HEL-12-3

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PHOTOGRAMMETRIC DEFINITION OF A WAVE SURFACE

by

FRANCIS H. MOFFITT

HYDRAULIC ENGINEERING LABORATORY
COLLEGE OF ENGINEERING

UNIVERSITY OF CALIFORNIA
BERKELEY

SEPT. 1966

University of California
Hydraulic Engineering Laboratory

Submitted under Contract DA-49-055-CIVENG-65-5
with the Coastal Engineering Research Center, U.S. Army

Technical Report
HEL-12-3

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Berkeley, California
September 1966

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Introduction

The one- or two-dimensional measurement of a wave surface is rather straight-forward, assuming the positioning and proper functioning of step gages or resistance gages. The two-dimensional measurement, however, is a function of time unless an adequate number of gages are used. The inherent lag in the recording device, and its tendency to smooth out the wave surface presents difficulties when the true wave configuration must be defined.

When measuring a strict three-dimensional wave surface, the fidelity of reproduction is drastically limited by the number of gages which are able to be installed from a practical standpoint. Furthermore, the influence of the gages themselves may disturb the natural state of the surface, depending of course on such factors as wave velocity, amplitude, type of wave generation, and so forth.

The ideal measuring system for establishing a three-dimensional portrayal of the surface defined by a wave pattern, such as a ships wake, is one which: a) is fairly simple; b) affords a practical infinity of measured points of the surface at one instant of time; c), does not introduce energy into or take energy from the wave system to be measured; and d) is not influenced by time lag, surface tension, or other disturbing

†Professor of Civil Engineering, University of California, Berkeley.
Prepared for presentation at the Semi-Annual Meeting, American Society of Photogrammetry, Los Angeles, California, September 1966.

elements of the measuring system. The photogrammetric system approaches this ideal. For this reason, it seems desirable to investigate the adaptation of some form of photogrammetry for application to the problem of defining a wave surface.

Photogrammetry is a system in which an object or an event in time and space is optically recorded onto a sensitized film or plate by means of an appropriate camera, and in which the subsequent image is measured in order to define, portray, digitize, or in some way classify the object or event. Stereo photogrammetry implies the use of two photographs of the object or event in order to be able to reconstruct the object or event in complete three dimensions. If the object to be measured is in a static state, then one camera is used at two different positions in order to obtain the stereoscopic pair. However, if the object or event is in a transitory or ephemeral state, two cameras are essential. Furthermore, the two photographs must be exposed simultaneously or nearly so, depending upon the time rate of change of the object or event. A water wave surface can be considered as an object of a transitory nature, and thus it must be photographed simultaneously from two different viewpoints in order to be measured photogrammetrically. By this method, the surface is literally "frozen," and the results are measured at the convenience of the investigator.

Present Study

The purpose of the present study is to determine the feasibility of applying the stereo photogrammetric method to the measurement of the wake of a ship model produced in a towing tank and in a model basin.

Towing Tank Studies

The towing tank is eight feet wide inside to inside, 200 feet long, and the water is approximately five feet deep. The tank is located at the Richmond Field Station of the University of California. The ship model is five feet long and 10 inches across the beam. It was connected rigidly to a boom projecting back from the carriage which travels at adjustable speeds on longitudinal rails located on top of the side walls of the towing tank. The wake generated at two different speeds was measured. The first was a model speed of approximately 1.5 ft. per second, which is equivalent to a 300-ft prototype travelling 6.9 knots; the second was a model speed of 4.8 ft. per second, being equivalent to approximately 22 knots.

Cameras

Two Wide Angle Rolleiflex cameras with 55 mm. Carl Zeiss Distagon objectives (Nr 3506224 and Nr 3507345) were used for the photography. The two cameras had been calibrated previous to the study by the method of Sewell[1] in order to determine the focal length of the lenses, the principal point of the focal plane, and the radial lens distortion. These elements, known as the elements of inner camera orientation, are required for the subsequent reduction of the photographic data. The focal length of Nr 3506224, adjusted for overall lens distortion is 54.268 mm; the calibrated focal length of Nr 3507345 is 54.308 mm. The distortion curve of Lens No. 3506224 is shown in Fig. 1. The cameras were set for a focus of 10 ft. on each camera at the time of photography, giving principal distances of 55.251 mm for Nr 3506224 and 55.291 mm for Nr 3507345.

The Rolleiflex cameras are equipped with adaptor backs which receive plate holders containing glass plates. The camera, adaptor back and the plate holders are shown in Fig. 2. Glass plates are desirable in order to insure planarity of the image at the instant of exposure and to preclude distortions due to possible film buckling in the focal plane.

In order to provide synchronization between the firing of the two cameras, a pair of Rowi pneumatic air releases were coupled by a copper tube tee to a common air bulb such that the length of hose from the tee to each of the actuating cylinders at the cameras was the same. Care was taken to prevent kinking of any part of either of the hoses at the time of photography. Preliminary testing for synchronization was made by photographing a 10-second sweep stop watch at the instant the watch hand was on numeral 5 (six-o'clock position) and then observing the resulting pair of photographs under a stereoscope. If the watch hand appeared to depart from the plane of the watch dial, as seen through the stereoscope, synchronization could be checked to approximately 1/50 second. The tests indicated no observable stereoscopic parallax, indicating a synchronization of at least 1/50 second. Final test was made directly in the ship model photography as explained later.

Controls

The Rolleiflex cameras were used because they afforded flexibility of location, a fairly large size format, and good physical stability. The fact that these cameras and the Distagon objectives were designed not for metrical but for pictorial photography was recognized at the outset. The fairly large radial distortion has little or no effect on the quality of pictorial photography- but does introduce appreciable distortions in a photogrammetric measurement system, resulting in secondary systematic errors. Also, the fact that the Rolleiflex cameras do not contain fiduical or collimation marks forced the investigator to establish the principal points of the photographs in a manner which could introduce sizeable random errors.

Because of the probability of a combination of troublesome systematic and random errors occurring, an overabundance of control points was necessary in the object space. These points were physically realized by means of steel bars 3/16 inch thick and 3/4 inches wide arranged to cantilever out from the sides of the towing tank and to clear the water surface by about four inches, as shown in Fig. 3. After they had been bolted in place, the elevations of the points on the bars were determined by means of a K & E PL5022 tilting level and a light steel band graduated to 1/64 inch. The distance between the end marks of each long bar was measured directly with an ordinary steel tape measure. This latter measurement was not extremely critical, being used to establish scale in the subsequent photogrammetric measurements.

<u>Mounting the Cameras</u>

The camera base consisted of a 2-inch by 4-inch aluminum channel beam into which were tapped holes to receive machine bolts to hold specially-designed C-brackets. These brackets were mounted in such direction so as to give each of the camera axes an angle of 20° off the vertical and convergent toward one another. This constitutes the classical 20° convergent photography arrangement used in aerial cameras for special purpose mapping of terrain of relatively low relief. The convergency of the camera axes enchances the accuracy of vertical measurements compared to parallel-axis photography covering the same area.

The channel beam was secured to steel roof purlins by means of conventional C-clamps, with the camera base approximately centered over the towing tank in a direction perpendicular to the longitudinal axis of the tank. This orientation was necessary to eliminate possible false stereoscopic parallax introduced by movement of the water surface between exposures due to slight nonsynchronization of the camera shutters.

Special fixtures called Rolleifixes which automatically position the Rolleiflex cameras were secured to the C-brackets and the cameras were then mounted on the Rolleifixes. Finally, the shutter-actuating cylinders of the pneumatic release were attached to the cameras, and the hoses brought over to the side of the tank and dropped down so as to be clear of the moving parts of the towing apparatus and at the same time be convenient of access to the photographer. The photographic arrangement is shown in Fig. 4.

Photogenic Definition of Water Surface

One problem which plagues the hydraulics researcher is the difficulty of photographing the surface of a body of water. Because of the transparency of water, the surface character must be enhanced in order to provide a satisfactory photograph. This problem was overcome in a most satisfactory manner by broadcasting the confetti obtained from an IBM card punch machine over the water surface before each run of the ship model. These punches, which measure approximately 0.037 inch by 0.081 inch by 0.003 inch thick have excellent photogenic characteristics in that they are light in color, they contrast well with the almost total lack of light from the towing tank itself, and they are small enough to conform to the water surface with high fidelity. Test runs were made with and without the punches, and no noticeable difference in the results could be detected in the resistance gage recordings. Thus, they are felt not to interfere with the natural wave shape generated by the ship's wake.

Lighting for the surface was provided by four No. 2 photoflood lamps in fairly narrow satin reflectors. The lamps were located outside the tank, two on either side, and near the corners of the 8 ft. by 8 ft. area to be photographed. They were oriented about 20° down from the horizontal, and far enough back so as not to throw a direct reflection off the water surface into the camera lenses.

Defining Datum

In a perfect stereo photogrammetric system, the only requirement for control would be the elevations of three non-collinear control points located near the water surface together with the elevation of the water surface itself in a state of rest, and a measured distance between two points lying near the water surface. The Rolleiflex system however, not being designed for photogrammetric measurements, is subject to systematic and random errors, as previously cited. These errors combine to form what is known as model distortion or model warpage. If it can be assumed that random errors can be kept tolerably small, then the effect of the systematic errors can be eliminated by some form of calibration technique. The technique used in this study was self-contained. It consisted of photographing the water surface in the quiescent state prior to the test runs of the ship model. It is sufficient to mention at this point that all measurements of the surface of the ship wake were ultimately referred to the measurements of the undisturbed water surface in order to reduce all measurements to datum and thus eliminate model warpage caused by the systematic errors and those random disturbances which could be evaluated.

Photography

The first two pairs of photographs were taken of the water surface at rest. Eastman Kodak Metallographic plates, size 6.5 cm. by 9 cm. by 0.040 inch thick were used. The ASA film speed rating for this emulsion must be determined by sensitometry or experimentation. It is, however, somewhere between ASA 1 and ASA 5. The first pair was exposed at 1/30 second with a diaphragm setting of f/4. The second pair was exposed at 1/60 second at f/4. These four plates were processed for eight minutes in Kodak developer D76 at 71°F. The resulting plate negatives were drastically underexposed.

The exposure time of 1/30 second was the slowest which could be tolerated without suffering image blur on the subsequent wave photographs. Also, the diaphragm setting was the largest possible with the Distagon lenses. In order to be able to take advantage of the stable characteristics and fine grain of the metallographic plates, the lighting would have to have been increased in luminosity by a factor of approximately 25. Because of the limited scope of this study, the development of a new light source was not feasible. Therefore, the high-speed (ASA 400) Kodak Tri-X Pan film was used for subsequent photography.

Two pairs of photographs were again taken of the water surface at rest. The first pair was taken at 1/30 second, f/5.6; the second at 1/60 second, f/5.6. Four runs were then made with the ship model. In the first, the model was towed at 1.5 ft. per second, and the exposure was made when the stern of the ship reached the middle of the area covered by the photography. In the second, the model was towed at the same speed, but the exposure was made as the ship stern approached the end of the test area. The third and fourth runs duplicated the first two except that the towing speed was increased to 4.8 ft. per second.

Reduction of Negatives to Diapositive

In order to realize an affine transformation in the stereoscopic model, namely one in which the horizontal and vertical scales were equal, the negatives were reduced in a specially designed universal reduction printer, shown in Fig. 5. The printer accepts diapositive plates for Multiplex and Balplex plotters as well as negative plates produced in the Wild P30 phototheodolite and the Rolleiflex cameras. It is equipped with a Goerz Red Dot Artar process lens with a 16-1/2 inch focal length mounted on the compound head of a jewelers lathe. The distance from the edge of the lens barrel to the diapositive plane is established by means of a gage rod of appropriate length, (32.000 inches in this study) and the remaining distance set off by means of the longitudinal motion of the compound head, giving the necessary image distance from the rear node to the diapositive plane. The negative plate holder is set at the appropriate distance from the front edge of the lens barrel to the negative plane in the same manner, except that the final value is obtained by the micro-motion of the negative plate holder. This establishes the appropriate object distance from the front node to the negative plane.

The Balplex 760 plotter in which the measurements were made has a principal distance of 55.00 mm. The object and image distances were therefore as follows:

Lens No.	Object Distance	Image Distance
3506224	842.9 mm	839.1 mm
3507345	843.2 mm	838.8 mm

It is to be noted that at this particular range of magnification, the distance between object plane and image plane is the same for both camera lenses, and only the process lens had to be moved a total of 0.3 mm longitudinally to accommodate both lenses.

Diapositives were exposed on Kodak medium contrast Aerographic Positive plates 11 cm by 11 cm by 0.090 inch. The plates were processed in Kodak developer D76 for a period of 3-1/2 minutes at 70°F.

Balplex Instruments

The balplex 760 plotter is an ellipsoidal-reflector, double-projection stereoscopic plotting instrument containing lenses set at 55 mm principal distance to give an optimum projection distance of 760 mm or 30 inches. The lenses are capable of being canted about an axis normal to the optical axis so that when the projectors are oriented with 20° convergence, the plane of best definition can be made to lie parallel with the surface of the mapping table in the plotting space. This satisfies the condition, formulated by Scheimpflug, that the negative plane, the lens plane, and the image plane must all intersect in a common line.

As shown in Fig. 4, the vertical distance from the camera base to the water surface is 105 inches. This fixes the Balplex model scale at 30"/105" or 1/3.5. That is to say, 1 mm in the Balplex model is the equivalent of 3.5 mm or 0.14 inch in the wave tank, both horizontally and vertically.

Relative orientation of the two projectors was performed using points on the control brackets, these points having being designed for the dual function or relative and absolute orientation. The considerable amount of lens distortion of the Distagon objectives, when enlarged by

13 diameters in the Balplex projectors would certainly preclude the possibility of obtaining relative orientation in a satisfactory manner if the photography conformed to the normal parallel axes orientation of the cameras. Since the 20°-convergence and the B/H ratio selected for the photography gives an overlap of about 100%, as shown in Fig. 6, and since both camera lenses produce essentially the same distortion curves, the y-displacement at any point in the model area caused by one photograph is essentially equal to the y-displacement caused by the other photograph. However, difficulty was encountered in obtaining a satisfactory overall orientation, no doubt due to a combination of random and systematic errors in this relatively crude system.

The model scale was set by reference to the distance between the two end points of each of the longitudinal bars of the control bracket. Leveling was performed on these same corner points. After an average overall fit to the four corner points was obtained, all the vertical control points were read and recorded.

<u>Measurement in Control Model</u> - a 1-cm grid was ruled on the Wild coordinatograph covering an area approximately 30" x 36". The grid was placed on the map table under the control model which represented the water surface at rest, and centered approximately beneath the projector base. The control points were plotted onto this grid for future orientation.

The elevation of each grid intersection was measured in the model and recorded to 0.1 mm. The total usable area measured approximately 24" x 29". Rows and columns were numbered for correlation with subsequent measurements. These readings defined the first approximation to the datum, and varied over the area by a maximum of 1.6 mm in a fairly systematic fashion. In effect, the datum appeared as a broad dome in which the middle was 1.6 mm higher than the corners. It was not perfectly symmetrical, no doubt reflecting random errors of interior orientation and also relative orientation.

Measurement of Low-Speed Model - The first low speed run was omitted from the study because it did not contain a sufficient portion of the ship wake to be useful in hydrodynamic studies. The Balplex model of the second low-speed run was oriented on the same points and in the same manner as the control model. Following the leveling operation, all the vertical control points were measured and recorded.

The 1-cm grid was oriented to the model by means of the plotted control points. The measurement diagram for this run is shown in Fig. 7. The measurements were made at 5-mm intervals along the rows and columns shown on the diagram. These measurements were then subjected to primary and secondary corrections as explained later.

Measurement of High-Speed Model - The second high speed model was oriented as discussed above, with all vertical control points being read. The measurement diagram for this model is shown in Fig. 8. The measurements along all the lines were taken at 5-mm spacings including those along the diagonals. These measurements were then subjected to primary and secondary corrections.

Selection of lines for Measurement - In a study such as the one under discussion, the photogrammetrist and the hydraulic engineer must consult together at the point when the surface phenomenon is ready to be measured. The hydraulic engineer must delineate, quite precisely, which area is to be measured or which line is to be profiled. One of the distinct advantages of the Balplex plotter over all others for this type of analysis is its capability of showing the entire model at one time. The engineer can then scan the model, make a judgment as to which areas or which lines will give the most information for the investigation at hand, and then indicate these areas to the photogrammetrist.

In order to present the entire model for critical study, the grid sheet was placed on a drafting board which, in turn, was blocked up so that the grid sheet intersected the mean datum. The orienting device shown in Fig. 9 was used to orient the map sheet beneath the projectors by reference to the control points previously plotted on the grid. The lines for profiling shown in Figs. 7 and 8 were then selected by the engineer for measurement. The grid sheet was then lowered to the map table and again oriented to the control. Finally the measurements were then made as discussed above.

Reduction of Measured Data

Two main sources of error in the measurement of each point are 1) the model deformation due chiefly to uncompensated lens distortion, and 2) random errors in the interior and relative orientation process. The first source is manifest in the absolute readings of the vertical control points and the absolute readings on the control level datum, that is, on the model of the water at rest. The second source is detected by the variations in the readings of the vertical control points, following the model-leveling operation, from model to model. In Fig. 10, it is to be noted that the total discrepancy between fixed vertical control and the measured values in the control model ranges from -0.5 mm to +1.1 mm. If these corrections are applied to the datum measurements of the control model in the vicinity of these control points, the corrected values of the datum elevations show a spread of only 0.8 mm. The distribution from a mean datum is shown in the histogram of Fig. 11. Very little can be inferred statistically from the discrepancies at the 12 points except that the spread and distribution tend toward randomness.

The systematic nature of the vertical discrepancies shown in Fig. 10 and the random nature of the discrepancies after correction for systematic errors point to a very practical procedure for correcting the measured elevations of the wave surfaces in subsequent models. The first step is to prepare a correction diagram for each subsequent model reflecting the difference between the measured vertical control points in the control model and the measured values of the same points in each wave model. These diagrams are shown in Figs. 12 and 13. The second step is to superimpose the correction diagram over the datum grid elevations. The sum of the too values, datum grid elevation plus correction, is the final datum elevation at each grid point.

Finally, the corrected elevation of any point on the wave surface, above or below the level datum, is obtained by subtracting the final datum elevation at that point as determined above from the measured wave elevation at the same point. With the technique employed for establishing control and defining the level datum, the overall accuracy obtained in this phase of the study is of the order of 0.5 mm in the Balplex model. This is approximately 1/1500 of the projection distance.

Fidelity of wave shapes is considered to be much better than this, however, possibly of the order of 0.2 mm in the Balplex model, or 0.7 mm. in the towing tank.

The adjusted profiles of some selected lines shown in Fig. 8 are presented in Fig. 14. Unfortunately the small scale of these profiles does not show the detail obtainable in the numerical profiles in which secondary ripples in the ship wake can be identified. The apparent discrepancy between the profiles to right and left is not at all necessarily due to measurement errors. These discrepancies are due primarily to variations in the actual wave profiles caused by non-symmetry of the towed model.

MODEL BASIN STUDY

Having established the capability of defining a wave surface reliably to an accuracy of 0.5 mm in the Balplex model with the Rollieflex-Balplex combination, the study was shifted to the University of California's newly-completed model basin. The hydraulics study was the investigation of the pattern, form, amplitude, and decay of a ship's wake as the ship moves through shallow water at various speeds. Secondary information was the correlation between ship length and wave period at various velocities; ship attitude; and the energy distribution function astern of the ship in shallow water conditions.

The model basin measures 64 ft by 150 ft by 2-1/2 ft, completely enclosed in a large steel-frame building. It was filled with 8 inches of water for this study. The sailing line for the ship model was located on the centerline of the basin, with provisions for towing the model at varying speeds by weights and pulleys. The ship model was 5 ft 4 in long and 8 inches across the beam.

Arrangement of Cameras and Control

The area of interest to the investigator is shown in Fig. 15. Nine vertical control points (also used for scaling) were located as shown. These points were physically realized by threading a 1/4-inch steel rod into a 6" x 8" x 1/4" steel base plate, with the rod end extending upward

6 inches above still water. The upper end of the rod was drilled to receive a brass stud onto the upper surface of which was glued a 1" x 1" square white target containing a black bulls-eye 1/8 inch in diameter. The small diameter of the rods was considered by the hydraulic engineer not to have disturbed the ship wake pattern any significant amount.

Two tripods, consisting of legs made from 3-ft lengths of 3/4" galvanized steel pipe, and uprights made of 18-ft lengths of 2" galvanized steel pipes, held the 2" x 4" aluminum channel beam in position to support the cameras. The tripods were guyed to structural members of the building. The cameras were mounted 14 ft apart, with 20° convergence, in the same manner as they were for the towing-tank photography. The base was at a height of 19 ft 4 inches above the water surface.

Auxilliary Instrumentation

In order to obtain independent measurements for use in verifying or establishing the reliability of the photogrammetric system, two resistance gages were installed as shown in Fig. 15. Each gage contains a pair of probes connected to one branch of a Wheatstone bridge, and which extend into the water. The water itself closes the circuit of that branch. As the water rises, the resistance in the branch decreases, causing an unbalance in the bridge, which in turn produces an increase in current in the cross bridge. The output from the bridge is conducted to an oscillograph which records the height of the water on a drum recorder.

The vertical scale of the gage is calibrated quite simply by raising or lowering the probes with reference to a vernier, and either noting the vertical displacement on the drum recording, or adjusting the circuitry to bring the vertical displacement to some predetermined spacing on the recording paper. The horizontal scale is presumably established by the speed of the recording paper past the recording pen. The horizontal scale is thus a time scale.

Photography

Perhaps the most awkward part of the second phase of the study was the photography. Based on the results of the towing tank photography, Kodak Tri-X film was again used. This fast film eliminated the necessity of artificial lights, there being enough embient light coming through the skylights. It should be mentioned that two of the skylights over the target area had to be covered to prevent blotting out of the water surface by reflection.

The card punch confetti was broadcast over the target area by means of a long-handled spatula from a position on the catwalk shown in Fig. 15. This in itself was an awkward operation both because of the area to be seeded and because of currents in the basin which tended to move the confetti out of the target area.

The first synchronous exposure was made of still water to establish the datum control. The exposures were made at 1/60 sec at f/4.0. The cameras were set to focus at 20 ft.

The ship model was then towed at speeds of 2.22, 2.78, 3.20, 3.94, 4.20, 4.45, 4.55, 5.07, 5.65 and 7.32 ft per second. The first three runs were exposed at 1/60 second at f/4.0; the remaining seven runs were exposed at 1/125 second at f/4.0. The first three speeds produced deep-water conditions in that the ship wake which was generated did not "feel" the bottom of the basin. The next four speeds produce shallow water conditions below what is referred to as critical speed. The last three speeds also produced shallow water conditions, but above the critical speed.

Following each run, the film had to be advanced. This necessitated dragging a 20-ft step ladder which weighs about 100 pounds through the water in order to get at each of the two cameras, and then dragging it off to the side and out of the target area. The action of moving the ladder set up eddies and currents in the model basin which had to be dissipated before the area could be re-seeded. This required an interval of perhaps 20-30 minutes. The cameras were fired when the ship model reached the approximate position shown in Fig. 15.

Production of Diapositives

The Tri-X film was developed in FR X 44 fine-grain, high-speed developer for 6-1/2 minutes at 68°F. This developer permitted an ASA rating of 800 for Tri-X Pan film.

The reduction printer was set for an average of the proper settings for the two different lenses, because the 0.3 mm shift of the lens between the two settings was not considered significant with object and image distances the order of 840 mm each. The diapositive plates were developed in Kodak D76 for 4 minutes at 74°F.

Balplex Scale

The ratio of Balplex projection distance to camera height for the model basin photography was 30"/232" or 1/7.73. The Balplex scale was therefore established as 1/8, that is, 1 mm in the Balplex model is equivalent to 8 mm or 0.314 inches in the model basin. The usable model was approximately 18 inches across by 21 inches front to back.

Control Model

The control model, as well as all subsequent models, was relatively oriented by means of the control targets; scaled with respect to the 3 central longitudinal targets; and leveled with respect to the four corner targets. Following the final leveling, all the control points were read and recorded. A 5-cm grid was ruled to cover the model area, this interval representing 16 inches in the model basin. The grid intersections were read and recorded by rows and columns as previously discussed.

Deep Water Runs

The first deep-water run at a model speed of 2.22 ft per second did not produce a wake with amplitudes sufficient for deliniation or measurement. The total amplitude was on the order of 0.5 mm at Balplex model scale.

The second and third deep water models were measured by identical procedures. The 5-cm. grid was plotted on vellum, and the correction diagram, derived from vertical control readings as discussed previously and shown in Figs. 12 and 13 for towing tank photography, was superimposed. The corrected datum elevations were recorded at each grid intersection. The vellum was then blocked up on a drafting board to coincide with the average datum in the model and was oriented by means of the device shown in Fig. 9.

The hydraulic engineer and the photogrammetrist then delineated the crest lines of the bow wakes and the stern wakes as shown on the measurement diagram of Fig. 16. Selected cross-profile lines were also drawn. The sailing line, the side of the ship model, and the gage line for the nearest resistance gage were also drawn. These lines were then marked at 1/8-inch intervals (corresponding to 1-inch intervals in the model basin), and the sheet was then reoriented to the Balplex model.

A beginning point for each line was identified for bookkeeping purposes. The model was then measured at each 1/8-inch tick mark, and recorded to 0.1 mm.

In order to determine the attitude of the ship model at various speeds, the height of the bow and the stern were measured. This is the point at which the camera synchronization can be checked. At the low speeds, the shutter speed was set at 1/60 sec. This interval represents a distance in the Balplex model of approximately 0.05 inch at model speed of 2.22 ft/sec, increasing to 0.08 inch at model speed of 3.20 ft/sec. The ship model thus appears blurred in the stereomodel. Now if the shutters are out of synchronization by say 1/100 sec, a y-parallex will be produced of the order of 0.7 to 1.2 mm over the ship. No significant parallax could be detected, probably due to the blurring of the images. The shutters were thus considered to be in satisfactory synchronization for these low speed runs.

Profiles measured along the crest lines of the bow wake produced at a speed of 3.20 ft/sec., and are shown in Fig. 17. These profiles were used by the hydraulic engineer to establish the peaks of the crest, among other things, in order to measure the angle of these peaks with the sailing line, as shown in Fig. 16.

The profiles taken along the gage line were used for comparison with the resistance gage recordings. This comparison will be discussed in the section under accuracy. The profiles taken along the sailing line and the side of the ship were used to determine the periods of the transverse wake (not shown in Fig. 16) at various speeds, and to determine the decay in amplitude of these waves astern of the ship.

Shallow-Water Runs

The measurements of all the shallow-water runs took the form of surface contouring, with a contour interval of 0.635 mm in the Balplex model, corresponding to 0.2 inch in the model basin. A correction diagram was prepared for each stereo model, based on the readings of the vertical control points following the leveling operation. The correction diagram was then used to prepare the corrected datum grid for each model respectively. The grid, containing the numerical values of the corrected datum, was then oriented beneath the Balplex model. As the contouring proceeded, the tracing table reading was more-or-less continuously corrected (actually in steps of 0.1 mm) to reflect the true height above or below datum. Spot heights along broad crests and troughs were read to provide greater fidelity.

The heights of the bow and stern above datum were measured in each run. Only at the highest speed (7.32 ft/sec) did the photography show the shutters to be out of synchronization. The y-parallax over the ship model in this case amounted to about 1.5 mm, indicating a delay of the order of 1/175 sec. Also, at this speed, y-parallax in varying amounts was detected in the model surface due to the physical horizontal displacement of the water as the wake passed over the area. The y-parallax was eliminated over this model from area to area by a BY motion of one of the projectors in order to perform the contouring. Any false x-parallax of course contributed to errors in the contouring.

Contour maps of three of the runs made under shallow-water conditions are shown in Figs. 18, 19, and 20. The speed of the run which produced the configuration shown in Fig. 18 is the lowest of the shallow-water tests. This map shows the three sets of wakes very clearly, the bow wake, the stern wake, and the traverse wake. The high points of the crests can be inferred quite easily. Wave lengths are also easily measured. Also from the bow and stern elevations, the ship model is seen to sit well in the water at this speed.

The configuration in Fig. 19 was produced at a speed of 4.55 ft/sec., as the ship model approached critical speed. The first bow wake is seen to approach an angle of 90° with the sailing line. Water is observed to pile up in front of the ship model. Wave length is increased. The broad transverse wakes, evident in Fig. 18, are not readily apparent at this higher speed. Also, the ship is seen to be riding much higher in the water, with the bow well-raised.

The highest speed, 7.32 ft/sec, produced the wake shown in Fig. 20. The angle of the first bow wake has fallen off very drastically, a characteristic of supercritical speeds. The ship is moving too fast for the water to pile up in front. The ship is riding high although the bow has dropped relative to the stern. Transverse wake is not readily discerned.

These are but a few obvious phenomena which can be determined from the contoured wakes. Any desired profile may be taken from the map. The surface can be digitized to analyze the energy distribution in the water. The maps afforded the hydraulic engineer a complete quantitative three-dimensional picture of the surface of the water which can be subject to a variety of hydrodynamic studies.

Verification of Accuracy

Probably the most positive test of the accuracy and fidelity of geometric reconstruction obtained by the Rollieflex-Balplex combination is that of taking the readings at closely spaced intervals over the entire model of the water in its quiescent state. This was discussed earlier, in which case the model was leveled to the four corner vertical control points. The resulting discrepancies are due mainly to systematic errors of objective distortions and random errors of principal point marking,[2] relative orientation and stereo-operator error. Given the premise that the major portion of systematic warpage can be identified by means of enough vertical control judiciously positioned in the model area, the remaining maximum random errors in this system are found to be of the order of $\pm$ 0.4 mm measured vertically in the Balplex model. The investigator feels that the system can produce overall accuracy of the order of 0.5 mm at Balplex model scale.

As an indication of the accuracy of the contour maps, a profile was taken along the gage line three feet out from the sailing line on the map of the run at 4.45 ft/sec. This profile is shown in Fig. 21. The map profile is compared with that obtained with the gage recording device. The latter profile was determined as follows. The presumably-known speed of the paper in inches/sec. was used to establish 1-second intervals on the profile. The horizontal distance in the model basin was then plotted as 4.45 ft for each 1-second tick mark. The amplitude was scaled from the recorded profile. The time history of amplitude was then plotted to the same scale as the photogrammetric profile along the gage line. Finally, the two profiles were superimposed and then shifted in the abscissa direction to effect an average overall coincidence.

The chief sources of discrepancies between the photogrammetric profile and the gage profile are: 1) Residual random errors of the photogrammetric system; 2) false x-parallax introduced by non-synchronization; 3) lag in response of recorder; 4) recorder inertia; 5) error in accepted speed of recording paper; 6) error in the accepted speed of the ship model;

and 7) acceleration of the ship model through the target area. The maximum vertical discrepancy in the profiles as plotted is about 15 mm, or about 2 mm in the stereo model. However an examination of the profiles shows a backward horizontal shift in the front slope of each wave. This tends to indicate recorder lag or recorder inertia, which when corrected for, reduces the maximum vertical discrepancy to about 4 mm, or 0.5 mm in the Balplex model.

Conclusions and Recommendations

This present investigation, the technique of which was also applied to wind-generated waves using a 9-point vertical control array, definitely establishes the feasibility of a photogrammetric system in defining wave surfaces. The system itself, being only an approximation on account of large systematic errors, is shown to be adequate provided that sufficient and well-placed control is established, and that the necessary corrections are made. The data reduction, however, is quite tedious and time-consuming, to say nothing of the actual photography.

The greatest improvement in the wave-measuring system is to be found in the cameras. The Rolleiflex wide-angle Distagon covers an angular field of approximately 50° from side to side. The format size is excellent. However, the Balplex plotter can accomodate an angle of slightly over 75° from side to side. Thus, the ideal camera should have this angular coverage. This would allow a substantial reduction in the distance from the cameras to the water surface without sacrificing coverage. A maximum lens distortion of 20 microns on a 2-1/4 inch square format would provide the accuracy required in this type of measurement.

The camera lens must have provision for focussing at finite distances as close as perhaps 30 inches for certain studies. This would afford the opportunity of establishing 1:1 scale in the Balplex projector. Focus could be effected by a series of shims between the focal plane and the camera body, by shims between the lens and the camera body, by a helical displacement of the lens, or by rack and pinion movement of the lens. Either the the shimming methods could prove satisfactory, but the lens displacement methods would seem to afford opportunity for up-setting interior orientation.

The focal plane must, of course, contain some form of fiducial marks. Ideally, provision should be made for independent exposure of the marks because the background field in wave photography is characteristically dark. In the present study, the shadowgraphs of the corners of the focal plane opening, which are extremely sharp and well-defined in the Rolleiflex, were used to identify the principal joint according to the results of the camera calibration. In some wave pictures, however, all four corners did not appear. This required that the film be placed over an exposed plate of a light neutral field and be lined up as well as possible with the corners and edges, the corners of the plate then being used to define the principal point.

It would certainly be possible, although perhaps inconvenient, to design a vignetting frame to be placed in front of the objective, with light portions of the frame protruding into the picture area sufficiently to give background light in the vicinity of each fiducial mark. This technique was used in one of the Rolleiflex calibration procedures on the optical bench with very good results.

The cameras should be capable of recycling by remote control, eliminating one very awkward step in the photography. In order to keep the camera fairly lightweight and compact, the system might preclude the use of plates. On the other hand, for high accuracy, and in many applications in the field of hydraulics, the positions of the cameras could very well allow manual changing of plates between exposures with little inconvenience.

The problem of synchronization between the two exposures is very serious because a movement of the upper surface of the water invariably takes place no matter what type of wave is generated. Although for many types of waves, the camera base can be made to lie practically normal to the displacement vector, as is the case with wind-generated waves, the displacement in the surface layer of a ship wake is not all in the direction of the ship movement. This introduces false x-parallax which produces a false stereo model surface. The action of a shutter opening and closing is purely mechanical. It is highly improbable that two shutters can be made to reach their peak of light gathering simultaneously to let us say 1/500 second. The obvious solution to the synchronization problem is one instantaneous pulse of high-intensity, short-duration light, synchronized with the opening and closing of the shutters. This system presents many difficulties, all of which must be overcome by research and development.

Seeding the water surface to make it photogenic would seem to be a fairly mundane operation. This operation can be quite simple, as was the case in seeding the towing tank. It was extremely difficult, however, in the model basin because of the large area to be covered from a fairly remote position. It must be borne in mind that the seeding operation must immediately preceed the ship model run; otherwise the particles will drift out of the target area because of currents remaining in the basin. Some form of blowing system using a hose and nozzle might be developed to broadcast the particles. This problem can certainly be overcome by experimentation.

In the present study, the reduction of much of the data for hydraulic research was extremely tedious. For example, the tick marks plotted on the crest lines, the gage line and the sailing line shown in Fig. 16 all had to be scaled in x and y from the manuscript sheet. Also, for determining the wave energy distribution function, the ship resistance function and other hydrodynamic quantities, the contour maps must be gridded to obtain elevations in a regular pattern. Profiles must also be prepared from the maps for various analyses.

A great amount of time and effort would be eliminated if the Balplex plotter were to be digitized by existing well-established and high successful instrumentation. Accuracy of readout of the tracing table position would control, since the horizontal accuracy necessary for aerotriangulation is not at all necessary for defining a wave surface. Horizontal accuracy on the order of 0.01 inch is obtainable in several existing coordinatographs which have been digitized for semi-analytic photogrammetry. This is more than adequate for wave-surface mapping. Digitized models and profiles offer very interesting possibilities of automatic plotting of profiles and sections as well as of numerical reduction of hydraulic data.

The instrumentation and procedures adopted for this present study are to be considered as experimental only. The results are most encouraging and they warrant further development. The idea of being able to "freeze" a transitory phenomenon such as the surface of a body of water subject to wave action, and precisely measuring this surface, is quite exciting. It offers possibilities of using generated waves to simulate other physical phenomena which can then be precisely measured.

References

1. Sewell, Eldon D., "Field Calibration of Aerial Mapping Cameras," PHOTOGRAMMETRIC ENGINEERING, Vol. 14, 1948, pp. 363-398.

2. Konecny, G., "Interior Orientation and Convergent Photography," PHOTOGRAMMETRIC ENGINEERING, Vol. 31, 1965, pp. 625-634.

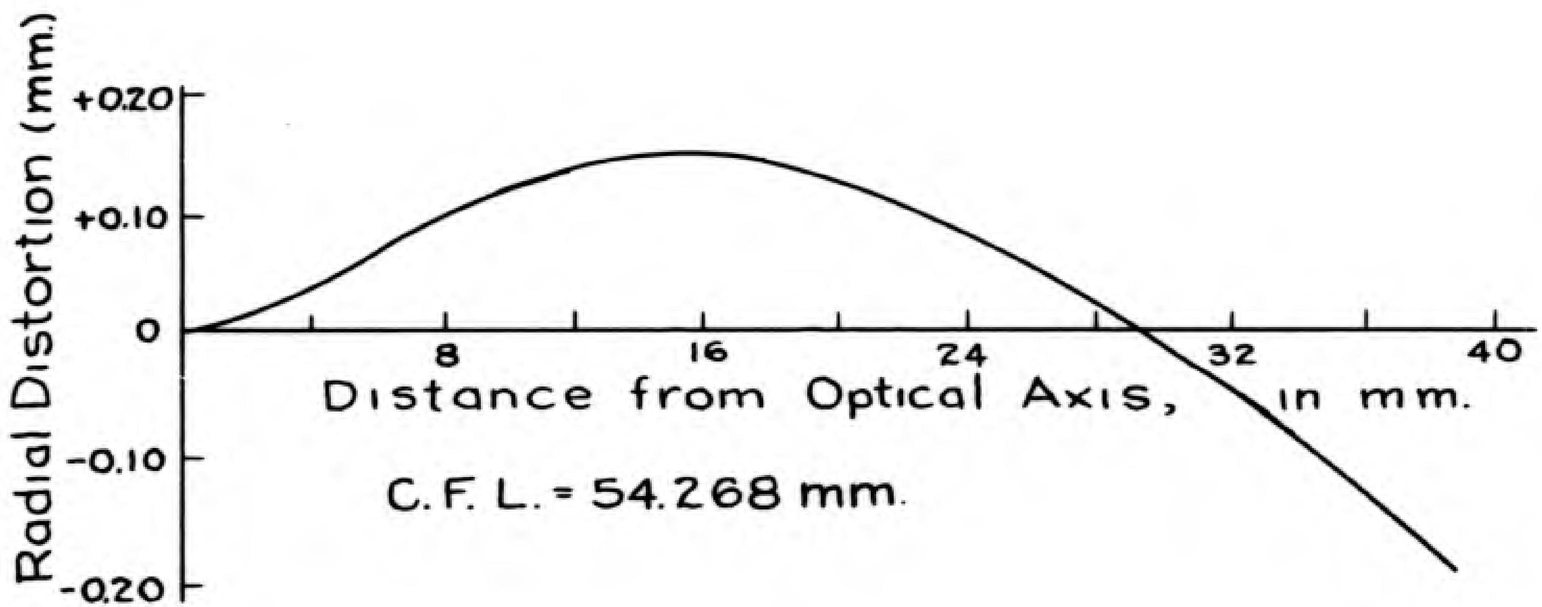

Fig. 1. Distagon distortion curve - Lens No. 3506224.

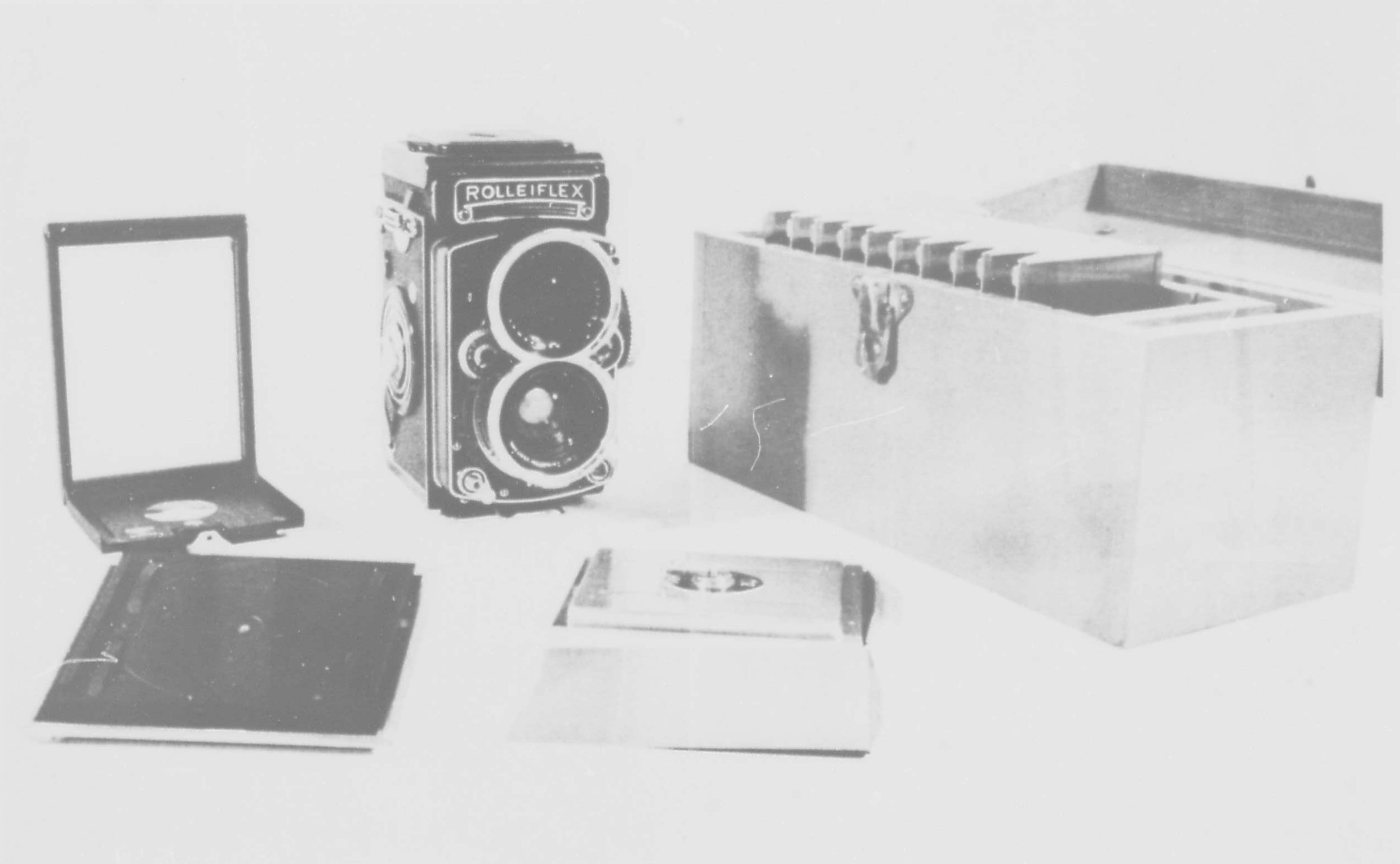

Fig. 2. Rolleiflex and adapter back accessories.

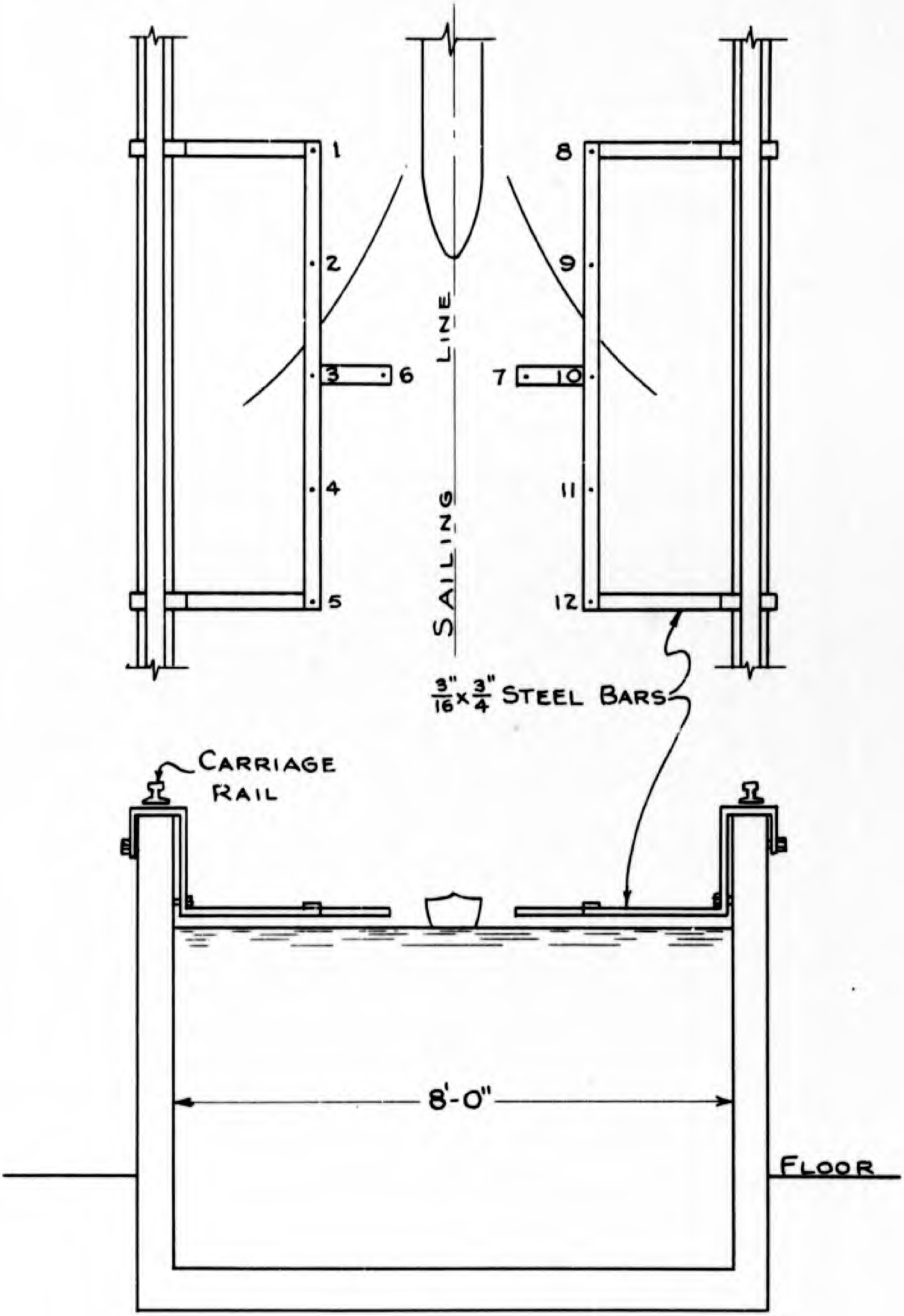

Fig. 3. Arrangement of control in towing tank.

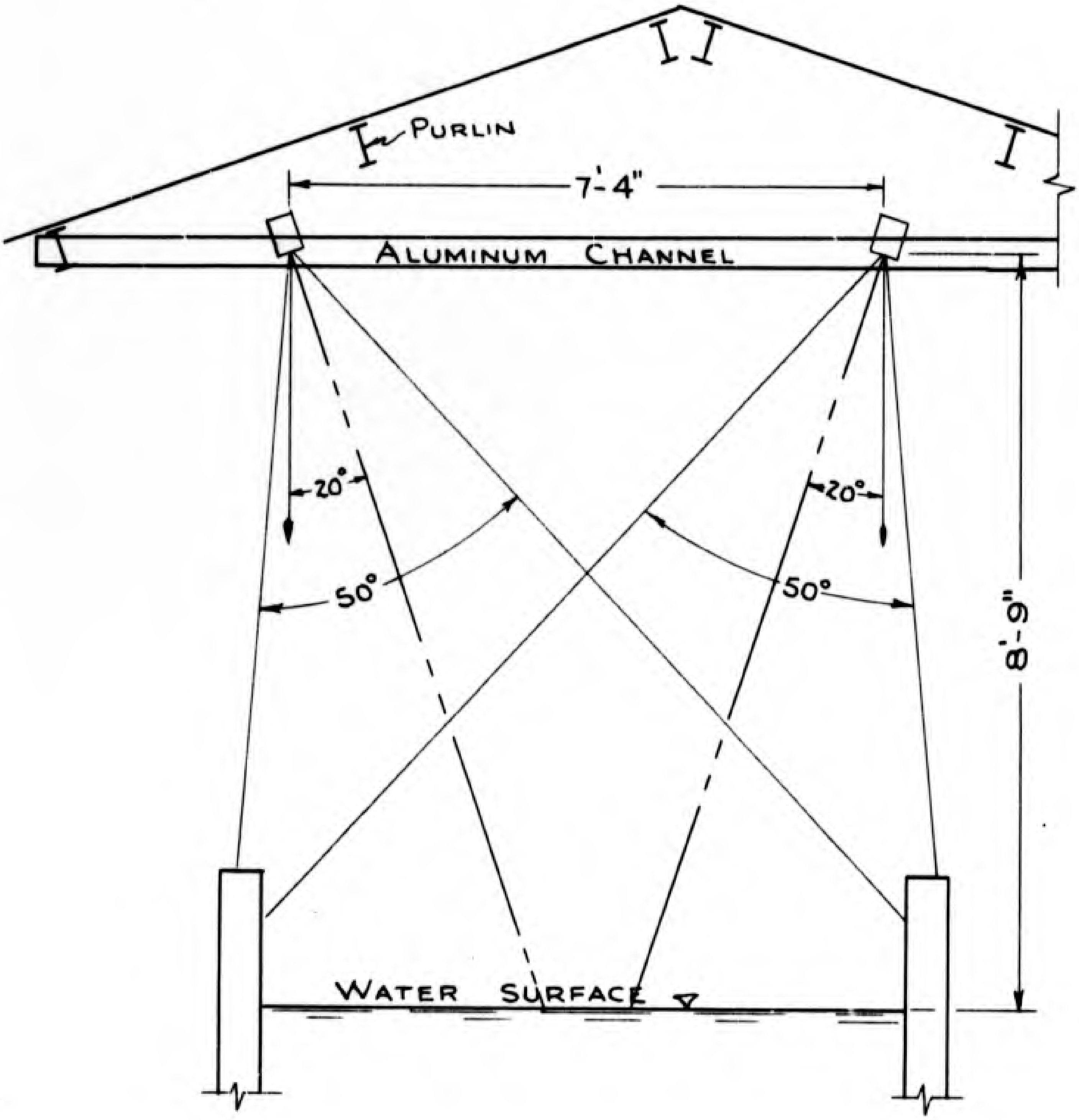

Fig. 4. Camera arrangement in towing tank.

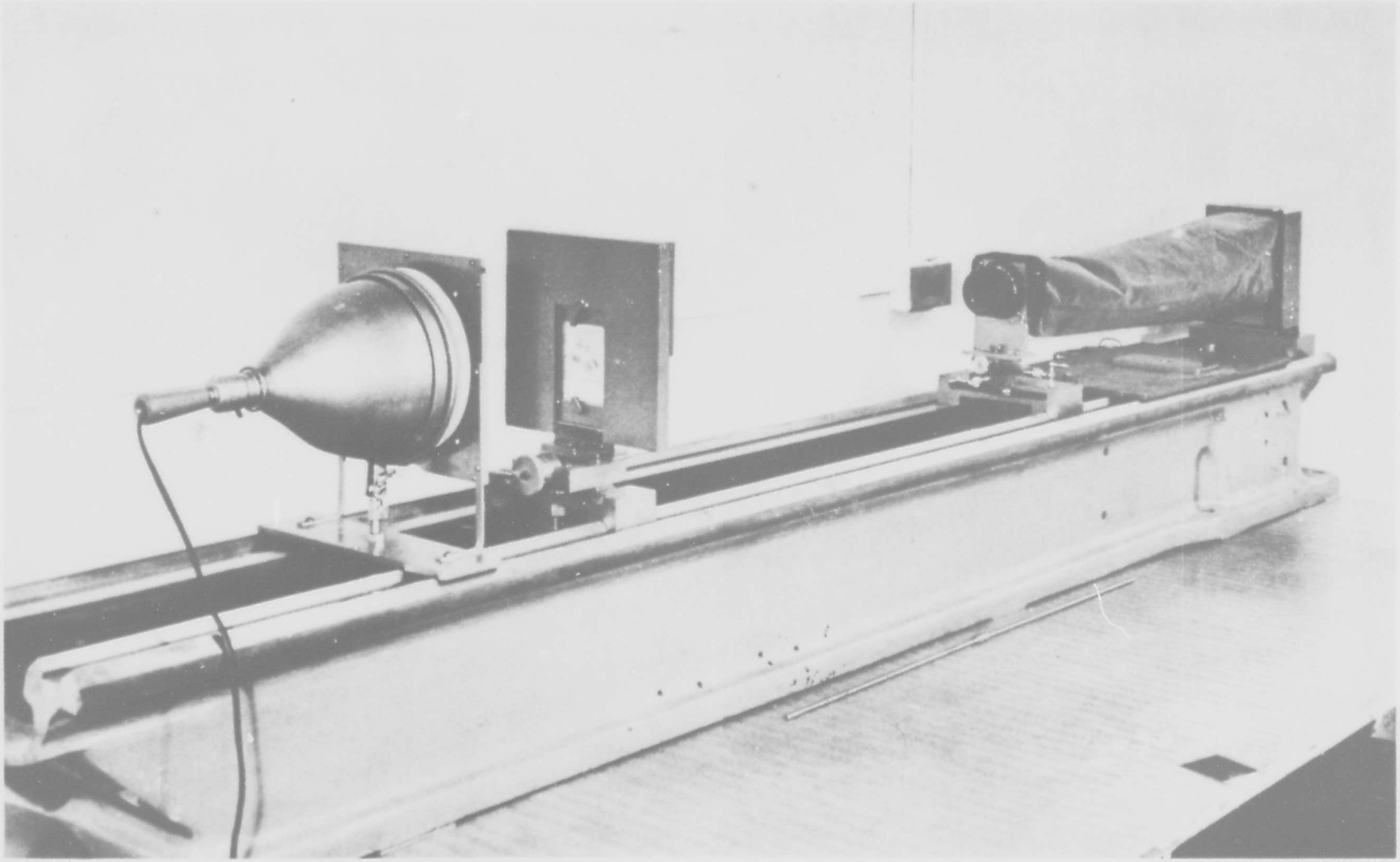

Fig. 5. Universal reduction printer.

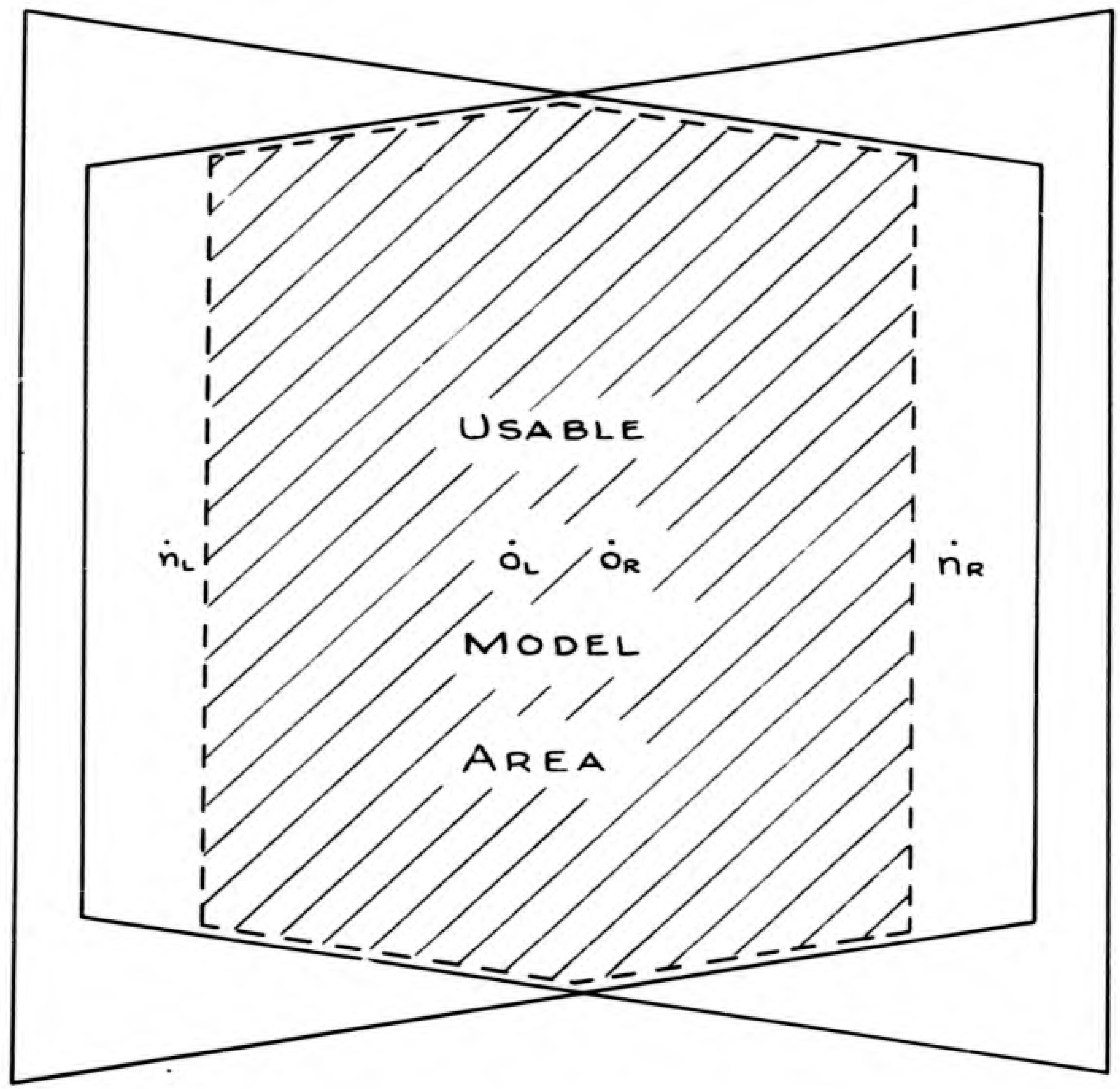

Fig. 6. Model formed by 20°-convergent photography with B/H ratio of 0.84 and 50° lateral coverage.

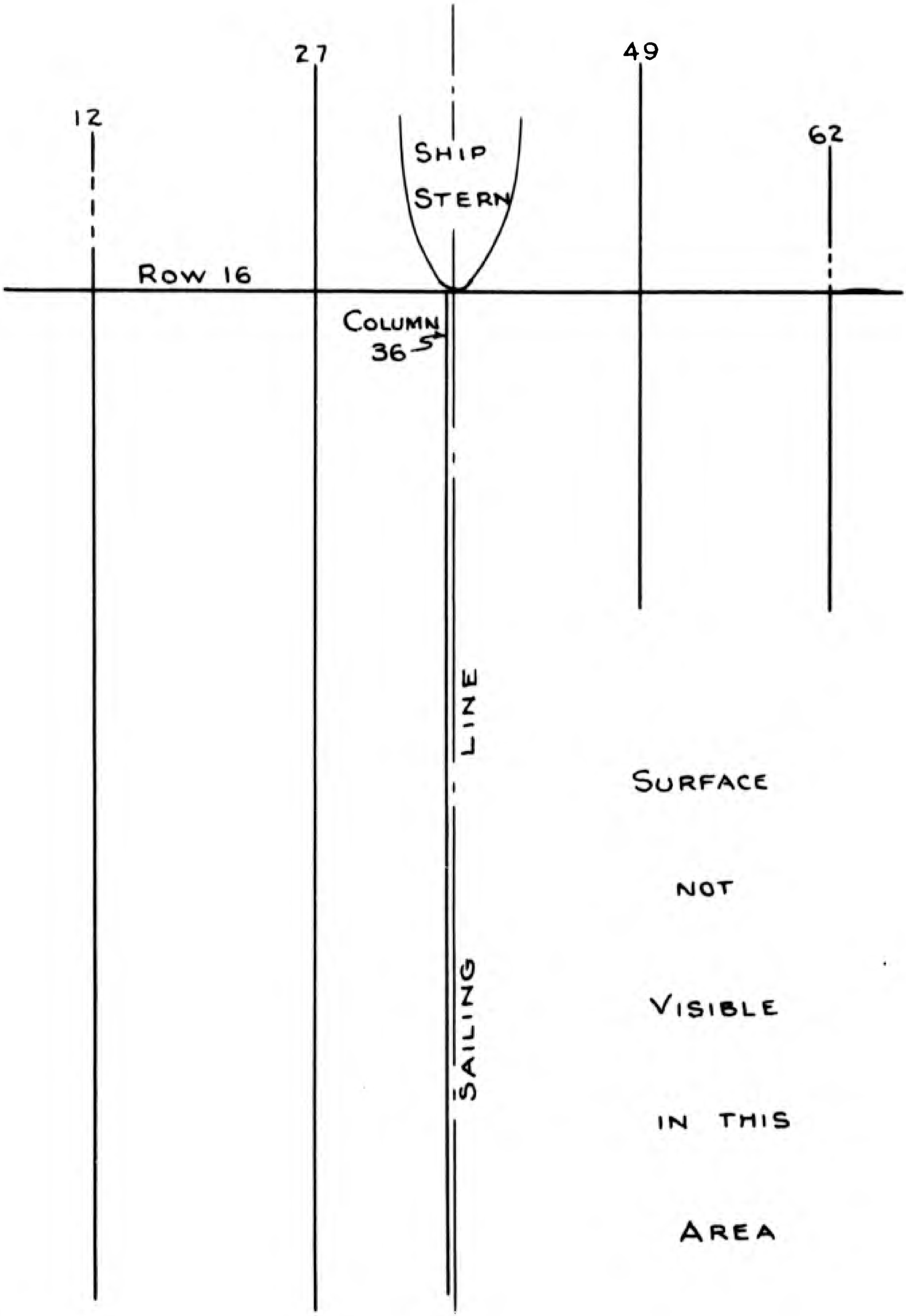

Fig. 7. Measurement diagram – Low-speed run.

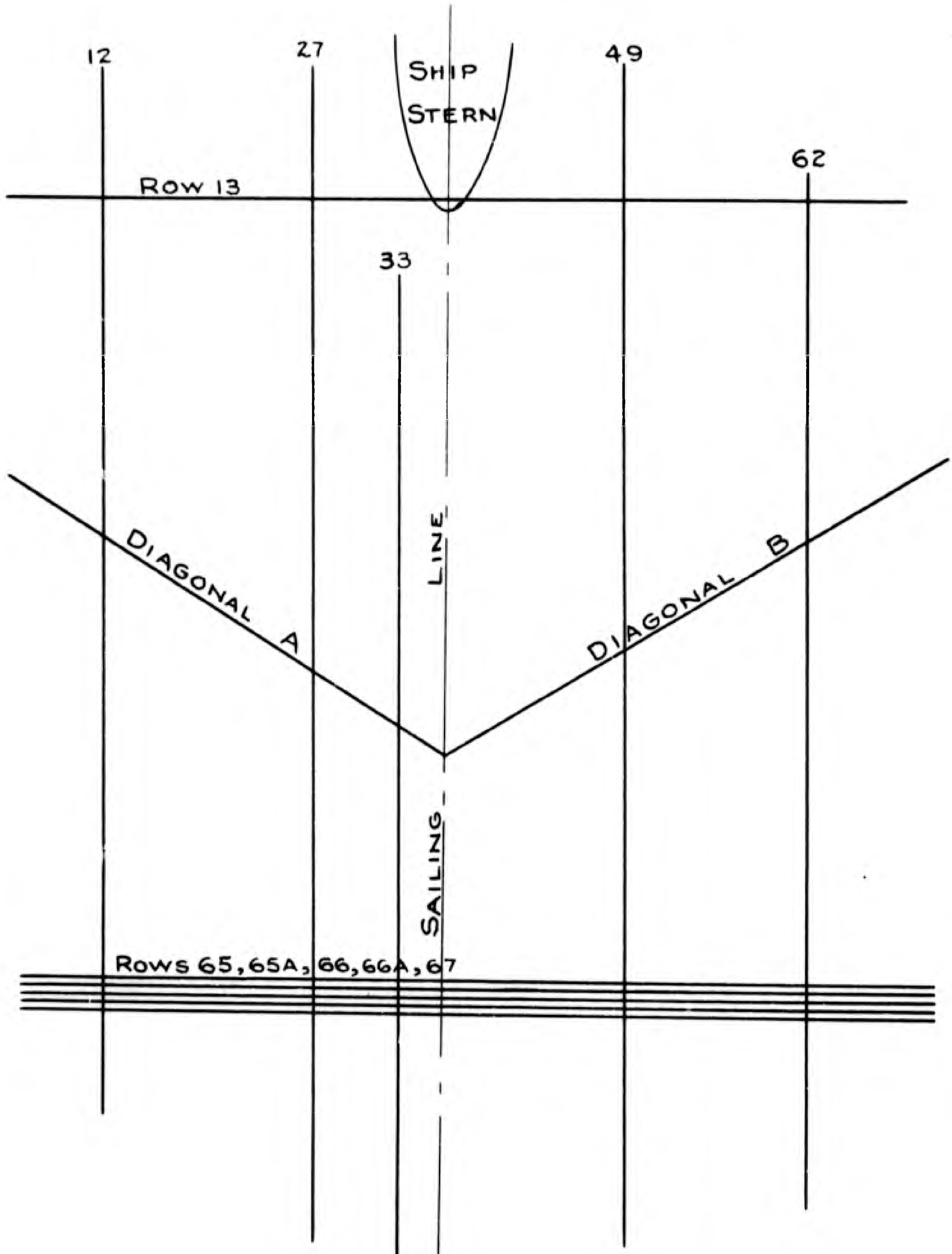

Fig. 8. Measurement diagram – High-speed run.

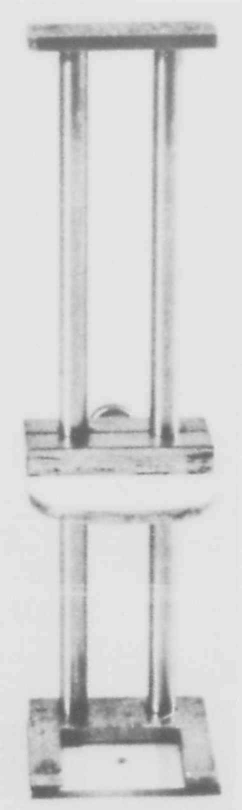

Fig. 9. Orienting device.

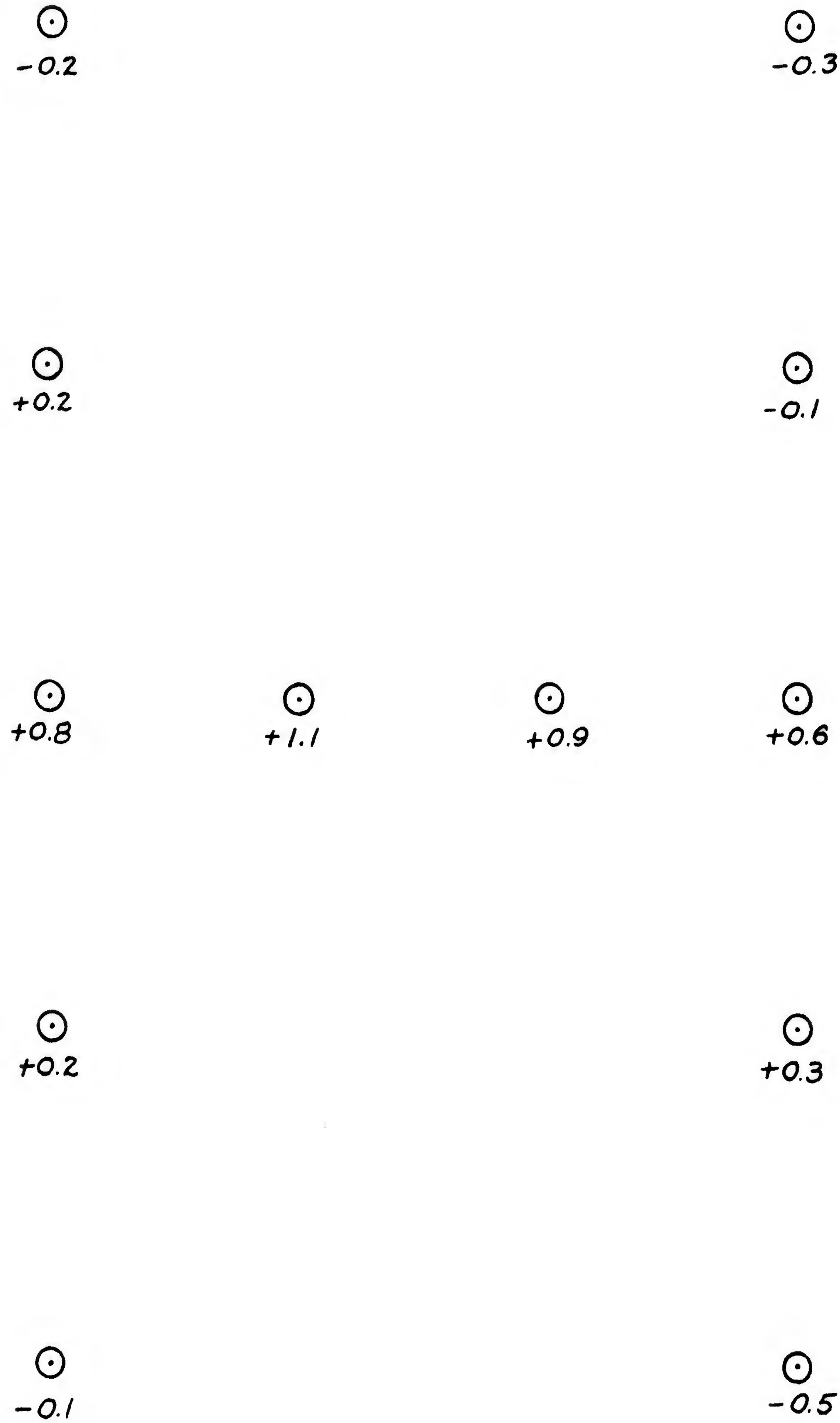

Fig. 10. Discrepancies in measured values of vertical control points in first model.

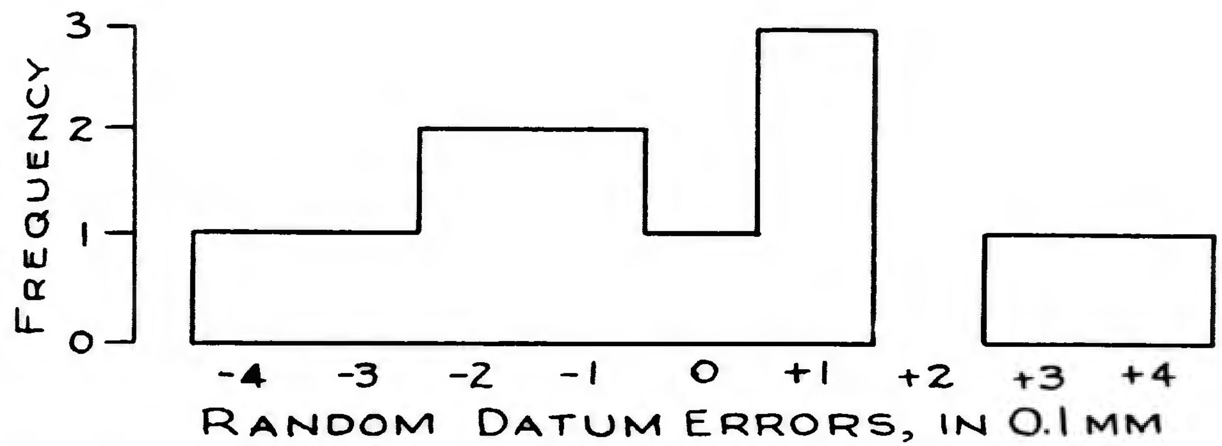

Fig. 11. Distribution of random errors of datum after correction for systematic errors.

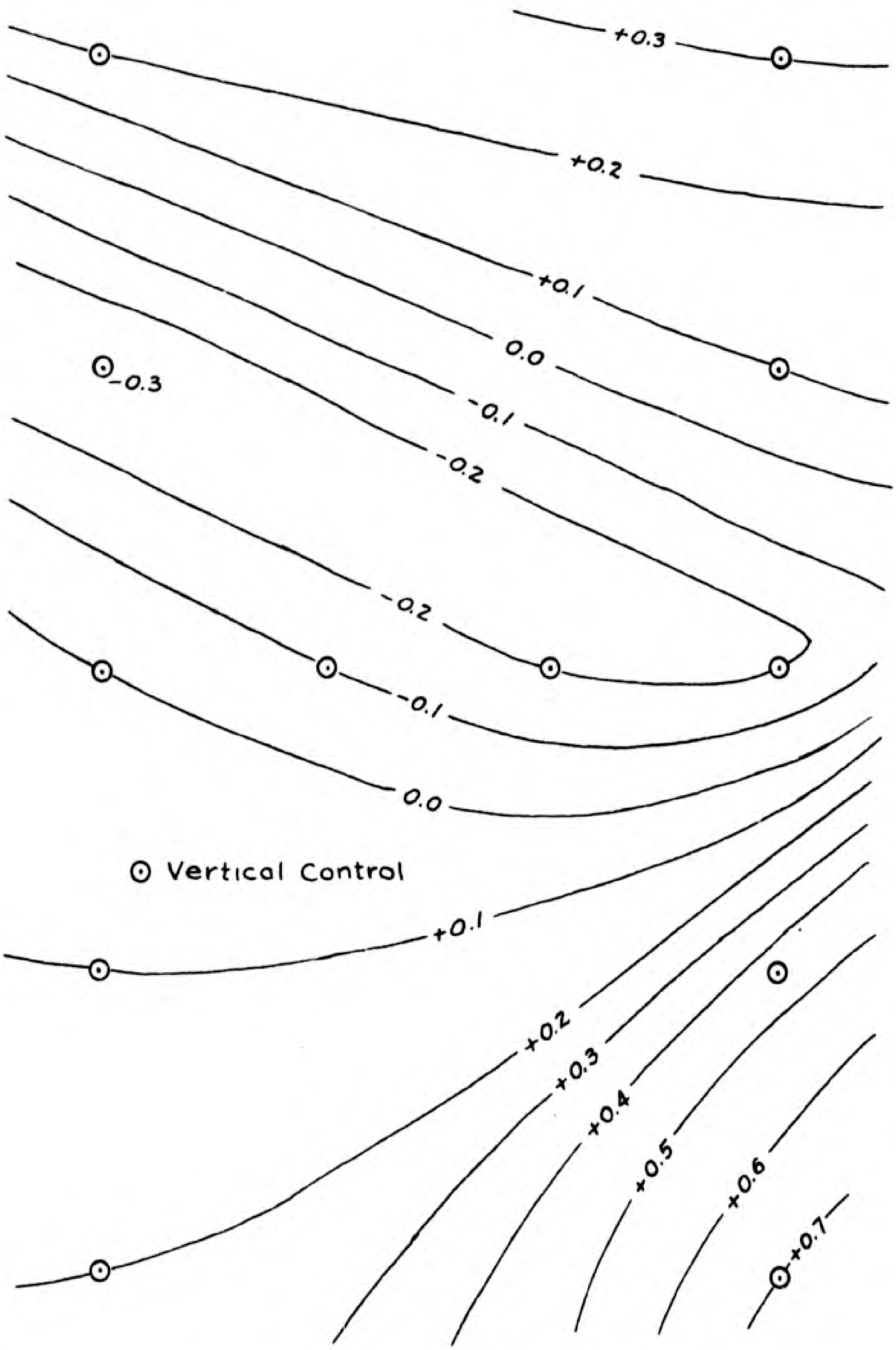

Fig. 12. Correction diagram - Second low-speed run.

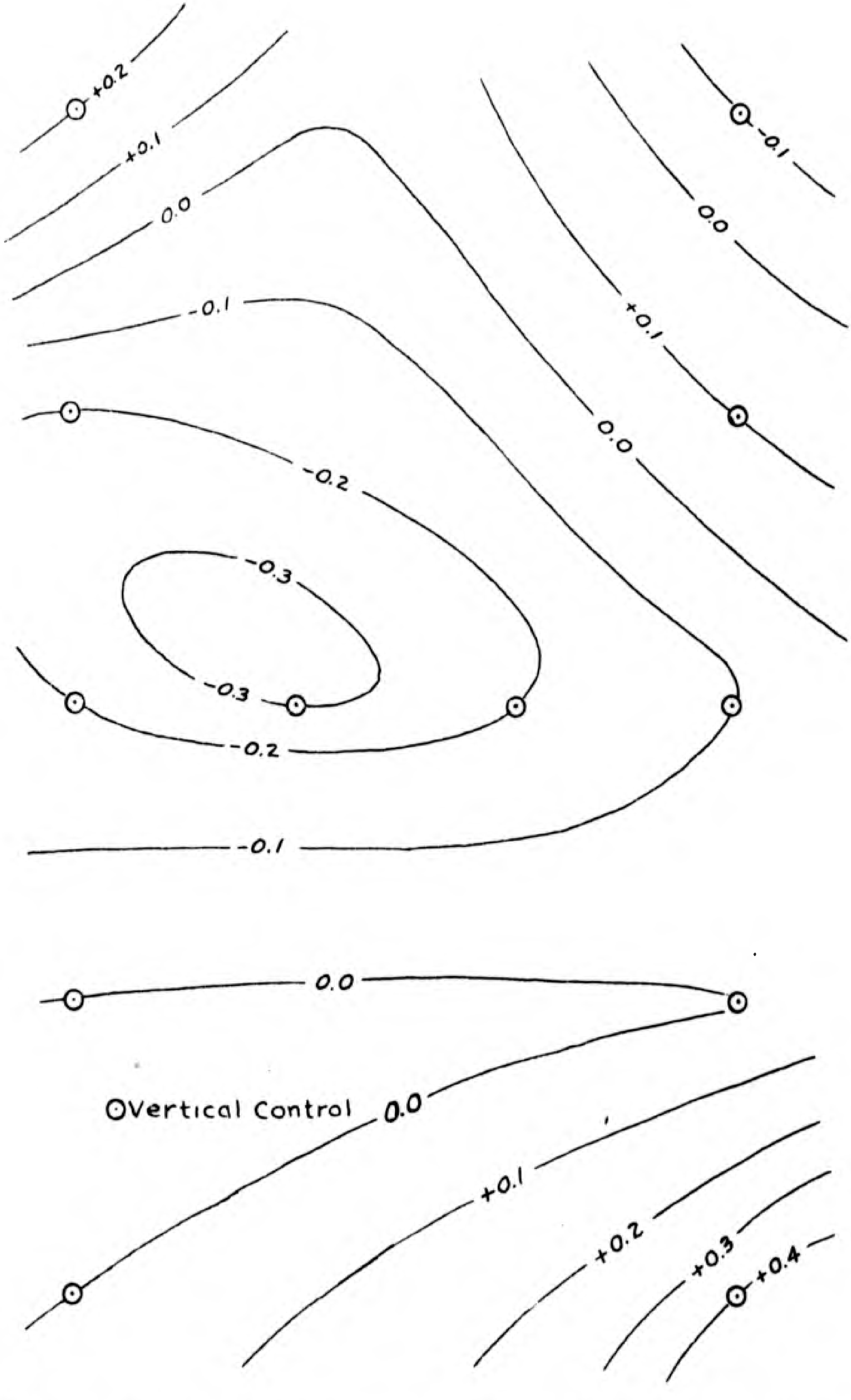

Fig. 13. Correction diagram - Second high-speed run.

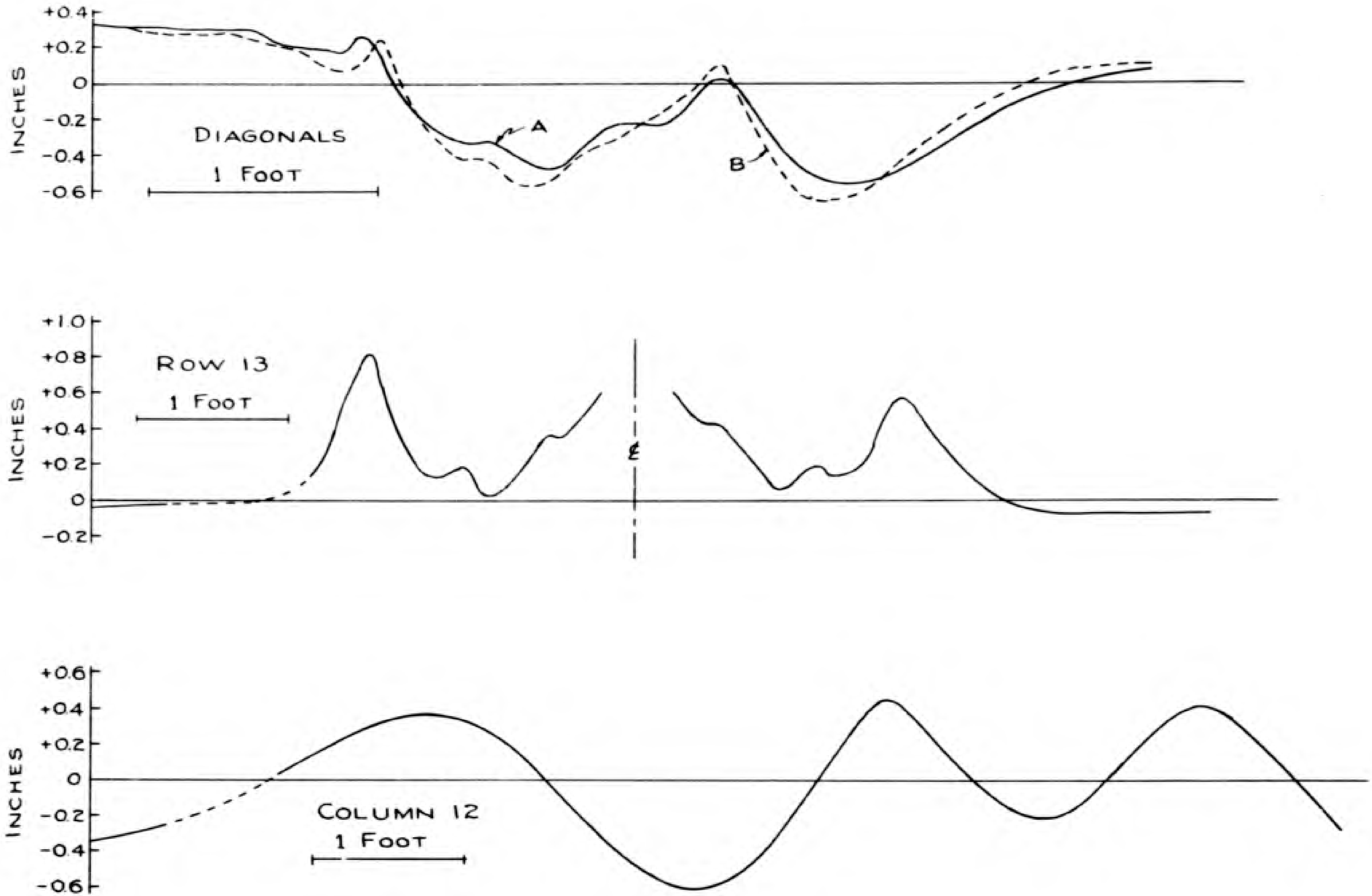

Fig. 14. Profiles from high-speed run.

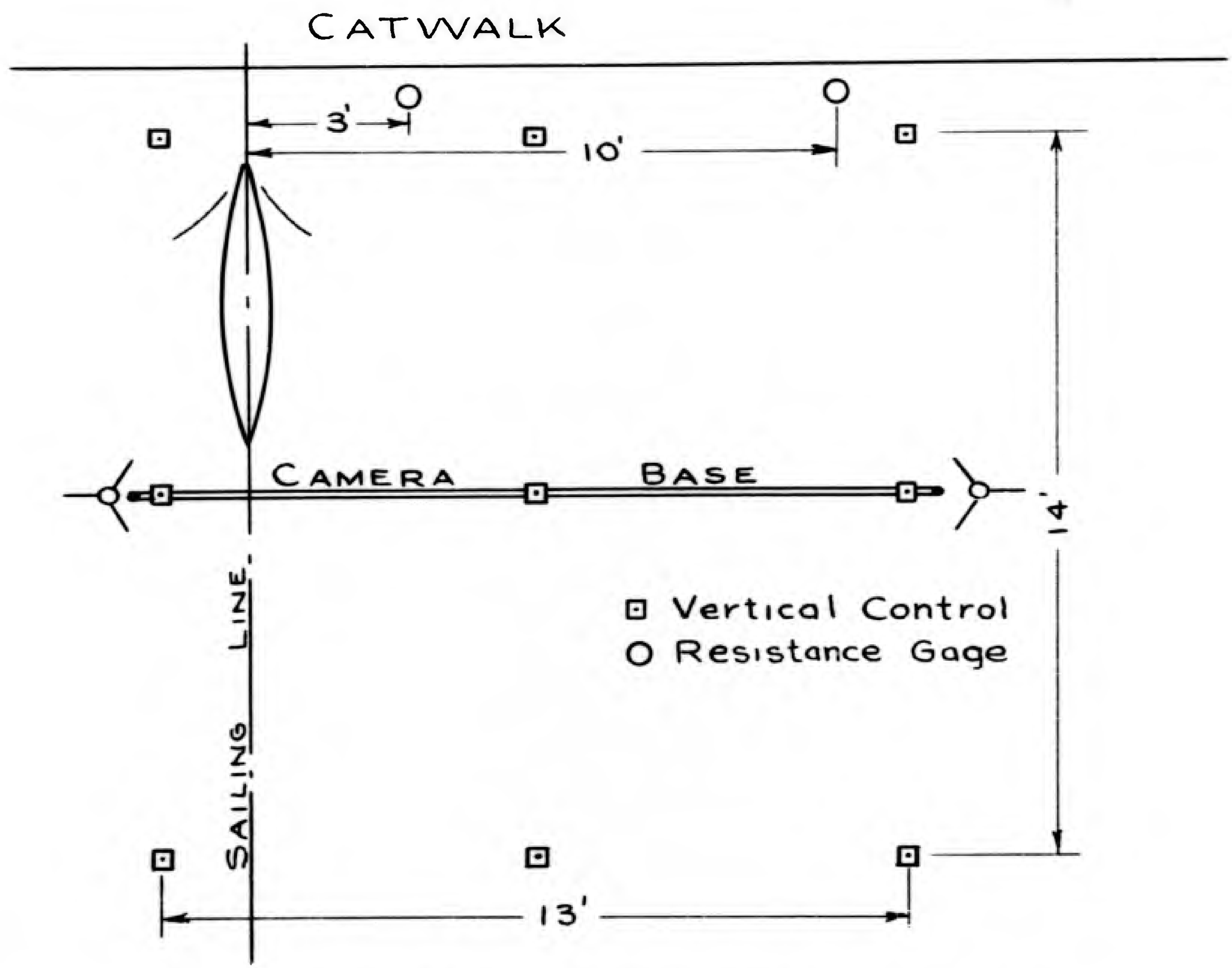

Fig. 15. Arrangement for control, photography, and towing of ship model in model basin.

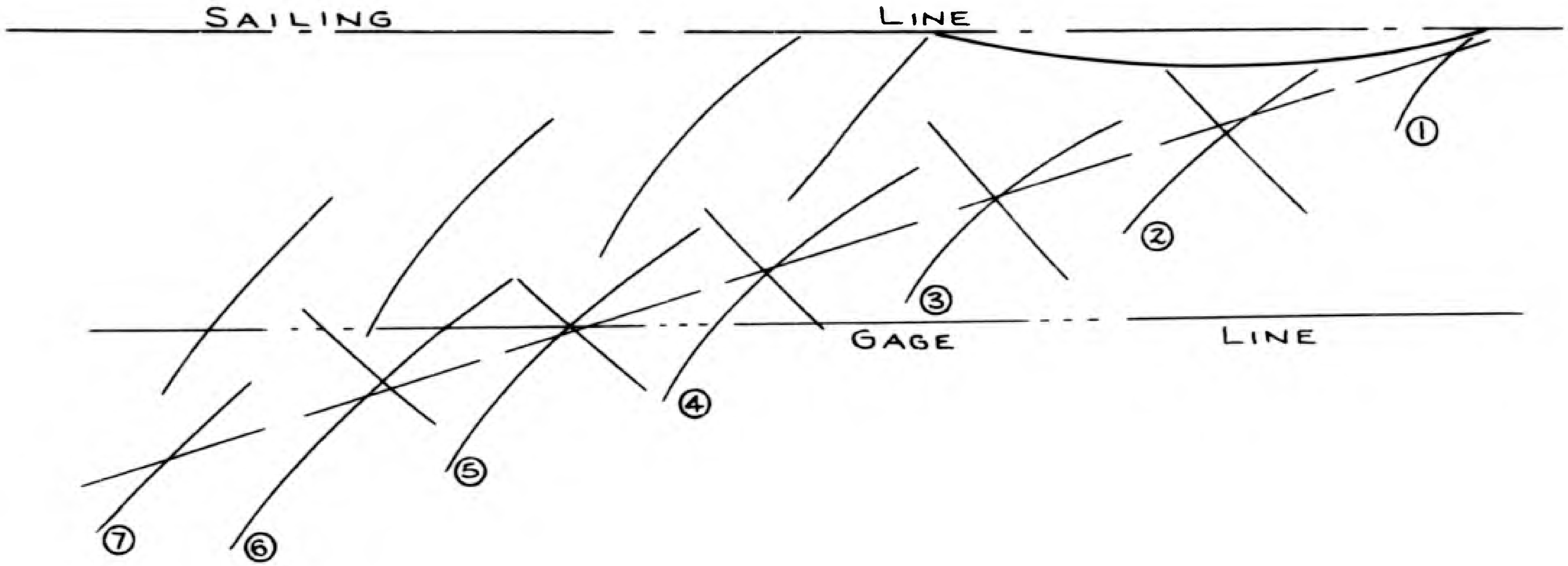

Fig. 16. Measurement diagram - Deep water run (V=3.20 f.p.s.)

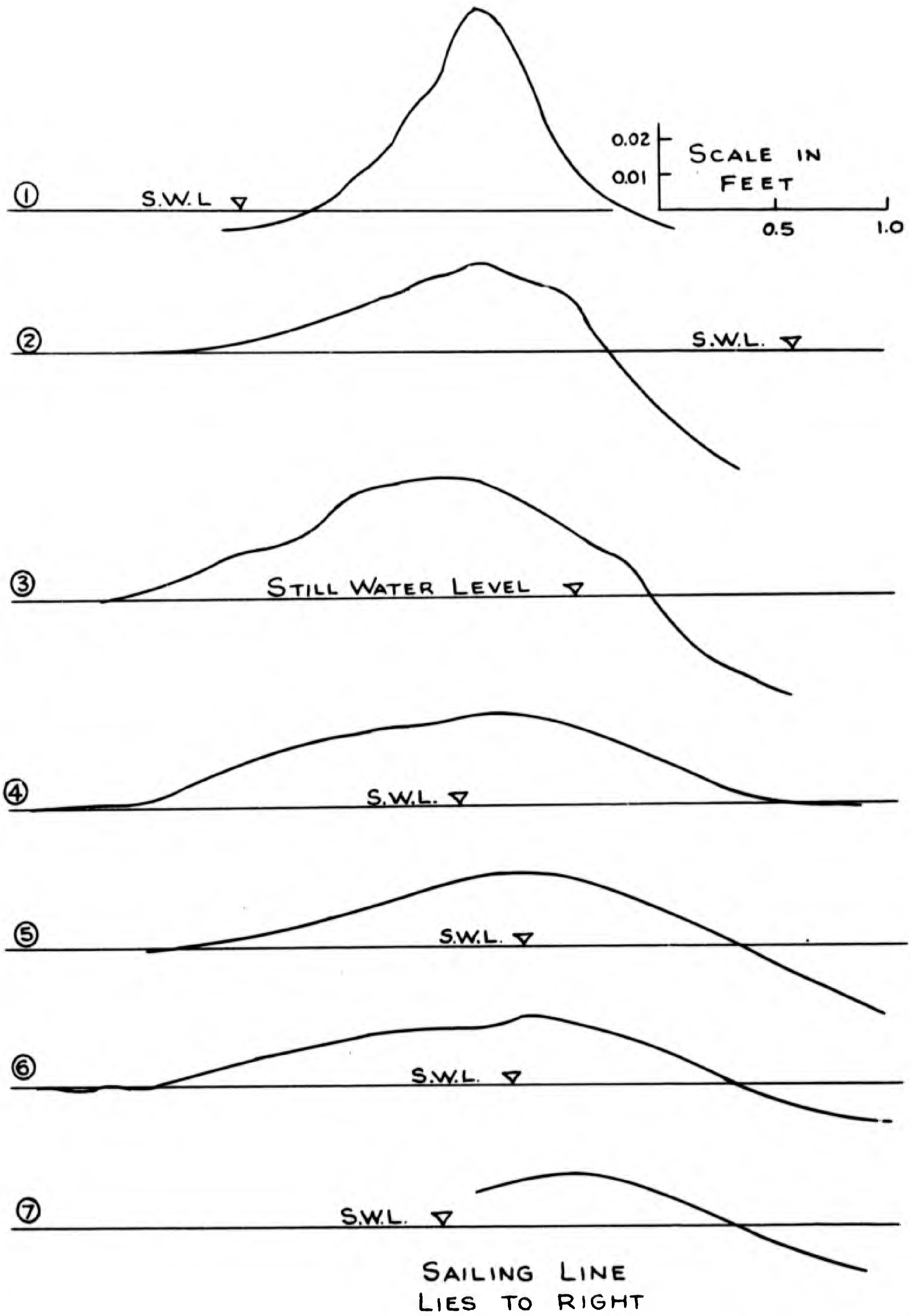

Fig. 17. Crest profiles - Ship model speed = 3.20 ft./sec.

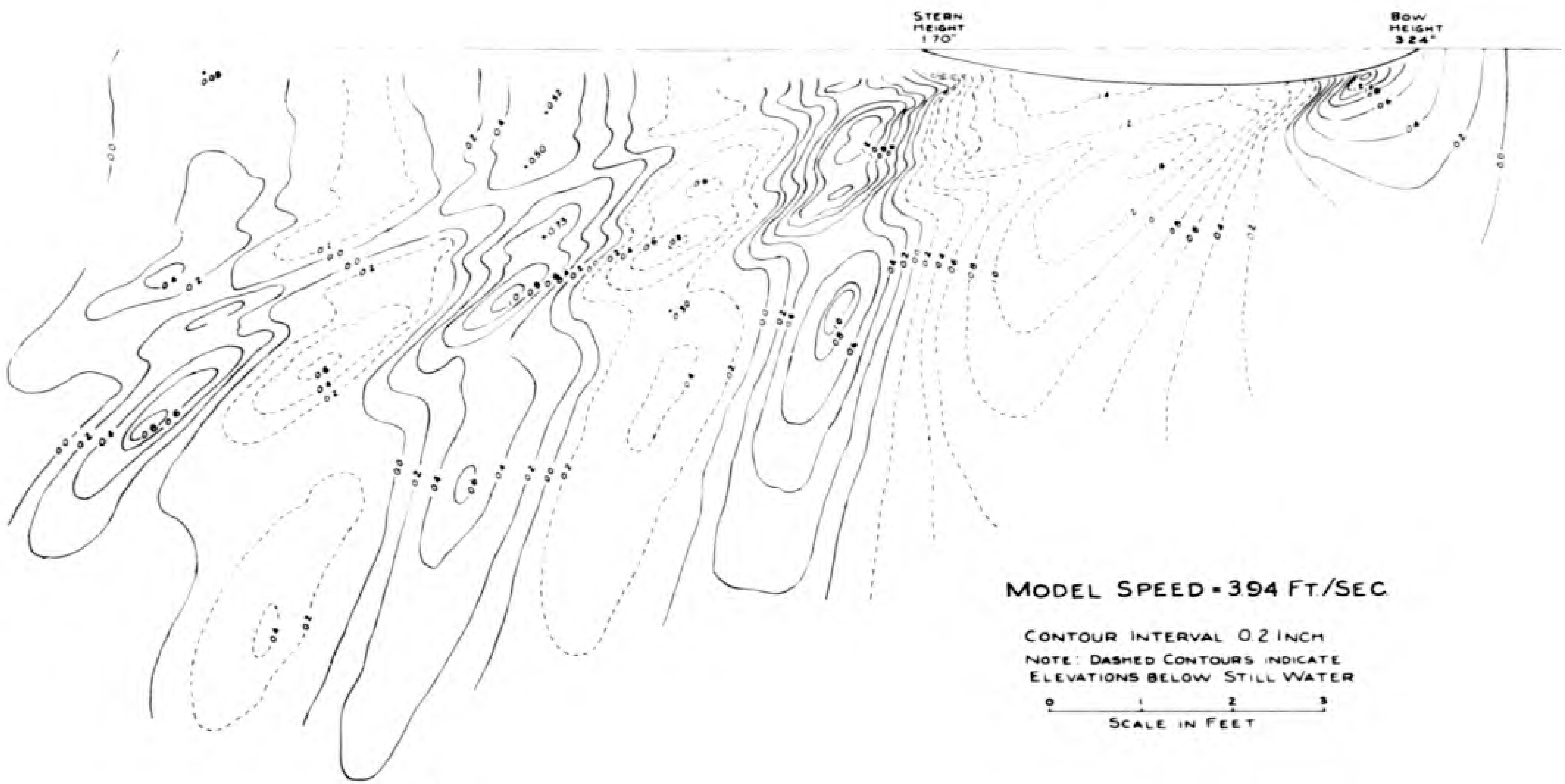

Fig. 18. Ship wake contours.

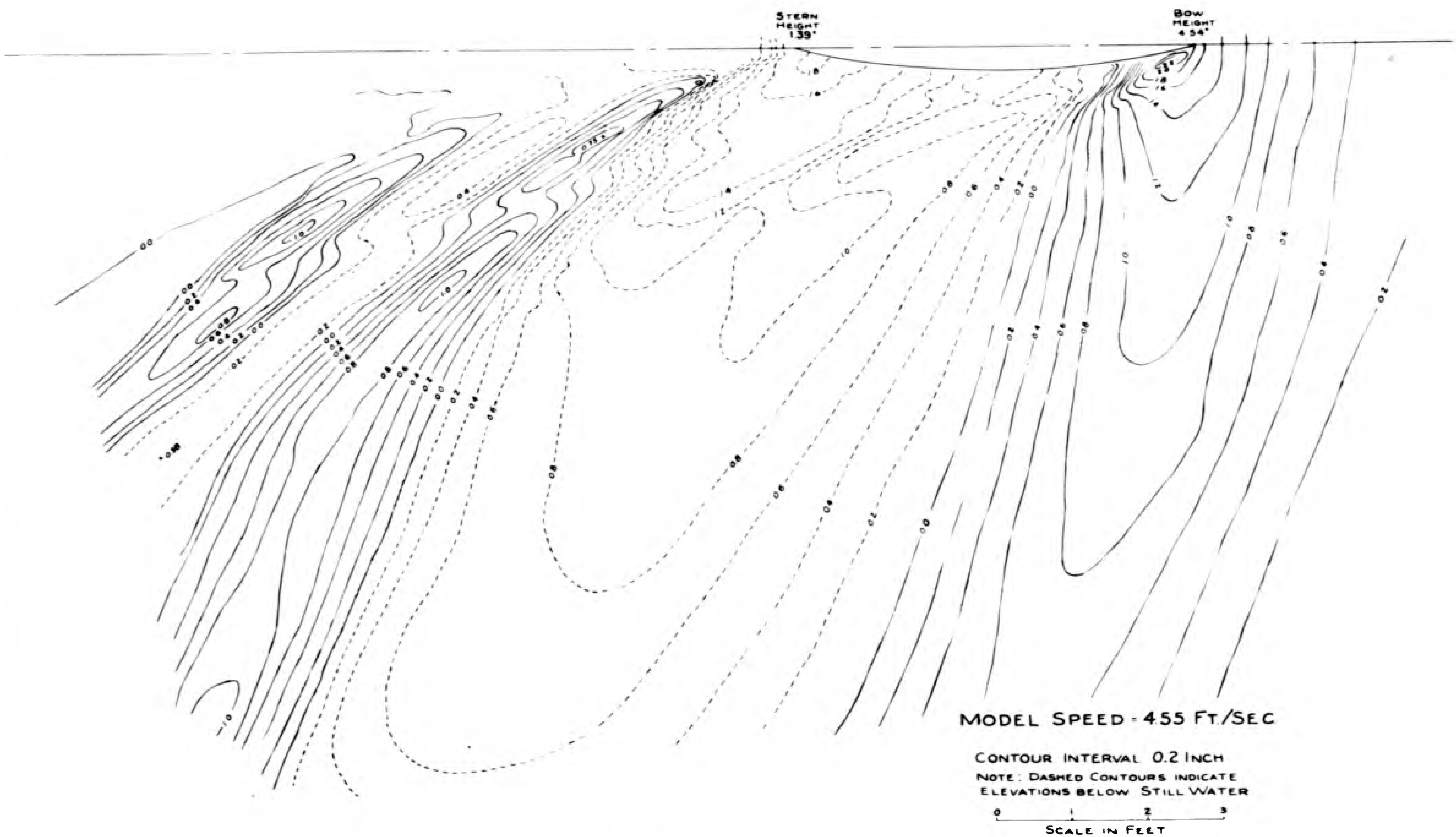

Fig 19. Ship wake contours.

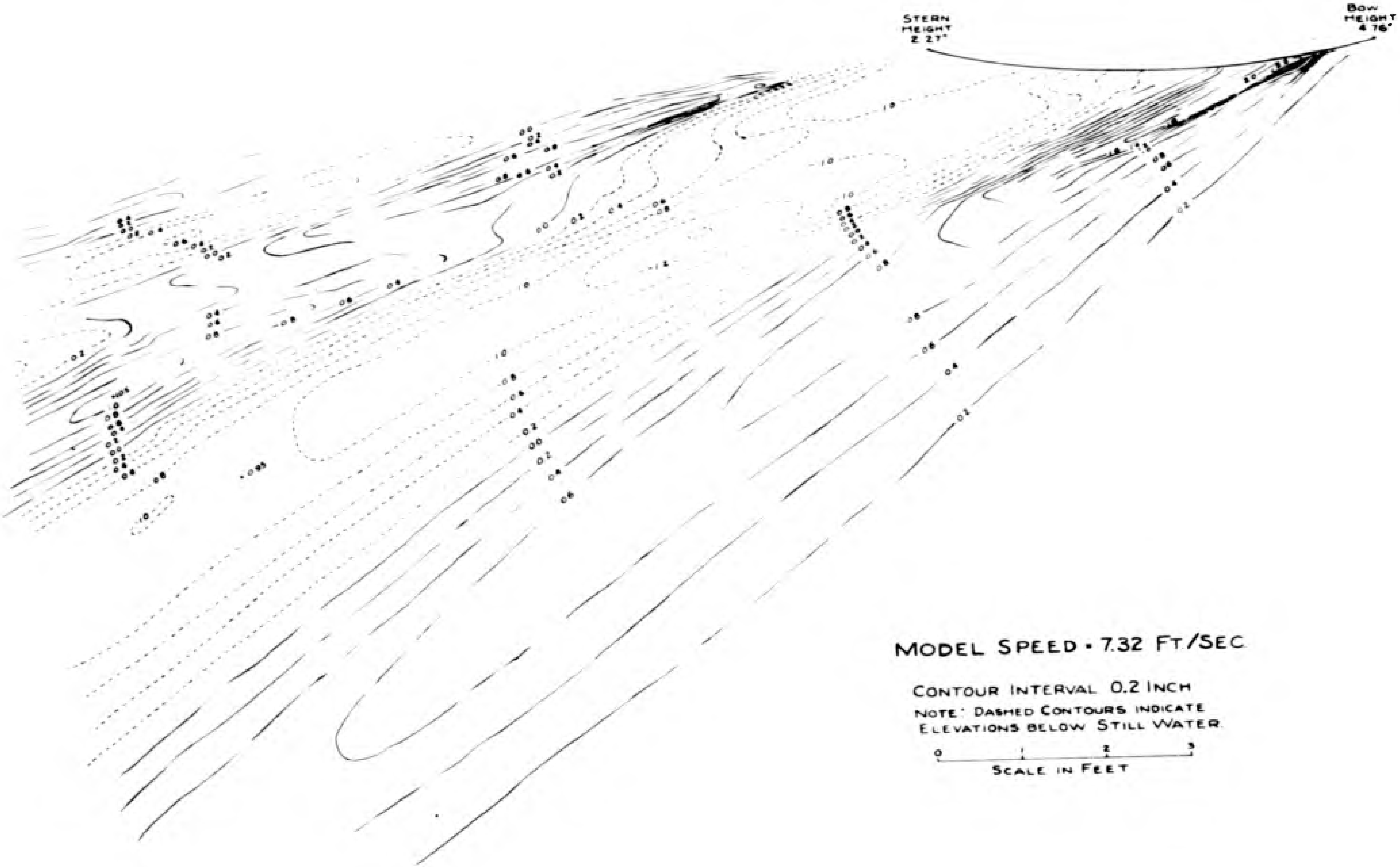

Fig. 20. Ship wake contours.

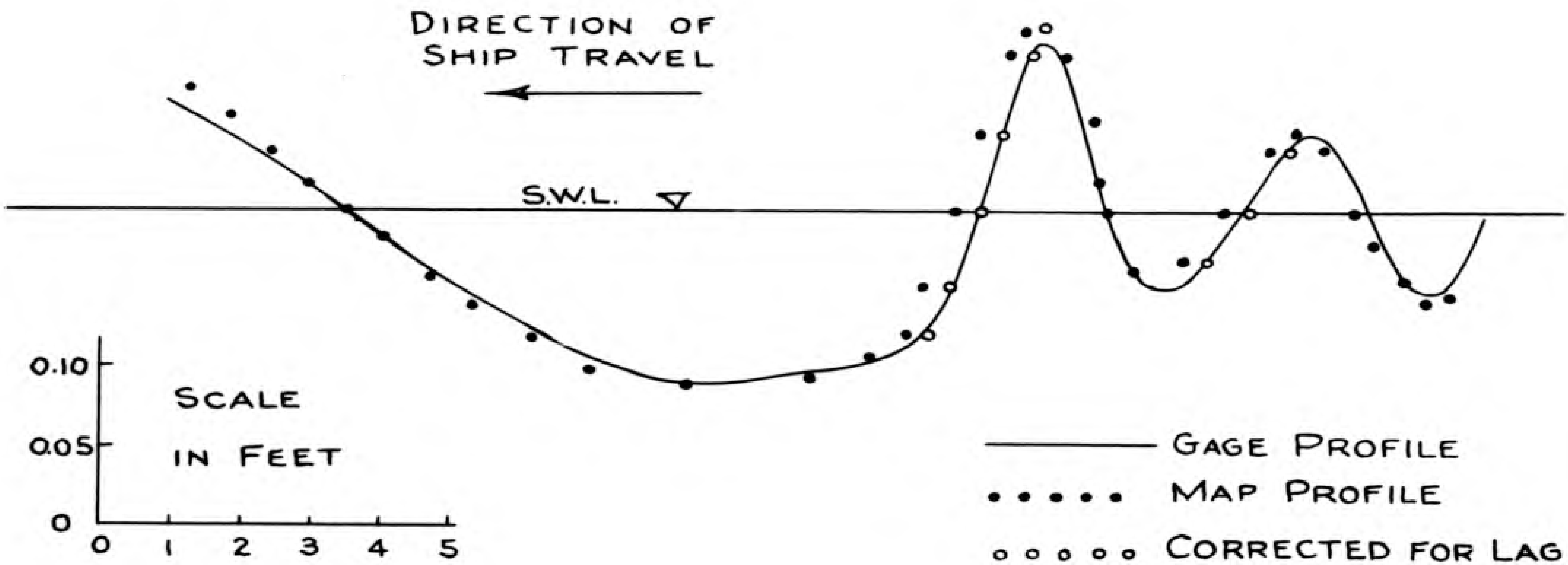

Fig. 21. Gage-line profile comparison -Ship model speed = 4.45 ft./sec.