GEODETIC OPERATIONS IN THE UNITED STATES AND IN OTHER AREAS THROUGH INTERNATIONAL COOPERATION

1960–1962

Publication 60–3

F. R. GOSSETT

U.S. DEPARTMENT OF COMMERCE
COAST AND GEODETIC SURVEY

UNITED STATES DEPARTMENT OF COMMERCE
LUTHER H. HODGES, Secretary
COAST AND GEODETIC SURVEY
H. ARNOLD KARO, Director

GEODETIC OPERATIONS IN THE UNITED STATES AND IN OTHER AREAS THROUGH INTERNATIONAL COOPERATION

January 1, 1960, to December 31, 1962

[Report to the International Association of Geodesy of the International Union of Geodesy and Geophysics, International Council of Scientific Unions]

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PREFACE

This publication constitutes one of a series of triennial reports to the International Association of Geodesy on the geodetic activities of various agencies in the United States, and it covers the period from January 1, 1960, through December 31, 1962. It will be distributed at the Thirteenth General Assembly of the International Union of Geodesy and Geophysics to be held at Berkeley, California, in August 1963. The material of this report has been arranged in five parts corresponding to the five Sections of the International Association of Geodesy.

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By F. R. Gossett, *Chief*, *Geodesy Division*, *U.S. Coast and Geodetic Survey*

GEOMETRICAL DETERMINATION OF POSITIONS

U.S. Coast and Geodetic Survey

During this 3-year period, approximately 4,000 horizontal control points were established each year. The program of filling in area networks within the primary arcs accounted for a major portion of the work accomplished. In some of the larger area nets, first-order cross arcs were observed across the middle of the areas. Surveys in connection with the Interstate Highway Program accounted for approximately one-third of the total number of points established.

The use of electronic equipment for measuring distances increased during this reporting period. The Model 2 Geodimeter was used for the measurement of base lines in the existing primary network and in some of the new area nets. A program of measuring bases in the primary nets was started a few years ago, and this program will be continued until bases are established at uniform intervals throughout the basic U.S. triangulation net. The Tellurometer and Model 4 Geodimeter were used primarily in connection with traverse on the Interstate Highway surveys. In the latter part of 1962, tests were made with the Model 4D Geodimeter to evaluate the accuracy as compared with the Model 2. Although these tests have not been completed, preliminary results indicate that distances measured with the two instruments agree within 2 centimeters.

A high-precision survey was accomplished in Florida to position nine ballistic cameras. The cameras are used for missile and satellite tracking, and the requirements of the survey were to obtain positions with an accuracy of one part in 400,000 relative to Cape Canaveral. The camera stations, at distances of 40 to 50 miles from the Cape, were positioned from an area triangulation net with 43 distances measured with the Model 2 Geodimeter. The results of the survey indicated that the camera stations were established with an accuracy well within the required limits. A report of this survey is published in Technical Bulletin No. 13 of the Coast and Geodetic Survey.

In 1962, the high-precision surveys in Florida were extended south along the coast approximately 150 miles. This survey was accomplished by establishing elongated diamond-shaped figures with two points of the figure about 25 or 30 meters apart. The four long sides of the diamond, each side about 10 miles in length, were measured with the Geodimeter and the short diagonal was taped. Astronomic azimuths and positions were observed at intervals of approximately 20 miles. The results obtained from this traverse survey indicated that stations were established, relative to Cape Canaveral, with an accuracy on the order of 1 part in 1,000,000. Late in 1962, a similar project was started to extend the high-precision surveys north to Savannah, Ga. Reconnaissance surveys have been started to connect California with Cape Canaveral by this method of high-precision traverse.

A project of historical importance was a resurvey of the north-south boundary between the States of Delaware and Maryland. The survey was made at the request of officials of the two States to restore and preserve the boundary monuments established 200 years ago by the two English surveyors, Mason and Dixon. This survey indicated that a large majority of the monuments now marking the boundary are very close to, if not exactly in, their original positions as established by Mason and Dixon.

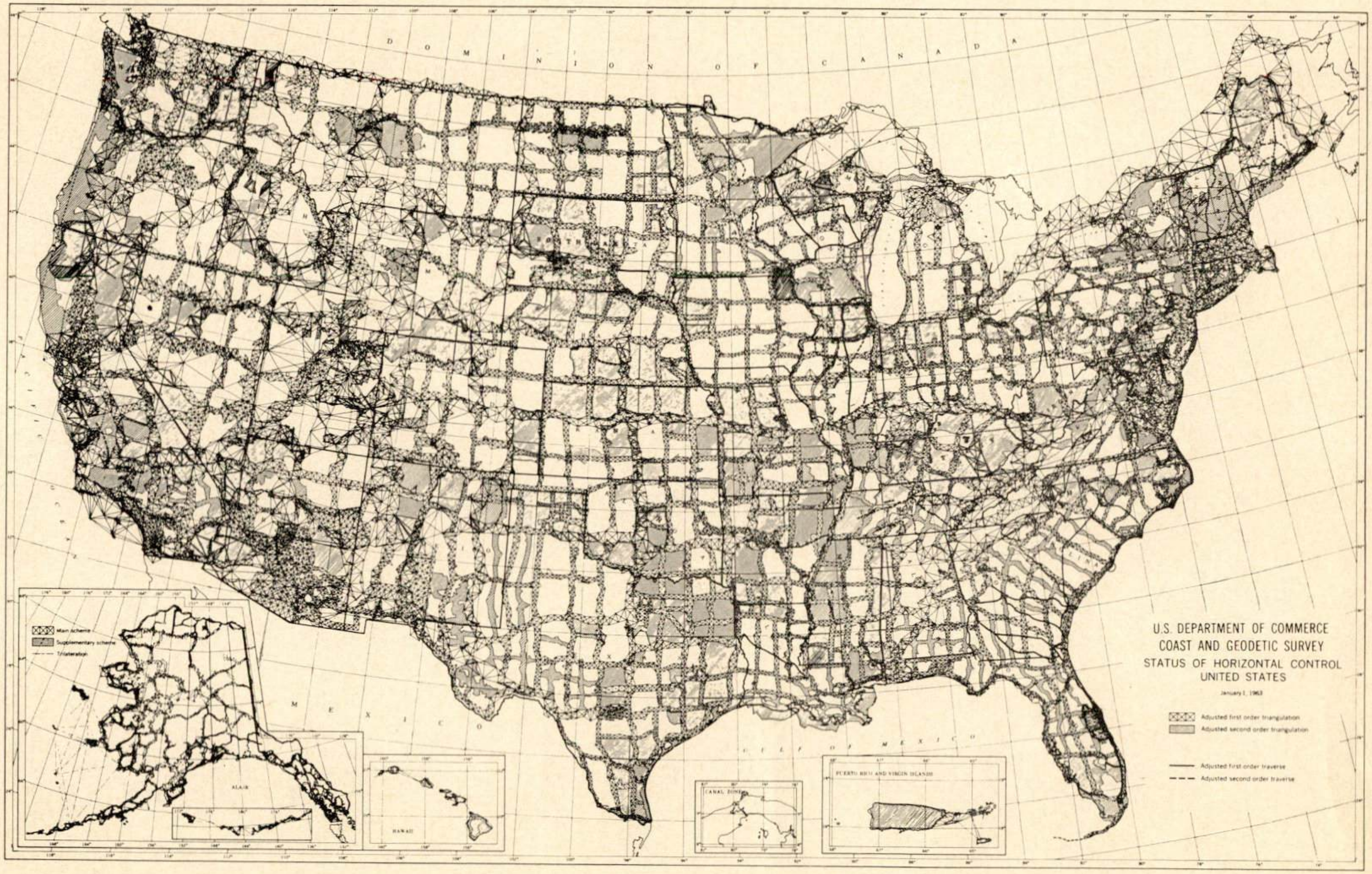

Figure 2.—Extension of the triangulation net of the United States.

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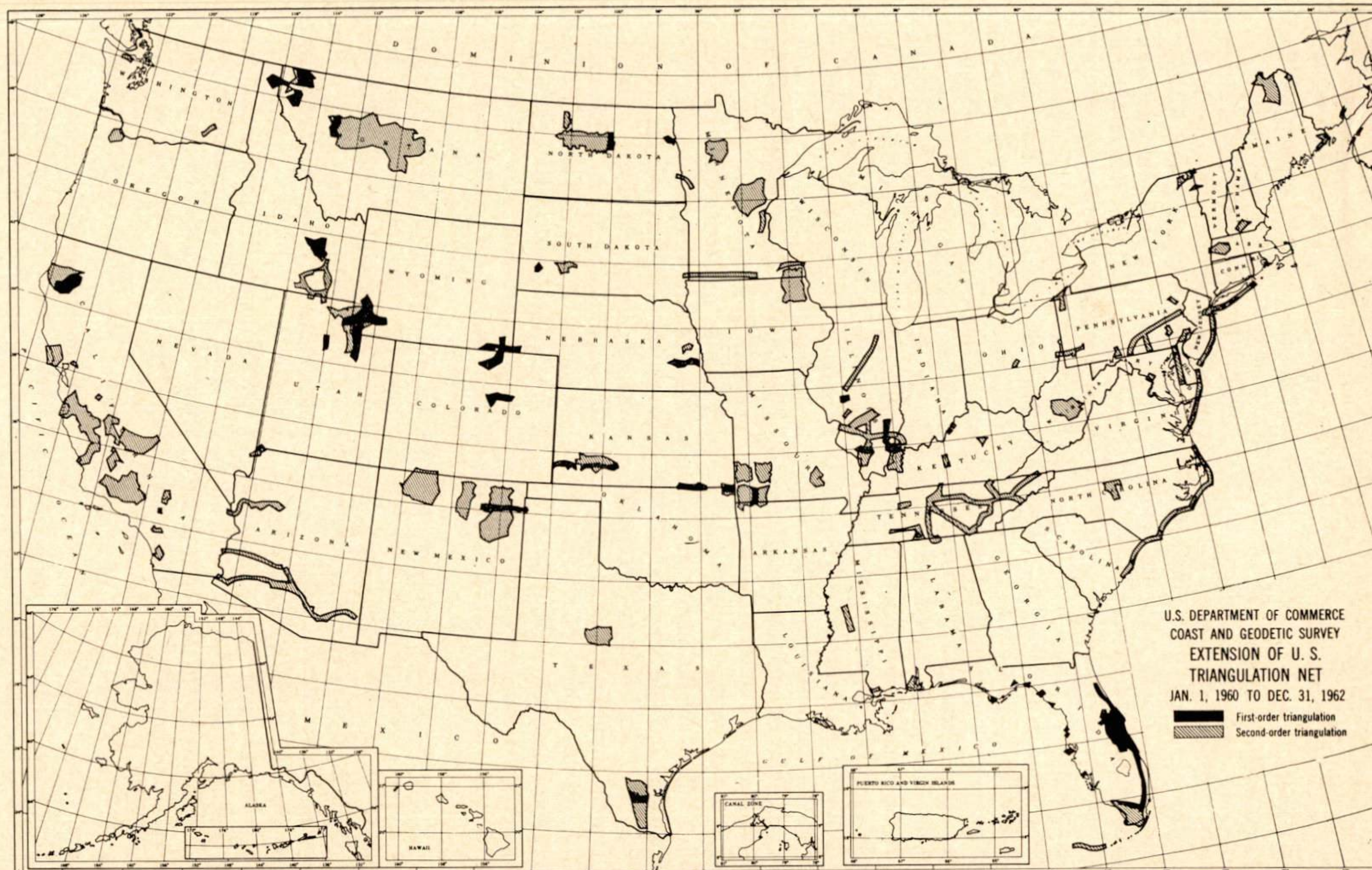

Figure 1.—Triangulation net of the United States.

Electronic computers are used for most of the

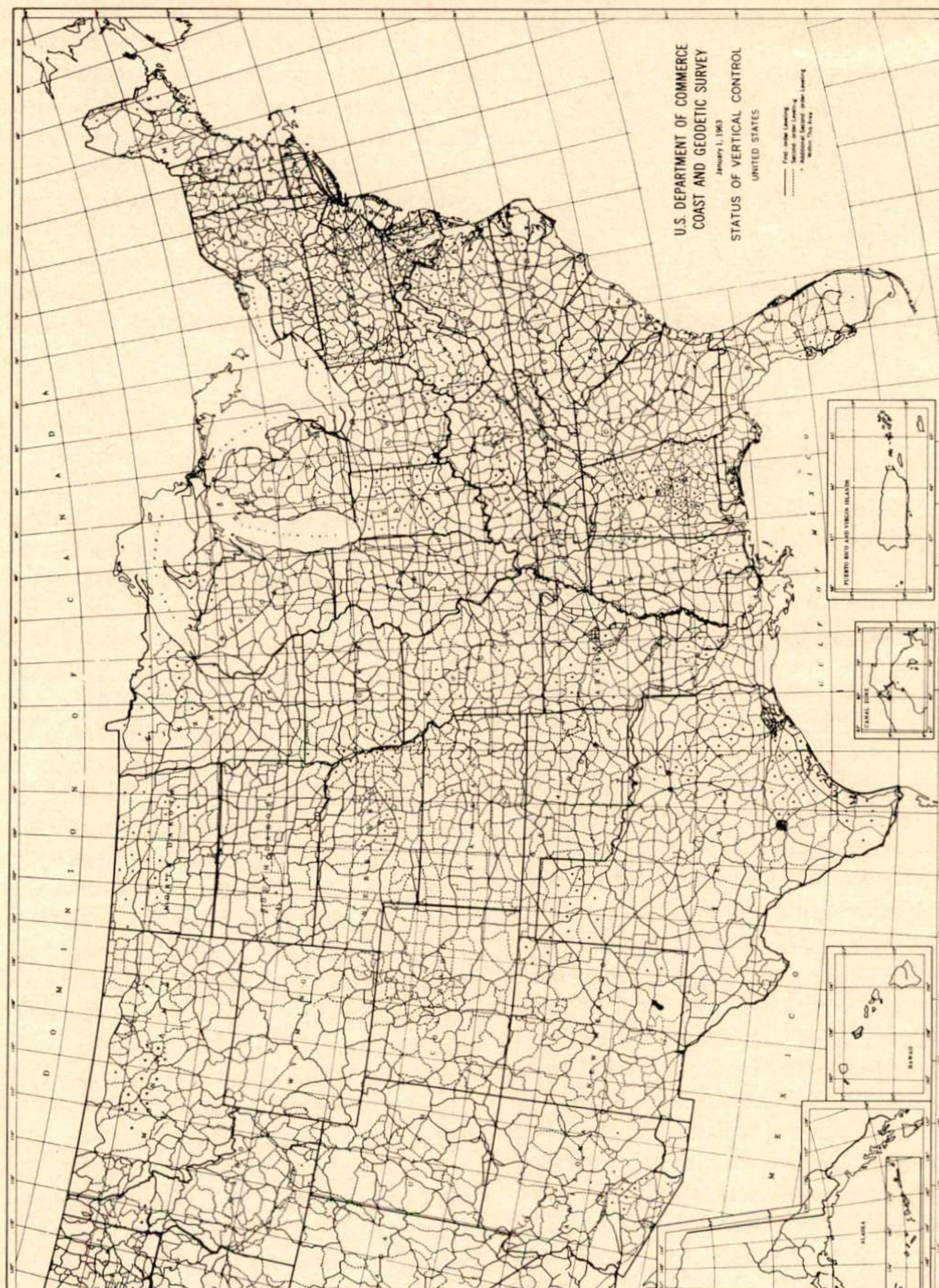

Figure 5.—Level net of the United States.

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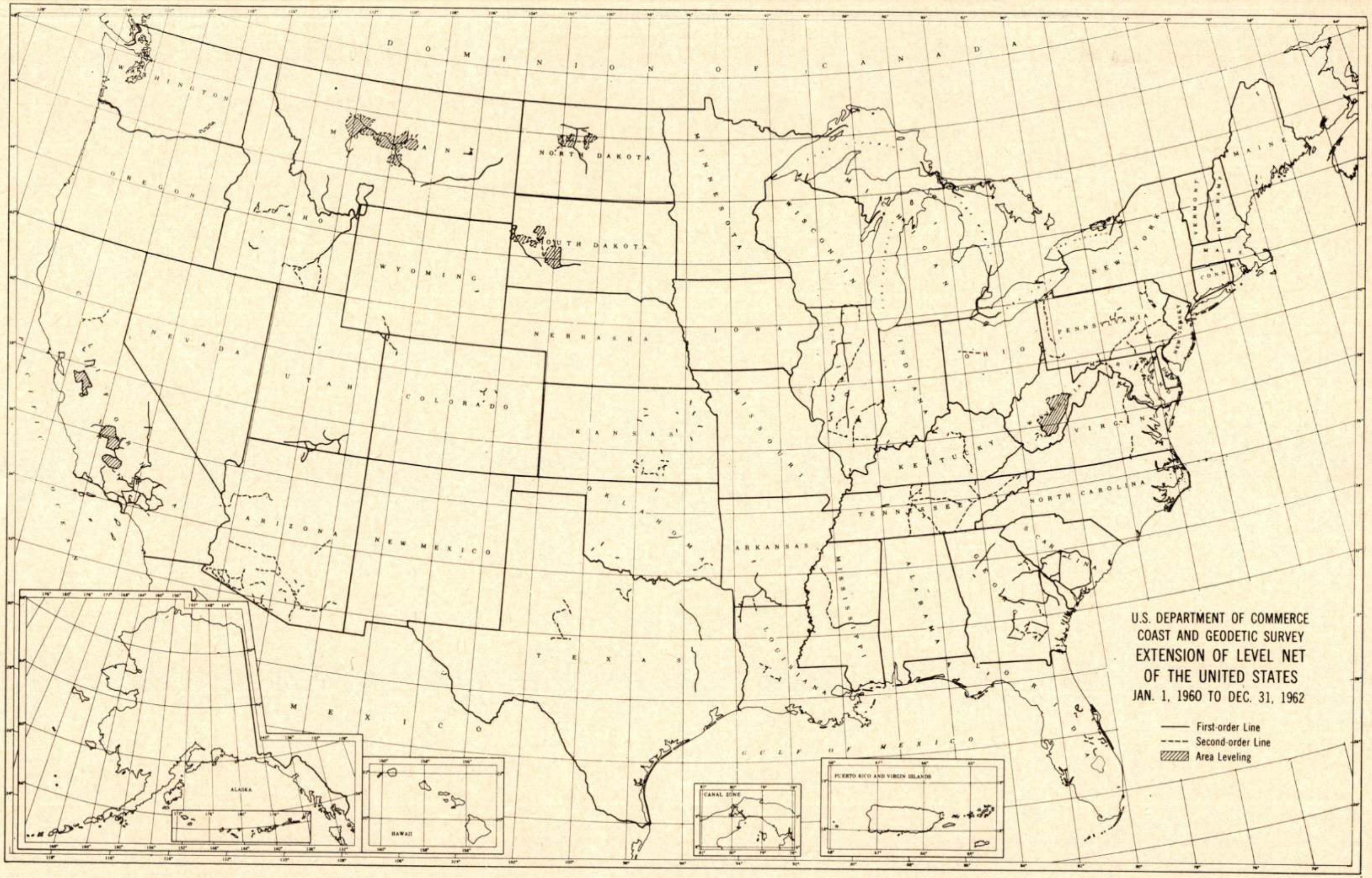

Figure 6.—Extension of the level net of the United States.

Canyon Dam is completed, and leveling was established as near the shore of the proposed lake as possible.

Many lines of leveling in the first- and second-order control net were established during the depression period of the 1930's. During this expanded program there were 75 leveling units in the field at one time. These lines are now at an age where releveling is desirable. It is hoped that a program may be instituted for releveling all lines 25 to 30 years of age or older in order to bring the net up-to-date. This would provide valuable data for geophysical studies in earth movement, sea-level variations, as well as provide up-to-date data for engineering purposes. It is planned to relevel certain selected lines using a criterion of 3 mm. $\sqrt{K}$ for section checks and using the plane-parallel plate method of observing.

Two adjustments have been made for theoretical study of all first-order leveling in the United States using the most recent leveling. The first adjustment consisted of 1,016 equations and only one mean-sea-level connection. This was for the purpose of studying the slope or inequalities of mean sea level. In the second adjustment the same leveling was used as in the first adjustment but in addition there were 17 open coast tidal stations at which mean sea level was held at zero. This adjustment had 1,032 equations. The probable error of the leveling in the first adjustment was 2.0 mm. per km. and in the second adjustment the probable error was 2.2 mm. per km.

The type of bench mark most frequently established is the concrete post which is about 4 feet in length, about a foot in diameter, and weighs about 600 pounds. Since one of the very important items in leveling is the establishment of marks that will remain stable, basic marks are now installed at 5-mile intervals. These marks consist of copper-coated steel rods driven to considerable depth.

Each of the level parties is supplied with a gasoline hammer for driving these rods which are ½ inch in diameter and 8 feet long. The 8-foot sections are coupled with a brass coupler and the rods driven to refusal. After reaching refusal the rods are cut off at ground level and a disk compressed to the rod. Usually if refusal has not been reached at 50 feet, driving is sufficiently difficult to furnish a stable mark; however, some rods have been driven to depths of 125 feet. Supplementary marks consisting of copper-coated nails and brass washers are now being placed in roots of large trees.

Metal posts with an attached aluminum sign bearing the legend "WITNESS POST—PLEASE DO NOT DISTURB NEARBY SURVEY MARKER" are now placed near our bench marks.

U.S. Geological Survey

During this period, the Geological Survey completed 28,167 miles of third-order and 98 miles of second-order leveling. This leveling was supplemented by the use of two new elevation meters with fully transistorized electronics. These new elevation meters were received in April 1961. Since then, they have been operated along highways to accomplish about 18,000 miles of fourth-order supplemental control for photogrammetric mapping. Operating speeds vary up to 25 miles per hour, according to the condition of the road surface, with average daily production of about 40 miles of leveling. The maximum reported in one day, with ideal conditions, was 102 miles. Accuracies within 2 feet are obtained routinely; with extra precautions, 1-foot accuracy is obtainable. In a typical area, operating costs for obtaining supplemental control were reduced from $15.23 per square mile by conventional methods to $11.20 per square mile by elevation meter.

U.S. Army, Corps of Engineers

Under cooperative geodetic programs 2,601 miles of second-order leveling were accomplished in Libya, and 1,435 miles in Iran.

The Inter-American Geodetic Survey collaborative program completed adequate systems of first-order leveling based on mean sea level in two Latin American countries. Continued assistance was furnished to 15 Latin American countries in the development of a comprehensive network of geodetic leveling. During this reporting period 17,340 miles of first- and second-order levels were observed, and 64 tide gaging stations were maintained to provide mean-sea-level determinations for the leveling. Since the beginning of this collaborative program, approximately 97,000 miles of leveling, establishing precise elevations for 82,000 bench marks, have been completed in Latin America, and mean sea level has been determined at 130 coastal points. Three of the Pacific Ocean tide stations have been incorporated in the Seismic Sea Wave Warning System.

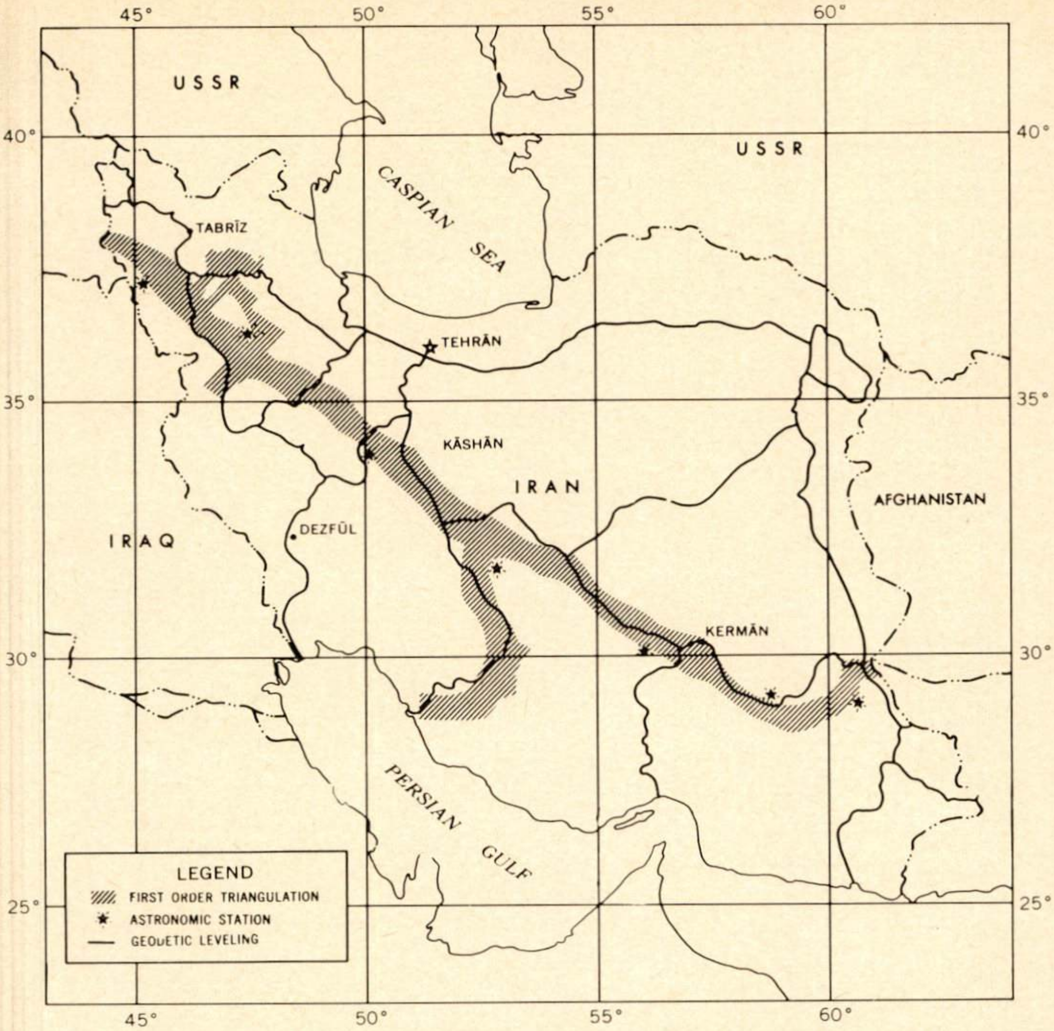

Figure 7.—Geodetic control in Iran.

Vertical geodetic control established by the Lake Survey consists of groups of bench marks in 136 harbors on the Great Lakes, and level lines of special first-order accuracy along the outflow rivers of the lakes. Elevations of the bench marks are listed on the recently established International Great Lakes Datum (1955). The 279 miles of special first-order levels, involving 459 bench marks, were run as follows:

a. Along the St. Marys River from Detour to Point Iroquois, Mich., a total distance of 81 miles, involving 127 bench marks.

b. Along the Inland Route from Cheboygan to Petoskey, Mich., a total distance of 51 miles, involving 64 bench marks.

c. Along the Fox River and Lake Winnebago from De Pere to Oshkosh, Wis., a total distance of 50 miles, involving 49 bench marks.

d. Along the St. Lawrence River from Cape Vincent, N.Y., to the Thousand Island Bridge, a total distance of 34 miles, involving 29 bench marks.

e. At various harbors on Lakes Ontario, Michigan, and Superior, a total of 60 miles, involving 186 bench marks.

f. At Selfridge Air Force Base, a total distance of 2.5 miles, involving four bench marks.

GEODETIC ASTRONOMY AND ARTIFICIAL SATELLITES

U.S. Coast and Geodetic Survey

FIELD OBSERVATIONS

Observations of latitude, longitude, and azimuth were continued throughout the United States and in other areas for the control of triangulation arcs, geoid studies, and detection of crustal movement. Numerous observations were also accomplished in various localities to provide data for the testing of inertial devices and for other special purposes.

First-order astronomic positions were observed mainly with Wild T–4 theodolites but occasionally with Bamberg meridian transits. Latitudes were determined by the Horrebow-Talcott method, using from 15 to 20 star pairs. Longitudes were derived from five to seven star sets of about six stars each. Time control was obtained from WWV or WWVH signals as recorded on battery-driven drum chronographs and compared with mechanical chronometers at 1-hour intervals. Transistorized radio receivers have been adopted as standard equipment to conserve weight and in view of their excellent performance on the short-wave bands. Typical probable errors obtained are 0.″10 in latitude and 0.s007 in longitude. In certain cases, where the highest accuracy is not required and maximum progress is essential, the first-order program is curtailed to eight star pairs for latitude and three or four star sets for longitude.

Second-order positions were observed with Wild T–3 theodolites, employing Polaris and a matching south star for latitude and four east-west star pairs for longitude. Personal equation was determined by comparing with first-order astronomic values, usually at intervals of five or six stations. Timing of longitude star passages was estimated by the observer from continuously audible 1-second time signal pulses, or recorded on a chronograph by means of a manually operated microswitch. The latter method was instituted in 1961, when it became possible to employ the lightweight battery-driven chronographs originally developed for first-order work. The chronograph method resulted in better stability of personal equation and a reduction in the time required to train new observers. Internal probable errors are typically 0.4 second of arc in each component, but due to personal equation uncertainties the actual probable error in longitude is estimated to be 0.8 second of arc.

Astronomic azimuths were observed with Wild T–3 theodolites, except that the Wild T–4 was employed in latitudes higher than 50 degrees. Close circumpolar stars were observed at any hour angle in the middle and high latitudes, while east and west stars near elongation were observed in equatorial latitudes.

First-order astronomic observations were made at 210 stations for position and at 217 stations for azimuth. Second-order observations were made at 192 stations for position and 23 stations for azimuth. Of special importance was a series of first-order Laplace stations established in 1961 for a Hiran trilateration survey extending from the main islands of Hawaii westward along the archipelago to Midway and Kure Islands. In 1962 an astronomic party developed a long-line Laplace azimuth traverse over the existing triangulation network from the southern end of Hawaii Island westward to Kauai Island, to improve azimuth control for the Hiran arc. Laplace azimuths were observed at alternate stations to control orientation of precise Geodimeter traverses in the southeastern United States. Astronomic positional coverage on an area basis for geoid development was nearly completed in Maine at the end of 1962.

VARIATION OF LATITUDE

Two of the five northern-hemisphere International Latitude Service observatories on the 39th parallel were continuously operated by the Coast and Geodetic Survey at Gaithersburg, Md., and Ukiah, Calif. At Gaithersburg, 10,071 star pairs were observed on 793 nights, with complete observations on 290 nights. At Ukiah, 11,716 star pairs were observed on 713 nights, with complete observations on 552 nights. Early in 1962, transmittal of weekly observing records to the Central Bureau in Mizusawa, Japan, was inaugurated to aid in the rapid processing and dissemination of polar motion data.

SATELLITE TRIANGULATION PROGRAM

Since October 1961 the Coast and Geodetic Survey has been developing a Satellite Triangulation Program, primarily to improve the internal accuracy of the triangulation network in the 48 conterminous States, and to provide and improve our geodetic connections to Hawaii and Alaska, including the Aleutian Islands. It is hoped that this network can later be extended to other continents.

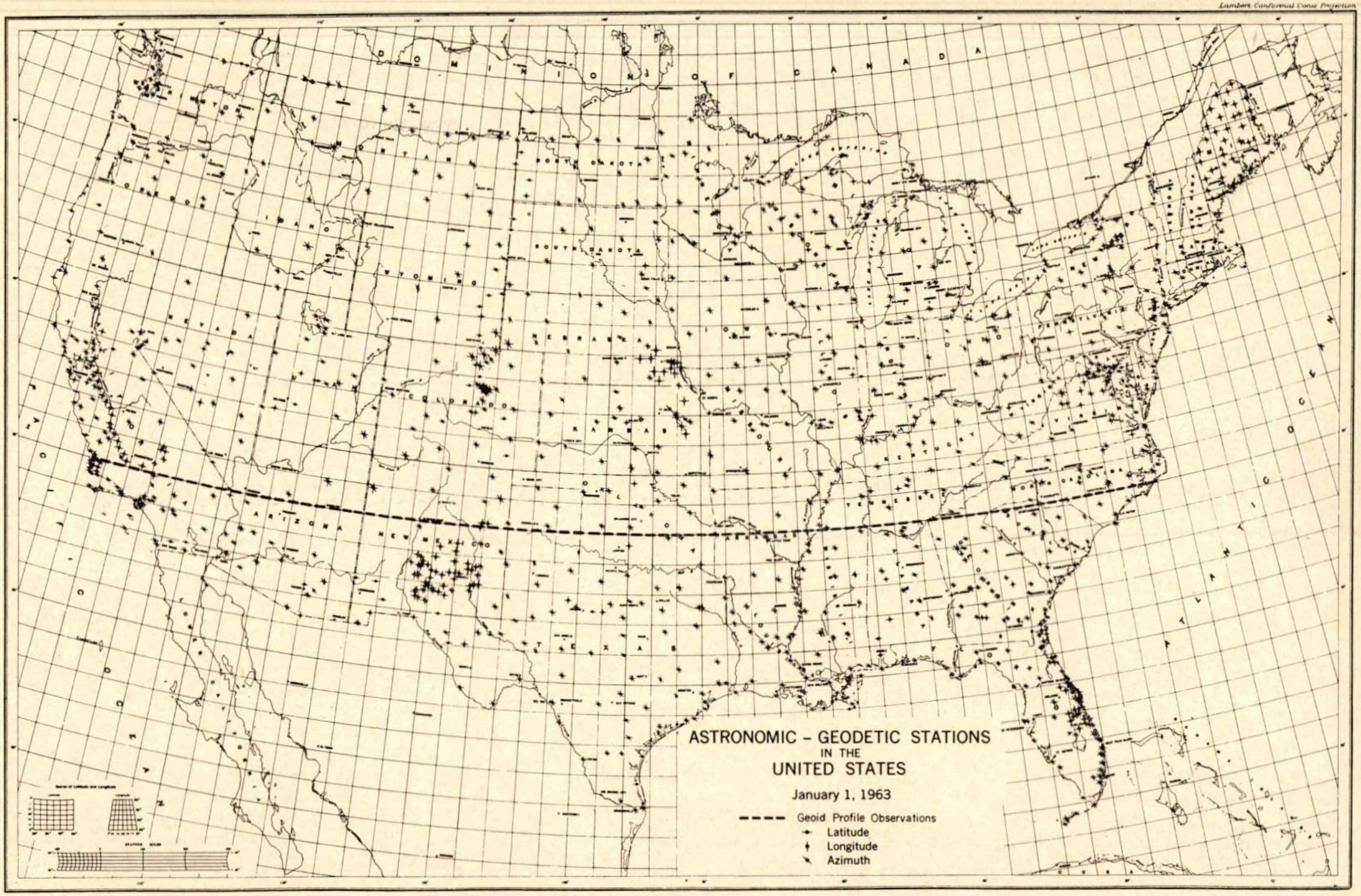

Figure 8.—Astronomic-geodetic stations in the United States.

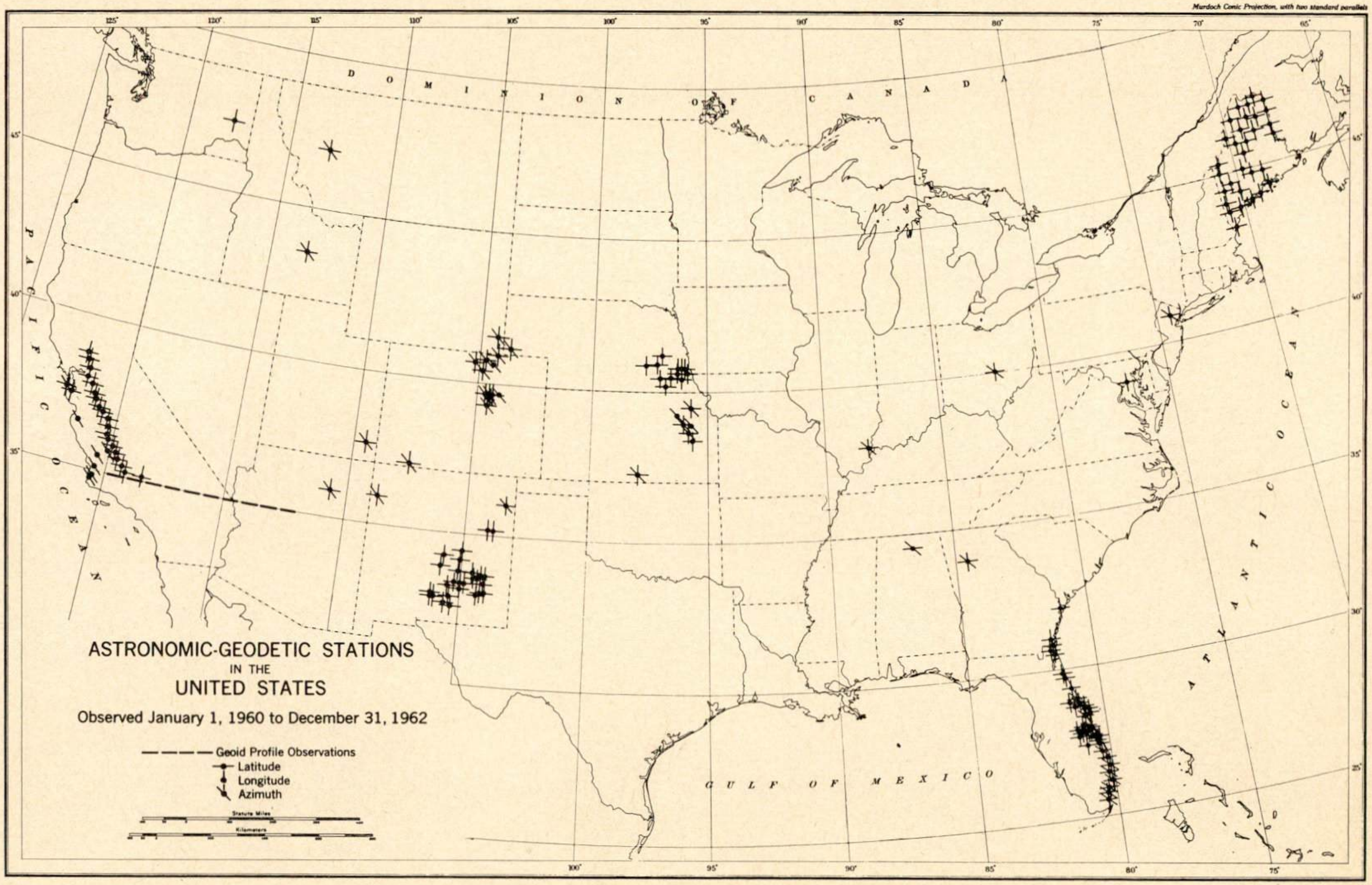

Figure 9.—Progress in astronomic observations in the United States.

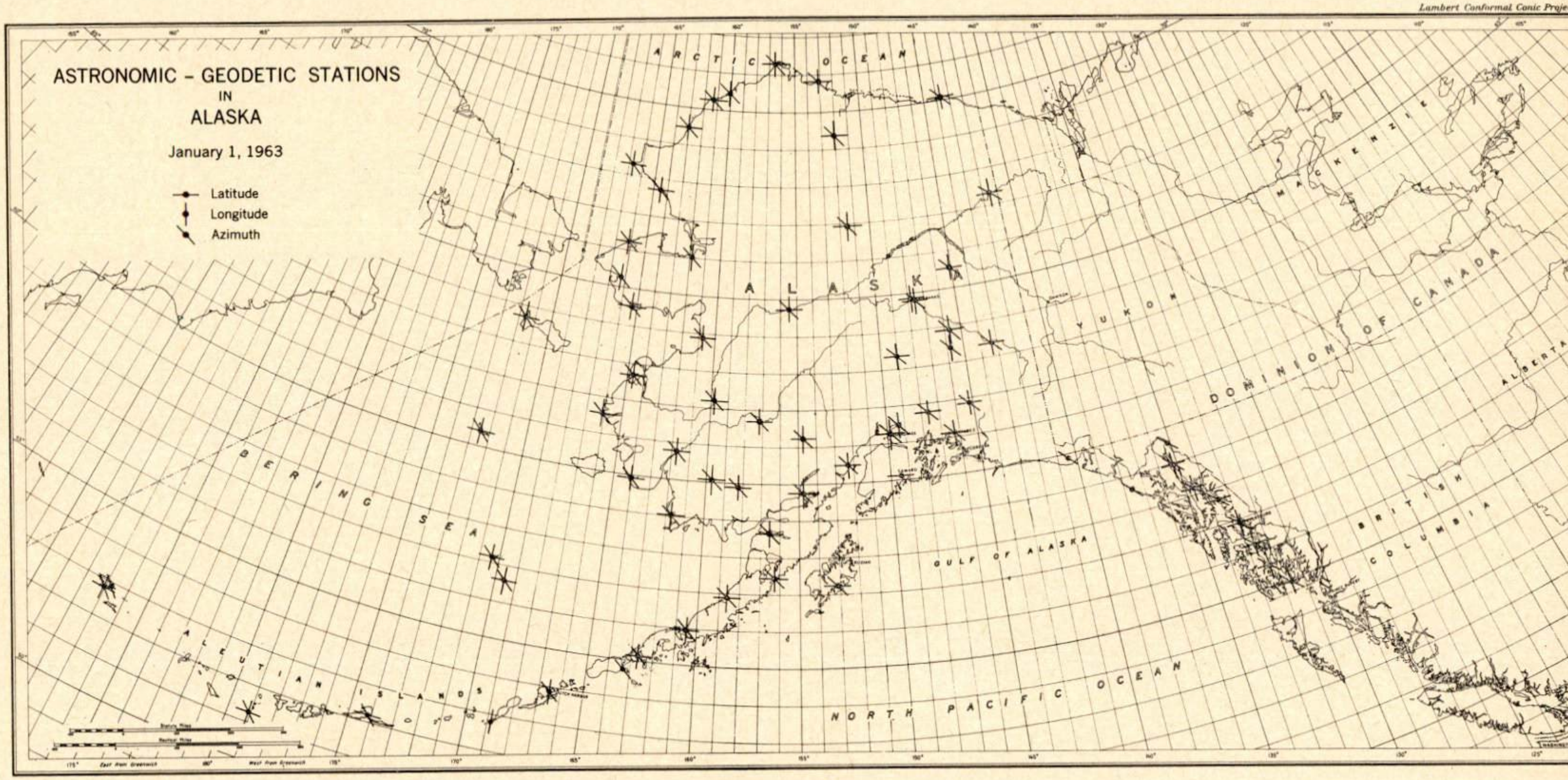

Figure 10.—Astronomic-geodetic stations in Alaska.

This program is based on the tracking of satellites, such as ECHO I, in the geometric mode from three to four camera stations. Precise transcontinental base lines with an accuracy approaching one part per million are planned to strengthen the geodetic network in the 48 States, in order to provide a highly accurate scale for the three-dimensional space triangulation configuration.

To obtain the expected accuracy from the program, it is important that the camera lens be of the highest quality, that special flat ballistic photographic plates be used, that the timing of each satellite image on the plate be known to better than 1 millisecond with respect to a time standard common to all cameras in the network, that the comparator measurements be accurate to a few microns, and that the latest data reduction techniques be used.

In January 1962, the Coast and Geodetic Survey received its first satellite tracking system, featuring well proven components of the highest mechanical and optical quality. The system was developed at the Ballistic Research Laboratory, Aberdeen Proving Ground, Md., and includes the renowned Wild BC–4 Ballistic Camera equipped with the Astrotar lens cone, and both rotating disk and iris type shutters. Shutter operation, timing, and synchronization are accomplished by an associated electronic synchronization system.

During 1962, an extensive calibration program was conducted on the first system. This program included tracking ECHO I at all exposure durations, various f-stop settings, and different image intervals. Calibration plates of star trails were obtained at all f-stops to determine radial and tangential distortion patterns. Vertical angle observations were made with the Wild T–4 to study refraction anomalies under varying weather conditions. Numerous other tests were made on the camera to determine the accuracy with which the camera could be oriented.

Test plates were obtained with over a thousand 40-micron images of ECHO I spaced across a single plate. The image size can be optimized for accurate comparator measurements by varying the f-stop setting and exposure duration. Timing of each image is well within ½ millisecond, and prolonged testing of the rotating disk shutters indicated jitter to be about 50 microseconds.

Data reduction on all plates was accomplished on high-speed electronic computers using analytical photogrammetric techniques developed by Dr. Hellmut Schmid, at BRL/APG.

Equipment has been received or is still on order to outfit three satellite tracking systems by late spring of 1963. A comprehensive three-camera calibration program will begin at that time.

U.S. Geological Survey

Since 1957, the Geological Survey has been obtaining mapping control in the Antarctic by astronomic observations. Most of the positions were obtained by altitude measurements to the sun. In 1961, a program of stellar observations during the continuous daylight of the Antarctic summer was initiated with success. A method for determining position, based on a change in azimuth with respect to time instead of the customary altitude method, was tested and procedures developed for its use. The azimuth method of position determination was proposed by C. H. Ney of the Geodetic Survey of Canada, and described in the June 1954 issue of the Transactions of the American Geophysical Union.

During the period covered by this report, 25 astronomic positions were observed on the Antarctic Continent. Eight of these positions were determined by the azimuth method, five of which are included in a 1,570-mile, helicopter-supported, geodetic traverse, described in the first section under Antarctic Operations.

U.S. Army, Corps of Engineers

Astronomic observations by the Army Map Service in support of triangulation, Hiran, datum adjustments, and geoid studies have been as follows: Fifteen first-order astronomic positions established in Libya, in support of the first-order arc of triangulation; 5 in the test area in Phoenix, Ariz.; 7 in Iceland; 10 in Greenland; and 4 in the Hawaiian Archipelago.

First-order astronomic positions were established during the period 1960–62 at 48 different locations throughout islands adjacent to the southeast coast of Asia by survey parties of the Army Map Service, the Army Map Service, Far East, the China Map Service, and commercial contractors. The Army Map Service, Far East also accomplished astronomic observations on Guam and Saipan for position determination, in support of surveys to accomplish geodetic ties within the Marianas; on four island stations in the southwest Pacific area, in support of the Hiran project there;

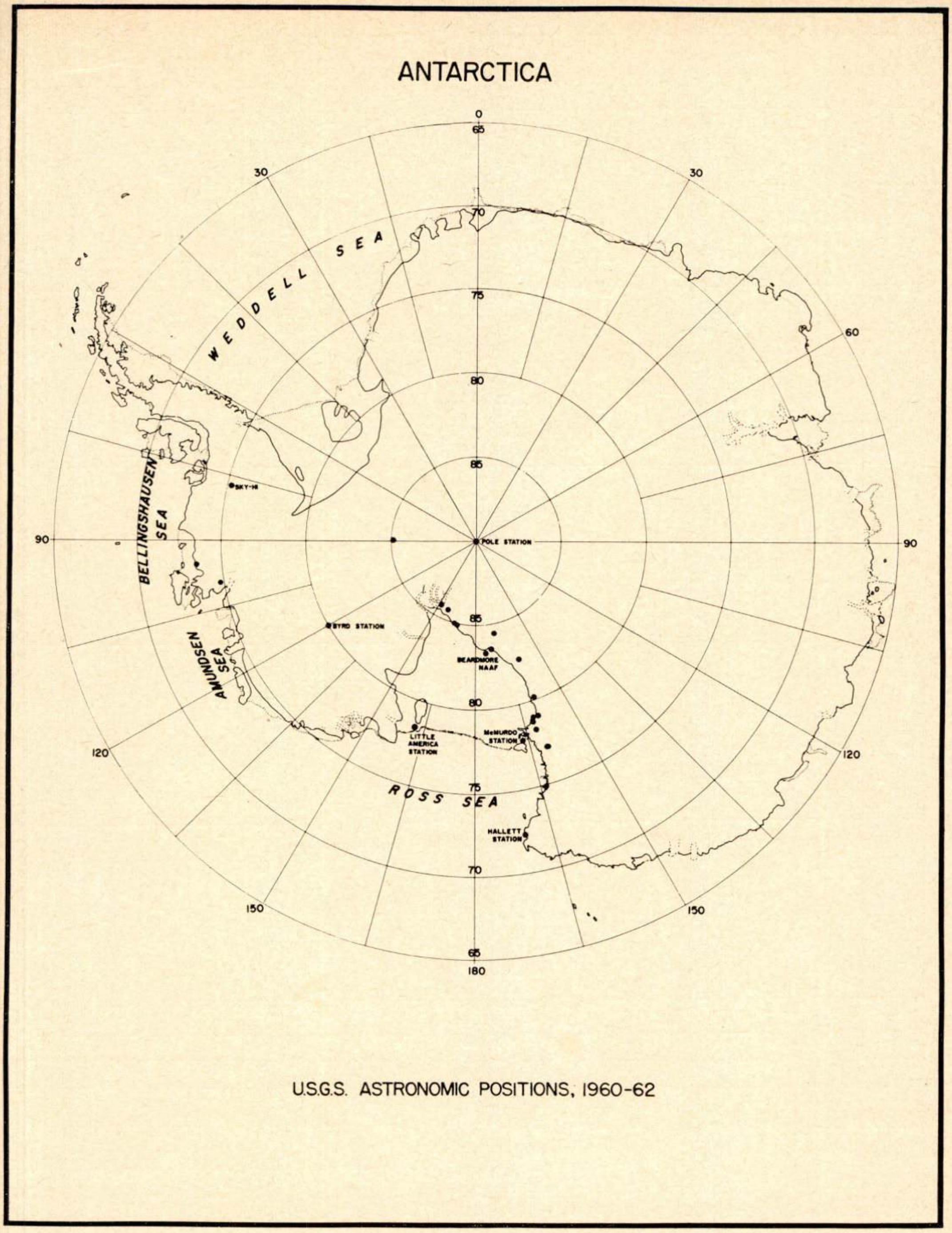

Figure 11.—Astronomic positions in Antarctica.

and observed two astronomic positions within the Kwajalein Atoll during the summer of 1962, in support of a special project monitored by the District Engineer Office, Mobile, Ala.

The Inter-American Geodetic Survey program, in support of geodetic activities in 15 Latin American countries, established 66 additional Laplace stations. Fifteen second-order stations were also established. A total of 378 astronomic stations have now been established since the beginning of the collaborative program.

OCCULTATIONS

The Army Map Service, Far East, continued its program of occultation observations to relate geodetic data of North America to that of Japan,

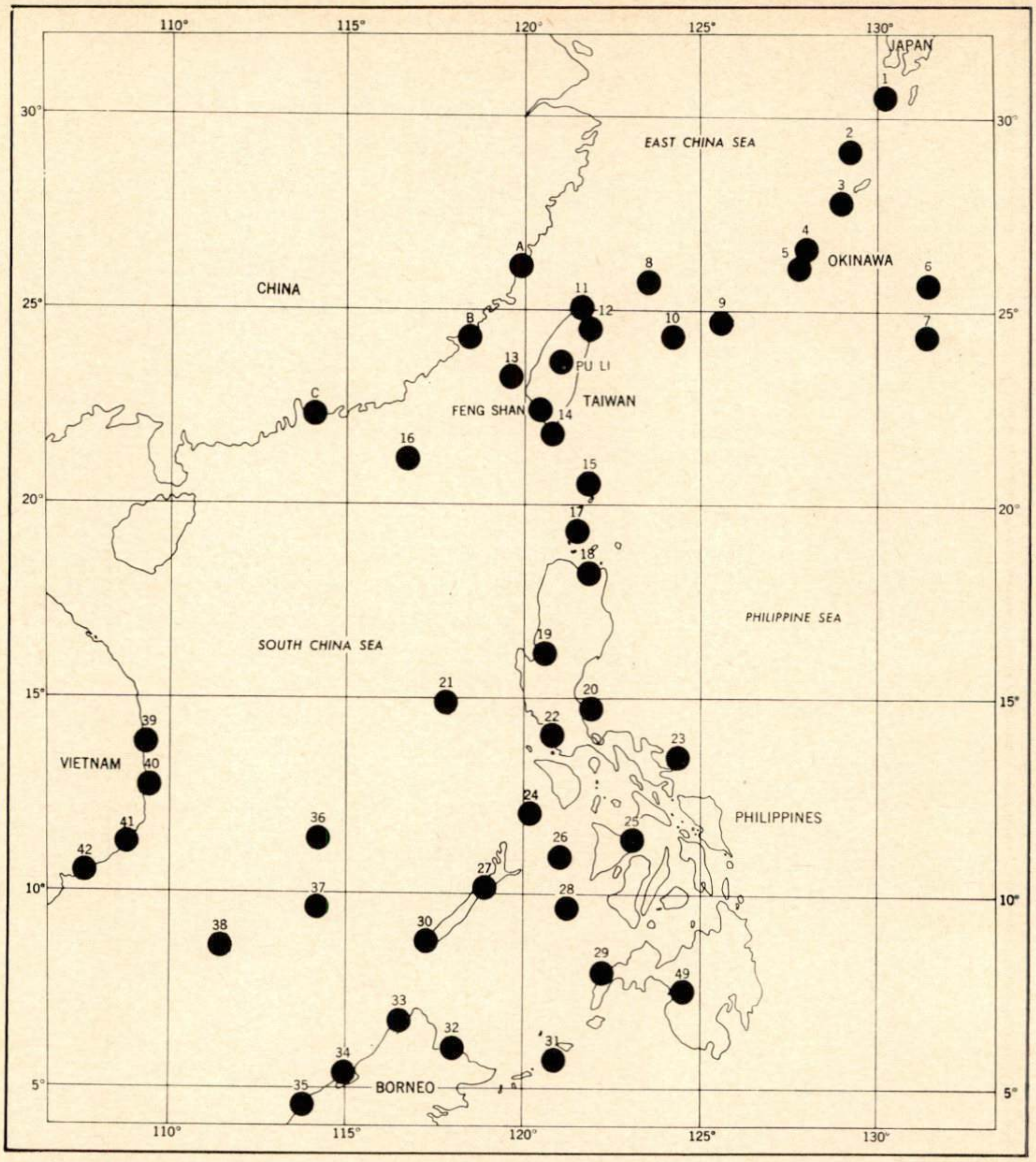

Figure 12.—First-order astronomic positions on the southeast coast of Asia and adjacent islands by the Army Map Service.

Taiwan, the Philippines, and various other Pacific Islands.

The Army Map Service prepared predictions of occultations throughout the world for 1964 and 1965 to be used in planning observation programs, and reduced the available 67 successful occultations observed from 2 or more sites. Reductions were made both with and without use of lunar profile charts. Preliminary analysis of the results indicates an improvement of previously reduced positions for each of 22 points in the Pacific area. A further solution using nine of these points was made, and provided a connection between Tokyo datum and North American datum.

LONG-LINE AZIMUTH MEASUREMENT

A technique for determining azimuths for exceptionally long lines where conventional methods cannot be used has become fully operational during the 1960–62 period. In determining an azimuth by this technique, an intense light is transported by aircraft across a straight line connecting two widely separated stations, usually Hiran stations, on which an astronomic azimuth for each has previously been determined and indicated on the ground by an azimuth mark. This light is flown at sufficient altitude to be observed and tracked by ground parties equipped at each of the two stations with special theodolites and cameras that photograph the horizontal circles of the theodolites which are initialed to the azimuth marks.

The photographing is controlled from the aircraft by a radio impulse that triggers the camera simultaneously, at intervals, while the aircraft is in the process of crossing the line connecting the two stations. The information on direction obtained in this way, combined with the previously determined information on direction of the azimuth mark, determines the desired azimuth of the line.

The major projects on which azimuths have been determined by this technique are the East Pacific Survey Project –9; the Southwest Pacific Project –4; the northeast coast of South America –2; and the Marshall Islands project. Azimuth operations on all of the projects have involved the services of the Air Force, the Army Map Service, and the Army Map Service, Far East. The Navy participated in the East Pacific and Southwest Pacific Survey Projects.

U.S. Air Force

AIR PHOTOGRAPHIC AND CHARTING SERVICE

Eleven first-order astronomic positions were observed at Hiran stations in the Cuba-Central America and the northeastern South America trilateration networks.

Twelve first-order astronomic stations were observed at missile sites in the European and Pacific areas.

One hundred and ten modified first-order and 480 second-order stations were observed in the continental United States in support of the missile program.

The Air Force has developed a geodetic stellar camera capability. Nine 1,000-millimeter focal length ballistic cameras have been used since November 1, 1962, for observations on the geodetic satellite, ANNA 1B. Six cameras are located at triangulation stations in the United States; the remaining three are at stations in Germany, Australia, and the Canal Zone. Geocentric coordinates will be determined for each camera station. The results (reduced data) of the observations were not available at the close of this reporting period.

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

During the December 1961 to January 1962 period, AFCRL, completed a field test, in the Vero Beach, Fla., area, of their technique for establishing azimuths between nonintervisible stations. This technique, employing photographically observed line crossings of an aircraft-borne stroboscopic light, shows promise as a complement to the Hiran trilateration technique.

On October 31, 1962, satellite ANNA 1B was successfully launched from AMR. This is a triservices geodetic satellite. AFCRL furnished the optical beacon and is directing the optical observing program for Project ANNA.

AFCRL has completed and successfully tested two large-scale computer programs necessary for the development of flash time requests for the ANNA optical beacon and also for the assignment of look angles to the entire worldwide optical observing net. Flash times are selected after giving weight to best observing geometries, type of cameras involved, position of moon, number of previous observations by a given station, etc.

AERONAUTICAL CHART AND INFORMATION CENTER

In support of the ANNA geodetic satellite, this Center provided the necessary geodetic information for the selection of the optical sites, developed the techniques and EDP programs for the mensuration of the optical data, and is currently analyzing and reducing all USAF optical data for the ANNA satellite. In addition, Project ANNA data will be used by ACIC to compute absolute positions of the observation stations, improve reference ellipsoid parameters, compute geodetic datum ties, and improve the representation of the earth's gravitational field.

ACIC and AFCRL jointly investigated the application of anomalous gravimetric data to missile trajectories. Gravity disturbances (gravity anomaly plus Brun's term) were computed along simulated trajectories and impact errors determined by numerical integration. This study has been expanded upon by ACIC and now includes the investigation of the effect of all geodetic and geophysical errors on ballistic missile systems.

U.S. Naval Oceanographic Office

During 1962, first-order astronomic observations were made by the Oceanographic Office at the following locations: Truk Island, Ponape Island, Nagatic Atoll, Kapingamarangi Atoll, Satawan Atoll, Tabar Island, Manus Island, and Buka Island.

U.S. Coast and Geodetic Survey

Gravimetric observations of the Coast and Geodetic Survey were accomplished entirely with Worden and LaCoste-Romberg gravity meters during the 1960–62 period.

The gravity base network was extended over two transcontinental traverses along lines of primary bench marks on the 32d and 38th parallels. The traverses were measured at a spacing appropriate for reduction of spirit-level observations (average 8 km.), with intermediate stations in cases of large elevation differences. Similar observations were made along the east coast between North Carolina and Florida; in the mountainous region of Colorado; from Colorado northward and eastward to a junction with the midcontinent line; and from central California northward to Seattle, Wash., and eastward to Montana. Several long distance east-west gravity meter connections were measured directly using commercial air transport to strengthen the national base network.

Calibration operations included a complete rerunning in both directions over the midcontinent base between Brownsville, Tex., and Winnipeg, Manitoba, using LaCoste-Romberg geodetic meter G–6. Similar repeat observations were made over the Washington-Ottawa base and the 240-mgal base between Washington and Sperryville, Va. Also, additional gravity meter observations were made between the first-order stations in Washington and Ottawa to strengthen that connection and provide additional calibration comparisons between the two countries.

Data from area coverage surveys are compiled on IBM tabulation sheets and include simple Bouguer and free-air anomalies. Terrain corrections are not determined because of the low topographic relief in the regions covered.

The first surface-ship gravity meter acquired by the Coast and Geodetic Survey, LaCoste-Romberg S–11, was operated nearly continuously on the U.S. Coast and Geodetic Survey ship *Pioneer* from April to November 1961. As part of the oceanographic program, gravity was observed on a series of track lines running southward from the Aleutian peninsula and between meridians 155° W and 160° W. A number of diagonal lines were run over the Aleutian Trench from Kodiak to Adak, and readings were taken at oceanographic stations along two meridians west of 160° W. Gravity values were obtained for about 85 percent of the time the ship was at sea. Gravity checks on cross lines showed discrepancies of less than 10 mgals in 70 percent of the cases. LaCoste-Romberg meter S–12 was installed on the U.S. Coast and Geodetic Survey ship *Surveyor* which departed Seattle, Wash., in mid-February 1962. Measurements were taken while the ship proceeded on a submarine cable survey project extending westward to Okinawa via Hawaii, Wake, and Guam. The *Surveyor* returned to Seattle in June, and in July departed for operations in the Chukchi Sea. On return from this project, the *Surveyor* made additional surveys of the Aleutian Trench along north-south and diagonal lines from Adak to Kodiak, and across the Gulf of Alaska. Gravity was observed on the *Pioneer* in conjunction with the 1962 oceanographic program in the north Pacific until late March, when the ship was diverted temporarily to a special project. In early August the *Pioneer* began operations at a series of oceanographic stations in the Pacific, including gravity observations at the stations and while en route between them.

To evaluate performance of surface-ship gravity meters under actual sea conditions, a gravity test area was surveyed in May 1962 out to the 60-fathom curve off San Francisco, Calif. A total of 127 gravity stations were established at a spacing of 3 miles. Observations were made from the U.S. Coast and Geodetic Survey ship *Bowie* with a LaCoste-Romberg underwater meter furnished by the Naval Oceanographic Office.

U.S. Geological Survey

Gravity surveys in connection with geologic investigations and crust of the earth studies have been made in parts of 23 States by the Geological Survey. Major gravity programs are centered in Alaska, the New England States, the Pacific southwest, and in several widely separated areas in support of the seismological program of the Branch of Crustal Studies. A regional survey of land observations was made on Kodiak Island, Alaska Peninsula, and adjacent islands in support of shipboard observations made by the U.S. Coast and Geodetic Survey ship *Pioneer*. A gravity survey in the Hawaiian Islands is related to a study of volcanoes. Most surveys are of the regional type and are closely correlated with regional geologic

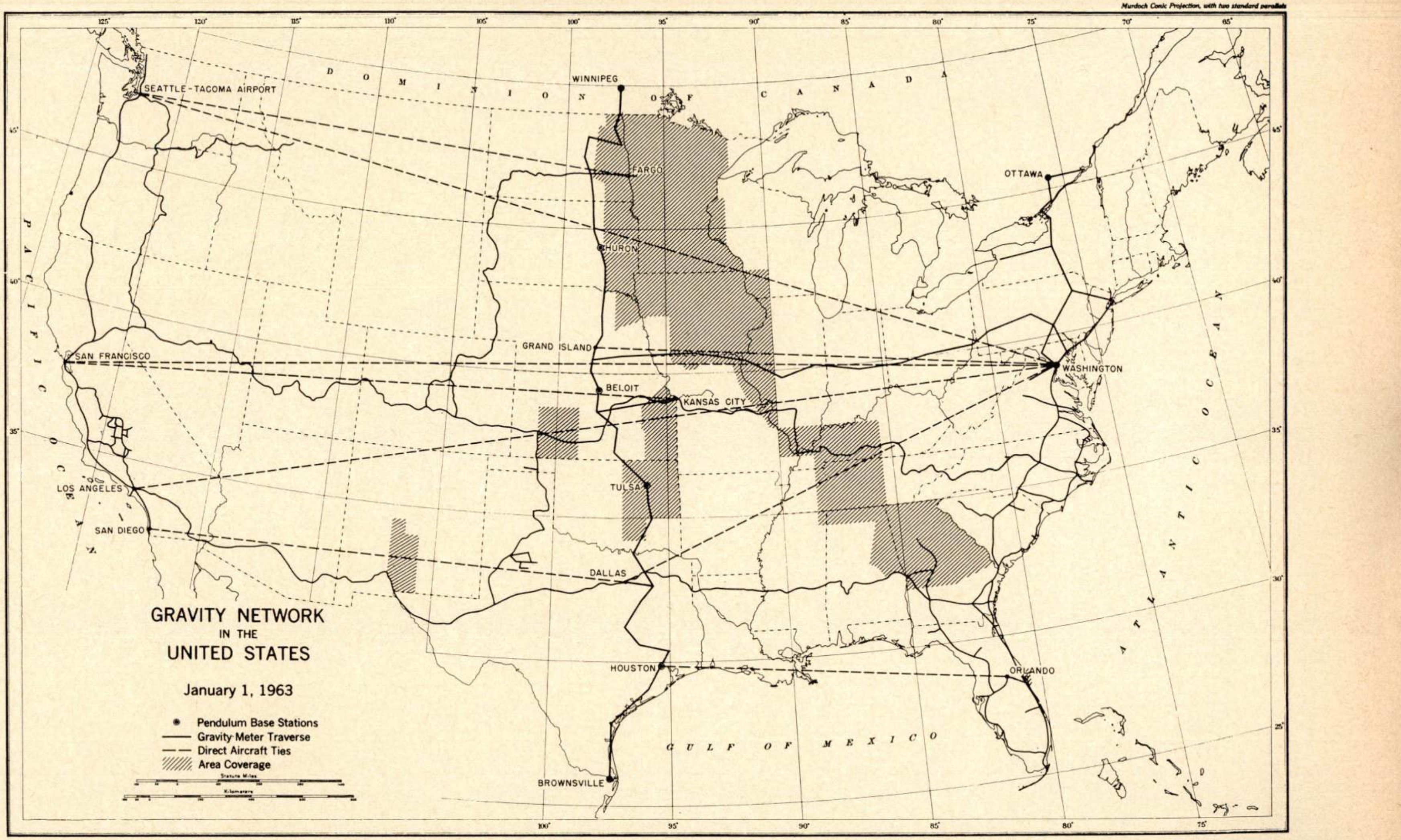

Figure 13.—Gravity network of the Coast and Geodetic Survey.

Figure 14.—Extension of gravimetric observations by the Coast and Geodetic Survey.

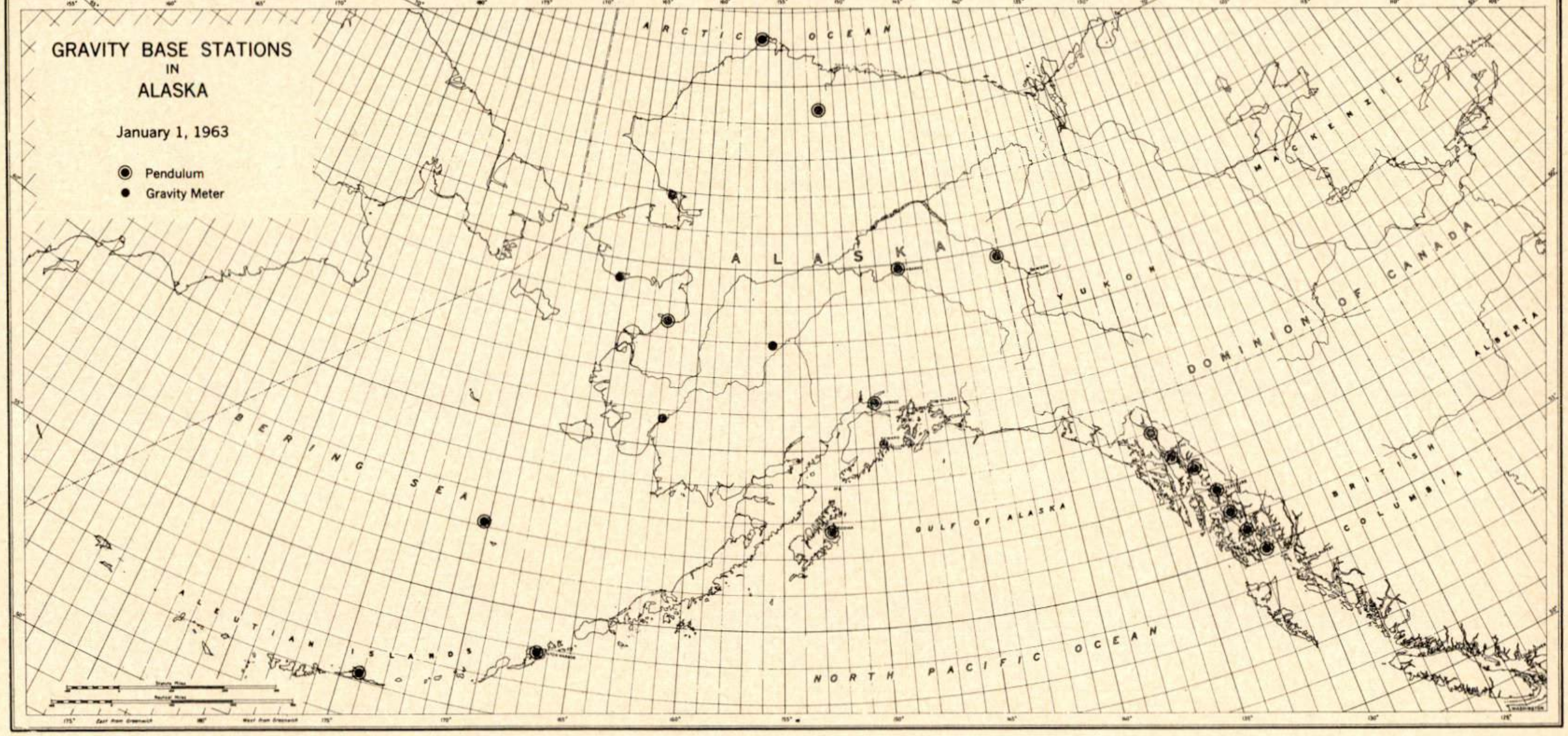

Figure 15.—Coast and Geodetic Survey gravity base stations in Alaska.

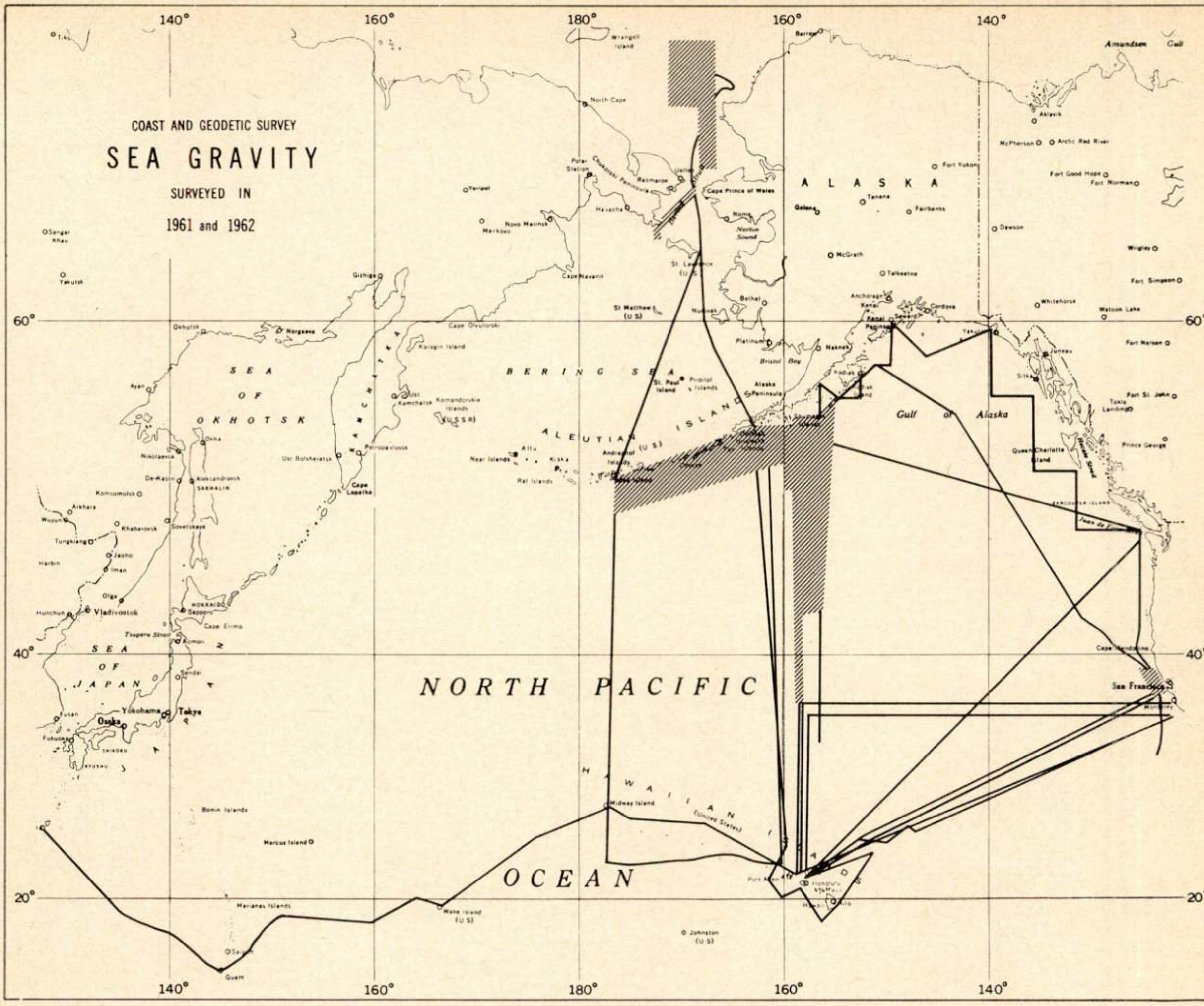

Figure 16.—Coast and Geodetic Survey sea gravity observations.

mapping programs. A few surveys consist of detailed studies over relatively small features such as mineral deposits and alluvium-filled bedrock depressions.

Nearly 29,000 stations were measured during 1960–62 in these various areas. The combined areal coverage is about 175,000 square miles. The station spacing varies from 100 feet in detail investigations to as much as 7 miles for regional work. Elevations for surveys are obtained from various types of bench marks, altimetry, and spot elevations on Geological Survey topographic maps.

Most gravity surveys are referred to Dr. G. P. Woollard's airport and university network in the United States; in a few instances they are referred to Coast and Geodetic Survey pendulum stations. Base networks for regional surveys are measured with a precise low-drift gravity meter. Standard Bouguer reductions for a density of 2.67 g. per cc. are made for all stations, and many stations are reduced for several additional densities according to the local rock types. Bouguer reductions include terrain corrections where they are significant to the interpretations of anomalies. Airy-Heiskanen (T=30 km.) anomalies for 150 stations were compiled prior to 1960 for a study of the Sierra Nevada in east-central California.

Gravity reductions including terrain corrections have been programed for use on the Geological Survey's electronic computer. The program has been in operation since 1959.

The Geological Survey will publish and distribute both a free-air and a Bouguer gravity map of the United States in cooperation with the American Geophysical Union's Committee for the Geological and Geophysical Study of the Continents. The gravity maps are being compiled by a group of editors under the direction of Dr. Woollard.

U.S. Army, Corps of Engineers

The Army Map Service completed gravity observations at 12 stations of the Southwest Pacific Hiran survey; 63 across the Greenland Ice Caps, with logistical support by the U.S. Army Transportational Environmental Operations Group; and at 15 stations of the North Atlantic Hiran network—7 in Iceland and 8 in Greenland. All observations were referred to existing World Gravity Base Reference stations in the respective areas, and those in Iceland and Greenland were also tied back to the U.S. Pendulum Base station in Washington, D.C.

The Army Map Service, Far East, by November 1962, had completed 754 gravity observations in the Far East and Southeast Asia. Field operations are underway to accomplish an additional 2,762 observations throughout the area. Military personnel of the 29th Engineer Company (Survey Base) accomplished about one-third of the observations; and the remainder were completed by a local National Survey Agency or commercial contractor.

The Inter-American Geodetic Survey provided technical and logistical support to a cooperative program of strengthening and extending gravity reference base nets in all the countries of Latin America which invited the assistance. Reference nets have been strengthened by the addition of 178 reference stations, in order to include and evaluate available detailed gravity coverage. Comparative accuracy has usually been within ±0.1 mgal. Absolute accuracy is limited by available standards for instrument calibration. In addition to the base nets, 8,652 detailed gravity observations were accomplished along lines of leveling in Mexico, Guatemala, Costa Rica, Cuba, Colombia, Peru, Bolivia, Chile, Brazil, and Venezuela. In Venezuela, a portion of the observations were made specifically to improve the studies for the La Canoa Datum. The total detailed gravity observations accomplished under the collaborative program through 1962 stands at 19,436.

U.S. Air Force

AIR PHOTOGRAPHIC AND CHARTING SERVICE

During the period covered by this report the following gravimetric observations were accomplished.

Ten pendulum and gravity meter base stations were reoccupied and 60 new base stations were established in northeastern South America using 2 temperature-controlled Worden Master Meters.

Ties were made between the following gravity base stations using two temperature-controlled Worden Master Meters: Orlando, Fla.-Washington, D.C.-McGuire Air Force Base, N.J.-Gander, Newfoundland-Prestwick, Scotland-Frankfurt, Germany-Wiesbaden Air Force Base, Germany-Bad Harzburg, Germany; Wiesbaden Air Force Base-Munich, Germany, and Wiesbaden-Rome, Italy.

In 1961, a short-range Worden Master prospecting meter was used to connect 17 base stations between Key West, Fla., and Charleston, S.C., on the east coast calibration line.

Three Worden Masters, one miniature and one large LaCoste-Romberg gravity meters belonging to the Air Force and one miniature geodetic LaCoste-Romberg, owned by the University of Wisconsin, were calibrated over seven pendulum bases on the east coast calibration line between Bogota, Colombia, and Loring Air Force Base, Maine. Twelve intermediate stations were observed.

Three gravity base stations were reoccupied and 13 new base stations were established in the Hawaiian Islands with 2 temperature-controlled Worden Master meters.

Beginning in July 1961, 25 pendulum and gravity meter base stations were reoccupied and 118 new base stations were established in Southeast Asia. This work was accomplished in cooperation with the University of Wisconsin and the Army. Two miniature geodetic LaCoste-Romberg meters were used.

The University of Wisconsin under contract to the Air Force reobserved key base stations on the Point Barrow-Mexico City Calibration Line with the Gulf quartz pendulum (M Set) and a large LaCoste-Romberg geodetic gravity meter.

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

Land Gravity Studies

During 1960–62, regional ground gravity surveys were completed in Massachusetts. Spacing was similar to class B. Charts showing both Bouguer and free-air anomalies at 5-mgal contour intervals have been completed for all of Massachusetts.

During 1960–62, ground gravity surveys with spacing similar to class B were completed in the vicinity of Edwards Air Force Base, Calif., in support of AFCRL's airborne gravity research effort.

By summer 1962, a completely new network of gravity stations was established at 72 Air Bases throughout the country. This work also includes a gravity meter calibration line which runs from Key West, Fla., to Presque Isle, Maine.

Airborne Gravity Program

From January through May 1960, the AFCRL LaCoste-Romberg prototype airborne gravity meter was tested in a C–130 aircraft at Edwards Air Force Base, Calif., and at Tinker Air Force Base, Okla.

From March to May 1962, and from July to September 1962, the AFCRL LaCoste-Romberg airborne gravity meter and an AFCRL-modified Askania-Graf Sea Gravity Meter were successfully tested at Edwards Air Force Base, Calif.

Theoretical Gravity Studies

Normal Gravity.—The theory and practical computation methods for the continuation of the normal gravity and gravitational field of an ellipsoid of revolution have been fully developed. Closed formulas and power series are available to compute any parameter of the normal field in terms of both geocentric Cartesian and gravimetric systems.

Anomalous Field.—Three different methods have been developed for the computation of gravity anomalies or disturbances at high altitudes. (1) The direct method, which determines the anomalies and disturbances at any elevation directly from the gravity anomaly field at the earth's surface. (2) The coating method, introduced by Helmert but recently modified, applies a coating of disturbing masses to the model of the normal field for determination of the anomaly field in different altitudes. (3) A third group of methods which are based on different derivations of the potential. In addition to the above theories and techniques for the upward continuation of gravity, five different methods have been developed for interpolations and extrapolations of gravimetric quantities in the earth's gravitation field.

New Gravity Formula.—A set of new gravity formulas has been computed from the free-air and isostatic anomaly coverage of the earth. The different solutions are under study and a recommendation to replace the present International Gravity Formula may come as early as 1963.

Other Theoretical Research.—The statistical analysis of free-air, Bouguer, and isostatic anomalies is continuing by using the gravity material over different selected representative areas. Several interim results, such as correlation coefficients and Zonal Harmonics of the direct and indirect effect of the topographic-isostatic reduction, have been published.

Gravity Experimentation and Instrumentation

Reversible Pendulum Absolute Gravity Experiment.—The AFCRL experiment is an outgrowth of a pendulum apparatus previously developed (described below) by AFCRL for relative gravity measurements. It employs the reversible pendulum technique previously used by Heyl and Cook in Washington, D.C., during the 1930's, but it has many novel features to eliminate the difficulties and inaccuracies encountered in earlier experiments. In addition, a great advantage has been offered by the advancements brought about in the state-of-the-art by modern technology. The pendulums used in this experiment are only 4 inches long. They are made of optically flat rectangular blocks of special clear quartz wrung together by molecular cohesion in the fashion of a two-rung ladder. This configuration not only permits a small apparatus to be used, but it also eliminates the troublesome flexure of the long 1-meter pendulums. Two pendulums are swung together in antiphase on sapphire knife edges to eliminate the sway of the support, but only one pendulum is actually used for the gravity determination. The object of the "absolute" experiment is to configure the pendulum so that it has the same period of swing, under the attraction of gravity force, no matter from which end it is suspended, hence the nomenclature "reversible pendulum." The points of suspension of the AFCRL pendulum are actually the inner optically flat surfaces of the two "rungs" of the "ladder." Since the distance between these surfaces must be known very accurately, they have been partially silvered and an interferometric technique is used to measure this distance to a very high precision. These measurements can be made while the pendulum is actually swinging. The pendulums are enclosed in a temperature-controlled high vacuum chamber. It is significant to note that the entire observational procedure, including the reversal of the pendulum, can be performed without opening the vacuum chamber.

Although many novel features of this experiment make it extremely distinctive from previous efforts, it is unique in that the small pendulum design has permitted the fabrication of a portable apparatus. Now, for the first time, it will be possible to make the experiment at other sites where absolute gravity determinations have been and are being made, thereby permitting a direct comparison of results.

Preliminary experimental measurements are currently being conducted and it is hoped that our first results will be available shortly after the beginning of 1963.

Relative Pendulum Apparatus.—A new pendulum apparatus has been developed by AFCRL which will permit more rapid and accurate gravity observations to be made. In this apparatus, pendulums are contained in an ion-pumped vacuum-sealed temperature-controlled chamber. The pendulums are of a flat bar type and are only 4 inches long. They are made of molybdenum and have sapphire knife edges. The pendulums are swung in pairs in antiphase on a central quartz optical flat to eliminate sway of the support. Without opening the chamber, any two of the six pendulums can be selected and used for an observation. This permits many pairs of pendulums to be used in rapid succession, which increases the observational accuracy and eliminates the long delays necessary when a vacuum chamber must be opened to change pendulums. The pendulum period is measured by an optical and electronic timing system which automatically programs a multiplicity of measurements for each individual observation. Resultant time intervals are recorded on paper by a digital printer and the pendulum period is immediately available at the end of each observation without any further elaborate reduction process. Preliminary field tests completed during 1962 indicate that the apparatus is capable of measurements accurate to the order of ± 0.1 mgal.

Gravitational Constant Experiment.—During 1962, AFCRL initiated a program to design a new experiment leading to the determination of the gravitational constant. No results of this effort are available at this time.

AERONAUTICAL CHART AND INFORMATION CENTER

The Aeronautical Chart and Information Center (ACIC) became custodian of the U.S. Air Force (USAF) Gravity Library in January 1960. Under the direction of Headquarters, USAF, the Center assumed operating, collecting, classifying, evaluating, and reducing activities for worldwide gravity data and the publication of suitable graphics. ACIC is investigating methods of utilizing available geologic, seismic, and other geophysical information to produce gravity values to approximate the gravimetrically void areas of the world. ACIC supported the Air Force airborne gravity meter test by computing surface and elevated gravity, Eötvös Corrections, and reducing navigational data.

U.S. Naval Oceanographic Office

Gravity meter observations have been accomplished by the Naval Oceanographic Office on several cruises during this period. A profile of observations was obtained on the U.S.S. *Triton* during its historic submerged circumnavigation of the earth. These data will be published as soon as the navigational data are adjusted and plotted. A broad ocean survey was also conducted aboard U.S.S. *Rehoboth* providing several lines of data in the central Pacific.

In addition to sea observations aboard ships, an area of approximately 225 square miles was surveyed with an underwater gravity meter in the vicinity of Rhode Island Sound. This survey provides a means of evaluating and comparing ship and submarine gravity instruments under operational conditions. A second such test range was established in cooperation with the Coast and Geodetic Survey in the approaches to San Francisco. Several lines of gravity observations were also established in the Chesapeake Bay for use as an evaluation and training area.

In conjunction with Project MAGNET, an airborne worldwide geomagnetic survey, geodetic gravity meter observations were initiated in 1962 at national base stations throughout the world. These observations will be provided to the International Gravity Bureau for use in strengthening the World Gravity Base Network. Observations have also been made between Washington, D.C., and Ottawa, Canada, as a base line for other observations between Washington and Augusta, Maine, to be used as a check range for gravity meters. The Oceanographic Office also provided a meter for a transcontinental tie by Dr. Morelli between New York, Baltimore, and San Francisco.

Gravity data are being collected from all areas of the world, and an indexing and recording system is being established using punched cards. Although most of the work of the Naval Oceanographic Office is in support of Navy requirements, every effort is being made to cooperate with the oceanographic community in the test and evaluation of ocean gravity instrumentation and survey procedures.

PHYSICAL GEODESY

U.S. Coast and Geodetic Survey

The geoid profile extending across the United States on the 35th parallel was completed in May 1960. Astro-geodetic deflections were observed at 186 stations at an average spacing of 14 miles. The section has been compared with one derived from the Army Map Service geoidal map of North America. After rectifying a difference of geoid height datum, the comparison shows a standard deviation of ±2.5 m. at 5° longitude intervals and a generally good match along the parallel; the AMS section has a somewhat larger systematic tilt downward to the west at the Pacific Coast end. Estimates for the geoid profile indicated a probable error accumulation of ±2.7 m. in the geoid height over the 4,000-km. distance, as contributed by the astronomic data, deflection interpolation, and triangulation uncertainties. Experimental computations were undertaken to match the astro-geodetic geoid profile with various gravimetric geoid representations, and find the corresponding scales of centered ellipsoids having a flattening of 1/298.3. It was found that a gravimetric geoid having a rise of some 9 m. in the center of the profile, relative to the two ends, would give a semimajor axis of 6,378,180 m.

In 1960 an astro-geodetic network was developed in east central Florida to provide geoid undulations for positioning of tracking cameras at Atlantic Missile Range installations. Relative geoid heights were determined for 32 points. Gravimetric analysis was employed for interpolating deflections in cases where the astro-geodetic station spacing was larger than allowable. Least-squares adjustment of a closed loop in the network indicated a probable error of ±5.8 cm. at the most distant point. In 1962 a similar network comprising 16 stations was established in the Bahama Islands.

Gravimetric deflections were determined at 10 stations in the central United States and at 1 station on Ascension Island.

Orthogonal components of the anomalous gravity field at altitudes up to several hundred miles were determined for numerous rocket trajectories. The anomalies were calculated from the Stokes surface coating as derived from surface gravity and geoid height data.

U.S. Army, Corps of Engineers

The Army Map Service study on this subject continues, but has not resulted in any major new finding relative to the geoid since the IUGG meeting in Helsinki in 1960. However, activity conducted relative to this study has resulted in some items of interest with respect to the lunar distance.

The geoidal profile along the 30th meridian in Africa was used to compute the length of the chord between the observatories at Greenwich and at the Cape of Good Hope in terms of kilometers. With this length as scale the mean lunar distance was computed, as deduced from the parallax observations of crater Mosting A made by W. Christie and D. Gill in 1905–10. The result is 384,413.3 km. or 384,415.5 km. depending on the weighting system.

The geoidal map of North America and the Astro-geodetic World System were then used to insert geoidal heights into the computations of the lunar distance from occultations, made by J. A. O'Keefe in 1952. The modified result is 384,400.9 km. at mean parallax of 3422″.603.

The Astro-geodetic World System combined with recent estimates of the mass of the moon was also used to compute the dynamic parallax of the moon as 3422″.610 ±0.13, and the corresponding lunar distance as 384,400 ±2 km. This result disagrees with Christie and Gill, but agrees very well with those from occultations and from radar measurements (Yaplee).

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

On October 31, 1962, the first satellite designed for geodetic purposes, ANNA 1B, was launched into orbit. The principal tracking systems carried by ANNA 1B were the TRANSIT type Doppler beacon, developed by Applied Physics Laboratory of the Johns Hopkins University, and

Xenon flash lamps of about 8,000 candle-second intensity developed by Edgerton, Germeshausen & Grier, Inc., for the Air Force Cambridge Research Laboratories. Participating in the tracking of ANNA are the Navy TRANSIT Doppler system, using frequency pairs of 162–324 mcs. and 54–216 mcs., and several types of camera systems from various organizations: the 500 mm. f/1 Baker-Nunn Cameras (Smithsonian Astrophysical Observatory); 1000 mm. f/5 fixed cameras (Air Photo and Charting Service); 1000 mm. f/5 equatorially mounted cameras (NASA); 300 and 600 mm. fixed cameras (Coast and Geodetic Survey and missile test ranges); and other types. Experience has indicated that the fixed cameras obtain a small, sharp image accurately measurable but usually difficult to identify.

Prior to ANNA, radio tracking used in geodetic studies have been the Navy TRANSIT Doppler and the NASA MINITRACK interferometer, using frequencies of 108 and 136 mcs. Optical tracking employed in geodetic studies has been almost entirely by the 12-station network of Baker-Nunn Cameras of the Smithsonian Astrophysical Observatory, utilizing solar illumination of the satellite.

Tracking systems currently in development for geodetic purposes, but not yet obtaining useful results, are continuous-wave radio ranging systems and Laser searchlights with retrodirective reflectors.

Another satellite of geodetic significance to be launched in 1963 is SYNCOM, which will have a nearly circular, equatorial 24-hour orbit resonating with the equatorial ellipticity, J_{22}, and other harmonics J_{nm} for which $n-m$ is even and m is non-zero.

Advances in measurement also of importance to satellite geodesy have been the adoption of very low frequency (VLF) time signals and the extension of synchronization of time signals.

Nearly all results from satellite geodesy published so far have been determinations of variations in the gravitational field. The early determinations of the zonal harmonics J_2 through J_5 were confirmed by several workers using a variety of observational data. Since 1961, improvement in knowledge of zonal harmonics has principally been the work of Kozai (1962), who has obtained determinations of the zonal harmonics up to J_9 using 13 orbits. An interesting feature of these results is that the harmonics J_5 through J_9 are much smaller than the J_3 and J_4.

The tesseral harmonics, or longitudinal variations, of the gravitational field are more difficult to determine because the daily, semidaily, etc., oscillations in the orbit which they cause are less than one-tenth as large as the long-period variations due to the odd-degree zonal harmonics. Starting in 1961, several analyses of satellite orbits for some of the tesseral harmonics were made, with a considerable scatter of results. Recent solutions for the equatorial ellipticity term, J_{22}, range from 1.0 to 1.8×10^{-6} in amplitude and from 8° W to 25° W in direction of the principal axis. The difficulties are mainly due to the inadequate accounting for drag on the orbit, coupled with nonuniform distribution of observations, a statistical problem on which further research is needed.

Studies have been made for station position shifts from simultaneous and near-simultaneous observations by Veis and others, but the only results so far published have been byproducts of orbit analyses for gravitational purposes.

Many theoretical papers on close satellite motion have been published. The theories most extensively applied in practice are those of Musen (1959) and Brouwer (1959). The development which appears to account most precisely for the effect of the oblateness is that of Vinti (1959, 1961), who employed an ellipsoidal representation of the gravitational field. Theoretical attention has turned more recently to the resonance problems associated with the critical inclination of 63.4° (for which Izsak (1962) appears to have the most complete solution), and with the 24-hour orbit, useful for determining J_{22}.

Satellite orbit research for other perturbations such as atmospheric drag, radiation pressure, and luni-solar effects are perforce of interest to geodesy but outside the scope of this review.

U.S. Air Force

AERONAUTICAL CHART AND INFORMATION CENTER

Late in 1959, newly acquired satellite material and gravimetric data were included in the development of improved World Geodetic Systems by AMS and ACIC. The two independently derived systems were compared, found compatible, and combined to form the Department of Defense World Geodetic System in April 1960 (WGS 60). Research efforts are in progress at ACIC to improve and refine WGS 60, by the inclusion of additional Hiran, gravimetric, and geodetic satellite data. ACIC has produced an astro-geodetic geoid undulation chart of the United States based on WGS 60 by revising an AMS Geoid Contour Chart based on NAD 27, shifting the contours, and applying the Vening-Meinesz Transformation Formulas.

MISCELLANEOUS NOTES

Important Geodetic Meetings, 1960–62

ORLANDO, FLA., JANUARY 10–12, 1961

A Seminar on Military Geodesy was sponsored by the U.S. Air Force, Cambridge Research Laboratories.

WASHINGTON, D.C., APRIL 26–28, 1962

A Symposium on the Use of Artificial Satellites for Geodesy was sponsored by the Committee on Space Research, established by the International Council of Scientific Unions.

Personalia

The following personalia covering the period of this report will be of interest to those affiliated with the International Association of Geodesy:

Capt. John H. Brittain, Chief, Geodesy Division, U.S. Coast and Geodetic Survey, retired July 31, 1961. He was succeeded by Capt. F. R. Gossett.

Mr. Charles A. Whitten transferred early in 1962 from the Geodesy Division, U.S. Coast and Geodetic Survey, to become Chief of a newly organized Electronic Computing Division. Mr. Buford K. Meade succeeded him as Chief of the Triangulation Branch of the Geodesy Division.

Mr. William M. Kaula, formerly Chief, Research and Analysis Division, Department of Geodesy, U.S. Army Map Service, transferred to the National Aeronautics and Space Administration during the reporting period. He was succeeded at the Army Map Service by Mr. Soren W. Henriksen.

Mr. Bela Szabo, formerly Chief, Geophysical Studies Section, Aeronautical Chart and Information Center, St. Louis, Mo., transferred during the reporting period to a position of Research Geodesist, Geodesy and Gravity Branch, Geophysics Research Directorate, Air Force Cambridge Research Laboratories, Bedford, Mass.