Comprehensive Survey of Sedimentation in Lake Mead, 1948-49

GEOLOGICAL SURVEY PROFESSIONAL PAPER 295

Prepared in collaboration with the U.S. Department of the Interior, Bureau of Reclamation; U.S. Department of the Navy, Chief of Naval Operations, Bureau of Ships, Bureau of Ordnance, Bureau of Naval Personnel, Hydrographic Office, and Navy Electronics Laboratory; U.S. Department of Commerce, Coast and Geodetic Survey; University of California, Scripps Institution of Oceanography

G. SURVEY OF THE LAKE

By GUNNAR LEIFSON, U.S. Navy Hydrographic Office

The hydrographic survey of Lake Mead was undertaken to obtain the data necessary (a) for determination of the volume and distribution of sediment deposits, and the occurrence and extent of other changes in reservoir boundaries; and (b) for the preparation of new reservoir area and capacity curves. The survey was conducted in accordance with well-established principles of hydrographic surveying, employing conventional methods of lead-line sounding in the canyon section (Lower Granite Gorge) east of longitude 113°57′ (as described by L. C. Pampel, p. 73) and advanced techniques of echo sounding in the main part of the lake west of that longitude.

The part of Lake Mead west of longitude 113°57′, extending from Pierce Ferry for about 65 miles to Hoover Dam, is in general a chain or series of wide basins connected by short narrow canyon sections. Plate 5*A* illustrates conditions in Boulder Canyon and Virgin Basin. In this part of the reservoir, lake conditions exist at all stages, with depths ranging up to 450 feet and widths ranging from 650 feet in Boulder Canyon to about 5 miles in the basin areas. The water is generally clear, and the only velocities are the very low ones resulting from circulation of water in the lake and those induced by density-current action (pp. 109–125).

In this main part of the lake the surveying techniques were essentially those of deep-water hydrographic surveying controlled by sextant observation on control points on shore. Serious consideration was given to the employment of Shoran equipment for position control in these areas. Although the employment of Shoran would have reduced materially the amount of horizontal control survey needed, it would also have required specialized personnel and camp parties. After due consideration, this plan was abandoned in favor of more orthodox methods. In the more confined areas of the small bays and canyons, the boat positions were determined and the courses controlled by observations from two transit stations ashore, or from one transit station with the aid of one sextant reading made aboard the boat.

In the general sense, a hydrographic survey involves a large number of operations, all planned to obtain the information requisite for production of a nautical chart. Such surveys include, besides the accurate charting of the ocean bottom, the measurement of tides and currents, magnetic measurements, geodetic control surveys, and even topographic surveys, for the topography of land areas adjacent to the shore and visible from seaward is important as an aid to navigation. In accomplishing his work the hydrographer is at a disadvantage as compared with the topographer, in that the area he wishes to map is hidden from view; because it is obviously impractical to measure the depth at every point, the submarine relief has to be deduced from a systematic series of depth measurements spaced at such intervals that the slope between measurements can be considered uniform.

In modern hydrographic practice, depths are measured almost exclusively by some form of automatic recording echo sounder. These sounders are manufactured in a variety of types suitable for recording depths ranging from a few feet to 24,000 feet. Corrections must be applied to the recorded depths for position of water surface above or below the assumed datum, for depth of projector below the water surface, and for true velocity of sound in the water being surveyed. The equipment is normally installed permanently in the hull of a boat, and in modern practice on the ocean the boat is operated at a speed as high as 10 knots (12 miles per hour), sea conditions permitting. This speed would be excessive on inland lakes, where the work is characteristically close to shore.

Numerous methods are available for fixing the position of the sounding boat at regular intervals along a sounding line. In harbor and coastal areas the three-point sextant fix method is standard practice. This method has the advantages that no parties are needed on shore; the boat position is immediately available to the boat operator; and, as only angles are used, accurate scale of work sheet is immaterial. The three-point fix depends on the geometric fact that the angle subtended by a chord is the same at all points on the circumference of the circle. The measurement of two simultaneous angles defines the boat position at the intersection of two position circles. If the two circles intersect at a satisfactory angle, an accurate position is determined. If the two circles are coincident, no fix is obtained. Some judgment, therefore, is required by the hydrographer in the selection of shore objects for the fix. For convenience in the rapid graphic plotting of the boat position, sextant angles are always observed on three shore objects, the center object being common to the two observations.

All the corrections that must be applied to recorded depths are not generally known at the moment of survey, hence all field data must be replotted. The replotting is done at some convenient location ashore, where corrections can be computed and work can be done with greater care than is possible in a boat. This operation is called the smooth plot. The best grades of paper, plastic, or metal sheets are used. The sheets are provided with a polyconic projection grid of meridians and parallels computed on the spheroid of reference in use for the area surveyed.

In the survey of Lake Mead, where the principal objective was not navigational information but rather a determination of volume of sedimentation as well as area and capacity, the hydrographic survey is reduced to its most elementary form—namely, measuring true depths below a known datum plane and fixing the position of these measured depths in true relation to the geodetic control net on shore.

In the summer of 1947, when the Geological Survey informally requested the Navy Hydrographic Office to participate in the Lake Mead survey, the Hydrographer, Rear Admiral R. O. Glover, designated the writer as the representative of the Hydrographic Office for the hydrographic aspects of the project—especially the application of standard hydrographic techniques to the survey of the lake.

The guiding principle in the preliminary planning was to hold the cost of the survey to a minimum without sacrificing accuracy. In accordance with this policy, portable shore signals were designed that could be moved ahead as the survey progressed. The location of the shore signals was to be permanently marked and referenced so that any future survey would be on the identical datum with the planned operation. The scale of the field work was also planned to be the same as the existing topographic sheets of 1:12,000. This scale would permit a continuous field check between the hydrographic profiles and the topographic maps without the necessity of scale conversion, and would also reduce the labor of the final area-capacity computations. The spacing between boat lines was tentatively set as 200 yards for the Boulder Basin area. It was felt that this spacing, being only slightly more than the maximum depth, would reveal any unusual bottom formation.

The results of preliminary lines run in Boulder Basin were inspected by the writer in April 1948. It was apparent from the sketchy information that the lake bottom was more regular than had been anticipated, and also that the amount of sediment present in the narrow canyon areas would have only a nominal effect on the volume and area-capacity computations. In order to advance the estimated completion data, therefore, it was decided to complete the work in Boulder Basin with lines at 200-yard spacing as planned, increase spacing of lines in other basins to 300 yards, and run four parallel lines through the canyons with supplementary cross lines as necessary. When this program was adopted, the writer's contact with the survey was completed.

An interesting aspect of the hydrographic survey of the lake was the opportunity for a comparison of results of the hydrographic and topographic surveys. The number of times a hydrographer has the advantage of an excellent topographic map of a survey area are indeed few. It was gratifying to see the close agreement between echo-sounding profiles and the corresponding cross sections laid down on the topographic maps.

OUTLINE OF PROCEDURES

By M. R. Ullom, U.S. Navy Hydrographic Office, and F. C. Ames, U.S. Geological Survey

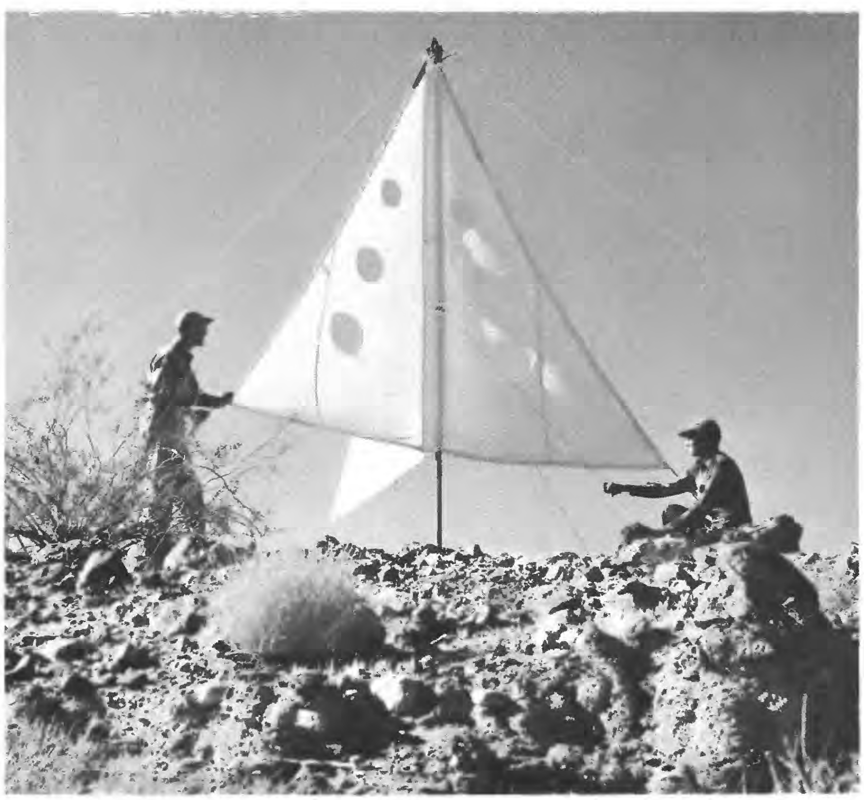
This section describes the general features of the hydrographic survey of the lake west of longitude 113°57′, including accounts of the fieldwork, the preparation of maps, and the calculation of sediment volumes. The more technical features of the lake survey, including details of the methods used and the results obtained, are covered in other sections of this chapter.

The part of Lake Mead west of longitude 113°57′ consists of several major basin areas connected by narrow canyon sections. Within these major subdivisions there are numerous small bays and coves along the shores of the basins, and narrow inlets or side canyons in the canyon sections. Owing to the great difference in size and shape of these areas and the differences in sight distances involved, it was necessary to survey the different areas separately, using slightly different techniques in each type of area.

HORIZONTAL CONTROL

The first step in the survey was the establishment of a network of horizontal-control stations along the shorelines of the lake at elevations close to the high-water line. Locations for these control stations were chosen with these basic criteria in mind: To provide

A. BOULDER CANYON AND VIRGIN BASIN, LAKE MEAD
Airphoto by Bureau of Reclamation.



B. SHORE SIGNAL USED DURING THE LAKE MEAD SURVEY
Photograph by Bureau of Reclamation.

good spacing and good alinement for use with the type of boat-position observations planned in each area, and to provide good triangulation figures. Geodetic positions of the stations were determined by third-order triangulation, as described by R. M. Wilson (p. 44).

To permit sextant observation of the control stations from the sounding boat, it was necessary to erect and maintain flags or targets, called shore signals. The erection of signals constituted a major task of the hydrographic survey, inasmuch as 312 control points were employed as locations for shore signals. In the basin areas it was necessary that these signals be visible to the naked eye at distances up to 5 miles and a large signal designed by the Navy Hydrographic Office was used (pl. 5*B*). This consisted essentially of a 16-foot mast with three triangular sections of cloth spaced at 120-degree intervals around it. The mast was made of light iron tubing, 2 inches in diameter, jointed in the middle and guyed with 7 cables—3 secured to the center of the mast and 4 at the top. Height of the cloth triangles was 12 feet and the horizontal side was 5.5 feet. Skirts of various colors and material were tried; and it was found that white indianhead cloth was superior to all others, because it withstood the buffeting of wind remarkably well and possessed the highest visibility of any tried. Seventeen signals were built with white indianhead skirts and moved from place to place along the lake shore as the survey progressed. In the more confined areas where sight distances were 1 mile or less, smaller and more easily erected signals were used.

As the work progressed it was found that additional stations were needed in a few areas because of limitations of visibility, height of stations above the water surface, size and rate of change of angles along the prescribed sounding courses, and changes in plans regarding type of boat-position observations to be used. Such elaboration of shore control was found necessary in Black, Boulder, and Iceberg Canyons; in the narrower parts of Las Vegas Wash; near the Boulder Islands; and around the shores of some of the larger bays. Forty-eight additional control points were established, and were cut in with comparative rapidity by intersection from the nearest triangulation stations of the third-order net. A closing error of 1 minute was considered satisfactory for the relatively small triangles involved.

Several auxiliary stations were set up by the shore signal party as needed. Most of these stations were located by reading all three angles of the triangle formed by the new station and two of the basic triangulation stations. Some were located by intersection from the basic triangulation stations (closing angle at the new station not observed), and a few were located by the three-point-fix method. All angle observations were made with an engineer's transit, except at a few canyon stations where sight distances were short and transit setups extremely difficult; at such points three-point-fix observations were made by sextant. In general the auxiliary stations established by the shore signal party were marked by iron pins and rock cairns when they were located above the high-water line, but were left unmarked when located below the high-water line.

PLOTTING OF SOUNDINGS

Two sets of map sheets of the lake were prepared for use on the survey. One set, called boat sheets, was used for delineation of the sounding lines to be run, and for field plotting of the boat courses actually sailed. The other set, called smooth sheets, was used for the final smooth plotting of the boat courses, entry of the bottom elevations as computed from the echo-sounding recorders, and delineation of contour lines as indicated by the sounding data. The grid for both the boat and smooth sheets was a polyconic projection computed from the tables given in Special Publication 5 of the Coast and Geodetic Survey (1935). This projection was used primarily to conform with the maps prepared for the Soil Conservation Service by Fairchild Aerial Surveys in 1935, and to permit a direct visual comparison between the two surveys. The scale of boat sheets and smooth sheets was 1:12,000, or 1,000 feet to the inch, which was also the same as for the 1935 maps.

Prior to sounding, 19 boat sheets were prepared covering the same areas as the smooth sheets, or some smaller area contained on a single smooth sheet. The boat sheets were simply penciled charts of parts of the lake, drawn on standard cloth-backed detail paper. Data shown on these sheets were the same as on the smooth sheets, except that the contour delineated below the 1,200-foot level was the 10-foot contour nearest the anticipated lake elevation at the time that the area would be sounded. The highest 10-foot contours around hazardous shoals were also traced from the 1935 topographic maps, to serve as an aid to navigation. The desired positions of sounding lines were then indicated for the guidance of the soundboat officer during sounding observations. Guided by a study of the 1935 topographic maps, sets of parallel sounding lines were drawn on boat sheets, oriented so that a maximum of bottom definition would be obtained with a minimum of effort on the part of the sounding crew. In areas where relatively weak three-point fixes might inadvertently be used by the sextant men, the stronger three-point fixes were determined in the field office and appropriately indicated on the sounding lines.

The smooth sheets are of finest quality drawing paper, two sheets bonded to a central sheet of aluminum foil, averaging 40 by 60 inches in size. Eleven sheets were laid out to cover the lake, basin by basin, insofar as possible within the limitations of conveniently handled sheet sizes. Sheets were overlapped sufficiently to allow duplicate plotting of at least the two control stations nearest the margins, to insure ease of plotting the three-point fixes over the junction between sheets. Data initially plotted on each sheet included the polyconic grid system by 1-minute intervals, shore-line and island contours at elevations 1,150 and 1,200 feet as determined from the 1935 maps of the Soil Conservation Service, and the locations of the third-order triangulation stations. Auxiliary control stations were plotted as they were established, and smooth plotting of the sounding data was accomplished as rapidly as those data became available.

SOUNDING PROCEDURES

The echo-sounding equipment provided continuous soundings along designated lines or courses. Soundings were run along parallel lines, as described in detail by C. C. McCall (p. 58). In the bays radial lines were spaced to give not more than about 400-yard intervals at the outer ends of the radials, and in the narrow parts of the canyons radial lines were spaced 70–100 yards apart. As the sounding work progressed the elevations determined from each day's soundings were compared with the 1935 map elevations, and if the comparison showed a need for additional sounding lines, they were indicated on the boat sheets and the soundings were obtained before operations were moved to new areas.

Three types of echo-sounding instruments were used, each having a different oscillation frequency—one low enough to be only slightly above the sonic range, and the others in the supersonic range. The low frequency was used to determine the interface between sediment and original bottom, as well as the interface between water and present sediment surface. Excellent results were obtained in sediment thicknesses up to 90 feet, in Boulder Basin and certain other areas where the sediment was not too dense; figure 46 shows fathographs obtained respectively in Gregg Basin, Virgin Basin, and Boulder Basin. The high-frequency instruments gave the best definition of bottom configuration in areas where the bottom was rough and steeply sloping. The echo-sounding records are analyzed by G. B. Cummings and C. E. Mongan, Jr. (p. 68).

True depths to the water-sediment interface were determined at intervals by picking up samples of that interface in a modified Foerst sampler (p. 151) suspended on a measured line. The recorded depths, properly adjusted for sound velocity, were found to agree with these measured depths very closely even over the least dense sediments, indicating that the sound impulse was reflected from the actual top of the sediment.

In the basins and larger bays, determination of boat positions was accomplished by the three-point-fix method, with angles measured by sextants aboard the sounding boat. This method was selected because it required the least number of control stations ashore, thus minimizing the horizontal-control and signal-erection work. The method also had the distinct advantage of permitting the officer in charge of soundings to observe and plot his position at frequent intervals, thus enabling him to follow preselected lines without the aid of range stations or instructions from a shore party.

Control by three-point fix was impractical in some areas because of the large number of shore signals that would have been required, or because of the excessive rate of change of the angles to be observed when operating close to the signals. In the bays or coves, control was maintained by means of two transits set up on shore at triangulation stations located in such a way as to give good intersection angles at the boat over as large an area as possible; lines were run radially from one transit and positions along the lines were observed with the second transit. In canyon reaches, control was accomplished by using one transit and one sextant. The transit was set up to direct the boat along selected radial lines, and the sextant was used to observe the angles at the boat between the transit station and successive control stations along the canyon wall. This method required nearly as many stations as would the three-point fix method, but it minimized the rate of change of the angles observed by the sextant operator and provided greater accuracy than would have been attainable by three-point fixes. Hydrographic sextants with worm-gear drive vernier wheels were used for all sextant observations, and engineer's transits were used for the transit observations. Angles were read to the nearest minute of arc on both instruments.

In the broader basins observations for boat position, or fixes, were obtained at intervals of 2 minutes. In the open water areas away from shore the sounding boat was run at 5 to 6 miles per hour and the 2-minute fix frequency provided a fix point approximately every 1,000 feet. Near shore or in areas with numerous shoals, the boat speed was reduced to about 3 miles per hour, and fixes occurred at about 500-foot intervals. In some of the canyons and coves, where very close control was desired, fixes were made at 1-minute intervals and boat speeds varied from about 2 to as much as 6 miles per hour.

The sound traces were read at 15-second intervals, and the readings were recorded in sounding journals, together with fix times, angles, and other data. Final scaling for use in smooth-sheet plotting was accomplished in the office and no fixed time interval was adhered to, except for entries at the "fix" points. Intermediate readings were made at 50-foot depth intervals over long stretches of uniform slope and at important breaks in slope. In this final scaling a movable scale, calibrated to read elevation, was set over the chart in such a way as to incorporate the draft, index, and sound-velocity corrections with the lake elevation for the day, and bottom elevations were read directly from the sounding charts.

In most of the reservoir area the bottom slope appeared to have a negligible effect on recorded depths. However, on very steep slopes and especially near canyon walls and underwater cliffs, some foreshortening of actual depth was detectable, and in some places stray echoes and side echoes from the walls were quite pronounced. In a few places, where the canyon wall extended from water surface to sediment surface at a fairly uniform steep slope, echoes were recorded from both sediment surface and side wall, even when the boat was known to be many feet shoreward of the true intersection between sediment and side wall.

HORIZONTAL CONTROL

By R. M. Wilson, U.S. Geological Survey

Accurate location of position was a prerequisite, not only in the hydrographic surveys, but in many other phases of the Lake Mead survey. A horizontal reference system is essential for correlation of various observations with those made at other times or places. The system must be physically permanent, so that measurements and observations separated by long intervals of time may be compared without doubt as to their relative positions.

When Hoover Dam was constructed, the available topographic maps included river plans at a scale of 1: 31,680, showing 50-foot contours below elevation 1,200 feet (U.S. Geol. Survey, 1924). Plans for an accurate contour map of the entire reservoir area were given active attention late in January 1935, only a few days before the gates of the new dam were closed and water began to accumulate to form Lake Mead. The contract for the mapping was awarded to Fairchild Aerial Surveys by the Soil Erosion Service, later to become the Soil Conservation Service, of the United States Department of Agriculture. Detailed topographic maps were prepared from aerial photographs (U.S. Soil Cons. Service, 1935; Brown, 1941), based upon the framework of an extensive triangulation net which was established by the Fairchild Aerial Surveys (1935).

One of the objectives of the 1947–48 triangulation for the Lake Mead investigations was to recover as many of the Fairchild stations as could be tied in economically, and so test the precision of their coordinates. One consideration that made these ties a particularly urgent requirement was that many of the Fairchild stations were below the spillway elevation of the dam and were submerged when Lake Mead was filled with water; the remaining points of the Fairchild triangulation thus represented only disjointed fragments of the original triangulation system. Confirmation of the accuracy of the Fairchild triangulation was also desired for the survey of Lower Granite Gorge (p. 73), which was referenced to several of the Fairchild stations.

For similar reasons, it was desirable to tie in points of other previous surveys to the basic and common datum. Stations established by the Bureau of Reclamation, by Brock and Weymouth, and by the Los Angeles Department of Water and Power were also tied in wherever possible, so that all these surveys might be coordinated on a common datum. The Bureau of Reclamation was particularly interested in these ties, as a basis for determining whether there were any significant errors in the earlier surveys which might have introduced discrepancies or uncertainties into the capacity table for the reservoir, or which might affect future comparisons with the contour map made in 1935.

Another purpose of the new triangulation was to establish convenient reference points for the 1948–49 hydrographic survey, and to mark them permanently so that similar studies in the future can be referred to the same marks. Most of these reference points were located just above the high-water mark of the reservoir for two reasons. First, they are most easily reached there by boat transportation; and second, sextant angles read from a boat on the lake to the shoreline stations should be very nearly in a horizontal plane in order to avoid the corrections that otherwise would be necessary.

PROGRAM FOR TRIANGULATION

The plans for the 1947–48 triangulation provided that the work should be accurate within third-order limits, as defined by the Board of Surveys and Maps in 1933—that is, triangles should close with a maximum error of 10 seconds, and an average error seldom exceeding 5 seconds. A study of available maps of the area revealed, however, that triangulation of third-order precision could not feasibly be carried near water level through the narrow parts of the channels and arms of Lake Mead. It was deemed permissible therefore to tie in the shore reference points with narrow arcs of triangulation, sometimes consisting of only a chain of single triangles. These sections of the survey could then be tied together by third-order triangulation at higher levels, which in turn would connect to the first-order Coast and Geodetic Survey stations.

It was recognized in planning the program that the triangulation control must be kept well in advance of other phases of the work. The hydrographic surveys and the sounding and sampling operations in Lake Mead would require established shore control points for defining the positions of observations taken in those operations. It was important, therefore, to start the geodetic control early and have shore reference points established in areas where the other phases were to begin, in order to avoid delay in the hydrographic survey. Because of this requirement, preliminary position computations were made as the triangulation progressed, leaving until later the least-squares adjustments and the final computation of coordinates.

The techniques employed in the hydrographic survey influenced the selection of a system of coordinates for expressing the position of reference points. The Navy personnel who made the soundings were familiar with the reading of sextant angles to shore points for boat positions. These positions were then plotted on the boat sheets by the use of three-armed protractors and similar graphic means. The boat sheets were prepared on a polyconic map projection, and the control points were plotted in their appropriate positions in terms of geographic coordinates.

The use of rectangular coordinates was considered, but rejected. Had the state plane coordinate systems been used, it would have been necessary to divide the survey into two parts, one for Nevada and the other for Arizona, or alternatively, to map the entire survey in the system for one of these States, overlapping it into the other State. A coordinate system established particularly for Lake Mead and its surrounding area might have been feasible, but it would have been confusing because of the state systems already in existance in the area. It was decided, therefore, to use the basic geodetic coordinates. If at some time in the future it becomes desirable to refer these coordinates to some other system, the appropriate transformation can then be made.

DESCRIPTION OF OPERATIONS

In the field work to establish the horizontal control needed for the project, it was necessary to compute the positions of the new triangulation stations nearly as fast as the field observations developed, in order to make them useful during the subsequent phases of the investigation. The field work began in November 1947 and continued without interruption until December 1948. All field computations were completed by March 1949.

The work was begun in Boulder Basin and in Black Canyon just above Hoover Dam. Much ingenuity was required for carrying the low-level chain of triangles through Black Canyon, for the walls of this canyon are very steep and suitable station locations are hard to find (pl. 6). Many of the lines of sight were very short, particularly in the narrow chains through the canyons, so that great care had to be exercised at each station in centering of signal and instrument. This centering was always accurate to one-half inch or less.

All the narrow chains of triangles through the canyons were connected adequately at frequent intervals by the higher level third-order triangulation. This higher level triangulation from Boulder Basin eastward across the Virgin Canyon and to Pierce Basin was, in turn, connected at frequent intervals with the first-order triangulation net of the Coast and Geodetic Survey. The long arc of third-order triangulation up Overton Arm was tied rigidly to first-order Coast and Geodetic Survey stations to the north. Care was taken to make sure that no arcs of triangulation were left outstanding as unchecked spurs.

The instrument used was a Wild T-1 repeating transit. Angles were generally measured five times direct and five times reversed. The signals for sights of 3 miles or more consisted of wooden 2- by 2-inch poles 8 feet in height. These poles carried a flutter flag about a yard square, and cross targets about 1 foot square. For shorter distances, sections of 1-inch pipe, 4 feet long and painted white, were used. All signals were guyed in position by wires.

SUMMARY OF RESULTS

The triangulation for horizontal control can be considered in four major areas: Boulder Basin, Virgin Basin, the long and winding channel from Virgin Canyon to Pierce Basin, and the long northward extension called Overton Arm. Considered as the sum of linear longitudinal distances through the triangulated arcs, the total is approximately 180 miles. In addition to the shoreline triangulation included in the mileage, there was also the higher level, large-figure triangulation required to maintain over-all accuracy and to connect with the Coast and Geodetic Survey first-order arcs.

In Boulder Basin several Coast and Geodetic Survey lines served as bases. These lines were CASH-PROM, PROM-HEM, ROUGH-HEM, HEM-CASH, VEGA-LA MESA, LA MESA-BOULDER, and E8-

SUGARLOAF (fig. 9). Except for the chain of single triangles through Black Canyon, the net consisted entirely of central-point and quadrilateral figures, and strong figures were easily obtained in most of the area. Boulder Canyon (pl. 5*A*) presented a problem because of its narrow, twisting shape. However, a continuous chain of quadrilaterals was carried at water level up to the very narrow part of the canyon, which is about a mile long. Since it would have been both uneconomical and time consuming to force a strong system through this narrow section of the canyon, the main net was carried at a higher level to connect with a length derived from the Coast and Geodetic Survey base BOULDER–BONELLI. An outer continuous system was also established in Boulder Basin area and extended to Virgin Basin in order to tie in the lakeshore net wherever possible and to facilitate the problem of least-squares adjustment. Figure 9 shows the triangulation net established for this region.

The shoreline of Virgin Basin was easily adapted to strong figures. The principal problem centered about a method to reduce the long line BOULDER–BONELLI with the least possible loss of accuracy. From this line it was necessary not only to control Virgin Basin, but also to establish strong bases from which to extend the net northward up Overton Arm and eastward to Pierce Basin. In addition, a base must serve as a tie needed for the net which was extended from Boulder Basin over Boulder Canyon and into Virgin Basin. The quadrilateral that was finally used reduced this long base, and by subsequent reductions using strong figures, adequate bases were obtained for the above-mentioned purposes. Figure 10 shows the triangulation in the Virgin Basin area.

The Overton Arm net was extended northward from the base established in Virgin Basin, by means of strong quadrilateral and central-point figures, and a tie was effected to the Coast and Geodetic Survey line GLEN–BM Z50. This was the easiest part of the survey, because Overton Arm is relatively straight and fairly uniform in width. Figure 11 shows the triangulation in the Overton Arm area of the lake.

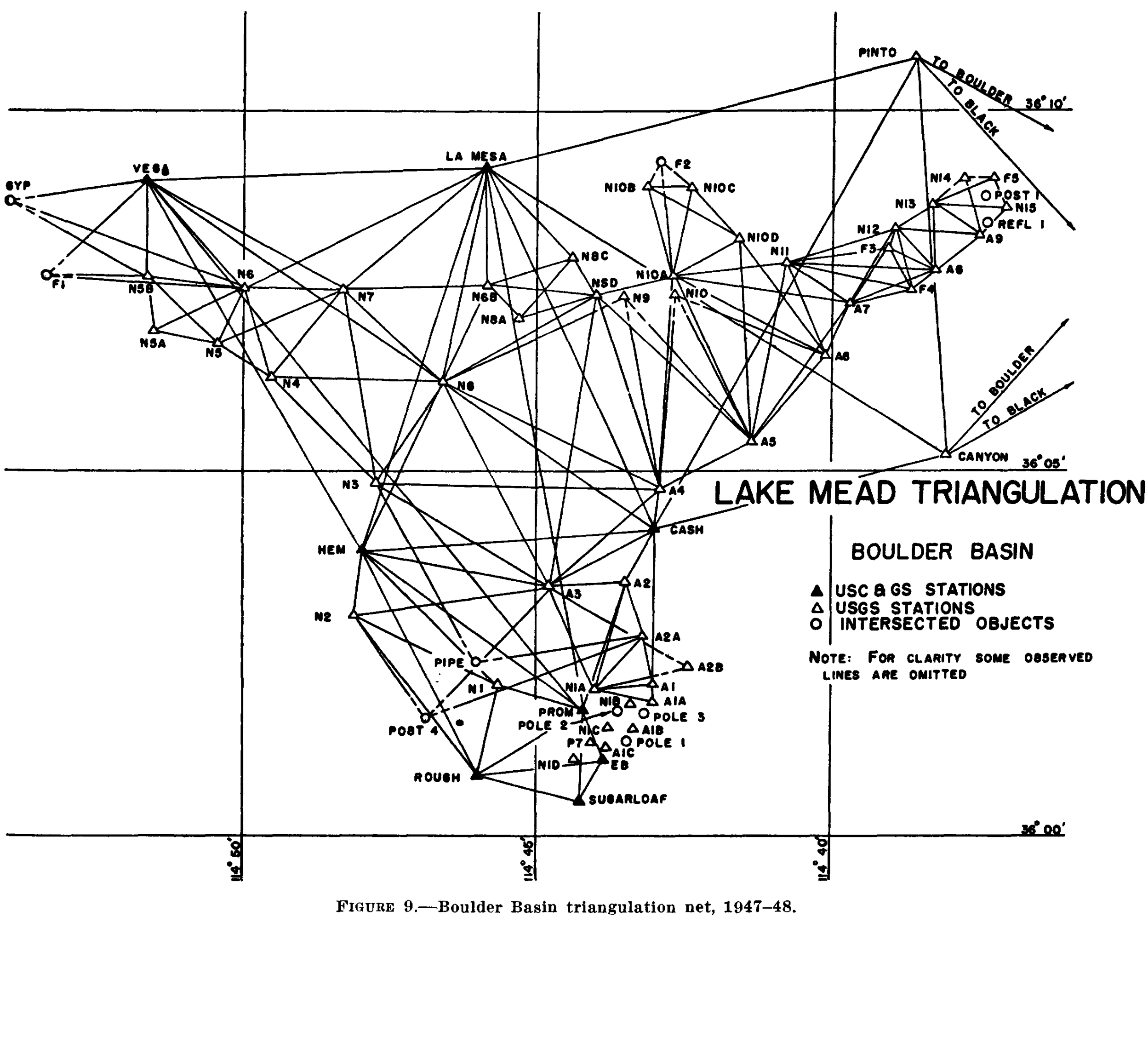


FIGURE 9.—Boulder Basin triangulation net, 1947–48.

BLACK CANYON AND BOULDER BASIN OF LAKE MEAD

Photograph by Bureau of Reclamation.

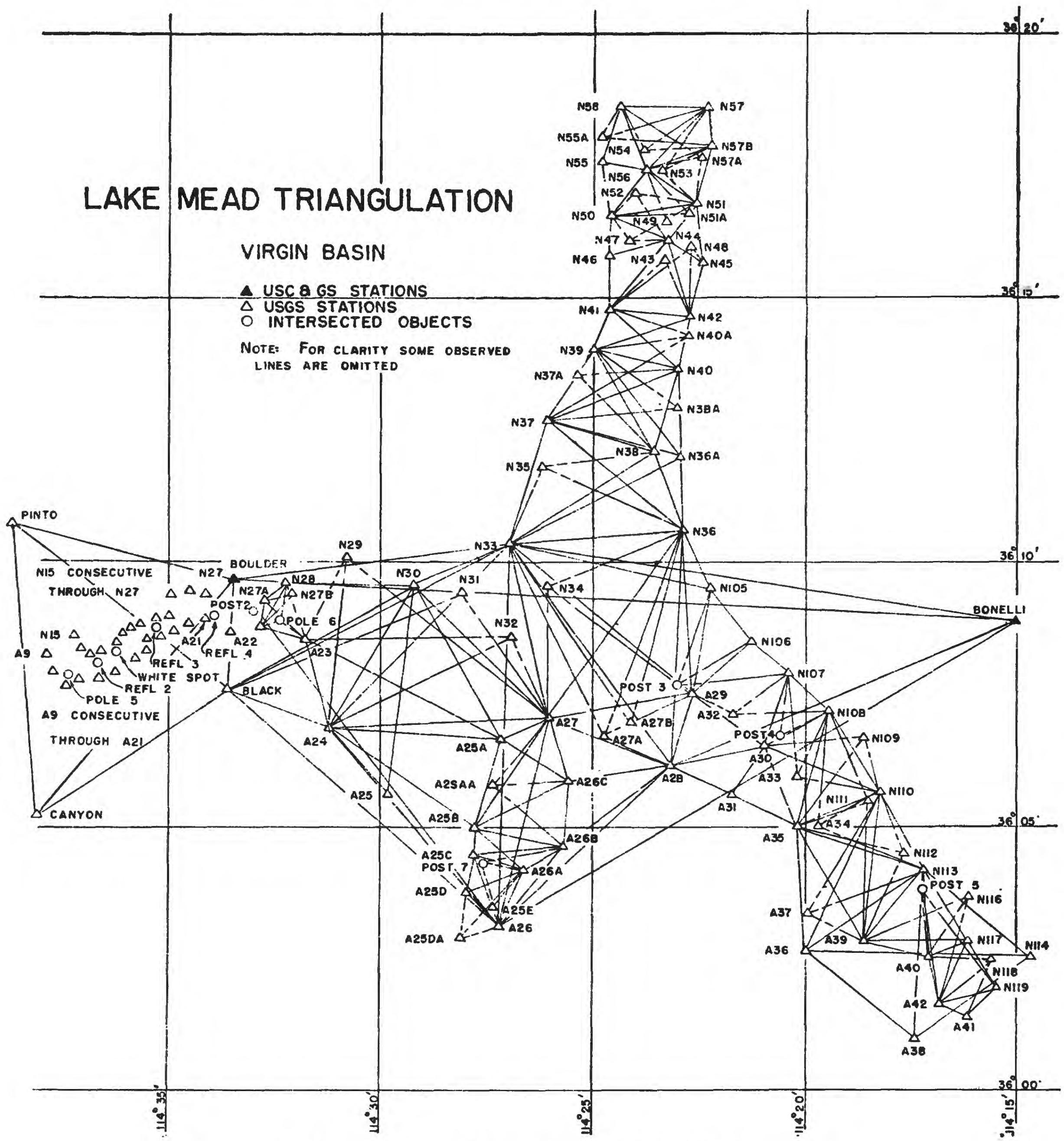


FIGURE 10.—Virgin Basin triangulation net, 1947–48.

The area from Virgin Canyon to Pierce Basin was the most difficult section of the entire project. Because of the narrow, tortuous canyons (pl. 3), and alternate expansion and contraction in the width of the reservoir, it was necessary to carry a single-triangle chain near water level, and an additional outer net of large figures, in order to maintain third-order accuracy. These single-triangle chains, of course, were tied at both ends. The base for the beginning of this net was derived from the BOULDER-BONELLI base in Virgin Basin. From that base a net of quadrilaterals was extended to Virgin Canyon, and then large single triangles were carried forward to tie to the main net near Hualpai Wash. From Hualpai Wash a chain of quadrilaterals was extended to Sandy Point, but from there to Pierce Basin single triangles were used almost exclusively. Figure 12 shows the triangulation in the area included between the Virgin Basin and Pierce Ferry.

Between Hualpai Wash and Pierce Ferry, four Coast and Geodetic Survey stations were used as basic control

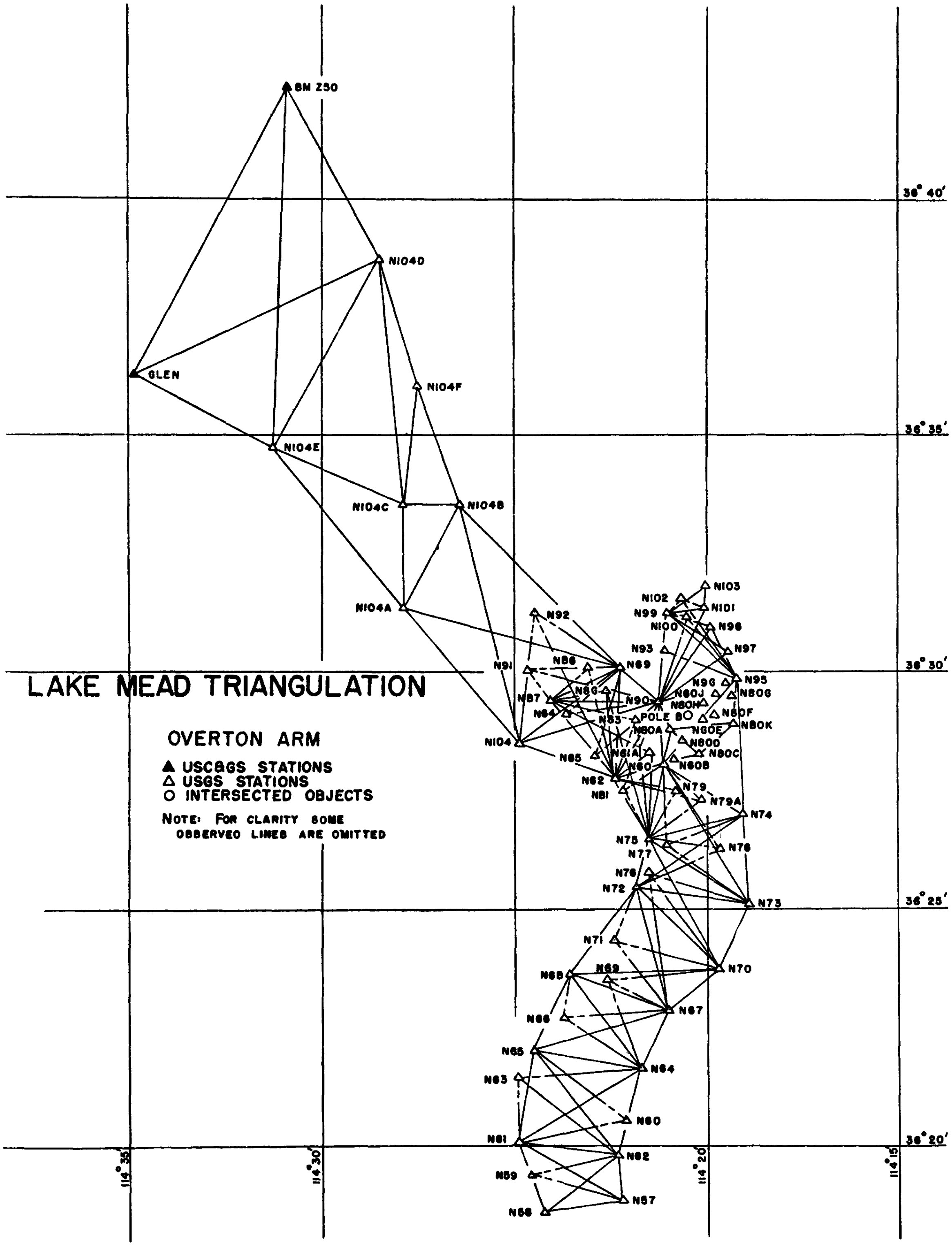


FIGURE 11.—Overton Arm triangulation net, 1947–48.

to establish the shore base lines needed to begin and tie the various single triangle nets. These stations were BONELLI, GRAND WASH, TUT, and RAMPART. By establishing two or three additional high-point stations, a strong net consisting of central-point figures was obtained. This net served as a tie, near Hualpai Wash, for the net carried forward from Virgin Basin; as a starting point for the single-triangle net

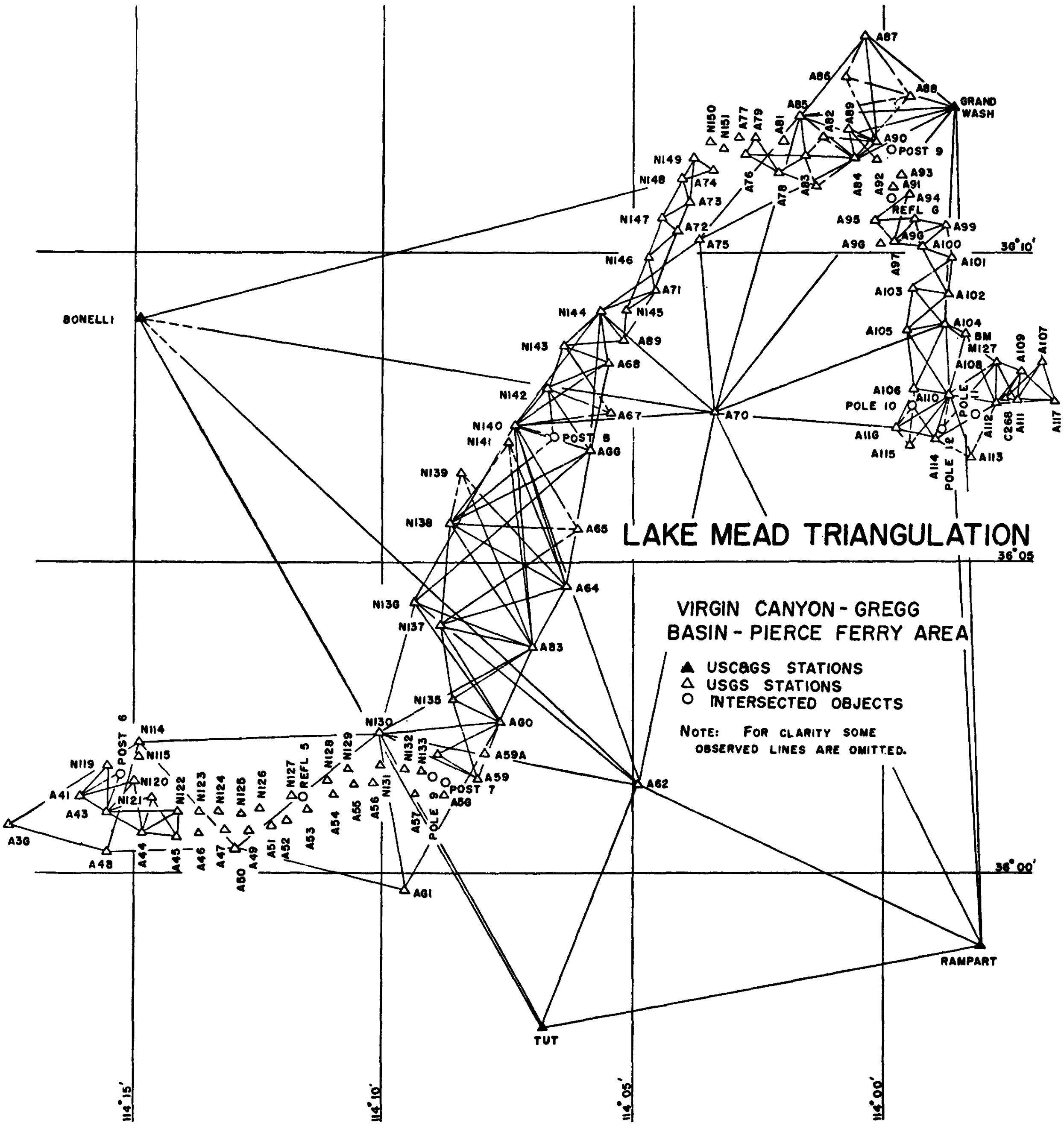


FIGURE 12.—Triangulation net in the Virgin Canyon—Pierce Ferry area, 1947–48.

near Sandy Point; and as a tie for the single-triangle net at Pierce Ferry.

Altogether, 336 new reference points and triangulation stations were established, each marked with the standard bronze tablet of the Geological Survey. All new tablets were stamped with a designating letter and number and the year established: for a station on the Arizona shore designated as "A50 1948," the "A" indicates that the station is in Arizona, the number "50" being the serial number of the station, and "1948" the year the station was established. Stations on the Nevada shore are similarly stamped except that the letter "N" is used to designate the State. All stations are numbered approximately in consecutive order eastward from Hoover Dam. Letters after the number merely designate stations that were added after the numbering system was established for an area. No reference marks were set.

A brief description was written for each station that was marked with a tablet. Airline distances were given from various prominent objects around the lake, the object in which the tablet was placed was noted, and the distance above or below the high-water mark was recorded. However, by far the easiest way to find these stations would be to plot the positions on topographic maps, and to look for them with the aid of the map. A list of coordinates for all stations, with azimuths and distances between them, has been lithographed by the Geological Survey (McIntosh, 1951). The geographic positions of all stations are also listed in the supplemental base data report.

In addition to those permanently marked points, about 35 navigation lights or other objects were located by intersection only and were not marked by tablets. Fifteen stations of the Coast and Geodetic Survey were recovered and occupied. Twenty-six of the stations established by Fairchild Aerial Surveys were tied in, also four stations of Brock and Weymouth, one station of the Bureau of Reclamation, and two stations of the City of Los Angeles. The position closures involved in all these ties were well within third-order limits, which indicates excellent work in the earlier triangulation by the Fairchild Aerial Surveys and by others in this area. The analysis discloses that the Fairchild triangulation is dependable and accurate, and was entirely adequate for use in making the maps under the original contract, presumably also for the horizontal control in the 1948–49 survey of Lower Granite Gorge (p. 74).

In the higher level net of the 1947–48 triangulation, which was composed of large figures, there were 171 triangles for which the average closure was 4.23 seconds. In the shore-level net, including some very short sights and small triangles, there were 346 triangles with an average closure of 5.03 seconds. The maximum triangle closure in the latter work was 24 seconds, but only 39 triangles had closures over 10 seconds.

OFFICE COMPUTATIONS

The closure discrepancies that appeared at the ends of the various arcs and systems were removed by an adjustment that was undertaken and completed in several parts and stages. Some of these parts involved rigorous least squares, and others involved less rigorous but faster methods that appear justified in view of the very small closure errors developed. For this adjustment, the work was divided into main-scheme and secondary systems.

The unadjusted observations in Boulder Basin gave such consistent values at the check stations that no adjustment was deemed necessary. An arc of large quadrilaterals and central-point figures, extending from triangulation stations LA MESA and CASH eastward to GRAND WASH and RAMPART, was adjusted by least squares to serve as a base for the subordinate work. This arc included 11 new stations and 7 Coast and Geodetic Survey stations. The position changes introduced by the adjustment amounted to less than 1 foot in either latitude or longitude except for two of the new stations at the eastern end. At each of these two stations, the adjusted positions differed from their preliminary values by approximately 2 feet.

The Overton Arm net was held at the southern end by its tie to the main-scheme adjustment and at the northern end by the tie to line GLEN–BM Z50. Inasmuch as there were no other intermediate factors to control the adjustment and the preliminary computations appeared to be internally consistent, it was deemed adequate to adjust the entire Overton Arm net as a single unit by the method of "isodiffs" (Speert, 1938). For this purpose line N33–N36, of the least-squares adjustment, was treated as a single tie, and line GLEN–BM Z50 was treated similarly. The whole net was then swung into azimuth to fit these two ties, and the necessary scale factor was applied to all computed lengths to make the over-all length of the net fit these two ties. A correction was determined for the position of each station from its location on the "isodiff" graph. All azimuths in the net received the same correction and all lengths the same proportional increase. At both ends of the net, in the figures adjoining the two fixed bases, individual corrections were computed for each line into both ends of the fixed bases.

A special study was made of each of the narrow chains of triangles and quadrilaterals along the canyons and smaller basins. A small position discrepancy at any point might very easily have thrown the work outside of third-order limits because of the unusually short lines involved in these figures. Wherever position discrepancies appeared that approached or exceeded third-order limits when concentrated in the closing line of a chain, that chain was adjusted by the "isodiff" method to distribute the accumulated error and to avoid any undue concentration at the closing point.

VERTICAL CONTROL

By F. C. Ames, U.S. Geological Survey

Vertical control was required in the hydrographic survey of the lake for conversion of the sounded depths to the corresponding bottom elevations above a selected reference plane or datum. All soundings were referenced to the water surface at the time and place of sounding, and a prerequisite for vertical control was the collection of adequate records of the water-surface elevation at those times and places. On a small single-basin lake, records at one or two locations might be adequate, but on a large multibasin lake such as Lake Mead, it was felt that there might be significant differences in elevation of the water surface in different parts of the lake at times, owing to the influence of wind, differences in barometric pressure, the flow of water through the lake, or other causes. To determine the occurrence, nature, and extent of these possible differences, records of water level were maintained at several points around the lake.

In this section of the report are described the collection and analysis of water-stage records at the various gage sites, the correlation of the water-stage records, and the magnitude of the errors that might occur in converting the recorded soundings to elevations above reference datum. A permanent gage at Hoover Dam provides a continuous record of water-surface elevations at the dam. The operations and analyses discussed in this section established the fact that this record is sufficiently accurate to be used without adjustment for conversions of sounded depths to bottom elevations. In determining whether adjustments are needed, it is to be noted that the records of the echo sounders operating in the foot scale could be scaled to about the nearest half foot, but in the fathom scale only to the nearest 2 or 3 feet.

COLLECTION OF WATER-STAGE RECORDS

Records of water-surface fluctuations were obtained from recording gages located at strategic points around the lake. A permanent gage had been in operation at Hoover Dam since 1935, and this was used as the basic reference gage during the 1948–49 survey. The gage, which had been used in the survey of 1935 (Brown, 1941, p. 393), thus served as a direct tie between the two surveys, after correction for differences in the gage settings with respect to datum as described on page 57. As the work progressed, auxiliary gages for the determination of local variations in water level were installed at the other points indicated in plate 7.

Three of the auxiliary gages were maintained at fixed locations throughout the course of the survey: gage 3, in a cove on the southeast shore of the Boulder Basin; the Boulder Wash gage, at the western end of Virgin Basin; and the Pierce Ferry gage, in a cove at Grapevine Wash in Pierce Basin. The primary function of the gages at Boulder Wash and Pierce Ferry was to provide information as to changes in relative water levels along the length of the reservoir. Gage 3 in Boulder Basin was originally intended as temporary only, but early records indicated variations between true lake stage and the stage as read from the Hoover Dam gage. Therefore gage 3 was left in place throughout the survey to provide continuous data regarding these variations.

The other auxiliary gages were operated in conjunction with the hydrographic survey, during which they were moved from place to place as the sounding party progressed from one basin to another. The primary function of the temporary gages was to provide a record of local variations in water level that might be of sufficient magnitude to require attention in the conversion of soundings to bottom elevations.

GAGE INSTALLATIONS

The gage at Hoover Dam is a Stevens remote-registering gage with the actuating Selsyn motor mounted over a stilling well built into the dam. The gage indicator dial and a Stevens water-stage recorder are located in the watermaster's office in the powerhouse.

All auxiliary gages were installed in portable stilling wells and shelters, as portability was a major requirement for the equipment at the temporary locations, and it was anticipated that fairly short stilling wells would accommodate the range in stage likely to occur during the period of operation at any selected location. A reconnaissance at the two locations originally selected for more permanent installations indicated that the difficulties and costs of erecting stilling wells to cover the anticipated 50-foot range in stage would far exceed the difficulties and cost of moving short portable wells up and down the banks. Accordingly, all stilling wells were fabricated from 24-inch diameter, galvanized, corrugated iron culvert pipe. The bottoms of the wells were closed and intake action was restricted in order to damp out surges due to wind on the lake. A staff gage consisting of enamel gage sections was bolted to each stilling well to serve as a reference gage. Instrument shelters were fabricated from 1-inch lumber and bolted to the top of the stilling wells.

The wells for the temporary locations were 10 feet long; with a crew of four men no great difficulty was encountered in moving these up and down the banks or from one location to another. The wells for the more permanent locations were 16 feet long, in two 8-foot riveted sections joined by standard band couplers. The handling of these wells proved rather awkward and difficult for the crew of four, even with the aid of light block-and-tackle equipment. During periods of rising stage the removal of these long wells from the lake for reerection on higher ground was particularly difficult, because it was not feasible to provide power equipment at the isolated sites for the 1 or 2 hours that would have been required for each move. Except for the press of other work it would have been better to use 10-foot wells at all locations, even though more frequent moves would have been required. A minor difficulty with the long wells was the excessive intake action around the band coupler, which permitted considerable surge in the well when the water surface was above the coupler, as much as 0.3 foot when the lake was rough. The surge obscured the indication of seiche patterns to some extent but did not detract from the value of the record for determinations of lake stage.

Initially the gages were located in narrow, very well protected coves, to avoid pounding by waves and to minimize surge induced by wave action. Subsequent observations indicated rapid reduction of wave height toward the heads of even fairly open coves, and it was found that gages could be located safely in small coves opening directly to the main lake. Installation was made by standing the well on the bottom near the center line of the cove, and supporting it with three guy wires attached to stakes or other anchors in the banks, a few feet higher than the top of the well. All gages were transported and serviced with the aid of a Navy airplane-personnel boat, because there were no access roads to the selected sites.

WATER-STAGE RECORDERS

Two types of water-stage recorders were used for the auxiliary gages: the Stevens Type F weekly recorder, and the Stevens Type A–35 continuous recorder. The Type F recorders were used at locations 1, 2, and 3 in Boulder Basin, where the gages were easily reached from Boulder City for the necessary weekly servicing. The Type A–35 instruments were used at all other locations.

On both types of recorder the stage can be interpolated readily to the nearest 0.01 foot, and the mechanical linkage is such that the probable error from lost motion does not exceed 0.01 foot. The Type A–35 has a time scale of 2.4 inches per day, by means of which time can be interpolated to the nearest 10 minutes without difficulty. Time-travel error on these instruments seldom exceeds 1 hour per month; with the aid of monthly inspection, corrections can be applied with confidence to the smallest interval to be interpolated. The Type F recorder has a time scale of 1.2 inches per day; the time can be interpolated to about the nearest 20 minutes; and time-travel error seldom exceeds 30 minutes per week. Thus the records obtained from both types of recorder may be expected to be correct within 10 to 20 minutes in time, and within 0.01 foot in gage height. However, the accuracy of elevations derived from the gage-height records at Lake Mead may be somewhat less (p. 55).

496918 O—60——5

DEVELOPMENT OF A COMMON GAGE DATUM

The auxiliary gages were set initially to a convenient arbitary datum, tied in to local reference marks by differential leveling. Whenever it was necessary to move a gage up or down slope, the relation between gage scale and reference marks was redetermined as a check against possible disturbance subsequent to the initial setting, and after each move the new relation was determined and recorded to permit eventual reduction of all readings to a common datum.

The true elevation of the zero of each gage with respect to the common datum for the survey was determined by comparing daily mean gage heights at the auxiliary gage with daily mean elevations at the Hoover Dam gage, and averaging the results over long periods. The accuracy of this determination rests on the validity of the assumption that the lake has a level surface during periods of calm weather and small flow through the lake.

At Boulder Wash and at Pierce Ferry it was possible to determine apparent elevations for the gage zeros by leveling from nearby bench marks. The elevations of the bench marks were derived by interpolation between the leveling of 1940–41 and that of 1949–50, in order to minimize the effect of differential settlement. Elevations thus obtained were 0.02 foot higher at Boulder Wash and 0.03 foot higher at Pierce Ferry than the elevations obtained by the water-level transfer from Hoover Dam, differences that are so small as to be within the allowable limits of accuracy of the leveling and of the average water-level determinations. The leveling has thus served to confirm the horizontality of the lake surface during periods of calm weather and small flow through the lake.

Determination of the elevation of the zero of each auxiliary gage was as follows: The average difference between daily mean auxiliary gage heights and daily mean elevations at Hoover Dam for the first 10 to 20 days of record was taken as a trial figure. The figure was added to each daily mean gage height as the record accumulated, the difference between the apparent elevation thus obtained and the elevation at the dam was computed, and the differences were plotted on a "difference-time" chart (fig. 13). If, after 60 days or more, any predominance of plus or minus values was noted, appropriate correction of the trial figure was made to bring the average daily difference to zero. Comparison of differences was continued for the entire period of record at each gage, to establish the validity of the adjusted value as closely as possible, and to discover any tendency of the average difference to depart from zero during periods of changing discharge through the lake.

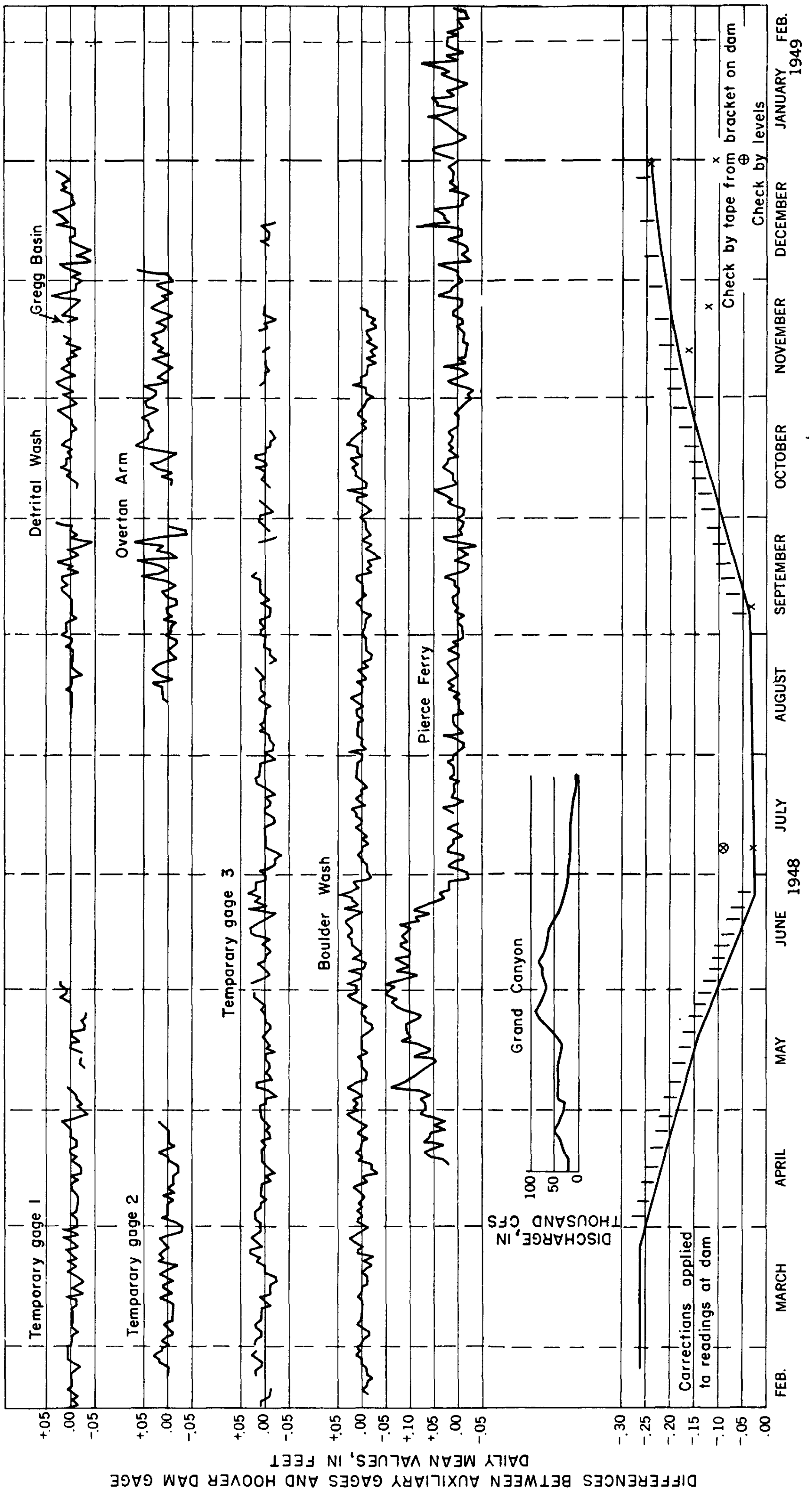


FIGURE 13.—Variations of water stage at auxiliary gages and at Hoover Dam gage with respect to true lake elevations at Lake Mead.

One result of these comparisons was the discovery of a gradual change in the relation between the gage readings observed at Hoover Dam and at the auxiliary gages in Boulder Basin and in Boulder Wash. The rate of change of this relation was most rapid in May and early June; it remained fixed during July and August, and then started to reverse in September, returning to its original value by December (fig. 13). The discovery led to detailed study of the conditions of operation of the gage at the dam.

The Bureau of Reclamation had found by periodic leveling that the relation between true lake stage and the Hoover Dam gage reading had been variable throughout the period, and that the variation appeared to follow a seasonal pattern: the gage readings were higher in winter than in summer with respect to true water-surface elevation. The range of the variation appeared to be about 0.25 foot, which was approximately the amount of variation observed between the auxiliary gages and the permanent gage during the 1948–49 survey. In an effort to confirm the variation and determine its cause, a reference-mark bracket was installed at the dam to permit frequent checks of the gage reading by simply measuring down to the lake surface with a steel tape. Such checks were made periodically after September 1948. These data indicated that the source of error must be in the Hoover Dam gage or the stilling well in which it operated.

One source of error was found to be the result of differences between the density of water in the lake and water in the gage well, resulting from differences in water temperature. The intake to the well, at elevation 940 feet, is generally 200–260 feet below water surface; and for interconnected water columns of such height, small differences in density cause appreciable differences in relative water levels. Computations based on temperatures in the lake at the dam and in the gage well, observed at various seasons in previous years, indicated a difference in relative water levels of about 0.01 foot in summer and about 0.11 foot in winter, the well water being warmer and therefore higher in both seasons. Computations made on the basis of additional temperature observations during the 1948–49 survey confirmed this value, which would account for an annual variation of 0.10 foot.

Efforts to determine the source of the remaining 0.15 foot of error led to a check on the calibration of the gage mechanism. In direct comparison between the change in gage-dial reading and the measured travel of the float tape, over as wide a range as possible, it was found that the calibration of the gage was correct so long as the holes in the tape remained properly alined with the spines on the float wheel. However, during changes of stage there is a marked tendency for the perforated tape to ride up on the spines. A second test, to determine the calibration error introduced by operation with the tape out of the spines, showed the error to be 0.0039 foot per foot change in stage. With a normal annual range in lake stage of roughly 40 feet, the total error between high and low stage is about 0.15 foot. The calibration error and the change in relative water levels due to density changes are additive, and the sum of the two equals the observed range of error in gage reading with respect to true lake elevation.

ANALYSIS OF WATER-STAGE RECORDS

Most of the large changes in water stage resulted from changes in storage in the reservoir, and were recorded uniformly by gages in all parts of the lake. Some patterns of fluctuation, however, indicate variations of the water surface from a level plane, and are recognized by variations between the stages recorded at the several gages.

SEICHES

The water-level records reveal considerable seiche action in the lake during periods of moderate to strong winds. There appear to be several seiche patterns, varying from very short-period, small-amplitude oscillations to fairly long-period cycles of variable amplitude. No detailed technical analysis of these seiche phenomena has been made, but the following general observations indicate the complex behavior shown by the graphs.

The long-period seiches are recorded strongly at all gages in Boulder Basin (including the gage at Hoover Dam), and at Pierce Ferry near the other end of the main part of the lake. The general shape of the graphs is roughly sinusoidal, but the detailed pattern is usually quite irregular, with many superimposed small-amplitude variations. At times the slopes of the rising and falling limbs of the oscillations are quite dissimilar—that is, the time interval from crest to trough differs from that from trough to crest. Frequently the shapes of successive cycles are quite different.

The approximate period of these long-period seiches varies from 3½ to 4 hours, and normally a crest is recorded in Boulder Basin at the same time as a trough at Pierce Ferry. Sometimes the seiche cycle at Pierce Ferry leads the corresponding cycle in Boulder Basin by 180°, and sometimes the reverse is true, presumably depending on the source of the disturbance generating the seiche. The amplitudes of the long-period seiches vary from a barely perceptible sinuosity of the trace, up to 0.10–0.15 foot in Boulder Basin, and up to 0.30–0.35 foot at Pierce Ferry. Normally gage 1 showed the greatest amplitude of any gage in Boulder Basin, though exceptions were noted. The maximum recorded amplitude was about 0.6 foot at Pierce Ferry on the night of December 3–4, 1948, during a period of very strong wind with gusts estimated at velocities up to 60 miles per hour. The time interval between the first two crests was barely 3¼ hours, increasing to 4 hours between subsequent crests.

The long-period seiches recorded at Pierce Ferry and in Boulder Basin are presumably controlled by, and travel throughout, the length of the lake. All the seiches shown at Pierce Ferry were reflected on the Gregg Basin gage during its short period of operation, but with considerably smaller amplitude, and sometimes with extensively modified patterns. Only a small number of the long-period seiches were recorded on the Detrital Wash and Overton Arm gages, and very few are discernible at all on the gage at Boulder Wash. When the seiches did appear on these gages the amplitude was always much less than at the ends of the lake.

The short-period seiches detected on the various graphs had periods of about 18 to 20 minutes at Pierce Ferry and about 25 minutes at Boulder Wash, Gregg Basin, and Detrital Wash. The amplitudes seldom exceeded 0.05 foot and were normally only 0.01 to 0.03 foot. These may be single-basin seiches controlled primarily by conditions within the basin.

Between the two extremes of short- and long-period cycles, various other frequencies occurred from time to time at all locations. These cannot be correlated between gages, and a detailed analysis would undoubtedly be very complex and difficult.

TIDES

The records were examined superficially but unsuccessfully for indication of tidal fluctuations. Any such fluctuations are completely obscured by the more pronounced variations due to other causes. In particular, the variable rate of rise or fall in lake level resulting from variable outflow for power generation tends to mask any diurnal fluctuations that might be caused by tides.

WIND EFFECTS

In the preliminary planning for the survey it had been anticipated that sustained winds of moderate to strong intensity might cause fairly large differences in water-surface elevations between leeward and windward sections of the lake. Because the axis of prevailing winds in the Lake Mead area is north and south, the gages in Boulder Basin and in the Virgin Basin–Overton Arm section were located in such a way as to indicate any north-south pileup of water.

The longest reach between gages in Boulder Basin was the 8 miles between Hoover Dam and gage 2; no differences attributable to wind were detected in this reach, even under the influence of many strong south winds during March and April 1948. The reach between gages in the Virgin Basin–Overton Arm section, about 22.5 miles, is completely exposed to the north-south winds and is entirely open except for a constriction at the Overton Islands, about 8 miles south of the Overton Arm gage. Even in this reach the observed differences in water-surface elevation were negligible. The greatest difference noted was 0.20 foot at 6 p.m. on September 24, 1948, after several hours of a south wind at 30 to 35 miles per hour. Following these negative results it was deemed unnecessary to measure possible pileup in the 13-mile Gregg Basin–Iceberg Canyon reach, which is also oriented approximately north and south.

SLOPE EFFECTS

The records indicate that the stage at Pierce Ferry increases with respect to the stage at Hoover Dam in approximately direct proportion to the inflow. There was a sustained positive difference between the lake surface at Pierce Ferry and at the other gages throughout the period of high inflow from April to July 1948. This difference increased 0.14 foot during a change of inflow from about 5,000 cfs to 90,000 cfs, and appears to bear a direct relation to the flow, changing about 0.01 foot for each increment of 6,000 cfs of discharge at Grand Canyon (fig. 13).

The differences between gages represent the slope, or fall, of the water surface downlake from Pierce Ferry. A large part of this fall probably takes place in the canyon sections above Virgin Basin. The record at the Gregg Basin gage does not cover the period of high inflow, and evaluation of fall between that point and the dam is not possible. Changes in fall between the Boulder Wash gage and the dam are too small to be detectable in the record available. During period of low flow (5,000–10,000 cfs) the fall from Pierce Ferry to Hoover Dam apparently is about 0.01 to 0.02 foot.

EVALUATION OF DISCREPANCIES

From the discussion above, it is evident that the conversion of sounded depths to bottom elevations by referencing to the record of the Hoover Dam gage is subject to some error, by reason of the variation of the lake surface from a horizontal plane and because of the failure of the Hoover Dam gage to record the true water surface at the dam.

The factors that might cause the elevation of water surface at the dam to differ from that at other points in the lake are as follows:

1. Slope of the lake surface, practically nil most of the year, may increase to 0.20 foot with inflow of 120,000 cfs. The water surface at Hoover Dam gage at that time would be 0.20 foot lower than the water surface at Pierce Ferry.

2. Seiche action may cause a variation of 0.15 foot in Boulder Basin, and twice as much at Pierce Ferry, but with a period of 3 to 4 hours such variations would be averaged out in the daily mean water-surface elevation.

3. Wind action has caused a maximum observed pileup of 0.2 foot in the long, north-trending Overton Arm, but only negligible effects in Boulder Basin.

4. The lake stage rises rapidly during the annual freshet in the Colorado River. In 1948 the stage rose more than 0.5 foot during each day from May 20 to June 20, and a maximum daily rise of 1.08 feet occurred May 27. The use of daily means or of midday gage heights may introduce errors of as much as 0.15 foot in conversions of soundings made early or late in the day.

The maximum operational error in the Hoover Dam gage readings is about 0.25 foot, which is the same order of magnitude as the variations from horizontal surface caused by seiches, wind, or inflow. In the analysis of variations of the lake surface from the horizontal it was of course necessary to correct for these operational errors in the Hoover Dam gage; the graphs of figure 13 show the variations between the auxiliary gages and the corrected gage record or true water surface at the dam.

The errors that might be introduced in the determination of bottom elevations because of all these factors are much less than the total of the maximum errors listed above. Thus wind effects and slope effects were found to be negligible in Boulder and Virgin Basins; a fortuitous combination of seiche effects, hourly change in water level, and operational error at the dam gage could cause an error of no more than 0.5 foot in the conversion of individual soundings in those basins. The survey of Pierce Basin and other areas in the eastern part of the lake was undertaken during a period of low inflow, when slope effects were negligible; here, too, the conversion of individual soundings might be in error by as much as 0.5 foot, by reason of maximum seiche action and errors in the dam gage. In Overton Arm, individual soundings might include some effect of wind pileup, but there the seiche action would be negligible, so that the total error would be no greater than in other parts of the Lake.

A maximum error of 0.5 foot is of no practical significance in the computation of elevations of the reservoir bottom, because it is within the limit of accuracy of the soundings. The Hoover Dam gage record was thus sufficiently accurate to be used without correction for conversion of the sounded depths to bottom elevations, and adjustment of the preliminary bottom elevations, as computed daily throughout the course of the survey, was not required.

SELECTION OF REFERENCE DATUM

When the gage at Hoover Dam was installed in 1935, it was referenced to sea-level datum by leveling from bench marks whose elevations were derived originally from the general adjustment of 1912. This datum is known locally as the powerhouse datum.

Since 1935 the setting of the gage has been checked periodically by leveling from convenient bench marks to the lake surface and comparing the elevation obtained with the gage reading. Different evaluations of the bench-mark elevations have resulted in differences in gage settings. Comparisons between the elevation figures actually used from time to time and the true elevations above the datum of 1929, leveling of 1935, indicate that the difference was only 0.18 foot during the 1935 survey made for the Soil Conservation Service, and was about 0.5 foot from 1937 to 1948. Starting in September 1948, correct elevations above powerhouse datum have been used and the resulting difference has been 0.55 foot. The temporary datum planes have been high in all cases. The gage readings on which the channel cross sections for the 1935 survey were based are in error by less than 0.2 foot, and well within the limits of accuracy of the computations. Gage readings during the present survey, when referenced to powerhouse datum, require an adjustment of plus 0.55 foot to correct them to the datum of 1929, leveling of 1935.

So far as the computations of capacity are concerned, the method of vertical control used in the hydrographic survey permits the computer to choose his reference plane (provided he adheres to the same reference plane consistently). Specifically, the method of survey ties the elevation of reservoir bottom to the dam, and the capacity is fixed by the relation of the dam to the reservoir, rather than by the relation of either to sea level.

In chapter I the tables of area and usable capacity are computed for elevations based on powerhouse datum, and the elevation of the spillway (1205.4 feet) and of the gates in raised position (1221.4 feet) are referenced to the same datum. However, the tables of capacity and sediment storage by basins, and the comparisons between 1935 and 1948, are computed for elevations based on the datum of 1929, leveling of 1935, which was the datum used in the original (1935) computations of reservoir capacity. From this datum the elevations at the dam as well as all elevations of reservoir bottom are 0.55 foot greater than those measured from powerhouse datum; the capacity of the reservoir is of course the same regardless of the datum used, but the capacity at each indicated elevation, if measured above the datum of 1929, is slightly less than if measured above powerhouse datum.

If the gage readings (and hence the bottom elevations) are computed on the basis of the elevations determined by more recent leveling (such as the leveling of 1941 or 1950), then the storage at each indicated elevation will be somewhat greater than that for the same elevation above powerhouse datum, but the capacity when full remains the same because the elevation of the spillway is less by the same amount.

SOUNDING OPERATIONS

By Lt. C. C. McCall, USN

Sounding operations were carried out in the manner prescribed by the Navy Hydrographic Office. Each of the Navy personnel on the survey received preliminary training at the Hydrographic Office in the methods and techniques of conducting a hydrographic survey. The training included instruction in horizontal-angle readings by use of the sextant, correct timing procedure, the proper keeping of records in a sounding journal, and plotting by use of the three-armed protractor. Upon their arrival at Lake Mead, the group was given final instruction and training in teamwork by M. R. Ullom of the Hydrographic Office. After several days of training, the sounding crew was running lines that would meet the standards required for a hydrographic survey. This trained crew conducted all sounding operations throughout the survey.

At the start of each day's work the following checks were made on the equipment used on the survey: sextants, for accuracy; motor speeds of echo depth sounders (a check that was repeated at intervals during the day); and zero setting of the recorder. Calibration of the echo-sounding instruments was also checked daily by use of a "check bar" lowered on an accurately measured cable to depths of 30, 60, 90, and 120 feet. From these readings the velocity of sound in water was determined for the day's sounding operations. A few comparisons were made with wire-line soundings over relatively flat areas of hard bottom, and these indicated agreement with the bar checks. The relation of recorded depth to true depth varied with the water temperatures, and these variations were found to follow closely the differences in computed sound velocities for the various temperatures. Recorded soundings were corrected accordingly before conversion to bottom elevations.

In preparation for running each sounding line, the sounding boat was maneuvered to the line position by study of approximate fixes plotted on the boat sheet, on which the sounding lines had already been drawn. After the boat was on position to start the line, the sounding clock and echo sounder were started and a fix was taken. When the sound boat was underway every effort was made to follow the straight course.

Boat speeds during sounding operations varied with the conditions. When sounding over hard bottom in open water, a speed of approximately 5.5 miles per hour was maintained. However, over thick sediment deposits it was sometimes necessary to slow to approximately 3.5 miles per hour to get a clear recording on the sound trace. During close inshore sounding, the boat speed was reduced to about 2 miles per hour to give a safety factor against possible grounding. Most of the hazards to navigation had been marked on the boat sheets from the topographic maps of the Fairchild Survey, but, from early experience in Boulder Basin, it was found necessary to keep a sharp lookout from the bow of the sounding boat when approaching the shoreline.

During the travel of the sounding boat along a line, fixes were taken at intervals of 2 minutes. Anglemen read angles between three established signals placed on the shoreline. The left angleman observed the angle between the left and center signals; the right angleman, the angle between the center and right signals. These angles were observed by using a sextant in the horizontal position, and the images of the signals were continually superposed during the counting period. The angles were read to the plotter, who set them upon a three-arm protractor and plotted boat position on the boat sheet. The line was acceptable if one fix was missed but not acceptable if two consecutive fixes were missed.

Soundings were recorded in the sounding journal every 15 seconds and fixed or marked on the sound trace every 2 minutes or whenever a fix was taken. At this time the number of the fix was recorded on the chart and also in the sounding journal. A check was made between the soundman and the recorder every fifth fix to make certain that all recordings were in continuity and agreement.

As the end of each 2-minute sounding interval was approached, the recorder gave the anglemen a 30-second warning, then a 10-second warning, and at the 5-second mark would start counting the remaining seconds, until the end of the 2-minute interval was reached, when he would call "Mark." At this time the anglemen read to the recorder the angles observed, and those angles were plotted immediately to determine whether the boat was traveling along a satisfactory course.

Each of these plots was numbered on the boat sheet with the identical fix number recorded by the recorder and the soundman.

In calm water it was possible to run a full line without a course change, but in rough weather it was necessary at times to make changes in course in order to follow the designated line. These course changes were made as near to a fix as possible, or to the 1-minute interval halfway between fixes, to facilitate the processing of the smooth sheets.

LOW-FREQUENCY DEPTH-RECORDING EQUIPMENT

By W. C. Blaisdell, National-Simplex-Bludworth, Inc.

Two types of low-frequency depth-recording equipment were used at Lake Mead—namely, the U.S. Navy type NJ–8 depth recorder equipment and the U.S. Navy type NK–6 portable depth recorder equipment. Both were designed to produce rapid, accurate, automatic, and permanent records of depths of water by the method of ultrasonic echo sounding. They were selected for use in Lake Mead because the frequency of 14.25 kc used for the transmission of sound through water insured great penetrating power, making it practicable to obtain reflections from the top layer of any sediment or other body of distinctive density. By this means an accurate record in depth of each successive change in the density of the medium was obtained.

An annular reflector reflects all the transmitting energy from the transducer pack vertically downward, causing high intensity of the beam through the medium. Similarly, the use of the same type of reflector in the receiving transducer enables it to pick up very small returning echoes. In addition, the intensity of the reflected signal can be adjusted so as to differentiate clearly between the mediums of reflection.

NJ–8 DEPTH-RECORDING EQUIPMENT

The NJ–8 depth-recording equipment is a permanently installed, rapid-recording, echo-sounding instrument designed for use in shallow to moderately deep water, operating at 2 ranges: 200 feet and 200 fathoms. It meets Navy requirements in shock and vibration tests. It consists essentially of 4 separate units: a recorder cabinet containing the graphic recording mechanism and echo amplifier, a signal sender, and the transmitting and receiving transducers. A 115-volt ($\pm$0.5 percent), 60-cycle ($\pm$1.5 cycles), single-phase, a-c power supply of approximately 260 watts is required. If the ship's power supply is 24, 32, 115, or 230 volts dc, a suitable motor-alternator set, having a power consumption of approximately 600 watts, and a fuse and relay cabinet for remote starting of the alternator are supplied.

RECORDER

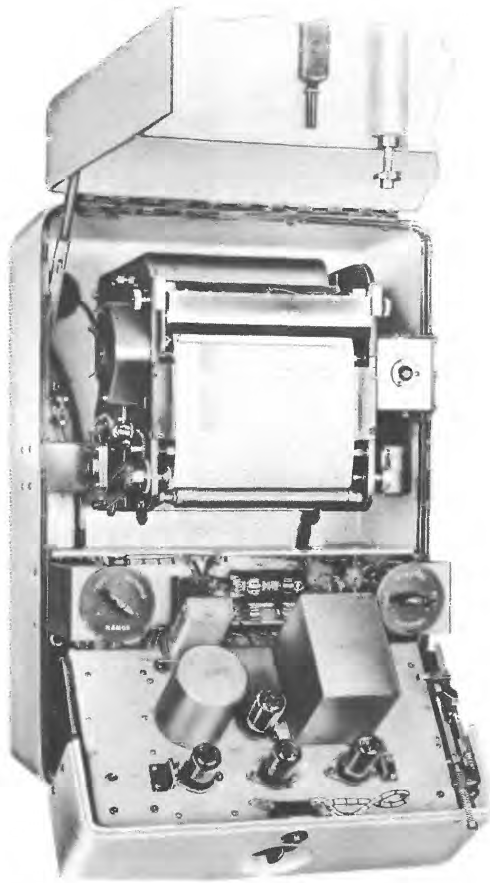
Recorder cabinet.—The recorder cabinet, which houses the recording mechanism as well as the amplifier chassis, is of three-piece cast-aluminum construction. The entire front breaks open into two doors (pl. 8). The upper door provides access to the recorder mechanism and the lower door allows for the servicing of the amplifier. Both doors are drawn securely shut against a rubber gasket by a locking handle. Interlock switches close the power circuits.

The operating controls, located on the covers, consist of a four-position rotary power switch, a two-position range switch, a gain control, and a fix button. The rotary power switch, in successive positions, disconnects the power supply from the entire equipment, maintains the amplifier ready for operation, and connects power to the mechanism drive motor. The range switch in "feet" position provides for depth recordings up to 200 feet, and in "fathoms" position to 200 fathoms. Depressing the "fix" button records a horizontal line the full width of the chart for reference purposes.

The record paper is of a dry facsimile type, impregnated with conductive materials and surface coated with an electro-sensitive substance that turns black upon the passage of electricity. The recording is visible through a shatterproof glass port on the cover, and this port may be raised to record bearings or other pertinent data.

Recorder mechanism.—This unit is resiliently mounted in the upper part of the cabinet. The mechanism consists of a 1/50-hp, 1,800-rpm synchronous motor, a gear box and positive clutch, a drum upon which a spiral wire is carefully positioned, a positive-driven paper-propulsion device, a main adjustable keying assembly, a cam-actuated auxiliary keying switch and associated phasing switch, a zero button, a printer bridge assembly, and a fathoms-marking contact.

The drum, paper-propulsion device, and cam shaft are driven by the motor through the positive clutch and reduction gear box. The drum rotates at 600 rpm on the feet range and 100 rpm on the fathoms range, and the cam shaft rotates at one-third the speed of the drum. Because an impulse is transmitted with each revolution of the cam shaft, recordings are made at rates of 200 per minute on the feet range and 33⅓ per minute on the fathoms range. The paper-propulsion device positions the recording chart paper by guide rollers and moves it over the drum and under the printer blade at the rate of 1 inch per minute on the feet range and ⅙ inch per minute on the fathoms range.



NJ-8 RECORDER, OPENED FOR INSPECTION OR SERVICING

A. NJ-8 DRIVER-RECTIFIER, SHOWING HORIZONTALLY MOUNTED STROBOTRON TUBE

B. NJ-8 TRANSDUCER, SHOWING CONICAL REFLECTOR HANGING FROM CASE COVER

Inside the reflector can be seen the stack of torroidally wound nickel laminations.

The auxiliary keying switch is in series with the main keying brush and is closed by the cam for a short interval, once each revolution of the cam shaft. The switch is adjustable for proper closure and synchronization so that when this switch and cam are properly adjusted with reference to each other and to the main keying assembly, the keying circuit is closed with every third revolution of the recording drum and an impulse is sent to the transmitting transducer.

The phasing switch is in series with the amplifier output and the printer blade. This switch can be adjusted in the same manner as the auxiliary keying switch so that recording is limited to the first revolution of the drum after keying, thus avoiding false depth recordings. The cam-rise surface is of such length that recording is obtained the full length of the drum. Thus, proper synchronization between transmitted and received signals is obtained, and the position of the recording on the chart is a direct indication of the depth of the water below the transducers.

The printer bridge assembly contains the printer bar, to which is fastened the printer blade, two pilot lights for illuminating the observation area, and an adjustable fathom-marking stylus. When the range switch is in the fathoms position, voltage from the amplifier power supply is applied to this stylus, and when it is adjusted so that it rests on the chart paper, a recording is made. Thus a vertical line is recorded in the left margin of the paper as a reference that the recordings are in fathoms. After a recording has been removed from the instrument it is possible to distinguish between feet and fathoms by means of this marginal identification. The printer blade and spiral wire are in contact through the paper at only one point at any given instant. An electrical impulse, received by the printer blade at the moment of contact, arcs through the paper, leaving a permanent black dot. Successive dots form the chart recordings. The range marking in the left margin is recorded in the same manner.

Echo amplifier.—The amplifier is a self-contained unit consisting of a tuned input transformer, four resistance-coupled voltage-amplification stages, and a power stage with a tuned output transformer. It has its own power transformer and rectifier tube for plate supply.

It is designed to receive a signal pulse at 14.25 kc and, subject to the setting of the gain control, to amplify this signal voltage sufficiently to produce a permanent record on the recorder chart by the arc-discharge method. The amplifier components are mounted on an aluminum chassis, which is shock-mounted on the lower door of the recorder cabinet.

DRIVER-RECTIFIER OR SIGNAL SENDER

A resiliently mounted cabinet, with a cast bronze base and a ventilated sheet metal cover, encloses the electronic circuits that produce the electrical impulses required by the transmitting transducer. The filtered supply from a low-voltage rectifier tube stores energy in a capacitor, which, in turn, is discharged through the strobotron transformer each time the keying contacts are closed in the recorder. The resulting pulse, delivered to the strobotron (pl. 9*A*), causes this tube to flash through the discharge tube transformer, in turn producing an extremely high potential pulse that is applied to the discharge tube. Ionization of the gas in this tube causes it to conduct, thereby releasing to the transmitting transducer, in the form of an intense pulse, the energy that has been stored in the capacitor by the high-voltage rectifier. The very high current induced in the transducer produces the magnetostriction effect desired.

Part of the output energy of the signal relay is fed back to the recorder mechanism through the zero-depth button to the printer blade, for the purpose of recording a zero-depth mark on the chart.

TRANSMITTING AND RECEIVING TRANSDUCERS

The transmitting transducer converts electrical impulses from the echo sender, under the control of the keying switches in the recorder, into pressure waves that pass through the water to the bottom and from there are reflected back to the receiving transducer. The receiving transducer converts the pressure waves to electrical impulses, which, when amplified, mark the chart in the recorder.

Each transducer consists of a stack of torroidally wound nickel laminations (pl. 9*B*), mounted in a reflector lined with cellular rubber, which, in turn, is mounted on an adjustable bracket, allowing compensation for a dead rise of the bottom hull plate up to 15°. This unit is enclosed in a cylindrical housing that is bolted to a leveling ring, which must be welded to the outer skin plate of the ship with the transducer diaphragm in contact with the water. The housing is filled with castor oil.

The transducers may be mounted either fore and aft or athwartships across the keel. For accurate shoal soundings they should not be placed more than 6 feet apart. The operating frequency of the transducers, 14.25 kc, is outside the range of interference from ordinary water noises such as chafing objects.

The impulses from the echo sender set up a magnetic field in the laminations of the transmitting transducer. The laminations contract as the field increases and expand as the field decreases. The effect is known as magnetostriction, which sets up mechanical vibrations that are transmitted through the liquid within the transducer housing. These vibrations are transmitted to the water and thence to the bottom, where they are reflected back to the receiving transducer.

The receiving transducer is identical with the transmitting transducer; it is mounted in the same way but is premagnetized by a momentary impulse of direct current. The reflected vibrations are transmitted to the liquid in contact with the laminations, causing expansion and contraction of these laminations and thereby a change in the magnetic field in the receiving transducer. This change in the magnetic field induces an electrical impulse in the winding of the transducer, and the impulse is transmitted to the input of the echo amplifier through the interconnecting wires.

MOTOR-ALTERNATOR SET

The speed of the mechanism is strictly dependent upon the frequency of the output of the motor-alternator set, and proper operation of the equipment can be attained only when this frequency is held within 0.5 cycle of 60 cycles per second. Frequency regulation is accomplished by means of a centrifugal governor, operating across a resistor in series with the shunt field in the motor of this unit, so that speed changes cause the contacts to open or close, thereby tending to oppose speed changes by field compensation.

A magnetic controller, suitable for use with the motor-alternator set, is supplied as an accessory for use when required. It contains a relay for remote starting of the motor-alternator set, a capacitive filter for prevention of radio interference, and protective fuses in the d-c supply to the motor-alternator set. The relay operates from the ship's d-c supply under the control of the power switch on the cover of the recorder.

NK–6 PORTABLE DEPTH-RECORDING EQUIPMENT

The NK–6 depth-recording equipment is a semiportable supersonic, rapid-recording, echo-sounding instrument designed for use in shallow to moderately deep water and for temporary installation in a launch or vessel.

The instrument operates in two ranges, 200 feet and 200 fathoms. It consists essentially of three separate units: a recorder cabinet, containing the graphic recording mechanism, signal sender, echo amplifier, and motor-speed indicator; a submersible unit containing the transmitting and receiving transducer; and a 12-volt storage battery. The power consumption is approximately 120 watts at 12 volts dc.

RECORDER

Cabinet.—All essential parts of the NK–6 recorder, except the transmitting and receiving transducers and the battery, are in one metal case, which has an additional canvas cover for protection from the weather. The operating controls consist of a four-position rotary power switch, a two-position range switch, a gain control and a "fix" button. A motor-speed indicator and voltmeter are located on the cover. The recording is visible through a shatterproof glass port on the cover and this port may be opened to record bearings or other pertinent data on the chart.

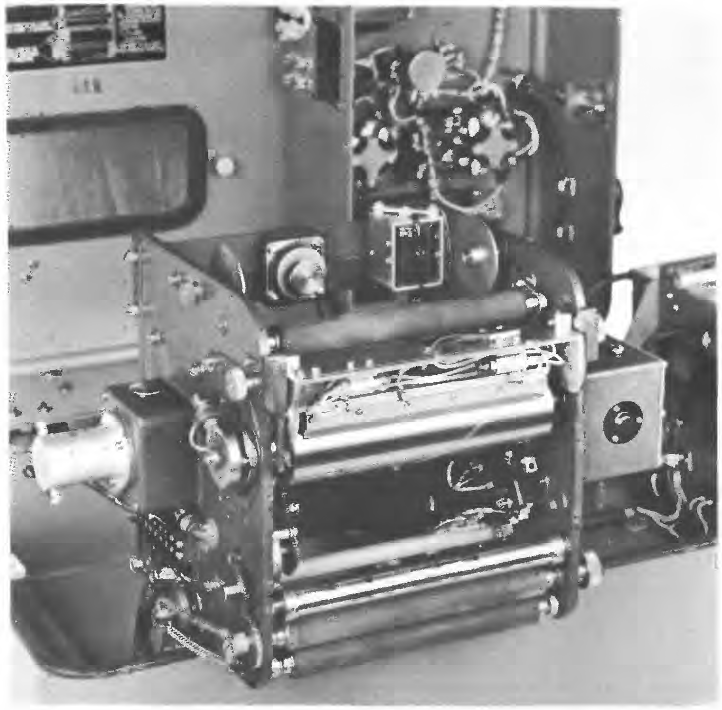
Recorder mechanism. — This unit is resiliently mounted in the left compartment of the recorder case. It consists of a 3600 rpm, series-wound, governor-controlled, 1/30-hp drive motor; a gear box and positive clutch; a drum upon which a spiral wire is carefully positioned; a positively driven paper-propulsion device; a main keying assembly; the cam-actuated auxiliary keying switch and associated phasing switch; a printer bridge assembly; a fathoms-marking contact, to record a vertical line in the left margin of the chart; and a two-hole permanent magnet alternator directly connected to the drive motor shaft, which furnishes a-c power to operate the reed tachometer used for the motor-speed indicator (pl. 10*A*).

The drum, paper-propulsion device, paper, method of marking, cam shaft, and auxiliary keying and phasing switches of the NK–6 equipment are similar to and operate like corresponding equipment in the NJ–8 recorder mechanism.

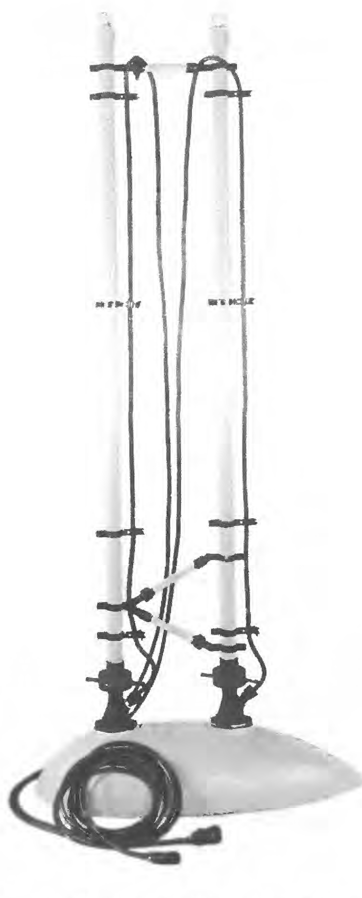
When the range switch is set on fathoms, the fathoms solenoid operates and transfers the clutch in the gear box from the feet to the fathoms position and reduces the speed of the drum and cam shaft. It also applies voltage from the rectifier circuit of the driver-rectifier to the fathom-marking contact. This contact is adjustable so that when it is properly positioned with respect to the spiral wire on the drum, a recording is made on the chart paper. Thus, a vertical line is recorded in the left margin of the paper as a reference that the recordings are in fathoms. When the range switch is in feet position, the feet solenoid operates and transfers the clutch to the feet position.

Signal sender and echo amplifier.—The unit is resiliently mounted in the right-hand compartment of the sounding recorder.

The driver-rectifier section of the chassis consists of a nonsynchronous vibrator, which in conjunction with the step-up transformer and the full wave rectifier tube, furnishes high voltage to charge a capacitor and also screen and plate supply for the receiver-amplifier. At the instant the main keying brush

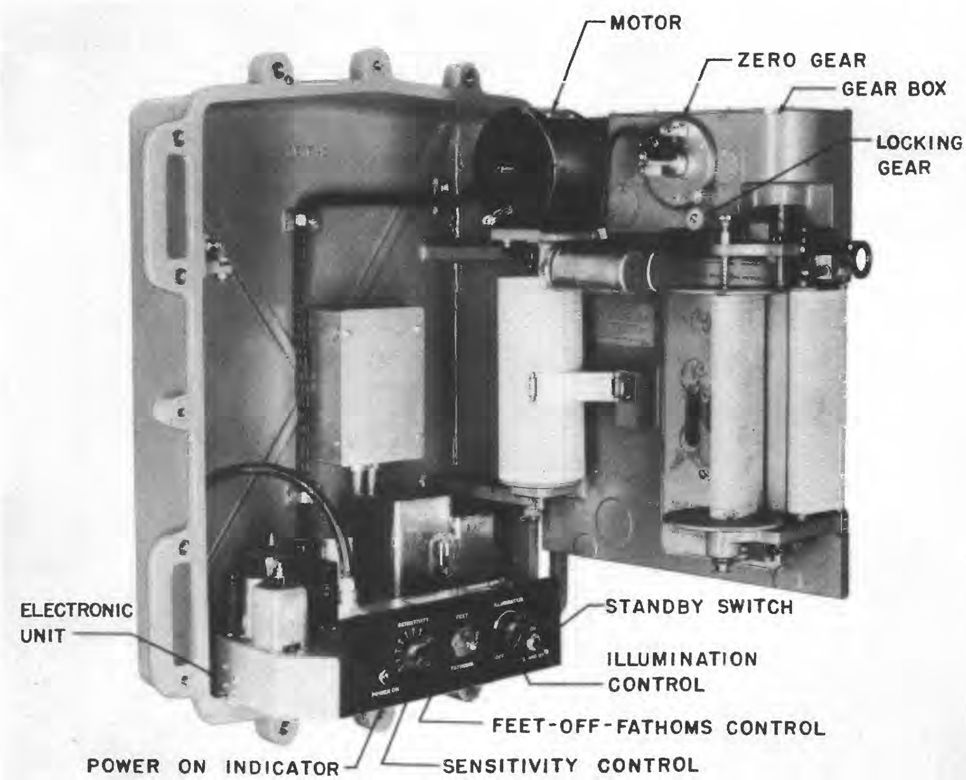


A. NK-6 RECORDER, SHOWING CAREFULLY POSITIONED SPIRAL WIRE ON DRUM

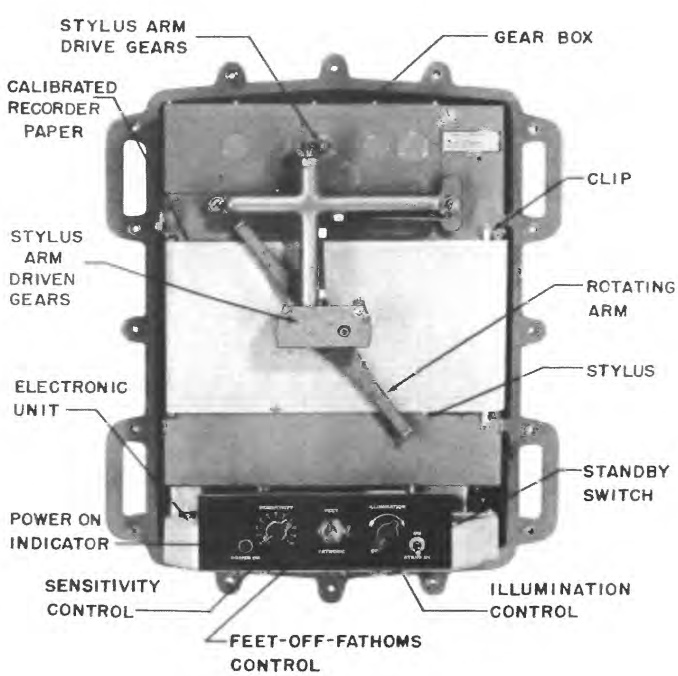


B. NK-6 SUBMERSIBLE UNIT, CARRYING TRANSMITTING AND RECEIVING TRANSDUCERS

This is a portable overside-mounting arrangement.



A. NGB-3 DEPTH RECORDER, INSIDE VIEW



B. NGB-3 DEPTH RECORDER, SHOWING RECORDING UNIT and the auxiliary keying switch make contact, current flows through the primary of the step-up transformer, and induces a voltage in the secondary which ionizes the gas in the gaseous discharge tube (strobotron), thereby discharging the capacitor through the transmitting transducer. A part of the discharge is impressed on the cathode of the first tube in the amplifier to record a zero signal on the recording chart paper.

The reflected impulse is conducted from the receiving transducer to the input transformer of the amplifier section of this chassis. The amplifier is a three-stage resonant type, tuned to a frequency of 14.25 kc. The second stage is resistance coupled, and the input, output, and third stages are transformer coupled. The output is connected through an isolating capacitor and the phasing switch to the printer blade. The sensitivity of the amplifier is controlled by adjustment of the gain potentiometer, which varies the bias of the second stage. The signal energy is amplified sufficiently to produce a permanent record on the chart by the arc-discharge method.

SUBMERSIBLE UNIT

The submersible unit (pl. 10*B*) consists of a transmitting and receiving transducer in a streamlined cast aluminum housing, 37 inches long and 14 inches wide. Each of these transducers is magnetostrictive and consists of a stack of thin annular nickel stampings, mounted on a spindle inside an air-filled reflector and immersed in castor oil. Each pack is torroidally wound with an energizing coil of neoprene insulated wire. The operating frequency of the transducer is 14.25 kc. The transmitting and receiving transducers are identical in all respects, except that the receiving unit is permanently magnetized. This submersible unit should be installed so that its bottom is at least 2 feet below the water surface and on a horizontal plane and its axis parallel with the center line of the vessel. There should be at least 1 foot clearance between it and the vessel.

HIGH-FREQUENCY DEPTH-RECORDING EQUIPMENT

By Robert P. Geddes, Jr., and Birt Blackman, Bendix Aviation Corp.

NGB–3 DEPTH-RECORDING EQUIPMENT

The principal high-frequency depth-recording equipment used at Lake Mead was the U.S. Navy type NGB–3 depth-recording equipment. It is designed to measure depth in water by the echo method and to chart that information on recording paper. The instrument operates at a frequency of 50 kc. It receives and amplifies the echo, measures the intervening time interval, and records this interval as a depth measurement that is subject to correction for temperature and other factors. It can record depths between the limits of 2½ feet and 50 fathoms. This equipment was selected because of the sharp definition it developed between the water and the top of the sediment layer, even when the sediment layer was thin and the difference in density slight.

This depth recorder is designed for two depth ranges: from 2½ to 50 feet, and from 1 to 50 fathoms. When the "feet" range is used, ultrasonic impulses are sent out at the rate of 576 per minute. When the "fathoms" range is used, 96 pulses per minute are transmitted. The equipment comprises a principal housing, a transducer (the diaphragm of which is submerged in water), and interconnecting cables. The principal housing is 23¾ inches high, 18¾ inches wide, 11 inches deep, and weigh about 90 pounds. The recording unit and the electronic chassis are inside the housing (pl. 11*A*). The electronic chassis has a subchassis, which mounts a vibrator power supply unit that is interchangeable with other units having different input voltages; a 24-volt unit drawing 2.75 amperes was used in the survey.

The recording unit (pl. 11*B*) has a pivoted rotating arm, which carries the marking stylus. The arm is driven at high or low speed depending upon the "feet–off–fathoms" switch setting. Calibrated paper is pulled horizontally across the face of the platen and over a stainless-steel grounding plate. The recording of echoes is accomplished by means of an arc that burns the paper surface at the point of contact between stylus, paper, and stainless-steel grounding plate, causing the initial pulse and returning echoes to appear as a dark trace. The calibration of the paper is in either feet or fathoms at option. The initial mark on the "feet" position appears as a long dark trace at 0 to approximately the 2½-foot mark on the paper. The initial trace on the "fathoms" position appears as a narrower and much darker trace and can be distinguished readily as a fathom trace, thereby identifying the marks left on the paper as definitely in feet or fathoms.

The transducer is 8¼ inches high and 5 inches in overall diameter, and it weighs approximately 3 pounds. It is connected to the electronic unit contained in the principal housing by means of a twin-axial cable. The electrical energy is converted into 50-kc mechanical impulses in the transducer crystals. Returning echoes are reconverted into electrical energy by the transducer and are delivered to the electronic unit through the transducer cable. In operation the transducer diaphragm is pointed downwards with a tilt not over 5° from horizontal. The transducer may be completely submerged in water.

CIRCUIT ANALYSIS

The electrical circuits of the NGB–3 depth recorder are shown diagrammatically in figure 14. Primary power is channeled to the power supply through a jack in the principal housing and is fed to a "hash" filter circuit, composed of inductors and capacitors. One leg is in each side of the line and the winding is such that the two fields cancel out. Primary power continues through the jack and switch to where the power supply is plugged in. All input power supplies must furnish 110 volts ac at 60 cycles for the synchronous induction motor, 250 volts dc at 15 milliamperes to power the electronic unit, and 6 volts for the filaments and lamps. The power supply includes a typical full-wave rectified circuit using a 6X5GT tube. Transformers are furnished with an electrostatic shield between the primary and secondary windings, and an electrostatic lamination shield is built into each transformer. Each is fed to the feet–off–fathoms switch, and current for phase 2 field of the synchronous motor flows through the electronic unit jack and principal housing plug. A 3-microfarad power-factor correcting capacitor is connected across the 110-volt a-c line to provide proper phase relation. The motor phase-shifting capacitor is connected in series with phase 1 winding of the synchronous motor and connects back to the feet–off–fathoms switch. Reversal of the motor is accomplished by reversing the position of phase 1 winding of the motor across the 110-volt a-c line.

The single-phase induction motor operates with no electrical connection to the rotor. It has two stator windings in which a rotating field is established. The rotor turns mechanically because of the reaction of heavy circulating current against the rotating field around it. A capacitor in series with phase 1 winding provides a calculated phase lag for motor starting. Direction of rotation is reversed by reversing the connections of phase 1 stator winding in the switch.

Timing.—Timing of the outgoing initial impulse is originated by a contact cam mounted on a shaft extending through the rear of the gear box assembly. The switch closes at the instant that the stylus arm is

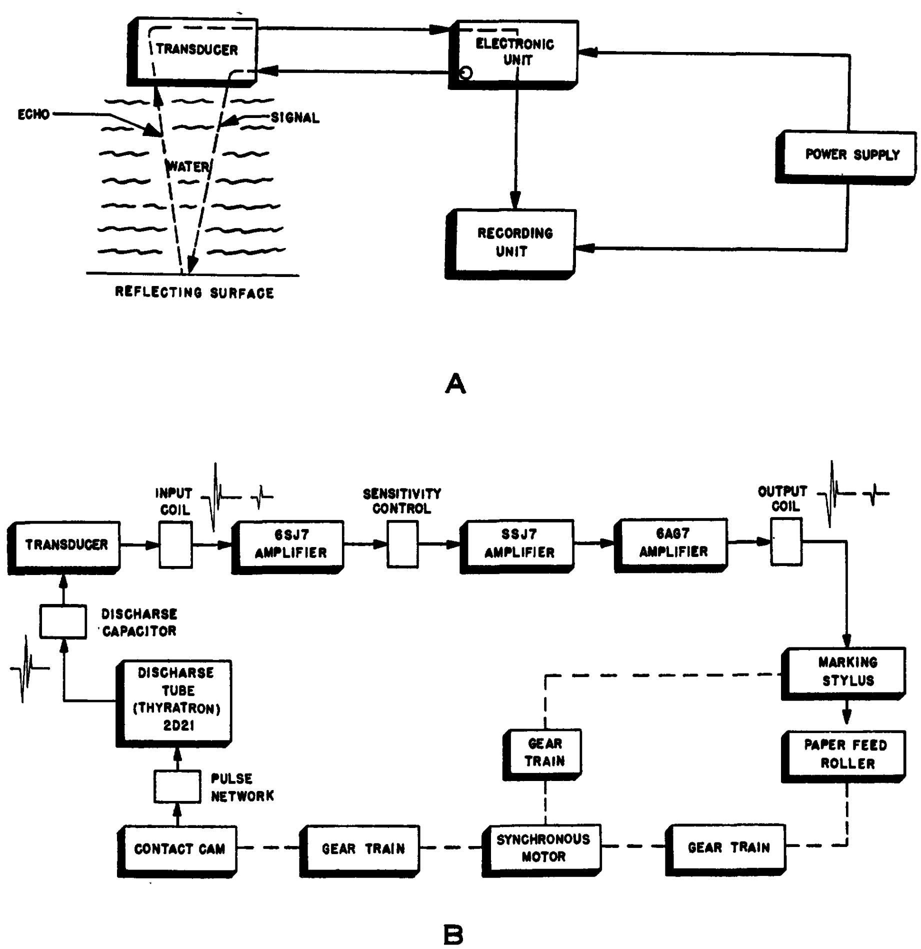


FIGURE 14.—Block diagrams illustrating electronic circuits and principle of echo sounding. *A*, Principle of echo sounding; *B*, Operation of echo sounder.

rotating past the 0 mark on the calibrated paper. Coaxial cable is connected through connectors and jacks to the pulsing capacitor. The pulse is received at the thyratron tube grid, as this grid is negative and is merely driving the tube into a region of greater cutoff. However, when the switch is opened a sharp positive pulse appears momentarily at the control grid, causing it to fire and discharge the capacitor through the autotransformer type of inductor in the transducer housing. At the same time, a voltage appears across the series-resonant circuit, causing a neon glow tube to fire and rapidly quench the oscillations that have begun to take place in the entire circuit. A short initial pulse is thus fed through the electronic unit amplifier and appears as a zero mark on the calibrated paper.

Transmission.—Shock excitation is produced in the autotransformer transducer coil in the process of discharge through the thyratron. A large pulse of electrical energy shock excites the 50-kc resonant circuit in the transducer and produces a dampened wave. The crystal assembly in the transducer converts the electrical energy into 50-kc mechanical energy by virtue of its piezoelectric property. This energy goes into the surrounding castor oil in the transducer, which in turn transfers it through the rubber diaphragm into the water.

Reception.—The signal progresses through the water to a reflecting surface and returns to the transducer in the form of an echo. The crystal assembly in the transducer, having reversible piezoelectrical properties, converts this reflected energy back into electrical form. The output of the transducer unit goes back through the cable system in the reverse direction. The incoming pulse appears across the grid and is amplified in a conventional manner through electronic tubes. The sensitivity control is placed in the control grid of one of these tubes and serves to regulate over-all gain in the amplifier. Actual marking of the paper occurs in the same sequence as for the initial pulse previously described.

EVALUATION OF THE ECHO SOUNDING

By G. B. Cummings and C. E. Mongan, Jr.,
U.S. Bureau of Ships

The sonar equipment and methods used to determine the depth of water and thickness of sediment in Lake Mead are based on the echo-sounding principle: a pulse of sound energy is emitted from a projector, travels through the water, is reflected, and returns as an echo to the projector, which has been arranged in the meantime to receive the echo. The echo can then be recorded in various ways, such as on a cathode ray screen or on the paper chart of a recorder.

Several factors were considered in choosing the echo sounders used. The difference in density between the water and the top of the sediment layer was very small in some localities, and relatively high-frequency ultrasonic waves (50 kc or more) were required for the accurate determination of the depth to this interface between the water and the sediment. In contrast, relatively low-frequency waves (14.25 kc) were used to penetrate the sediment layers down to the hard bottom. It was also desirable to arrange for switching and cross hookups between the component parts of several equipments, in order to provide flexibility of use and continuous operation.

Most of the sounding of Lake Mead was done with the Navy type NGB–3 depth-recording equipment, operated at 50 kc, and by the Navy model NJ–8 depth-recording equipment, operated at 14.25 kc. The Navy model NK–6 portable depth-recording equipment, which also operates at 14.25 kc, was used for some observations. In addition, depth-recording equipment with a frequency of 88 kc was used experimentally.

The NJ–8 echo depth sounder had been installed by the Naval Base at San Diego prior to shipping the boat to Boulder City. The transducers were installed in the bottom of the hull of the picket boat, amidship and as close to the keel as possible. During the first phase of the survey this installation was satisfactory, but later on portable transducers were used with the NJ–8.

The first sounding operations were made with the NJ–8 exclusively; it was found that this equipment gave a very clear picture of the sediment deposits in the old river bottom. As this was a desired finding, it was decided to use only the NJ–8 when the surveying was over the old river bed. When it was not over the old river bed, the NK–6 or NGB–3 was used for sounding. The NK–6 is designed to use the same transducers as the NJ–8, and switching arrangements were developed to use the same transducers and power supply for both equipments. The NK–6 gave a very good recording trace and was much simpler and easier to maintain than was the NJ–8. Sounding operations utilizing the NGB–3 recorder produced a sound-trace recording that was dark and easy to read.

ANALYSIS OF RECORDS

The NGB–3 equipment, operating at 50 kc, gave a consistent indication of the top of the sediment. Sound of this frequency did not penetrate the sediment. Where the sediment was very thin, the trace of the interface was slightly fuzzy. Independent determinations showed that the transition layer was 1 to 4 inches thick.

The instruments operating at 14.25 kc produced an echo from the water-sediment interface and an echo from the bottom of the sediment. Additional echoes were recorded at some locations in the lake, which were attributed to changes in density of the layers of sediment. In the soft sediment of the Boulder Basin, penetration of 140 feet of sediment was obtained near the old cofferdam at Hoover Dam. This sediment had a specific gravity of about 1.2, and a 50-pound weight dropped easily through it. Up the lake 20 miles east of the dam, the reflections were poor and were not consistently obtained from the bottom of the sediment. Here the sediment was more compact, and a 50-pound weight would penetrate only 3 to 4 feet. However, some of the sediments farther uplake were penetrated, as for instance near Pierce Ferry, where on one occasion there was reflection from the bottom of a sediment layer 130 feet thick. The average thickness of sediment in the old river bed was about 70 feet.

Standard methods of computing sound velocity in waters of differing salinity were checked and found to be adequate. Water that contained a concentration of 700 ppm of mineral salts (about average for Lake Mead water) was considered pure water. Corrections for sound velocity were made to all charts prior to transferring the depth information to the smooth sheets.

A comparison of the sonar depths with readings from sounding lines indicate an accuracy within 1 to 3 feet. The observations, showing reflections from the interface at one frequency and penetration of the sediment at another frequency, present an acoustic problem that has not yet been solved. It seems clear that the difference of impedance at the interface is inadequate to explain the effects. The thermal structure of the lake is such that there is too small an increase in temperature at the interface to account for the reflections. It seems plausible, therefore, than an energy-absorption process is going on in the sedimentary layer, and that such a process is a function of the particle size, the water content, and the frequency of the sound. The details of this functional relation have not yet been established. Data, obtained by Raitt [3] by sending low-frequency pulses through marine sedimentary layers, indicate that the transmission losses in the sediment are less at lower frequencies. This observation would be in accordance with the trend of the observations made at Lake Mead.

Observations made during the survey indicate:

1. The high-frequency equipment (50 kc) showed the top of the sediment within 2 feet of accuracy; thus, the top of the sediment was established over a large area.
2. The low-frequency equipment (14.25 kc) penetrated through the sediment to the hard bottom below. It showed a reflection at the top of the sediment and also one at the bottom; thus, this equipment confirmed the results obtained with the high-frequency equipment and gave a series of measurements that could be coordinated with the bottom contours obtained from the survey of 1935.
3. A third equipment, which operated at a high frequency (88 kc), was used to a limited extent on an experimental basis; it indicated the sediment level within 1 foot of accuracy and otherwise gave results that were complementary and confirmatory to those obtained by the other instruments.
4. The depths obtained by the Navy depth-recording equipments were in close agreement with the results obtained by cable and reel depth measurements where the depths permitted the latter observations to be made.
5. Core measurements and samples showed that the top of the sediment-water interface is quite sharp. This is in accord with the soundings obtained by the high-frequency devices.

Much additional research will probably be necessary to answer fully all questions raised by this survey, some of which are indicated in the discussion above. It is apparent, however, that a suitable device for a sediment and bottom-structure survey can be designed as a result of this survey. It would combine in one instrument the following characteristics:

1. Variable frequency (10–80 kc), with separate transducers, if necessary, for successful penetration of and discrimination between layers.
2. Variable power (15 watts to 1 kilowatt) to implement 1 above.
3. A suitable recorder, with time-fix indication.
4. A cathode ray indicator with suitable photographic attachment and visual viewer. This device would assist in bottom-structure analysis by return-pulse analysis techniques.

Such an equipment can be built and would solve a majority of the survey problems showing characteristics similar to those found in the Lake Mead survey.

HYDROGRAPHIC SURVEY: SUMMARY OF RESULTS

By F. C. Ames, U.S. Geological Survey

A map of Lake Mead just before it began to fill in 1935 was prepared by the Soil Conservation Service (1935) from topographic surveys by Fairchild Aerial Surveys, Inc. The map was published in 52 sheets, at a scale of 1:12,000 with contour intervals of 5 and 10 feet, together with an index sheet at a scale of 1:250,000. The data obtained in the present surveys (1948–49) were used to draw new contour lines wherever signifi-

[3] Raitt, Russell, 1949, Unpublished report of researches: San Diego, California University Marine Physical Laboratory.

cant changes since 1935 were noted. The new contours—at intervals of 5 and 10 feet for the gently sloping sediment surface and 50 feet elsewhere—and the sediment boundaries have been printed (U.S. Geological Survey, 1951) on overlay sheets to fit 43 of the numbered sheets of the 1935 map, the only ones affected. Both surveys were used by the Coast and Geodetic Survey (1952) in the preparation of navigation charts of Lake Mead in six sheets at a scale of 1:48,000.

The sounding records obtained in 1948 reveal a range of depths from the shallowest water in which the sounding boats could operate, about 3 feet, to a maximum of nearly 450 feet above the sediment surface in Boulder Basin when the lake was at a high stage. The elevation of the sediment surface was lowest at the dam. In Boulder Basin, where both the sediment surface and the prelake topography were recorded on the sound traces, the indicated elevations of the prelake topography checked very closely with the 1935 map elevations, as shown in plate 12, a representative profile in Boulder Basin.

EVIDENCE OF SEDIMENT ACCUMULATION

Nearly all of the significant changes in reservoir bottom between 1935 and 1948 have resulted from deposition of sediment by the Colorado River. The evidence indicates that these sediments are confined almost entirely to the old river channel, except in Pierce Basin, Grand Wash Bay, and small parts of Boulder Basin. The general distribution of sediment contributed by the Colorado River is therefore well shown by profiles along the centerline of the former river channel—the thalweg—as presented in plate 13. This profile shows the maximum sediment thickness in 1948 to be about 270 feet along the thalweg in Pierce Basin, near longitude 113°57′. Downlake from this point the sediment surface slopes, steeply at first and then progressively more gently, toward Hoover Dam. Comparison with the Colorado River profile in 1935 shows that the sediment along the thalweg attains a minimum thickness of 45 feet in the Temple Bar area and increases progressively toward the dam, where it is more than 100 feet thick. According to the section normal to the former river channel, the sediment surface is practically level, though slightly concave upward. In parts of Gregg Basin the sediment surface is from 1 to 3 feet higher near its edge than along the thalweg.

In Pierce Basin, Grand Wash Bay, and some parts of Boulder Basin, some sediment has been deposited on side slopes above the main body of the fluvium. In the lower part of Pierce Basin, sediment occurs in the bottoms of former washes and on benches as much as 30 feet higher than the sediment surface in the thalweg. In Grand Wash Bay some sediment has been deposited nearly 2 miles from the old Colorado River channel, at elevations as high as 50 feet above the sediment surface in the channel. In Boulder Basin between longitudes 114°42′ and 114°44′, a thin layer of sediment has evidently been deposited on small flat benches in the original bottom, at elevations as much as 10 feet higher than the sediment surface along the thalweg.

The Virgin River has deposited sediment from the high-water line of the reservoir south to latitude 36° 25′, but there is no measurable quantity of sediment in any part of the former Muddy Creek channel.

EVIDENCE OF SLUMPING

Aside from the accretion of sediment, the Lake Mead reservoir has, in general, remained relatively unchanged since the original survey in 1935. Only four slump areas of any consequence are noted, three in Boulder Basin and one in Virgin Canyon. The largest of these is an area along the north shore of Boulder Basin near latitude 36°08′, longitude 114°40′, where lateral displacements between original and new contours amount to several hundred feet. About 12,000 acre-feet of earth between elevations 925 and 1,220 feet have slumped, of which some probably came to rest below the present sediment surface at elevation 750 feet (p. 209).

The two other Boulder Basin slump areas are much smaller. One is on the north shore near latitude 36°07′, longitude 114°44′, where there was slumpage of 500 to 600 acre-feet of material that in 1935 had stood between elevations 1,050 and 1,250 feet. At the other, east of Boulder Islands near latitude 36°03′, longitude 114°45′, occurred the movement of 300 to 400 acre-feet of material that had been between elevations 750 and 900 feet.

Near the middle of Virgin Canyon is a slump area that extends about 2,000 feet along the north side, where the steeply sloping side-wall material has slipped downward about 40 feet (p. 209). There is also surface evidence of two or three minor slips on the south side of Virgin Canyon. The tops of all these slide areas are entirely above the reservoir flow line, and it is not known precisely how the slides have affected reservoir capacity. The echo-sounding equipment could not show the precise position of side walls below water because of the steepness of the side slopes. Furthermore, in such a canyon section it is questionable if the original map would be an accurate frame of reference. A dependable estimate of underwater change could have been determined only by lead-line soundings along a series of cross sections monumented and defined prior to the earth movement. The direction and amount of slippage revealed above water, however, indicate that decrease in the reservoir capacity could have been no more than a few hundred acre-feet.

EVIDENCE OF EROSION

Stream erosion since 1935 has been great enough in one locality to cause some increase in the reservoir area. At the mouth of Detrital Wash the channel above the average lake level has been scoured in places to depths of about 10 feet. This cutting, which probably occurred during extreme floods on the lower Colorado River in 1939 (Gatewood, 1945), has enlarged the area of the reservoir at an elevation of 1,230 feet by about 100 acres. The material scoured from Detrital Wash has undoubtedly accumulated on the lake bottom, but apparently in such a thin layer that it could not be detected by comparison of the 1948 topography with the pre-Lake Mead topography.

Some minor alterations of shoreline are clearly attributable to wave action. A few steep-sided headlands of rather loosely cemented sand and gravel are subject to under cutting and caving along the north shore of Boulder Basin and on the east shore of Overton Arm near latitude 36°20′. Blocks of material have fallen away and lie at the base of such headlands, but it is not known how much of this disintegration occurred as a result of normal weathering long before Lake Mead was formed, and how much has occurred as a result of wave cutting. At any rate, such areas are so small that quantitative determination of the volumes of rock moved by waves was beyond the scope of the current survey.

Except for these gravel headlands and the rock-walled canyons, most of the lakeshore slopes moderately and consequently is not subject to serious undercutting and caving. Certainly caving above the high-water line at elevation 1,220 feet is rare indeed. Therefore it may be said with assurance that the reservoir has not suffered any net decrease in capacity worthy of consideration as a result of wave action.

There remains the visual evidence of compensating changes in the capacity-elevation relation caused by wave-built terraces. Such changes are the result of the shifting of material from one elevation to another below the high-water line. The lake stage fluctuated between 1,154 and 1,193 feet during the course of the hydrographic survey, and most of the reservoir bottom within this range could not be adequately mapped by sound boat because it was either near shore or above the shoreline. Consequently, data are not at hand from which a quantitative statement might be adduced regarding littoral change. Such sounding as was accomplished alongshore within the operating range did not reveal important alterations which might be attributed to wave erosion at any place. However, small wave-built terraces do exist at intervals all around the lake and it is likely that, in the aggregate, these terraces represent the movement of a considerable quantity of material within the operating range of the reservoir, which is generally between elevations 1,150 and 1,200 feet.

A simple analysis indicates that the volume of material in these terraces is small and that wave action is negligible as an agent affecting reservoir capacity change at Lake Mead. Boulder Basin, whose shores exhibit more terracing than any other basin of the lake, has a perimeter of about 300,000 feet. Let it be assumed that one-third of the perimeter, or 100,000 feet of shore, has an average slope of 20° and is terraced by 3-foot vertical steps between elevations of 1,150 and 1,200 feet. Let it then be assumed that all the material in the terraces was carried below 1,150 feet, and that the outer edge of each terrace lies in the original shore plane. Both these assumptions exaggerate the true conditions and imply an earth movement much larger than actually occurs. Even so the change involved is only 480 acre-feet, which is less than 0.03 percent of the 1,453,000 acre-feet that can be stored in Boulder Basin between elevations 1,150 and 1,200 feet.

In addition to the shore proper, islands and some underwater peaks are subject to wave erosion. Such erosion is quite evident in places, where 10 to 50 feet of material has been stripped away from the tops of some prominences. Erosion of this nature is most marked in Las Vegas Bay, where islands and offshore shoal areas are far more numerous than in the rest of the lake, and where a considerable proportion of the material can be dissolved by the lake water. Hence, the proportion of material removed from shoals and islands in Las Vegas Bay is far greater than the average for the entire lake. It is estimated that only about 50 acre-feet of island and shoal erosion has occurred in that bay between longitudes 114°45′ and 114°50′ and between elevations 1,150 to 1,180 feet. The reservoir capacity of the same area and between the same elevations is 211,600 acre-feet. Thus even in the area of maximum observed erosion the alteration of offshore features is a negligible element of reservoir change.

REFERENCES CITED

Brown, C. B., 1941, Mapping Lake Mead: Geog. Rev., v. 31, p. 385–405.

Fairchild Aerial Surveys, Inc., 1935, List of geographic positions of triangulation stations established in connection with the aerial survey of the Lake Mead area.

Gatewood, J. S., 1945, Floods of September 1939 in Colorado River basin below Boulder Dam: U.S. Geol. Survey Water-Supply Paper 967–A.

McIntosh, W. F., 1951, Arizona-Nevada triangulation for the Lake Mead investigation, third order: Sacramento, Calif., U.S. Geol. Survey mimeo rept., 32 p.

Speert, J. L., 1938, Readjustment of triangulation datum: Am. Soc. Civil Engineers Trans., v. 103, p. 1002–1018.

U.S. Coast and Geodetic Survey, 1935, Tables for a polyconic projection of maps and lengths of terrestrial arcs of meridians and parallels based upon Clark's reference spheroid of 1866: U.S. Coast and Geod. Survey Spec. Pub. 5, 189 p.

——— 1952, Lake Mead: U.S. Coast and Geod. Survey Charts 5457 A and B, 5458 A and B, and 5459 A and B, scale 1:48,000.

U.S. Geological Survey, 1924, Plan and profile of the Colorado River from Lees Ferry, Ariz., to Black Canyon, Ariz.-Nev.: U.S. Geol. Survey River Survey Map, 21 sheets (14 plans, 7 profiles), scale 1:31,680, contour interval 50 feet.

——— 1951, Lake Mead sedimentation survey. (Overlay for 43 sheets of Soil Conservation Service maps of 1935, showing sediment surface in 1948–49. Reproduced for official use. Available for examination in offices of the Geological Survey, Washington, D.C., and Bureau of Reclamation, Boulder City, Nev.)

U.S. Soil Conservation Service, 1935, Topographic maps of Lake Mead area: Sheets 1–52 at scale 1:12,000, and index sheet at scale 1:250,000.