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R. S. PATTON, Director

Special Publication No. 23
(1929 Revised Edition)

THE UNITED STATES COAST AND GEODETIC SURVEY

ITS WORK, METHODS, AND ORGANIZATION

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In addition to nautical charts, the publications of the Coast and Geodetic Survey include:

Coast Pilots.[1]—Twelve separate volumes covering the Atlantic, Pacific, and Gulf coasts, and the coasts of Alaska, Philippine Islands, Hawaiian Islands, Porto Rico, and Virgin Islands.

Tide Tables.[1]—Issued annually in advance.

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[1] Available only from Coast and Geodetic Survey. Ask for catalogue.

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The United States Coast and Geodetic Survey maintains mailing lists containing the names and addresses of persons interested in its publications. When a new publication or a new edition is issued on any of the subjects covered by the mailing list, a circular showing its scope and contents is sent to each person whose name and address is on the mailing list of the subject covered by the publication.

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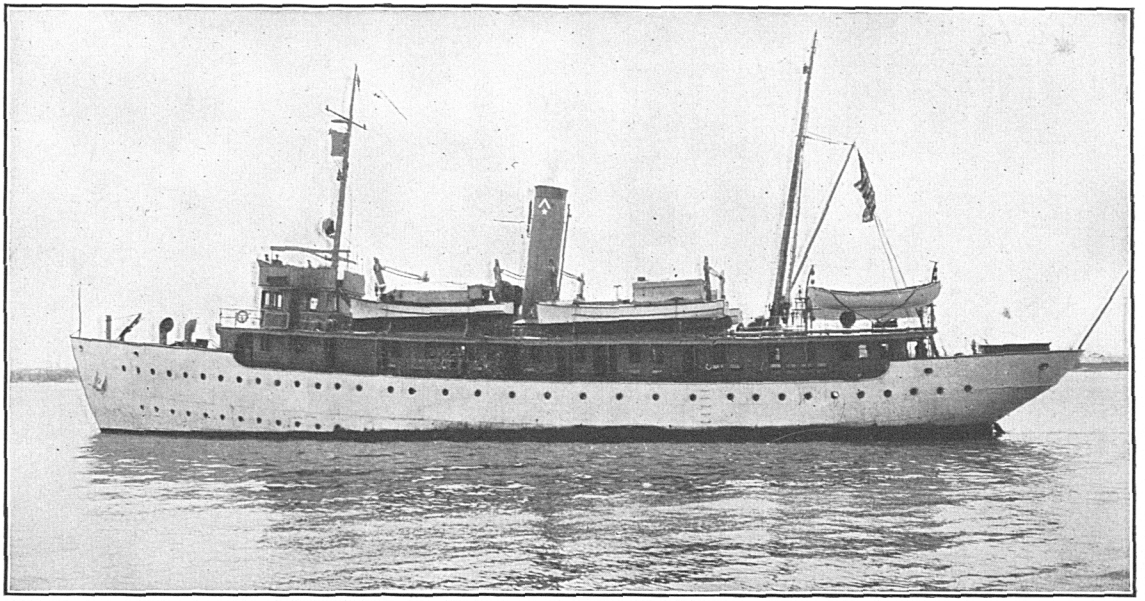

FRONTISPIECE.—UNITED STATES COAST AND GEODETIC SURVEY SHIP "SURVEYOR" ENGAGED IN COMBINED SURVEYS ON PACIFIC COAST

This vessel, built expressly for the Coast and Geodetic Survey, is 172.8 feet long, 34.1 feet beam, draft 12 feet. She can keep to the open sea for 30 days without refueling or provisioning. She sends out four parties in small launches. Her chevrons and star were won in the World War by sinking the submarine which sank the *Lusitania*.

UNITED STATES COAST AND GEODETIC SURVEY

ITS WORK, METHODS, AND ORGANIZATION

INTRODUCTORY

To all peoples whose territories touch the sea or who have any interest in the commerce of the sea a full and complete knowledge of the coast, its nature and form, the character of the sea bottom near it, the locations of reefs, shoals, and other dangers to navigation, the rise and fall of the tides, the direction and strength of currents, and the character and amount of magnetic disturbance are of the greatest practical value. To supply this knowledge, the governments of the principal maritime nations have in modern times made surveys of their coasts by the most exact methods.

Some idea of the importance to this country of such operations may be formed when it is remembered that the coast line of the United States and Alaska, measured along its general trend, exceeds 11,500 statute miles in length. To represent the actual shore line, which includes all the islands, bays, sounds, and rivers in the littoral or tidal belt, these figures would have to be increased to 91,000 miles; and to the foregoing must be added the shore line of Porto Rico, Guam, Tutuila, Wake, the Hawaiian, the Midway, and the Philippine Islands, and the Virgin Islands of the United States. The length of the general shore line of these islands exceeds 5,400 miles, and their detailed coast line is in excess of 12,000 statute miles.

HISTORICAL OUTLINE

In 1807, during the administration of President Thomas Jefferson, Congress authorized the establishment of a national Coast Survey as a bureau under the Secretary of the Treasury. The plan adopted for its execution was that submitted by Ferdinand R. Hassler. Because of the external relations of the country it was impracticable to take any steps toward putting the plan in action until 1811, when Hassler was directed to proceed to Europe to arrange for the construction of the necessary instruments and standards, some of the most important of these being made after his own design. The outbreak of the War of 1812 seriously interfered with his commissions, their completion being thereby delayed until the close of 1815, and in consequence actual field work was not possible until 1816. The work was suspended in 1818 and resumed in 1832.

For the purpose of furnishing geographic positions and other data to State surveys the scope of the bureau was enlarged in 1871, and in 1878 its designation became the Coast and Geodetic Survey.

On the organization of the Department of Commerce and Labor in 1903 the bureau was transferred to it from the Treasury Department and in 1913 to the Department of Commerce. The plan upon which it is at present organized is based on the broad scientific foundation proposed by Hassler and approved by Jefferson; and its present methods are the perfected results of experience gained in the field and office during more than a century of its existence.

Under the direction of a director there are two great divisions of its work—the field and the office. In accordance with the plan of reorganization of 1843, the work on shore was divided between civilian assistants and officers of the Army, and the hydrographic work was placed almost entirely in charge of officers of the Navy.

In 1861 the officers of the Army and Navy were detached, and since that date no officers of the Army have been assigned to duty on the survey. After the Civil War the assignments of officers of the Navy gradually increased in number, so that the hydrographic work was about equally divided between them and the civil assistants during the period which extended to 1898, when the officers of the Navy, because of conditions created by the outbreak of the war with Spain, were finally relieved, and in 1900 Congress authorized the establishment of the survey on a purely civil basis.

EQUIPMENT AND PERSONNEL

The survey operates a fleet of 10 steamers and 6 motor vessels, of which 4 were built for the survey, 10 were transferred from the Navy Department, and 2 are loaned by the Philippine government. The personnel of the survey is at present divided as follows:

1. Field force, composed of 141 hydrographic and geodetic engineers, junior hydrographic and geodetic engineers, and aides, 8 magnetic observers, 21 tide observers, 45 mates, engineers, surgeons, deck officers, etc., 550 enlisted men, and an average of 160 additional employees who are necessary to insure the effective work of field parties on shore, besides a number of laborers hired for brief periods when needed.

2. Office force, composed of disbursing agents, chiefs of division, clerks, mathematicians, draftsmen, engravers, instrument makers, printers, editor, etc., numbering 208. The office is that part of the establishment which receives the records, original sheets, etc., representing the results of field work. These are registered and deposited in the archives until in turn they are taken up for examination, computation, and adjustment, prepared for publication, and finally published. In the office, charts are compiled from original surveys, by this and other Government bureaus, and printed by photolithography or by transfer from engraved copper plates. For the convenience of administration the operations of the main office at Washington are carried on by eight divisions, each having some specified portion of the general work to perform.

There is a field station at Manila, and the officer in charge, representing the director, has authority to arrange for the conduct of insular field and office operations, to prepare and publish charts and sailing directions and all other information which he decides is

necessary or desirable for the use of mariners and the public generally. There are field stations also at Boston, New York, New Orleans, San Francisco, Seattle, and Honolulu.

SYSTEMS OF SURVEY CONTROLS

Because of the continental extent of the survey's field of operations, a system of first-order and second-order triangulation for the determination of geographic positions by geodetic methods must furnish the control or framework on which its results are based. This control system, while not yet complete, has been carried to some extent into every State in the United States. In connection with this framework of triangulation some exceptionally large figures were introduced. The longest line on record, observed from both ends, is that from Mount Helena to Mount Shasta, which is over 190 miles in length.

A third-order triangulation for topographic and hydrographic purposes has been completed along the entire Atlantic and Gulf coasts and the coasts of Porto Rico and the Virgin Islands and along practically the whole of the Pacific coast except Alaska. The triangulation of the Philippines has been practically completed, and in Alaska the first-order triangulation has been completed from Dixon Entrance to Skagway, and considerable progress has been made with the third-order triangulation along the coast.

In the determination of astronomic positions the exact methods originally developed in the survey have been followed and perfected. The use of radio for longitude determination is an important recent development. (See p. 10.)

Chapter I.—ASTRONOMIC WORK

The United States Coast and Geodetic Survey has carried on astronomic work in the United States and its possessions, including the Philippines and Alaska, for many years. The purpose of this work is to give the location of cities, islands, and other widely separated places in connection with the surveying and mapping of the coasts and interior of the country, to locate the stations at which magnetic observations are taken, and to supply certain data needed in the adjustment of the triangulation net of the country. Astronomic work consists of the determination of time, latitude, longitude, and azimuth.

DETERMINATION OF TIME

The time observations made by the Coast and Geodetic Survey are, in general, of two classes, depending on the accuracy required. For the less accurate work observations are made on the sun or stars by means of a sextant or vertical circle. With these instruments the angular distance of the sun or a star from the zenith, the point directly overhead at the place of the observations, is measured and, at the instant the observation is made, the time is read on a chronometer or watch.

Other data needed in the determination of local time—that is, in the determination of the error of the chronometer or watch—are the approximate latitude and, for observations on the sun, the approximate longitude of the station at which the observations are being made. The coordinates of the star's position—namely, its angular distance from the Equator, called declination, and its angular distance from the hour circle through the vernal equinox, called right ascension—are needed for the computation. These may be found in the American Ephemeris and Nautical Almanac, published by the Naval Observatory, Washington, D. C., or in similar books published by other countries.

In order that the effects of refraction and instrumental errors may be eliminated from the results to a great extent, observations are made on a star to the eastward of the station and on another to the westward. The error of the determination of time with a sextant or vertical circle is approximately one-half second.

THE ASTRONOMIC TRANSIT

In the most refined work of the Coast and Geodetic Survey time is determined with an instrument called an astronomic transit. One type of this instrument is shown in Figure 1. Descriptions of the instruments may be found in Special Publications Nos. 14 and 35 of the Coast and Geodetic Survey or in any modern textbook on geodetic surveying and astronomy.

In its general principles the astronomic transit is somewhat similar to the ordinary surveyor's transit, except that it is much larger and has no circle for reading horizontal angles. It consists of a telescope with a rotation axis rigidly attached at right angles to it and terminating in pivots which are supported in two wyes or standards. The telescope contains wires placed in the focus of the objective, so that the image of a star at which the telescope is pointed will be in the same plane as the wires. The eyepiece of the instru-

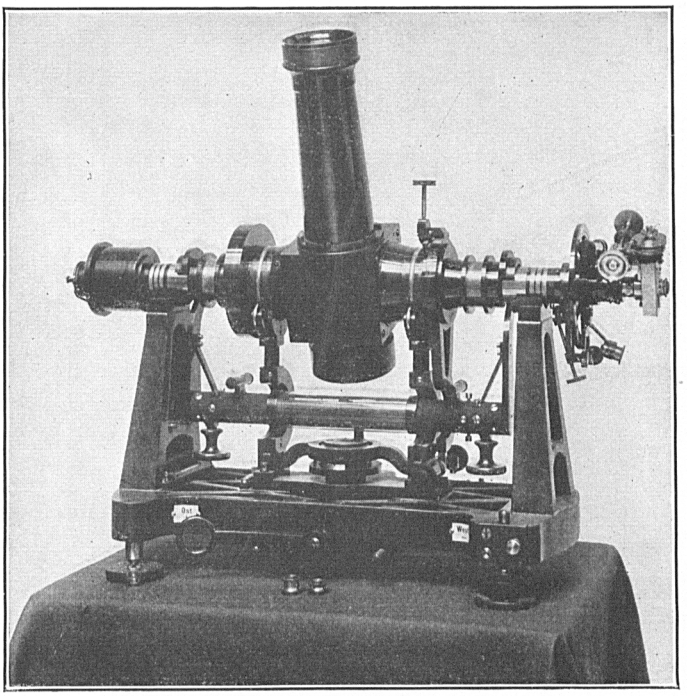

FIG. 1.—BROKEN-TELESCOPE TRANSIT WITH TRANSIT MICROMETER

A prism in the axis of the telescope bends the light rays at right angles and makes it possible to have the eyepiece of the instrument at one end of the horizontal axis in a convenient position for observing. By attaching a delicate level to the horizontal axis this instrument may be used also for latitude observations. At the eye end of the telescope is a device called a transit micrometer which contains a movable observing wire. The observer keeps this wire on the star while it is crossing the field of view and an automatic record of the star's passage is obtained on the chronograph by means of electrical contacts in the micrometer.

ment consists of a simple lens or combination of lenses which magnify the wires and the image of the star in order to make them visible to the observer.

When the instrument is in adjustment the line joining the center vertical wire in the telescope and the center of the objective lens is at right angles to the horizontal axis of the telescope, the horizontal axis of the telescope is truly horizontal, and the vertical plane described by the line of sight as the telescope is swung on its horizontal axis is coincident with the plane of the meridian. It is impos-

sible to have the adjustment of an instrument absolutely perfect, and, therefore, methods of observing are followed which will eliminate, or at least greatly minimize, the errors due to the lack of perfect adjustment.

Previous to 1905 the usual method for making time observations with the transit was known as the key and chronograph method. At the instant the star crossed each one of the number of vertical wires in the instrument the observer pressed a key connected in the

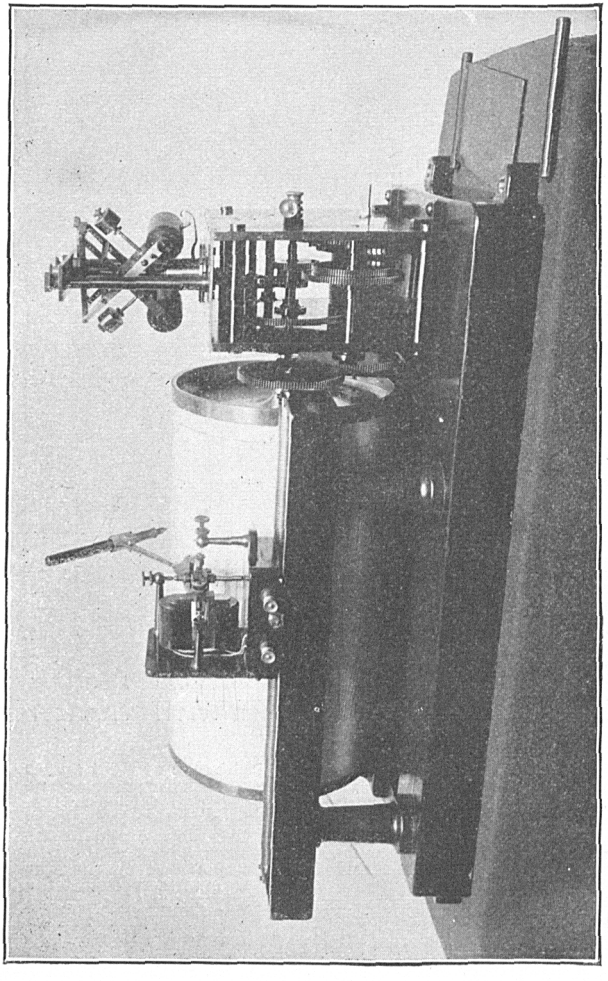

FIG. 2.—CHRONOGRAPH

The large drum of this instrument is turned at a constant speed by a system of weights and gears controlled by a governor. During time observations the ticks of the chronometer and the times of passage of the stars across the meridian are recorded automatically, on a sheet of paper placed around the drum, by a pen operated electrically.

chronograph circuit, and thus recorded the time on the chronograph sheet.

The chronograph, as the name implies, is an instrument for "marking" or recording time. (See fig. 2.) It has a drum revolving at a uniform speed on which a pen or pencil traces a line in the form of a helix. The pen is operated by an armature which causes it to make a jog in the line whenever the electric circuit is broken. The chronometer is connected in this circuit and auto-

matically breaks the circuit every second except the sixtieth of each minute. The line on the chronograph sheet will therefore show a jog or notch for each second of the chronometer except the sixtieth, and an extra notch for each time the circuit is broken by the key. The exact time when the key was operated can therefore be scaled directly from the chronograph sheet. (See fig. 3.)

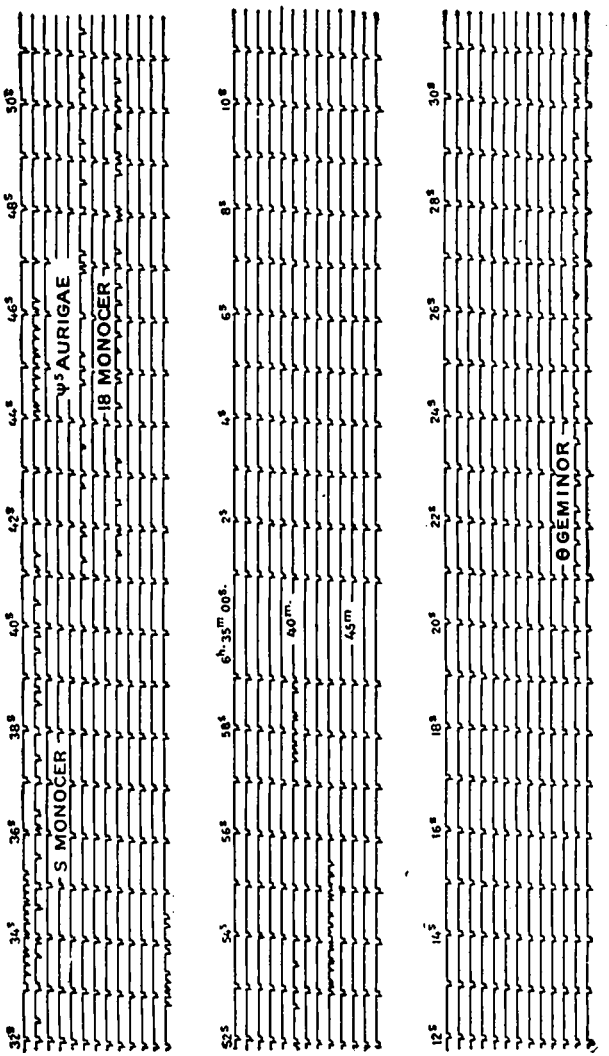

FIG. 3.—PORTION OF CHRONOGRAPH SHEET

The equally spaced breaks in the lines were made by the chronometer. The additional breaks were made by the transit micrometer and record the passage of stars across the field of view of the transit. The time of each star's passage may thus be measured directly from the sheet.

AUTOMATIC METHOD OF TIME DETERMINATION

The modern method of noting the times of transit of the star across the field of the telescope is that of the self-registering micrometer. In this micrometer is a movable thread which can be made to follow the star as it crosses the field. By means of a series of automatic electric contacts in the micrometer eyepiece a record of

the star's passage across the meridian is made automatically on the chronograph as described above.

The great advantage of the automatic method of recording the time at which the star passes the meridian is that it reduces what is called the personal equation, which is present in the key and chronograph method. The personal equation is an error unconsciously made by the observer in constantly observing either too soon or too late the passage of a star across the wires. The more expert the observer the more nearly constant is his personal equation.

Since the right ascension of a star is the local sidereal time of its passage across the meridian, the error of the chronometer may be easily computed from the data furnished by the observations described above. The details of the methods employed in making these computations are given in United States Coast and Geodetic Survey Special Publication No. 14, entitled "Determination of Time, Longitude, Latitude, and Azimuth."

A determination of time with an astronomic transit usually consists of observations on five or six stars which are especially selected to form a group. The probable error of a determination of time from such a group is usually not greater than about 0.02 second.

DETERMINATION OF LONGITUDE

As is well known, the position of a place on the earth's surface is expressed in terms of latitude, the angular distance north or south of the Equator, and of longitude, the angular distance to the east or west of some adopted initial meridian. The meridian that is in almost universal use at the present time is the meridian which passes through the observatory at Greenwich, England. A meridian is simply an imaginary line formed by the intersection of a plane with the earth's surface or with the celestial sphere. This plane contains the earth's axis and is at right angles to the plane of the Equator.

The determination of the longitude of a place consists, therefore, in measuring the angular distance between the adopted initial meridian plane and the plane of the meridian through the place whose longitude is sought; or it may consist in the determination of the angular distance between the meridian through some place already referred to the initial meridian and the meridian through the new station.

The angle between any two meridians can be expressed in degrees, minutes, and seconds of arc or in hours, minutes, and seconds of time. There is a simple relation between these two measures. An hour is equivalent to 15°, a minute of time is equivalent to 15′ of arc, and a second of time to 15″ of arc. With this known relation between time and arc we have a means by which to determine the difference of longitude. This consists simply in determining the difference between the local times at the two places, one where the longitude is known and the other where it is unknown.

Before the invention of the electric telegraph it was necessary in determining a difference of longitude to transport a chronometer set to the local time of a place where the longitude was known—as, for instance, Greenwich, New York, Paris, or some other place—and compare this time with the local time as determined by observations

at the new station. This is the method used by navigators when radio time signals are not used.

Other methods of determining the differences of longitude are to observe the local time that the moon crosses the local meridian, or that stars are occulted by the moon, or that the eclipse of a satellite of Jupiter occurs. While these methods avoid the uncertainty in the rate of the chronometer when carried from one place to another, the resulting differences of longitude are not of a high degree of accuracy, and the computation of the local time and the Greenwich time at which the observations take place is a laborious process.

Another method that has been used by explorers in the determination of longitude is that of observing flashes of light on mountains. These flashes are made by mirrors reflecting the light of the sun or by explosions of powder. The two observers note their local times at which the flash occurs, and later the information is sent by each observer to the other and the difference in time becomes known.

TELEGRAPHIC METHOD

Previous to 1922 the most exact method of determining the difference of longitude was by means of the electric telegraph. In this method arbitrary breaks of an electric current in a wire joining the two places of observation are recorded on chronographs at the known and the unknown longitude stations. On each chronograph are recorded also the seconds breaks of the local chronometer. The exact time of each of these chronometer breaks is known from observations on the stars made to determine the error of the chronometer. The time of each of the arbitrary breaks of the electric current can be scaled off very accurately from the chronograph sheet. This is done at each of the stations, and the record of each observer is sent to the other. From the data thus obtained the difference of time between the two observatories can be computed with great accuracy.

In order that the transmission time through the electric system due to relays, etc., may be eliminated from the results, the breaks of the electric circuit are made partly at one station and partly at the other. When this has been done, the mean of the recorded times of the breaks will be free from any error due to the transmission time. The arbitrary breaks of the electric current are made during an interval in the observations on the stars.

Usually two determinations of the local time are made in connection with longitude observations—one by a set of observations on five or six stars just before the arbitrary breaks are made and the other by a similar set just after the breaks. These two determinations furnish a rate of the chronometer. A statement in regard to the time determination is given on page 4.

A precise or first-order determination of a difference of longitude by telegraph depends on at least three nights of successful exchange of signals when time observations have been made at each end of the line. The probable error of such a determination is usually less than 0.02 second of time.

RADIO METHOD

Radio signals have been used by the Coast and Geodetic Survey in longitude determinations since 1922. Methods involving the use of the radio were formerly objectionable from the standpoint of accuracy because a personal equation entered into the reception of the signals by ear. The radio recorder perfected by the United States Bureau of Standards has overcome this objection by effecting the mechanical registration of the signals. The incoming radio signals make available a local current of sufficient strength to operate the chronograph pen. A complete portable radio-receiving outfit is carried by the observing party in addition to the regular instrumental equipment.

The method of making the star observations is the same as for telegraphic longitudes when wires were used, but there is substituted for the exchange of arbitrary signals between two observers at different stations a record of the radio time signals at the unknown station only. These signals are the United States Naval Observatory time signals, sent by radio from Annapolis or Arlington. They are recorded on the same chronograph as the breaks of the local chronometer, and the time comparison thus obtained determines the longitude of the station referred directly to the Naval Observatory at Washington. Only one observing party is necessary in the field when the radio signals are used, and the success of this method in Alaska indicates that there need be no place where instruments can be carried whose longitude can not be accurately determined.

The longitude determinations by the Coast and Geodetic Survey are now made principally for the purpose of furnishing data by which the triangulation network of the country may be adjusted to the proper geographical position. A description of the methods used is contained in Special Publication No. 14 of this bureau, entitled "Determination of Time, Longitude, Latitude, and Azimuth;" in Special Publication No. 35, "Determination of the Difference in Longitude between Each Two of the Stations, Washington, Cambridge, and Far Rockaway"; and in Special Publication No. 109, "Wireless Longitude." The results of all longitude determinations in the United States up to 1921, inclusive, are given in Special Publication No. 110, entitled "Astronomic Determinations by United States Coast and Geodetic Survey and other Organizations."

DETERMINATION OF LATITUDE

Latitude may be defined as the angular distance of an object or place north or south of the Equator. Hence, the latitude of a place becomes known when this angular distance has been determined.

The approximate determination of the latitude of a place may be made by the simple method of observing, with a surveyor's transit or a sextant, the altitude of the North Star as it passes the meridian. The North Star, or Polaris, is not exactly coincident with the extension of the axis of the earth to the celestial sphere. This star makes a circle approximately $2\frac{1}{4}°$ in diameter around the pole. It is readily seen that if we know the altitude of Polaris at the time it crosses the meridian below the pole, the latitude of the place is that

altitude plus the polar distance of the star. This polar distance is 90° minus the declination of Polaris. Similarly, if we should observe the altitude of Polaris when it is on the meridian above the pole, the latitude of the place would be the altitude minus the polar distance. The latitude of a place may be observed also by determining the altitude of the sun as it crosses the meridian.

The declinations, or the angular distances of stars to the north or the south of the celestial Equator, have been determined by years of observations at fixed observatories, and the results are contained in such publications as the American Ephemeris and Nautical Almanac, the Boss Catalogue of Stars, and other star catalogues.

The method of determining the latitude of a place by observations on Polaris and on the sun is subject to considerable error due to what is called refraction or the bending of the rays of light coming to the earth from these bodies. The refraction is the greatest near the horizon and gradually decreases to zero at the zenith or the point on the celestial sphere directly above the observer. It varies somewhat from hour to hour and day to day but is approximately the same for the same angle of elevation in all directions from the observer.

This principle has been used in what is called the Talcott method for the determination of the latitude of a place. In this method two stars are used—one to the south of the zenith and one to the north—that cross the meridian within a few minutes of each other. The zenith distances of the two stars selected seldom differ by as much as 20′. When using this method, it is necessary to know within a few minutes the latitude of the place at which the observations are to be made in order that the proper stars may be selected. This latitude can be scaled from a map or can be determined roughly by an observation on Polaris or the sun, as mentioned above. Knowing the approximate latitude of the station and the local time, the star catalogues can be used to find a pair of stars that will meet the requirements of the Talcott method; that is, that will cross the meridian within a few minutes of each other and with zenith distances nearly the same.

MAKING LATITUDE OBSERVATIONS

Either the zenith telescope shown in Figure 4 or the broken telescope transit shown in Figure 1 may be used for making latitude observations. When the latter is used, a delicate level tube must be attached and another micrometer must be substituted for the transit micrometer. After the instrument has been thoroughly adjusted in the manner that is common to astronomers and surveyors, and the line of collimation or line of sight of the telescope has been placed almost exactly in the meridian, the telescope is set to such a position that the angle it makes with the zenith is about one-half the sum of the zenith distances of the two stars. At the eye end of the telescope of the instrument there is a micrometer with which is observed the difference in the zenith distances of the two stars. In the micrometer there is a wire fastened to a frame that moves on the micrometer screw. This wire is made to bisect the star as it crosses the meridian. The micrometer screw and head are then read to a small fraction of a second of arc.

The telescope is then turned 180° on its vertical axis into position for the second star, and the movable thread is made to bisect that star. The difference between the micrometer readings on the two stars gives the differences in their zenith distances. A very sensitive

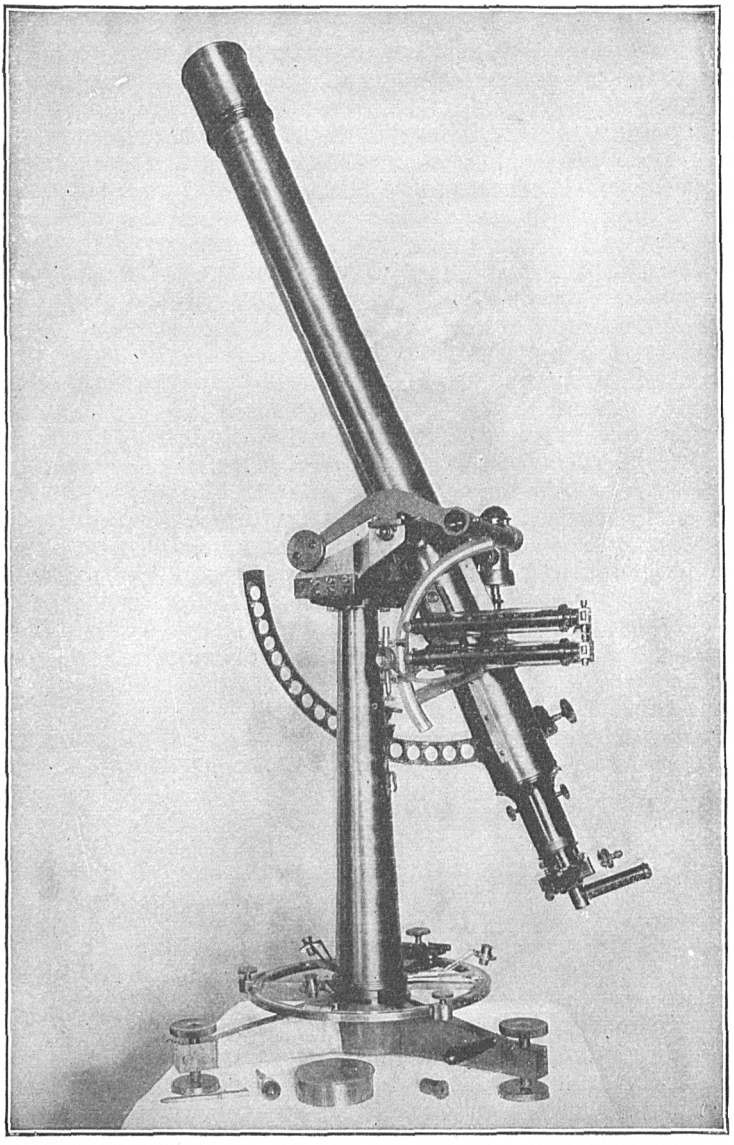

FIG. 4.—ZENITH TELESCOPE

This instrument is used for observing astronomic latitudes.

level tube is attached to the instrument and this is read immediately after the observation on the stars to obtain a value for the tilting of the vertical axis of the instrument. With the data obtained from the observations and with the known declinations of the stars, ob-

tained from the star catalogues, the latitude of a station can be computed.

No observation can be made which is entirely free from error, but the effect of the errors of observation, though small, can be almost entirely eliminated by observing on a great number of stars. A precise latitude of the United States Coast and Geodetic Survey usually consists of observations on at least 12 pairs of stars, and the error of the resulting latitude is usually less than 0.1 second, which corresponds to a distance of about 10 feet. This means that the astronomic latitude of a place on the earth's surface can be determined within this amount.

Descriptions of the instruments and their adjustments and the methods of observing and of computing latitudes are given in Special Publication No. 14 of this bureau, entitled "Determination of Time, Longitude, Latitude, and Azimuth"; in Special Publication No. 35, "Determination of the Difference in Longitude between Each Two of the Stations, Washington, Cambridge, and Far Rockaway"; and in "Directions for Magnetic Measurements." In the last publication are given methods for obtaining approximate latitudes which are used where the latitude determination need not be of high accuracy. The results of all latitude determinations in the United States up to 1921, inclusive, are given in Special Publication No. 110, entitled "Astronomic Determinations by United States Coast and Geodetic Survey and Other Organizations."

DETERMINATION OF AZIMUTH

In all surveying and mapping operations it is necessary to know the true north or the direction of the meridian at various points covered by the survey or map.

In the work of the Coast and Geodetic Survey the direction of the true meridian must be known in connection with the triangulation and magnetic observations made by the bureau. Astronomic azimuths are used to control the geodetic azimuths carried through triangulation. Before the astronomic azimuth can be used for this purpose it must be corrected for what is called the station error or deflection of the vertical at the point of observation. In magnetic work the direction of the true meridian must be known in order to determine the angle between that direction and the direction of the magnetic meridian indicated by the magnetic needle.

The direction of the true meridian is obtained by observations on the sun or on Polaris. In order to compute the azimuth from the observations it is necessary to know the approximate latitude of the place and the local time at which the observations are made and, in the case of the sun, the approximate longitude of the place of observation. The sun is changing materially in declination and right ascension from hour to hour, while a star, on the other hand, changes only by an insignificant amount.

OBSERVATIONS ON THE SUN

Observations on the sun are usually made with an ordinary surveyor's transit or theodolite and consist simply of pointing on the sun with the instrument, noting the time at which the observation is

made, and then pointing the instrument on some target or mark. The observations are repeated a number of times to minimize the errors. The true bearing of the sun or the angle that the line from the observer to the sun makes with the true meridian at the time of the observation can be obtained from the American Ephemeris and Nautical Almanac. When the angle between the mark and the sun is combined with this true bearing of the sun, the true bearing of the line from the observer to the mark is obtained.

When observations are made on the sun for azimuth, the local time is usually obtained from a comparison of the chronometer or watch with the time signals sent from the Naval Observatory, either by radio or over the telegraph wires of the country. If these time signals can not be received conveniently, time is obtained by observations on the sun or stars with a vertical circle or a sextant. The error of the result in the determination of azimuth by observations on the sun is usually about 20″ to 30″.

OBSERVATIONS ON POLARIS

Where a rough value only of the azimuth is needed, it is obtained by making observations on Polaris at the time this star is at eastern or western elongation. When it is in one of these positions, the local time need be known only within a few minutes in order to obtain fair results in the azimuth. This is because Polaris is not changing rapidly in azimuth at that time.

When the most exact azimuths are required, the observations are made on Polaris with a large theodolite, which is also used in the measurement of horizontal angles. Before observations on Polaris are begun it is necessary to determine accurately the local sidereal time. For this purpose observations are made on several stars to the eastward and westward of the meridian with a special vertical circle. The time must be determined again after the completion of the observations on Polaris in order to have a knowledge of the rate of the chronometer during the azimuth observations. The error of the determination of the clock correction is usually about one-half second. Radio reception of United States Naval Observatory time signals is frequently used in place of the star observations for obtaining the clock correction.

For the azimuth observations the instrument is first pointed on a mark which may be a distant triangulation station from which a signal light is shown. The position of the telescope with relation to the horizontal circle of the instrument is read with the micrometer microscopes, then the instrument is pointed on Polaris and the time of pointing noted. The microscopes are again read, and the inclination of the horizontal axis of the telescope is determined by the reading of a very sensitive level. The telescope is then reversed in its supports or wyes, the inclination of the horizontal axis again determined, and a second observation on Polaris and another on the mark are made. This combination of observations completes a set and gives one determination of the azimuth of the mark. From 12 to 16 of these sets are made in order to minimize the errors of observation.

The computations consist in determining the azimuth or bearing of Polaris with relation to the meridian at the time the observations

were made. When this azimuth is combined with the angle between Polaris and the mark, there is obtained the bearing of the line between the observer and the mark. This is the result sought. The error of the determination of a first-order Laplace azimuth is about 0.3″. This is very small, as may be realized when we consider that 1 foot at a distance of 40 miles subtends an angle of 1″. Therefore, the azimuth may be considered as uncertain to the extent of about 4 inches in a distance of 40 miles.

After the true bearing of some line has been determined by azimuth observations the exact meridian or true north and south line can be laid off on the ground by simply setting off an angle equal to the bearing of the observed line to the right or left of this line as the case may be. Descriptions of the methods used in determining astronomic azimuth are given in United States Coast and Geodetic Survey Special Publication No. 14 and in Directions for Magnetic Measurements.

The results of all azimuth determinations in the United States up to 1921, inclusive, are given in Special Publication No. 110, entitled "Astronomic Determinations by United States Coast and Geodetic Survey and Other Organizations."

Chapter II.—BASE LINES

In a triangulation it is necessary to determine by direct measurement the length of one of the lines of the scheme from which to start. From this line, as a base, and the observed angles, a computation will give the lengths of the other lines of the triangulation. It is usual in an extensive scheme to have direct measurements of one or more additional triangle sides to strengthen the computed lengths and to guard against gross errors. The direct measurement of those sides of the triangles used as bases has been a difficult problem for surveyors and geodesists until recent years. At present the bases can be measured with great accuracy by means of tapes or wires made of the alloy of nickel and steel called invar.

Among the earliest forms of measuring apparatus used were wooden bars and glass tubes. These were not satisfactory, and they gave way gradually to metal bars, which apparently were first used in 1788 in Italy, and a little later, in 1798, in France. The bars were usually made of steel or brass, and they maintained their lengths most satisfactorily, but the great difficulties involved were the determination (1) of their exact lengths in terms of some standard unit at some given temperature, (2) of the amount of change in length for a given change in temperature, and (3) of the exact temperature of the bars during the field measurement.

The first difficulty was overcome by standardizing the bars in a room which could be maintained at a constant temperature. Then the coefficient of expansion was determined by standardizing the bars in the room at widely different temperatures. It was impracticable to obtain the temperature of the single-rod bar during field measurements in daylight with a high degree of accuracy. Many methods of insulating and protecting the metal rod were employed, but the temperatures read from the mercurial thermometer inserted in the case did not correctly indicate the actual temperature of the rod. A base measured with single brass or steel rod bars, with a small probable accidental error, might have a large actual error. As an example, a base measured by a set of these bars in Colorado, with a probable accidental error of only 1 part in 752,000, was, in 1913, remeasured with invar tapes and the difference in the two lengths was 1 part in 59,000.

It is probable that steel or brass single-rod bars would give more accurate results if used only on cloudy days, or if they were used at night, when the temperature is apt to be more constant, for then the temperature given by the thermometers would be more nearly that of the bars. But cloudy days in some regions are not numerous, and to measure a base at night is a difficult and tedious undertaking.

COMPOUND BARS

In order to minimize or eliminate the effect of errors in temperature, various compound bars were devised. One type consisted of two parallel rods of different metals, such as platinum and copper,

or steel and brass, the two rods of a bar having very different rates of expansion. Theoretically, the average temperature could be obtained by noting the difference in length of the two components, which were arranged with suitable scales for making the comparison. This principle of differential expansion was applied in several differ-

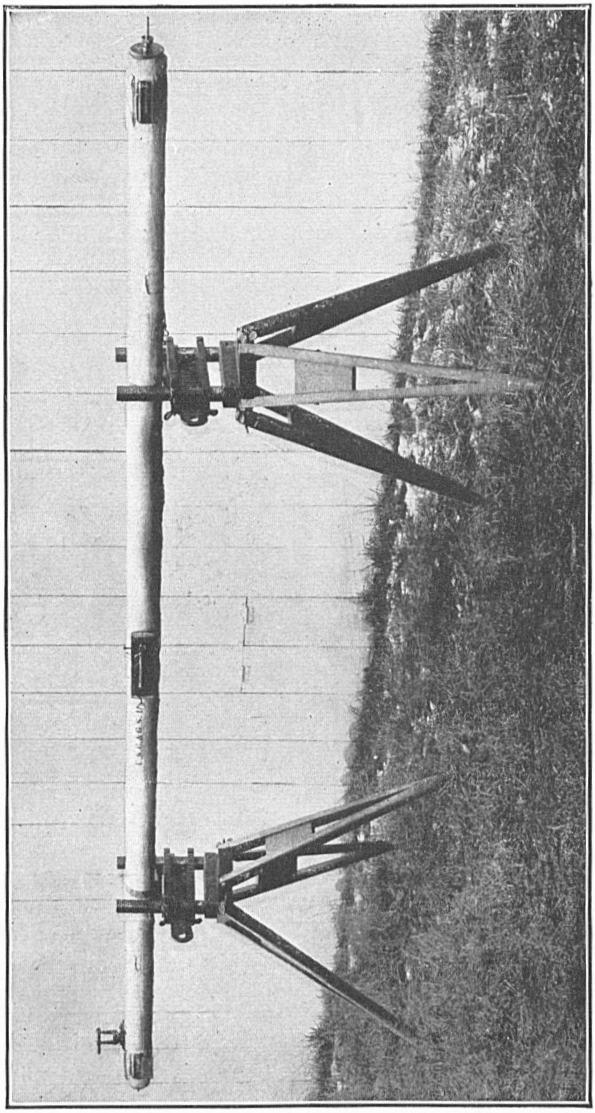

FIG. 5.—DUPLEX BASE APPARATUS

This illustrates the old method of measuring a base, a very slow, tedious, and expensive method. It was superseded many years ago, and invar tapes are now used exclusively for base measurement.

ent ways. Other compound bars were designed to give a constant length by a compensating arrangement of the components.

Excellent results were obtained with the Bache-Wurdemann compensating bars of the Coast and Geodetic Survey, but it was found that slightly different results were obtained with rising and with falling temperatures. This trouble was minimized by having the

bars standardized under each condition. The Eimbeck duplex bars of the survey also gave a high degree of accuracy in the measurements, but they were not used much, as the use of the tapes was begun shortly after they were made.

USING BARS IN FIELD MEASUREMENTS

In the field measurements the bars were supported by portable tripods. The bars were either "line measures" or "end measures." In the first type the length of the bar is the distance between two very fine lines engraved on the top of the bar near its ends. The successive bar lengths were referred to powerful microscopes mounted on posts set along the line of the base. In the "end measures" the length of the bar is the distance between its ends, and the procedure

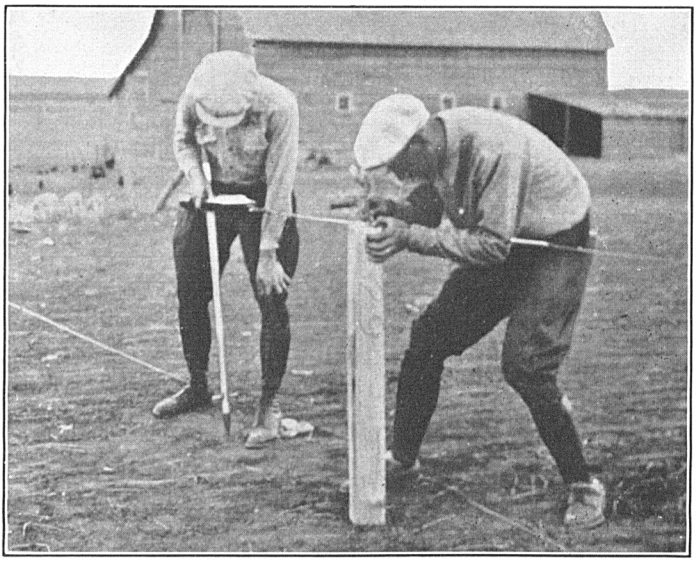

FIG. 6.—BASE MEASUREMENT WITH INVAR TAPE

Making forward contact.

was to set two bars end to end and then move the rear one ahead and bring its rear end into contact with the forward end of the bar left in place.

In one of the earliest methods of measuring, the two bars were brought nearly together and the distance between them was measured by a wedge properly graduated and standardized. The wedge was inserted between them, and the points of contact of the bar ends on the wedge would enable the distance between the bars to be determined accurately. These small distances would be added to the whole number of bar lengths.

The usual and better method of making the contact of the two bars was to have a sleeve fit over one end of each bar, the sleeve being connected with the bar by a spring. The bar was normal when a graduation on the sleeve coincided with a graduation on the bar. A slow-motion device enabled the operator to move the forward rod

in its case until the contact with the rear bar was perfect and the two graduations on the bar and sleeve coincided. This procedure was repeated throughout the length of the base.

The only bar used in the United States, and probably in the world, which will give entire satisfaction so far as accuracy is concerned is a "line measure" called the "iced-bar apparatus" of the Coast and Geodetic Survey, which was designed by Dr. R. S. Woodward. During measurements this bar is placed in a trough filled with crushed ice. Thus, the bar is kept at a uniform and definite temperature, that of melting ice. Of course, measurements can not be made when the temperature of the air is below the freezing point. The trough is mounted on a carriage which runs along a portable track. The successive bar lengths are referred to microscopes placed on posts set along the base. The cost of using this bar in the field is prohibitive, and it has been and is now used only for the purpose of standardization of other apparatus, and for this it is unexcelled.

USE OF STEEL WIRES AND TAPES

Steel wires and tapes were used in general surveying long before they were used for the measurement of first-order base lines. They were apparently first used successfully for bases by Professor Jaderin, of Sweden, about 1882. Tapes were experimented with at the Holton first-order base, Indiana, in 1891, and found to be as accurate when used at night and much more economical than bars. Tapes were used in 1893 and 1897 in measuring the bases at St. Albans, W. Va., and at Versailles, Mo. In 1900–1901 steel tapes of 100-meter and 50-meter lengths were used in connection with the Eimbeck duplex bars in the measurement of nine first-order bases on the ninety-eighth meridian. The result of this campaign proved conclusively that the tapes used at night gave an accuracy as great as that obtained with the best bars.

In 1906, the Coast and Geodetic Survey tested tapes made of the alloy of nickel and steel (called invar) by measuring six first-order bases with both steel and invar tapes. The invar tapes gave results of even greater accuracy than the steel tapes, although the former were used in daylight, while the latter were used at night. All of the tapes were 50 meters in length, this length having been found more satisfactory than 100 meters.

The average coefficient of expansion of the invar tapes used by the Coast and Geodetic Survey is only 0.0000004 per degree centigrade, or about one twenty-fifth that of steel. Having available a metal with such a low coefficient of expansion, the great problem in base measurement has been solved. Bars of this metal would, no doubt, give a measurement almost without error, but invar tapes give results which are very satisfactory, and, as a base can be measured with tapes for 35 per cent or less of the cost of bar measurements, it is practically certain that no more base lines will be measured with bars. Tapes have the additional advantage that they may be used over broken ground and steep slopes where the bars could not be used.

The data available indicate a remarkable constancy in the values of the lengths of some of the earlier invar tapes, though others used

in recent years do not appear to be so stable. It may be stated that the invar tapes are not so susceptible to injury during field work as was supposed to be the case soon after their introduction. Each of the base parties which used the tapes under discussion had only two members who were skilled in the use and treatment of tapes, the other persons in the party being unskilled men. The members of each party were cautioned to use every care in handling the tapes, but, even so, it seems remarkable that so few of the tapes have been injured.

Invar wires are used in some of the other countries with great success. The advantages of wires over tapes about equally balance the advantages of the tapes over the wires. Each type of apparatus will give results far greater in accuracy than that required. The wire is less affected by the wind. The tape is more easily reeled and unreeled than the wire. The wire may become twisted without detection, while this seldom happens with the tape. The wire seems to be more subject to kinks than the tape. Owing to the thinness of the tape, a smaller diameter may be used for its reel than for the reel of the wire.

METHOD OF SUPPORT

The method of supporting the tape or wire during measurements, of applying the tension, and of marking successive lengths varies greatly. Each method has its advocates and its special advantages. The method employed in the Coast and Geodetic Survey is to set stakes firmly throughout the length of the base. At 50-meter intervals (the length of the tape) a stake 4 inches in cross section is used. The intermediate supports are nails driven horizontally into stakes set just off the line. Usually only one intermediate support is used, and, except in rare cases, its top is in a straight line with the tops of the two end supports. The tape lengths are transferred to copper strips nailed to the tops of the end supports, the strips being of the same thickness as the sleeves of the tape which carry the graduations. The tension is given by a spring balance attached to a stretcher. A line of levels is run over the base in both directions to get the grades from which corrections to give the horizontal distance are computed. The setting of the stakes and the leveling may be done in even strong winds, while the calmest days are utilized for measuring with the tapes.

Another method of supporting the tape which has been successfully used in the measurement of first-order bases is the use of movable iron tripods. This method is especially useful when the base is measured over ice or along a paved highway or street in which stakes can not be driven. Each tripod has a ball and socket joint which permits the marking table to be placed on grade, and in some cases a double ball and socket, so that it can be adjusted over a point as well as placed on grade. The wooden marking table has a strip of copper fastened to it, to which the tape ends are transferred the same as when stakes are used. Sometimes the marking tables of movable tripods are fitted with graduated invar strips and then the tape ends are indicated by the readings on the strips. These strips are especially useful for measurements over ice.

MEASURING A BASE

It is customary to divide the base into sections of about a kilometer in length and to measure each section twice, using a different tape for each measurement. The two results to be acceptable must have a smaller discrepancy than 10 millimeters times the square root of the distance expressed in kilometers. The mean of the two measurements is taken as the final length. Usually three different tapes are used for each base, different combinations of two of the three tapes being used on different sections in such a way that each of the three tapes is used in one-third of the measurements. The probable error in the measured length of a first-order base line is usually less than 1 part in 1,000,000.

The base party usually consists of six persons, and only one needs to have had previous experience in the work. In fact, the measurement of even a first order base is so simple an operation that this work is now considered a mere incident of the triangulation and is done by the triangulation party. This plan has two decided advantages: First, the lengths of the bases will be known when the triangulation of an arc has been completed; and, second, the base work can be done at much lower cost than when a party is especially organized and outfitted for measurement of bases.

The average field cost of measuring a base by the triangulation party is about $50 per kilometer. The cost by special parties may be 50 per cent greater than this. The cost of the measurements with base bars varies greatly, but the minimum is several times greater than that with the tapes.

See also the following publications of the Coast and Geodetic Survey: Appendix 8, Report for 1892, On the Measurement of the Holton Base, Indiana, and the St. Albans Base, West Virginia; Appendix 3, 1901, On the Measurement of Nine Base Lines Along the Ninety-eighth Meridian; Appendix 4, 1907, Six Primary Bases Measured with Steel and Invar Tapes; Appendix 4, 1910, The Primary Base Lines at Stanton, Tex., and Deming, N. Mex.; Special Publication No. 120, Manual of First-Order Triangulation, which contains detailed instructions for first-order base measurement; Special Publication No. 145, Manual of Second and Third Order Triangulation and Traverse, which covers second and third order bases.

Chapter III.—TRIANGULATION

The main object of a geodetic survey is to furnish the necessary control for all other surveys. This control includes the determination of the relative positions of some principal points of reference upon which to base the work. It involves the measurement of base lines and the measurement of the angles of the triangulation system. In other words, the distances and directions between certain points must be determined.

When the area to be surveyed is small or unimportant, the distances may be measured directly upon the ground, with chain or tape, and the directions may be obtained by the use of a compass or surveyor's transit, but when a survey is to cover an extensive territory or when great precision is desired, another method must be adopted. Aside from the difficulties and delays experienced in making accurate linear measurements upon even moderately level ground, the natural obstructions, such as bays, rivers, mountains, and forests, frequently render direct measurement impracticable. To overcome these difficulties, the method called "triangulation" is employed. It rests upon the trigonometric proposition that if one side and the angles of a triangle are known the remaining sides can be computed.

A line, forming a side of one of the triangles and called the base, is measured with extreme care. The angles of each triangle are measured and the distances between the points are then computed, one from another, through the successive triangles, proceeding in regular order from the measured line or "base."

Triangulations are usually classified as "first-order," "second-order," and "third-order," according to their accuracy. No longer is a triangulation classified according to the size of the triangles involved. First-order triangulation is used in extending the fundamental control over the country and in accurate city surveys, such as those in New York, Cincinnati, Rochester, and Atlanta.

In the earlier days, when it was necessary to extend the first-order triangulation across the country rapidly, very long lines were used whenever possible, these lines in many cases being over 100 miles in length. At present the economical length of line for first-order work is considered to be from 25 to 40 miles. The length of line should be as a rule, such that the total cost of the work of reconnaissance, building, and angle measurement will be a minimum per mile of progress. First-order triangulation is used as the framework for all other surveys. The accuracy of this class of triangulation is that represented by an average triangle closing error of about 1 second of arc—that is, the sum of the three measured angles of a triangle will, on the average, vary from 180° plus the spherical excess by not more than 1″. Spherical excess is the correction that must be applied to the angles of a spherical triangle to reduce it to a plane triangle. The size of this correction depends on the area of the triangle.

RECONNAISSANCE

The success of any triangulation depends to a great extent upon the reconnaissance, which is the most difficult and exacting task of an extensive survey. No two regions call for the same treatment, but some general considerations can be briefly outlined here.

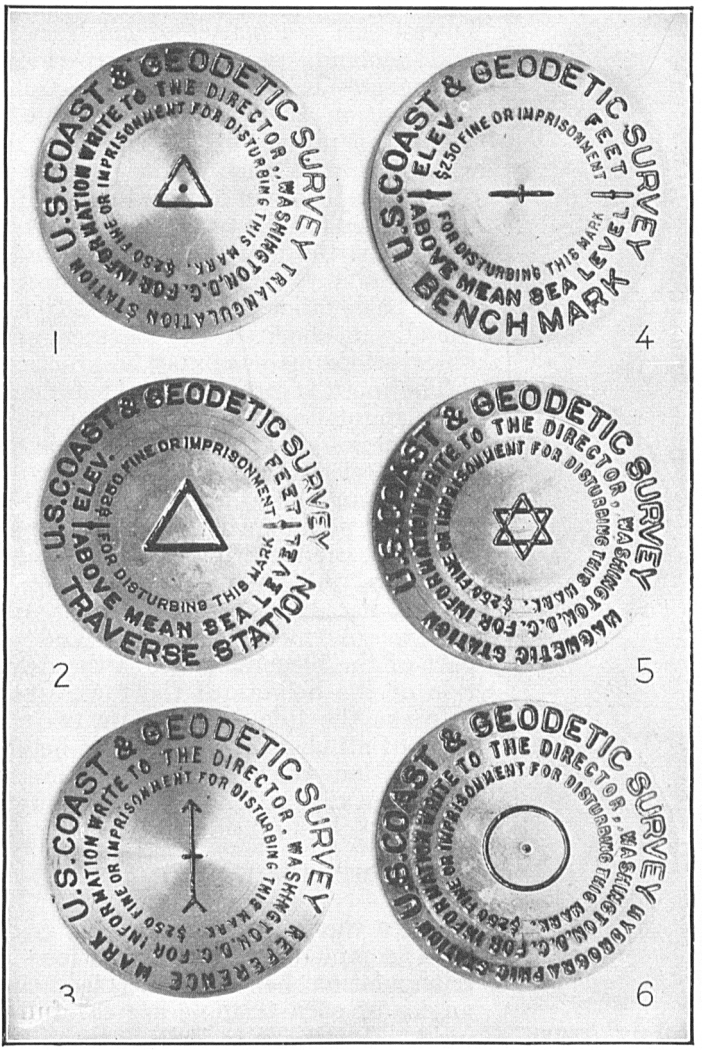

FIG. 7.—STANDARD STATION MARKS OF THE UNITED STATES COAST AND GEODETIC SURVEY

(1) Triangulation station mark; (2) traverse station mark; (3) reference mark; (4) bench mark; (5) magnetic station mark, and (6) hydrographic station mark.

A reconnaissance may be preliminary to minor triangulation along the seacoast, a river, or an estuary, where but a moderate degree of accuracy is required, and the range of selection of points is limited by the purpose for which the triangulation is to be used;

namely, the control of a hydrographic or topographic survey along the shore. Or, again, it may have to do with the arrangement of a great triangulation to cover a wide region. In the latter case careful study will be required in order that the resulting project may best satisfy all the conditions.

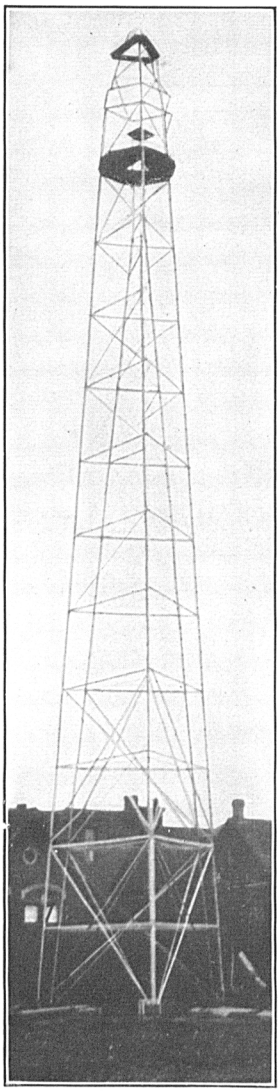

FIG. 8.—BILBY STEEL TOWER USED IN TRIANGULATION

A reconnaissance for triangulation of the largest size is a matter of much complexity and demands great skill, experience, and judgment. It includes the collection of all information that will be valuable in the future operations of the building and observing parties, such as the proper selection of stations, location of base lines, and sources of supplies for the parties. Heavily wooded country is the most troublesome and makes it necessary to climb the tallest trees, or to raise poles taller than the trees, from which the distant horizon can be seen and such observations made as may be practicable.

The most favorable country for a scheme of triangulation is a valley of proper width, with peaks on either side. It is possible then to select the proper stations with little clearing and building. Naturally the most elevated points will be chosen, provided their location will give the best-shaped triangles, for the selection of low points might necessitate the building of high towers. A most important and difficult part of the reconnaissance is the determination of the heights of the towers necessary to make the line joining any two of them clear of all obstructions. These heights will depend on the relative elevation of the ground at the stations and of the intervening region.

MEASURING THE ANGLES

When the reconnaissance of a region has been completed and the stations of the triangulation has been selected, the three angles of each triangle are carefully measured. Instruments called theodolites, of various sizes and stands or piers of different kinds are employed, according to the character of the country, the size of the triangulation, and the facilities at hand. These conditions also determine the kind of signals or objects to be used at the distant stations. At great distances the only objects which can be used are heliotropes by day and powerful lights by night. The heliotrope is a small mirror so arranged that it reflects the sunlight toward the observer.

During recent years most of the observing for first-order triangulation has been done at night. To make the stations visible, a very efficient electric signal lamp operated by dry-cell batteries has been designed. By the use of a special bulb, with a small, compact filament placed exactly at the focus of a parabolic reflector, nearly all the light is concentrated in the desired direction, and the lamps may be seen at great distances. An automatic clock control has been devised to turn on the light in the early evening and turn it off late at night. (See fig. 11.) Fewer light keepers are required with this type of lamp and the cost of the triangulation is considerably decreased.

The theodolites ordinarily used on first-order triangulation are instruments with well-graduated circles 8 to 9 inches in diameter. The circle is read to a second of arc by each of two or three micrometer microscopes, the mean of the readings constituting one observation of a direction. Were all the conditions perfect, a single

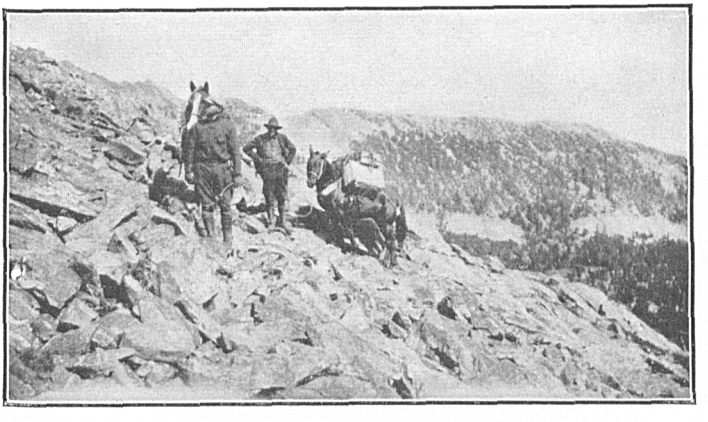

FIG. 9.—PACKING UP A MOUNTAIN PEAK WITH HORSES

In localities where pack horses can be obtained, they are used to transport the heavy instrumental equipment as far as possible up the mountain peaks.

careful observation of each direction would be sufficient. But the most excellent instruments have some defects, the most careful observers are liable to some slight error, and, above all, the line of sight, passing through miles of atmosphere of varying density and temperature, is subject to influences which defy analysis and which can be neutralized only by making observations under different conditions. It is therefore customary to make several observations on each station, covering a period of several hours. In order also to eliminate errors due to irregular graduation of the horizontal circle, these successive observations are made on different parts of the circle by shifting it through a definite portion of the circumference after each set of observations.

OBSERVATION TOWERS

Triangulation with very long lines is possible only in regions of high mountains where the curvature of the earth is overcome by the

natural elevations making it possible to see for long distances. In flat country, especially where it is heavily wooded, shorter lines must be used and the stations made intervisible by the erection of towers. It has been necessary, in regions of tall timber, to elevate the instrument to a height of 120 feet, with a superstructure above

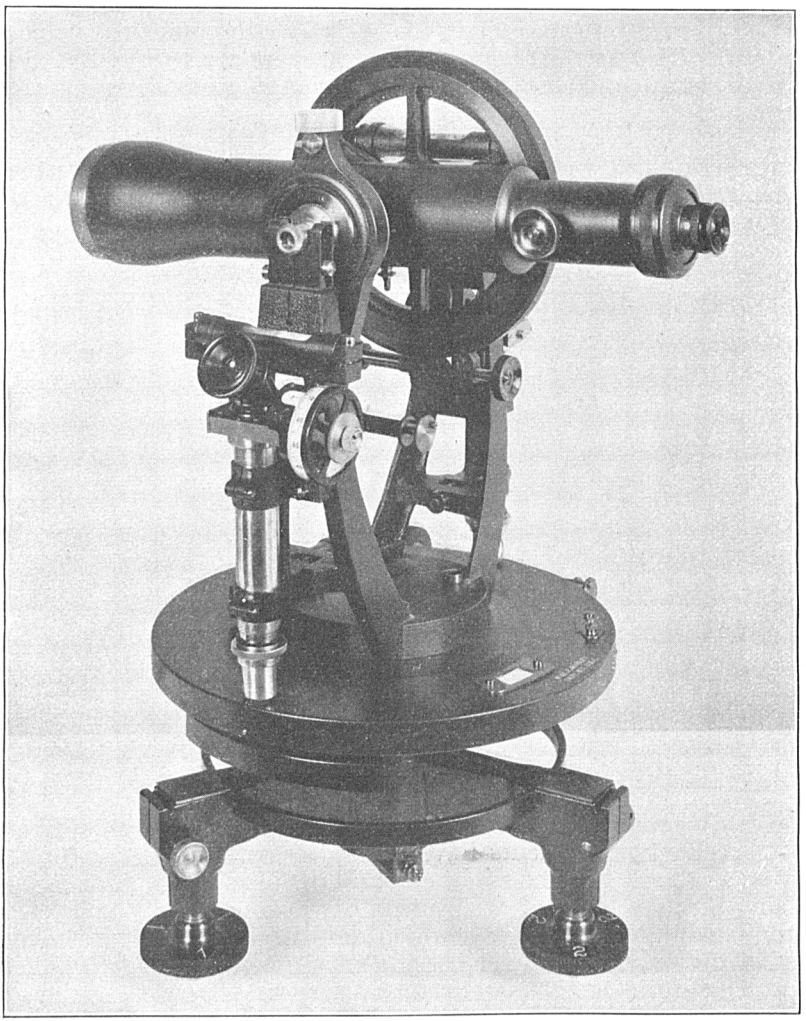

FIG. 10.—PARKHURST THEODOLITE, 9-INCH CIRCLE

Used for measuring angles on first-order triangulation. Developed by D. L. Parkhurst of the U. S. Coast and Geodetic Survey.

the instrument tripod for signal lamps. The structure upon which the theodolite rests must be entirely separate from that upon which the observer stands in order that the movements of the observer may not disturb the observing instrument. Ordinarily with wooden towers it is desirable to keep the height of the instrument tripod down to 75 feet in order to lessen the vibrations due to the wind,

but the outer structure is sometimes extended upward to a height of 125 or even 140 feet in order to elevate the signal lights which must be observed upon from other stations.

In 1927 steel towers were first used to replace the wooden structures. (See fig. 8.) Each steel tower consists of a double triangular structure, the inner one supporting the theodolite and the outer one

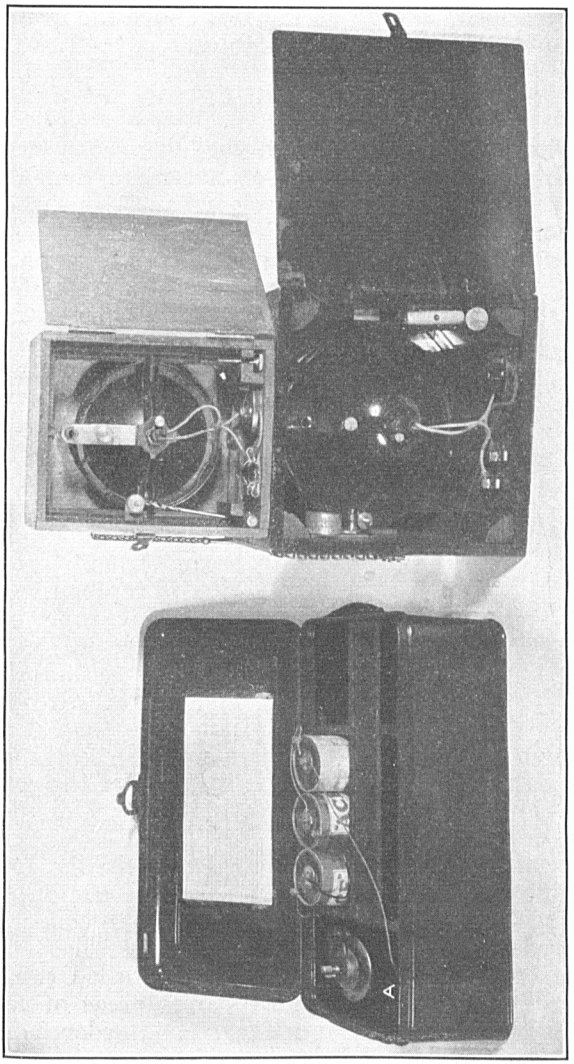

FIG. 11.—NEW CLOCK-CONTROLLED ELECTRIC SIGNAL LAMP

Triangulation observations are usually made at night and strong lights are required to make distant stations visible to the observer. In the electric signal lamp apparatus shown above the backs of two lamps are shown on the right; the upper one has a reflector 5 inches in diameter, the lower one a reflector 7 inches in diameter. The battery box on the left has a clock (A) which turns the light on at a certain time and turns it off at a later hour when the observer has finished work.

the observer's platform. The towers can be used at varying heights up to nearly 150 feet for the top of the instrument tripod. They have been found to be even more stable than wooden towers and can be so quickly erected and taken down that they will probably always be used in the future instead of wooden towers where road conditions permit.

In regions of very tall timber, such as are found along the west coast of the United States, tree towers are used. These are made by climbing the tallest tree in the vicinity of the station, cutting out its top, preparing a "crow's nest" as an observer's platform, and using the stump of the tree as the instrument support. Usually other trees are felled into the tree upon which the instrument is placed for a bracing. Theodolites have been mounted on tree towers, built as described, as high as 183 feet above the ground, and signal lamps have been shown from tree towers as high as 215 feet.

ACCURACY OF TRIANGULATION

By means of first-order triangulation the distance between two points may be obtained with an error of not more than one one-hundred-thousandth of the distance. For instance, if the distance is 100 miles the error will probably be less than 5 feet.

In second-order and third-order triangulation the same general principles apply as in first order triangulation, but the details of the work will vary with the circumstances. Heliotropes and lamps are rarely used, and the angles are nearly always measured with smaller theodolites, and a smaller number of measures are made. The accuracy of second-order triangulation is represented by an average closing error of a triangle of not more than 3 seconds of arc and that of third-order by not more than 6 seconds.

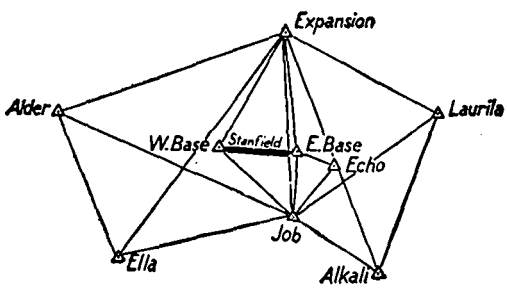

FIG. 12.—STANFIELD BASE NET

The heavy line represents a base line, a length actually measured on the ground. The lengths of the other lines shown have been computed from this measured length by using the measured angles of the triangles.

Up to the present time most of the main-scheme coastal triangulation, executed by the Coast and Geodetic Survey for the control of its hydrographic and topographic surveys in the United States has been of third-order accuracy.

Second-order triangulation has been used principally for three purposes: First, for the main scheme of an isolated region of moderate extent such as the Philippine Islands; second, to connect third-order with first-order triangulation when the latter lies at a considerable distance from the area requiring the detailed third-order control; and, third, as the detailed control over areas of economic importance. The increasing demand for second-order horizontal control, under the last set of conditions, and the growing economic importance of the entire coastal region of the United States, led the Director of the Coast and Geodetic Survey to decide, early in 1928, to make the entire coastal main-scheme triangulation of second-order accuracy. Third-order triangulation will still be used along rivers and inlets or in places where a connection to first or second order triangulation can be made at intervals of not more than 50 miles.

COMPUTATIONS

After measuring the angles of any class of work the triangle sides are computed. The latitudes and longitudes of all stations are also computed by geodetic formulas, which are adapted to a particular spheroid representing the earth's size and shape. All distances determined by triangulation are referred to sea level.

In the survey of a city or other survey of limited extent it is customary to use a system of rectangular coordinates based upon plane surveying in addition to the geographic coordinates—latitude and longitude. In the plane system all points are referred to an arbitrarily selected pair of rectangular coordinate axes instead of to the actual meridians and parallels.

It is possible, knowing the geographic coordinates of triangulation stations in a certain area, to obtain by simple formulas the rectangular coordinates. After an origin has been selected all the directions are referred to the true meridian passing through it.

MARKING STATIONS

If the triangulation is to serve any further purpose, it is very essential that the stations be marked in a permanent manner. The practice in the Coast and Geodetic Survey is to have at every station a standard metal triangulation mark, which, if practicable, is set in rock or concrete. (See fig. 7.) There is also placed an underground mark which is separated from the surface mark. In addition there is set at least one reference mark, which is referred to the station by an angle and distance. This reference mark is not only important in serving in place of the station mark if the latter is destroyed but it aids in the recovery of the station mark. If the station mark is in bedrock it is surrounded by a triangle cut in the rock, so that it will be possible to recover the station approximately if the metal disk has been removed.

It is especially important in the execution of a triangulation scheme that careful and accurate descriptions of all stations be made. The description should enable one who is unfamiliar with the locality to find the exact point determined and to positively identify the monuments marking the station.

The triangulation of the United States has been done by the United States Coast and Geodetic Survey, Corps of Engineers (U. S. Army), International Boundary Commission, United States and Canada, and other organizations.

See also Report for 1911, Appendix 4, and Special Publications Nos. 28, 71, 91, 93, 120, 137, 138, and 145.

Chapter IV.—FIRST-ORDER TRAVERSE

Traverse is a surveying operation designed to furnish the latitudes and longitudes of a number of points which form the control or base stations for detailed surveying operations. Traverse is used in those areas which are so flat or so heavily wooded that it would be excessively expensive to carry on triangulation, owing to the necessity of having high signals to elevate the surveying instruments above intervening obstructions. The traverse lines nearly always follow railroads, and therefore very little signal building and clearing of lines are necessary.

First-order traverse, as carried on by the United States Coast and Geodetic Survey, consists, practically, of a series of base lines placed end to end. The measurement of each of the lines is made with almost the same accuracy as is used on first-order base lines. The angle formed by each two contiguous lines of traverse is measured in the same way as in first-order triangulation, but only about one-half as many measurements of the angle are made. The observations are made on poles as well as on heliotropes and lamps, as the lines between traverse stations are shorter than in first-order triangulation. The probable error of the measurement of an angle is about double that of first-order triangulation.

Traverse was used very little in control surveys by the Coast and Geodetic Survey previous to the year 1917. Since that year an elaborate system of first-order traverse lines has been established in Georgia, Virginia, North Carolina, South Carolina, Florida, Louisiana, Indiana, Illinois, Minnesota, and Wisconsin for the purpose of furnishing control for military and other maps in the parts of the country through which the lines run.

A section of a line of traverse usually consists of the distance between the intersections of a tangent with the two contiguous tangents of the railroad. A tangent is the technical name of a straight piece of track of a railroad. At each of the intersections of two contiguous tangents is located a station of the traverse, but occasionally when a tangent is very long or the profile of the railroad is such that it would be difficult to observe between the two ends of a tangent one or more stations are placed to the side of the railroad. Usually the traverse stations are not more than 5 miles apart. Whenever a traverse runs through a town of considerable size, at least two traverse stations are established close to it in order that the results may be used by the local engineers and surveyors in their work.

TRAVERSE MEASUREMENT

The length of each of the lines of the traverse is measured with great accuracy with an invar (nickel-steel) tape 50 meters in length, such as is used in measuring base lines. There are two marks on the

tape, one at each end, which are almost exactly 50 meters apart under standard conditions. The exact difference between the distance from one mark to the other and 50 meters is determined at the United States Bureau of Standards. The tape is used on the traverse under exactly the same conditions, as far as practicable, as obtained when the tape was standardized at the Bureau of Standards before being sent to the field.

What is desired is the horizontal distance between the ends of the tape when it is stretched out. In order to have this, it is necessary to know the difference between the temperature of the tape when the measurement is made and the temperature of the tape when it was standardized. The temperature of the tape is obtained from readings of two thermometers attached to the tape during the measurements. From this it is possible to compute a correction to the

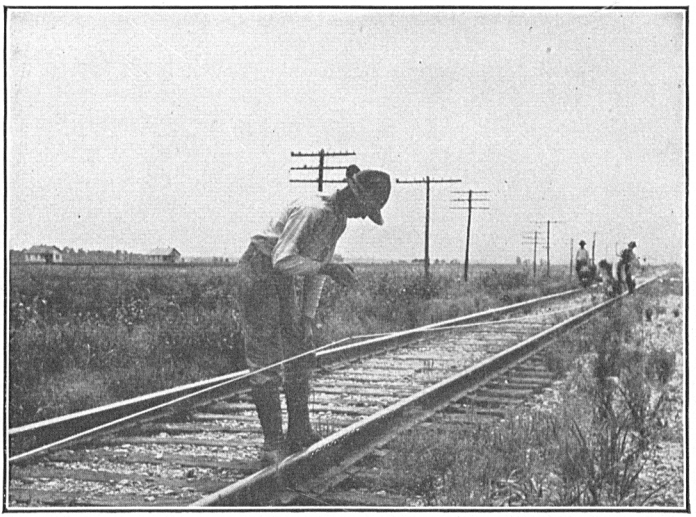

FIG. 13.—PLACING THE TAPE ON THE RAIL

The middle of the tape is held up while the tension is being applied in order to eliminate as far as possible the friction between the tape and the rail.

measured distance. If the temperature is higher than the standard temperature, the correction must be added, while if the temperature is lower than standard, the correction must be subtracted, provided the tape has a positive coefficient of expansion. Another correction that is necessary is for the inclination of the tape or grade. It is readily seen that if the measurement is made on a slope the distance between the ends of the tape will be greater than the corresponding horizontal distance between the ends.

It is necessary to apply the same pull on the tape that was used during the standardization. This pull is usually 15 kilograms (about 33 pounds) and is applied by a spring balance attached to one of the two especially designed stretchers. When this tension has been applied and the tape is held on the top of the rail, it assumes practically a straight line between its ends. If the tape was not

stretched with this rather high tension, the small bends in the tape would make it impossible to get an accurate measurement.

There is usually a distance of several hundred feet from the point at which the curve begins at the end of a tangent to the traverse station. Along this distance stakes are placed to support the tape during the measurement. When measuring over the stakes, the forward end of the tape is marked by a knife cut on the top of the stake. While measuring along the tops of the rails the rear mark on the tape is brought into coincidence with some mark that has previously been made on the rail and the mark on the forward end of the tape is transferred to the rail by a glass cutter.

FIG. 14.—FORWARD END OF TAPE

A tension of 15 kilograms (about 33 pounds) is applied to the tape by means of a spring balance and a tape stretcher. The end of the tape is marked on the rail with a glass cutter. Two thermometers are attached to the tape, one at each end, and these are read and recorded for each tape length.

MAKING CORRECTIONS

The grade, or inclination, corrections to reduce the measured distance to what it would have been if the rail had been horizontal are obtained from the results of a line of first-order levels which is carried along the rail. This leveling determines the elevations of the traverse stations, and the rail opposite each traverse station, milepost, and railroad station, these elevations being used as control for the less accurate leveling. The differences of elevation of consecutive tape ends are determined by a Y level or by an instrument called a track level which has recently been designed and constructed by the Coast and Geodetic Survey.

In addition to other corrections it is necessary to apply one which will reduce the horizontal distance between two stations to what it would have been if it had been measured at sea level. It is readily seen that in order to have the control surveys, extending over a

large area, accurately fit the earth and not be distorted, all distances must be referred to sea level. In order to reduce the distance to sea level, it is necessary to know the average elevation of the line, the general direction of the line, and the shape and size of the earth.

In all measurements in surveying it is wise to use such methods as will make it possible to discover mistakes in the work. In order to guard against mistakes in the measurement of the traverse lines with the 50-meter invar tape, a rough measurement is made with a 300-foot steel tape. The measurement with the latter is rather crude in comparison with the work that is done with the invar tape, but it is of sufficient accuracy to discover any large mistakes, such as added or dropped tape lengths or a setback for set-up, or vice versa. Set-ups and setbacks are distances in the traverse line which are shorter than a full tape length. It is seen that it would be impossible to make a mistake in each measurement which would have exactly the same value when tapes of different lengths and different units are used.

As in triangulation, each traverse station is marked by a metal disk, properly inscribed, set into solid rock or especially constructed blocks of concrete. (See p. 28 and fig 7.)

ACCURACY AND ADVANTAGES

A traverse line usually starts from some station of the triangulation net of the country whose latitude and longitude and the azimuths of the triangulation lines radiating from it have been determined. After the distances and angles of the traverse have been measured, the geographic positions of each of the stations of the traverse and the azimuths of the lines of the traverse can be computed. At frequent intervals along the traverse the azimuth of a line must be determined astronomically by observations on Polaris.

At the office of the Coast and Geodetic Survey in Washington an adjustment of the traverse line is made to fit it into the general network of the triangulation and traverse lines of the country in order that there will be no inconsistencies in the work. In the adjustment the astronomic azimuths that are observed along the line of traverse are used to control the geodetic azimuths which are carried through the measured angles from the preceding azimuth station or from the line of triangulation where the traverse started.

It has been found that the accuracy which can be obtained with first-order traverse is as great as that obtained by first-order triangulation. (See p. 28.) It is reasonably certain that the distance between any two points of a traverse which has been adjusted for azimuth and loop closures is known within about 1 part in 100,000.

The traverse has an advantage over triangulation by having its stations much closer together and in places that are more accessible, and therefore can be used by surveyors and engineers to greater advantage. Besides, the traverse lines are run along railroad tracks where transportation of parties, instruments, and equipment is easier than in triangulation. On the other hand, triangulation has advantages over traverse because its stations are usually on high points, and thus are visible from much larger areas than is the case with stations of the traverse. Besides, the triangulation stations are usually 10 or

15 miles apart, and it can be seen that in carrying on an arc of triangulation a belt of country of approximately 10 or 15 miles in width is controlled, while with the traverse there is only a single line.

Small motor velocipede cars were generally used to transport the parties in the earlier traverse work, but recently automobile trucks have been found more economical for this purpose, especially where there are good highways parallel to the railroad.

After the completion of the work in the field and the office, the results of the first-order traverse, consisting of the geographic positions of the stations, the distances and azimuths of the lines, and the descriptions of the stations, are published in pamphlet form for the use of engineers and map makers.

The Coast and Geodetic Survey has carried on very little second-order traverse, although it has perfected methods to be used in this class of work in place of second-order triangulation wherever the conditions make it more economical to do so. The second-order traverse is almost exactly similar in character to the first-order traverse, except that the methods used are not quite so refined.

Anyone who wishes to study the traverse work and methods of the United States Coast and Geodetic Survey is referred to Special Publication No. 137 of that organization, entitled "Manual of First-Order Traverse," and to Special Publication No. 145, entitled Manual of Second and Third Order Triangulation and Traverse. Special Publications Nos. 79, 86, and 101 give the results of traverse lines in Indiana, Illinois, southern Wisconsin, and North Carolina. They also give the details of the field work and explain the methods employed in adjusting traverse lines.

Chapter V.—TOPOGRAPHY

A topographic map is one on which the natural and artificial features of the country are represented in their proper geographic positions by conventional symbols.

The two most important symbols on maps, where they occur, are the "shore line," or boundary between land and water, and "contour lines," which are lines of equal elevation above a selected plane, such as the sea level. A contour is, in fact, a representation of what the shore line would be if the level of the water were to rise to the elevation indicated by that particular contour.

In order to show the undulations of the ground, contour lines are drawn for some constant vertical interval—20 feet, for instance. On large-scale maps they have superseded the representation of heights by hachures, or shade lines, which only picture the configuration of the country, without furnishing the means, as the contours do, of stating in terms of some linear unit the difference of elevation.

In reading a map one is able to tell the nature of the country from the various symbols—whether it is high or low, rugged or gently undulating—by the number and arrangement of the contours or hachures, and whether it is marshy or sandy, wooded or rocky, and so on, by conventional symbols.

A topographic map is particularly valuable for the study of the physical conditions relating to engineering projects in general, such as the preliminary location of railroads and highways, the problems relating to water supply, drainage, etc. It serves as a basis for directing military movements and planning military works of defense. Combined with hydrography, it forms a chart on which is shown the relation of land to water for purposes of navigation and the improvement of harbors and waterways.

Charting the coasts of the United States is the chief function of the Coast and Geodetic Survey, and topography is necessarily included as one of the important features of its work.

A topographic survey has for its object the collection of data for the construction of a topographic map. The character of the map in regard to accuracy, scale, and fullness of detail depends on the purpose which it is intended to serve. Military topographic sketches are frequently made by using a pocket compass, the stride of the observer or his horse serving to estimate the distance. More elaborate methods are used where greater accuracy is required and greater detail is desired.

TOPOGRAPHIC METHODS

Different topographic methods require the use of various instruments and may, for the purpose of description, be classed under five heads, from the fact that each method is identified with some particular instrument or combination of instruments with which the principal part of the work is done.

CHAIN, OR STEEL TAPE, AND LEVEL METHOD

In this method the whole area is subdivided into rectangles by a system of distances measured with a chain or steel tape and marked by pegs whose elevations are determined with a level and rod. The positions and elevations of the pegs having been plotted, the

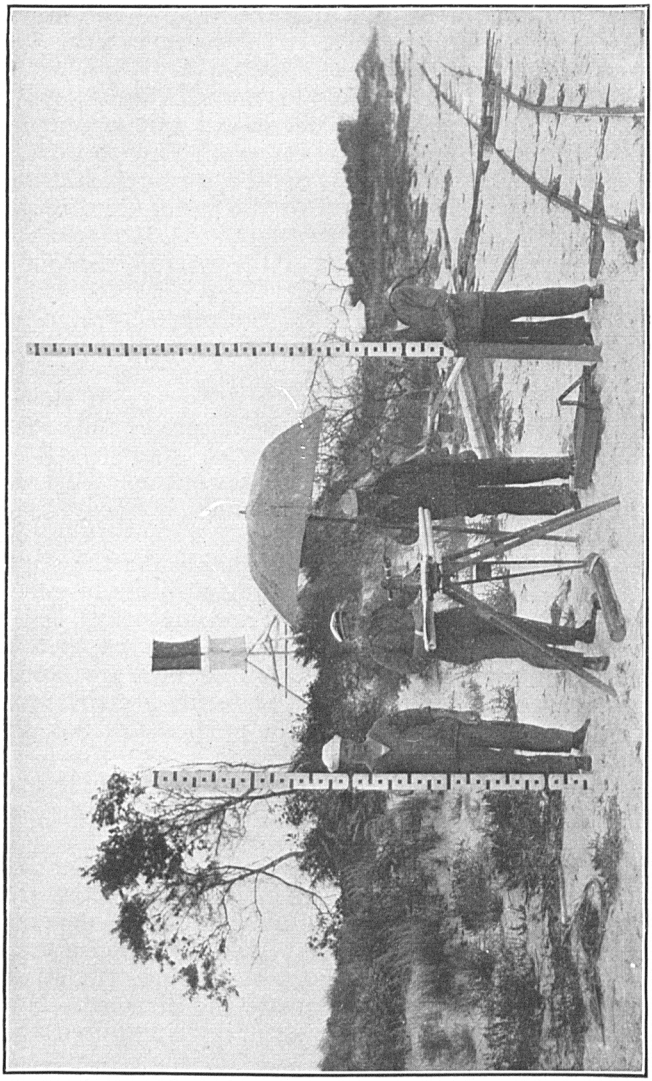

FIG. 15.—TOPOGRAPHIC FIELD PARTY AND EQUIPMENT, WITH HYDROGRAPHIC SIGNAL IN BACKGROUND

contours are drawn on the plan with reference to them, and all other details are located by measurements from them. This method is best adapted for small areas where work of construction is shortly to follow the survey.

The topography of the ordnance survey of Great Britain was executed by traversing the country with a network of straight lines

measured with a chain, the accuracy of the work being controlled by starting each line from one triangulation point and ending at another. Offsets were measured from the line wherever it was necessary to locate details. The elevations of a number of points on the ground were determined by the level, and the contours were sketched with reference to these after the rest of the details had been plotted. This is the simplest of all instrumental methods in the field, but it is not efficient where there is little detail or where the ground is unsuitable for chaining.

TRANSIT AND STADIA METHOD

This method is a development of the preceding one. The country is likewise traversed by lines, but instead of chaining, the distances are read through the telescope of the transit on the stadia rod held at any desired point. The level is also dispensed with, as the height of any point can be determined by computation when its distance is known and the vertical angle to it is observed. A vertical circle is attached to the transit for this purpose. All the names of the objects sighted upon, as well as the distances and angles to them, are entered in a notebook, together with sketches of the locality, to assist the draftsman to interpret the notes.

ORDINARY PHOTOGRAPHIC METHOD

Topographic surveys can be made with an ordinary landscape camera, but there are many advantages in having one especially designed for the purpose. The essential feature of this method consists in occupying a sufficient number of camera stations to cover fully the territory to be mapped, so that every topographic detail of importance may be photographed from at least two stations.

This is one of the most rapid of all instrumental methods in the field, since a great deal of topographic material can be gathered photographically in a short time. It has the serious drawback that for areas abounding in detail the plotting becomes overwhelming. It has been found most useful in mapping rugged mountainous regions with characteristic features which can be identified in photographs taken from two or more different points of view.

AIRPLANE PHOTOGRAPHIC METHOD

Airplane photographs, where the optical axis of the camera is vertical or at a known angle, were used to a very large extent during the World War in locating military features within the area occupied by the enemy. The experience then gained is being utilized in developing methods and apparatus for topographic surveys. At present it is not certain to what extent they will supersede the usual methods. The most promising field for surveying and mapping from an airplane is over flat country, or country with low relief, and in revision surveys. The changing features are shore lines, woods, roads, and villages, and these features can be readily placed on the old map by fitting in the new features shown on the photograph to the unchanged features shown on both the old map and the photograph.

PLANE TABLE AND STADIA METHOD

By the foregoing methods the map is constructed in the office, but when the plane table is used the construction of the map is coincident with the field work. This is the principal method used for topographic work by the Coast and Geodetic Survey. For this purpose the plane table is a universal instrument. All the necessary operations for producing a map are executed with it in the field from the country as a model. Other instruments may at times be employed as auxiliaries, but in general it alone fulfills all requirements.

Owing to the rapidity with which results are obtained by the method of graphic triangulation, and the facility which the plane table affords the topographer for determining his position at an unknown point by the graphic solution of the 3-point problem, and in the effectiveness of the stadia, it is an instrument peculiarly fitted for delineating coast topography, which includes such features as outlying islands and ledges, inaccessible rocky bluffs, and large marsh areas intersected by numerous streams. (For further details see Topographic Manual, Special Publication No. 144, 1928.)

Chapter VI.—HYDROGRAPHY

Hydrography is that branch of surveying which defines the depth and configuration of the bottom of the ocean and of lakes, bays, rivers, and other bodies of water. Such surveys furnish the information from which nautical charts are constructed. The preparation of these charts and the hydrographic surveys on which they are based constitute the two major activities of the Coast and Geodetic Survey. Physical hydrography, which relates to tides and currents, is elsewhere described; this chapter deals only with hydrography of depth and of bottom configuration and composition.

Hydrographic surveying consists of two separate and distinct operations—(1) measurement of the depth and (2) determination of the exact geographical position of the depth measurement. The accuracy of the survey, and hence the value of the chart based upon that survey, depends upon the precision with which both operations have been performed.

Hydrographic surveying is closely related to, and to a considerable extent depends upon, geodetic and topographic surveying. Depth measurements, usually known as soundings, are fixed in geographic position so far as possible by reference to geodetic control points on the adjacent shores. Also, hydrographic surveys are correlated with each other, and adjacent surveys joined, by means of their geodetic control. Topographic surveys indicate the position and delineation of the shore, the relief and character of the adjacent terrain, the prominent features, both natural and artificial, and the visible rock and objects offshore, all of which information is required for the construction of the nautical chart.

A nautical chart is similar in many respects to a topographic map. It might even be regarded as a topographic map of an area which had been flooded to the elevation of that contour which became the shore line. The methods employed in hydrographic surveying, however, are entirely different from those of topographic surveying. In topographic surveys the surveyor sees the land which he surveys—he travels over it and takes such measurements as will enable him to describe it on paper by conventional signs and symbols—while in hydrographic surveys the surveyor must examine and measure that which is concealed by the water and must adopt such means of exploration that no important feature of the bottom configuration will be omitted.

The hydrographic surveyor must always delve into the unknown and the invisible and get such information as will enable him and, through him, the cartographer to construct a true picture of that which lies under water. Actually, all that he really knows of the sea bottom are those comparatively few spots that he has touched with his depth-measuring apparatus, but he must be able to draw from such information correct inference as to what lies on each side

and all around the spots which he has explored. To be able to do this with some degree of certainty the hydrographic surveyor must have had wide experience in such work and a precise knowledge of characteristic bottom formations and compositions that can be gained only by years of experience.

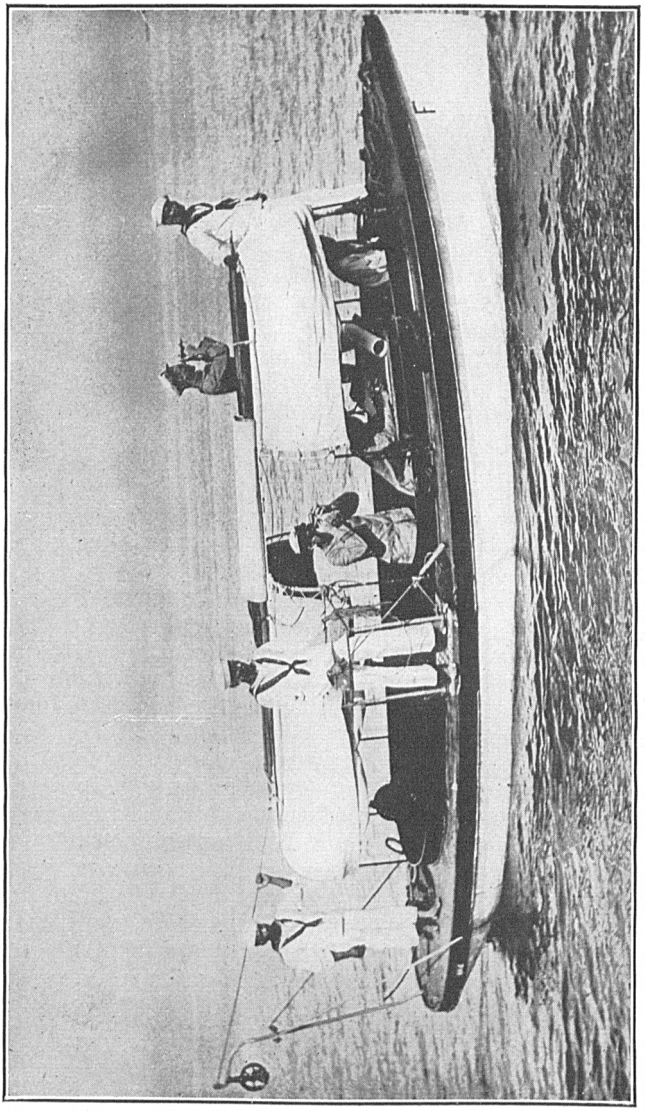

FIG. 16.—DETERMINING POSITION ON SOUNDING LINE ON LAUNCH WORK (PHILIPPINE ISLANDS)

While the methods of hydrographic surveying are for the most part not difficult to understand, in fact may be easily learned, the art of applying them efficiently involves many problems difficult of solution. Not the least of these problems are those that arise from rough seas and strong, varying currents which prevail in some localities during all seasons. A knowledge of the science of geology

in several of its branches is necessary for the complete interpretation of hydrographic data, and this knowledge must be made use of by the surveyor during the progress of the field work to insure a complete survey at a minimum cost.

METHODS OF DEPTH MEASUREMENT

There are several methods by means of which the two essential operations of hydrographic surveying—depth measurement and position determination—may be performed. Any one of the methods for getting position may be employed with any one of the methods for measuring depth, but usually there are natural or other conditions that render one method of position finding and one

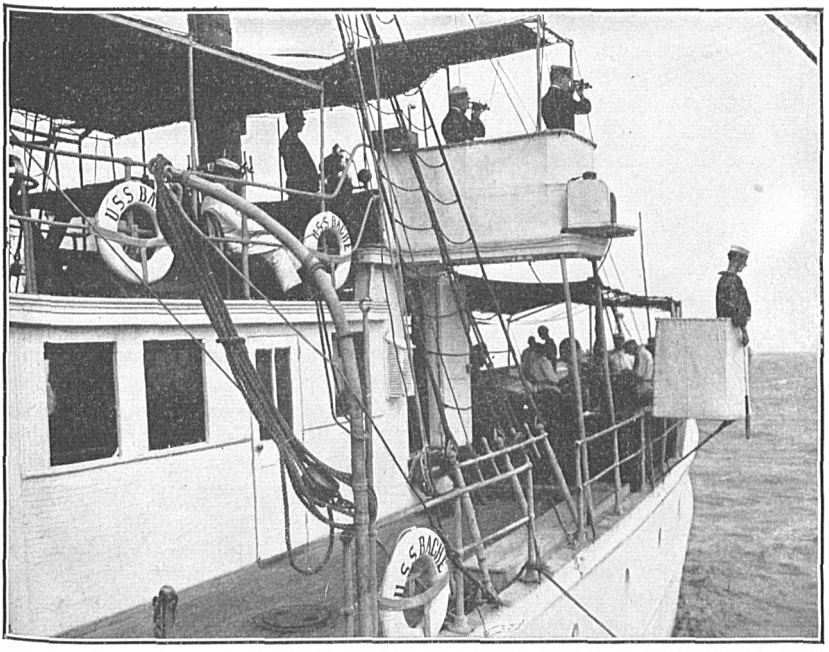

FIG. 17.—DETERMINING POSITION ON SOUNDING LINE FROM SHIP

method of depth measurement preferable to all others for the survey of any one area. Frequently, however, especially in the survey of a large area of widely different depths, conditions vary to such an extent in different parts of the area that two or more methods are employed for each operation.

HAND LINE AND LEAD

The simplest method of measuring depth, and the one that has been in use from the earliest days of marine surveying, is by means of the hand line and lead. A line about one-fourth of an inch in diameter is divided into fathoms and feet, in accordance with a standard system of marking, by strips of cloth and of leather and

cord. These lines are now made of waterproofed cotton braided around a bronze-wire cable which prevents changes in length from moisture and tension. To the end of this line is attached a mass of lead of hexagonal cross section, tapering slightly toward the end to which the line is attached. The bottom of the lead is concave to permit "arming"—that is, the fitting of this hollow with tallow to collect a specimen of the bottom.

Soundings (depth measurements) are usually taken from a power boat or ship while the craft is moving at slow speed. The leadsman stands on a small platform which projects over the side of the craft and heaves the lead forward far enough so that by the time the lead has sunk to the bottom it will be vertically below him. He then quickly gathers in the slack of the line and reads the mark that comes nearest to the water surface. If soundings are required closer than to the nearest foot he estimates the fraction in excess of the whole number of fathoms and feet. When the water surface is broken by swells and waves he estimates the mean water level and notes the length of line below that level. This method is employed generally where the depth does not exceed 15 fathoms and may even be extended to 20 fathoms by a skillful leadsman.

MECHANICAL METHODS

It is necessary to reduce the speed of the surveying vessel as the depth increases in order to allow sufficient time for the lead to sink to the bottom before the leadsman's platform comes vertically over the lead. Otherwise the lead line will incline backward from the leadsman and not indicate the true depth. Accordingly, where depths exceed about 15 fathoms it is customary to resort to mechanical means for projecting the lead farther ahead than a man can heave it or to resort to some other means for measuring depth. Reduction of the speed of the surveying vessel slows up the progress of the work.

Depths of from 15 to 40 fathoms can be measured at a good rate of progress by either the trolley method or the machine-hand lead method, both of which are means for getting a greater length of cast than is practicable by hand. In the former method a wire cable is stretched tight between short booms extending from the side of the vessel, one near the bow and the other near the stern, the forward boom being much lower than the after one. The leadsman's stand is beside the afterboom. To get a cast, he attaches the lead to a device called a trolley, which runs down the cable when released and drops the lead on arrival at the forward boom. The lead, which is usually of about a 30-pound weight, is hauled up by a power reel. The line is similar to the hand line, but is considerably heavier to stand the strain of the heavy lead.

The machine-hand lead method has superseded the trolley method to some extent, although under some conditions preference is given to the latter. In this method the hand line is used for measuring the depth, but the heavy lead is lifted by a small wire cable and power reel. The reel is mounted forward on the vessel and the hoisting cable runs over a pulley secured to a short boom near the reel. The leadsman's stand is near the stern, as with the trolley.

When taking a sounding the man at the power reel releases the reel and lets the lead drop and sink freely. The leadsman pays out line while the lead is sinking and then gathers in the slack and reads the line when it becomes vertical, indicating that the lead is on bottom vertically under his stand. The reel is then started and the lead hove up to the pully at the boom. Excellent results have been obtained by this method after the sounding crew have mastered their duties.

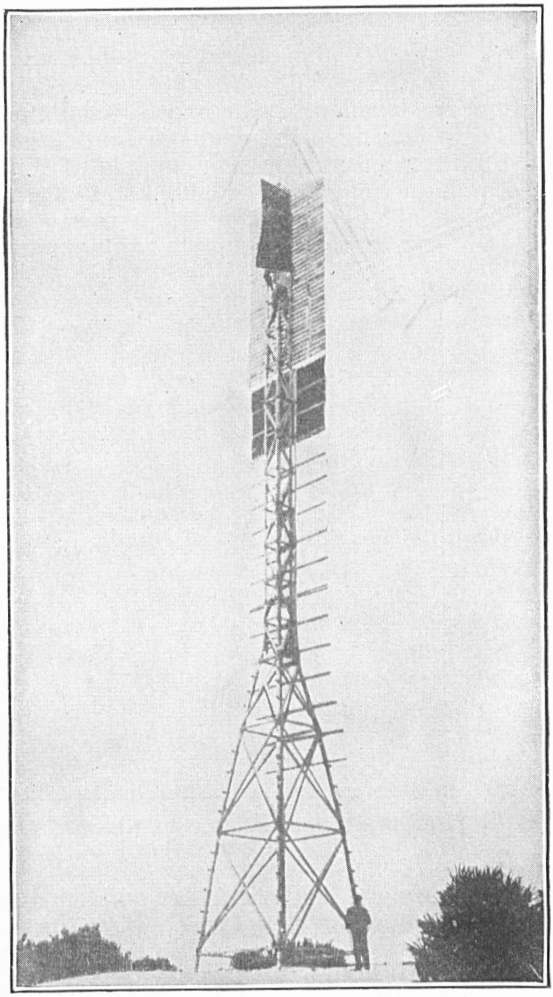

FIG. 18.—TYPE OF SIGNAL USED IN OFFSHORE HYDROGRAPHY

PRESSURE-TUBE METHOD

Another method of measuring depths not in excess of 100 fathoms is by means of a pressure tube. These tubes are so constructed that water can enter through a small orifice by compressing the air within the tube but can not escape. Since the pressure increases uniformly with the depth, and the volume of air contained in a vessel contracts in a definite ratio to the pressure exerted upon it, it is possible to measure depth by determining the extent to which the air contained in a submerged-pressure tube has contracted under the pressure of the water above it.

The pressure tube is attached to the sounding lead, or to the lead line just above the lead, and lowered to the bottom of the sea. Water enters the tube to an amount depending upon the depth compressing the air in the tube to a pressure equal to that of the outside water. The tube is then hauled up and the quantity of water trapped in the tube is measured. By using a properly constructed measuring scale the quantity of water in the tube will indicate the depth to which the tube has descended.

Pressure tubes can be used for measuring depths up to 100 fathoms, but beyond that depth the additional quantity of water that will

enter the tube per fathom of depth is so little that accurate measurements of depth can not be made. The great advantage of this method is that the soundings can be taken without stopping the surveying vessel, although it is necessary to slow down to about 5 or 6 knots to get good results. With the pressure tubes that have been designed by the Coast and Geodetic Survey quite accurate results can be obtained in depths of 100 fathoms or less.

DEEP-SEA SOUNDING MACHINE

For greater depths there was until recently but one means of getting soundings—the deep-sea sounding machine. This is a reel of 1 fathom circumference, capable of holding 6 miles or more of steel piano wire, geared or belted to a steam engine or electric motor.

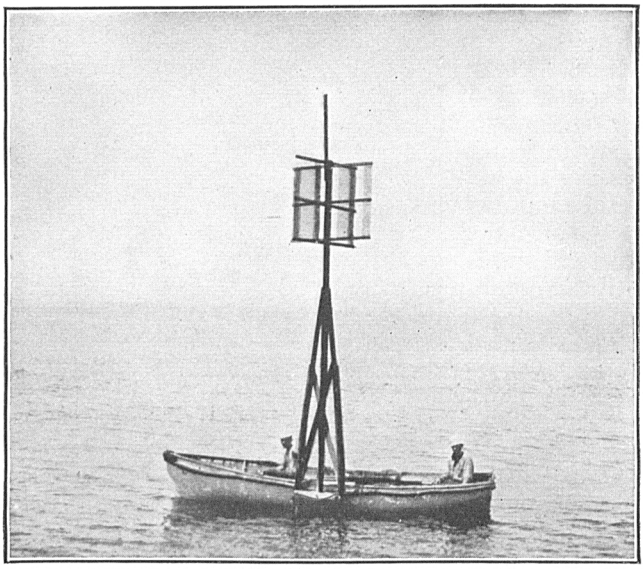

FIG. 19.—TYPE OF FLOATING SIGNAL USED IN OFF-SHORE HYDROGRAPHY

Suitable means are provided for quickly disconnecting the reel from the engine or motor and for stopping the reel instantly. To obtain a deep sounding the vessel is stopped. The wire, to which is attached a heavy sinker, is led from the reel to a pulley suspended from a short boom extending over the side of the vessel and then down to the surface of the water. The reel is released from the engine and allowed to revolve slowly, unwinding the wire until the bottom is reached, as evidenced by a reduced tension in the wire. The number of fathoms of wire let out is indicated by the number of revolutions of the reel and also by a counter attached to the pulley at the boom. The reel is then connected with the engine or motor, which is started, and the wire reeled in.

For depths of a few hundred fathoms it is customary to use a small wire cable and a lead sinker of 30 to 40 pounds weight. But

for depths in excess of 1,000 fathoms it is necessary to use a fine single-strand steel wire (piano wire) and a heavier sinker—60 pounds for the greatest depth—to determine positively when the bottom has been reached, as the weight of wire alone is sufficient to maintain considerable tension, even when the sinker is on the bottom. This wire, although of a tensile strength of about 200 pounds, is not strong enough to bring back a 60-pound sinker and other attached apparatus, together with the submerged wire, from a great depth. Accordingly, it is the practice to drop the weight, an iron pear-shaped casting, on the bottom. This is done by attaching the weight to a special contrivance called a detaching tube, instead of directly to the wire, in such way that the detaching tube releases the weight on contact with the bottom. The detaching tube also grasps and brings up a sample of the bottom when not of rock or other solid formation.

Sounding wire can not be paid out safely at a greater speed than about 100 fathoms per minute after the first few hundred nor reeled in at much greater speed, so that a single sounding taken in an ocean depth of 3,000 to 4,000 fathoms may require from one to one and a half hours, and the greatest depths more than two hours.

ECHO-SOUNDING METHOD

A recently devised method of sounding that is rapidly superseding all others where a ship can be employed is known as echo sounding. This method makes use of two principles—(1) that sound travels through water at a constant speed, depending upon the density and temperature of the water, and (2) that sound is reflected back from the sea bottom just as an echo is given back in air from a wall or other vertical, large surface. Knowing the velocity of sound in sea water, we can determine the depth if we can measure with sufficient precision the time required for a sound wave to descend to the bottom and return to the source of that sound—twice the depth. This is accomplished by means of a very accurate time-measuring device on the survey ship, so constructed that it measures to about one one-thousandth of a second the time interval between the emission of a sound and the reception of the echo from that sound.

This time-measuring device, called a fathometer, is constructed so that the time interval is translated into depth units (fathoms) by automatically combining this time interval with some arbitrarily selected velocity of sound value. In this way depth is obtained directly by a single reading on the instrument. Since, however, velocity of sound in sea water varies somewhat from place to place, due to differences in temperature and salinity, and at different depths in the same locality, due to differences in pressure and temperature, a small correction must be applied sometimes to the fathometer sounding to get the exact depth.

The sound is produced by an electric oscillator—a steel plate vibrated by an electric magnet—attached to the underbody of the ship; outside near the keel. The echo is received by means of a hydrophone, an apparatus similar in principle to a telephone trans-

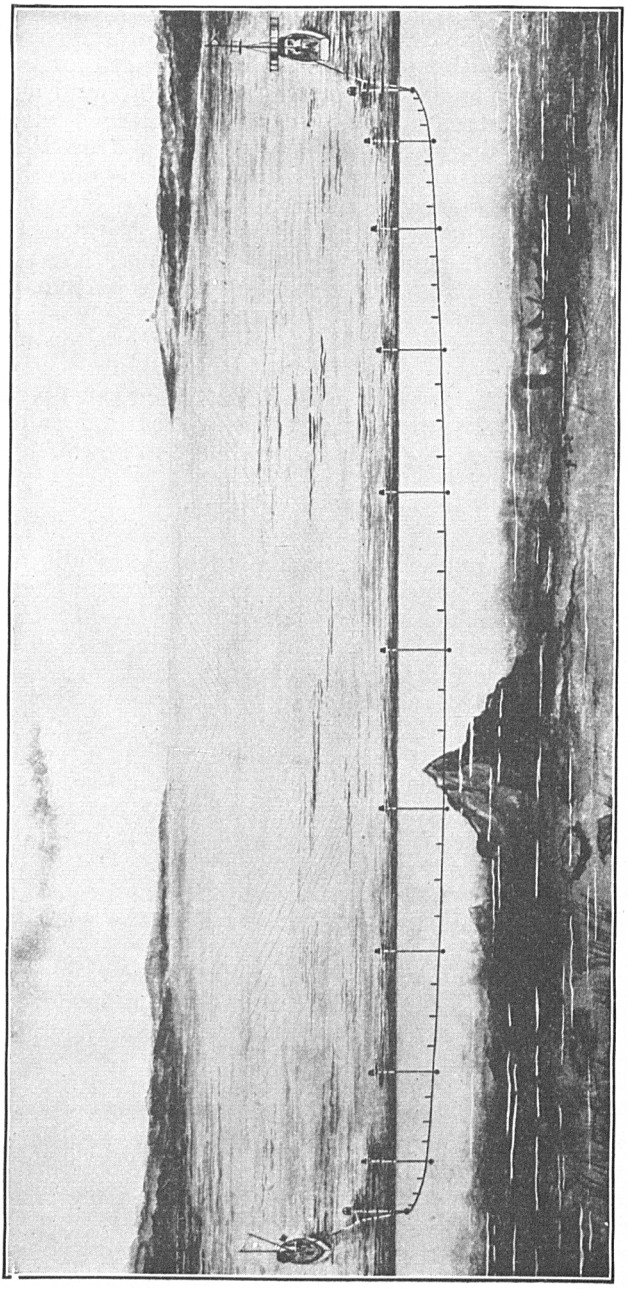

FIG. 20.—WIRE DRAG

mitter, submerged in a tank full of water in contact with the plating of the underwater body of the ship.

Echo sounding is now used extensively in the Coast and Geodetic Survey for surveying in all depths of 15 fathoms or more whenever a survey ship can be employed. Results obtained compare favorably with those obtained by sounding machine or pressure tube.

METHODS OF POSITION FINDING

SHORE CONTROL

The geographic position of a sounding, which is just as important as the depth, can be determined in several ways, depending upon the proximity and nature of the nearest land. The simplest and, in general, the most satisfactory way is by means of observations upon visible objects on the adjacent shores. If three objects, such as structures, prominent rocks or trees, or even well-defined mountain tops, the geographic positions of which are known, can be seen from the position of the surveying craft while sounding, the position of that sounding can be determined accurately by measuring simultaneously the angles between the right and center objects and the center and left objects.

These angles are measured by two observers, each with a sextant, at the instant the sounding is taken. The angles are then set off on a 3-arm protractor, and the protractor is so placed on the chart or boat sheet that each arm touches the plotted position of one of the objects. The center of the protractor will indicate the position on the chart or boat sheet which has the same relation to the plotted positions of the visible objects, with reference to direction and distance, that the position of the sounding has to these objects—the correct position for charting that sounding.

This method is used almost exclusively on harbor surveys and on coastal surveys to the limit of visibility of shore objects. Since the distance seaward that the shore objects can be seen depends upon the elevation of these objects, as well as upon the clearness of the atmosphere, it is apparent that the extent to which this method can be used varies greatly in different localities. An elevated coastal terrain surmounted by high distinctive peaks furnishes visible control far offshore when the atmosphere is clear—often as far seaward as it is necessary to extend accurately controlled surveys.

BUOY CONTROL

Along the low coasts it is often necessary to resort to floating control objects because of the lack of natural objects and the impracticability of constructing artificial objects (signals) of sufficient height to be seen more than a dozen miles or so. It is then the practice to anchor buoys as far seaward as they can be seen from a survey vessel stationed at the outer limit of visibility of the shore objects. These buoys are cut in by sextants from the highest position on the survey ship after the position of the ship has been established from angles on the shore objects. The buoys are usually anchored parallel to the shore and about 3 miles apart. After they have been located

by three or more intersecting lines they are plotted on the chart or boat sheet and are used for getting the position of soundings in the same way as the shore signals.

By means of such buoys it is possible to extend fixed position work some 6 or 7 miles farther offshore. However, additional lines of buoys can be used, each line of buoys determined from the line next shoreward from it in the same manner that the first line was determined from the shore objects. It is therefore possible to extend fairly good hydrographic control a long distance offshore by means of buoys, but there are numerous difficulties arising from the use of a great number of buoys that limit the practicability of this method, usually to one or two lines of buoys.

SUBAQUEOUS SOUND RANGING

A more accurate and far more expeditious method of fixing the position of soundings beyond the range of visibility of shore objects is subaqueous sound ranging. This method has the additional advantage that it can be used during hazy and foggy weather and at night, so that a surveying party can carry on operations continuously whenever the sea is not too rough for accurate sounding. There are, however, conditions in some localities which have prevented the sucessful operation of sound ranging, and a solution of these difficulties is constantly being sought.

Subaqueous sound ranging is accomplished by measuring the time required for sound to travel through the water from the survey ship to two or more places near shore, the exact geographical positions of which are known. These time intervals multiplied by the velocity of sound through the water gives the distances from these known places, and, hence, the position of the ship.

The procedure is as follows: A small bomb of high-explosive material is detonated under water near the ship, and the instant of explosion is recorded by a time-measuring apparatus on the ship. The arrival of the sound waves from the explosion is picked up by hydrophones at the several stations near shore and reported electrically, through cables, to radio stations on shore. Each of these radio stations responds automatically to the reception of the sound waves by its hydrophone station and transmits a radio code signal to the ship's radio receiving set. The instant of reception of these code signals is recorded on the ship time measuring apparatus, thus giving the time interval between the explosion and the reception of the sound at each of the hydrophone stations. Time intervals can be determined to one one-hundredth of a second, and the sum of all errors is so small that the position of the survey ship can be determined usually with an error of not much in excess of 1 per cent of the distance from the shore stations.

"DEAD RECKONING"

"Dead reckoning," so called, is still used in hydrographic surveying beyond the range of visibility of shore objects where buoy control is impracticable and where subaqueous sound ranging can not be used. This is the least accurate method of fixing the position of soundings, although surprisingly good results have been obtained

with careful steering and where a study has been made of the ocean currents, both tidal and wind driven.

A method has been developed in the Coast and Geodetic Survey which has been referred to as "precise dead reckoning," because every possible precaution has been taken to get the best obtainable information regarding ocean currents and to eliminate, in so far as possible, the uncertainties of navigation. Where it has been possible to verify precise dead reckoning work, positions have been found to be not greatly in error. When resorting to this method the hydrographer stops every two hours, anchors his ship, and determines the direction and strength of the current and of the wind and uses this information in computing the most probable track of his ship.

Hydrography performed far offshore is controlled by a combination of dead reckoning and astronomic observations. In this work dependence is placed principally upon star fixes. The altitudes of three or more stars, well distributed around the horizon, are measured by sextants, and a position line is computed for each star. The intersection of these lines determines the position, which is either at the intersection, if all lines intersect at a point, or is at an equal distance from each line, if they form a small triangle or several-sided figure. As many such fixes are obtained as may be practicable and, between fixes, soundings are located by dead reckoning tied in to the astronomic fixes.

SIZE OF SURVEY VESSELS

Hydrographic surveying is usually performed from power boats, steam launches, and small steam or motor ships, which have practically replaced pulling boats and sailing craft. A large item in the cost of hydrographic surveying is the cost of upkeep and maintenance of these vessels, including the wages of such of the personnel as do not take direct part in the survey work but are essential to the maintenance of the survey party. Consequently, the smaller the craft that can be employed on any survey the lower will be the cost of that survey.

It is the policy of the Coast and Geodetic Survey to utilize small launches and power boats to the limit of their capacity and wherever they can work with safety to the surveying personnel; beyond that limit to use steam or motor vessels of from 100 to 300 tons displacement and to make use of full-powered ships only in the most exposed and remote localities and to keep the size of such ships as small as practicable, not much over 1,000 tons displacement.

THE WIRE DRAG

Hydrographic surveys by sounding methods alone develop the slopes of the bottom, but they do not reveal with certainty all of the hidden dangers to navigation that may lie in the pathways of ships. In regions like the coast of Maine and in Alaska, where there are isolated rocks and ledges on the bottom, or in the tropical regions fringed with coral reefs and dotted with coral heads, the work must be supplemented by special examinations with special appliances.

Owing to the extension of commerce and its increasing demands, bringing in use ever larger and deeper-draft vessels, much special

examination is now required. To meet these requirements and in order to be certain that an area is free of all obstruction to navigation to a specified depth, the water area is swept over by an appliance known as a wire drag, which is essentially a suitable wire of any desired length (up to 15,000 feet long, so far used), supported at intervals by buoys so arranged that the wire can be maintained at any required depth, irrespective of the changes in the stage of the tide. This apparatus is towed through the water by two launches or vessels, and if no obstruction is encountered it is certain that no dangers exist at a less depth of water than that at which the drag was set.

The use of the wire drag has now become such a necessity in a finished hydrographic survey in areas where there is a possibility of isolated rocks that a brief account of its construction and use is of interest. Sweeps or drags were used long ago for locating pinnacle rocks or small ledges whose positions were approximately known, but the improvement of such apparatus, so as to be an economic instrument for general application in searching out possible obstructions to navigation, is recent and as now used has reached a high degree of efficiency.

As described in Coast and Geodetic Survey Special Publication No. 118, the drag consists of a horizontal member known as the bottom wire, which is composed of a number of sections or units of double-galvanized, seven-strand, steel wire, one-eighth inch in diameter, supported at intervals by uprights, made of flexible wire cable, with suitable buoys and sinkers, and at intermediate points by hollow metal floats. At each end of the drag the buoys are large enough to support the large sinkers attached, with a reserve buoyancy sufficient to permit them to float high enough to be seen across the length of the drag. The intermediate buoys are smaller and when at rest project about 10 inches out of the water. Towlines from the boats are attached to the bottom wire. The depth of the drag may be changed while in use.

One of the best features of the wire drag is the rapidity with which an area can be examined. The length of drag now commonly used is 4,000 to 5,000 feet, except when used in channels of less width than this. The average speed of the drag through the water is about a mile and a half per hour, and the area that can be covered in a day depends largely upon local conditions, such as natural or artificial obstructions. As many as 15 shoal spots have been found in a single day's work.

After a shoal spot or other obstruction is located by the drag soundings are taken before the drag is released. To ascertain that the least depth has been found, the area is again swept over with a drag depth slightly less than the least sounding obtained. If the drag strikes, the operation is repeated until the least depth found by sounding is cleared by the drag.

The drag is removed from the water at the close of each day's work. This operation requires about 25 minutes for a drag 5,000 feet long, and the time required for other lengths is proportional to this. It requires about the same length of time to set out the drag ready for work. Changes in the depth of the drag, made necessary by changes in the stages of the tide, are made with a separate launch

while the drag is going ahead with its work. For handling this drag and towing it when in use it has been found that large launches are essential; boats of 80 horsepower and 14-foot beam are employed.

The use of this drag is confined to examination of narrow channels and in the vicinity of shoals. For wide channels and where deep water is charted, a modification of the drag known as the sweep allows for a more rapid investigation of the area. Briefly, the sweep differs from the drag in that a less number of buoys and uprights are used, with the result that the bottom wire lies in a series of curves between uprights instead of being kept horizontal. This makes no difference in deep water but is impracticable for investigation of a shoal. The sweep can be set out and taken in much more rapidly than the drag. A sweep 10,000 feet in length has been completely set out in nine minutes. An area of 65 square miles has been swept in one day.

Great accuracy is required of the hydrographer, even where the water is so deep that there is no possible danger of the largest ship afloat touching bottom, because the hydrography shown on a mariner's chart has a twofold object: First, to point out to the navigator the invisible dangers which he must avoid; and, second, to reveal the configuration of the bottom and also its physical characteristics so truly that by the use of his sounding appliances he may fix his position in relation to those dangers, or when offshore or the coast line is invisible, determine his distance from land. The results of the hydrographic work shown on the charts are of prime importance to the navigator. The manner of chart publication and issue is described in another part of this book. For details of the theory and practice of hydrographic surveying the reader is referred to the service manuals pertaining to hydrography and other classes of field work which are published by the Coast and Geodetic Survey from time to time.

Chapter VII.—TIDES

The tidal work of the Coast and Geodetic Survey had its origin in the necessity for correcting the soundings taken in hydrographic surveys for the rise and fall of the tides; that is, for reducing to a common level, or datum plane, soundings made at varying stages of the tide. The further needs of the mariner, engineer, and scientist have resulted in the development and extension of the work until it covers at the present time the following fields: Determination of datum planes for surveying and other engineering purposes, the prediction of tides and currents and the preparation of the annual tide and current tables, the preparation of current charts, and the study of mean sea level and its relation to crustal movements. The tide observations also furnish data used in the study of phenomena associated with earthquakes and storms and the study of tidal phenomena in general. The tide records are also frequently used in admiralty court cases in which the condition of the tide at a certain time is involved.

TIDE OBSERVATIONS

The times and heights of the tide are considerably influenced by terrestrial agencies, such as river discharge, winds, and variations in atmospheric pressure. As a consequence, any plane of reference—such as, for instance, that of mean low water—which is determined from a short series of observations at one time may differ considerably from the low-water plane determined at another time. It is therefore necessary to have long series of observations at a number of places, which are representative of the tidal conditions of large areas. Stations established for the purpose of obtaining such observations over a number of years are designated as primary tide stations. Short series of observations at any other place may then be corrected by comparison with simultaneous observations at a primary tide station. Approximately 20 to 25 primary tide stations are maintained in harbors and on the coasts of the United States and Alaska, the number varying from time to time as old stations are discontinued, or new ones established. A number of these stations are maintained cooperatively with other Federal, State, or municipal authorities, the cooperation working to the advantage of all organizations concerned.

Tide observations may be made either with a plain tide staff or with an automatic tide gage. When the latter is used a plain staff or a tape gage is also installed for the purpose of checking the automatic-gage record and referring the results to permanent bench marks.

The tide staff may be a plain board graduated in feet and tenths, about 5 inches wide, 1 inch thick, and of a length greater than the extreme fluctuation of the water surface in the locality in which it is to be used. It is secured in a vertical position, with its lowest graduation below the probable lowest water.

In a harbor where there is considerable refuse and fuel oil in the water the graduated scale on a tide staff which is left in the water continuously soon becomes illegible. To overcome this difficulty the survey has adopted a standard portable tide staff with a fixed support. The tide staff can be removed from its support after each reading and stored in the tide house. A metal plate fastened to the back of the tide staff and another one on top of the support provide a means to insure that the tide staff will always be set at the same

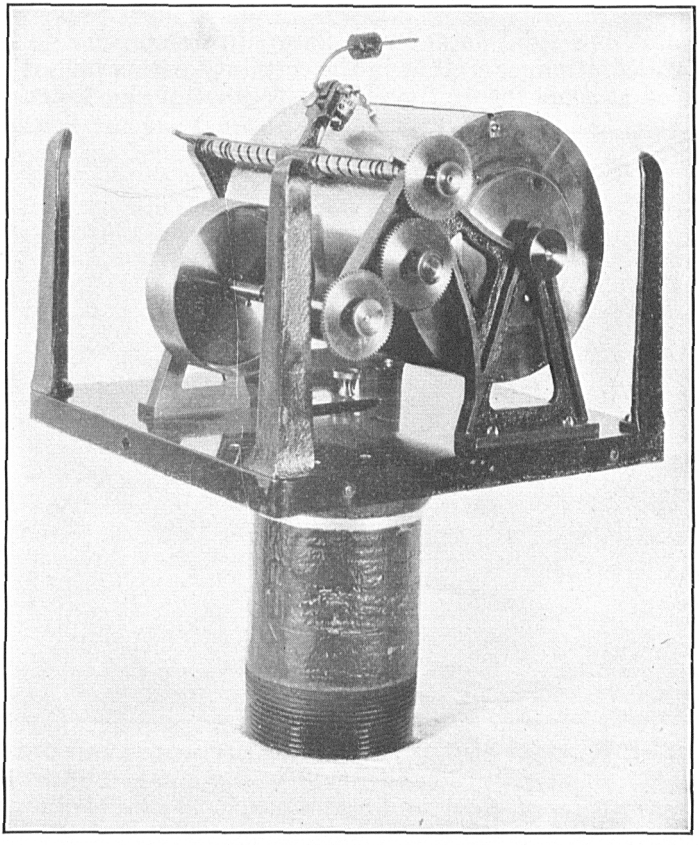

FIG. 21.—PORTABLE FIELD AUTOMATIC TIDE GAGE

This gauge was recently developed by the instrument division of the Coast and Geodetic Survey. It is for use of hydrographic parties in the field, and is only 10 inches square, but furnishes a complete record of tidal fluctuations.

elevation when placed in its support. A vitrified scale is now used on the tide staff to facilitate cleaning.

An automatic tide gage operates continuously, with only occasional attention from an observer. The automatic gages used by the Coast and Geodetic Survey produce a graphic record of the rise and fall of the tide in the form of a curve. The automatic tide gage consists, essentially, of a clock to move a sheet of paper forward at a uniform rate of speed, and a float which, rising and falling with the tide, moves a pencil or pen to and fro at right angles to the

motion of the paper. The record curve is automatically constructed by these combined motions, and the times of the high and low waters, as well as the height of the tide for any desired time, may be readily scaled off from these curves. For short series of observations the easily installed portable tide gage (fig. 21) is generally used, but at primary tide stations, where observations are to be continued for a number of years, the standard tide gage (fig. 22) is used.

TIDAL DATUM PLANES

The value of a tidal datum as a plane of reference lies in its simplicity of definition, as well as in the certainty with which it may be reproduced at some future time if lost because of the destruction of

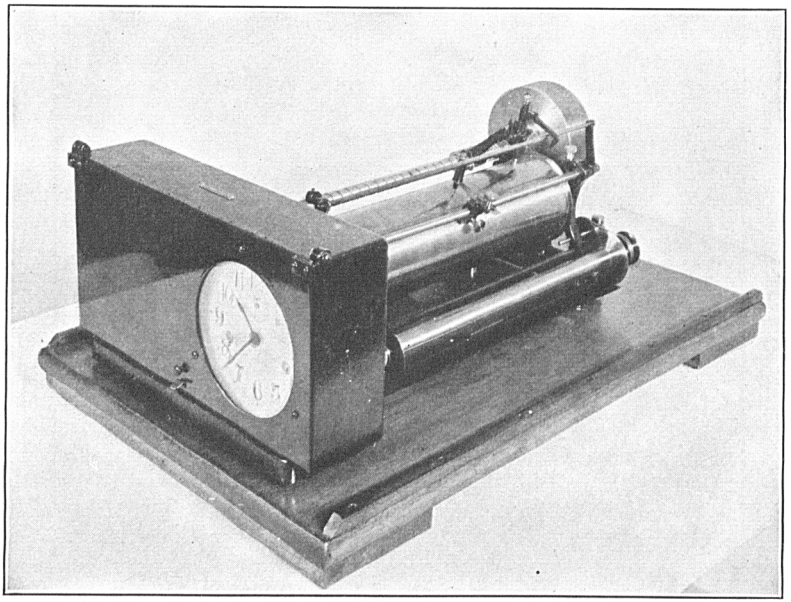

FIG. 22.—U. S. COAST AND GEODETIC SURVEY MODEL AUTOMATIC TIDE GAGE

Used at the primary tide stations at representative points along the coasts for obtaining a continuous record of the rise and fall of the tides.

all bench-mark connections. A low-water plane is the most satisfactory for the purposes of the mariner, because by its use a chart will show the least depth which he may expect regardless of the stage of the tide. The plane of mean low water has therefore been adopted on hydrographic charts for the whole of the Atlantic coast. On the Pacific coast, because of the diurnal inequality of the tides, the plane of mean lower low water is used; that is, all soundings shown on charts of the Coast and Geodetic Survey have been reduced, no matter what the stage of the tide at the time the soundings were made, to a mean low-water plane on the Atlantic coast, and to mean lower low water on the Pacific and Alaska coasts.

Planes determined by high waters or higher high waters are at times adopted for other engineering purposes, but the most satisfac-

tory plane, in general, is that of mean sea level, since it is the most easily determined of all the tidal planes and also since the other tidal planes may be derived from it by a knowledge of the range of tide and of its diurnal inequality. The planes of mean low water, mean high water, mean higher high water, etc., are all local, since they depend upon the range of the tide at a given place; that is, these datums when extended from place to place along a coast would be wavy or rolling surfaces, while mean sea level may be considered as an equipotential surface forming a continuous, smooth datum. Mean sea level may be defined, then, as that level at which the waters of the oceans would come to rest if freed from all disturbing influences of tides, wind, weather, and varying barometric pressures.

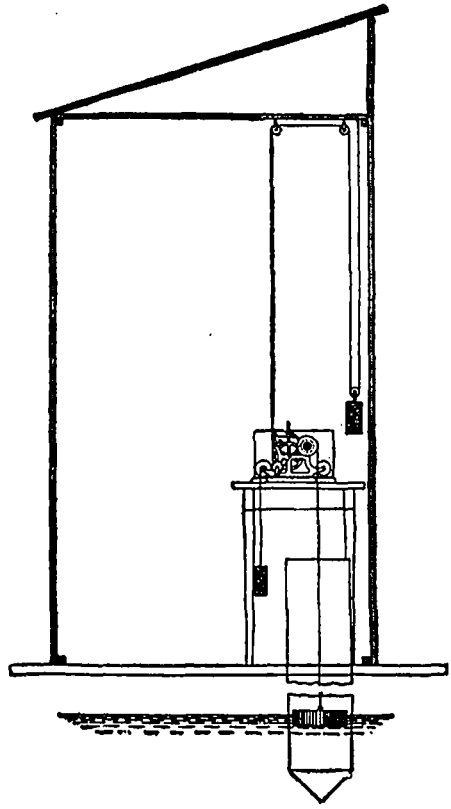

FIG. 23.—SECTIONAL VIEW OF AUTOMATIC TIDE-GAGE STATION

Illustrating the method of installation at the principal tidal stations.

BENCH MARKS

All along the coast, wherever tides are observed the Coast and Geodetic Survey establishes tidal bench marks, the elevations of which with reference to the planes of local high water, mean sea level, low water, and other tidal planes, are determined. These bench marks then furnish for local use accurate data regarding the various planes of reference made use of by the engineer.

In geodetic work the tidal plane of mean sea level has been carried to many parts of the interior of the country and referred to numerous bench marks by a network of first-order leveling. In this work a high degree of precision is required in the determination of mean sea level and the initial points for the level net are taken at the bench marks at primary tide stations where a number of years of observations have been secured.

Descriptions of many of the bench marks have been published. Others are in manuscript form and copies can be secured at a reasonable cost.

TIDE TABLES

In the early days of light-draft vessels advance knowledge of the tides was of little importance, but with the advent of the deep-draft vessels of modern commerce the tides have become of considerable

importance in navigation, for the state of the tide determines when certain harbors may be entered, when bars may be safely crossed, and when short cuts over shoal places may be attempted. To aid the navigator, the Coast and Geodetic Survey has for a number of years published in advance, annually, tide tables giving for every day of the year the times and heights of high and low waters for the more important ports of the world. By means of tidal differences given in these tidal tables the mariner may also obtain the tides for a large number of other ports in all parts of the world.

While the tides are due to the gravitational attraction of the sun and moon, they are very greatly modified by terrestrial features. As a consequence, the tides present striking differences not only in time of occurrence and in range but also in type. Thus, along the Atlantic coast of the United States the tide is almost wholly semi-diurnal; that is, there are two high and two low waters each day,

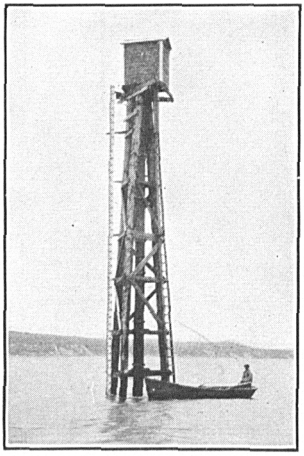

FIG. 24.—(a) LOW WATER AT TIDE STATION, ANCHORAGE, ALASKA

The water level reads 7½ feet on the tide staff.

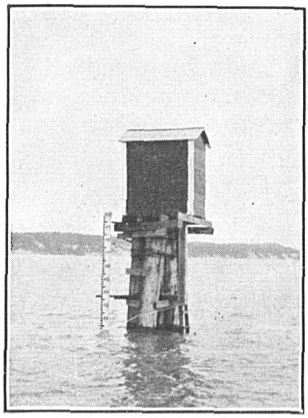

FIG. 24.—(b) HIGH WATER AT TIDE STATION, ANCHORAGE, ALASKA

The water level reads 41 feet on the tide staff.

and the afternoon tides are quite similar to the morning tides. On the Pacific coast, however, the tide is of the mixed type; that is, the afternoon tides are quite unlike the morning tides, and on occasion there is but one high water and one low water in a day.

Even with the same type of tide we find great differences in range. In the upper part of the Bay of Fundy the tide rises, in the six hours from low water to high water, a vertical distance of more than 40 feet. During the same interval the tide at Nantucket Island shows a range of but little more than 1 foot. In the upper part of Cook Inlet, Alaska, the range of tide is approximately 30 feet. Figure 24 shows a tide station at Anchorage as it appeared at both high and low water.

The tides, then, are local phenomena, and for purposes of predictions they are assumed to be composed of a number of constituent tides which are due to the motions of the moon and the sun and to their relative positions; and, since the tides are local

phenomena, the first step in the making of a tide table for any port is to obtain continuous tidal observations at that port, extending over a period varying from one month to a year or more. These observations are then subjected to a mathematical treatment known as the harmonic analysis, which resolves the tide into its constituent simple harmonic waves or harmonic constants, the periods of which have astronomical definitions, while the amplitudes and phases are derived from observations. The amplitudes (semiranges) and the phases (times of occurrence reckoned from a fixed origin), as obtained from this analysis for each component, are set on cranks and dials of a tide-predicting machine. This machine sums the elementary or constituent tides into the tide wave of nature and indicates on its face each successive high and low water which is copied in tabular form, printed, and issued to the mariner as a tide table.

Each of the leading maritime nations issues tide tables, and for the United States this important work is done by the Coast and Geodetic Survey. These tables were first published by the survey in 1853, and for the first 14 years they consisted of more or less elaborated means for enabling the mariner to make his own predictions as occasion arose. In 1867 tables were issued for a few ports on each coast of the United States. They have since been considerably increased in scope until at the present time they cover the entire maritime world.

TIDE-PREDICTING MACHINE

Prior to 1885 the predictions of the tides were made by means of empirical tables and graphs. Beginning with 1885 the predictions were made by use of an ingenious machine devised by William Ferrel, of the Coast and Geodetic Survey. This machine differed somewhat from that of Lord Kelvin, who conceived the idea of such a machine, and who devised the first one in 1872. When the predictions were extended by the survey to cover the world, it was found that the Ferrel machine was not well adapted to the prediction of certain types of tides, and since 1912 the predictions have been made on a later machine, designed and constructed in the office of the survey. A view of this machine is shown in Figure 25. It has been described in a survey publication, "Description of the United States Coast and Geodetic Survey Tide Predicting Machine No. 2." By use of this machine a tide table for any single port can be made in about 10 hours, giving the time and height of every high and low water for every day of the year.

Before beginning the predictions for any port, the constants, representing the different components of each constituent tide, are set on the proper cranks and dials which are so arranged that when the machine is put in motion by means of a crank and gears it will sum up the effects of all these elementary waves into the tide of nature. The machine is also so constructed that this summation is indicated through dials on the face of the machine as high and low waters, with their heights and times of occurrence. This machine takes account of 37 of these elementary tides.

It is obviously impracticable to predict the tides for all ports. To obtain the state of the tide at places where no full predictions are made, it is necessary to refer such places to some port having a simi-

lar type of tide for which predictions have been made as a standard port.

The study of the tides dates back to ancient times. Several centuries before the beginning of the Christian era the intimate relation between the tides and the moon had been noted. Little progress was made, however, until toward the close of the seventeenth century, when Newton formulated the law of gravitation and proved that the

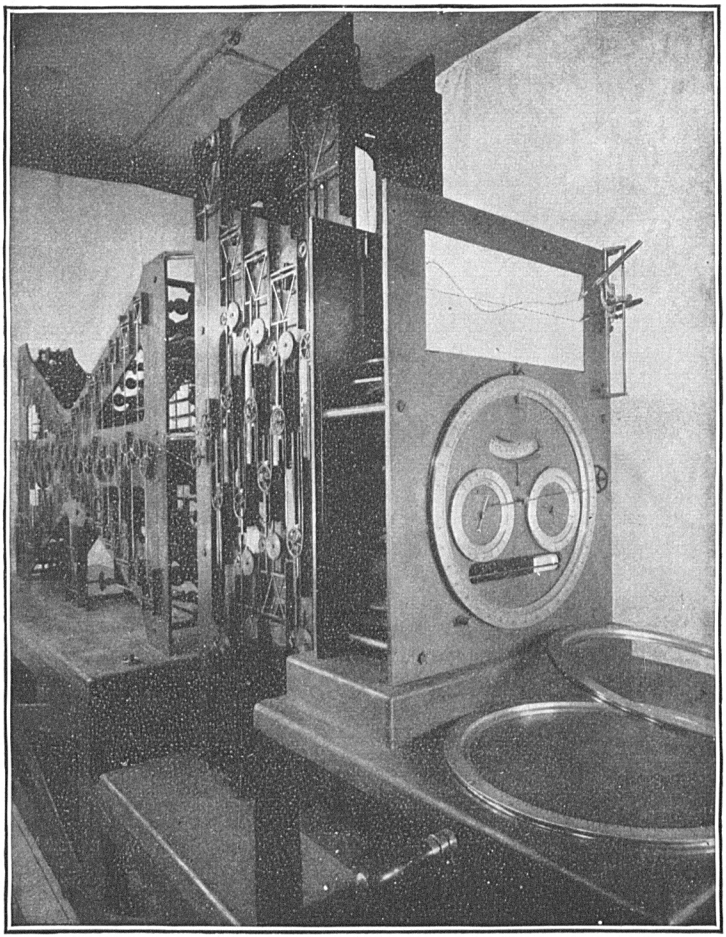

FIG. 25.—THE COAST AND GEODETIC SURVEY TIDE-PREDICTING MACHINE

When set to certain predetermined constants this machine automatically gives the times and heights of the tide for any port in the world and for any year.

tides were one of its necessary consequences. Since that time the labors of many distinguished mathematicians have contributed to the considerable advance made in the subject. To that advance the Coast and Geodetic Survey, through Ferrel and Harris—the most brilliant of its tidal workers—has made notable contributions. A further reference to ocean tides will be found in the chapter on Oceanography.

Chapter VIII.—CURRENTS

Accompanying the vertical movement of the water caused by the tidal forces of sun and moon, a horizontal movement also takes place, giving rise to currents in the water. Since the primary object of the current work of the Coast and Geodetic Survey is for the purposes of navigation, the importance of these currents to the mariner and engineer are emphasized in this description.

Currents have always been a factor of importance in navigation. In thick weather, when the navigator is unable to determine the position of his ship by reference to terrestrial or celestial objects, it becomes highly important that he know the velocity and direction of

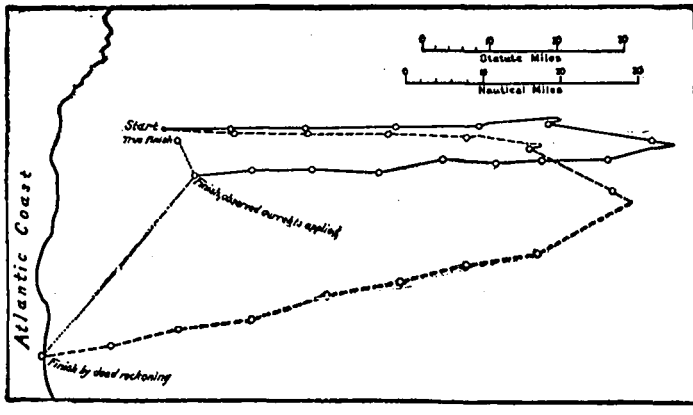

FIG. 26.—THE EFFECTS OF CURRENTS ON SHIP'S POSITION

The course of a vessel *with* and *without* current information. The *dashed line* shows the course of the vessel plotted according to "dead reckoning," no allowance being made for currents. The *full line* shows the course of the vessel plotted according to "dead reckoning," with allowance for set of the vessel by currents. The vessel was stopped at the positions indicated by circles and the direction and force of the current observed.

the currents to which his vessel may be subject; also, where swift and dangerous tidal currents exist, the mariner must know the time of occurrence of slack water when such places may be safely crossed.

Figure 26 will serve to illustrate and emphasize the importance to the mariner of adequate knowledge of coastal currents. This is a sounding line plotted from the record log of a survey vessel engaged on offshore hydrographic work and was not exaggerated for the sake of emphasis. The dashed line shows the course of the vessel plotted according to "dead reckoning," no allowance being made for currents; the full line, the course of the vessel plotted according to "dead reckoning," with allowance for set of the vessel by currents. The vessel was anchored at the positions indicated by circles and the direction and velocity of the current observed at these anchorages.

It should be stated, however, that the actual time from the beginning to the end of the line of soundings was about 30 hours.

CURRENT TYPES

In addition to those currents due to astronomical forces working through the tides, others are brought about by meteorological conditions and physical differences in sea water in different parts of the oceans. These astronomical forces, combined with terrestrial conditions, as in the case of the tides, give rise to several types of currents which are described in detail hereafter: (1) The rectilinear or reversing type, illustrated by the currents in most inland bodies of water, such as Chesapeake Bay and Hudson River; (2) the hydraulic type, illustrated by the currents in straits connecting two independently tided bodies of water; for example, the East River, N. Y., and Seymour Narrows, British Columbia; (3) the rotary type, illustrated by the currents in the open ocean and along the coasts; (4) wind-driven currents of a temporary nature, produced by the effect of friction of local winds on the surface of the water; and (5) the permanent currents comprising the main ocean circulation, illustrated by the Gulf Stream of the Atlantic and the Kuro Siwo of the Pacific.

The first three types are of tidal origin and are therefore periodic, while the last two are nonperiodic and are due to meteorological conditions, such as winds, variations in barometric pressures over the oceans, and differences in temperatures and densities of the sea water in different parts of the ocean.

RECTILINEAR, OR REVERSING, TYPE

The type of current known as the rectilinear or reversing type is found in all inland bodies of water connected with the ocean. These currents do not change in rotary fashion like the tidal current in the ocean, but come to a slack and reverse, the direction being designated flood when referring to the horizontal movement of the water toward the land or upstream and ebb when referring to the movement away from the land or downstream.

This current is intimately related to the tidal régime of the body of water. In a body in which the tides are due to a progressive wave, the time of the reversal of the current, or slack water, occurs about half tide, and the strength of flood and ebb occurs about the time of high and low water, respectively. In a body which has a stationary tidal wave slack water occurs about the time of high and low water and the greatest current velocity about the time of half tide.

HYDRAULIC TYPE

The hydraulic type of current is illustrated by the currents in straits connecting two independently tided bodies of water. While hydraulic type currents are reversing currents, they are due, not to tidal action of the purely stationary or progressive type, but rather are due to a temporary difference in head between the two bodies of water, brought about by tidal action. The currents in the East River, N. Y., are examples of this type, and a brief description of them will serve to illustrate this type in general.

The East River connects Long Island Sound with New York Bay, and the tides in these two bodies of water are decidedly different. The tides in Long Island Sound are due to a stationary wave, and the range of tide increases from 2 feet at Montauk Point to 7.2 feet at Willets Point, at the west end of the Sound. The tide in New York Bay is brought about by a progressive wave, and the range decreases from 4.7 feet at Sandy Hook to 4.4 feet at Governors Island. This difference in range of tide at the two ends of the East River is sufficent in itself to produce a hydraulic gradient; but, in addition, the time of the tide at Willets Point at the north entrance to the East River is later by over three hours than the time of the tide at Governors Island at the south entrance. This difference in time is, in fact, the larger factor in producing the temporary difference in hydraulic head.

As examples, high water occurs at Willets Point when the tide is about mean sea level at Governors Island, and therefore the current at this time is setting to the southward through the East River; and at the time of high water at Governors Island the tide at Willets Point is about mean sea level and the current then is setting toward Long Island Sound.

This difference of tidal conditions in Long Island Sound and New York Bay, at times causing a hydraulic gradient of 4 feet in the distance of 17 miles from Willets Point to Governors Island, gives rise to currents in Hell Gate which attain a mean velocity at strength of about 5 knots and occasionally of 8 knots.

While it is a comparatively simple matter to predict the time that the heads will be equalized and that slack water should occur with conditions such as these, account must be taken of the momentum of this mass of water and of the time of the continuance of the flow, due to this inertia, after equalization of head. This information can be attained only from observations, and to obtain mean conditions these observations must be continued over a considerable period, since the range of the tide between springs and neaps varies more than 20 per cent, and therefore the current velocity at the different phases of the moon varies proportionately.

ROTARY TYPE

On the open coast the tidal current is not of the rectilinear or reversing type, with its period of slack water; it is never slack, its direction changing constantly in a rotary movement at a rate of about 30° per hour on the Atlantic coast. In other words, twice in each tidal day the direction of the current changes clockwise to every point of the compass. On the Pacific coast the offshore currents change in direction at a rate varying between 15° and 30° per hour.

Since the rotary tidal currents along the coast are so closely related to tidal action, in that their velocities and directions are comparable with the times of high and low water at some standard port, it is evident that those components of coastal currents, due to tidal action alone, may be as readily and accurately predicted as tides are. Predictions may be made, then, by reference to the times of the tides at some standard port, of the direction and velocity of the tidal current for any moment at any light vessel along the coast.

WIND-DRIVEN TYPE

The problem for the navigator, however, is not so easily solved, for the tidal current is only one of the components of the total coastal currents. The other, due to the local winds, is not only nonperiodic, defying accurate predictions a long time in advance, but in general is also of greater velocity than the tidal currents and therefore proportionately of greater menace to coastwise shipping.

Recent investigations and the comparatively long series of continuous current observations obtained during the past few years at different light vessels along the coasts of the United States have brought out the important fact that, contrary to the belief of the mariner, a local wind creates a current setting not in its own direction but in a direction about 15° to the right of the wind on the Pacific coast and about 20° to the right on the Atlantic coast.

Since a large number of observations of this character are necessary for averages of any degree of accuracy and also for the elimination of tidal current in the resulting data, it is evident that the observations of wind-driven currents have to be made over a considerable period to get a number of winds of 10 miles an hour, 20 miles an hour, etc., from various points of the compass.

While a deflection to the right in the Northern Hemisphere is to be expected from theoretical considerations, due to the earth's rotation on its axis, it is modified along the coasts by configuration of the bottom, bottom friction, and form of the coast line. Therefore, while a general law may be given of the average current produced by any given wind velocity, observations are necessary at intervals along the coast, particularly well inshore, to determine the actual velocities for that particular locality. On sailing lines for coastwise navigation, however, the general law will hold with sufficient accuracy for practical results within 5 to 20 miles offshore. It has been found that the velocity varies fairly proportionately with the wind velocity and is about 2 per cent in knots of the wind velocity in miles per hour on the Pacific coast and 1½ per cent on the Atlantic coast.

The importance of a knowledge that the set of the current is to the right of the wind direction lies in the fact that a wind blowing parallel with the coast produces a current which may tend to set a coastwise vessel onshore, a fact which until now has been unsuspected by the navigator. As an example, a vessel bound up the Pacific coast with a following 60-mile wind will overrun her log, due to wind-driven current alone, by 1.2 knots per hour and be set in toward the land 15° on the average to the right of the wind direction. In practice, of course, it is necessary to take into consideration the combination of this wind-driven current with the periodic tidal current and to apply the resultant for correcting the course made good by a vessel.

Though the total coastal current to which a vessel may be subject is made up of a combination of two components—the periodic or tidal current and the nonperiodic or wind-driven—analysis of a long series of current observations made at any station serves to separate the two, so that a proper correlation may be made between each component and its causes; that is, the velocity and direction of the

tidal current may be referred to the state of the tide at some standard port and the velocity and the direction of the wind-driven current correlated with the force and the direction of the wind prevailing at the time.

PERMANENT CURRENTS

While the main oceanic circulation involves a study of currents which are, in general, produced by predominant winds, such as the trades, and possibly by differences in barometric pressures, densities and temperatures over the oceans, little of a quantitative nature has been done toward a systematic study of these phenomena. In fact, that which has been accomplished may be considered as a reconnaissance only, and volumes may be devoted later to a thorough study of the subject upon obtaining the vast amount of quantitative data necessary to such a study.

The set and drift of these currents have been mapped in a general way; but the principal information is of a qualitative nature obtained from a record of the drift of bottles and of wrecks and from a difference between the true and the dead-reckoning positions of vessels the determination of which does not permit of a high degree of accuracy. But all these furnish qualitative data only, and quantitative data can come only from systematic observations, which may be considered an international rather than a national problem. A further reference to the ocean currents will be found in the chapter on Oceanography.

CURRENT OBSERVATIONS

While the rise and fall of the tide is of considerable importance to the mariner when on soundings, it is of no importance to him over the greater part of the world—the oceans. Currents, on the other hand, must be reckoned with both when navigating inland waters and in keeping account of position at sea by dead reckoning. Unknown or unsuspected currents have undoubtedly been one of the principal contributing causes of many vessel strandings. And in spite of this fact less attention has been given to systematic observations and study of ocean currents than has been given to any other branch of the subject of oceanography.

Three reasons may probably be assigned for this neglect of a phenomenon so closely associated with the subject of tides: Obviously, tidal observations may be made far more economically than current observations for which expensive vessels, with full complement of officers and crew are necessary. Secondly, associated with periodic tidal currents are nontidal currents, which are in general produced by the wind and are nonperiodic. Data for the predictions of tidal currents, since they are periodic, may be obtained from observations extending over a comparatively short period of time, while the nontidal, being nonperiodic, require a considerably longer series of observations to furnish average conditions and to allow of predictions of any degree of accuracy. Again, another reason for this lack of systematic current observations at sea is that the oceans may be considered the highways of commerce for all nations and therefore the study of its problems an international rather than a national undertaking.

The principal maritime nations have made current observations, however, on their inland waters and along their coasts. Predictions are made and published for the use of the mariner of those currents due to tidal action. The Coast and Geodetic Survey has within the last few years given attention to the study of coastal currents, both tidal and wind driven. Current tables have been issued containing information on this subject which is of vital importance to the safeguarding of life and property in coastwise shipping, particularly on the Pacific coast. In the more than thousand miles of Pacific coast line from the Mexican border to the Strait of Juan de Fuca harbors are many miles apart, sailing courses long, and periods of foggy and stormy weather of comparatively frequent occurrence; and it so happens, too, that the currents on the Pacific coast, like the tides, are more complex than those on the Atlantic.

In recent years the Coast and Geodetic Survey has undertaken systematic tidal current surveys of the important waterways of the United States. The results from these surveys, together with results from observations previously obtained in the same localities, are being published from time to time in a series of harbor publications.

While the study of currents is intimately associated with that of the tides, it presents even more complex features. The tide over large areas shows considerable uniformity in time and in range, but the currents within the same region will present striking differences in time, in direction, and in velocity. The investigation of currents is therefore recognized as an important branch of the work of the Coast and Geodetic Survey. In the observation of currents either a current meter or a simple current pole is used. The meter is of the bucket type with a telephone receiver, which permits the number of revolutions to be recorded.

Good results have been obtained in the observations of surface current velocities on the light vessels along the coast by the use of the current line, which consists of the ordinary log line used in the days of the sailing ship for estimating the speed of the vessel, except that it is graduated to a 60-second interval for use with a stop watch instead of a shorter interval, as used with the old sand glass. The sailing ship log is replaced by a pole 3 inches in diameter and 15 feet long, weighted with lead at the lower end to float upright with about 1 foot out of water. The line is graduated for the 60-second interval from the proportion 3,600 sec.: 60 sec.=6,080 feet: X, or 101 feet, 4 inches representing 1 knot. The knot is subdivided into tenths by means of silk fishline tabs.

CURRENT TABLES AND CHARTS

For the purpose of aiding the navigator the Coast and Geodetic Survey publishes annual current tables which include daily predictions of the times of slack water and the times and velocities of the strength of current for a number of important waterways, including San Bernardino Strait, Philippine Islands, and current differences by means of which corresponding predictions may be readily obtained for over 1,000 other stations. In addition to the predictions the current tables include notes on duration of slack, the Gulf Stream, coastal tidal currents, wind currents, the combination of currents, and current diagrams which show the velocities

of the flood and ebb currents and the times of slack water and strength over a considerable stretch of the channel of certain tidal waterways. For economy and convenience to the mariner the current tables are published in two separate volumes—one for the Atlantic coast of North America, and the other for the Pacific coast of North America and the Philippine Islands.

The Coast and Geodetic Survey has commenced the publication of a series of tidal current charts for the more important harbors of the United States.

The publication for each harbor consists of a set of 12 charts which show the hourly direction and velocity of the tidal current. Besides supplying a means of determining at a glance the direction and velocity of the current at various localities throughout the harbor, these charts also present a comprehensive view of the tidal current movement for the harbor as a whole.

Although designed primarily for the mariner, these charts are useful to the engineer, the scientist, and all other persons confronted with the solution of the numerous problems involving the circulation of the tidal waters in our important harbors.

Chapter IX.—TERRESTRIAL MAGNETISM

The magnetic survey of the United States may be said to have had its beginning in 1843, when a plan for the reorganization of the survey of the coast was adopted. This plan included a provision for making "all such magnetic observations as circumstances and the state of the annual appropriations may allow." Up to 1877 the work of the Coast Survey was confined almost entirely to the coast States, and the magnetic observations were in most cases made in conjunction with some other branch of the survey work. With the broadening of the field of its activities, as indicated by the change of title to "Coast and Geodetic Survey" (in 1878), observtions were extended to the interior States, but up to 1899 the progress was slow. In that year an increase of the annual appropriation made it possible to undertake a systematic magnetic survey of the country and led to the formation of a separate division in the Washington office to take charge of the work.

The early magnetic work of the Coast and Geodetic Survey developed in response to the demands of the navigator and the surveyor. The use of the compass has now been extended to the navigation of aircraft. The records of field observations and results obtained at the magnetic observatories are now used by geophysical prospectors who use magnetic methods in the search for oil and minerals, and by those who are investigating the relations of radio transmission to the earth's magnetism and the closely allied phenomena of earth currents and atmospheric electricity.

The primary object of the survey of the coast of a country is to supply the mariner with all the information needed for the safe navigation of the adjacent waters. When no landmarks or heavenly bodies are visible he must depend upon the mariner's compass for his guide. Unfortunately the compass needle does not, in general, point true north, nor is its direction at any particular place constant. In the United States, for example, the compass needle points 22° west of true north in northeastern Maine and 25° east of true north in northwestern Washington. In Maine it now points as much as 8° more to the west than it did 150 years ago. It is evident, therefore, that a knowledge of the compass variation (magnetic declination) is indispensable to the navigator when using his compass.

With iron and steel ships the problem of the navigator is further complicated by the effect upon his compass of the component parts of the ship. The solution of this part of the problem requires a knowledge of the dip (inclination) and the intensity of the earth's magnetic field.

Nearly all of the early land surveys in the United States were made by compass, and the boundaries in the deeds were defined by compass bearings. With the lapse of time and increase of land

values, controversies arose as to the location of boundary lines which had not been marked or of which the markings had disappeared. In order to retrace the lines of a piece of land surveyed originally by compass, the surveyor must know the change in the direction of the compass needle—that is, the change in the magnetic declination in that particular locality between the date of the original survey and the resurvey. The Coast and Geodetic Survey has now collected a large amount of data regarding the secular change of the magnetic declination in this country since the date of the earliest observations and has made a careful discussion of the collected material. As a result it is in a position to furnish the best information available for the settlement of such disputes in regard to boundary lines.

MAGNETIC SURVEY OF UNITED STATES

In view of the difficulties experienced in retracing old compass surveys, accentuated as they were by inferior instruments and often by carelessness or lack of knowledge on the part of the early surveyor, it became important to guard against a similar condition as to present-day compass surveys. This could only be done by determining in detail the distribution of the magnetic declination throughout the country, as well as its change with lapse of time, at the same time providing local surveyors with meridian lines or other means of testing their compasses. When the systematic magnetic survey of the country was undertaken in 1899, the following plan was adopted:

1. The determination of the three magnetic elements—declination, dip, and horizontal intensity—at places 30 to 40 miles apart on the average, distributed over the whole country, followed by a more detailed investigation of areas of local disturbances.
2. The reoccupation from time to time of a sufficient number of "repeat" stations to determine the secular change of the magnetic elements.
3. The operation of magnetic observatories for the control of the field observations, for a more detailed record of the variations of the earth's magnetism, and for the accumulation of the data needed for the study of the nature and cause of the phenomenon.

Following this general plan, the distribution of stations has been based largely upon the county subdivisions of the States and observations have been made at all but about 100 of the county seats, thus making readily available the data needed by the county surveyors to test their compasses. In addition, a number of areas of marked local disturbance have been examined in more detail. About 50 "repeat" stations are occupied each year, the average interval between successive occupations being about five years.

In addition to the work in the continental part of the United States, magnetic surveys have been made of Porto Rico, Hawaii, and the Philippine Islands, and many observations have been made in Alaska, principally along the coast and the Yukon River.

Magnetic observatories of the Coast and Geodetic Survey have been in operation at Cheltenham, Md., since 1901; at Sitka, Alaska, and near Honolulu, Hawaii, since 1902; at Vieques, P. R., from 1903 to 1924; near San Juan, P. R., since 1926; at Baldwin, Kans., from 1901 to 1909; and at Tucson, Ariz., since 1909. At these ob-

servatories continuous photographic records of the fluctuations of the earth's magnetism have been secured.

To supplement the observations on land and extend our knowledge of the distribution of the earth's magnetism beyond the shore lines, some of the vessels of the Coast and Geodetic Survey have been equipped with suitable instruments for determining the magnetic elements at sea. Valuable results have been secured in connection with the regular survey work of those vessels. Because of

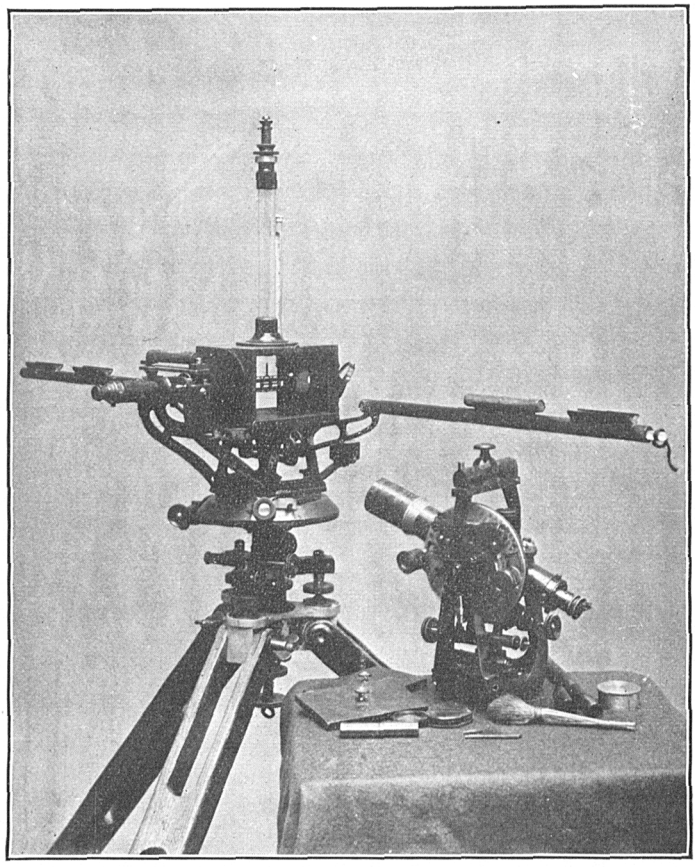

FIG. 27.—MAGNETOMETER (WITH THEODOLITE)

Used to determine the magnetic declination and horizontal intensity; also time, latitude, and azimuth.

the steel construction of the newer surveying vessels, however, magnetic observations at sea are now confined to determination of compass deviations needed in navigating and occasional development of areas of local disturbance in inland waters.

MEASURING THE EARTH'S MAGNETISM

The earth is surrounded by a magnetic field, and the measurement of the earth's magnetism at any place involves the determination of

the direction and intensity of that field. The declination, dip, and horizontal intensity are the quantities usually measured. From them the total intensity and the components in the three coordinate planes may be computed by means of simple formulas.

MAGNETIC DECLINATION

The magnetic declination (often called variation of the compass) is the angle between the true (astronomic) meridian and the magnetic meridian. The direction of the true meridian is usually determined by observations of the sun with a small theodolite, two sets in the morning and two sets in the afternoon. The direction of the magnetic meridian is usually determined with a magnetometer (fig. 27) in which a magnet is suspended by a very fine fiber, so as to be free to turn in the horizontal plane.

DIP OR INCLINATION

The dip or inclination is the angle which the lines of force of the earth's magnetic field make with the horizontal plane. It may be measured by means of a dip circle (fig. 28) in which a magnetized needle is supported so that it is constrained to turn about a horizontal axis. The measurements are usually made when this axis is perpendicular to the plane of the magnetic meridian.

Dip or inclination may also be measured by means of an earth inductor (fig. 29) in which there is a coil of copper wire wound on a cylindrical core. An axis in prolongation of a central diameter of the core rests in bearings in a ring, so that the coil may be rotated by means of a piece of flexible shafting. The ring has an axis at right angles to the rotation axis of the coil, which is supported in a horizontal position on bearings in uprights attached to the alidade. Attached to the ring is a graduated vertical circle, parallel to the axis of the coil, by means of which the inclination of the axis of the coil to the horizon may be read. The current induced in the coil when it is rotated is conveyed through a commutator and brushes to a galvanometer.

The instrument is set up with the coil in the plane of the magnetic meridian. The inclination of the coil is then changed until a position is found in which there is no deflection of the galvanometer when the coil is rotated. The axis of the coil is then parallel to the lines of force of the earth's magnetic field, and the angle of dip is read on the vertical circle.

HORIZONTAL INTENSITY

The determination of the horizontal intensity is made with a magnetometer (fig. 27) and involves two operations, called "oscillations" and "deflections." The observations at a station usually involve two sets of each, arranged in the order: Oscillations, deflections; deflections, oscillations. The oscillations serve to determine the product of the magnetic moment of the suspended magnet and the horizontal intensity; the deflections serve to determine the

ratio of these same two quantities when the magnet which was suspended during oscillations is used to deflect a second magnet suspended in its place.

THE MAGNETOGRAPH

At the magnetic observatories of the Coast and Geodetic Survey the variations of the earth's magnetic field are recorded by means

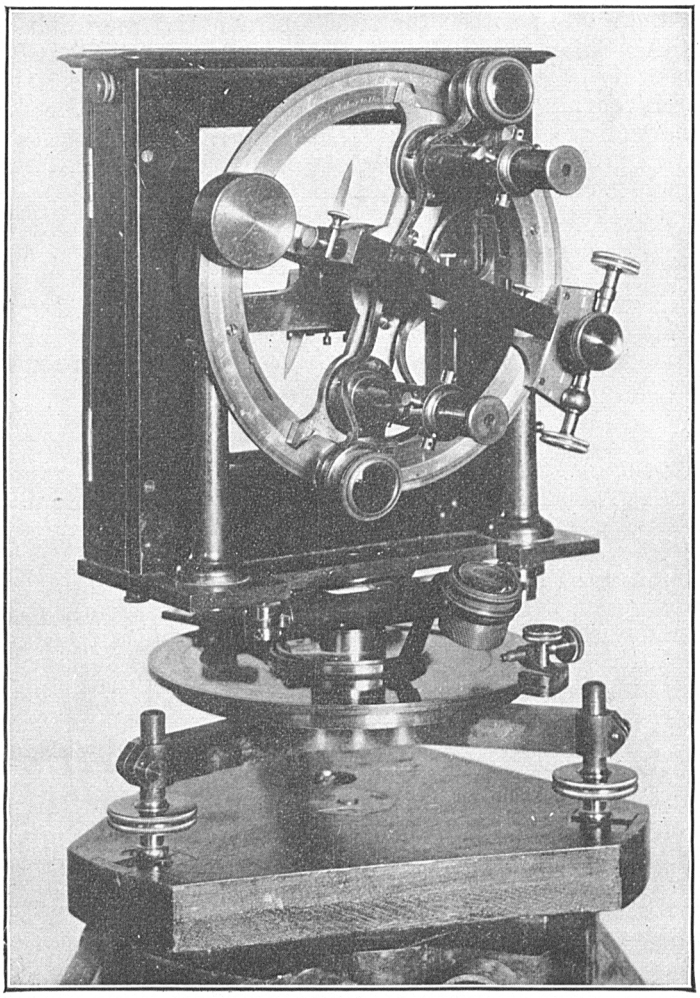

FIG. 28.—DIP CIRCLE

Used to determine the magnetic dip or inclination.

of a magnetograph (fig. 30) consisting of a recording apparatus and three variometers—one for declination, one for horizontal intensity, and one for vertical intensity. In each variometer there is a delicately suspended magnet to which is attached a small mirror. Light from a small lamp is reflected by this mirror to a sheet of sensitized paper wrapped around the drum of the recording

apparatus. This drum revolves once in 24 hours, and the spot of light traces an irregular line on the paper. The varying distance between this and a straight line made by the reflection from a fixed mirror measures the variation of the magnetic element which that variometer is designed to record. Observations are made at regular intervals to determine the scale value of the variometers and the absolute values corresponding to the straight lines, the so-called base-line values.

The buildings in which the magnetographs are mounted are so constructed that outside changes of temperature are transmitted to the interior very slowly. In this way the diurnal variation of temperature inside seldom exceeds two or three tenths of a degree, and the seasonal changes are reduced and smoothed out.

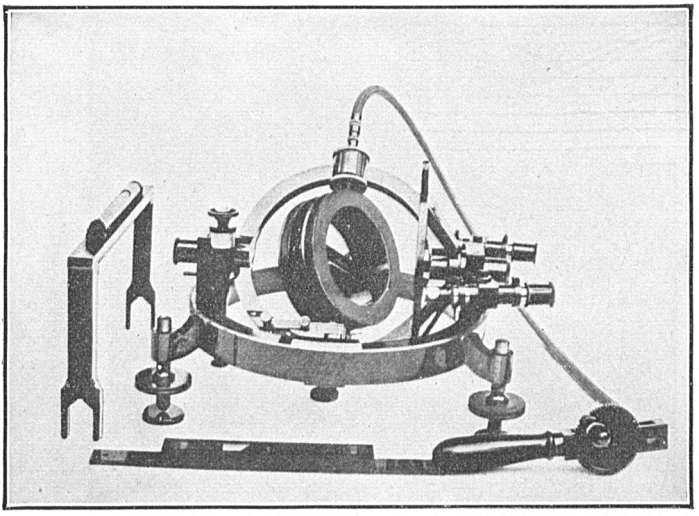

FIG. 29.—EARTH INDUCTOR

Used to determine the magnetic dip or inclination.

PUBLICATION OF RESULTS

It is the policy of the Coast and Geodetic Survey to publish the results of the magnetic observations as promptly as possible, so that they may be available for general use by the public. They are published in various forms:

1. On every coast chart, the value of the compass variations for one or more positions for a specified year, and the annual rate of change are given. Similar data for prominent points along the coast are given in the various Coast Pilots.

2. The results of the field observations, together with brief descriptions of the stations occupied, are published annually as separate publications.

3. About once in five years, an isogonic chart is issued on which the distribution of the magnetic declination for a specified year is shown graphically by means of lines of equal magnetic declination. This chart is accompanied by secular change tables showing the

change of the magnetic declination since the earliest available observations at one or more places in each State. With the aid of these tables the surveyor can determine the change of declination for which he must make allowance when attempting to retrace the lines of an old survey.

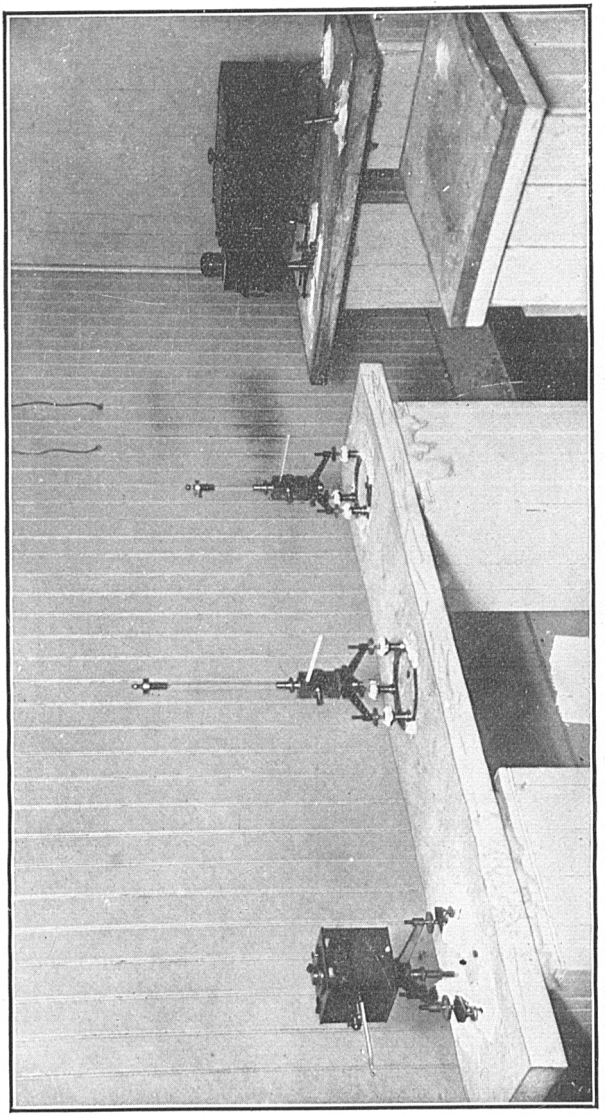

FIG. 30.—MAGNETOGRAPH

Used to secure a continuous photographic record of the variations in the declination, horizontal intensity, and vertical intensity.

4. About once in 10 years the accumulated results have been published collectively, together with corresponding reduced values for a specified year. These tables are accompanied by maps, on which the distribution of the declination, dip and horizontal intensity, vertical intensity, and total intensity are shown graphically by isomagnetic lines.

5. The observatory results are published every two years and include values of declination, horizontal intensity, and vertical intensity for each hour, maximum and minimum values for each day, daily means and hourly means for each month, tables showing the average diurnal variations of the magnetic elements and components for each month, reproductions of the magnetograms showing the more marked magnetic disturbances. Earthquake tabulations, which were included in these publications through 1924, are now published in the quarterly seismological report.

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Chapter X.—NAUTICAL CHARTS AND AIRWAY MAPS

Nautical charts are designed primarily for the use of the navigator. They also serve in other ways the interest of commerce, and are valuable for military defense, planning harbor improvements, the study of physical hydrography, and the problems of oceanography.

Three bureaus of the Government are authorized to publish nautical charts, but under restrictions which define the duties of each and prevent duplication: The Coast and Geodetic Survey in the Department of Commerce, the Hydrographic Office in the Navy Department, and the Corps of Engineers in the War Department.

The Coast and Geodetic Survey is charged with surveying the coasts of the United States and the coasts under its jurisdiction, with researches to determine the origin and courses of the great ocean currents known as the Gulf stream and the Japan stream, and from these surveys to issue charts suitable for the purposes of navigation, commerce, and the public defense. The Hydrographic Office is authorized to republish charts issued by other nations and to publish charts based on surveys by our Navy of coasts not under the jurisdiction of the United States. The Corps of Engineers surveys the Great Lakes and issues the charts necessary for their navigation.

EXTENT AND CHARACTER OF CHARTS

For purposes of navigation, nautical charts may include large areas like one of the oceans or seas, showing the shores and outlying dangers, and perhaps indicating the principal currents and winds. Charts may also embrace much smaller areas, on larger scales, permitting greater fullness of detail, and thus presenting graphically the channels that can be followed, with the depth of water, the position of lights, beacons, and buoys, together with sufficient topography to enable the mariner to identify the locality as he arrives in sight of land. The largest-scale charts are generally those of harbors, and exhibiting, as they do, all the important details, including topography, are of great value to the engineer for the study of physical conditions with a view to the improvement and military defense of the harbors.

To supply the different needs of the navigator, the Coast and Geodetic Survey issues various series of charts. On the Atlantic coast, for example, there are four distinct series. In three of these series the charts are located so that each chart overlaps the edges of the adjacent charts in the same series. In this way the entire coasts are charted on three different scales.

SAILING CHARTS

In the first series, known as sailing charts, the scale is small and each chart embraces a long stretch of coast. They are intended for the use of the navigator in fixing his position as he approaches the

coast from the open ocean or when sailing between distant coast ports. They show the offshore soundings, the principal lights and outer buoys, and such natural landmarks as may be visible from a considerable distance at sea.

GENERAL CHARTS

Charts in the second series are called general charts of the coast. Their scale is three times as large as that of the sailing charts, and each chart covers a more limited area. They are employed for coastwise navigation when the vessel's course would be mostly within sight of land, with her position fixed by landmarks, lights, outer buoys, and characteristic soundings.

COAST CHARTS

Charts in the third series, called coast charts, are constructed on a scale five times as large as the general charts of the coast. One inch on these charts represents about 1 nautical or 1¼ statute miles. Such charts are necessarily confined to short stretches of coast, and they are made for close coastwise navigation where a vessel's course would carry her inside of outlying reefs and shoals. They are the ones best suited for entering bays and the larger harbors and for navigating the large inland waterways.

HARBOR CHARTS

The fourth series consists of harbor charts on large scales, intended to meet the needs of local navigation. Harbor charts are not laid out on a uniform scale and according to a rigid system, as is the case in the first three series. Hence, they will be found on several scales and, generally, each chart having no connection with any other one. These charts are much fuller in hydrographic and topographic details than are the charts of the other three series, and therefore serve a variety of interests, in addition to navigation, for which the other charts would not suffice on account of lack of information.

CHART-MAKING MATERIAL

The various field activities of the Coast and Geodetic Survey are carried on to supply the information needed to prepare the charts, and to supplement their use with the aid of Coast Pilots, tide tables, etc. All the field data are sent to the Washington office (or, in the case of the Philippine Islands, to the Manila office), where the triangulation and other geodetic and magnetic work and the tidal data are examined by expert mathematicians who make the necessary adjustments to connect them with work already done.

Hydrographic and wire-drag surveys are always unfinished when received from the field, owing to the necessity of supplying certain information and checks which can be done only in the office. Expert cartographers there complete the plotting, inking, and verification of these sheets.

To one not acquainted with the subject it will be a surprise to learn how much original survey material and published data enter

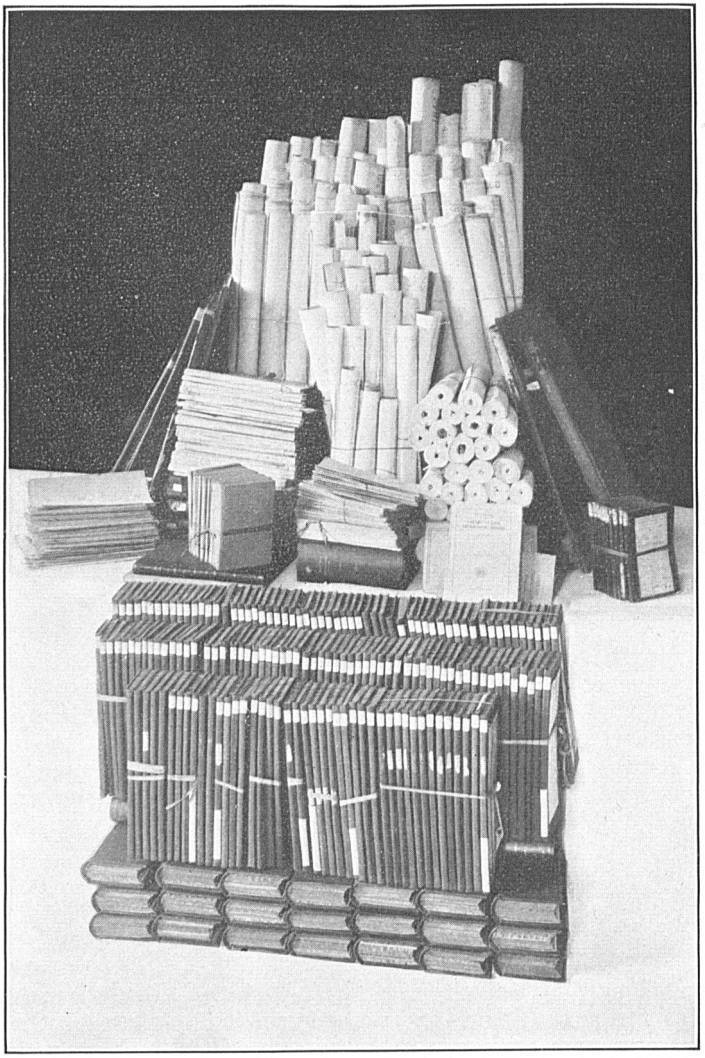

FIG. 31.—RECORDS USED IN COMPILING A COAST AND GEODETIC SURVEY CHART

This illustration shows the 469 field-survey sheets, sounding and tidal records, and volumes of data required to supply information for the production of a single chart.

into the preparation of a chart. The following statement shows the material used in preparing one of the Alaska charts and is well below the average in the quantity of material required:

Material used in constructing a typical Coast and Geodetic Survey chart

Chart No.	Approximate area (square miles)	Original material				Compiled material		
		Volumes of field records	Topographic sheets	Hydrographic sheets	Surveys by other organizations	Larger-scale C. & G. S. charts	Foreign charts	Volumes of Coast Pilots, Light Lists, etc.
8102	1,600	1,000	102	124	17	10	5	8

PROJECTIONS

The surveys and other field data having been examined and adjusted, the preparation of the chart may be started, the first step being the construction of a projection. This is the term applied to the framework of lines found on nautical charts and which represent the parallels of latitude and meridians of longitude. Sometimes, for the sake of simplicity, only the intersections of these lines are shown on the body of the chart.

Owing to the curvature of the earth's surface, it is not possible to represent it upon a plane surface, such as a sheet of paper. without introducing some distortion and the sacrifice of some desirable quality. Many different types of projection have been devised, but, with the exception of a few special charts and airway maps, the Coast and Geodetic Survey employs only two kinds—the Mercator and polyconic.

Mercator projection.—The Mercator projection is used for the principal charts of the coast and for all oceanic areas. The meridians of longitude are represented by parallel straight lines and the parallels of latitude by straight lines separated by spaces that increase between successive parallels when proceeding from the Equator toward the poles.

A glance at a globe will show that the actual distances between the meridians on the earth's surface diminish as one goes toward the poles, while there is practically no difference on the earth between the parallels. It is evident, therefore, that the scale of a Mercator chart becomes larger and larger toward either pole. This variable scale, which increasingly exaggerates all details as one gets farther from the Equator, constitutes the principal drawback to this projection. It has, however, certain advantages for the navigator that are not found on other projections.

Polyconic projection.—The use of this projection is confined mostly to surveying purposes. It possesses an advantage over the Mercator and most other projections in that it shows the directions and distances of all points in their correct relation to each other, provided the projection is not extended over too large an area. Formerly this projection was used for many of the charts published by the survey, but such charts are now being replaced by others on the Mercator projection as rapidly as existing facilities permit.

CHART CONSTRUCTION

The chart is constructed on Bristol board mounted on an aluminum plate. This eliminates the expansion and contraction that paper undergoes with varying atmospheric conditions and results in a finished compilation free from distortion. The Bristol board is mounted so that after the projection lines are laid down the plate may be cut into sections for convenience in handling. The sections may also be placed in the hands of several cartographers to hasten the completion of the compilation.

With the projection as a framework and guide for their proper location, the details of the land area are taken from the topographic field sheets. If the chart is on a large scale, such as a harbor chart, where it is desired to show every detail, an exact copy of the field sheet may be taken. If, however, the chart is on a small scale, minor details are omitted and others are generalized.

To show the depths on the water areas of the chart, the soundings are taken from the hydrographic field sheets and correctly located, as in the case of the topography, with reference to the meridians and parallels. For the sake of clearness a selection is made from the closely spaced soundings on the field sheet, only those soundings being used which are necessary to plainly show the configuration of the sea bottom. On large-scale charts the outline of the bottom is shown in minute detail, as was done in copying the topography. The smaller the scale, the greater the generalization and the larger the number of details omitted.

In addition to the representation of hydrographic and topographic features, the charts contain much information in condensed form relative to the variation of the magnetic compass, tides, currents, meteorology, and descriptive notes concerning channels, dangers to navigation, and other related subjects.

The names are now placed on the drawing, which is then turned over to another cartographer, who verifies every detail, paying especial attention to those features whose omission or misplacement might result in disaster to the navigator.

At this stage, the chart is known technically as a rough drawing or compilation; rough, however, only in the sense that pains were not taken to make the lines smooth or the figures and letters well-shaped, as they will finally appear on the printed chart. The work is the product of the engineer rather than of the artist.

REPRODUCTION

The chart is now ready for reproduction. This embraces numerous steps before the chart is finally ready for issue. The first step is to reproduce the compilation by some method that will give an exact copy but with the uneven lines, letters, and symbols changed to the fine, smooth, artistic quality required by the conventional style and standards of the Coast and Geodetic Survey. This is accomplished by any one of the following methods: (1) Engraving on copper, (2) drawing, (3) lithographic process.

The method selected for each new chart is largely a matter of expediency. With the present organization of the chart division,

that method is chosen which will result in a maximum output and the earliest publication of the chart. The first method is used where there is on the chart a large proportion of conventional symbols, as marsh and sanding, which can be cut mechanically. The second method is used only to a limited extent and in time will probably be discarded. The third method is one recently developed. It eliminates several of the operations necessary in the first method, admits of the use of mechanical devices, and results in a chart, as it leaves the press, that is freer from distortion than does any other method as yet devised.

ENGRAVING

The first step in the engraving method is to construct on the copperplate the projection (lines of latitude and longitude) of the chart that is to be reproduced. The compilation of the chart is then photographed in sections to secure negatives for use as matrices. With the use of transparent celluloid and wax, a copy of the compilation from the matrices is laid down on the copperplate, a small area at a time, each area being fitted into place by fitting the projections from the matrices to the projections on the copperplate. This transfer is then stained on the copper with the fumes of ammonium sulphide, thus affording the engraver an exact copy of the compilation from which to work.

The work is then engraved on the plate, each detail being reproduced exactly in the position it occupied in the compilation. In this engraving the artistic quality, which as we have already noted was lacking in the compilation, is added.

Most of the work of the engraver is done by hand. Some parts, however, such as the soundings and certain conventional symbols, are cut by mechanical appliances. In engraving the chart the same care that was used in making the compilation is exercised to insure absolute accuracy.

When the engraving is finished, an impression is pulled from the plate, verified by an engraver, and any necessary corrections made. Another impression is then pulled which receives a thorough verification by the cartographer.

To hasten the engraving of large charts, when desirable, the projections are so constructed on the plate as to permit cutting the copper into four sections. Thus, four engravers can work on the same chart simultaneously.

In engraving the chart the title, notes, compasses, and outside borders are omitted. These are added in another step of the reproduction, not to the chart on the copperplate, but to the chart when it is photographically processed to an aluminum printing plate, as explained later in this chapter.

When the plate is finished and found to be correct in every detail it is turned over to the electrotyper, who produces an "alto," which is stored for future use. This is desirable because later changes to the plate in the form of erasures can be more readily made on an alto from which a new basso is produced by electrotyping. This shows in blank the area where the erasure was made.

DRAWING

When the drawing method is selected for reproducing the compilation, the compilation is made with pencil, which permits the draftsman to redraw the chart on the same paper, changing the uneven lines of the compilation which is in pencil into smooth, even work in ink, correctly interpreting the drawing of the engineer in the application of the conventional symbols and producing a chart of the standard required by the Coast and Geodetic Survey. Lettering and names that appear on the compilation are set up and printed in special type conforming to the standard of the chart, and then clipped and pasted in position on the chart. All of the soundings, sanding, symbols, etc., are drawn by hand.

In this method, also, the title, notes, compasses, scales, and seal are omitted, to be added, at a later step, to the lithographic printing plate.

A thorough verification of the drawing is made by the cartographer, any necessary corrections are made, and the finished drawing is advanced to the next step in reproduction and becomes the copy for the making of negatives used in the process of producing the lithographic printing plate.

LITHOGRAPHIC PROCESS

In this method each section of the compilation is photographed to wet plate negatives, great care being taken to maintain on the negative the exact scale of the compilation.

These negatives—usually four in number for the average chart—are coated on the film side with asphaltum, which is allowed to dry. This coating permits the compilation to be clearly seen when the negative is placed on the lithographic draftsman's easel but destroys the printing qualities of the negatives.

The reproduction of the compilation is then accomplished by the lithographic draftsman, the four negatives permitting four draftsmen to work on the chart at the same time. The asphaltum-coated negative provides the draftsman an ideal copy of the compilation on which to work.

The draftsman cuts the lines, lettering, symbols, etc., of the chart through the asphaltum, using steel points of varying sizes. Thus is produced, as in the previous methods, a chart of artistic quality conforming to the conventional style and the standards of the Coast and Geodetic Survey.

The soundings (figures representing depths), the marsh ruling, and the lettering which show the bottom characteristics are cut on the negative with mechanical appliances.

When completed the negatives are carefully verified and any necessary changes are made. The negatives are then ready for the making of the lithographic printing plate.

The seal, title, notes, compasses, and scales of the chart are omitted in this method also, to be added later to the lithographic printing plate.

PLATE PRINTING

Formerly it was the custom of all nautical chart-producing organizations to print the charts directly from engraved copper plates. Engraving has been a familiar art for many years, whereas lithographic printing is of comparatively recent development. Even to-day there is no other method available which produces such sharp, clear outlines and such legibility of minute detail as that obtained in an impression from a good copper plate.

The method, however, is a slow and laborious one. Most of the work must be done by hand, with the result that two men operating one press can print only from 80 to 100 charts a day. Obviously, therefore, the method is not suited to quantity production. The method used also causes considerable distortion of the resulting print which, in a product of this character, it is very desirable to avoid. For these reasons the method of printing direct from copper plates has been discarded in general by the Coast and Geodetic Survey. A few charts are still printed direct from the copper plates, but these are confined to charts of remote or unimportant localities for which the demand is so limited that only a few need be printed at any one time.

LITHOGRAPHIC PRINTING

In the Coast and Geodetic Survey lithographic printing is done from aluminum plates on which the charts have been reproduced by the photographic process.

PHOTOLITHOGRAPHIC REPRODUCTION OF ENGRAVED CHARTS

This method was developed by the Coast and Geodetic Survey, which considers it, for this specific purpose, materially superior to any of the processes heretofore in use. By this method the work engraved on the copper plate can be transferred to an aluminum printing plate without distortion or change of size and printed on the lithographic offset press.

An extremely highly finished Baryta paper is used for securing an impression from the engraved copper plate, in a manner developed by the survey and explained as follows: Before the impression is taken from the copper plate the Baryta paper is coated on the back with a solution made of gelatin, flour, starch, and water; the paper thus coated is allowed to dry before using. It is then placed between damp sheets of paper in preparation for the impression. As the moisture of the damp sheets prepares the face of the paper for the impression it likewise dampens the solution on the back and makes it tacky.

In pulling the impression the paper is laid face down on the copper plate. Over this, in contact with the tacky back, is laid a heavy sheet of blotting paper. When run through the press the heavy pressure causes the two papers to stick firmly together; the blotting paper absorbs the moisture of the Baryta paper and its texture prevents shrinkage.

The result is a sharp, intensely black impression, furnishing an ideal subject for photolithography, with the distortion which heretofore existed in charts which were produced either directly or indirectly from copper plates largely eliminated. From this point the process is the same as that for the reproduction of drawings, described in the following paragraphs.

PHOTOLITHOGRAPHIC REPRODUCTION OF DRAWINGS

The drawing of the compilation in ink becomes the subject from which negatives used in photographic process printing are made. The subject is photographed in sections, from one to four negatives being made, depending upon the size of the chart. These reproduce every detail and are exactly of the scale of the drawing. In this work the skill of the photographer is taxed to obtain the greatest possible sharpness and definition and to secure negatives which fit each other exactly, so that when laid down side by side each line exactly joins its continuation on the adjacent negative. The negatives after retouching are exposed on a sensitized aluminum plate, with the result that when developed and properly treated the drawing is reproduced as a positive on the printing plate.

PHOTOLITHOGRAPHIC REPRODUCTION BY THE LITHOGRAPHIC PROCESS

In this method the negatives of the compilation, as prepared by the lithographic draftsmen (explained under "Lithographic process"), are used. From these negatives the printing plate is produced in the same manner as described under "Photolithographic reproduction of drawings."

Seal, title, notes, compasses, and scales are made up from standard forms. Negatives are made of these, and during the photographic process of making the lithographic printing plate they are exposed in the proper place on the aluminum plate.

PRESSWORK AND FINAL DETAILS

The final step in preparing the chart, irrespective of the method by which it is to be printed, is the drawing of the symbols of the lighthouses and buoys where they belong. The application of this information is delayed until the chart is ready to go to press, for the reason that changes in these aids to the navigator necessarily are made with considerable frequency, and it is essential that all these details be correct on the date when the chart is issued.

Over 96 per cent of Coast and Geodetic Survey charts are now printed by lithography. Of these over 93 per cent are printed offset; that is, the paper does not come in contact with the aluminum printing plate, but instead the impression is made on a rubber blanket from which it is offset to the chart paper. This process gives sharp and unbroken lines.

The offset process is used for the black, which is, in fact, the chart. Colors are used to accentuate certain features such as the red buoys and, on small charts, the lights. The land is covered by a tint and, on some charts, shoal waters are tinted blue. The

object is, of course, to improve legibility. Both rotary and flat-bed presses are used for colors.

NEW EDITIONS OF CHARTS

In most cases only a short time elapses after a new chart has been printed before it needs revision to keep it up to date. This will be understood when it is stated that there are over 16,000 lighthouses, beacons, and buoys maintained along our coasts, and among these there were over 1,300 changes within a year. Further, the river and harbor improvements, under the Corps of Engineers, result in deeper and wider channels or new breakwaters, which must be noted on the charts. The charts must also keep pace with the changes in the water fronts of harbors and the growth of cities and towns along the coast, so that the navigator will be able to identify his position on the chart by reference to these objects.

Besides these changes due to the works of man, the great natural agencies are also constantly at work altering the features shown on the charts. The action of currents and waves is continually cutting away or building up the shore, particularly on sandy coasts exposed to storms, and while these visible effects on land are being produced, others even more important are going on beneath the surface of the water; channels and shoals shifting, new ones coming into existence, or old ones disappearing.

All these changes from the various sources indicated give an idea of the problem of keeping a chart up to date and why it is necessary to print small editions and revise the charts frequently.

The charts of the Coast and Geodetic Survey are sold to the Public at a price which is estimated to cover only the cost of paper and printing. The main purpose in selling the charts at this low rate is to encourage the use of the latest editions, the employment by mariners of an old chart, instead of the latest edition, being highly hazardous. A number of vessels have been lost solely because old charts were used. At present about 700 different charts of the waters under the jurisdiction of the United States are being published, and the number of copies issued during the fiscal year ended June 30, 1929, was 238,561.

A nautical chart is essentially a diagram for practical use by navigators. All ornamentation and unnecessary details are studiously avoided. The symbols employed to represent the various features are the result of many years of experience. To aid in interpreting the hydrography and to make plain the shoals and passages, depth curves are given on the charts. The shoaler areas are made conspicuous by the use of fine dots (sanding), and frequently a blue tint is used for the same purpose.

AIRWAY MAPPING

Under the air commerce act of 1926 the Secretary of Commerce delegated to the Coast and Geodetic Survey the duty of making the maps of the civil airways of the United States for the guidance of aviators. This was undertaken in November of 1926.

Two series, strip maps, and airway maps are being constructed, both to the scale of 1:500,000, or about 8 miles to the inch. The

strip map covers an area 80 miles wide along the established airways, while the airway maps designed for general flying will be a series of about ninety sheets of convenient size which will cover the entire United States.

These maps show streams, roads, railroads, towns, and elevations, and emphasize airports, auxiliary landing fields, beacons, high-tension lines, and courses. They are compiled from topographic maps of the United States Geological Survey, highway, post route, State, and county maps, and information supplied by organizations and individuals. Flights over the area are made to check the accuracy of the compilation.

The bureau is the distributing agency for these maps as well as the strip maps of the Air Corps of the United States Army. The price is uniform at 35 cents a copy, with a reduction of 10 cents a copy on orders for 20 or more.

Chapter XI.—COAST PILOTS

Coast Pilots are published to supplement nautical charts. They furnish the mariner with a wide variety of important information, much of which is of such a character that it can not be placed conveniently on a chart. They contain descriptions of practically all important features along the coast and are carefully indexed. Each Coast Pilot volume thus serves as a geographical directory of the area it covers. The principal maritime nations of the world publish information and directions of this character for the use of mariners.

As early as 1796 a volume known as The American Coast Pilot (the first Coast Pilot published in America,) by Capt. Lawrence Furlong, was published in Newburyport, Mass., by Edmund M. Blunt, and the first edition met with so ready a sale that a second edition of the same work was published in 1798. Coast pilot information, however, can not be collected by private enterprise, except at great cost and with imperfect means, and at the present time all the private publications containing such information relative to the coast of the United States are compilations from Government publications and are generally based on the work of the Coast and Geodetic Survey.

CONTENTS

The Coast and Geodetic Survey publishes 12 Coast Pilot volumes covering the coasts of the United States, Porto Rico, and the Virgin Islands, Alaska, Hawaiian Islands, and the Philippine Islands. The information contained in each volume is usually given under three main headings, as follows:

GENERAL INFORMATION

This section gives a general description of the coast and information concerning pilots, quarantine, weather, radio service, Coast Guard stations, tides, currents, etc.

DESCRIPTIONS AND SAILING DIRECTIONS

This section contains detailed nautical descriptions of the coast and harbors, including information relative to depths, facilities for obtaining supplies and repairs, wharfage, anchorages, special rules and regulations, etc., and sailing directions for navigating along the coast and entering all harbors.

APPENDIX

In the appendix are included a discussion of navigational aids and the use of charts, and miscellaneous information such as navi-

gational rules, general harbor and anchorage regulations, and meteorological tables.

Each Coast Pilot also contains an index map showing the limits of the charts covering the region treated in the volume and in many cases views of important landfalls, landmarks, and lighthouses.

In addition to the Coast Pilots, the Coast and Geodetic Survey also publishes three Inside Route Pilots. These cover the inland waterways along the coast of New Jersey, along the Atlantic coast from New York to Key West, and along the Gulf coast from Key West to the Rio Grande. These volumes contain descriptions and directions for the various routes and are especially arranged to meet the needs of navigators of small craft who make extensive use of the inside passages along the coast. Each volume contains a set of route charts on which the main routes are indicated by red lines.

COMPILATION

The compilation of coast and inside route pilots necessitates work both in the office and field. Office work consists of the collection of the latest data from the field records and special reports of the surveying parties of the Coast and Geodetic Survey, from the reports and surveys of the United States Engineers engaged in the improvement of harbors and waterways, and from numerous other sources of information.

The compiler of a pilot volume then takes up a comprehensive field examination of the region covered by the pilot. Every part of the coast treated in the volume is visited; the information collected in the office is verified and, if necessary, corrected on the spot; such additional artificial aids and natural landmarks as are of use to the mariner are noted; hydrographic examinations of reported dangers and changes are made; and pilots, shipmasters, and all other persons or organizations with local knowledge are interviewed in order that information may be obtained from every available source.

On return to the office from the field the manuscript for the volume is prepared, edited, and sent to the printer. Proof sheets of the text are then revised to include information relative to changes and corrections received after the completion of the manuscript, and the pilot is then printed and issued to the public.

SUPPLEMENTAL INFORMATION

As the coast covered by the various pilots are subject to constant change, it is obvious that the text of each volume must be corrected at frequent intervals if it is to furnish the mariner with up-to-date information. To maintain these publications in the most useful form corrections are therefore issued in the Notice to Mariners, a joint publication issued weekly by the Bureau of Lighthouses and the Coast and Geodetic Survey.

At intervals of about one year a supplement containing all available information regarding changes and corrections is issued for each volume. Supplements are printed on one side of the paper only and are in convenient form for insertion of clippings at the proper points in the pilot volumes.

In some cases important information that can not be completely given in the Notice to Mariners is published in one or more correction sheets issued during the intervals between the annual supplements.

After a period of from four to six years, when the corrections to a pilot volume have assumed proportions that impair its usefulness and when it is probable that a sufficient number of unreported changes have occurred, a new edition of the volume is compiled and issued.

Coast and Inside Route Pilots are published and issued by the Coast and Geodetic Survey at the cost of printing and binding. Each volume when sold is accompanied by the latest supplement and correction sheets. Supplements and correction sheets are also furnished without charge, upon request, to previous purchasers of a pilot volume.

Chapter XII.—OCEANOGRAPHY

The primary interest of the Coast and Geodetic Survey in oceanography is well defined as being solely connected with the physical characteristics of the ocean as distinguished from the life of the ocean.

These physical characteristics have been divided by some oceanographers under two general headings: First, static oceanography, including the temperature, density, and chemical properties of water, depth, and character of bottom, etc.; second, dynamic oceanography, including such phenomena as tides, currents, waves, etc.

The first oceanographer in the United States was Benjamin Franklin. This is evidenced by an excellent map of the Gulf Stream published in 1770 from information received from American whalers and merchant ship captains.

The first oceanographer of the Coast and Geodetic Survey was Lieut. George M. Bache, who was a direct descendant of Franklin. Lieutenant Bache, while engaged on deep-sea exploration in the Gulf Stream off the coast of Virginia, was washed overboard from the United States Coast Survey brig *Washington* and lost with 10 members of his crew on September 8, 1846.

Our present knowledge of oceanic depths adjacent to and along the steamer tracks between our Atlantic and Pacific coast ports, including the approaches to the Panama Canal, has since the termination of the World War been amplified to a large extent by the Coast and Geodetic Survey's vessels returning to their stations on the Pacific coast.

During the latter part of 1923, the Coast Survey steamer *Guide*, in making the trip from the east to the west coast of the United States via the Panama Canal, obtained very valuable information. On this trip, for the first time, the sonic depth finder was used by a Coast Survey vessel to obtain depths. Data were accumulated which proved extremely useful in the determination of the velocity of sound in water under different conditions of temperature, salinity, density, etc. The comparison of the depths obtained by the usual method of wire measurement and by the method of accurately measuring the time interval for sound to travel from the surface to the bottom and return, as measured by the sonic depth finder, was in excellent agreement.

OCEAN DEPTHS

It so happens that some of the greatest known depths of both the Atlantic Ocean and the Pacific Ocean are located in waters adjacent to islands belonging to the United States. In the Atlantic, north of Porto Rico, a sounding of 4,662 fathoms (27,972 feet) has been obtained, and in the Pacific, off the east coast of the Philippines, the ocean bottom is below the level of the sea a distance of 5,348 fathoms, or 32,089 feet.

The greatest known depth of all the oceans was measured by the German cruiser *Emden*. While en route from Celebes Island in the Dutch East Indies to Nagasaki, Japan, an ocean depth of 34,416 feet, or about 6½ land miles, was discovered and recorded. This is a depth greater by 5,414 feet, or more than a mile, than the greatest known height of the Himalayas. Prior to this the greatest depth known was 32,644 feet, off the eastern coast of Japan.

To obtain measures of the great ocean depths, several successful sounding machines have been perfected. Recently a sounding machine was designed by the Coast and Geodetic Survey which has proven very satisfactory and with which all vessels of the survey are equipped. This machine is a great improvement over the sounding machine designed by Sigsbee, which had been successfully used for a number of years.

The successful use of the sonic depth finder in deep-sea soundings has made possible the obtaining of depths at a very much reduced cost, but this apparatus can not entirely supplant the sounding machine for oceanographic work, as temperatures of the water, character of the ocean bottom, salinity of the water, etc., which are important physical phenomena, must still be obtained by the use of wire soundings.

All deep-sea sounding machines are dependent on the use of a very fine steel measuring wire with a heavy detachable shot as a sinker. The amount of wire passing over a recording measuring wheel gives the depth in fathoms or meters as may be desired. This sinker and wire are allowed to run out from a revolving drum with all freedom possible, but even under the best conditions it takes, for example, a full half hour for the shot to reach bottom at 3,000 fathoms; and in greater depth the time of falling of the shot and wire is rapidly increased by the friction of the longer wire.

Nothing is so impressive of the magnitude of the depths of the ocean as the watching, second after second, minute after minute, for a half hour or more, the rapidly revolving drum from which the sounding wire is unwound in its downward fall; and when the bottom is struck and the shot is automatically detached, as indicated by the slight slackening and tremor of the wire conveyed to the surface, there comes a sudden realization of the 3 or 4 miles of elevation of the observer above the bottom of the ocean.

TEMPERATURES

Oceanographic temperature observations are made on a larger and stronger wire than that used for soundings, a series of specially devised self-registering reversing thermometers being secured to the wire at different points as it is lowered.

When the lower end of the wire is at the desired depth, a weight, called a messenger, is started down which not only causes the first thermometer to reverse, but also releases a second messenger which is attached to it. The second messenger then continues its journey to the second thermometer, which it both reverses and causes to release a third messenger, and so on for a period of a half hour or more until the last thermometer of the series has registered its temperature by capsizing.

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OCEAN CURRENTS

A statement of oceanography as connected with the work of the Coast and Geodetic Survey would be incomplete without some mention of the study and investigation of the great ocean river known as the Gulf Stream. To this work, under special authorization by Congress, much time and energy has been devoted, as is shown by the many publications giving the results and discussion of the work of such oceanographers as Bache, Pourtales, Mitchell, Sigsbee, Pillsbury, and others. The work of the United States Coast and Geodetic ship *Blake*, under the command of Sigsbee and Bartlett, is particularly well known through the two volumes of Agassiz issued under the title "Three Cruises of the *Blake*."

To measure ocean currents at the surface, where the depths are not too great to anchor a ship by ordinary means, is a comparatively simple undertaking. At greater depths, it is a problem that has not been satisfactorily solved, although Pillsbury, in his famous investigations of the Gulf Stream, while in command of the United States Coast and Geodetic Survey ship *Blake*, succeeded by the use of specially designed machinery in anchoring the *Blake* at a depth of 2,100 fathoms (12,600 feet).

The measurement of surface currents involves the measure of the motion of a suitable floating object, in direction and velocity, in reference to a fixed point. But underwater measurements involve not only the register of a revolving wheel representing the velocity of the movement of the water but also the register of the direction of the movement as measured by some form of a compass. Several very ingenious current meters have been devised that will accomplish this purpose, but they are too complicated for an adequate description in this present publication.

OCEAN TIDES

The subject of tides, as connected with the work of the Coast and Geodetic Survey, has been described in a separate chapter under that heading, but it has one phase which is so clearly one of oceanography that it may be briefly mentioned. It relates to the question of the origin or cause of the dominant tides as developed in the Stationary Wave Theory of Tides, by Dr. Rollin A. Harris, of the survey.

From the viewpoint of the ordinary student the problem of the tides is one that was settled in its main features as long ago as the discovery of the laws of gravitation by Newton. As a matter of fact, it is only in recent times that anything like a satisfactory explanation of the dominant ocean tides has been developed in a practical form. The reason assigned for this is that "definite or applicable theories concerning the causes of existing tides were impossible before the depths of the oceans had become generally known."

Knowing the depths and the shape of the ocean basins, knowing the laws of the oscillating movements of water in such basins, and knowing the laws of the action on the oceans of the tide-producing forces of the moon and sun, it is theoretically possible to calculate the character and extent of certain great stationary waves, extending from continent to continent, or otherwise as the shape of the ocean

basins may demand, whose period of oscillation shall correspond to and be maintained by the periodic action of the tide-producing forces.

That such oscillating oceanic waves do exist had been surmised for some time, but it was left to Harris by his development of the cotidal lines of the oceans and the dynamic laws of the fundamental movements of ocean waters to demonstrate that the Stationary Wave Theory of Tides is in accordance with the actual observations of the phenomena of the rise and fall of the tides.

OTHER PHYSICAL PHENOMENA

Other physical phenomena of oceanography within the province of the Coast and Geodetic Survey, such as the salinity, density, and composition of sea water, etc., are many and constantly increasing as the subject of oceanography is enlarged on its many sides.

Apparently there is no sphere of both scientific and practical endeavor which is at the same time so vast and so little exploited as that of oceanography. In fact, the great depths of the oceans with their unknown physical and biological features are perhaps the only remaining portions of the world that can be justly said to be still unexplored.

Chapter XIII.—LEVELING

Leveling is the operation of determining differences of elevation between any two points on the surface of the earth. There are few surveying or civil-engineering operations in which leveling does not occur in some form. While for many purposes only the relative elevations of points are required, it is desirable for the proper coordination and comparison of leveling results that all elevations be referred to a common datum or surface of reference. In the network of leveling which covers the United States the elevations are expressed in meters and feet above the mean level of the sea. The mean level of the sea is assumed to be at the same elevation on the open coasts of the Atlantic and Pacific Oceans and the Gulf of Mexico, and it provides a datum easily established and accessible at many widely separated points.

The two principal methods now in use in the Coast and Geodetic Survey for the determination of elevations are by first-order leveling and by the measurement of vertical angles. The first is the most accurate method known and differs from ordinary leveling only in the sensitiveness of the instruments used, the care with which the observations are made, and the refinement of the computations; the second is of a lower degree of accuracy, but suffices for many purposes.

FIRST-ORDER LEVELING

The instrument used in first-order leveling (see fig. 32) consists, essentially, of a telescope carrying a delicate spirit level mounted in such a manner on a portable tripod that it may be quickly and readily placed in a horizontal position. Graduated rods are held at two points, the instrument being placed midway between them. The telescope is sighted first on one rod and then on the other. The difference of the readings of the rods is the difference of height between the two points. The length of sight is usually short and should not exceed 165 yards. By repeating the operation at successive stations the difference of elevation of widely separated points is determined.

Various types of instruments have been used for first-order leveling, some of them being nearly like the Y level used extensively by engineers on construction work and others differing widely from it. The principal characteristics which distinguish the form of first-order level now in use in the Coast and Geodetic Survey are the irreversibility of the telescope and level; the absence of wyes; the rigid fastening of the level vial to the telescope, and its juxtaposition to the latter, in the barrel of which it is countersunk; the use in the construction of the telescope and adjacent parts of a metal known as invar which has a very small coefficient of expansion; the protection of the level vial and the middle part of the telescope from sudden

and unequal changes of temperature by incasing them in an outer tube; and an arrangement by which, without any change of the observer's position, the level bubble can be clearly seen by his left eye at nearly the same instant in which the distant rod is observed through the telescope by his right eye.

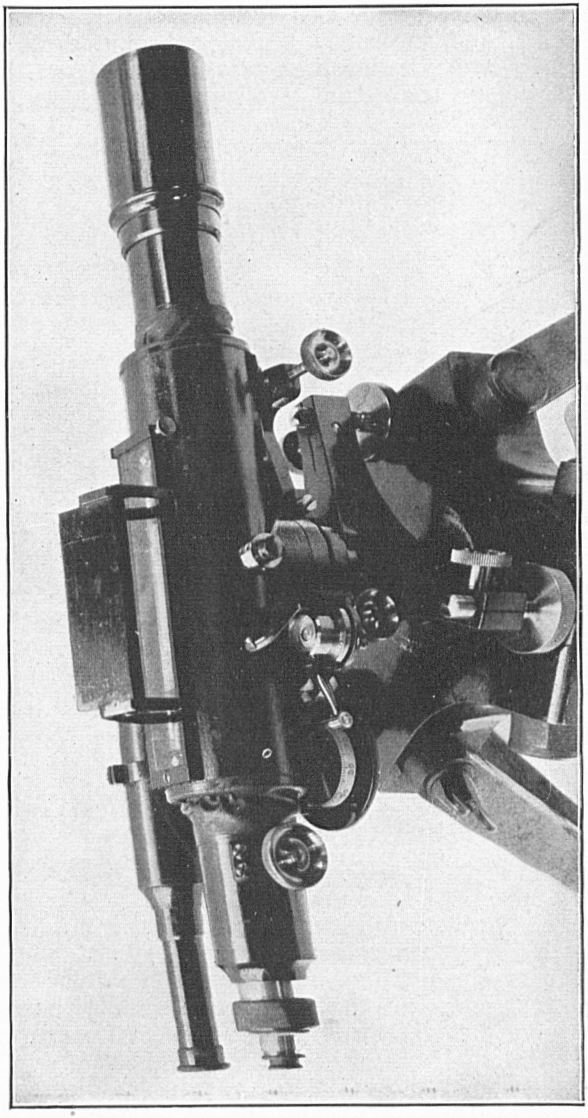

FIG. 32.—FISCHER FIRST-ORDER LEVEL

This instrument is so constructed that the observer may watch the level bubble with one eye and keep it centered at the same time he is reading the rod with his other eye.

The readings are made upon a graduated metal strip of invar. The strip, which is about 1 inch wide, fits loosely in a groove of a flat wooden rod about 10 feet long, and it is free to move upward for temperature changes, being fastened rigidly only at the bottom of the rod. The bottom of the rod is made of metal and terminates in a flat base of hardened steel about 1 inch in diameter. When leveling

along a railroad, the top of a spike, which serves to hold the rail in place, is used as the rod support, while off the railroad the rod is supported on the top of a steel pin driven in the ground.

For a complete description of the instrument, the rods, and the method of graduating the rods see Coast and Geodetic Survey Special Publication No. 129, Geodetic Level and Rod.

The first-order leveling of the Coast and Geodetic Survey is run along the railroads and improved highways. Automobile trucks are used for transporting the leveling party to and from the working grounds, but during the actual leveling the party walks.

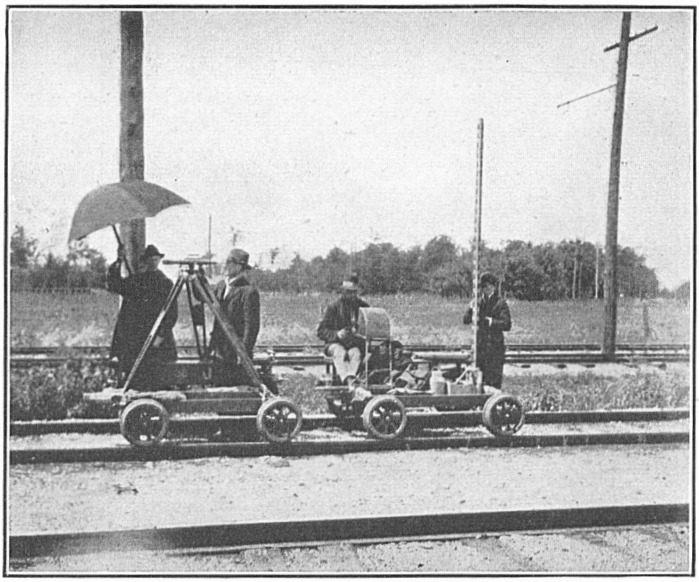

FIG. 33.—MOTOR VELOCIPEDE CARS IN FIRST-ORDER LEVELING

The first-order level is shown here mounted on one of the cars. An adding machine on the other car is used to record the observations and to sum up the back sights and fore sights.

ACCURACY

A line of levels is broken up into sections about a mile in length, and each section is always run twice, in opposite directions. In case of disagreement of the results beyond prescribed limits, one or more additional runnings are made. Permanent points called bench marks are established at short intervals for the use of surveyors and engineers.

For the leveling done since 1899 the maximum discrepancy allowed between two measurements on a section 1.6 kilometers (1 mile) long is 5 millimeters, or one-fifth of an inch. For sections of other lengths the discrepancy allowed is proportional to the square root of the length.

A much more severe test of the accuracy of the leveling is obtained from the closures of large circuits, 50, 100, or 1,000 miles in circumference. Elevations being carried from one point continu-

ously in one direction around the circuit, the computed elevation for the starting point on closing the circuit should agree with that assumed for it at the start if there are no errors in the leveling.

In the network of first-order leveling which now covers the United States there are over 100 such circuits, varying in circumference from 100 to 4,700 miles. The lines are so interlaced that each line usually forms a part of two circuits. The greatest error indicated by the circuit closures in any line of the whole system, involving over 52,000 miles of leveling executed by the Coast and Geodetic Survey, the Corps of Engineers (U. S. Army), and other organizations, is 2 millimeters per kilometer, or about one-eighth of an inch per mile, while the average error is 0.3 millimeter per kilometer, or about one-fiftieth of an inch per mile. The leveling done in recent years by the Coast and Geodetic Survey has an average closing error less than 0.2 millimeter per kilometer.

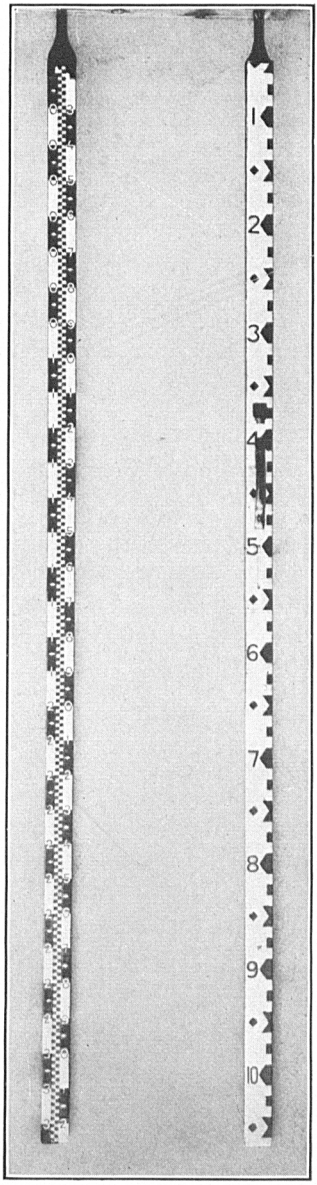

FIG. 34.—ROD USED IN FIRST-ORDER LEVELING

EXTENT

Since the adoption of the present instrument and methods the Coast and Geodetic Survey has completed over 32,000 miles of first-order leveling. The average rate of progress of this leveling was about 75 miles per month per party of six men, each mile being leveled at least twice, once in a forward and once in a backward direction. During the month in which the most rapid leveling was done 165 miles of the line were completed by a single party. The cost of this recent leveling has been from $7 to $16.50 per mile of progress, leveled in both directions.

It is intended to extend the present network of first-order leveling over the United States until there will be but few points in the country more than 50 miles from a first-order-leveling bench mark.

LEVELING BY VERTICAL ANGLES

Leveling by vertical angles, or trigonometric leveling, is carried on in connection with triangulation. It consists in measuring at any station the angle of elevation or depression of a distant station. The sight in this case may be of very great length and in mountainous regions

sometimes exceeds 100 miles. The distance to the station sighted being known, the difference of elevation between the observer's station and the distant point is computed.

In making the computations of heights from such observations it is necessary to apply large corrections on account of the refraction of the ray of light coming from the distant point to the observer. This refraction is variable, having different values at different hours of the day, on different days, and in different seasons. Because the physical condition of the atmosphere can not be known over long lines of sight, the accuracy of the trigonometric leveling falls considerably below that of first-order leveling.

The plan followed for preventing the accumulation of errors and improving the elevations determined by trigonometric leveling is to connect these measures at various points with first-order bench marks and to adjust the trigonometric levels to fit the first-order leveling between those points. When this has been done, the resulting heights are of sufficient accuracy for all except very detailed topography. Several thousand points have been so determined in various parts of the United States. The connections with first-order leveling work and other tests of the accuracy of the trigonometric leveling indicate that it is an even chance that the difference of elevation of two points, determined by trigonometric leveling, is correct within 1 or 2 inches to the mile when vertical angles have been observed in both directions over the line.

For further information on leveling see the various leveling publications of the Coast and Geodetic Survey, especially Appendix 8, 1899; Appendix 3, 1903; Precise Leveling in the United States, 1903–1907; and Special Publications Nos. 18, 28, 41, and 140.

Chapter XIV.—SEISMOLOGY

The study of earthquakes by the Coast and Geodetic Survey is related to its other activities in various ways. While it was not until 1925 that this activity was formally assigned to the survey, seismographs had been in operation at the magnetic observatories ever since the observatories were established. The seismographs were necessary in order to distinguish the disturbance of the magnetic instruments due to earthquakes from the disturbance due to magnetic storms. However, so many important earthquakes were recorded on these instruments that the records became invaluable.

The importance of the records was increased by the fact that all but one of the observatories is in or near an earthquake region.

Great earthquakes are often accompanied by changes in the earth's surface, as in the California earthquake of 1906. The position of a number of triangulation stations was changed so that they had to be redetermined for use in controlling surveys. This redetermination gave accurate measurement of the earthquake effects. Extensive triangulation work has been completed to connect the parts of California especially affected by earthquakes with the stable areas to the east. This will make it possible to determine changes accompanying future earthquakes and also to find out whether changes in the earth's crust are going on without the accompaniment of earthquakes.

In some regions, notably in parts of Alaska, there has been raising or lowering of the earth and, consequently, a change in the elevation of tidal bench marks at the time of earthquakes. Such changes have been very marked in Yakutat Bay accompanying the great earthquake of 1899, and there is evidence that there were similar effects in the north end of Lynn Canal near Skagway. Severe earthquakes, such as that at Yakutat Bay result in changes in the topography and hydrography, and resurveys are made necessary. These give valuable information in regard to the effects of earthquakes.

Seismographs for recording distant earthquakes are operated by the Coast and Geodetic Survey at its five magnetic observatories and at the University of Chicago, where a station established by the Weather Bureau has been continued.

An earthquake sets up vibrations in the earth's crust which are transmitted through the earth as well as along the surface for great distances, sometimes completely around the earth. When the origin and the time of occurrence of an earthquake are known, the records of the seismograph make it possible to determine the rate of propagation of the vibrations or waves.

It is found that waves of different character travel with different velocities, and this fact makes it possible to compute the distance and time of occurrence at the origin of an earthquake from the time of arrival of the various kinds of waves recorded by the seismo-

graph. When the distances from a number of stations have been determined in this way, the location of the origin can be fixed with considerable accuracy. The information supplied by the records of seismographs constitutes a most valuable contribution to the study of the nature and properties of the crust and interior of the earth.

THE SEISMOGRAPH

A seismograph (fig. 38) consists, essentially, of a steady mass suspended in such a way that movements of the earth are communicated to it in only a slight degree. A suitable recording device, fixed rigidly to the ground, registers any movement of the earth at the station relative to the suspended steady mass.

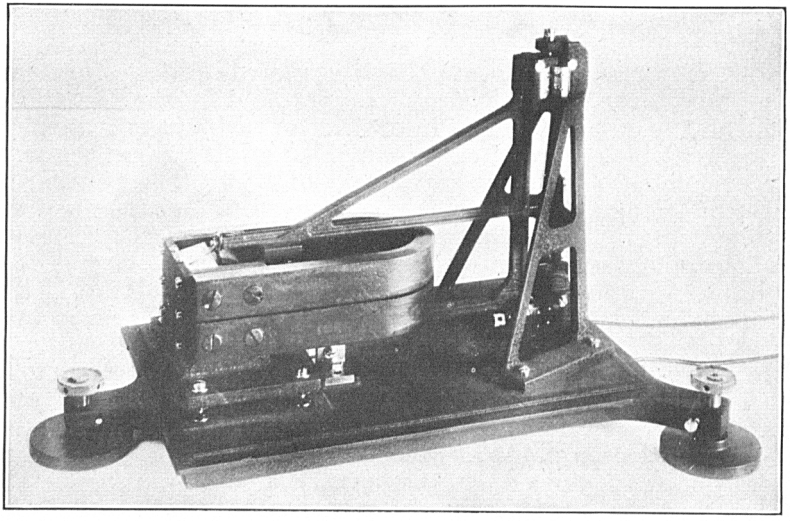

FIG. 35.—WENNER SEISMOMETER

Used to secure photographic recording of the vibrations set up in the earth by an earthquake. This seismometer was developed by Frank Wenner of the Bureau of Standards.

For recording horizontal motions of the ground the usual type of instrument is the horizontal pendulum, in which the steady mass is attached to a horizontal arm, one end of which abuts against the base of a vertical column while the other is supported by a wire from the top of the column. Two of these are in operation at each of the magnetic observatories, one recording the north-south motion and the other the east-west motion. The relative motion of the steady mass and the recording device may be recorded either mechanically by a stylus on smoked paper, or photographically by a spot of light reflected from a mirror connected with the steady mass.

In the most modern type of instrument shown in Figure 38 the seismometer acts in the manner that has been described when an earthquake arrives. In this case the horizontal arm carries a coil which moves in a strong magnetic field. Electrical disturbances thus set up are transmitted to a galvanometer and the motions of the galvanometer are recorded. Among other advantages this permits

the recording to be done in a separate building from where the seismometer is installed.

The seismometers at the Honolulu and Tucson observatories and at the University of Chicago record photographically. In the near future the Sitka observatory will have a Wenner seismometer and one will probably also be installed at San Juan.

The positions of earthquakes occurring in or recorded within the United States are published at regular intervals. These are based on instrumental records of the Coast and Geodetic Survey and cooperating organizations and observations of the visible and felt effects of earthquakes by individuals. The work of securing these reports is being thoroughly organized. By means of telegraphic reports from cooperating observatories the positions of important earthquakes are determined within 24 hours, and are published in the United States and transmitted by radio to Europe and other parts of the earth.

The Coast and Geodetic Survey directly and in cooperation with other organizations is studying earthquakes in order to help in the solution of the many problems connected with them and to reduce as time goes on the damage resulting from them.

Chapter XV.—GRAVITY

Gravity is the term used for the tendency of bodies to fall toward the earth. It is the resultant of two opposing forces—gravitation, or the attractive force of the earth, and the centrifugal or repelling force due to the earth's rotation.

Gravity observations are an important and essential part of a geodetic survey. While operations for the measurement of the size of the earth, by extended and connected systems of triangulation, are of necessity confined to the land—that is, to one-third of the earth's surface—gravity observations can be made at disconnected points anywhere on the earths' surface, on islands, on the Arctic ice, and, with less accuracy, even on ships. From such observations the earth's compression—that is, its shape—can be deduced by mathematical processes with a high degree of accuracy.

A knowledge of the intensity of gravity is also essential in meteorology and for the determination of many physical constants, such as the mechanical equivalent of heat. By means of gravity determinations an extensive research has been made by the Coast and Geodetic Survey to determine variations from the normal densities of the materials in the outer portion of the earth. (See chapter on Geodesy.)

VARIATION

The variation of the force of gravity at different places on the earth's surface was first discovered by Richer in 1671. He found that a clock which kept accurate time at Paris, France, lost two minutes daily when transported to the island of Cayenne, South America, though there had been no change in the length of the pendulum.

Later, it was found that gravity varies with the latitude, with the elevation, and with the character of the topography of the surrounding country. Thus, a mass weighing 200 pounds at sea level at the Equator will weigh approximately 201 pounds at sea level at either pole; a mass weighing 400 pounds at sea level will weigh approximately 399 pounds at an elevation of 5 miles in the same latitude; and a given mass will weigh more at the top of a sharp mountain peak than if it were at the center of an extensive plateau of the same elevation as the peak, providing the latitude is the same in both cases. It is understood that these weights are recorded on a spring balance and not on beam scales.

PENDULUM FOR MEASURING GRAVITY

The pendulum forms the most precise as well as the most convenient way for measuring gravity. The early forms of gravity pendulums were made about 1 meter in length and had a period close to one second. These pendulums were difficult to handle and

transport on account of their large size and as they were swung in the open air they did not give very accurate results. Some forms were reversible for measuring the absolute value of gravity while others were swung in only one position and could be used only for measuring differences of gravity.

It is a difficult matter to determine accurately the absolute force of gravity for a station, even with the greatest care and a large

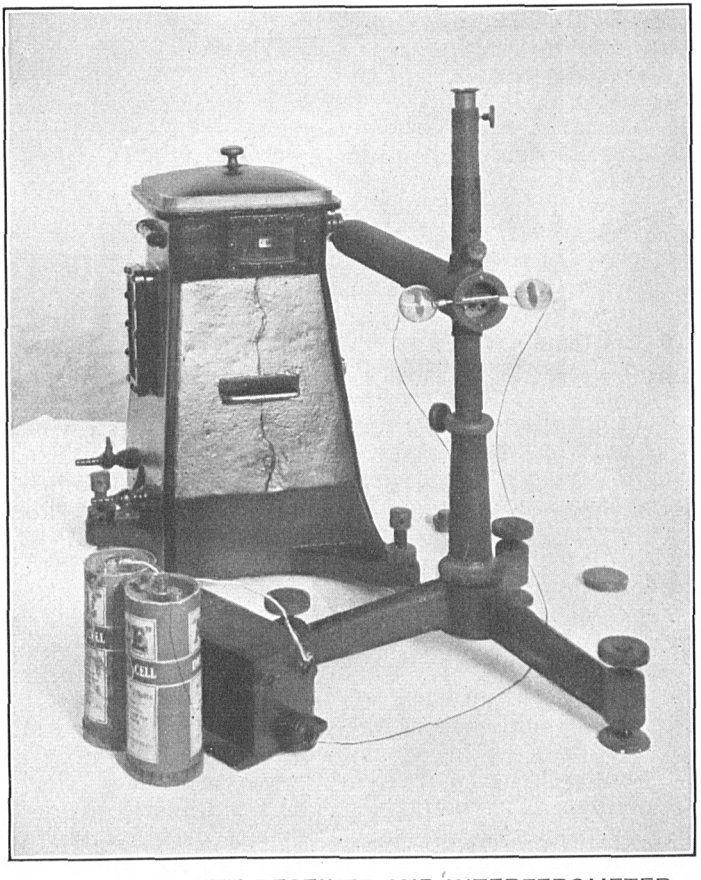

FIG. 36.—GRAVITY RECEIVER AND INTERFEROMETER

The receiver is a heavy brass box in which the gravity pendulums are swung under a partial vacuum. The oscillations of the pendulum within this receiver cause it to weave slightly, and this makes it necessary to apply a correction to the results. The amount of this movement, or flexure, is measured with an interferometer, the instrument shown to the right, which will detect a movement as small as one ten-millionth of an inch.

number of observations. On the other hand, it is comparatively easy to determine with great accuracy the difference of gravity between two places with the invariable pendulum.

All observations for obtaining the values of gravity in the United States are made by the relative method. Until very recently the base station for the United States was a brick pier in the basement of the former Coast and Geodetic Survey office in Washington.

This pier has now been destroyed by building operations, but a new base pier will soon be established in the new building of the Department of Commerce. The value of gravity at the old pier was obtained by the relative method from Potsdam, Germany, where the absolute value of gravity was obtained from many observations throughout a long period of years. All values of gravity in the United States, therefore, are referred to the absolute measurements at Potsdam.

The type of pendulum now used by the Coast and Geodetic Survey differs very materially from the early forms and was designed and constructed by members of the survey in 1890. Like the pendulum designed by Dr. R. von Sterneck in Austria several years previous to this time, it is only one-quarter of a meter long and has a period of oscillation of about one-half second.

GRAVITY APPARATUS

The gravity apparatus in present use consists of the following essential parts: Three pendulums, an air-tight brass receiver in which the pendulums are swung, a telescope for observing the oscillations of the pendulums, two chronometers, several thermometers, a manometer for measuring the air pressure within the receiver, and an interferometer for measuring the movement of the receiver caused by the swinging of the pendulum. The pendulum is a simple stem and bob of solid bronze or invar. It differs from an ordinary clock pendulum in having a small agate plane attached to its head which rests on an agate knife-edge in the receiver and in having no machinery to drive it or count its oscillations.

Before the measurements are started the pressure of the air within the receiver is reduced to less than one-tenth of one atmosphere. The resistance of the rarefied air and the friction between the agate knife-edge and the plane are so small that a pendulum will swing continuously for more than 12 hours, even though its initial arc is only about one-fifth of an inch.

The period of oscillation of the pendulum is observed and compared with the beat of the chonometers at the beginning and end of each 12-hour swing, and from these comparisons the average period of oscillation is computed. The pendulum is made of such a length that its period is nearly, but not quite, equal to a half second, and during a period of from three to six minutes it makes one less oscillation than the number of half seconds registered by the chronometer.

By an ingenious mechanical device, a beam of light is thrown into the receiver at each beat of the chronometer, and it there falls upon two small mirrors. One of the mirrors is attached to the head of the pendulum and swings with it, while the other is permanently fixed to the support and just to the side of the pendulum. When the pendulum is at rest, the two slits of light as reflected from these two mirrors appear as a single horizontal line, but in any other position of the pendulum the line of light as reflected from its mirror will appear above or below the line from the other mirror. Observing a coincidence consists in noting the time when the two slits of light appear in the same horizontal line, and the observing of two or

more consecutive coincidences enables one to deduce the period of oscillation of the pendulum in terms of the chronometer time.

ACCURACY OF MEASUREMENT

The measurement of the force of gravity at a station, to be acceptable, must not have a probable error greater than 1 part in 250,000. An actual error of 1 part in 250,000 corresponds to an error of only one one-millionth of a second in the period of oscillation of the pendulum. Such accuracy is not easily conceivable, but it is attained with no great difficulty by an experienced observer. Care is taken to keep the pendulum apparatus at as nearly a constant temperature as possible, and all variations are carefully observed.

One of the corrections which must be applied to the observed time of oscillation of the pendulum is due to the movement of the receiver resulting from the swinging of the pendulum. The receiver is a rectangular brass box about 10 inches square at the base and 11 inches high (inside dimensions), weighing 100 pounds. It is placed either on a solid concrete floor or on an especially prepared brick or concrete pier.

In spite of these precautions, the swinging of the pendulum through its very small arc causes a rocking of the receiver, and this in turn affects the period of the pendulum. This small movement of the receiver is measured by the interferometer, a very delicate instrument, which depends in principle upon the interference of light waves. Distances as small as one ten-millionth of an inch, one-twentieth of a wave length of sodium light, can be measured with it. Vibrations of the ground due to the passing of a truck a city block away or a train a mile away are easily detected. During such disturbances observations with the interferometer to determine the flexure of the pier and pendulum receiver can not be made. Some idea of the delicacy of this measurement may be obtained if it is noted that the correction to the period of the pendulum for flexure usually amounts to about one one-millionth of a second.

In order to eliminate from the gravity observations errors due to the rate of the chronometer, it is necessary to determine its error within a few hundredths of a second of time both at the beginning and end of a series of observations with the pendulum. This was formerly done by making time observations on the stars with an astronomic transit. During the last few years satisfactory results have been obtained by comparing the chronometers with the time signals sent out from the Naval Observatory. The signals sent out over the commercial telegraph lines were used at first, but since July, 1922, radio time signals have been used in determining the chronometer rates.

The radio signals are recorded automatically on a chronograph by means of a special radio receiving apparatus designed and constructed at the United States Bureau of Standards. The same type of radio apparatus is also used for longitude determinations. (See p. 10.) Gravity and longitude stations may now be located wherever desired, without reference to telegraph lines, and the cost per station is considerably less than by the old methods.

INVAR PENDULUMS

Since 1921 pendulums made of invar have been used in place of the old bronze pendulums and have given satisfactory results. The temperature coefficient of the invar pendulums is only about one-fifteenth that of the bronze pendulums, and ordinarily a tent is sufficient protection from temperature changes when they are used.

Temperature control was always a serious problem with the bronze pendulums, as an error of 1° C. in obtaining the temperature of the pendulums caused an error in the observed gravity four times the maximum allowable probable error. A constant-temperature room at each station was a necessity, and this practically limited the selection of stations to places where such rooms could be found, for the time and expense required to construct a constant-temperature room were almost prohibitive.

Invar pendulums are magnetic. They must be tested for magnetization before and after use at each station and must be kept as nearly demagnetized as possible, otherwise their periods will be affected to an appreciable extent by the magnetic field of the earth. The pendulums are tested by means of a compass declinometer which is equipped with two horizontal arms from which the pendulums may be suspended at known distances from the needle. If, as seldom happens, a pendulum deflects the needle by more than a predetermined small amount, it must be demagnetized by the use of a solenoid.

GRAVITY STATIONS

There are now about 325 gravity stations in the United States. They are distributed quite uniformly over the whole country except in a few critical areas where they have been placed close together to make possible some special scientific investigations in connection with geology or isostasy.

See also Special Publications Nos. 40 and 99 of the United States Coast and Geodetic Survey, which contain the results of 304 gravity stations in the United States.

Chapter XVI.—GEODESY, OR MEASUREMENT OF THE EARTH

From the earliest times man has inquired and speculated about matters concerning the earth upon which he walks and on which he spends his life, but his first crude ideas about its shape and magnitude were not developed up to the point of a fair resemblance to the facts until the civilization of the race had already grown old.

Geodesy is a natural development of the simpler operations of land surveying, but, unlike the latter, takes into account the sphericity of the earth. Land surveying was practiced from a very ancient date. Thus, in a papyrus of a date earlier than 1700 B. C. the author stated that his work was a compilation from older manuscripts. The notion that the earth's surface could not be a plane, but must be curved like the surface of an immense ball, should have been apparent to dwellers upon the seashore; yet the fact that the earth is, roughly speaking, spherical was not appreciated for many centuries after civilization had developed to such an extent that land surveying was practiced. The step from plane to spherical surveying was an important one, and when it was made geodesy, allied to practical astronomy, became an independent branch of science.

FIRST MEASURES OF EARTH'S RADIUS

Shortly before the beginning of the second century before Christ, the first measure, and a little later a second measure, of the earth's curvature, that is, of the radius of the sphere, were made in Egypt. The principle then employed has been used ever since. Essentially, it involves the determination of the distance between two remote points north and south of each other and of the meridian altitudes of the sun or of some star as seen from the two ends of the measured line. The difference of the measured altitudes gives the curvature of this arc of the great earth sphere expressed as an angle. This being known, as well as the length of the arc, the circumference or the radius of the sphere can be computed.

After these first measures in Egypt, a thousand years passed before a similar attempt was made—this time by the Arabs in Mesopotamia, about 825. This, in turn, was followed, after another long lapse of eight centuries extending through the Middle Ages, by several measures executed by different nations. The principle of triangulation which is used in the refined modern measures of distances was introduced in 1617.

MODERN GEODESY

Modern geodesy as it now exists began with the discovery of the law of gravitation by Newton, late in the seventeenth century. He proved that the earth, as a revolving and not wholly rigid

body, subject to its own attraction, must take the form of a slightly flattened sphere.

The form thus indicated by theory was apparently contradicted by measures along an arc in France between 1683 and 1716, which indicated the earth to be an elongated sphere. To settle the matter, two memorable expeditions were sent out—one to the equatorial region of what was then Peru (1735–1741) and the other to the polar region of Lapland (1736–37). Their work proved Newton's theory to be correct, since they found the length of 1° of latitude to be greater, or, in other words, the arc flatter, near the pole than near the Equator. Since then, in theory and in practice, geodesy has advanced on sure ground and with ever-increasing precision in its results.

Though the early measures of the earth's curvature were made along meridians only, the modern methods of measures and computations are such that all the triangulation in a connected network may be utilized in the determination of the size and shape of the earth.

The same instruments and methods of observing are employed in a triangulation designed primarily as a basis for accurate map making as are used in measuring an arc for the purpose of determining the earth's size and shape. Nearly all geodetic arcs have been obtained incidentally during the progress of extended national surveys.

GEODETIC ARCS

Since the revival and spread of science many surveys of countries, made primarily for mapping purposes but yielding, incidentally, geodetic arcs, have been carried out in different parts of the world. In making these measures France, Great Britain, Germany, Russia, and the United States have taken leading parts. Among the more recent measures there may be mentioned the Anglo-French arc, extending from the northern part of the British Isles southward into Africa; the great Russian arc, extending from the Arctic Ocean to the northern boundary of Turkey; the great Indian arc, extending from the southern point of India to the Himalayas; and the European arc of parallel 52°, extending from southern Ireland eastward to central Russia.

In the United States we have the transcontinental arc, extending along the thirty-ninth parallel from the Atlantic to the Pacific; the eastern oblique arc, extending parallel to the Atlantic coast from Maine to Louisiana; the ninety-eighth meridian arc, extending from Canada along the ninety-eighth meridian to Mexico, and thence through Mexico to the Pacific Ocean; the western arc, extending from Mexico along the Pacific coast into Alaska; the Texas-California arc, extending from central Texas to the Pacific coast; the one hundred and fourth meridian arc, extending from western Texas to Canada; the Utah-Oregon arc, extending from northern Utah, northwestward to Oregon, and thence down the Columbia River to the vicinity of Portland; the Alabama-California arc, extending from Huntsville, Ala., to western Arizona; the Texas-Louisiana arc, extending from the vicinity of Waco, Tex., eastward

to the Mississippi River; the Rio Grande arc, extending along the Rio Grande from the Gulf of Mexico to a connection with the Texas-California arc; the Great Lakes arc; and numerous other arcs of first-order triangulation and traverse. The total length of the arcs of first-order triangulation and traverse in the United States is about 27,000 miles, more than equal to the circumference of the earth.

The following brief statement gives some of the most important facts in regard to one of the arcs already completed in the United States and for which the final reports have appeared. This arc crosses the country along the thirty-ninth parallel from Cape May, N. J., to Point Arena, Calif., and is 2,625 statute miles (4,225 kilometers) long. The 10 base lines in this triangulation have an aggregate length of 53½ miles, one of them being nearly 11 miles in length. Many of the triangle sides in the Rocky Mountain region are over 100 miles long, and there is one line 183 miles long, over which observations were made in both directions. Some of the triangulation stations were more than 14,000 feet (4,300 meters) above the sea. Many astronomic observations were necessary to fix the position of this arc upon the earth and to determine the true direction of the lines of the triangulation. The astronomic latitude was determined accurately at 109 stations, the astronomic longitude at 29, and the astronomic azimuth or true direction at 73.

FORM OF THE EARTH

The form of the earth as given by the modern precise measurements is found to be such that with considerable exactness any section of it parallel to the Equator is a circle, and any section passing through both poles is an ellipse. The dimensions and form of this spheroid, or ellipsoid of revolution as it may be called more accurately, are usually stated by giving its equatorial and polar radii or semidiameters.

The most notable computations of the dimensions of the ellipsoid are those made by Bessel in 1841, by Clarke in 1866, and by the Coast and Geodetic Survey in 1909. Bessel's and Clarke's values were derived from a combination of all the arc measures in different parts of the world. The Coast and Geodetic Survey value depends only on the triangulation done in the United States; but, on account of the application of the theory of isostasy, as explained below, the dimensions deduced by the late Prof. John F. Hayford, while connected with the Coast and Geodetic Survey, are considered the most accurate and have recently been adopted by the International Geodetic and Geophysical Union as the international spheroid.

The Clarke ellipsoid has been used in the United States for many years for surveying and geographic purposes and is the basis for all the charts of the Coast and Geodetic Survey and for the maps of many other Government organizations. The Clarke ellipsoid is sufficiently accurate to be retained for those purposes. Its retention is especially desirable in order to avoid the immense amount of computation which would be involved in the adoption of a new ellipsoid of reference.

The dimensions of the earth as given by these different computations are as follows:

	Bessel (meters)	Clarke (meters)	International (meters)	International (English statute miles) [1]
Equatorial radius a	6,377,397	6,378,206	6,378,388	3,963.3
Polar semiaxis b	6,356,079	6,356,584	6,356,912	3,950.0
Difference $a-b$	21,318	21,622	21,476	13.34
Compression (flattening) $\frac{a-b}{a}$	$\frac{1}{299.2}$	$\frac{1}{295.0}$	$\frac{1}{297.0}$	----------

[1] 1 statute mile = 5,280 feet, or 1,609.347 meters.

THEORY OF ISOSTASY

Hayford took into consideration the theory of isostasy when making his determinations of the shape and size of the earth. One theory of isostasy postulates that at and beneath a certain depth below sea level, called the depth of compensation, found by investigation to be about 96 kilometers (60 miles), the earth's materials are in equilibrium as if they were fluid. Therefore, in each column of the same cross section which extends from the depth of compensation to the actual surface of the earth, whether land or water, there will be the same mass or amount of material. In other words, the materials in any column would weigh as much as the materials in any other column if the weighing were done at the same place. (See Gravity.) It is therefore assumed that elevated regions are held up owing to the lesser density of the materials composing the columns of which they form parts, and conversely the depression of the ocean bottoms is due to an excess of density in the material under them.

The above paragraph states what the condition would be with perfect isostasy. It is, of course, impossible to have complete isostatic adjustment in the earth's material because of some residual strength, but the investigations of the Coast and Geodetic Survey furnish conclusive proof that the isostatic condition in the United States approaches very closely to the ideal one.

DETERMINATION OF EARTH'S SHAPE

The shape of the earth, but not its dimensions, has been determined by the Coast and Geodetic Survey in recent years from observations of the intensity of gravity. In 1912 the flattening of the earth or its compression was determined from 114 gravity stations in the United States. The value of the flattening was found to be 1/298.4. In 1916 a second determination of the flattening of the earth was made which gave a value of 1/297.4. In this determination there were used 348 gravity stations in the United States, Canada, several countries of Europe, and India. It is believed that this value of 1/297.4 for the flattening or compression of the earth is the most accurate one in existence.

In the determination of this value of the flattening the gravity stations were reduced for the effect of the elevation of the station above sea level, the attraction of the earth's mass above sea level,

and the deficiency of the density in the ocean basins. There was also taken into account the attractive effect of the deficiency of the matter under the continents and the excess of material under the oceans. In other words, isostasy was considered in making the reductions.

To appreciate correctly the small amount of flattening at the poles indicated by the above figures, it should be noted that if a globe approximately 5 feet in diameter were constructed to scale to represent the earth its equatorial diameter would be but one-fifth of an inch longer than its polar diameter. To the eye unaided by the use of calipers or other measuring instruments this globe would appear to be a perfect sphere.

PROGRESS IN GEODESY

A powerful stimulus to progress in geodesy was given many years ago by the formation of a geodetic association in Europe, which was founded in 1861 and was made international in character in 1886. The United States became a member of this association in 1889. Previous to the World War nearly all progressive nations were members of the association. General meetings were held at least once in three years, at which geodetic problems were discussed and reports were made in regard to geodetic operations of the various countries.

In July, 1919, there was organized at Brussels, Belgium, by a number of nations, what is called the International Research Council. Under this council have been created several unions, one of them being the International Geodetic and Geophysical Union. One of the sections of this union deals with the subject of geodesy, and it has practically taken over the functions of the old International Geodetic Association. The first meeting of the union was held in Rome in 1922, the second meeting in Madrid in 1924, and the third in Prague in 1927.

For further information on geodesy, the reader is directed to the following publications of the United States Coast and Geodetic Survey: Figure of the Earth and Isostasy from Measurements in the United States; Supplemental Investigation in 1909 of the Figure of the Earth and Isostasy; Special Publications Nos. 10 and 12, each of which is entitled "Effect of Topography and Isostatic Compensation on the Intensity of Gravity"; Special Publication No. 40, entitled "Investigations of Gravity and Isostasy"; and Special Publication No. 99, entitled "Isostatic Investigations and Data for Gravity Stations Established in the United States Since 1915."

Chapter XVII.—ORIGINAL RECORDS AND DATA

The attention of the technical professions and the public in general is called to the large accumulation of original data and information in the archives of the Coast and Geodetic Survey.

The earliest records on file date back to 1816; while the first topographic and hydrographic surveys bear the date 1834, magnetic observations were made in the previous year, and tidal work began in 1832.

For over a century careful observers have obtained information bearing upon the physical condition of that portion of the earth constituting the United States and adjacent waters within about 60 miles of the coast and also extending over the Gulf Stream and Gulf of Mexico. This area has been extended from time to time, and the original data now cover Porto Rico, Hawaii, the Canal Zone, and large portions of Alaska, the Philippine Islands, and the Virgin Islands of the United States. The records of observations and surveys are systematically arranged and carefully preserved and constitute in many cases the only authentic record from which natural or artificial changes can be deduced.

The information required for general use has been or will be published in the regular and special publications of the bureau. Many of these are listed in the Catalogue of Charts, Coast Pilots, and Tide Tables, and in the annual List of Publications of the Department of Commerce. Either of these catalogues will be sent free on request.

The List and Catalogue of Publications of the Coast and Geodetic Survey, with its supplement, gives a complete list of publications down to the year 1908. Most of the publications thus listed are no longer in print but may be consulted in many of the large libraries in the United States. The list and catalogue is itself out of print but may be consulted in libraries.

Much of the information collected by the Coast and Geodetic Survey is available in original form for special use. Copies may be obtained free or at a nominal cost.

In connection with other work, surveys of some State and national boundaries have been made, and the resulting original records are also on file. Many thousand specimens of the sea bottom have been collected as the result of deep-sea sounding and are preserved. The information on file can be used in making special studies of changes along the coast due to erosion or the improvement of rivers and harbors.

Besides publications containing records of observations and surveys, the Coast and Geodetic Survey has issued a number of pamphlets of instructions and tables for use in the practical work of surveying and map making and others for popular information

concerning the work of the bureau and its connection with national progress. The titles are given in the catalogues above referred to.

In connection with the archives a working library is maintained which contains a very complete collection of reports and publications (including foreign publications) on surveying, hydrography, tides and currents, navigation, terrestrial magnetism, and geodesy and kindred subjects.

A large number of charts and maps form a part of the collection, all of which is available for public use.

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