SCIENCE IN THE UNITED STATES COAST AND GEODETIC SURVEY

by

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U. S. COAST AND GEODETIC SURVEY

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The Coast and Geodetic Survey is organised in such a way that all data needed in the construction of a nautical chart are supplied by its observers in the field and its personnel in the office.

This work consists of astronomical determinations of latitude, longitude and azimuth, the measurement of base lines, observations for triangulation, tide and current surveys, topographic and hydrographic surveys of the coastline and adjacent waters, wire-drag surveys to detect pinnacle rocks, wrecks, glacial boulders and coral reefs, and observations for the determination of magnetic elements affecting the mariner's compass. This is one of the few government bureaus that could, if it were absolutely necessary, function without assistance from any other agency in conducting its operations.

Assistance, however, is rendered by others. The Naval Observatory furnishes accurate time determinations used in the astronomical work. The Bureau of Standards standardises apparatus such as base tapes, thermometers and levelling rods. It graduates the circles for theodolites. Survey data secured by the Corps of Engineers in their river and harbour developments are used to keep charts up-to-date. The topographic maps of the U. S. Geological Survey are of assistance in planning field operations.

Since the bureau is designed to serve, it necessarily helps other government agencies and others outside the Federal government.

The above gives in brief outline the lines of work carried on for the construction of the nautical chart, but there is other work by the Bureau not involving the chart. This consists of gravity surveys, surveys for aerial navigation, triangulation and leveling over the interior of the country, astronomical work to furnish data used in the adjustment of arcs of triangulation, observations to determine the variation of latitude, seismological work, including the determination of the epicenters of earthquakes and investigations for increasing the resistance of engineering and architectural structures to damage by earthquake, and magnetic surveys throughout the interior of the country to determine magnetic elements useful in geographical investigations, and useful also to the practical land surveyor.

There are three scientific phases to the work of this government agency. First, the designing and improvement of instruments. Second, the making of observations and measurements, and third, the analysis and interpretation of data.

The development of instruments involves optics, magnetics and other branches of physics. It may be said that the instruments of the Coast and Geodetic Survey are nearly as up-to-date as those of any other similar agency in the world. Constant improvements are made in our instrumental equipment. If something is done in another country that would lead us to believe that one of our instruments could be improved, changes are made accordingly. Some instruments have been designed and constructed in the office of this bureau. An outstanding example is the tide-predicting machine designed and constructed by E. G. FISCHER in collaboration with R. A. HARRIS and other members of the Tidal Division.

The first invar level rod, so far as is known, was designed and made in the bureau's shop. It is not known definitely, but it is believed that the first portable automatic recording apparatus for radio time-signals for use with a chronograph was employed by the Coast and Geodetic Survey. This apparatus was designed by E. A. ECKHARDT, then a physicist at the Bureau of Standards, assisted by J. C. KARCHER and Morris KEYSER. Funds were transferred from the Coast and Geodetic Survey to the Bureau of Standards for carrying on development work involved. This apparatus has been somewhat modified, but in its essential parts it is similar to the original one made by ECKHARDT and his assistants.

The Coast and Geodetic Survey and the Bureau of Standards joined in purchasing an apparatus for graduating circles of theodolites. This apparatus has been modified and improved by the Bureau of Standards. Circles graduated with it have a very high degree of accuracy. The writer knows of no theodolite circles that are graduated with any higher degree of precision than those graduated by the Bureau of Standards.

A great step forward has been made in hydrographic surveying by the perfection of echo sounding apparatus by Herbert GROVE DORSEY and his assistants. The fundamental principles of the echo sounding apparatus were employed by Dr. DORSEY when he was with a commercial company making the fathometer. Later DORSEY joined the Coast and Geodetic Survey and has continued with marked success his research in the use of sound waves in determining the position of the surveying ship and the depths of the water.

The observations in the field with the instruments purchased or made in the office of the Coast and Geodetic Survey present many scientific problems. In hydrographic surveying the relation between the velocity of sound and the temperature and density of the water presents a number of very interesting and important problems, the solution of which is the subject of scientific research. Triangulation now carried on at sea by means of the radio-acoustic ranging method of locating a ship and the taut-wire method both involve scientific research and observations.

Research is involved in determination of the direction and velocity of the ocean currents and in the tidal observations used for the reduction of soundings to a single datum plane and for the determination of mean sea level.

The question frequently arises as to whether the charting of the coast and the waters contiguous thereto will be completed at some date in the near future. The answer to this question is that the charting of the coasts will never be completed so long as the actions of man and the forces of nature change the configuration of the shorelines and the bottoms of the ocean waters. There is a constant drifting of sand along the coasts; rivers and harbours must be dredged in order to provide the necessary depth for the increasing size and depth of vessels. Storms change the shoreline, and objects that formerly were aids to the navigator may have been shifted in position or have been destroyed and other objects may appear. The charts must show the new data.

Although for many parts of the coasts the charts are changed little and seldom through many decades, there are other sections which change rapidly and frequently. These changes must be taken into consideration by the chartmaker.

In the interior of the country the Coast and Geodetic Survey is engaged upon a very comprehensive geodetic survey involving the determination of the latitude and longitude of thousands of stations, the directions and distance between contiguous stations, and the elevations above sea level for tens of thousands of bench marks. The triangulation and leveling data are used as the basis for all classes of surveys and maps. They also have many uses in engineering operations and they are of particular value in the perpetuation of the boundary lines of public and private land.

Triangulation involves the determination of latitude, longitude and azimuth by astronomical observatioas, the measurement of base lines for length, and the measurement of the horizontal angles of the triangles. The astronomical work is fairly well standardized and the instruments that are used are well perfected. There are, however, scientific problems connected with the astronomical work involving the study of so-called night errors, the use of the radio time-signals and the variation of latitude. The mathematics connected with the determinations of apparent places of stars, and of the latitudes, longitudes and azimuths resulting from the observations, have been standard for many years.

The measurement of base lines presented difficult scientific problems prior to about 1900. For many years the base measurements were made with metal bars of various types. Although many bases were measured with satisfactory accuracy, there were serious difficulties presented by measurements in the field. During the past few decades base measurements in this country have been made with 50-metre invar tapes. Invar is not a very stable alloy, although it has the very desirable property of a low coefficient of thermal expansion. By having the tapes restandardized at frequent intervals, the errors resulting from changes in their lengths are kept within permissible limits.

The base line is a side of a triangle, and varies in length from 4 to 15 miles, or more, depending upon the character of the terrain. The probable error of the standardization of each of the base tapes by the Bureau of Standards is seldom greater than one part in a million. The base is measured with three tapes and in both directions. If for any section of the base the difference in measurements is greater than the prescribed amount, one or more additional measurements are made. The tapes are used in pairs in such a way that there is an intercomparison of the tapes of a set on each base line. If the lengths of the sections measured with one tape differ materially and constantly from the measurements with the other two tapes, then a fourth tape is substituted for the tape that stood out from the others.

The observations for the angles of the triangles in triangulation are made with the best available theodolites. The instrument that finds greatest favor with the observers of the Coast and Geodetic Survey was designed by and the first one constructed under the direction of Mr. D. L. PARKHURST, Chief of the Instrument Division of the Bureau. In the design of this theodolite, the best features of existing theodolites were used and in addition some new ideas were incorporated into it. It is rapid in operation and gives a high degree of accuracy in the results. More recently this instrument has been made by each of several manufacturers of surveying instruments in this country.

Nearly all of the measuring of the horizontal angles of the principal chain of triangles of an arc is now done at night. Years ago observations were made on poles, targets and heliotropes, but the poles and targets could not be seen for great distances, nor could they be seen over lines of even moderate length, unless the atmosphere was exceedingly clear. With the heliotrope the observing could be done only on clear days and then only in the early morning and late afternoon, when the atmosphere is usually steady. Now the observations are made at night on the light from an automobile headlight. A special bulb makes it possible to have a very narrow cone or ray of light from the lamp. The light has been observed with the unaided eye over distances as great as a hundred and fifty miles.

In general, the observations for the measurements of the angles of a main scheme triangle are repeated 32 times. The residuals of the individual measurements are usually small, unless atmospheric conditions are very unfavorable. At times the light appears to be quite unsteady. The observer learns with experience how to make the observations on such lights in a way that will give satisfactory results.

Usually there are five triangle sides radiating from a single station. With the PARKHURST and with other high-grade theodolites the observations can be completed with 32 observations over each line within an hour and a half on an average. There are cases where these observations have been completed within one hour and with none needing to be rejected because of large residuals.

One of the largest sources of error in horizontal angle measurements is lateral refraction. The stations should be selected at places such that no line of sight lies close to the side of a hill or ridge. Then again, the instruments should be elevated to such heights above the ground as to clear the layer of the atmosphere lying close to the ground and subject to disturbance. It generally has been found that lateral refraction is at a minimum, or may be entirely absent, for a line that lies close to sloping ground, when the wind is blowing towards the slope. When it is in the opposite direction, the lateral refraction may be as much as 4" or 5".

The average closing error of the triangles is about 1" and a maximum of 3" closing error is permissible. It is only occasionally that the closing error of a triangle exceeds that amount. When it does, the stations are reoccupied for additional observations.

In spite of all that can be done in the way of making accurate horizontal angle measurements, the arc of triangulation tends to swerve more or less. This swerving is sometimes ten or fifteen times the probable error of the azmiuth of a triangle side as carried through the computations. This swerving is overcome by the use of so-called LAPLACE stations. A LAPLACE station is merely a triangulation station at which both the astronomical longitude and the azimuth have been observed. A comparison of the longitude determined astronomically with that determined by the triangulation gives a measure of the deflection of the vertical in the prime vertical at the station. With a knowledge of the amount of such tilting a correction can be derived which is applied to the observed astronomical azimuth to obtain the corrected geodetic azimuth. The corrected geodetic azimuth is held fixed in the adjustment of the triangulation. In this way the swerving of the arc is overcome. These LAPLACE stations are established at intervals of from six to ten quadrilaterals along an arc.

Base lines are measured at varying distances along the arcs of triangulation in order to control the lengths of the triangle sides. The spacing of the base line depends to a large extent upon the number of triangles and the strengths of the distance angles of the triangles. In general, they are spaced at intervals of one to two hundred miles.

There are now approximately 58,000 miles of arcs of first and second-order triangulation in this country. A plan is being followed which calls for the spacing of the arcs of triangulation at intervals of about 25 miles. These are all rigidly adjusted together to form a single system for the three millions square miles of our area.

In 1924 a method for adjusting a large network of arcs of triangulation was devised by officials of the Coast and Geodetic Survey. By its use a new adjustment of the triangulation net of the country was started in 1924 and was completed in 1927, under the direction of O. S. ADAMS.

Within three years if the present rate of progress can be maintained, the triangulation net will be developed until a 25-mile spacing of arcs is attained. Much additional horizontal control surveying will be needed as the basis for topographic mapping, but with the net so well advanced as it is now the needs of the topographic engineers can be met promptly for any area in which they may wish to operate.

The Coast and Geodetic Survey is extending a network of lines of levels over the country with lines of the first-order spaced at intervals of about 100 miles and with second-order levels run in the intermediate spaces. There are at the time of this writing about 103,000 miles of first-order and 122,000 miles of second-order levels in the net. It is expected that within the next few months the network with 25-mile spacing of the lines will be completed, except for a few small inaccessible areas in the mountains.

The level net is tied into 21 tidal stations along the Atlantic, Gulf and Pacific coasts, at which mean sea level has been determined from a number of years of observations. The leveling net is so comprehensive and so strong that we now can feel satisfied that mean sea level as determined by tidal observations does not define an equipotential or level surface. Of course, there are some errors of observation in the leveling but the results after adjustment give at least the order of magnitude of the differences in elevation for mean sea level at the 21 tidal stations. If Galveston mean sea level be taken as the zero elevation, then mean sea level at St. Augustine, Florida, has an elevation of — 0.89 feet and the mean sea level at Boston is + 0.23 feet; at San Diego the elevation is + 1.08 feet, the elevation at San Francisco is + 1.11 feet and at Seattle + 1.57 feet.

An adjustment of the combined level net of Canada and the United States involving about 65 thousand miles of first-order leveling was completed in 1929. This adjustment furnished the most probable values of the elevations of the junction points of the net. Those junction points were held fixed and sections of the level net adjusted to them. Mean sea level was considered to have zero elevation at each one of the 21 principal tide stations of this country and at 5 tide stations on the east and west coasts of Canada. By combining the two nets stronger elevations were obtained than if the level net of the United States had been adjusted separately.

The running of lines of precise leveling has been considered a scientific problem during many decades. Atmospheric conditions affect the observations. The effect of sunlight must be considered. The question of the stability of the earth's surface is a factor in the determination and perpetuation of elevations of bench marks. Then again, there is the problem of the non-parallelism of level surfaces at different elevations. This must be taken into account in adjusting the elevations of bench marks along the line of levels. If it is not taken into account, a circuit of leveling that has been run perfectly, so far as observations and instrumental effects are concerned, may have an apparent error of closure of as much as 3 or 4 feet. In order to close circuits of lines the so-called orthometric correction is applied to a line of levels that is run in any other than an east and west direction, where the elevation of the terrain for the line exceeds a certain minimum.

At each one of the triangulation and leveling stations a metal tablet is set in either outcropping rock, in a permanent masonry or concrete structure, or in an especially placed block of concrete. The results of the geodetic surveys consist of these station monuments with their latitudes, longitudes and elevations. Necessarily, the station monuments are designed to last for many decades.

One of the most interesting scientific problems presented to the Coast and Geodetic Survey was the measurement of the base line near Pasadena, California, and the triagulation involved in the determination of the distance between Mt. Wilson and San Antonio Peak for use by the late A. E. MICHELSON in the determination of the velocity of light. The base was approximately 33,638 metres in length and was measured many times. The probable error of its length from field observations alone was only one part in 11,600,000.

In the triangulation used to transfer the length of the base to the line joining the two peaks, every precaution was taken. The closing errors of the triangles averaged only 0.55". The maximum closing error of a triangle was 1.57". The deflection of the vertical at each one of the stations was determined in order to correct the horizontal angle measurements because of the tilting of the axis of the instrument. The probable error of the distance between the two peaks of 35,373 metres derived from the probable error of the base measurement and from the observed angles of the triangles was one part in 6,800,000. Of course, the probable errors of the base and of the distance between the two peaks should involve the probable errors of the standardization of the base tapes. It is estimated that the actual error in the distance between the two peaks is between one part in five hundred thousand and one part in a million.

The triangulation and the leveling of the country furnish the basis for the determination of earth movements near the epicenters of earthquakes. The observations made prior to the earthquake can be repeated. The differences in the horizontal and vertical positions before and after the earthquake furnish a means of determining how much movement had occurred and how far to the side of the fault zone the earth's surface was affected. It is a very fundamental question as to whether an earthquake is caused by regionally acting forces or by those of a more local nature. Future studies of earth movements by means of geodetic measurements should throw light on this matter.

Another line of geodetic field work consists in the determination of the values of gravity. Improvements have recently been made in the apparatus formerly used. It is hoped that in the not distant future gravimeters may be designed that will make it possible to determine the value of gravity at a field station with great accuracy in a very brief period of time. The Coast and Geodetic Survey is now using the so-called BROWN apparatus, which is a development of the apparatus designed by the late T. C. MENDENHALL, former Superintendent of the Coast and Geodetic Survey. With the apparatus in its original form four to five stations could be established in a month. With the Brown apparatus only one day is needed for a station and if transportation and other conditions are satisfactory, from 20 to 24 stations a month can be established.

In terrestrial magnetism and seismology there are scientific problems involving the design and operation of instruments at permanent stations and at field stations. In the case of magnetic instruments progress has been chiefly along the line of study and modification of existing instruments and of improving rather than replacing earlier instruments. Such work is being done cooperatively with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

In seismology the advance has been even more marked. Instruments for recording distant earthquakes, and especially for recording strong nearby earthquakes have been developed in cooperation chiefly with the Bureau of Standards. Instruments for measuring the vibrations of buildings and other structures and of the ground have been developed in connection with earthquake studies by the Coast and Geodetic Survey and are now in active use.

Although the data secured by the Coast and Geodetic Survey for its chart construction and by its geodetic surveys are used principally for making charts and maps and in many other lines of engineering, they have many scientific uses also. The hydrographic chart furnishes the configuration of the ocean bottom. This is important in physical and biological oceanography and in physiography and geology. The continental shelf is geologically speaking a part of the continent. Its configuration is given by the accurate hydrographic chart.

Coast erosion is a subject of importance to the geologists and physiographers. The charts show the positions of the coastlines and successive issues of the chart show what changes have occurred.

The tidal data provide basic observational data for various scientific questions. Obviously they furnish the data for the further development of tidal theory and the solution of numerous complex hydrodynamic problems. They provide, also, basic elevation datums for geophysical investigations on land and sea. In addition, the results of the tide observations enter into such investigations as the body tides of the earth and its rigidity. The study of the tides furnishes practically the only precise quantitative approach to the fundamental question of changes in the relative elevations of land and sea.

Two lines of scientific research carried on by the Coast and Geodetic Survey during the past few decades involve the use of geodetic data. One is the determination of the figure of the earth, the other is isostasy. In the former, a large measure of success has been obtained. The figure of the earth derived from geodetic data by the late John F. HAYFORD when in charge of the geodetic work of the Survey was adopted in 1925 by the International Geodetic Association as the International Spheroid of Reference. That Association recommended its use by those countries that had not yet adopted a spheroid for their charting and mapping and for their other scientific work, and by other countries that were using a spheroid not considered to be of sufficient accuracy and wished to have a better one.

Since HAYFORD derived his spheroid in 1909 there have been accumulated vastly greater amounts of geodetic data, which are now available for deriving a new spheroid. It is hoped that this work may be undertaken very shortly, It is believed that with the great expansion of the triangulation net of the United States and with the addition of many gravity stations the figure of the earth could be derived from the three million square miles of this country which would be of even greater interest to scientific men.

While it is impossible to say that a spheroid derived from data in a restricted area only approximately one-sixtieth of the total surface of the earth will represent the average sea level surface of the whole world, yet it is possible that when the isostatic principle is applied, the figure of the earth derived from a small area will really be very close to what would be derived from geodetic data covering the entire land surface of the earth.

The Coast and Geodetic Survey has cooperated very fully with F. A. VENING MEINESZ of the Geodetic Commission of Holland, who devised an apparatus for the measurement of gravity at sea aboard submarines. The staff of the Survey has made isostatic reductions for a number of VENING MEINESZ' sea stations.

I have covered in this outline only a few phases of the scientific work of the Coast and Geodetic Survey that happened to be most familiar to me. To treat in a similar manner all of the work that is done by this bureau would extend this paper to undue lengths.

The Coast and Geodetic Survey, like most government organisations, is not organized primarily as a research institution. Perhaps it would be well if more research in the interpretation of data acquired by government institutions could be done by those who are in closest touch with the original data, that is, by the personnel of the institutions concerned. The Survey has always, however, been interested in the meaning of the observations it makes. In the subject of oceanic tides, the late R. A. HARRIS of the Survey was probably in his time the leading authority, not only of this country but of the world, and his contributions to theory are of a fundamental character and for the most part are still accepted. The theory of isostasy is in substance an interpretation of the observed deflections of the vertical and intensities of gravity at various points. The Survey has not confined its work to publishing the raw material, but through HAYFORD and his successors has discussed it and has tried to interpret it. Probably the Survey, in recent years, has done more than any other one single organization to bring about the general acceptance of the theory of isostasy. Much of course remains to be learned, especially as to matters of detail. Investigations are now being carried on, as for some time past, in connection with the figure of the earth as a whole, the form of the geoid, the variation of latitude, earth tides and related subjects. These are essentially problems in mathematics or in theoretical physics. As a natural part of the work of the Survey, investigations have been made of the theory of map projection, a subject more nearly allied to pure mathematics; this has recently developed into a group of plane coordinate systems primarily for the use of land surveyors and topographers; these systems are really special cases of map projection.

The mass of material collected by the Survey will be utilized for scientific purposes by its personnel, as far as opportunity permits. But the material is equally available to other investigators outside the Survey; it has been used by them to a limited extent in the past and it is to be hoped that more and more they will avail themselves of it in the future.