History of Geodetic Leveling in the United States

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ABSTRACT. The term "geodetic leveling" is defined in broad terms. Development of basic instrumentation for leveling is discussed. Geodetic leveling seems to have been started by the U.S. Coast Survey in 1856 along the Hudson River. The U.S. Lake Survey (Corps of Engineers) began geodetic leveling in 1875, based on the Coast Survey leveling of 1856. The Coast Survey commenced the Transcontinental Leveling at Hagerstown, Md., in 1877. Geodetic leveling was started by the U.S. Geological Survey in 1884, with a loop from Morehead City, N.C., inland to Knoxville and Chattanooga, Tenn., and back to Brunswick, Ga. The first general adjustment of the geodetic leveling network in the United States was made in 1900, containing links by the Coast and Geodetic Survey, Corps of Engineers, Geological Survey, and several railroads. Other adjustments were made in 1903, 1907, 1912, and 1929, the last of which defined the currently used National Geodetic Vertical Datum of 1929.

Introduction

Geodetic leveling has been defined as ". . . leveling of a high order of accuracy, usually extended over large areas, to furnish accurate vertical *control* . . . for all surveying and mapping operations."[1] There are two important considerations involved in this definition, "high order of accuracy" and extension "over large areas."

High order of *accuracy* (to be carefully distinguished from *precision*) is to be achieved only by use of a combination of a carefully designed and precisely constructed set of instruments (level and rods), used by a competent and conscientious observer, in accordance with a proper observing routine, together with a data reduction system that applies appropriate corrections for all the physical and environmental situations that may affect the condition and/or calibration parameters of the instruments and observing conditions. If this is accomplished, the magnitude of accidental errors will be minimized and the effects of systematic errors will be essentially compensated. It must be realized that, because of the requirement in the definition that geodetic levels will usually extend over large areas, it is extremely important to search out and understand all the sources of systematic error, so as to assure satisfactory compensation for them. Systematic errors tend to accumulate linearly, so that the effect of even the smallest error in a single operation (a single setup) can accumulate to intolerable magnitudes in long lines. Thus, to recapitulate, geodetic leveling produces accurate elevations, singularly free from the effects of systematic errors, even when extended over long distances. These results are accomplished through the use of precise instrumentation, precise observers, and fastidious application of procedures which were developed through study of all the scientific principles and hypotheses which are believed to affect the observations.

A distinction has been made between geodetic leveling and "precise leveling,"[2] in which the point is made that in geodetic leveling all known imperfections in the instrument system (collimation, rod calibration, temperature, imbalance between foresight and back-distances, etc.) are compensated by the application of computed corrections, whereas in precise leveling it is attempted to reduce the magnitude of the observational errors to tolerable limits by careful and frequent adjustment and calibration of the instrument system, by which process the calculation of systematic corrections is minimized or totally eliminated.

The distinction between ordinary "construction levels" and geodetic leveling was well stated by Molitor in 1901,[3] when he wrote, "Leveling, as commonly conducted, belongs to the most primitive surveying operations. However, when there is presented the problem of spanning the continent by lines of levels which shall be as accurate as the highest skill and most perfect instruments will permit, then it may be truly said that the primitive art has advanced to the status of a science. Leveling is simple only when it is permissible to neglect all small errors; it becomes more complicated and requires more painstaking in proportion to the accuracy required."

A narrow, clear-cut, technical definition for geodetic leveling has thus not been established in the past nor will one be brought out here. Let it suffice to point out that a considerable amount of early leveling that served the geodetic community was described as "precise" leveling.

Construction leveling was undertaken with satisfactory results by the ancient Egyptians in an attempt to connect the Nile River with the Red Sea, by the Babylonians in their extensive irrigation system in the Euphrates Valley, and by the Romans with their extensive systems of aqueducts, not only in Rome but in such distant localities as Spain and the Middle East; but these were dependent on crude instruments that had provision for sighting along a water surface[4] or by some mechanical application of a plumb line.[5]

The accomplishment of leveling which meets the definition of *geodetic* leveling depends on more sophisticated equipment whose facility depends on the invention of three important items: (1) the telescope, (2) the reticle with cross wires, and (3) the level vial.

The telescope seems to have been invented by a Dutch optician (spectaclemaker) by the name of Lippershey in 1608,[6] but was first used for scientific purposes by Galileo Galilei in 1609,[7] which provided a means of magnifying the image of a distant object, but was not very useful as a pointing device until the introduction of the reticle.

The reticle, which provides "cross hairs" at the common focus of the objective and the ocular, was not possible until the invention of the "positive" ocular lens by Johann Kepler in 1611,[8] and the actual placing of a measuring device at the common focus by the English astronomer, William Gascoigne, in 1639. Final accomplishment was attained in 1669 by Jean Picard,[9] working on a project of the Royal Academy of France to measure the length of a degree of latitude, who was the first person to put cross hairs in the reticle of a surveying instrument.

The invention of the level vial, i.e., a tube of glass with fluid sealed inside of it in such manner as to form a bubble, is credited to Melchisedech Thevenot who published its details and method of manufacture in 1666.[10] It was nearly a hundred years later that procedures were perfected to manufacture level vials with uniform curvature, hence the three critical components were assembled in a "spirit level" that was similar to the "engineer's level," which is still used occasionally today on construction work. It is said that this result was accomplished independently by Antoine de Chezy, road and bridge engineer, in France and by Jesse Ramsden, mathematical instrumentmaker, in England.[11]

The chronology of these developments is indicated by references in textbooks: e.g., Love, in 1760, in his classical *Geodaesia*,[12] under the heading, "How to know whether water may be made to run from a Spring head to any appointed place," makes the recommendation that ". . . it is better to get a water-level, such as you may buy at the Instrument-Makers . . ." and, on the other hand, by the appearance of a complete manual of leveling by Simms[13] in England with editions in 1836, 1842, and 1846, with treatment of correction for curvature and refraction, calculation of earthwork from cross sections taken with the spirit level, etc., and with reference to both the "Y Level" and the "Dumpy Level," spirit levels of designs with which 20th century engineers are familiar. Smart[14] states that the Y level was invented in 1740 by Jonathan Sissons of London, and the Dumpy level in 1845 by William Gavatt in England.

The first network of leveling which covered an area large enough to be considered "geodetic" was undertaken in France in the latter part of the 17th century[15] for the improvement of French waterways, under the direction of Jean Picard, the inventor of "cross hairs," but the low accuracy of this work precluded it from being classified in the geodetic category. The first scheme for leveling which met both criteria in the definition of geodetic leveling was again in France, executed under the direction of M. Bourdaloue between 1857 and 1860, with the results published in 1864.[16] The observational techniques were complex and were designed for the accomplishment of high accuracy and for the elimination of systematic errors and detection of blunders. It is said that this work required agreement between two measurements within 2 mm. $\sqrt{K}$, where K is the length of the line in kilometers.

The French work inspired the Swiss to engage in a similar effort. In 1864, a Swiss recommendation for the execution of a connected network of precise levels over a large part of Europe was adopted by the International Geodetic Conference. The methods of observation and the use of a mean sea level datum were included in the resolution. For the observations on this project, a precise spirit level instrument was designed by Kern of Aarau, Switzerland; these instruments were widely used in Europe and later several were used by the Corps of Engineers in the United States.

Leveling in the United States

The definition of "geodetic leveling" as used in this historical summary has been purposely left somewhat broad, which provides opportunity to include earlier work which may not quite conform to modern specifications of accuracy but which had considerable extent and made serious attempts at accuracy.

First Attempt at Geodetic Levels

Although some localized leveling was undoubtedly done in the United States in pre-Revolutionary times and also by the U.S. Coast Survey from its establishment in 1807 (tidal bench marks, etc.), the first effort on record to run what can be called geodetic levels was made by the U.S. Coast Survey in 1856–1857, when a line of levels was run by G. B. Vose in connection with a detailed study of the tides and currents in New York Bay and the Hudson River. A series of tide gauges was established along the Hudson River from New York to Greenbush (on the east side of the Hudson River, opposite Albany), and all were interconnected by the line of levels run by Mr. Vose. The following statement describes the operation, probably run by Y level:[17] "In order to place our results beyond all possible doubt, I directed Mr. Vose, to whom the leveling was assigned, to proceed slowly and with great care from station to station between New York and Albany. As you directed, a double series of levelings was made throughout the whole route and every doubtful step was retraced." With regard to the closeness of the results obtained, Mr. Vose says, "From a hasty computation which I have made, it appears that the probable error for the entire distance from New York to Greenbush does not exceed two-tenths of a foot." Further details as to the results of these levels, or as to the instruments used, or the actual observational procedures have not been published. As a product of this operation, the important bench mark "Gristmill" was established with its elevation assigned as 14.73 ft. (which elevation has been subsequently determined to be about a foot too high). This bench mark provided the mean sea level datum to which subsequent levelings by the U.S. Lake Survey were referred in determining elevations of the water surfaces in the Great Lakes.

Lake Survey Geodetic Level Lines

In 1875 the U.S. Lake Survey (Corps of Engineers), having requirements for precise elevations above mean sea level for the water levels in the Great Lakes and for bench marks in the adjacent harbor areas, made a serious effort to carry geodetic leveling into the Great Lakes area. Observers F. W. Lehnartz and L. L. Wheeler ran "duplicate" levels, in the same direction, from bench mark "Gristmill" at Greenbush, N.Y., along the Erie Canal to Higginsville, along wagon roads to Fish Creek, and along the New York and

Oswego Midland Railroad to Oswego, N.Y.,[18] establishing bench mark "A" at the harbor in Oswego. This bench mark was recovered by a National Geodetic Survey level party in 1975. Instruments were Y levels, one by Stackpole with a 6.42-second vial and the other by Wurdemann with a 3.17-second vial. Neither instrument had a micrometer or "tilting" screw. Balanced sight-distances were used, with the bubble position read with each observation and correction applied for inclination of the line of sight. The separate runnings between adjacent bench marks were required to agree within 0.1 ft. times the square root of the section length in miles (0.1 ft. $\sqrt{M} = 24$ mm. $\sqrt{K}$), which is quite large by today's standards. The actual agreement achieved on this line was .095 ft. $\sqrt{M}$.[19] In the same year, using similar methods, the same observers leveled between Lake Ontario and Lake Erie with a discrepancy of only 0.28 ft. Mr. Lehnartz then ran a single line connecting Lake Erie (Rockwood, Mich.) with Lake Huron (Lakeport, Mich.). Thus, levels were run across all the land connections from Hudson River–Lake Ontario–Lake Erie–Lake Huron/Michigan. An important concept introduced at this time was the operation of "water-level transfer," in which the mean surface of each lake, averaged over a 3–4 month period from water level gauges, was assumed to define a level surface. This principle was used to transfer "sea-level" elevation across the length of each lake, forming a continuous sequence of measurements with the above-mentioned level lines; providing the basis for assigning a mean sea level elevation at the gauge at Escanaba, Mich. (on Lake Michigan), based on the U.S. Coast Survey elevation assigned to bench mark "Gristmill" as determined by the Hudson River levels of 1856–1857 by Vose. Thus, for the first time, reasonably accurate elevations were made available for all the Great Lakes, except Lake Superior, based on surveying techniques other than reconnaissance methods such as barometric observations.

In 1876, the final link in the determination of Great Lakes elevations was accomplished by the Lake Survey, with the completion of a line of geodetic levels from Lake Michigan (Escanaba, Mich.) to Lake Superior (Marquette, Mich.). An important improvement in the procedures was provided by the acquisition of two Kern levels (designated Nos. 1 and 2) of the type used in the Swiss and other European leveling projects of the 1860's and the 1870's. The 1876 observations were made by Messrs. Lehnartz and L. L. Wheeler, who had made the observations from Greenbush to Oswego, etc., in the previous year. This type of instrument was used by the Corps of Engineers for many years for many important lines of geodetic levels, particularly along the Mississippi and Missouri Rivers and their tributaries. Major characteristics of the Kern levels (Fig. 1) are:[20]

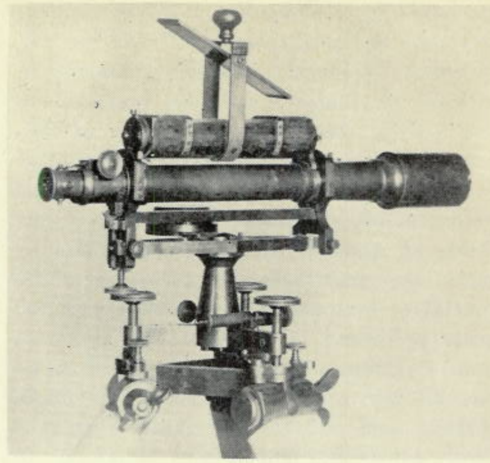

Figure 1. Kern level

—Y levels, with telescope reversible.

—Tilting screw for moving telescope slowly in the vertical plane.

—Sensitive level vials (4″.87 on No. 1, and 2″.15 on No. 2).

—Level vial enclosed in wood insulating case with plate glass cover.

There were some innovations in observational techniques,[21] e.g.:

—Daily determination of collimation error.

—Correction for inclination of line of sight.

—Reading of position of bubble in vial.

—Reading of three horizontal cross wires to detect blunders.

—Use of metric rods (centimeter divisions with millimeters estimated).

—Requirement that two independent observations of section between adjacent bench marks must not diverge more than 5 mm. $\sqrt{K}$ (K in kilometers).

—Limitation of sight length to 100 m.; difference between foresight and backsight distances not to exceed 10 m.

In 1877, the principle of "double-simultaneous" running was introduced by the Corps of Engineers. The method used two pairs of rods with one Kern instrument; the line of levels was carried forward with two independent observations of backsight and foresight, on separate turning points, at each instrument setup. The method generated two independent levelings of the route but required only one observer and one level, thus providing continuing checks on the work as the observations progressed.[22] This work was performed along the Mississippi River.

In the season of 1882–1883, J. B. Johnson, who was later professor of surveying, and dean, at the College of Mechanics and Engineering of the University of Wisconsin, introduced the method of observing which has popularly been known as the "three-wire" method.[23] The major departure from previous Corps of Engineers' (Mississippi River Commission) practice was in the precise centering of the bubble in the vial and *holding it centered* while reading on the rod (cf. also Johnson's text on surveying[24]).

Previous to this innovation, the standard procedure was to read when the bubble was *nearly centered*, noting the actual number of divisions that the bubble was *off center*, and subsequently applying corrections for this eccentricity. Detailed instructions for the new procedures were published by the Mississippi River Commission in 1891 and are reproduced in Johnson[25] (also discussed by O. W. Ferguson in the 1892 Report of the Mississippi River Commission).[26] These instructions specify that the double runnings of a section between adjacent bench marks shall agree within 3 mm. times the square root of the section length in kilometers (3 mm. $\sqrt{K}$), but the section length is defined as the distance from one mark to the next *and return*, i.e., K is twice the distance between the two bench marks. This is equivalent to 4.2 mm. $\sqrt{K}$ if K is defined as the single distance between bench marks. These instructions were essentially duplicated by the Missouri River Commission in 1893.

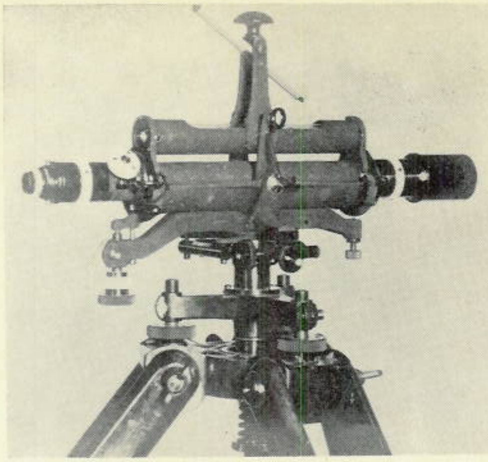

Figure 2. Mendenhall level

Although Kern levels Nos. 1 and 2 are definitely stated to be manufactured by Kern in Aarau, Switzerland, Johnson[27] states that the term "Kern level" was later used to designate a design type, some of which were manufactured by F. E. Brandis & Sons Co. in Brooklyn, N.Y. Although equipped with a tilting screw, the instrument was basically a Y level and had to be used with care; its constants had to be redetermined frequently to compensate for wear on the collars and pivots, and corrections, therefore, had to be applied to the observations. Further details concerning instruments and methods used by the Corps of Engineers are given by Molitor,[28] especially the "Mendenhall" level made by Buff and Berger (Fig. 2).

Geodesic Levels by the U.S. Coast and Geodetic Survey

It has already been noted that the U.S. Coast Survey first ran "precise" levels in 1856–1857 for the control of tide gauges on the Hudson River. Vertical control for reduction of triangulation base lines, etc., to sea level had been accomplished with adequate accuracy by trigonometric observa-

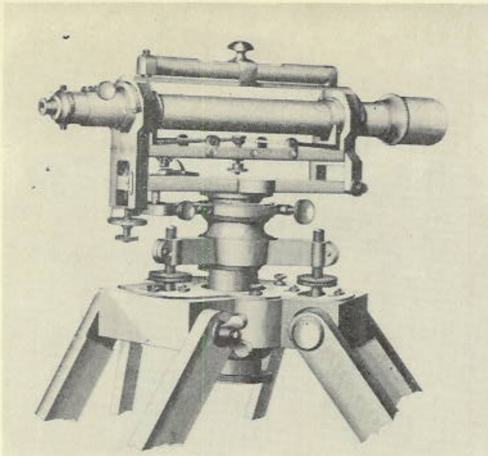

Figure 3. U.S. Coast and Geodetic Survey geodesic (Stampfer) level

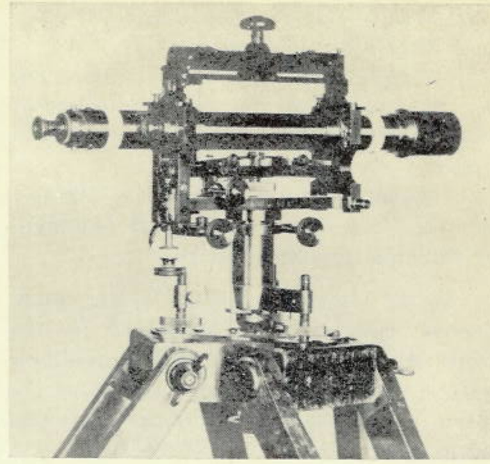

Figure 4. U.S. Coast and Geodetic Survey Stampfer level

tions (vertical angles) for the triangulation required for the charting along the coasts. However, the Coast Survey started planning a transcontinental arc of triangulation, approximately following the 39th parallel, in accordance with authorization by the Congress by the Act of March 3, 1871.[29] This act gave the Coast Survey a specific geodetic function in addition to its former purely charting function. In 1878, this new function was emphasized by legislation that changed its name to Coast *and Geodetic* Survey.[30] In planning the new transcontinental triangulation arc, it became obvious that more precise vertical control would be required than could be provided by trigonometric measurements. Requests for appropriations to finance the transcontinental triangulation were made regularly from 1871 to 1878, but the first request for funding ". . . to run lines of levels connecting points in the main and geodetic triangulations with sea level"[31] appeared in 1876. This request appears to be the founding of geodetic leveling by the Coast Survey. A more specific mention of the subject is made in the Annual Report for 1877,[32] where it is stated, "A leveling instrument of great precision, for use in geodesic leveling, has been designed and constructed at the office. A full account of it will be given after thorough trial in the field." (One of this set of instruments, No. 1, was originally made by William Wurdemann,[33] in the shop that he operated privately in Washington, D.C. This instrument, then, was modified in the shop of the Coast Survey.[34]) It should be noted that this manufacture was done by craftsmen in the Coast Survey only one year after the importation of the Kern levels by the Corps of Engineers in 1876. The "full account" of the new level is given in the 1879 Annual Report,[35] with a detailed mechanical description of the level and rod, and complete instructions for the observations, form for notes, and for the calculation of the reduction of the notes.

The 1879 discussion of the Coast Survey level (Figs. 3 and 4) states it was of the "Stampfer" type, which is described in principal detail in Warchalowski.[36] More precisely, it was a reversible Stampfer level, i.e., it was basically a Y level with the telescope reversible in the wyes about its optical axis, with the level vial mounted above the telescope in a "striding" configuration (supported on the same "collars" as the telescope), which was reversible (end-for-end) with respect to the telescope. The entire telescope mount supporting the wyes could be tilted vertically by means of a fine-threaded "tilting screw," which had graduations on the head of the screw and also a counter to read the number of whole turns.

The tilting screw was a "gradienter" which would provide a capability of reading the actual vertical inclination of the telescope. It was thus mechanically and geometrically equivalent to the Kern level in configuration.

The observing process was cumbersome, but geometrically correct in eliminating errors due to instrumental imperfections and failure of perfection in adjustment. Basically, a target was clamped on the rod in a position near the intersection of the "level" line of sight. The line of sight was then pointed on the target by turning the gradienter screw, with the telescope and striding level in the following combinations of positions:

1. Telescope direct, stride level normal.
2. Telescope direct, stride level reversed (end-for-end).
3. Telescope inverted (rotated 180° in the wyes about its optical axis), stride level reversed.
4. Telescope inverted, stride level normal.

The position of the gradienter screw was read in each position and also, in each combination, the gradienter was read when the level bubble was centered (or at some other selected position in the vial). The position of the target on the rod was also read by both the rodman and the recorder. Previous tests had determined the vertical angular displacement of the telescope line of sight induced by one complete turn of the gradienter screw and also the variation of inclination equivalent to the displacement of the bubble by one graduation in the vial. The series of readings made on each rod provided data by which corrections to the target setting were computed to derive the actual intersection of the "level" line of sight with the rod scale.

This basic system was used by the Coast and Geodetic Survey, with minor variations, from 1877 until 1900. The process was slow and required an excessive amount of computations to determine the corrections to the rod readings, but more than 9,000 km. of critical levelings were run throughout a large part of the United States before it was superseded by another system in 1900. The fundamental weakness in the system, however, did not lay in the excess work it required but largely in its dependence on an accurate knowledge of the angular value of one graduation on the level vial (sometimes called the "sensitivity" of the level vial), which, particularly with very sensitive vials, tends to change due to mechanical stresses in mounting the vial in the instrument, to stresses induced in adjustment and handling of the instrument, and also, importantly, to changes in ambient temperature.

The first line of leveling by the Coast Survey, officially dignified by the designation of "geodesic leveling," was the line following the 39th parallel triangulation, as contemplated in 1876 and for which the new level instruments and procedures were designed. The first field work was started in October 1877 with the establishment of bench mark "A" in the "water table" (foundation wall) of the Washington County Court House in Hagerstown, Md., by Sub-Assistant Edwin Smith, and by the actual running of geodesic levels along the turnpike to Williamsport, Md., and the establishment of bench mark "B" on the aqueduct which carried the Chesapeake and Ohio Canal over Conococheague Creek just north of Williamsport,[37] where the season's operations were terminated in December 1877. These two bench marks were recovered by the writer during the summer of 1975.

Work on the transcontinental levels was resumed by Assistant Andrew Braid in May 1878 who continued the line westward following the towpath of the Chesapeake and Ohio Canal to its terminus at Cumberland, Md., (bench mark "I") and thence along the Baltimore and Ohio Railroad to Athens, Ohio, where the season's work was terminated in December 1878.[38] This line was run by the "double simultaneous" method, where two sets of rods on separate turning points were observed to provide independent checks at each setup of the precision of the work. The instructions provided that the divergence between the two runs of each section between adjacent bench marks must not exceed 5 mm. times twice the section length in kilometers (5 mm. $\sqrt{2K}$).[39] This work, generally referred to as the Transcontinental Leveling, was extended to Mitchell, Ind., during the summer/fall of 1879 by Braid.[40] Mr. Braid then proceeded to New Orleans, La., where he started on a project sponsored by the Mississippi River Commission to run levels up the Mississippi River,[41] which were extended upstream to Greenville, Miss., by 1881.

Another very important accomplishment in 1881 by Mr. Braid was the connection of the Transcontinental Leveling to a sea-level determination. This was done by starting on tidal bench marks associated with the self-registering tide gauge installed at Sandy Hook, N.J., and operating during the period of 1876–1881. The line of levels followed railroads through Perth Amboy, Somerville, and Annandale in New Jersey, and Easton, Allentown, Reading, Harrisburg, and Chambersburg in Pennsylvania to bench mark "A" in Hagerstown, Md.[42] In 1882, the Transcontinental Leveling was extended from Mitchell, Ind. (its 1879 terminus), to St. Louis, Mo., crossing the Mississippi River by running levels across the Eads Bridge (the "Great Bridge" opened in 1874)[43] and also by the use of standard water-crossing techniques.[44] Observed elevations referred to mean sea level at Sandy Hook (there was no closed circuit to adjust); descriptions of bench marks, a sketch map of the route, and a discussion and report on the project at this date is given in the Annual Report of the superintendent of the U.S. Coast and Geodetic Survey (USC&GS) for fiscal year 1882.[45]

Work continued on the Transcontinental Leveling westward through Jefferson City and Kansas City, Mo.; Topeka, Abilene, and Ellis, Kans., Denver, Colo., and Cheyenne and Rock Creek, Wyo., in 1899. In the meantime, work continued up the Mississippi River, connecting with the Corps of Engineers (Mississippi River Commission) levels which extended up the Mississippi River from the mouth of the Arkansas River; then, the USC&GS levels turned and followed the Arkansas River through Little Rock to Fort Smith and Van Buren, Ark., and thence northward cross-country to make a junction with the Transcontinental Level Line in the vicinity of Kansas City, Mo., (1879–1894). A third major line started from the Mississippi River C&GS line at New Orleans (Carrollton), La., and ran east along the Gulf Coast to a tide gauge at Biloxi, Miss., (which gave a tie to "Mean Gulf Level"), thence to Mobile, Ala., and north along railroads through Meridian and Corinth, Miss., to a tie with the Corps of Engineers' Mississippi River line at Cairo, Ill., and finally closed out at the Transcontinental Level Line at Odin, Ill., about 102 km. east of St. Louis, Mo. This third major line was run in the period 1884–1890. The Transcontinental Levels were thus connected with mean sea level by tide gauges at Sandy Hook, N.J., and Biloxi, Miss. A third sea-level connection was provided by a level line run from bench mark "A" at Hagerstown, Md., through Washington, D.C., and Richmond, Va., to a tide gauge at Old Point Comfort, Va. This line was run by J. B. Weir in 1883–1884.

U.S. Geological Survey Levels

The U.S. Geological Survey (USGS), since its founding in 1875, has been assigned the task of the topographic mapping of the United States. This has required that the determination of elevations of sufficient accuracy for the controlling of contour lines must have been accomplished by whatever means were deemed appropriate for the purpose. However, the legislation appropriating funds for topographic surveys during fiscal year 1896–1897 contained the express provision ". . . in such surveys west of the ninety-fifth meridian, elevations above a base level located in each area under survey shall be determined and marked on the ground by iron or stone posts or permanent bench marks, at least two such posts or bench marks to be established in each township or equivalent area, . . . whenever practicable, near the township corners of the public-land surveys; and . . . east of the ninety-fifth meridian at least one such post or bench mark shall be similarly established in each . . . township of the public-land surveys." It is stated that this was interpreted "as to permit of the acceptance of some point within each area under topographic survey as a central datum point for that area, and the elevation of the initial bench mark established there was determined as nearly as practicable from existing elevations adjusted through by railway levels brought from the sea. In consequence, though all the elevations connected with the same central datum point will agree one with the other, yet they will not be reduced to exact sea level . . ." and "It is worthy of note, however, that nearly half of the work of the past season . . . is based on existing careful levels in New York, those of the State canals and United States Engineer Corps; in some portions of the south and west, those of the United States Engineer Corps; in much of the central United States, those of the United States Coast and Geodetic Survey and the Missouri and Mississippi River Commissions surveys."[46] This legislation and interpretation led to the institution by USGS of a system of permanent bench marks connected by "precise" leveling and with the resulting elevations referred to a common datum point in each area. The use of a standard bench mark disc was introduced. On each disc was stamped the elevation (to the nearest foot) and an abbreviation, by initials, to designate the local datum to which the elevation was referred. Lines of levels, in accordance with this system, were run in many different areas throughout the United States where topographic mapping was being done. Because of the use of local datum in each area, the running of long tie-lines to sea level was not necessary.

The instrument required by specifications and instructions issued in 1897[47] was the 20-in. engineer's level made by Messrs. Gurley & Co. of Troy, N.Y. Double-rodding was required for long lines and "limit of error in feet" was not to exceed $.05 \sqrt{M}$ (M = distance in miles). This specification is equivalent to third-order accuracy and therefore these levels would be considered marginal for classification as "geodetic." However, occasional lines were run with tighter specifications, i.e., error limit = $.03 \sqrt{M}$, and use of better instruments and procedures.[48] Levels thus run were designated "precise levels." The instrument used was made by Buff and Berger and is reputed to have been of the "Van Orden"[49] design. The first, and best-known, line run under these specifications by the Geological Survey was a cooperative survey for the State of North Carolina, running from a temporary tide gauge at Morehead City, and run "in such a manner as to cross every line of railway in the State, and thus reduce its elevations to sea level." This long line started in 1896 from Morehead City and ran through Newbern, Raleigh, Durham, Greensboro, Newton, and Asheville to the Tennessee state line at Paint Rock, reaching a maximum elevation of 769.7 m. (2,525 ft.) in a total length of 735 km. (457 mi.). In the following year, it was extended from Paint Rock, through Knoxville and Cleveland, Tenn., and Rome, Ga., and stopped at Atlanta, Ga.[50] In 1899, the line was closed by running from Atlanta through Macon and tying to a tide gauge at Brunswick, Ga., for a total loop length of 1,679 km. (1,043 mi.), from sea level at Morehead City, across the State of North Carolina, into Tennessee, and back across the State of Georgia to sea level at Brunswick.[51] This loop introduced accurate sea level elevations through a large area in the southeast United States where no other agency had operated. Similar lines were run by the Geological Survey in New York and Pennsylvania before 1900. An excellent discussion of USGS work in leveling before 1898 is presented by Herbert M. Wilson, who was active in that work, in his detailed paper published by the American Society of Civil Engineers in 1898[52] and additional discussion in his textbook on topographic surveying.[53]

Van Orden (Massachusetts) Levels

In 1884, the Commonwealth of Massachusetts undertook a complete topographical survey of the Commonwealth in cooperation with the U.S. Geological Survey. Part of the basic geodetic control, mainly triangulation, was undertaken by the Coast Survey. In connection with this it became evident that a basic line of geodetic levels crossing the state was needed to make sea level datum available for the mapping project and to provide elevations for the reduction of the triangulation. C. H. Van Orden, an assistant of the U.S. Coast Survey, had been assigned to the Massachusetts survey to assist in the triangulation, which was also required for a concurrent survey of the boundary lines of towns in the state. Although a member of the geodetic staff of the Coast Survey, it appears that he worked under the direction of the commissioners of the Topographical Survey. In 1893, Mr. Van Orden was assigned to the precise leveling project. This line started from a bench mark "on the Boston Art Museum steps, 14.737 ft. above mean sea level," furnished by "the city surveyor's office, as being a point in the complete circuit from the Charlestown Navy Yard bench."[54] The line followed the route of the Boston and Albany Railroad (later the New York Central and now part of the Penn Central) and ran through Worcester, Springfield, and Pittsfield, with its last Massachusetts bench mark at the state line, and then ran into New York, closing on the 1856–1857 Coast Survey bench mark "Gristmill" on the Hudson River and finally to a mark in Albany. This was the first line of geodetic levels in New England; indeed, it seems to have been the only one in New England until the Coast and Geodetic Survey ran a line across Maine in 1916,[55, 56] making international connections with Canadian levels at each end.

The Van Orden levels were run with a new precise tilting Y level (Fig. 5), made by Buff and Berger, with the level vial rigidly attached to the underside of the telescope (no striding level); and the observations were made by the simultaneous, double-run system, with all readings made with the bubble centered, being held centered by an assistant observer called the "bubble tender," while the observer made the rod readings, there being no micrometer readings to define the inclination of the line of sight, with the backsight and foresight at each setup being carefully balanced. This line is historically interesting because it made a new sea level connection for bench mark "Gristmill" to Boston, because it was the first precise level line in New England, because it involved the development of a new leveling technique by a Coast and Geodetic Survey engineer that was a departure from the established "geodesic level" technique, and because it was

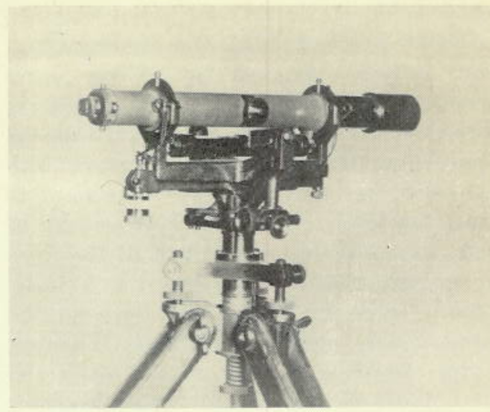

Figure 5. Van Orden level

the example for the U.S. Geological Survey to follow in its development of procedures for "precise leveling," starting in 1896. The instrument is sometimes referred to as the "Massachusetts Level." The results of the first Van Orden line were published by the Massachusetts Topographical Survey in their Annual Report for 1893.[57]

Railroad Leveling

Leveling by certain railroads has been occasionally incorporated in the network of geodetic leveling used in the United States. The earliest one used for this purpose was run by the Pennsylvania Railroad from Harrisburg to Braddock (near Pittsburgh), Pa., 385 km. (239 mi.) for which the data were turned over to the Coast and Geodetic Survey in 1899. The Baltimore and Ohio Railroad also made important contributions to the national leveling network.

USC&GS Committee on Precise Leveling

In November 1898, Henry S. Pritchett, superintendent of the Coast and Geodetic Survey, appointed an *ad hoc* committee, composed of John F. Hayford, Isaac Winston, J. J. Gilbert, and A. L. Baldwin, to consider the subject of precise levels and, in particular, to investigate "the accuracy of various methods, their relative freedom from systematic errors, and their relative quickness, cheapness, and facility for the reduction of observations."[58] The committee worked nearly full time and presented their report under date of February 9, 1899. The results of USC&GS leveling were compared with results of Corps of Engineers and USGS leveling. All were considered for magnitude of loop misclosures and, particularly, for evidence of unexplained systematic errors as revealed by accumulation of divergence between double runs (either simultaneous or forward/backward) or by loop misclosures, as well as comparison in terms of cost per kilometer, or kilometers/day.

Main conclusions were:

a. U.S. Corps of Engineers leveling was about the same accuracy as USC&GS.

b. U.S. Corps of Engineers leveling costs and production rates were about the same as USC&GS.

c. USC&GS leveling was subject to uncompensated systematic error that was azimuth-dependent, with maximum effect on lines running 20° east of north (or 180° reverse).

d. USC&GS systematic error was probably due to effects of varying temperature on the level vial and in parts of the instrument between the level vial and the line of collimation of the telescope. (The USC&GS "Stampfer" level had a striding level with the vial high above the telescope).

e. USC&GS systematic error may have been due to settlement or rising of instrument or turning points due to the long time required to make the multiple observations at a single setup in the C&GS routine.

Recommendations for changes were:

a. Use of direct-reading rods, without target.

b. Make readings with three-line reticle, estimating each reading to millimeter.

c. Bubble to be held centered continuously during reading, eliminating reading of bubble position when pointed on target.

d. Level not to be reversed, nor telescope rotated in the course of observations.

e. Alternate foresights to be taken before the corresponding backsights.

Summary—Status Geodetic Leveling in 1899

Three different U.S. Government organizations—the Coast and Geodetic Survey, Corps of Engineers (U.S. Lake Survey, Mississippi River Commission, Missouri River Commission), and Geological Survey—and a couple of non-federal organizations had worked for approximately 25 years to develop methods for the determination of accurate elevations above mean sea level of points distributed over very long lines. By using a number of different instruments—Kern, C&GS/Stampfer, Van Orden, others—a very intense effort was made by a number of highly qualified and dedicated engineers to the development of observational techniques aimed toward obtaining high accuracy simultaneously with high rates of production.

Many kilometers of leveling were run and an analysis was made by the Coast and Geodetic Survey which indicated that the results fell somewhat short of the hopes. Recommendations were made for the design of a new instrument and introduction of a new observational routine that would combine some of the varying routines used by the different agencies (to compensate for systematic error and speed up production rates). It was also decided that a combined adjustment should be made of all acceptable data from all qualified sources so that national use could be made of the combined efforts.

USC&GS Level of 1899

An immediate result of the recommendations made by the 1899 Committee on Precise Leveling was the production of an interim model of a new level having most of the characteristics suggested by the Committee. Three of the Stampfer levels in use since 1877 were remodeled as follows:[59]

—The height of the striding level was reduced.

—A mirror, prism system, and viewing ocular was attached, to permit observing the position of the bubble with the observer's left eye, allowing monitoring the centering of the bubble while reading the rod.

—The telescope barrel and metallic parts of the striding level were made of low-expansion nickel-iron alloy.

Also, consistent with the Committee, new instructions[60] were issued for observing, which essentially amounted to the introduction of the now well-known "three-wire" system. This eliminated the complicated system of reading the micrometer eight times on each rod, calculation for inclination of line of sight, etc.

These instruments and procedures were used in C&GS leveling in 1899 on three lines:

(1) From Denver, Colo. to Rock Creek, Wyo.,

(2) from Abilene, Kans., to Norfolk, Neb., and

(3) from Gibraltar, Mich., to Cincinnati, Ohio.

Adjustment of 1900

In 1900, the Coast and Geodetic Survey assembled all results of its own leveling and requested the Corps of Engineers (Lake Survey, Mississippi River Commission, Missouri River Commission, Deep Waterways Commission, *et. al.*), the U.S. Geological Survey, and the Pennsylvania Railroad to furnish data from all leveling that could be considered "geodetic" and undertook, for the first time, a general adjustment of all geodetic leveling in the United States. This adjustment, known as the "First General Adjustment," was accomplished, with the resulting descriptions and adjusted elevations being published in Appendix 8 of the Report of (fiscal year) 1899 of the superintendent of the U.S. Coast and Geodetic Survey. Available statistics for this First General Adjustment are:

USC&GS	9,318 km.
Corps of Engineers	7,496
Corps of Engineers, water leveling	2,291
U.S. Geological Survey	1,285
Massachusetts Topo Survey	320
Pennsylvania Railroad	385
Total lines	21,095 km.

Mean sea level determined by tide gauges was held fixed at five locations controlling the network:

Boston, Mass.	Sandy Hook, N.J.
New York, N.Y.	Washington, D.C.
Biloxi, Miss.	

Another gauge at Old Point Comfort, Va., was held in adjusting the spur line to there from Washington, D.C.

In Florida, gauges at St. Augustine and Cedar Keys were held in adjusting the single level line between those points, but that line was not connected to the network.

The network contained about 4,200 bench marks.

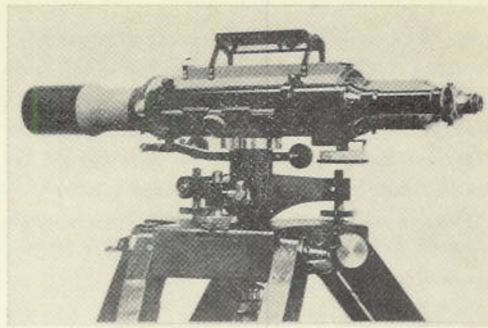

Figure 6. U.S. Coast and Geodetic Survey (Fischer) level of 1900, left side view

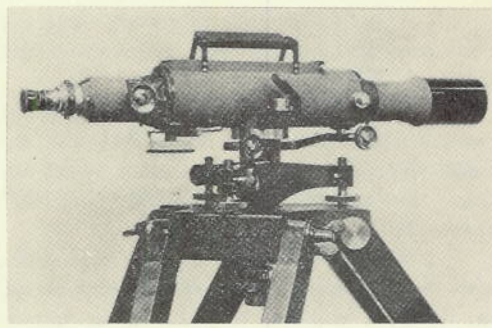

Figure 7. U.S. Coast and Geodetic Survey (Fischer) level of 1900, right side view

USC&GS (Fischer) Level of 1900

The interim version of the new level instrument produced in 1899 was superseded in 1900 by the entirely new instrument which has become known as the "Fischer" level (Fig. 6, left side, and Fig. 7, right side), named for its designer and builder, E. G. Fischer, chief instrumentmaker at the Coast and Geodetic Survey instrument shop. As with the 1899 instrument, the objective was to minimize the distance between the level vial and the line of collimation. In the Fischer instrument, this was accomplished by inserting the vial into the telescope tube —the concept of the striding level having been abandoned—and supporting the telescope tube, with its tilting mechanism, by completely enclosing it within a second outer tube, above which a small mirror was attached to permit viewing of the bubble through an external optical system as in the 1899 version. Another important innovation was the use of the newly-developed, low-expansion, nickel-iron alloy for the telescope tube, its supporting tube, and auxiliary parts. The combination of the use of low-expansion material and reduction to a minimum of the distance between the level vial and the line of collimation was intended to minimize the variation of the adjustment with changes in ambient temperature. That this instrument was successful in achieving this objective is obvious from the fact that it remained the "work horse" of production leveling at the Coast and Geodetic Survey for over 60 years —1900 to about 1962. The Fischer level was first described in detail in the Annual Report for 1900[61] and also in other publications.[62, 63]

Adjustment of 1903

By 1903, more than 10,000 km. of additional leveling had become available, many of which formed important new junctions, e.g., a new line by C&GS from Gibraltar, Mich., south through a connection with the Transcontinental Leveling at Cincinnati, Ohio, thence across Kentucky to junctions at Knoxville and Cleveland, Tenn., with the USGS long loop from Morehead City, N.C., inland through Asheville, N.C., Knoxville, Tenn., and return via Atlanta, Ga., to sea level at Brunswick, Ga., which loop was not included in the 1900 adjustment because it was not tied into the net. New work by the USGS, Corps of Engineers, and several railroads was incorporated into the net. A number of old unsatisfactory lines were replaced. Statistics are as follows:

USC&GS, prior to 1899	7,154 km.
USC&GS, 1899 and later	5,549
Corps of Engineers, excluding Lake Survey	7,006
U.S. Lake Survey	1,009
U.S. Lake Survey, water leveling	4,275
U.S. Geological Survey	2,802
Others, mostly railroads	3,994
Total	31,789 km.

Sea level connections were held at Boston, Mass., New York, N.Y., Sandy Hook, N.J., Annapolis, Md., Old Point Comfort, Va., Morehead City, N.C., Brunswick, Ga., and Biloxi, Miss. As in 1900, the line from St. Augustine to Cedar Keys, Fla., was separately held because it was not connected to the network.

This adjustment is fully documented in the Annual Report for 1903[64] and new elevations tabulated for approximately 6,900 bench marks.

Adjustment of 1907

The Adjustment of 1907 became necessary largely because the Transcontinental Leveling was accomplished (although departing from the 39th parallel) by completion of the link from Red Desert, Wyo., through Ogden, Utah, Pocatello, Idaho, and Pasco, Wash., to the tide gauge at Seattle, Wash., as well as by the addition of a total of about 6,500 km. of new lines. This was not a complete new adjustment of the whole net, many elevations remaining unchanged in eastern United States. The only new tide gauge added to the net was the one at Seattle. Total lines included in the network were (some old lines being dropped):

USC&GS, prior to 1899	6,923 km.
USC&GS, 1899 and later	9,542
Corps of Engineers, excluding Lake Survey	8,213
U.S. Lake Survey	1,009
U.S. Lake Survey, water leveling	4,378
U.S. Geological Survey	4,746
Others, mostly railroads	3,548
Total	38,359 km.

This adjustment was reported in a publication by Hayford.[65] The network was reported to contain about 9,100 bench marks.

Adjustment of 1912

By 1912, about 8,100 km. of additional levels were available in the net, a new long line had been added across the southern United States from the Mississippi River lines in Louisiana to a sea level connection at San Diego, Calif., with a north-south line crossing it and running from a new sea level connection at Galveston, Tex., through Fort Worth, to the original Transcontinental Levels at Abilene, Kans., and another connection north-south across Nevada to Ogden, Utah. Lines contained in the network adjusted in 1912 were:

USC&GS	22,498 km.
Corps of Engineers, excluding Lake Survey	9,317
U.S. Lake Survey	5,387
U.S. Geological Survey	5,712
Others	3,548
Total	46,462 km.

Mean sea level was held at gauge sites at:

Boston, Mass.	Brunswick, Ga.
Sandy Hook, N.J.	Biloxi, Miss.
Baltimore, Md.	Galveston, Tex.
Morehead City, N.C.	San Diego, Calif.
Seattle, Wash.	

Although orthometric corrections were discussed in the report of the 1900 Adjustment, they were applied for the first time in the 1912 Adjustment, although only in the western United States. This adjustment is reported in *USC&GS Special Publication No. 18*.[66] It is estimated that the net contains 11,100 bench marks.

The 1929 General Adjustment

After a pattern of comparatively short intervals between adjustments, 17 years elapsed before the next adjustment. The net had become much more extensive and complex and had more sea-level connections. An innovation introduced was the inclusion of the Canadian first-order network in the adjustment computation. The composition of the network by agencies is not determined, but the lengths included 75,159 km. of U.S. lines and 31,565 km. of Canadian lines for a total of 106,724 km. of leveling included in the adjustment. The U.S. and Canadian networks were connected at 24 points, extending from Calais, Me./Brunswick, N.B., to Blaine, Wash./Colebrook, B.C. There were 693 "links" in the network (including 19 long water-level transfers in the Great Lakes), 253 in Canada, 416 in the United States, and 24 international, which were combined to make 246 closed circuits and 25 sea-level circuits. The adjustment provided elevations for 450 junction points.

Mean sea level was held fixed at 26 gauge sites, 21 in the United States and five in Canada at the following locations:

Father Point, Que.	St. Augustine, Fla.
Halifax, N.S.	Cedar Keys, Fla.
Yarmouth, N.S.	Pensacola, Fla.
Portland, Me.	Biloxi, Miss.
Boston, Mass.	Galveston, Tex.
Perth Amboy, N.J.	San Diego, Calif.
Atlantic City, N.J.	San Pedro, Calif.
Baltimore, Md.	San Francisco, Calif.
Annapolis, Md.	Fort Stevens, Ore.
Old Point Comfort, Va.	Seattle, Wash.
Norfolk, Va.	Anacortes, Wash.
Brunswick, Ga.	Vancouver, B.C.
Fernandina, Fla.	Prince Rupert, B.C.

The elevations of junction points and of intermediate bench marks on "links" connecting the junction points define a datum to which the elevations of all bench marks in the U.S. vertical control network are referred. This datum is defined by the observed heights of mean sea level at the 26 tide gauges listed above and the set of elevations of all the bench marks resulting from the adjustment of the network to these specific sea level determinations.

It should be further noted that, while the extensive Canadian first-order net was used to strengthen the 1929 adjustment, the datum was not adopted in Canada because an independent adjustment of the separate Canadian network had been accomplished in 1928,[67] and the resulting elevations published in a series of official books. Consequently, since the 1928 adjustment defined the official datum for elevations in Canada, which is still in use today, differing elevations are published by the United States and Canada for the set of bench marks which constitute the junction points between the U.S. network and the Canadian network.

Shortly after the accomplishment of the 1929 adjustment, the resulting datum was designated as the "Sea Level Datum of 1929," because of its dependence on a series of mean sea level determinations.

It was known at the time of the adjustment that, because of currents, prevailing winds and barometric pressures, water temperature and salinity differentials, topographic configuration of the bottom in the area of the gauge site, and other physical causes, a series of discrete mean sea level determinations, based on tide gauge observations, would not define a single equipotential surface. The result of this situation is that, in actuality, no two determinations of mean sea level at different localities will be on the same level surface, and they will, therefore, have different elevations as determined by the differential leveling process.

In spite of these known variations in the elevations of local mean sea level, it was concluded (1) that these variations were probably of about the same order of magnitude as the observational errors in the leveling network, and (2) that confusion would be caused in the operations of the engineering community if the published elevations of bench marks near the coast would not be compatible with the local mean sea level as determined by tidal observations. Accordingly, in the 1929 adjustment, the network was constrained to hold fixed the observed local mean sea level at each of the 26 gauge sites listed above.

It is now known that this constraint resulted in some deformations in the level net as defined by the leveling observations alone. Furthermore, since the elevations of mean sea level at different sites do not vary linearly along the coast line segments that connect them, it follows that elevations of mean sea level as defined by tidal observations at intermediate points between the 26 points held fixed in the adjustment will not agree precisely with the "zero" elevations at the same points as defined by leveling adjusted to conform to the 1929 adjustment (the "Mean Sea Level Datum of 1929").

This has resulted in considerable confusion and misunderstanding, especially in these times when substantial emphasis is being applied to the precise determination of coastal boundary lines and offshore jurisdictional limits. These lines and limits are almost universally defined by reference to some line (mean low water, "ordinary high water line," etc.) defined by the rise and fall of the tide. It is a probable cause for considerable error to assume that these lines can be fixed by reference to the "zero" line as defined by leveling from bench marks whose elevations are referred to the geodetic datum for elevations.

To eliminate some of the confusion caused by the original name of the current geodetic datum for elevations ("Sea Level Datum of 1929"), the name of the datum has been changed to "National Geodetic Vertical Datum of 1929," eliminating all reference to "sea level" in the title.[68] This is a change in name only; the mathematical and physical definitions of the datum established in 1929 have not been changed in any way.

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Upon receiving his bachelor degree in civil engineering from The Catholic University of America, Washington, D.C. in 1933, Ralph Moore Berry accepted several minor assignments in the surveying field, after which he established a private practice in land surveying and civil engineering in Maryland. In 1941, he joined the professional civilian staff of the U.S. Coast and Geodetic

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Professor Berry, in 1941, was one of the Founding Fathers of ACSM. He has served as a director of ACSM and for four years as chairman of the Land Surveys Division of ACSM. He was awarded the status of ACSM Fellow in 1970, that of Life Membership in 1972, and received ACSM's highest honor, Honorary Member, in 1976.

He is also a Fellow and Life Member of ASCE and a member of ASP since 1936, the Canadian Institute of Surveying, the American Geophysical Union, and the Michigan Society of Registered Land Surveyors. He has had articles published in many technical journals.

Professor Berry received an honorary citation from ACSM in 1956, the Department of Commerce award for Meritorious Service from the Coast and Geodetic Survey in 1954, and a citation in 1965 from the Consulting Engineers Council, Michigan Section.

A registered professional engineer and land surveyor in Maryland and Michigan, he has served as geodetic consultant to the U.S. Geological Survey, the Corps of Engineers, U.S. Lake Survey, and many private surveying organizations. He designed and computed the standard tables for the Michigan State Plane Coordinate System, adopted by the Michigan legislature in 1964. ■

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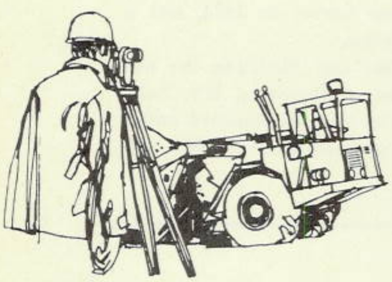

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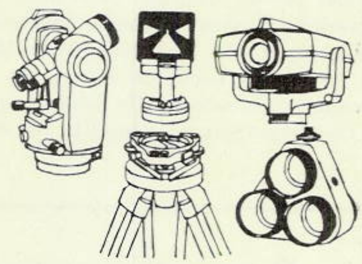

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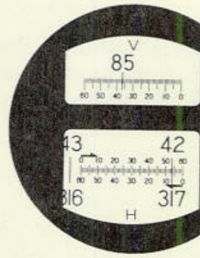

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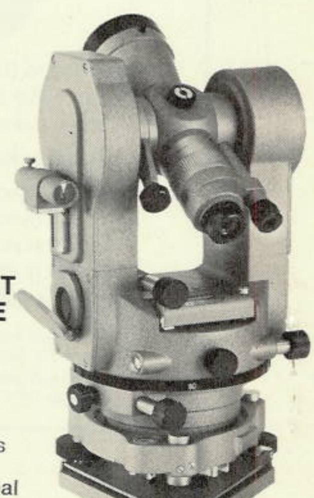

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