 (m)	S (m)	R_2 (ppm)	S (ppm)
May 1899	-	3.00064	-	210
Aug. 1899	3.00068	-	230	-
Oct. 1899	3.00109	3.00153	360	510
Nov. 1900	3.00122	3.00157	410	520
Jan. 1901	3.00099	3.00136	330	450
Mar. 1902	3.00086	3.00139	290	460
May 1902	3.00086	3.00139	290	460
Dec. 1902	3.00080	3.00134	270	450
Oct. 1903	3.0008	3.0012	270	400
Mar. 1904	3.0007	3.0012	230	400
Jan. 1905	3.0009	3.0014	300	470
Aug. 1908	3.0017	3.0020	570	670
Sept. 1910	3.0007	3.0002	230	70
Feb. 1911	2.9999	2.9996	-30	-130
Nov. 1911	3.0000	2.9997	0	-100
June 1913	2.999986	2.999593	-5	-140
Jan. 1914	3.000071	2.999872	20	-40

Table 5.--Calibration values for paraffin-saturated rods T and U. (Coefficient of expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value		Correction	
	T (m)	U (m)	T (ppm)	U (ppm)
May 1899	3.00073	3.00042	240	140
Dec. 1899	3.00150	3.00128	500	430
Jan. 1901	3.00136	3.00116	450	390
Mar. 1902	3.00124	-	410	-
May 1903	3.0015	3.0013	500	430
Jan. 1904	3.0010	3.0009	330	300
Jan. 1905	3.0015	3.0014	500	470
Oct. 1905	3.0020	3.0015	670	500

Table 6.--Calibration values for paraffin-saturated rods V and W. (Coefficient of expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value V (m)	Calibration value W (m)	Correction V (ppm)	Correction W (ppm)
June 1900	3.00076	3.00094	250	310
Jan. 1901	3.00156	3.00196	520	650
Mar. 1902	3.00118	3.00163	390	540
Apr. 1904	3.0014	3.0017	470	570
Jan. 1905	3.0011	3.0016	370	530
Dec. 1905	3.0014	3.0021	470	700
Aug. 1907	3.0015	3.0023	500	770

Table 7.--Calibration values for paraffin-saturated rods X and Y. (Coefficient of thermal expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value X (m)	Calibration value Y (m)	Correction X (ppm)	Correction Y (ppm)
Sept. 1906	3.0020	3.0022	670	730
Aug. 1907	3.0015	3.0016	500	530
Feb. 1909	3.0007	3.0009	230	300
Jan. 1910	3.0003	3.0005	100	170

Table 8.--Calibration values for paraffin-saturated rods AA and BB. (Coefficient of thermal expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value AA (m)	Calibration value BB (m)	Correction AA (ppm)	Correction BB (ppm)
Jan. 1908	3.0008	3.0013	270	430
Feb. 1909	3.0004	3.0010	130	330
Oct. 1909	3.0007	3.0012	230	400
Nov. 1910	3.0004	3.0011	130	370
May 1915	3.0005	3.0012	170	400
Nov. 1915	2.9994	3.0002	-200	70

Table 9.--Calibration values for paraffin-saturated rods CC and DD. (Coefficient of thermal expansion used to reduce data to 0 °C = 0.000004 m per °C)

Calibration date	Calibration value CC (m)	Calibration value DD (m)	Correction CC (ppm)	Correction DD (ppm)
June 1911	3.0013	3.0015	430	500
Jan. 1912	3.00085	3.0012	280	400

The calibration corrections for wooden Fischer rods were very large, in two cases more than 700 ppm. It is also clear from examining the tables that the calibration values were often very unstable, with changes as large as 370 ppm occurring between pre- and post-survey calibrations. The cause of these pre- and post-survey calibration differences is not certain. However, the available information strongly suggests that on most occasions the cause was environmental in nature.

Tables 4 through 9 indicate that the sign of change in calibration constant between pre- and post-survey calibrations is almost always the same for a rod pair, although the exact magnitudes of the changes may be different. Even the character of the change (i.e., whether occurring linearly over the survey period or suddenly) is usually the same for a rod pair. This similarity in calibration changes is most likely explained as variations in environmental conditions since both rods of a rod pair would normally be used and stored together and experience the same environmental effects. Because the calibration changes are far larger than any reasonable thermal effect, the most probable cause of change would appear to be the effect of humidity upon the rods. Perhaps saturation with paraffin to 20 percent of the rod's original weight was not adequate to prevent humidity-induced changes.

Occasionally, there is a large sudden change in the calibration value for one rod of a pair, but not for the other. In this case, a possibility which must always be kept in mind is that movement of one of the brass plugs occurred relative to the wooden part of the rod. If this were the case, the apparent "change in calibration" would be erroneous. The actual location of the black and white checkerboard pattern relative to the bottom of the rod would not be changed by the movement of the brass plug.

Because steel tape measurements were used to control interpolation of pre- and post-survey calibrations, no single fixed procedure existed for obtaining the calibration values used in processing the leveling observations obtained by using the rods. The range of procedures used can best be illustrated by citing two examples.

The December 1899 and January 1901 calibration values for rods T and U, listed in table 5, are associated with a survey performed between June 9, 1900, and December 4, 1900. The steel-tape calibrations carried out in the field did not seem to provide a basis for assuming any calibration "jumps." Thus, the simple mean of pre- and post-calibration values was used for the subsequent reduction of the leveling data.

The June 1900 and January 1901 calibration values for rods V and W, listed in table 6, bound a survey performed between July 1900 and January 1901. The differences between pre- and post-survey calibrations were much larger in this case than in the previous example, reaching 340 ppm for rod W. The steel tape measurements in the field indicated two jumps in calibration. In this case, the June calibration values were used to reduce data for the period July 23 to September 1, the means of the June and January calibration values were used for the period September 2 through November 19, and the January calibration values were used for the period November 20 to the end of the survey.

As noted previously, in 1915 C&GS took standard 1-meter Invar bars into the field and used them to calibrate the wooden rods at regular time intervals. Tables 10 and 11 list the results of these calibrations for two different pairs of rods. These results indicate that calibration changes of as much as 155 ppm occurred over time periods as short as 1 month. These changes were of the same order of magnitude as some of the "instantaneous" changes indicated by the steel tape measurements, which lends credibility to the idea that rapid change may have occurred in calibration of the wooden rods. On the other hand, the results documented in the next section on field calibration of "Invar" rods in 1916 suggest that substantial errors may have been introduced in field calibration determinations when using Invar bars.

Table 10.--Invar-bar field calibrations, from Reno to Las Vegas, Nev., in 1915

Calibration date	Calibrated rod length Rod AA (m)	Calibrated rod length Rod BB (m)
4/09/1915	3.000608	3.001274
6/05/1915	3.000447	3.001009
7/03/1915	3.000117	3.000800
7/28/1915	2.999651	3.000460

Table 11.--Other Invar-bar field calibrations in 1915

Calibration date	Calibrated rod length Rod V (m)	Calibrated rod length Rod W (m)
3/17/1915	3.000420	3.000380
5/ 8/1915	3.000490	3.000530
5/27/1915	3.000400	3.000500
6/10/1915	3.000400	3.000540
7/11/1915	3.000550	3.000590
7/29/1915	3.000180	3.000170
8/12/1915	2.999920	2.999760
8/21/1915	2.999890	2.999820
9/ 1/1915	2.999920	2.999940
9/10/1915	3.000080	3.000090
11/19/1915	3.000280	3.000560

An examination of all the data for paraffin-saturated wooden Fischer rods indicates that height-correlated leveling errors due to inadequate rod calibration may have been in the range of 100 to 200 ppm at various times. Extreme caution must be exercised in crustal movement analyses when using leveling data obtained with these rods.

FISCHER INVAR-SCALE RODS (1916-68)

Fischer rods with metal strips were first introduced in 1916. The C&GS Annual Report for 1916 (pp. 41-42) states that initially the metal used was gamma steel. (It is not clear how gamma steel differed from Invar.) Parkhurst (1927) reports the metal strip used in 1927 was Invar. However, the C&GS Annual Report for 1928 (p. 8) states that first-order leveling rods with graduations on Invar were introduced that year. In any case, from 1916 until the present, the metal used for the rods that will be discussed in this section was either Invar or a similar metal with a coefficient of thermal expansion between 1×10^{-6} and 2×10^{-6}m per °C. For brevity, all metal strips discussed in this section will be referred to as Invar. A few rods were constructed by C&GS between 1916 and 1940 that used a metal called hoop iron with a coefficient of thermal expansion about ten times greater than Invar. These rods will not be discussed. However, there is no indication that these rods were treated any differently than Invar rods with respect to scribing, painting of graduations, or calibration.

The initial Fischer rods are described in detail by Parkhurst (1927). Revised descriptions, reflecting improvements made in the rods, may be found in Parkhurst (1935, 1955). The standard Fischer rod consisted of three parts: a metal strip of Invar about 3.3 m in length attached to a metal footpiece and a wooden backing attached to the footpiece, which supported the metal strip. The reading scale consisted of the familiar black and white checkerboard pattern, painted on the Invar strip as 1-centimeter wide alternating black and white squares. On the wooden part of the rod are alternating black and white sections of 1-decimeter width. These sections aided in correctly reading the centimeter digit from the Invar strip. Figure 1 illustrates the front of a Fischer Invar-scale rod.

In reading a Fischer rod, the leveling instrument was used to interpolate between boundaries of the black-and-white, 1-centimeter segments painted on the Invar strip. Thus, the accuracy of a Fischer rod depended upon the accuracy of the locations of the boundary lines between these black and white segments. Maintaining the accuracy of location of these boundary lines and the overall scale of the rod required a two-step process. First, scribe marks were made on the Invar strip at predetermined intervals. The locations of the scribe marks were determined through transferral of length intervals from a standard Invar reference bar. The scribe marks were then used to control the painting of the black and white checkerboard pattern.

Painting of the black and white tessera on the Invar strip is referred to as graduation of the strip. This was accomplished in a number of different ways as will be discussed in the next section.

Scribing and Graduation of Fischer Rods

The scribing and graduation of Fischer leveling rods can be analyzed in terms of four distinct time periods (table 12) when different procedures were used. Rods were rescribed only on rare occasions. However, because of wear the graduations were repainted on the Invar strips every few years when the rods were in use.

Table 12.--Scribing and graduation of Fischer leveling rods

Time interval	Method of scribing	Method of graduation
1916-26	Unknown	Graduation boundaries established with steel square. Painting by hand.
1927-28	Scribe marks at 1.0, 2.0, and 3.0 m, using graduating machine and meter bar.	Graduating machine with 4-cm painting mask.
1928-51?	Scribe marks at 0.2, 1.2, 2.2, and 3.2 m, using standard reference bar.	Graduating machine with 4-cm painting mask.
1951? to the end of use of Fischer rods	Scribe mark at 0.2 m using precision gage blocks; scribe marks at 1.2, 2.2, and 3.2 m using standard reference bar.	1-meter Invar painting mask.

An initial set of nine Invar-type Fischer rods was introduced during the period 1916-17. An additional 14 rods were introduced in 1920-22. The only published information on either the scribing or graduation of these rods is the following excerpt from Parkhurst (1927; pp. 9, 11) describing how the graduations were placed on the Invar strips prior to the introduction of the graduating machine in 1927:

> This work was formerly done by coating the strip with white paint, then placing it beside a master scale and transferring the dimensions by means of a steel square and scriber. The black squares were then filled in by hand - a most tedious process. With this method it was impossible to obtain uniformity of width, as the scriber cut a shallow groove of finite width, into which the paint would flow, causing a general tendency for the black squares to be wider than the white. Irregularity of the lines of demarcation was also unavoidable...
>
> In the former process, the initial meter line was laid off roughly 1 m from the foot, a scratch line being made on the metal of the strip at this point, the actual distance being carefully measured later.

It is clear that the scribe marks at 0.2, 1.2, 2.2, and 3.2 m played a special role, even in these early Fischer Invar-scale rods because the scribe marks were used in calibrating the rods. However, it is not clear whether these scribe marks were placed on the Invar strip independently by using a standard meter bar as was done later, according to Parkhurst (1935).

Figure 1.--Fischer Invar-scale leveling rod.

Parkhurst (1927) states that the graduation method employed for these initial Fischer Invar-scale rods was unsatisfactory because the procedure was slow and inaccurate. Construction of a machine for more accurately painting the checkerboard pattern onto the rods was begun in 1924 and completed in 1925 (C&GS Annual Report for 1925, p. 51). Improvements in the machine continued until 1927, when it was used to graduate 10 new rods (C&GS Annual Report for 1927, p. 40). In addition to being graduated on the new machine, these rods also differed from the original rods in that the graduated Invar strip was recessed into the wooden part of the rod to prevent wear. Parkhurst (1927, p. 11) describes the graduating machine, circa 1927, as follows:

With the new machine, the comparison method is used thereby avoiding the necessity for cutting a long and accurate lead screw and for working at constant temperature. An invar bar of the same physical characteristics as the strip, accurately ruled in 1 cm. spaces, is located in a groove at the rear of the machine. A microscope is mounted on the carriage carrying a pair of fine parallel tungsten wires in its focal plane. A small electric bulb placed beside the microscope tube shines down upon the comparator bar, causing the ruled lines to stand out brilliantly. The tungsten wires show blackly against this brilliant background, and the setting of the carriage is surprisingly easy.

The cross slide of the carriage carries a vertical slide on which is mounted a cup-shaped turreting mask having four rectangular slots 1 cm. wide cut in the rim. The turret is lowered and pressed against the work by a small eccentric, and the open space is sprayed with a quick-drying black paint by means of a small air brush. As the mask is raised vertically, no difficulty is experienced with smearing the paint, and it is not necessary to wait until it dries. As soon as a square has been painted the mask is raised and the carriage traversed to the next space and the process repeated.

The multiplicity of openings is desirable to facilitate the cleaning away of paint accummulation along the edges of the mask, without delay to the work.

The resulting graduations, both white and black, are all of the same width. The lines of graduation are straight and sharp, and the sharpness is enhanced by the thinness of the black which does not provide a raised and shining surface to cause annoying reflections.

The graduating machine was also initially used to position scribe marks on the Invar strip (Parkhurst 1927). Stops were placed at the end of the machine in such a way that, when the strip with its footpiece attached was placed in position, the 1-meter mark on the strip was almost exactly 1 m from the lower end of the footpiece.

Improvements were made to the graduating machine in 1928, as stated in the C&GS Annual Report for 1928 (p. 37):

Certain improvements were made in machines used to graduate these rods which makes it possible to divide them more accurately. The invar comparison bar was ruled by the Bureau of Standards so that the meter interval is correct within plus or minus 10 microns or 4/10,000 of an inch. The method of transference of the meter intervals from the bar to the rod was so improved that it was possible to have the calibration carried one decimal point farther; that is, to hundredths of a millimeter instead of tenths as formerly.

Parkhurst (1935) describes the placing of scribe marks at 1-meter intervals on the Invar strips beginning at the 0.2-meter scribe mark, and using the marks to position the rod for painting the checkerboard pattern as follows:

> A line is carefully ruled on a small polished area of the level strip, 2 decimeters from the end of the footpiece. This interval is carefully checked and calibrated, and if found to be within the allowable limit of 0.1 millimeter, three additional lines each 1 meter apart are ruled along the length of the rod and their intervals calibrated. If the error in any interval is found to exceed 0.1 millimeter, the rods are rejected and regraduated. These reference lines are then used in locating the strip in the graduating machine in order to apply the black squares in their correct position.

It is clear from this quote that since the early 1930's scribe marks at the 0.2, 1.2, 2.2, and 3.2-meter points have been the key scribe marks on the Invar rods. These marks were placed on the rods initially, used to position the rod in the graduating machine, and used in calibrating the rods.

There are strong indications that the procedures stated in Parkhurst (1935) were used as early as mid-1928 after completing improvements to the graduating machine described in the previous excerpt from the C&GS Annual Report for 1928. There is also a strong indication that the rods originally scribed and graduated in 1927 were rescribed and regraduated in 1928.

The sequence of events for scribing and graduating the leveling rods appears to have been the following: The key scribe marks on the rods introduced during the 1916-22 time period were at 0.2, 1.2, 2.2, and 3.2 m, as stated previously. These scribe marks were used by NBS to calibrate these early rods from 1924 through early 1927. When the 10 new rods, which were scribed and graduated in 1927 with the new machine, were calibrated by NBS in mid-1927 the calibration intervals were 0 to 1.0, 1.0 to 2.0, and 2.0 to 3.0 m. This would appear to agree with the comments made by Parkhurst (1927) concerning the way in which the graduating machine was initially used to place the 1-meter mark accurately on the rods. The problem with this method of scribing and calibrating is the inability to separate an index error from a calibration error. In mid-1928, all 10 rods introduced in 1927 were recalibrated using the intervals 0.0 to 0.2, 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m, as was done prior to mid-1927. This same procedure continued to be used for all Invar Fischer rods introduced after 1928. For most of the rods recalibrated in 1928, the change in calibration was substantial. The most logical explanation for the substantial changes in calibration, together with the change in calibration intervals, is that the rods were rescribed and regraduated in early 1928, using the procedure described by Parkhurst (1935) which employed the improved graduating machine.

In time, methods of scribing and graduating the rods improved. Parkhurst (1955) summarizes the methods used by C&GS in 1955. The initial scribe mark at the 0.2-meter point was located with precision gage blocks. Based on a comment in the C&GS Annual Report for 1951 (p. 58), it appears that the introduction of precision gage blocks may have occurred that year. Once this initial scribe mark was located, a comparator was used to locate the scribe marks at 1.2, 2.2, and 3.2 m. The scribe marks were cut with diamond and were "only a few thousandths of an inch wide," according to Parkhurst (1955). Painting of the graduations was accomplished using a 1-meter long Invar mask (Parkhurst 1955, pp. 15-16), as follows:

The "working" graduations on the invar strip are in the form of a black and white checkerwork, the blocks being .01 ± .0001 m. in width. These are applied by spraying black lacquer through a 100 opening mask, made of invar of the same category as the rod strip so that changes in temperature, which may occur during the progress of the work, may be ignored.

This mask is specially designed and constructed, using L-shaped blocks mounted in channels in a frame, the position of each block being checked with gage blocks during assembly to insure that the mask openings are correctly positioned within the prescribed tolerance.

The corners of the blocks located at 0 and 1 m. are clipped approximately 1/8" to provide an opening for observing the reference lines on the invar. When preparing to paint, the mask is placed upon the invar strip and carefully registered by observing the reference lines and edges of the masking blocks through a small microscope to insure that they are in alignment.

The weight of the mask is sufficient to hold it in place, and the openings are sprayed with a quick drying dull black lacquer. The process is repeated until the entire rod is completed, after which the surface of the strip is given a light spray coating of clear pyroxylin base lacquer and, when thoroughly dry, a coating of auto body wax.

The date when the procedures for graduating the rods changed from the method described in Parkhurst (1935) to the procedures described later by Parkhurst (1955) is unknown. There does not appear to have been any significant changes in subsequent years in scribing and graduation procedures from those described in Parkhurst (1955).

Calibration of Fischer Rods

The calibration of Fischer rods, as with other rods, involved the measurement of a few selected length intervals using the bottom of the rod and a few scribe marks. The calibration procedures employed for C&GS Fischer rods are conveniently broken into eight periods, when different agencies or methods were employed. (See table 13.) During the intervening years between the time periods listed, no calibrations were performed.

From 1916 through 1923, C&GS calibrated its own leveling rods in the laboratory using standard Invar reference bars. The intervals 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m were calibrated using the standard reference bars. The lengths of the 1-meter segments were estimated to ± 0.01 mm during calibration. However, it is unlikely that the accuracy of the measurement was this good. A more probable accuracy for the measurement of the distance between the 0.2- and 3.2-meter scribe marks during calibration would be about 0.05 to 0.10 mm. The exact method of calibrating the 0.0 to 0.2-meter interval during this period is not clear.

Table 13.--Calibration methods and measurement intervals for Fischer leveling rods

Time period	Agency	Intervals measured (m)	Methods of calibration
1916-23	C&GS	0.0-0.2, 0.2-1.2, 1.2-2.2, 2.2-3.2	Standard invar reference bar.
1924 - Apr.1927	NBS	0.0-0.2, 0.2-1.2 1.2-2.2, 2.2-3.2	Standard reference bar?
June 1927-June 1928	NBS	0.0-1.0, 1.0-2.0, 2.0-3.0	Standard reference bar?
July 1928 - 1929	NBS	0.0-0.2, 0.2-1.2 1.2-2.2, 2.2-3.2	Standard reference bar?
1930-39	NBS	0.0-0.2, 0.2-1.2 0.2-2.2, 0.2-3.2	Standardized steel tape?
1942-45	NBS	0.0-0.2, 0.0-1.2 0.0-2.2, 0.0-3.2	Standardized steel tape?
1949-63	NBS	0.0-0.2, 0.2-1.2 0.2-2.2, 0.2-3.2	Standardized steel tape, precision gage block.
1964-68	NBS	0.0-0.2, 0.2-1.2 1.2-2.2, 2.2-3.2	Standard Invar meter bar, precision gage block.

In 1916, field calibration measurements with an Invar bar (originally initiated in 1915 to detect changes in wooden rods) were continued. In researching this report, the author identified a line leveled in 1916 from Clovis, N. Mex., to Pecos, Tex., where calibrations were performed in the field. Kumar and Poetzschke (1981) also identified a line leveled in 1916, from Little Rock, Ark., to Memphis, Tenn., where this procedure had been employed. The field calibration values for the Clovis-Pecos line were highly variable (table 14) and were not

Table 14.--Invar-bar field calibrations performed in the field in 1916 (Clovis, N. Mex., to Pecos, Tex.)

Calibrated rod length	
Rod 201	Rod 202
2.999468	3.000170
2.999974	3.000174
3.000060	3.000160
3.000191	3.000589

used even at that time for data reduction. The practice of calibrating the rods in the field was apparently discontinued after 1916. The real significance of the 1916 field calibrations of Invar leveling rods is the large temporal variability of the calibrations which seems unlikely to represent real changes in the lengths of the Invar rods. This casts doubts on the 1915 field calibrations of the wooden Fischer rods which were used for carrying out data reduction.

The National Bureau of Standards assumed responsibility for calibrating C&GS leveling rods in 1924. There is little information available on how calibrations were carried out between 1924 and 1949. A conjecture can be formed, however, based on the intervals for which calibration values were reported. Between 1924 and 1929, the results are reported for either the intervals 0.0 to 0.2, 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m; or the intervals 0.0 to 1.0, 1.0 to 2.0, and 2.0 to 3.0 m. The procedure of reporting the 1-meter intervals individually, as done by C&GS prior to 1924, suggests that NBS continued to use standard 1-meter invar reference bars for calibration during 1924-29. From 1930 to 1945, the calibration intervals reported were either 0.0 to 0.2, 0.2 to 1.2, 0.2 to 2.2, and 0.2 to 3.2 m; or 0.0 to 0.2, 0.0 to 1.2, 0.0 to 2.2, and 0.0 to 3.2 m. It is known from archival records that steel tapes were used from 1949 through 1963 for calibration to determine the intervals 0.2 to 1.2, 0.2 to 2.2, and 0.2 to 3.2 m. Precision gage blocks were used to calibrate the interval 0.0 to 0.2 m. Based upon the similarity of the calibrated intervals reported, it seems probable that the calibrations carried out between 1930 and 1945 were made using a steel tape, in a manner similar to that carried out in the period 1949-63. The method used for calibration measurements of the interval 0.0 to 0.2 m during the earlier period (1930-45) is not clear.

When a steel tape was used for calibration, the Invar strip was laid horizontally adjacent to the steel tape and a microscope was used to compare the steel tape and the Invar strip. The steel tape itself was under 10 to 25 lb of tension. The Invar strip was either under no tension or a nominal tension of no more than 5 lb (Kumar and Poetzschke 1981). During the period 1949-63, the calibration results were recorded to the nearest 0.01 mm. Data were rounded to the nearest 0.1 mm when the results were reported.

Beginning in 1964, the calibration procedure used by NBS again changed. From 1964 until 1968 when the calibration of Fischer Invar rods was discontinued, the intervals 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m were calibrated by using standard Invar bars. The interval from 0.0 to 0.2 m continued to be calibrated using standard gage blocks. During this period, the calibration was carried out with the rod remaining intact and the Invar bar placed under tension for all calibration measurements. The calibration measurements were recorded to the nearest 0.001 mm and rounded to the nearest 0.01 mm.

Results of Calibrations

Table 15 lists the mean calibration values in parts per million (ppm) and microns derived from various office calibrations for rods 201 to 209. The calibration values have been rounded to the nearest 5 ppm. Except for the 1925 calibrations of rods 201 and 202 by NBS, all calibrations were made by C&GS. Keeping in mind that the probable error of any single calibration determination is 30 ppm, there is a clear indication of overall change in calibration values for only rods 202 and 206, insofar as C&GS calibrations are concerned. The NBS calibrations of rods 201 and 202 appear to give somewhat larger calibration corrections than those obtained by C&GS.

Table 15.--Mean calibration values for rods 201 to 209. Values in parentheses indicate mean calibration correction (in parts per million). Values without parentheses show excess in 3 meter rod length (in microns).

Calibration dates		Rod number								
Year	Month	201	202	203	204	205	206	207	208	209
1916	9-11	(60) 180	(95) 280	(130) 390	(215) 640	(110) 330			(65) 190	(115) 350
1917	1-4	(50) 150	(65) 200	(135) 400	(225) 680	(150) 450	(10) 30	(100) 300		
1918	3-6	(85) 260	(190) 570	(125) 370	(185) 560		(25) 80	(120) 360		
1919	7					(145) 430		(105) 320	(60) 180	(70) 210
1919	10-12				(170) 510		(25) 70		(45) 130	(100) 300
1920	3	(60) 180	(170) 510			(175) 530		(95) 290	(50) 150	(170) 510
1920	8-11	(65) 190	(180) 540		(175) 530		(100) 300			(115) 340
1921	7								(50) 150	(125) 370
1922	2						(85) 250		(60) 180	(120) 360
1922	5					(150) 450				
1925	10	(135) 400	(235) 700							

Table 16 shows some average values of calibration corrections for individual 1-meter intervals of rods 201 through 209. The change in calibration of rod 202 represents a general increase in length of all 1-meter segments. The cause of this change is not clear. It could have represented changes in the length of the rod over a period of time or it could have been the result of rescribing. The change in calibration constant for rod 206 is clearly due to a change in position of the scribe mark at the 0.2-meter point only. Table 16 also shows that a change occurred in position of the scribe mark at the 2.2-meter point for rod 208. This change did not affect the overall calibration of the rod because the position of the 0.2- and 3.2-meter points remained unchanged. Tables 15 and 16 demonstrate that the calibration corrections for rods 201 through 209 are large and substantially nonlinear.

Table 16.--Average interval calibration values (in ppm) for rods 201 to 209

Rod No.	Calibration intervals			Number of calibrations averaged
	0.2-1.2 m	1.2-2.2 m	2.2-3.2 m	
201	16	106	70	5
202	52	109	77	2 (1916-17)
	131	178	233	3 (1918-20)
203	170	142	79	4
204	262	170	173	5
205	194	136	108	5
206	58	-35	37	3 (1917-18)
	254	-6	25	2 (1920-22)
207	95	146	70	4
208	19	86	65	3 (1916-19)
	11	219	-69	3 (1920-22)
209	100	153	113	6

Tables 17 and 18 list the mean and interval calibration results for rods 218 to 231, which were first introduced during the period 1920-22. The overall calibration corrections are smaller than those for the original rods (generally less than 100 ppm) and are more linear. Apparently, the techniques for scribing with the steel square had improved between 1916-17 and 1920-22. The initial calibrations during the period 1920-1922, reported in tables 17 and 18, were carried out by C&GS. Later calibrations were performed by NBS.

Table 19 shows the calibration results for the third set of Invar rods, consisting of 10 rods introduced by C&GS in 1927. As noted previously, these rods were calibrated using the intervals 0.0 to 1.0, 1.0 to 2.0, and 2.0 to 3.0 m during the period June 1927 through June 1928. Beginning in July 1928, calibration measurements returned to the intervals 0 to 0.2, 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m. Table 19 shows that the initial scribing in 1927 resulted in large calibration corrections. Beginning in July 1928, there was not only a return to the previous calibration intervals but a large reduction in the magnitude of the calibration correction. It appears that this change in calibration correction occurred when the rods were rescribed in early 1928.

Table 17.--Mean calibration values for rod numbers 218 to 231

Calibration dates		Rod number													
Year	Month	218	219	220	221	222	223	224	225	226	227	228	229	230	231
1920	10	(55) 170	(30) 90												
1921	4-5			(75) 230	(85) 260	(30) 90	(20) 60	(35) 100	(35) 110						
1922	2-5			(125) 380	(45) 140	(5) 10	(50) 150			(30) 90	0	(15) 40	(10) 30	(25) 80	(5) 20
1924	5			(65) 200	0	(65) 200	(35) 100	(65) 200	(35) 100	(35) 100	(35) 100	(65) 200	(35) 100	(65) 200	(35) 100
1926	1									(65) 200	(65) 200				
1926	11				(100) 300	(65) 200									
1927	4			(65) 200			(65) 200								
1928	7								(20) 60			(25) 80	(5) 20		
1930	6			(35) 100			(35) 100	(0) 0	(100) 300	(100) 300		(100) 300			
1930	10									(-35) -100				(-65) -200	
1930-31	12-1	(-35) -100		(-65) -200											(-65) -200
1942	6-8	0		0								0	0	0	(-35) -100
1945	6								0						
1952	4	0												0	

Table 18.--Average interval calibration values (in ppm) for rods 218 to 231, C&GS calibrations only.

Rod No.	Calibration intervals 0.2-1.2 m	1.2-2.2 m	2.2-3.2 m	No. of Calibrations averaged
218	71	19	83	1
219	47	22	22	1
220	127	82	95	2
221	96	65	39	2
222	30	0	67	2
223	64	1	39	2
224	46	20	33	1
225	59	8	46	1
226	33	83	-31	1
227	19	57	-70	1
228	45	-31	31	1
229	7	20	7	1
230	31	69	-20	1
231	3	29	-10	1

After the 1927-28 period, most of the leveling rods manufactured for the next 40 years were first calibrated during three relatively short time periods: 171 rods were first calibrated in the 1930-35 period, 259 rods in 1949-52, and 130 rods in 1955-57. The calibration measurements made by NBS after 1928 can best be divided into three groups: pre-World War II calibrations made in the period 1930-39, post-World War II calibrations made with steel tapes in the period 1949-63, and calibrations with an Invar bar carried out during 1964-68.

Figures 2, 3, and 4 graphically depict the results of the overall calibrations by NBS for the three time periods. The results for the 1949-63 period were taken from archival records before rounding. Because of the greater resolution, it is worthwhile to compare the 1949-63 and 1964-68 calibrations before considering the 1930-39 calibrations. As shown in figure 5, where the results of figures 3 and 4 are superimposed, the primary difference between the two calibration sets is a systematic difference of about 20 ppm. After taking into account this systematic difference, the variability of calibration values is essentially the same during the two time periods despite the fact that the 1964-68 calibration determinations were said by NBS to be more accurate.

Figure 6 superimposes the results shown in figures 2 and 4. Because the calibration results of the total 3-meter rod length in the 1930-39 period were rounded to the nearest 0.1 mm, calibrations are only available as discrete values at 33 ppm intervals. Although the rounding makes comparisons less clear, the data in figure 6 are compatible with the assumption that the scatter of calibration values in the 1930-39 period was no greater than in the 1964-68 period. In this case, however, there is an indication of a systematic difference of about 50 ppm in the calibration values.

Table 19.--Mean calibration values for rods introduced in 1927
(Calibration corrections in ppm)

Calibration date		Rod number									
Year	Month	243	244	245	246	247	248	249	250	251	252
1927		400	400	600	200	400	400	700	600	600	600
1928	1-2			500	200	100	-100	0	300		
1928	6			-100	0						
1928	7	-110	-60					40	-10		
1930				0	100	0				0	0
1931-33					-100		-100				
1939					-400						
1942-45		-100	-100		-100			0	0		
1951-53			-100	0						0	
1956									-100		
1960						-100		-40			
1967										50	

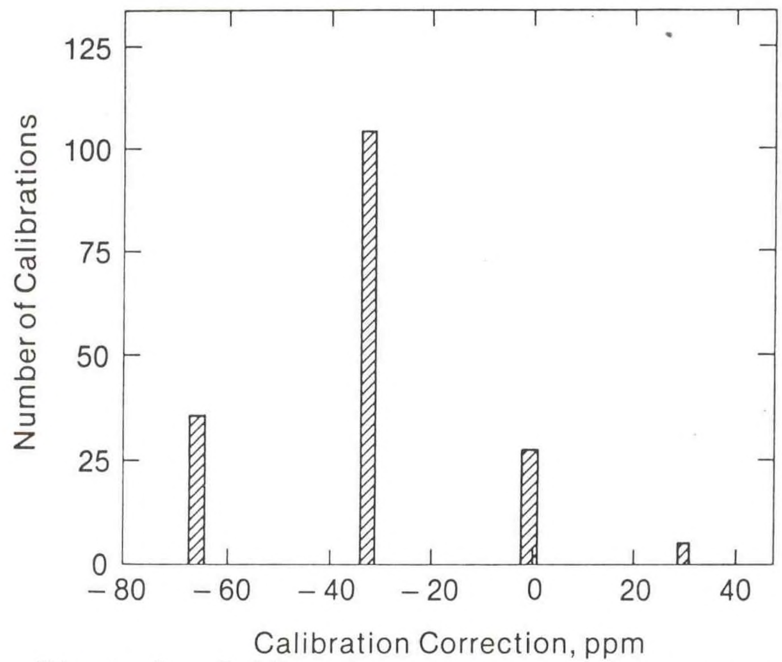

Figure 2.--Calibration corrections for Coast and Geodetic Survey leveling rods during 1930-39.

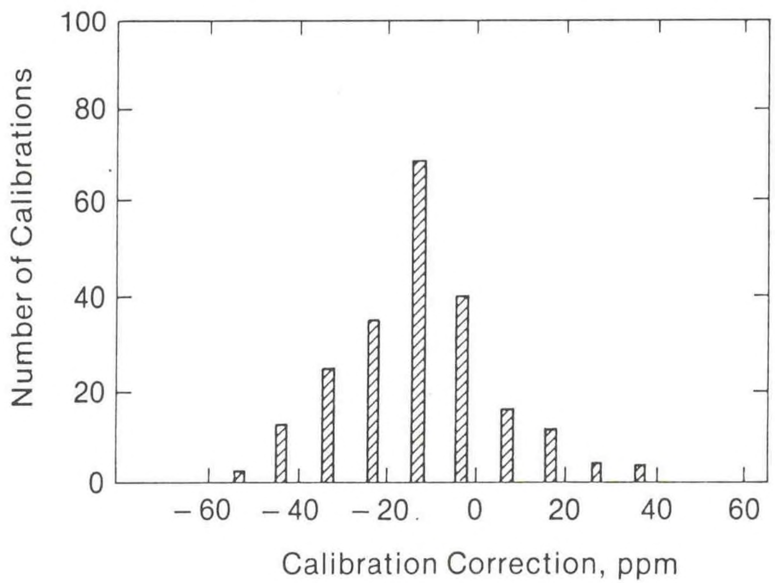

Figure 3.--Calibration corrections for Coast and Geodetic Survey leveling rods during 1949-63.

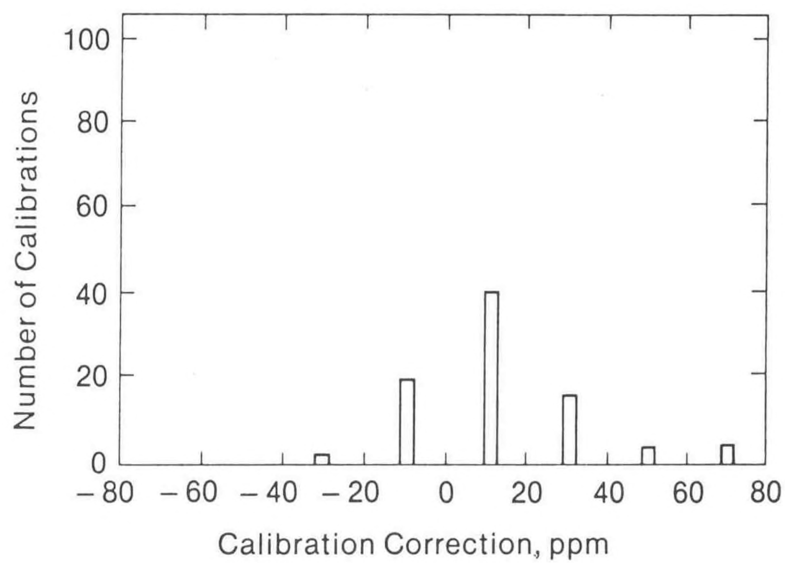

Figure 4.--Calibration corrections for Coast and Geodetic Survey leveling rods during 1964-68.

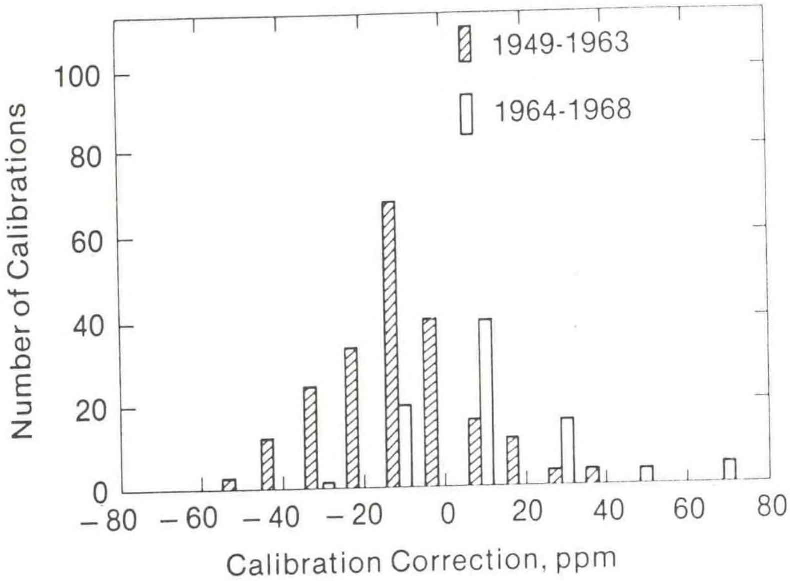

Figure 5.--Comparison of 1949-63 and 1964-68 leveling rod calibration corrections.

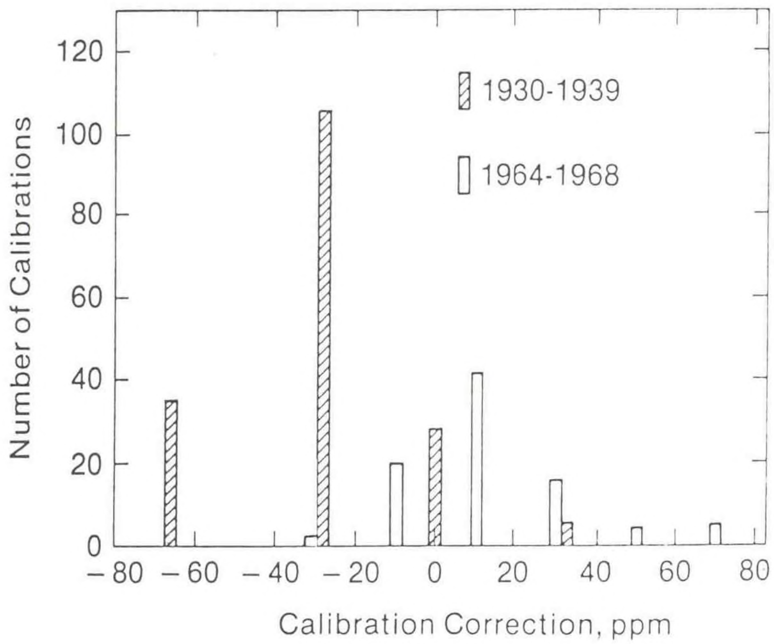

Figure 6.--Comparison of 1930-39 and 1964-68 leveling rod calibration corrections.

The results in figures 2 through 6 support the conclusion that during the time periods of 1930-39, 1949-63, and 1964-68 the difference between scribing and calibration due to random error is about ± 30 ppm rms. However, systematic differences on the order of 20 to 50 ppm between the scribing and the calibrations from time period to time period are evident.

One reason for the systematic differences was the change in calibration procedure introduced in 1964. Prior to 1964, the Invar strips were removed from the wooden part of the leveling rod before calibration. Beginning in 1964, the Invar strips remained in place and were not removed. Beginning in 1964, an important result of this procedural change was that the Invar strips were calibrated under a tension of about 25 lb, which was the nominal tension maintained during field use. Prior to 1964, the Invar strips had been calibrated either without tension or with little tension (3 to 5 lb).

In 1965, a test was performed to determine the effect of tension on calibration values. The test results are reported in a memorandum dated March 1, 1965, from Mr. J. S. Beers, Acting Chief, Length Section, Metrology Division, National Bureau of Standards to the Director, U.S. Coast and Geodetic Survey. Table 20 indicates the results of this test; the effect of applying tension changed the calibration of the rods by 25 to 60 ppm.

Table 20.--Rod calibration values without tension and with tension

Rod No.	Interval (m)	Interval corrections at 25 °C: Without tension (mm)	Interval corrections at 25 °C: With tension (mm)
268	0.2 - 1.2	-0.041	0.016
	0.2 - 2.2	-0.031	0.068
274	0.2 - 1.2	-0.070	-0.063
	0.2 - 2.2	-0.114	-0.076
364	0.2 - 1.2	-0.041	0.011
	0.2 - 2.2	-0.081	0.034
	0.2 - 3.2	-0.124	0.063
369	0.2 - 1.2	-0.034	0.031
	0.2 - 2.2	-0.035	0.097
	0.2 - 3.2	-0.054	0.148

The effect of tension could account entirely for the systematic differences between calibrations carried out during different time periods. There are two possible causes for this effect. Beers in his memorandum states: "The exact amount of the decrease in the length of the strip due only to the release of tension, and what amount is due to any small undulating departures of the strip surface from a common plane without tension cannot be ascertained." The possibility of the Invar strip having departures from planarity when not under tension could explain why the effects of applying tension were greater than might be expected if one considered only the expected elastic deformation of the strip taking into account its dimensions and Young's modulus for Invar.

From figure 5 it can be seen that the systematic difference between 1949-63 calibration corrections obtained without spring tension and 1964-68 corrections obtained with spring tension is not as large as might be expected from the results shown in table 20. A possible explanation for this is that the nominal spring tension of 25 lb was often not maintained in the field. C. F. Ellingwood (personal communication, 1982) has pointed out that the spring used to apply tension was a short compression spring which was subject to fatigue, and rods were often sent back from the field with much less than 25 lb pressure being exerted by the spring.

Relation of Scribe Marks to Painted Graduations

In using Fischer Invar-scale rods, the actual reading of the rods in the field is carried out by using the alternating black and white graduations painted on the Invar strip. Thus, errors caused by the leveling rods arise not only from errors in placing scribe marks on the rods, but also from errors in relating the painted graduations to the scribe marks. The errors in relating painted graduations to the scribe marks would not be reflected in the calibration corrections, which account only for errors in the location of the scribe marks themselves.

As indicated in a previous section, three different methods were used to place the painted graduations on the rods. During the period 1916-26, every intersection between painted graduations was scribed by using a metal square. Other than the comments already made about the unsatisfactory nature of this approach, and in the absence of documentation, little more can be said about the exact details of how the procedure was carried out.

From 1927 until 1968, either a 4-centimeter mask associated with a comparator (1927-1951?) or a 1-meter Invar mask (1951?-1968) was used for painting graduations on the rods. In addition to random errors, the use of the masks could have introduced certain types of systematic errors. In using the comparator and the 4-centimeter mask, each 1-meter segment of the Invar strip, 0.2 to 1.2, 1.2 to 2.2, and 2.2 to 3.2 m, was registered independently in the comparator when painting the graduations. The 0.2- and 1.2-meter scribe marks were used to register the first segment, the 1.2- and 2.2-meter marks to register the second segment, and the 2.2- and 3.2-meter marks to register the third segment. When using a 1-meter Invar mask, a somewhat analogous situation occurred. The 0.2- and 1.2-meter scribe marks were used to register the mask for one segment, the 1.2- and 2.2-meter scribe marks to register the mask for the second segment, and the 2.2- and 3.2-meter scribe marks to register the mask for the third segment.

Errors in placing the painted graduations on the Invar strips would occur due to differences in the length of the nominal 1-meter intervals on the Invar as defined by the scribe marks and the nominal 1-meter interval on the 1-meter mask. Errors would also arise due to errors in registering the Invar strip relative to either the comparator bar or the 1-meter Invar mask. The fact that each 1-meter interval was registered separately caused registration errors to occur as localized errors at the 1.2- and 2.2-meter points on the Invar strip. Therefore, it is worthwhile to consider the effects of the localized errors associated with placing graduations on the Invar strip.

When leveling a section the nominal procedure is to alternate rods, beginning and ending with the same rod. Designate the readings on rods A and B during the ith setup as a_i and b_i.

Then the total elevation change, ΔH, after N setups, assuming an even number of setups, will be

$$\Delta H = \Delta h_1 + \Delta h_2 + \ldots + \Delta h_N = (a_1 - b_1) + (b_2 - a_2) + \ldots + (b_N - a_N),$$

which can be rearranged to give

$$\Delta H = (a_1 - a_N) + \sum_{\ell=1}^{N-3} (a_{\ell+2} - a_{\ell+1}) + \sum_{\ell=1}^{N-1} (b_{\ell+1} - b_\ell).$$

Then errors due to lack of agreement between the 1-meter Invar mask or the comparator bar and the scribe marks on the rod can be expressed in terms of differences between subsequent readings on the same rod. Because the height of a leveling instrument is about 1.5 m, it is not possible to read just above the 1.2- or 2.2-meter points on the rod on one setup and just below the same discontinuity on the next setup when continuing to level on an uphill slope. If we denote the downhill reading A_1, the uphill reading A_2, and the localized error ε, the expected errors can be summarized as shown in table 21. Unless the errors in the lengths of the 1-meter Invar mask or the reference calibrator bar are greater than the scribing errors, and thus ε is much larger than the scribing error, the error due to the graduation discontinuities would not be expected to be any greater than the scribing error.

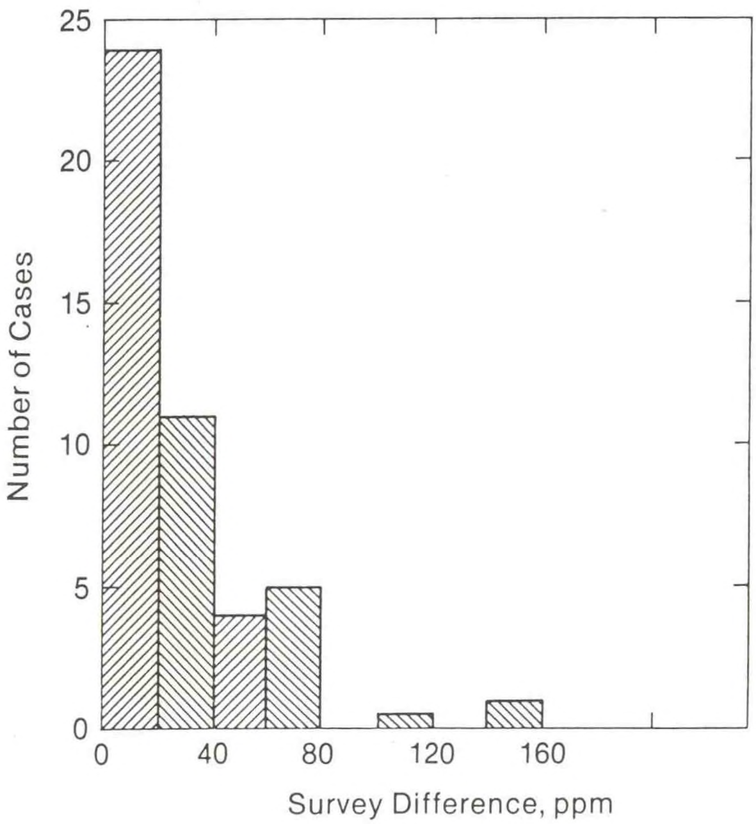

Figure 7.--Comparison of apparent scale differences of leveling rods used in repeated levelings in southern California.

Table 21.--Errors resulting from rod graduation discontinuities

Both A_1 and A_2 between 1.2 and 2.2 m:
Error = $(A_1 - A_2)\varepsilon$
Error is proportional to height difference
Error between 0 and ε.
A_1 between 1.2 and 2.2 m; A_2 between 0.2 and 1.2 m:
Error = $[1-(A_1 - A_2)]\varepsilon$
$(A_1 - A_2)$ between 0.5 and 1.5 m most of time
Error between 0.5 ε and -0.5 ε most of time.
A_1 between 2.2 and 3.2 m; A_2 between 1.2 and 2.2 m:
Error = $[1-(A_1 - A_2)]\varepsilon$
$(A_1 - A_2)$ between 0.5 and 1.5 m most of time
Error between 0.5 ε and -0.5 ε most of time.
A_1 between 2.2 and 3.2 m; A_2 between 0.2 and 1.2 m:
Error = $2\varepsilon - (A_1 - A_2)\varepsilon$
$(A_1 - A_2)$ between 1.9 and 2.7 m.
Error between 1.0 ε and -0.7 ε.

The actual error due to calibration and scribing of Invar rods can only be determined by comparing repeated levelings. Figure 7, which was taken from Strange (1980), shows the maximum possible rod calibration effects obtained by comparing 64 repeated levelings over 17 profiles.

The apparent scale differences between the rods indicate that the combined effects of rod calibration error and any effects of errors in graduations seldom exceed 50 ppm. This indicates that, in general, calibration and graduation errors are normally small after 1930, although in exceptional instances errors of more than 100 ppm have occurred (Strange 1981).

ACKNOWLEDGMENT

Special thanks are expressed to Mr. Cecil Ellingwood, retired chief of the Vertical Network Branch of NGS, and Mr. Gary Young, currently assistant chief of the Vertical Network Division of NGS, for reviewing this report and verifying its contents. I would also like to thank Mrs. Eleanor Andree for the tremendous effort on her part in editing the manuscript and Mrs. Karen Weathers for patiently typing the many iterations of this report.

References

Avers, H. G. and Cowie, G. D., 1916: Precise leveling from Reno to Las Vegas, Nev., and from Tonopah Junction, Nev. to Laws, Cal. Serial No. 49, U.S. Coast and Geodetic Survey, 49 pp.

Kumar, M. and Poetzschke, H., 1981: Level rod calibration procedures at the National Geodetic Survey (unpublished manuscript).

Parkhurst, D. L., 1955: Geodetic leveling instruments. Special Publication No. 334, U.S. Coast and Geodetic Survey, 22 pp.

Parkhurst, D. L., 1935: Geodetic level and rod. Special Publication No. 129 (revised), U.S. Coast and Geodetic Survey, 11 pp.

Parkhurst, D. L., 1927: Geodetic level and rod. Special Publication No. 129, Coast and Geodetic Survey, 11 pp.

Strange, W. E., 1981: The impact of refraction correction on leveling interpretations in Southern California. Journal of Geophysical Research, 86, (B4), 2809-2824.

Strange, W. E., 1980: The effect of systematic errors on geodynamic analysis. Proceedings of the Second International Symposium on Problems Related to the Redefinition of North American Vertical Geodetic Networks, G. Lachapelle, editor, Canadian Institute of Surveying, Ottawa, Canada, pp. 705-728.

The U.S. Coast and Geodetic Survey Annual Reports and the other C&GS publications cited in this publication are now out of print, but they remain a part of the historical records of the National Geodetic Survey. These documents may be viewed at the National Geodetic Information Center (NGIC), Rm. 14, 11400 Rockville Pike, Rockville, Md. Electrostatic reproduction of these documents may be requested from the Geodetic Reference Services Group, NGIC, NGS/NOS, Rockville, MD 20852.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Survey
National Geodetic Survey,
Rockville, Maryland 20852

OFFICIAL BUSINESS

LETTER MAIL

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-210

U.S.MAIL ®

THIRD CLASS