Horizontal Control Data

Special Publication No. 227 (REVISED 1957/1972)

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Reprinted in 1976

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Preface

A great amount of triangulation has been added to the precise horizontal control net of the United States during the past 25 years. The problem of processing the vast amount of data thus accumulated and making it available to the engineering public is a very difficult one. No longer is it feasible to publish the data for each arc in elaborate detail with comprehensive discussions of the field observations and the office adjustments From time to time, in the past, triangulation publications had been issued covering the data then available for a State or a section of a State. These publications, however, have been made as concise as possible by omitting all details not absolutely essential to the actual utilization of the data.

It has not been possible to issue these triangulation publications as rapidly as the data accumulated, and, even for areas covered by the publications, supplementary data are constantly becoming available because of the addition of new work or because of changes in the stations from many causes. To meet this situation, triangulation data are now issued in the form of lithographed copies of computed results and the unedited field descriptions of stations.

Requests for data are now met by furnishing the desired data in the form of these lithographed copies which contain the essential information but lack an adequate explanation of the data and their uses. One of the main purposes of this pamphlet is to meet this need for explanation and to supplement the rather abbreviated text of our triangulation publications. Another purpose of this publication is to acquaint the local engineer with the essential facts about horizontal control data and to persuade him to make full use of these data in his various surveying projects by showing him how simply this may be done in areas where control stations are available, especially now that State plane-coordinate systems have been devised. It is hoped that greater familiarity with the uses and value of triangulation stations will result also in even greater cooperation by local engineers in the preservation of the stations of the Federal net and in keeping this Bureau informed of changes affecting the use or preservation of its stations.

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Introduction

In the surveying and mapping of large areas the exact curvature of the sea level surface of the earth must be taken into consideration. For this reason, the basic surveys of a country are called geodetic surveys. There is an intricate net of precise geodetic surveys over the United States. It comprises the equivalent of about a dozen east-west arcs of triangulation and about 30 north-south arcs, although they are by no means in the regular pattern which might be inferred from this statement. The aim has been to have the main arcs spaced at regular intervals over the country and to have the intermediate areas well covered with supplementary arcs and area triangulation. This precisely determined network serves as a basis for intermediate and local surveys and for all kinds of accurate mapping.

Latitudes and longitudes have thus been determined for many thousands of marked stations scattered over the United States. Surveys of small areas may be based on any of these marked points at any time with the assurance that they may be correctly coordinated in position with all precise surveys and maps of the entire country and with all local surveys so connected. The permanency of the results of surveys thus connected to the national net is also assured since any marked points that become lost or that lose their integrity may be duplicated by new surveys based on nearby stations.

Triangulation is a very efficient method for making surveys over extensive areas. It avoids the tedious, time-consuming, expensive operation of measuring the lengths of all lines that enter into a survey. It consists of a system of connected triangles with all angles carefully observed but with only an occasional length actually measured on the ground. Each measured length is known as a base. By use of these measured angles and bases, the lengths of all other sides of the connected triangles may be computed by trigonometry. If the latitude and longitude of one point are known together with the azimuth to one of the other stations, the latitudes and longitudes of all other points and the azimuths of all other lines may also be derived.

Triangulation is a simple method when used over small areas where the earth's curvature need not be considered. Over large areas, the computations become rather formidable for the local engineer who may have had little opportunity to become experienced in the use of the special formulas and tables required. This difficulty has been almost entirely overcome by the introduction of State plane-coordinate systems. The data for triangulation stations of this Bureau include the x and y rectangular coordinates of each station as well as the latitude and longitude. In connecting to these stations the local engineer may consider only the plane coordinates and compute his surveys on the simple rectangular system with which he is entirely familiar. His surveys will be coordinated with the national net just as effectively as if he had used the more difficult geodetic coordinates of latitude and longitude. Furthermore, he may later derive the latitudes and longitudes of a few important points of his survey without too much difficulty, if he desires, by converting from one system to the other. (See p. 19.)

The data for all triangulation stations established by this Bureau are available for the use of engineers and surveyors. The data include the latitudes, longitudes, and plane coordinates of the stations, the detailed descriptions of their locations, and the lengths and azimuths of the lines between contiguous stations. There is only one important caution to be observed. The engineer using the data should be careful not to confuse the geodetic azimuths or directions of the lines with the plane-coordinate directions. The two kinds of azimuths may differ considerably since the convergence of the meridians is considered in deriving the geodetic azimuths but the plane-coordinate, or grid, azimuths are strictly rectangular with reference to a central meridian.

For areas not covered by the publications so far issued, lithographed copies have been made of the computed results of the triangulation and of the descriptions of the stations. The lithographed descriptions are mostly unedited copies of the descriptions received from the field but they have been carefully scanned to guard against undetected errors and blunders. Engineers and others who wish to use these data may obtain the lithographed copies from the Director, United States Coast and Geodetic Survey, Washington 25, D. C. The demands for this material are very heavy, however, and engineers are therefore requested to ask only for the data for which they have an immediate need.

Field Methods and Equipment

The different field operations required in measuring an arc of triangulation are as follows: First a reconnaissance is made to determine the best locations for the stations. Next the necessary towers or stands are erected to make the stations intervisible and the stations are marked. Then the angles at each station are carefully measured with a theodolite. If any bases are needed for the control of the lengths, they are measured next, and finally the necessary astronomical observations are made if the scheme is long enough between the connections to triangulation previously adjusted to require a strengthening of the azimuths, or what is known as Laplace control.

Reconnaissance

Reconnaissance may be described as the design of the triangulation. It is carried out by a small party, usually consisting of the observer and one assistant but sometimes of the observer alone. The party selects the sites for all the main and supplementary stations; tests the intervisibility of all stations which must be seen for the angle observations; specifies the necessary heights for the signals; collects information regarding roads, climatic conditions, and other facts likely to be useful to the signal-building and observing parties; and interviews property owners to secure permission for entry on the premises and otherwise pave the way for the triangulation party.

The work of the reconnaissance engineer is extremely important. If the stations he selects form poorly shaped triangles and quadrilaterals, of low strength of figure, an excessive number of base lines will be required. If some of the lines are found by the triangulation party to be blocked by intervening obstructions, overlooked by the reconnaissance engineer, the revision of the scheme or the building of higher signals may seriously delay the triangulation party and considerably increase the cost. Long training is essential to success in this important part of geodetic surveying. Detailed instructions for reconnaissance are contained in Manual of Reconnaissance for Triangulation, Special Publication No. 225.

Signal Building and Marking of Stations

In hilly or mountainous areas it is usually possible to place the stations on elevated points which are intervisible from the ground. In flat wooded areas, towers must be built to elevate the instrument and observer, as well as the lights on which the observations are made. In flat areas, the earth's curvature is sufficient to obstruct a line even if there are no trees in the way. The most convenient and economical type of tower for use in triangulation is the Bilby portable steel tower adopted by this Bureau in 1927. It is described in detail in Special Publication No. 158, Bilby Steel Tower for Triangulation (revised, 1940 edition). It consists of an inner tripod for supporting the theodolite and an entirely independent outer tripod for the observer, recorder, and lightkeeper, etc. (See figs. 1a and 1b.) The tower can be erected in 4 or 5 hours, can be taken down in even less time, and can be used over and over again. It varies in height up to 116 feet, depending upon the number of sections used. One or more of the bottom sections are left off for the shorter towers.

A special unit, known as the building party, works under the direction of the observing party and erects the towers as fast as they are needed. As soon as the observations have been completed on a station, the tower is dismantled and moved forward to be erected at a new station ahead. For a double observing party, there will ordinarily be 12 towers, 8 of which will usually be standing while 2 towers at the rear are being taken down and 2 at the forward end are being erected at new stations. When area triangulation is observed between arcs, more towers are required.

The building party also marks the stations and puts in the reference and azimuth marks. At each station an underground mark is set in addition to the surface mark if conditions permit. The marks consist of bronze disks, with inscribed legends cast in them, set in concrete posts or in large boulders or bedrock. The reference and azimuth disks have inscribed arrows which are pointed toward the station. The reference marks, two for each station, are set fairly close to the station, usually within 100 meters, but the azimuth mark is placed from ¼ to 2 miles distant in order that it may be used by the

Figure 1a.—Bilby steel triangulation tower in process of erection.

local engineer in obtaining an accurate starting azimuth. The azimuth mark is so placed as to be visible from the ground at the station, and it can therefore be used for local surveys without the need for towers or stands. Figure 2 shows the symbols and inscribed legends which are cast in the bronze disks for the various types of stations established by this Bureau during recent years. The preservation of all stations marked in this manner is extremely important and the cooperation of all engineers is earnestly requested. (See p. 21.)

Triangulation Observations

The angle observations on main-scheme stations for first- and second-order triangulation are made almost entirely at night. A very efficient type of electric signal lamp has been developed for night observations. The lamp is operated from dry-cell batteries and has a concentrated filament accurately placed at the focus of a parabolic reflector which produces a small but concentrated beam of light. A lightkeeper at each station on which observations are being made directs the beam accurately toward the observer's station. He can communicate with the observer when necessary by obstructing this

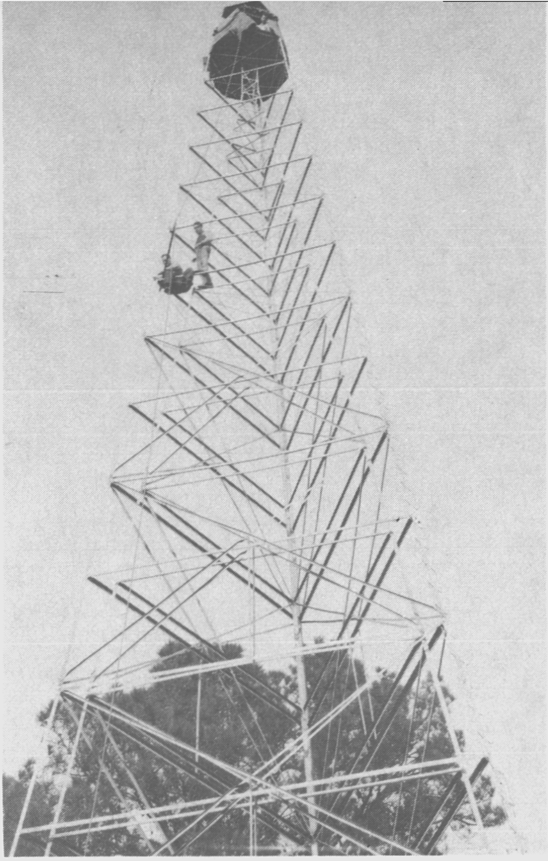

Figure 1b.—Completed tower.

beam and making a series of dots and dashes according to the Morse telegraphic code. It has been found that night observations are less affected by horizontal refractions and other atmospheric disturbances than are daylight observations. The lights have the additional advantage that they can be seen in cloudy weather, provided the clouds are not in the direct line of vision. Heliotropes, which are made visible by reflecting direct sunlight toward the observer, are sometimes used for daylight observations.

The angles of triangulation are measured with theodolites. These instruments are similar to surveyor's transits, except they are more precisely constructed and have micrometers for reading the circles. They are of two general types, the direction theodolite and the repeating theodolite. The former is used almost exclusively on first- and second-order triangulation. Detailed descriptions of both types and a discussion of their relative advantages will be found in Special Publication No. 247, Manual of Geodetic Triangulation. The repeating theodolite is much more adaptable than the direction theodolite for use at stations on high buildings or wherever the movements of the observer are apt to disturb the position of the instrument. This is because the observations on each angle require very little movement of

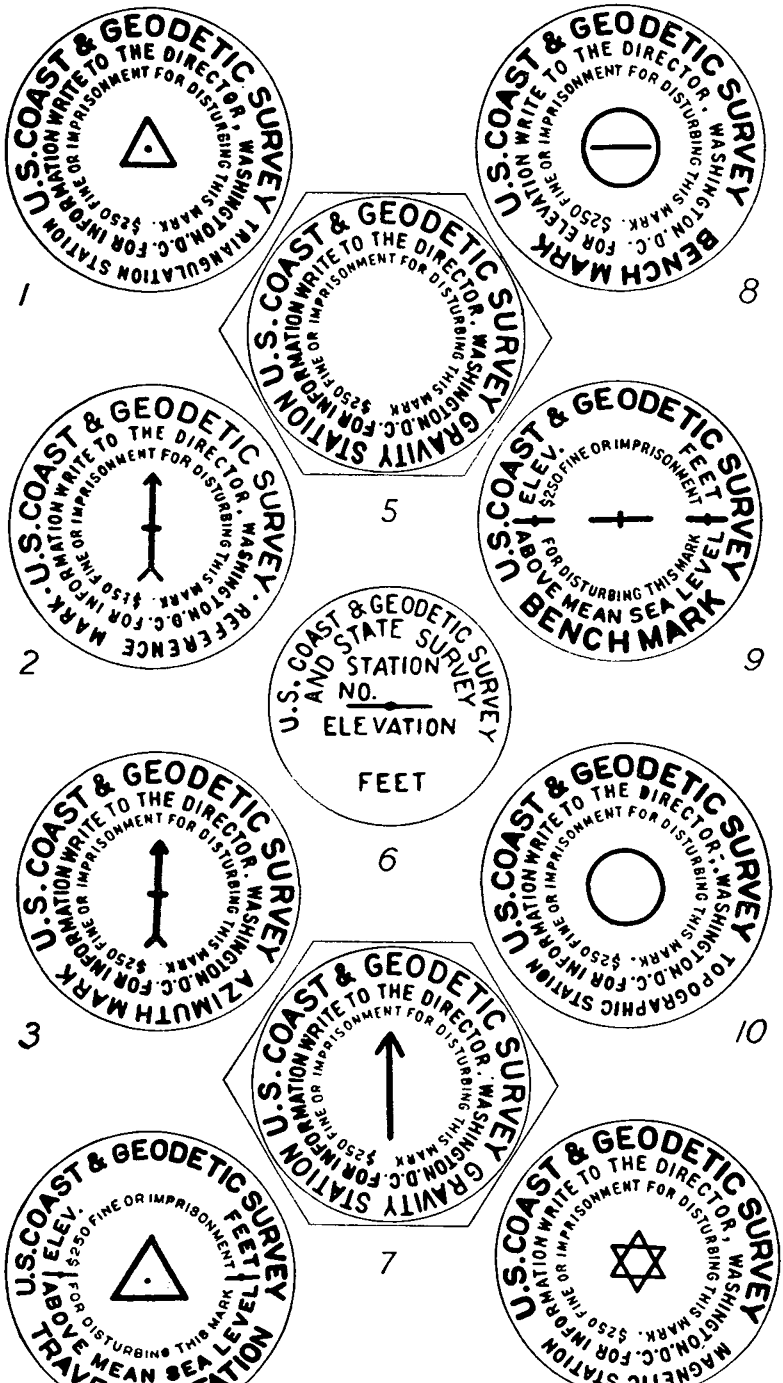

Figure 2.—Standard marks of the United States Coast and Geodetic Survey.

1. Triangulation station mark.
2. Reference mark.
3. Azimuth mark.
4. Traverse station mark.
5. Gravity station mark.
6. Local control survey mark.
7. Gravity station reference mark.
8. Tidal benchmark.
9. Geodetic benchmark.
10. Topographic station mark.
11. Magnetic station mark.

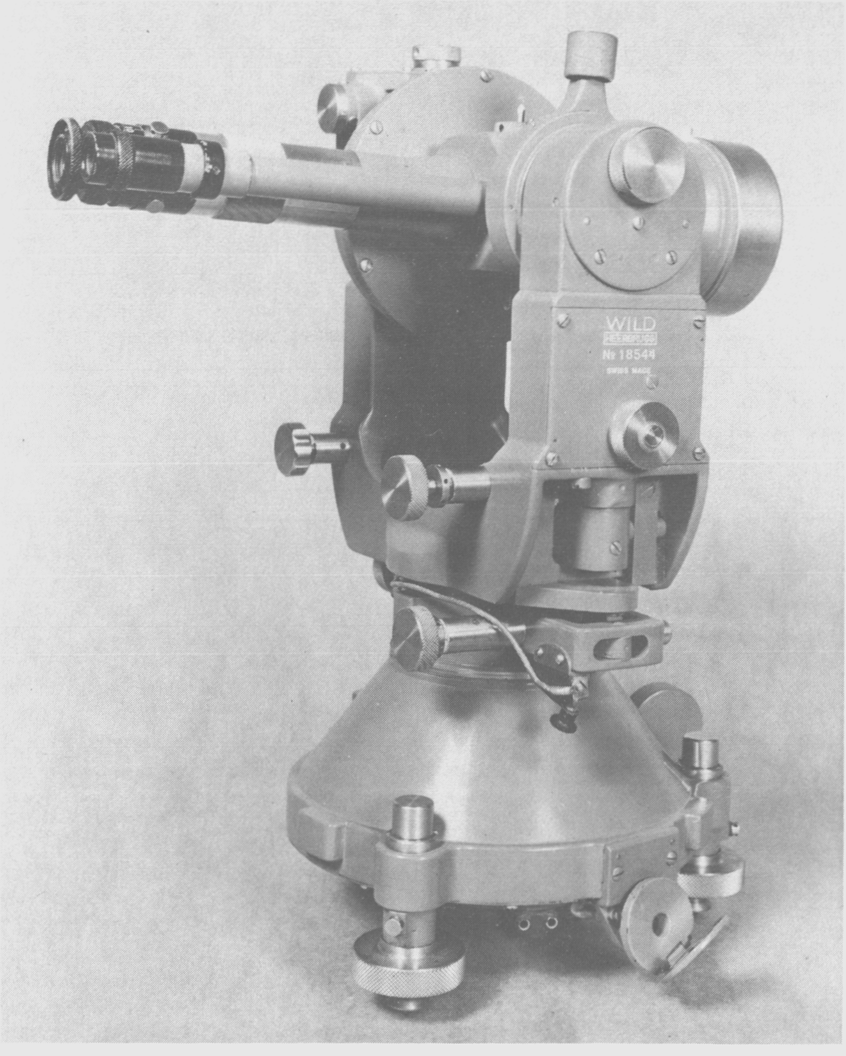

Figure 3.—Wild T–3 theodolite.

the observer when a repeating instrument is used. A direction theodolite is shown in figure 3.

If all the lights to be observed are visible when needed, the observations at a station may be completed during a single evening on all the contiguous main-scheme stations. There are other observations to be made, however. In order to supplement the principal stations of an arc of triangulation, a large number of additional points are always determined. Most of these additional points are known as intersection stations because they are not occupied by the observer but are determined by means of intersecting observations from two or more stations of the main scheme. If only two observations are made on them, they are known as "no check" stations, as the accuracy of the observations cannot be checked by closures of triangles or agreements of derived lengths.

The intersection stations consist of various objects, such as smokestacks, water towers, church spires, lighthouses, airway signals, etc., which are visible from the stations of the main scheme. No attempt is made to mount signal lamps on these structures, but the observations are made during the daytime, usually in the afternoon preceding the evening on which the main-scheme observations are to be made. A smaller number of observations, usually only one-fourth as many, are taken on the intersection stations than on the main-scheme stations, but the resulting positions are accurate enough for most local uses. "No check" points should, of course, be used with extreme caution in connecting local surveys to them, and they should always be verified, if possible, by additional connections to at least one other station, preferably a checked point.

Traverse

Before the development of steel towers in 1927, most of the horizontal control surveys in flat, wooded country were made by extending traverses along railroads and highways. Triangulation in these areas would have required wooden towers which would have made the work excessively expensive because of the additional labor required. Traverse differs from triangulation in that all lengths have to be measured in much the same manner as base lines, and that it lacks the automatic checks on the angle observations which are obtained from the triangle closures when the triangulation method is used. Traverse lines of first- and second-order accuracy are usually measured along railroads or highways because of the advantage of the cleared right-of-way. Along railroads the rail can be used as a support for the tape for most of the length measurements.

Traverse is inferior to triangulation both in execution and in use. Extreme care must be taken in the measurements to avoid blunders because of the lack of automatic checks. The stations determined are all along a single line and therefore do not serve as control for as large an area as an arc of triangulation of the same length. Opposed to this, however, is the fact that the stations are usually somewhat more easily accessible for the local engineer than are some triangulation stations. Since the adoption of the steel tower, very little first- or second-order traverse has been measured by this Bureau. The national control net, however, contains quite a large number of traverse lines which were measured before 1927.

Bases

The effective accuracy of triangulation depends both on the precision with which the various observations are made and also on the shapes of the triangles and quadrilaterals or other figures of which it consists, or what is technically known as the strength of figure. Strength of figure is explained at some length in Special Publication No. 225, Manual of Reconnaissance for Triangulation. As stated there, the letter R is the standard symbol for strength of figure. When written with the subscript 1 (R_1), it indicates the strength of figure through the best shaped triangles of a figure or scheme and when written with the subscript 2 (R_2) it indicates the strength of figure through the next best system of triangles.

The spacing of the necessary base lines in an arc of triangulation is determined by summing up the R_1 factors. When the R_1 factor reaches a certain limiting sum a base line must be measured. If the figures of the triangulation are poorly shaped, the R_1 factors are large and bases must be measured at shorter intervals than is the case when better shaped figures are used. The limiting values for the sum of the R_1's (ΣR_1) are shown in the table on page 10 for the different orders of triangulation.

Bases are measured with invar tapes because of the low temperature coefficient of invar. Most modern bases are measured along railroads or highways. Along railroads special supports are used to hold the tape above the rail in order to avoid errors due to friction and along highways heavy stakes are driven in the ground to support the tape. A uniform tension of 15 kilograms (33 pounds) is applied to the tape by means of carefully tested spring balances and the temperature of the tape is read and recorded for each tape length. Two or more tapes, each of which has been carefully standardized at the National Bureau of Standards, are used on each base, one for the forward measurement and one for the backward, and if the agreement between the two measurements of each section of the base is not within a certain specified limit, additional measurements must be made. Detailed instructions for base measurements are given in Special Publication No. 247, Manual of Geodetic Triangulation. The accuracies required for different orders of triangulation are given in the table on page 10.

Electronic or electronic-optical methods are now also employed in the measurement of base lines. Essentially these methods time the passage of light or radio waves transmitted over the base line.

Laplace Azimuths

Notwithstanding the high precision with which the angles of triangulation are measured, there is a tendency for arcs of triangulation to swerve away from their true orientation. This swerving could readily be corrected by the simple expedient of making astronomical azimuth determinations at suitable intervals and adjusting the triangulation to these azimuths, if it were not for the effect of deflections of the vertical. We ordinarily think of the plumb line as pointing toward the center of the earth, or at least toward the axis of the earth. This is not quite the case. Large mountain masses or other topographic features exert a sidewise attraction on the plumb line or on the levels of instruments. This may affect the astronomical observations by several seconds of arc; in fact, by as much as 20 or 30 seconds in extreme cases.

Uncorrected astronomical azimuths cannot be used, therefore, as true azimuths. Fortunately there is a method for determining quite accurately the effect of the deflection of the vertical on astronomical azimuth observations at a triangulation station. If the astronomical longitude is determined at such a station and compared with the geodetic longitude, or the longitude carried through the triangulation, the deflection of the vertical in an east-west direction becomes known within a small fraction of a second. This value of the deflection of the vertical can then be used to correct the astronomical azimuth observations and thus obtain a true azimuth to be held fixed in the adjustment of the triangulation. This corrected azimuth is known as a Laplace azimuth, and the station as a Laplace station.

Longitude and azimuth observations are therefore made at intervals along an arc of triangulation. It has been found from experience that a spacing of about 8 or 10 quadrilaterals between Laplace stations will provide sufficient azimuth control. As shown in the table below, the accuracy specified for Laplace azimuth observations is given by a limiting probable error of 0.3 second.

Standards of Accuracy

Control surveys are classified as nearly as possible according to the accuracy of the resulting lengths and azimuths of the lines. Since the absolute errors of these quantities cannot be ascertained, indirect gages must be used. For triangulation, the principal criterion is whether the discrepancy between a measured base and its length as computed through the scheme from the next preceding base is less than a certain fraction of the length of the base itself. In computing this discrepancy the side and angle equations, through the arc between the two bases, are first satisfied. The limiting values for the ratio of this discrepancy to length of the base are given in the following table for the different orders of triangulation. For traverse, a similar criterion for the closure in position is specified.

Another important indirect gage of the accuracy of the final results of triangulation is the average closure of the triangles. After allowance has been made for spherical excess, that is for the slight increase in the angles due to the spherical shape of the earth, the sum of the three angles of a triangle should be exactly 180°. The permissible variations from 180° for the different orders of triangulation are given in the following table, along with other specifications governing the accuracy of horizontal control surveys.

*Requirements for Horizontal Control**

Triangulation

	First order	Second order	Third order
Strength of figures:			
Desirable limit, ΣR_1 between bases	80	100	125.
Maximum limit, ΣR_1 between bases	110	130	175
Desirable limit, R_1, single figure	15	25	25.
Maximum limit, R_1, single figure	25	40	50.
Discrepancy between computed length and measured length of base or adjusted length of check line, not to exceed	1 in 25,000	1 in 10,000	1 in 5,000.
Triangle closure:			
Average, not to exceed	1 sec.	3 sec.	5 sec.
Maximum, not to exceed	3 sec.	5 sec.	10 sec.
Usual number of observations:			
Positions with 1-second direction theodolite	16	8	4.
Positions with 2-second direction theodolite	24	12	4.
Sets with 10-second repeating theodolite	5 to 6	2 to 3	1 to 2.
Base measurement:			
Actual error of base not to exceed	1 in 300,000	1 in 150,000	1 in 75,000.
Probable error of base not to exceed	1 in 1,000,000	1 in 500,000	1 in 250,000.
Discrepancy between 2 measures of a section, not to exceed	10 mm. $\sqrt{k}$	20 mm. $\sqrt{k}$	25 mm. $\sqrt{k}$.
Astronomical azimuth, probable error of result	0.3 sec.[1]	0.3 sec.[1]	

Requirements for Horizontal Control—Continued

Traverse

	First order	Second order	Third order
Closing error in position, not to exceed	1 in 25,000	1 in 10,000	1 in 5,000.
Probable error of main scheme angles	1.5 sec	3.0 sec	6.0 sec.
Number of stations between astronomical azimuths	10 to 15	15 to 25	20 to 35.
Correction for azimuth closure, discrepancy per main-angle station, not to exceed	1.0 sec	2.0 sec	5.0 sec.
Astronomical azimuth, probable error of result	0.5 sec	2.0 sec	5.0 sec.

*See Special Publication No. 247, Manual of Geodetic Triangulation, pp. xiv-xv, for an expanded list of requirements.

[1] This is the requirement for a Laplace azimuth. In the recent practice of the Coast and Geodetic Survey the only azimuths observed are Laplace azimuths.

Office Computations and Adjustments

There are two primary objects to be accomplished by the office processing of the field observations of control surveys. First, the data must be made consistent throughout and must be fitted to the existing adjusted net. Second, it must be put in the most convenient form for the use of surveyors and engineers.

The first part of the processing of the data is accomplished by means of special computations known as least-squares adjustments. These adjustments derive the smallest possible corrections to the angles which will accomplish the following results: Make the sum of the three angles of each triangle equal 180° plus the spherical excess; make the lengths of all sides of each quadrilateral, or more complex figure, consistent with all angles which may be used in computing these lengths; make the ends of each arc consistent in length, azimuth, latitude and longitude with the previously adjusted triangulation to which it is joined; and, finally, make the arc consistent with the intermediate measured bases and Laplace azimuths. Special equations are written to take account of each of these conditions, and then these equations are solved simultaneously. See Special Publication No. 138, Manual of Triangulation Computation and Adjustment. The method of variation of geographic coordinates is also employed in the adjustment of triangulation. (See Special Publication No. 28, Application of the Theory of Least Squares to the Adjustment of Triangulation.)

After the adjustment is completed, the final essential data for each station must be derived and placed in such form as to be readily available for the use of engineers and others having need for them. The following steps are required in this final processing of the data: The geographic position (latitude and longitude) of each station must be computed, together with the length and azimuth of each line of the triangulation; the plane (x and y) coordinates of each station must be computed on the State plane-coordinate system in use for that particular area, and also the grid azimuth of at least one line radiating from the station; the description of each station must be carefully revised and the directions to reference and azimuth marks converted to true azimuths; finally the data must be printed or otherwise reproduced and made ready for distribution.

Before describing in more detail some of the operations involved in the computations, it is desirable to review briefly the history of the national control net and of the adoption of the basic datum.

History of National Control Net

The horizontal control surveys of the United States were started during the early part of the 19th century at a number of points, mostly along the coasts, and existed at first as separate surveys, each based on one or more astronomical determinations of latitude, longitude, and azimuth. As examples of such detached surveys may be mentioned the early triangulation in New England and along the Atlantic Coast, a detached portion of the transcontinental triangulation along the parallel of 39° in the vicinity of St. Louis, Mo., and another detached portion of the same arc in the Rocky Mountain region, and three separate surveys in California in the vicinities of San Francisco, Santa Barbara Channel, and San Diego. These separate pieces of triangulation were later extended until several of them touched or overlapped. Finally the transcontinental arc was completed and joined all of these detached surveys into one continuous triangulation.

This made it possible, about 1900, to compute the net as a single coordinated survey and thus replace the independent systems previously in use which, of course, did not fit together properly at the junctions. The recomputation of all triangulation that had been completed up to that time would have been a fairly heavy piece of work and considerable study was therefore given to devising the best method and to adopting a datum that could be held fixed for a long time in the future. After much careful study it was decided to extend through the entire net the datum which had been used in New England and along the Atlantic Coast. This decision avoided a large amount of recomputation, of course, and at the same time it happened to give almost the ideal datum for the country as a whole.

Standard Datums

Before the triangulation over a large area can be computed, two fundamental things must first be known or be determined, namely, the exact shape of the mathematical figure which is a close approximation to the sea-level surface of the earth, and, second, the latitude and longitude of some one station of the net together with the azimuth of the line to one of the adjoining stations. The mathematical figure of the earth, or what is technically known as the spheroid, or ellipsoid, is determined by comparing the differences between astronomical determinations with the corresponding distances measured on the earth and by using gravity determinations. The astronomical determinations are particularly useful in deriving the size of the earth and the gravity determinations in obtaining its exact shape or the amount of flattening at the poles. As might be surmised, the precise solution of this problem requires much work and some very difficult mathematics. (See Special Publication No. 82, The Figure of the Earth and Isostasy from Measurements in the United States.)

Since the beginning of the nineteenth century the dimensions of the spheroid have been computed with considerable accuracy at least 20 different times. The early computations were based on comparatively small amounts of data and naturally did not represent the true shape and size of the earth quite so accurately as did some of the later computations. In 1924, at the triennial meeting of the International Geodetic Association held at Madrid, Spain, an international ellipsoid was adopted for use by all countries adhering to the Association that might be in a position to adopt a new datum or to recompute their triangulation nets. The international ellipsoid is based on dimensions derived in 1909 by John F. Hayford, who was at that time a member of the Coast and Geodetic Survey.

In 1880 this Bureau adopted what is known as the Clarke spheroid of 1866 as a basis for its triangulation computations. By the time the international ellipsoid was adopted by the International Geodetic Association, there were many thousands of stations in the United States based on the Clarke spheroid and there were also numerous computation tables which had been computed and published on this spheroid. The work involved in changing to a new spheroid would have been very great; and since the spheroid already in use differed only a small amount from the new one, it was decided that no change would be made. The principal dimensions of these two spheroids are as follows:

Comparison of spheroids

Name of spheroid	Equatorial radius (a)	Polar radius (b)	Flattening or ellipticity $\frac{a-b}{a}$
	meters	*meters*	
Clarke of 1866	6, 378, 206. 4	6, 356, 583. 8	$\frac{1}{294.98}$
International	6, 378, 388. 0	6, 356, 911. 9	$\frac{1}{297.00}$

Another prerequisite to the computation of the triangulation of a country is the adoption of the most nearly ideal position for some starting station, a matter of great importance and considerable difficulty. As explained on page 9 in connection with Laplace azimuths, astronomical determinations are rather seriously affected by the sidewise attraction of topographic features (deflections of the vertical) and therefore cannot be depended upon to give the best position for any single station. If a large number of astronomical determinations are made over a wide area such as the United States and with a fairly uniform spacing, it is then reasonably safe to assume that the deflections of the vertical will balance out to a large extent, that is, that the deflections to the north will about equal those to the south and those to the west about equal those to the east. The ideal starting position, therefore, is one that will make the average algebraic difference between the resulting geodetic and astronomical positions of identical stations approximately zero for the whole country.

The first datum adopted in this country was known as the United States standard datum. It was based on the Clarke spheroid of 1866 and had for its basic station a point in Kansas known as Meades Ranch. The following position was adopted for this station:

$$\text{Latitude} = 39°13'26''.686$$
$$\text{Longitude} = 98°32'30''.506$$
$$\text{Azimuth to station Waldo} = 75°28'14''.52$$

Although the azimuth to station Waldo was included in the fundamental data for Meades Ranch, this azimuth is now of secondary importance since the azimuths throughout the net are controlled by the many Laplace azimuths scattered through it. (See p. 9.) The adopted position of this fundamental point was tested by comparing all astronomical positions then available, which were connected to the net, with the corresponding geodetic positions, and it was found that the average algebraic residuals in both latitude and longitude were very nearly zero.

In 1913 this same datum was adopted also by both Canada and Mexico. This was a very important step in international cooperation because it placed nearly the whole of North America on a single geodetic datum and made it possible to coordinate the triangulation surveys of practically an entire continent. Such an ideal arrangement has never been accomplished in any other part of the world. In recognition of its new continental extent, the name of the datum was changed to North American datum.

North American Datum of 1927

In 1927 it became necessary to recompute the national control net. The Clarke spheroid and the position originally adopted for Meades Ranch were still satisfactory, but the adjustment of the net was far from ideal for the following reasons. The triangulation net of the country had been built up by continually adding new arcs to those already measured, and each new arc had been adjusted by making it fit the net which was already in existence and already adjusted. This method had the disadvantage that it forced distortions into the new arcs which should have been distributed through loops including both the new and the old arcs. It was the only feasible method to use until the main framework of the national net had been completed since it would have been quite impracticable to readjust the entire net, or even a large portion of it, each time a new arc was added.

In 1927 the western half of the control net, extending from the meridian of 98° to the Pacific coast, had been completed to the extent that a complete new adjustment could be made that would give a control framework of such high accuracy as to permit new arcs to be added without undue distortion. It was very desirable to undertake this new adjustment before the net became any more complex because of the great amount of computation involved. A special method for making the adjustment was suggested in outline by the late William Bowie and was worked out in mathematical detail by O. S. Adams. (See Special Publication No. 159, The Bowie Method of Triangulation Adjustment as Applied to the First-Order Net in the Western Part of the United States.) By use of junction figures the adjustment was divided into a number of different parts which could be carried on simultaneously. This made it possible to complete the work within a reasonable time.

A short time after the western half of the national net had been readjusted in this manner, the eastern half was recomputed in the same way, the field work for the main framework of the eastern part of the country having, in the meantime, been completed. The two adjustments resulted in a very accurate net for the whole country. Since their completion, new arcs have been fitted into the net without undue distortion and only rarely has it been necessary to upset the adjustment of small sections of the net to force some arc of the main net to take its share of loop closure discrepancies.

The reader may wonder why the name of the datum was changed from North American datum to North American datum of 1927 when no changes were made in the dimensions of the spheroid or in the position of the initial station. The principal reason for the change of name was to guard against the readjusted data becoming confused with the old data. Meades Ranch was the only station held fixed in position in the readjustment. All other stations in the net were changed in position. The changes were small in the vicinity of Meades Ranch but at greater distances were fairly large. In the State of Washington, for example, the change in position was slightly over 1 second in latitude and nearly 1.4 seconds in longitude. The new name for the datum therefore indicates new positions for the stations of the net rather than changes in the fundamental properties of the datum, except that the azimuth from Meades Ranch to Waldo was changed about 5 seconds.

Explanation of Horizontal Control Data

The recent practice of the Coast and Geodetic Survey is to compute the final results of its triangulation and traverse surveys on two different systems of coordinates, one based on geographic latitudes and longitudes and the other on plane rectangular coordinates. One great advantage of geographic coordinates is that they constitute a universal system for the whole world and any point located in this system is definitely related to any other point in the system. Geographic coordinates must be computed on the curved surface of the adopted mathematical ellipsoid which represents the shape of the earth. It is necessary to take account of the earth's curvature in this manner when extensive surveys are involved.

For limited surveys, rectangular coordinates may be used in place of geographic coordinates. The main advantage of rectangular or grid coordinates is that they are computed on a plane surface and that they are readily used by those engineers who have had little or no experience in triangulation surveys, because they are simple x and y rectangular coordinates, with the use of which all engineers and surveyors are familiar.

Geographic Positions

The triangulation and traverse data of this Bureau are first computed as geographic positions, that is, as latitudes and longitudes. The latitudes are of course referred to the Equator and the longitudes to the meridian of Greenwich. They are based in the actual computations on the adopted position of the initial station Meades Ranch as explained on page 13. The tables of geographic positions contain, in addition to the latitudes and longitudes, the lengths of all lines of the triangulation and their azimuths. Two azimuths are given for each line, one called the forward azimuth and the other the back azimuth. The latter is from the distant station toward the station listed in the first column of the table and does not differ from the forward azimuth by exactly 180° because of the convergence of the meridians passing through the two stations. Only for stations on the Equator or for stations on the same meridian are the forward and back geographic azimuths exactly 180° apart. Azimuths are given with reference to true south and in a clockwise direction. South is 0° or (360°), west is 90°, north is 180°, and east is 270°.

The lengths of the lines are given in both meters and feet as a convenience to the user of the data. The logarithm of the length in meters is also given for each line because of its usefulness when the line is used as a basis for other surveys. The logarithm is taken directly from the computations. The length in meters is obtained from the logarithm and the length in feet by conversion of the length in meters. In the method of adjustment by variation of geographic coordinates employing high-speed electronic calculators, the length in meters is obtained directly and the feet and logarithms are derived therefrom. An explanation of the use of the two systems of units will be found on page 20.

Plane Coordinates

The plane rectangular coordinates of horizontal control stations are derived from their geographic positions. Although the engineer using these coordinates does not need to know exactly how they are computed he may wish to know something about the methods employed and what determines the size of the area included in each independent system, etc.

About 1932, it was decided that the horizontal control data of this Bureau would have greater usefulness if they were available also as plane coordinates. A careful study was made by O. S. Adams to determine what types of projections would be most suitable as bases for plane-coordinate systems and what would be the most desirable size for the area to be included in each independent zone. He found that the Lambert conformal conic projection would be an excellent one for areas of greatest extent in an east-west direction and the transverse Mercator projection for areas of greatest extent in a north-south direction. With regard to size of area, it was decided that counties would be too small as they would involve too frequent change of zone and that many of the States would be too large to use as a single zone. The criterion finally adopted was to make the areas such that the maximum scale error would rarely exceed 1 in 10,000. This meant that the larger States had to be divided into two or more zones with widths not greater than about 158 miles. The boundaries between zones were made to follow county boundaries in order that only one zone would be needed in any one county. Liberal overlaps of the zones were provided in the computation of coordinates.

Each Lambert zone is based on a cone which intersects the earth along two standard parallels. These parallels are so selected in each case as to make the maximum scale errors between the parallels about equal to, or a little less than, the maximum errors outside them, the two being of opposite sign. In other words, the compression of areas between the parallels is made about equal to the expansion outside. (See fig. 4.)

The transverse Mercator projection is similar to the ordinary Mercator projection but related to a central meridian instead of to the Equator. It is made to intersect the earth along two lines parallel to the central meridian in order to balance out the scale errors, as in the Lambert projection described above. It, too, compresses the areas between these two lines and expands the areas outside much as in the Lambert projection. Figure 5 illustrates how the transverse

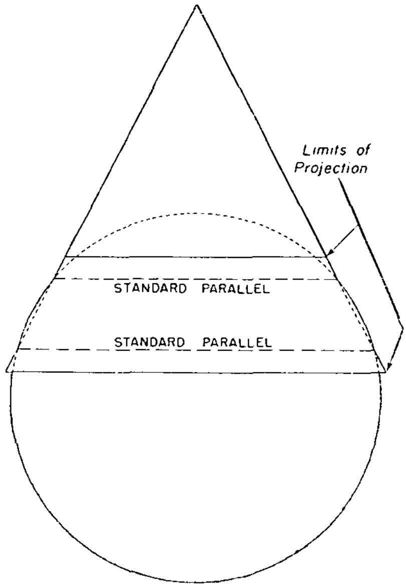

Figure 4.—Sphere and intersecting cone illustrating the Lambert conformal conic projection.

Mercator projection was used for the three plane-coordinate zones in Idaho.

In order to avoid negative values for the coordinates of stations, a constant is added to the x values derived by the computations. This makes the apparent origin of coordinates differ from the true origin of the computations.

Several publications have been issued by this Bureau to describe the plane-coordinate systems, to show how they were computed and to explain how they may be used. As previously stated, it is not necessary for an engineer to make a detailed study of how the coordinates are computed. Except for special problems that he may encounter only rarely, he may work directly from the x and y coordinates of the stations and not be too much concerned as to how these are derived from the geographic positions. The plane coordinates for the triangulation stations of this Bureau are computed as soon as possible after the adjustment is completed. The following publications will be useful to anyone wishing to make a detailed study of the methods used for the computations:

Special Publication No. 193, Manual of Plane-Coordinate Computation.
Special Publication No. 194, Manual of Traverse Computation on the Lambert Grid.
Special Publication No. 195, Manual of Traverse Computation on the Transverse Mercator Grid.
Special Publication No. 235, The State Coordinate Systems.

The essential plane-coordinate data for a station consist of the following items: The name of the State, the designation of the zone used as a basis for the computations, the x and y coordinates of the station in feet, and finally the grid azimuth of at least one line radiating from the station. The other azimuths may be derived by com-

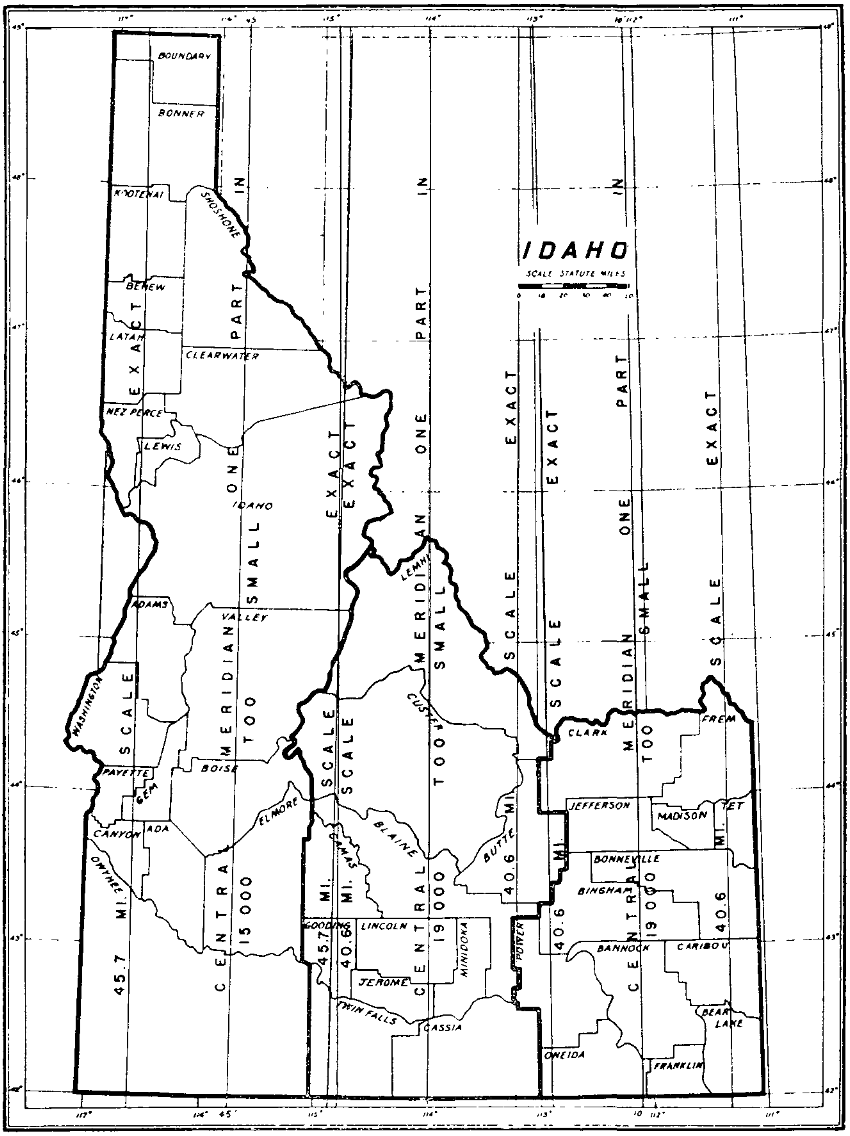

Figure 5.—Use of transverse Mercator projection for plane-coordinate zones in Idaho.

paring this azimuth with the forward azimuth of the same line as given in the geographic position table and by applying the difference [1] to the other azimuths in the latter table to give the grid azimuths. The back grid azimuth is not given because on a rectangular system it differs exactly 180° from the forward azimuth. If a station is near the edge of a zone its coordinate data are given on the adjacent zone also in order that the engineer may use whichever zone is more convenient for him and may usually thus avoid the somewhat troublesome computations required to change from one zone to another.

One difficulty with plane coordinates is that the area covered by a single zone is limited in extent because it is impossible to represent a large area of the earth's surface on a plane surface without serious distortion of some kind. This means that surveys covering fairly large areas will sometimes include stations in more than one plane-coordinate zone. Another difficulty is that the grid azimuths at a station will not be referred to the true meridian except for stations located at the central meridian on which that particular plane-coordinate system is based. In other words, the convergence of the meridians cannot be incorporated in a rectangular system of coordinates. One other but minor difficulty should be mentioned. If extreme accuracy is desired in surveys based on these coordinates, scale factors must be used in certain areas of each coordinate zone. The scale factor is unity along two lines in each zone but is less than unity between these lines and greater than unity outside them, the size of the factor in each case depending upon the distance from the lines. (See p. 16.)

In some of the triangulation publications of this Bureau the plane-coordinate data for each station will be found at the end of the description of the station. Where the triangulation data are issued in lithographed form, the plane coordinates are listed in tables similar to the tables of geographic positions. Anyone wishing to convert from geographic coordinates to plane coordinates, or vice versa, or anyone wishing to apply scale factors will need the appropriate plane coordinate projection tables. These are available in the form of Special Publications, one for each State. They may be purchased from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

Uses for Horizontal Control Data

The basic horizontal control net of this country has many very important uses. It serves to locate national,, State, and county boundaries and also many private boundaries. It serves as a rigid framework for all types of accurate maps such as the topographic maps of the United States Geological Survey. It makes possible a greater precision in the surveys of large cities than can be obtained by other methods. It coordinates into a single related system all local surveys connected to it and helps to assure the perpetuation of any marks established by such surveys.

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[1] This difference is known as the θ or $\Delta\alpha$ angle.

The State plane-coordinate systems which have been devised by this Bureau (see p. 16) enable engineers and surveyors to connect to the control net with great facility wherever stations of the net are within a reasonable distance from a proposed local survey or engineering project. Many States have legalized the definition of boundaries of private and public property in terms of plane coordinates on the zone specified by the Coast and Geodetic Survey for the particular area. An example of how a local survey may be connected to the control net is given in Serial No. 347 (Revised, 1940 edition), Use of Coast and Geodetic Survey Data in the Surveys of Farms and Other Properties.

The utility of the national control net is increasing rapidly. For many years after this country became a nation, land was very cheap as a rule and the owners of property were not greatly concerned in having their boundary lines precisely determined. The cost involved would have been excessive in relation to the value of the land. In many areas compass surveys were considered adequate for the purpose. Today the picture is very different. Land is valuable over a large part of the area of the country. Inaccurate surveys cannot be tolerated. The property owner wants to know definitely where his boundaries are located and wants to be able to reproduce them exactly if necessary at any future time. By far the most economical way to accomplish these desired results is to have the surveys based on stations of the national net. This assures accuracy and permanency and frequently makes it possible to carry out the survey in less time than otherwise required.

Use of Metric and English Units

Because of its greater convenience, the metric system is used by the Coast and Geodetic Survey for its horizontal control surveys. For the convenience of engineers, surveyors and others who use the data, most lengths are given also in the more familiar English units. All lengths of lines are given in both meters and feet in the tables of geographic positions.

In the descriptions of stations, the distances to reference marks and other measured distances to nearby objects are ordinarily given first in meters and followed, in parentheses, by the distance in feet in each case. Other distances in the descriptions which may have been only roughly determined, or occasionally only estimated, are given only in the units used in the field descriptions. For example, the field description may state that a station is about 100 yards from a fence corner or 35 paces from the corner of a barn. These distances are not converted to other systems of units.

The conversion from meters to feet, or the reverse, may be made very quickly by the use of factors, especially if a multiplying machine is available. A length in meters should be multiplied by the factor 3.2808333 to change it to feet. If it is desired to change from feet to meters the factor is 0.30480061. Notice that one additional decimal place is given on the second factor. This is done to give the same number of significant figures in each factor. The same rule has been used in making up the following condensed conversion table.

If a computing machine is not at hand, conversions may be made by use of the following table thus avoiding some of the labor of hand multiplication. As a very simple example of how the table may be used, a length of 24.6 feet is converted to meters as follows:

20 feet	=6.096 meters	(tabular value with decimal point moved one place to right)
4 feet	=1.219 meters	
.6 foot	=0.183 meter	(tabular value with decimal point moved one place to left and last figure rounded off)
Sum	=7.498 meters	

Condensed conversion table

Meters	Feet	Feet	Meters
1	3.280833	1	0.3048006
2	6.561667	2	.6096012
3	9.842500	3	.9144018
4	13.123333	4	1.2192024
5	16.404167	5	1.5240030
6	19.685000	6	1.8288037
7	22.965833	7	2.1336043
8	26.246667	8	2.4384049
9	29.527500	9	2.7432055
10	32.808333	10	3.0480061

Cooperation in Preservation of Marks

There are many thousands of marked triangulation stations widely scattered over the entire area of the United States. These marks and the data regarding their positions and descriptions, etc., represent the final results of all field and office work of horizontal control surveys and are very valuable. A station is useful only as long as it can be recovered, and therefore great care is used in the marking and describing of each station established. Inscribed bronze disks are set in bedrock or in masses of concrete both to mark the station and to furnish reference points which can be used to determine the location of the station if the station mark cannot readily be found or if it has been destroyed. A station can usually be quickly located for the first few years after it was established, but after a lapse of many years the changes which are apt to take place in the nearby natural and cultural features make it increasingly difficult to find the mark by means of the original description. Engineers and others who have occasion to visit or use a triangulation station and who find that the description needs modification will perform a public service by reporting the present condition of the mark and its surroundings to this office. The report should be addressed to the Director, United States Coast and Geodetic Survey, Washington 25, D. C.

The preservation of accurately determined survey stations is of direct concern to every citizen of this country for the following reasons: He helped to pay for these stations and is therefore a joint owner. He is saved the expense of much needless litigation over the location of public and private boundary lines whenever these stations are available as basic starting points for the location of these lines. His community is benefited by the more accurate and efficient surveying and mapping of all local projects connected to these stations, as for example, general city and farm surveys, surveys for flood control or water-power development, surveys for the relocation of roads and many other projects.

Field parties of this Bureau are instructed to obtain the permission of the property owner before establishing a station and to pay any damages caused by the establishment of the station. Sometimes it is not possible to find the owner of the property and the station is established without permission. When a station is established on cultivated ground, the mark is placed below the surface of the ground so as not to interfere with plowing.

The Government makes no claim to the land on which the station is located and permission is always given a property owner to destroy a station if necessary in the improvement of his property.

Relocation of Marks

Triangulation stations are always placed where they are least likely to be disturbed or destroyed and yet can be found without too much difficulty. New construction, the relocation of roads or beach erosion are anticipated as much as possible and locations likely to be affected are avoided. In spite of these precautions, however, station marks are frequently and unavoidably destroyed. If this destruction can be foreseen in time, it is sometimes possible to establish a new station in a safe location nearby and connect it to the old station so precisely that it can be used in place of the original station for most purposes, after a suitable revision of the data. This Bureau has no funds for this specific purpose and therefore must depend upon the cooperation of interested engineers and others whenever such a change in a station must be made, except in the rare cases when a field party of this Bureau happens to be working in the vicinity at the time the change must be made.

As soon as it becomes known that a station is to be destroyed, a letter should be sent to the Director of the United States Coast and Geodetic Survey, Washington 25, D. C., giving a description of the station in sufficient detail to make it possible to identify it with certainty at this office and stating the reasons why the old mark is to be destroyed. If a replacement station can be established by the correspondent or by some local engineering organization, a new bronze disk will be furnished by this office and also detailed instructions for doing the work as contained in Serial No. 632, The Preservation of Triangulation Station Marks. The work must of course be done carefully and accurately as otherwise the new station will be entirely unsatisfactory to use in place of the old station.

Publications

The reader will have found a number of references to the publications of this Bureau in the preceding pages. If he wishes to obtain any of the currently available publications and if he has cooperated with the Bureau to an appreciable extent, he may obtain them without charge by writing to the Director, United States Coast and Geodetic Survey. It is well for him to state in the letter the nature of the cooperation he has extended to the Bureau as the cooperation may have been in some other Division than the one to which his request will be referred.

If he has not cooperated, he may purchase the publications at a nominal cost from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. A list of the available publications of this Bureau with the price of each is given in a List of Publications of the Coast and Geodetic Survey. This list may be obtained by application to the Director, United States Coast and Geodetic Survey, Washington 25, D.C.

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NOAA--S/T 76-2472