MEASUREMENT OF TIDAL CURRENTS AT LITUYA BAY (ALASKA) INTRODUCING AERIAL PHOTOGRAMMETRIC METHODS

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ABSTRACT

The U. S. Coast and Geodetic Survey made the first tidal-current observations at the entrance to Lituya Bay, Alaska, in the summer of 1959. Three methods of measurement were employed to determine the maximum flood and ebb currents and to determine their Greenwich time interval. (1) The Roberts radio current meter was used near the entrance, but out of the main current stream, to make a 100-hour record of the times of slack and maximum current for both flood and ebb tides; (2) Mast-bearing free floats were tracked through the narrow entrance by observers on opposite shores. The observations were made with sextants using radio to coordinate the reading times. This method was not satisfactory for either time or velocity determination; and (3) Free floats without masts were photographed with an aerial photogrammetric camera to obtain the best determination of the maximum surface-current velocity. The photogrammetric method is described in detail from the planning stages to the data reduction.

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The mariner's use of currents in navigation dates back to antiquity. Many of the great writers such as Homer, Plato, Aristotle, Newton and others wrote of the tides and tidal currents. The first chart of the Gulf Stream was drawn by Benjamin Franklin in the late 1700's from observations made from sailing vessels in these waters. The first systematic current observations by the Coast and Geodetic Survey were made around 1850. From this it is seen that the knowledge of currents is not new and is considered vital to the mariner and others interested in the sea. The primary purpose of current observations is to provide the mariner with the daily predictions of the times of flood, ebb, and slack water as well as to give him the expected velocities of the current.

Current is defined as the horizontal motion of the water as distinguished from the tide which is the vertical rise and fall of the sea. There are two types of current—tidal, which is periodic and astronomical in nature; and non-tidal, which is due to causes other than the tide-producing force and is usually meteorological in origin. Tidal currents may be rotary or reversing. Rotary currents are usually found offshore where land barriers do not restrict the direction of flow. They flow continually with the direction of flow changing through all points of the compass during a tidal period. Reversing currents flow alternately in approximately opposite directions with a period of slack water at each reversal of direction.

The instruments used by the Coast and Geodetic Survey to observe currents are the pole, Price meter, and Roberts radio current meter. For a detailed description of these instruments and their operation, the reader is referred to various C & GS manuals (1) (2).

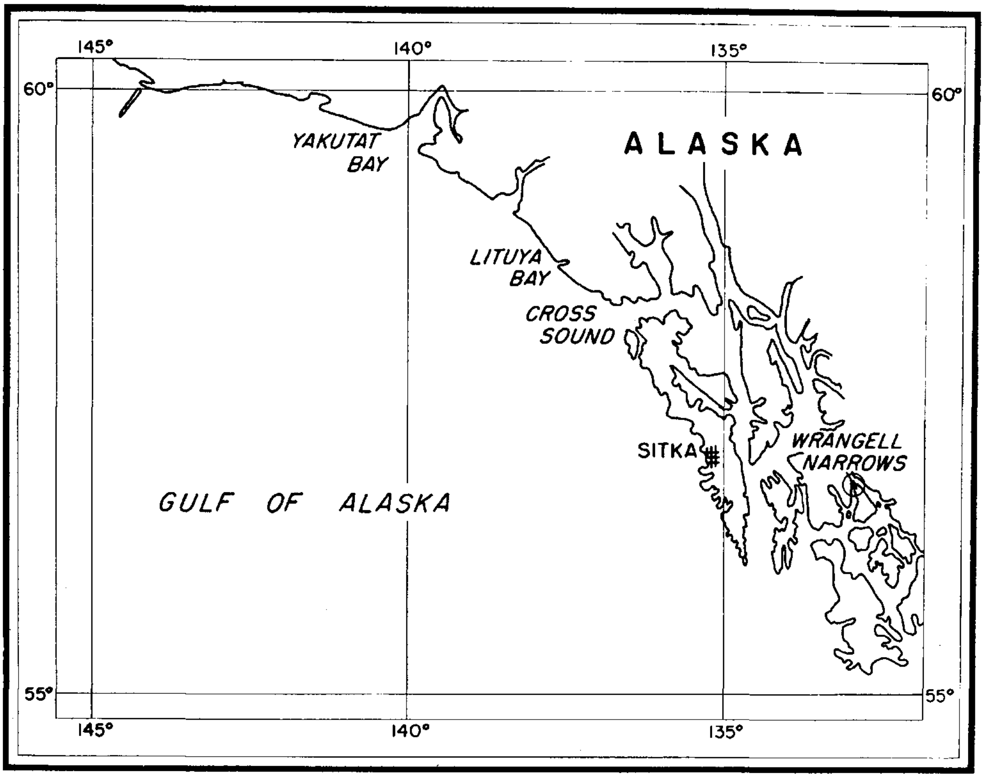

Figure 1. — Map showing location of Lituya Bay, Alaska.

Lituya Bay is located on the northeast side of the Gulf of Alaska between Cross Sound and Yakutat Bay and is shaped like a " T ", six and one-half miles in length (figure 1). The width is about one mile except at the entrance which narrows to about 1/4 mile. The depth of water ranges from 5-6 fathoms at the entrance to 120 fathoms in the deepest section of the bay. There are no settlements in the bay and it is used as a refuge mainly by fishermen. During the summer months the three glaciers at the

(1) Coast and Geodetic Survey : Manual of Current Observations, Special Publication No. 215, Revised (1950) Edition, Washington D.C., 1950.

(2) ROBERTS, Elliott B. : Roberts Radio Current Meter Mod II Operating Manual. Coast and Geodetic Survey, Washington, D.C., 1952.

head of the bay have a very high fresh-water runoff. This is shown by data taken at an oceanographic station located halfway between the points of land about 3/4 mile inside the entrance just before the bay widens out. The temperature and salinity data (3) for this station observed on 27 August 1959 are as follows :

Depth	Temperature (°C)	Salinity (‰)
0 m	8.22	18.72
10 m	11.33	30.40
20 m	11.36	30.76
35 m	10.95	30.82
57 m	10.76	31.11

The currents in Lituya Bay entrance are known to be very strong. Commander A. M. SOBIERALSKI of the Coast and Geodetic Survey reported in 1926 that the tidal current had an estimated velocity of 8-12 knots, and that the ebb current, when running out against a southwest swell, caused bad topping seas and combers across the entrance. He estimated slack water to last from 10-20 minutes and to occur about 1 hour and 30 minutes after low water at Sitka. Based on these estimates, it was believed that the normal methods for observing currents would not be adequate in this entrance. This paper discusses the methods used to observe these strong tidal currents.

The velocity of the current in a channel can be computed roughly using the following formula and data for Lituya Bay :

$$V = \frac{AR}{PC}$$

where :

V = the average velocity of the current at the entrance in feet/sec.;
A = area of the bay = 11.4 square miles;
R = diurnal range of tide = 9 feet;
P = approximate tidal period for ebb = 6 hours 40 min. (400 min.);
C = cross-sectional area at the entrance = 27 200 sq. feet;

Therefore,

$$V = 464\,640 \frac{(11.4 \text{ sq.mi.})\ (9 \text{ ft})}{(400 \text{ min.})\ (27\,200 \text{ sq.ft})} = 4.3 \text{ feet/sec.} = 2.5 \text{ knots}$$

where 464 640 is the factor for converting square miles to square feet and minutes to seconds.

However, the central surface velocity is about 4/3 as great as the average velocity through a cross section of a regular channel. Also, the velocity at strength of current is about 3/2 as strong as the average velocity for an entire tidal period. Therefore, the central surface velocity at time of strength of current is about twice the average velocity or roughly 5.0 knots. This is much less than the estimated velocity of 8-12 knots, mentioned earlier.

(3) BAKER, Leonard S. : Report of Current Survey in Lituya Bay (unpublished) Coast and Geodetic Survey, 1959.

No regular series of current observations had been made in the entrance to Lituya Bay prior to 1959. During the summer of 1959 the Coast and Geodetic Survey Ship *Bowie* under Commander H. J. Seaborg made tidal-current observations in the entrance and approach to the bay. Three different methods were used in observing the time and velocity of the currents. Each had its advantages and disadvantages. Knowing the velocity of the current to be exceedingly strong, it was decided not to risk the loss of a buoy and Roberts radio current meters by anchoring the buoy in the entrance. Instead, the buoy with the current meter suspended under it was placed about 0.4 mile inside the entrance. Here a 100-hour series of half-hourly current observations was made for determining the times of flood, ebb and slack water. The observations were reduced by comparing them with the corresponding phases taken from the daily predictions for Wrangell Narrows. This station was chosen as the reference station because its times of flood, ebb, and slack water varied consistently with the times of the corresponding phases at Lituya Bay entrance. The time differences as computed then could be applied to the daily predictions at Wrangell Narrows (given in Tidal Current Tables, Pacific Coast of North and South America and published annually by the Coast and Geodetic Survey). The mariner could in this manner obtain the predictions of the currents at Lituya Bay entrance for any day.

No reduction was made of the velocity of the current as obtained from the meter because the magnitudes of the observed velocities were not indicative of the true velocities in the main channel. Observed flood velocities were all less than 1.0 knot. These low velocities resulted from the buoy not being placed in the main channel.

The second and third methods for determining the currents in the entrance made use of free floats. In the second method a series of simultaneous directions was observed from two known positions on either side of the entrance on a free float passing through the entrance. It was intended that such measurements would determine lateral displacement of the float from the channel axis, as well as increases in velocity as the float approached the restricted portion of the entrance. It was known beforehand that continuous observations necessary to fix the times of flood, ebb and slack water could not be determined by this method, and no attempt was made to do this. This method proved disappointing, as the velocities obtained from measuring the distance and times the free floats traveled through the entrance did not give the strongest currents. The commanding officer of the survey ship reported (3) that to anchor the ship and maintain its position throughout the maximum flood at a point that would have put the floats in the center of the entrance would have placed the ship in a very dangerous position in regard to the foul area on the north side of the entrance. The free floats did not get in the main current but hugged the southeast side of the entrance. Wind also interfered with the floats, tending to decrease the accuracy of the velocity as determined. The report contains a very interesting comment, worthy of being mentioned at this time. It states : " The current does not have a true slack water. Slack before ebb was observed on the south side of the entrance but the ebb had started on the north side. The reverse is true of the flood current ".

From these observations as determined by both radio current meter and free floats, we were able to determine that the current did not approach the 8-12 knots as previously reported. Observations by Roberts meter, even though they were not in the entrance, gave good determination of Greenwich intervals. Another determination of the velocity was obtained by the third method—photographing free floats as they passed through the entrance.

The Coast and Geodetic Survey had sought an opportunity to demonstrate the usefulness of aerial photographs for tidal-current determination for several years when this project came along. The need for aerial photographs of the entrance of Lituya Bay prior to attempting to take a hydrographic survey vessel through the treacherous passageway developed in the planning stages of the hydrographic survey. A recent earthquake had caused avalanches which denuded slopes of woodlands to a height of 1 700 feet and caused a tidal wave which cleared the banks of the bay to an average height of 100 feet. This made it necessary to assume that the distribution of submerged rocks in the shoal inlet had changed since the last survey was made.

We took advantage of the opportunity to photograph the inlet at low tide when our aerial photographic mission passed by the area en route to Yakutat, Alaska, in May. This photography was made with color film to obtain maximum water penetration. Although the airphoto mission arrived at the inlet 40 minutes after slack before flood, we were still able to plot a safe passageway for the hydrographic party.

While studying these photographs stereoscopically, we found that the color emulsion had recorded an unusually large amount of the swirling froth formed by the flooding tidal current. The line of flight was along the axis of the current channel making it possible to measure the distance the water moved during the 12-second interval between the successive photograph exposures as stereoscopic relief or apparent elevation. That is, what appeared to be stereoscopic contours or lines of equal elevation were actually lines of equal current velocity as shown in figure 2. The heavier sections of the current-velocity lines — labeled A through D — were stationary froth lines of distinct shape under which the sea water was flowing quite rapidly. The lighter sections of the current-velocity lines were drawn as depression contours with a vertical spacing of 0.3 mm at photo scale. The two points labeled E and F mark the location of areas where the water was moving in the opposite direction to the tidal current at the rate of one-half knot. No attempt was made to plot the component of movement at right angles to the main current stream because it was too small to be resolved from the froth-line images. This study has been included in this paper to show the possibility of using froth or other natural floats such as ice or debris for mapping water currents.

The actual determination of maximum current at Lituya Bay was made with white floating targets of painted $4' \times 8' \times 1/4''$ plywood sheeting which were released in the current stream by the hydrographic survey vessel later in the season. The planning and execution of this coordinated effort between the hydrographic survey ship and the photographic airplane

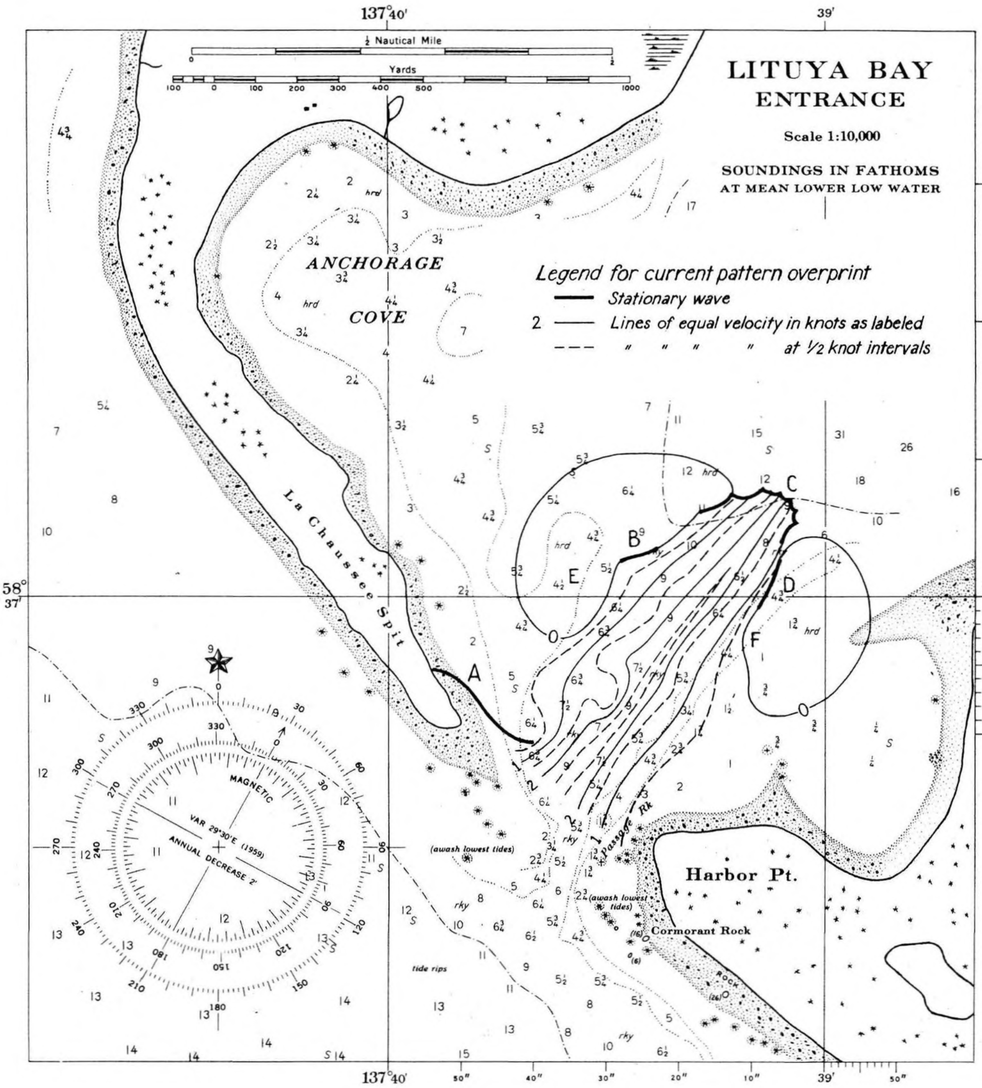

Figure 2. — Nautical chart of Lituya Bay entrance with overprint showing current-velocity curves.

required the consideration of several restrictive factors which will be discussed in the next few paragraphs.

The first restriction was the period of days when both the hydrographic and photographic parties would be in the area. The time was limited by the photographic mission which was scheduled to be available from 15 July to 1 September, while making aerial photography of nearby areas. This gave the hydrographic party time to determine the exact time difference between the slack before flood and slack before ebb at Lituya Bay with respect to the predicted times at the reference station at Wrangell Narrows before the photographic mission arrived.

The second restriction was that the angular altitude of the sun had to be great enough to assure adequate illumination for aerial photography and not so great that the reflection of the sun on the water would reach more than halfway across the photograph. Figure 3 shows the probable

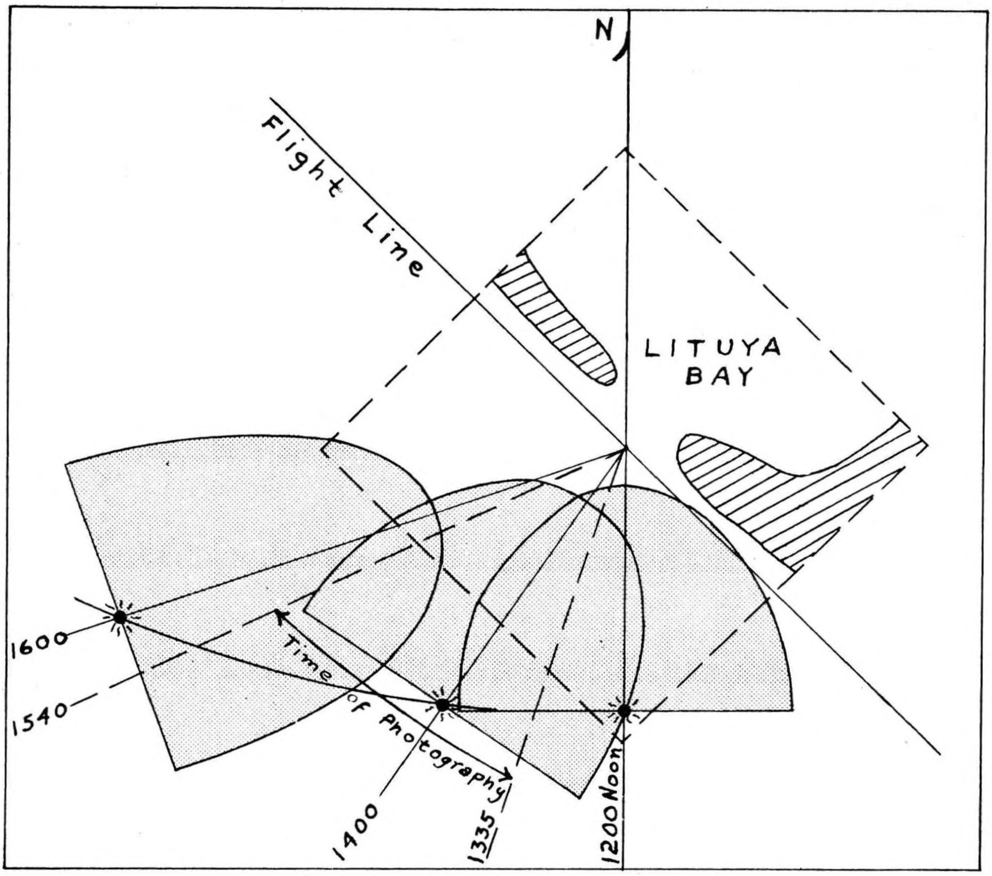

Figure 3. — Flight-planning diagram showing sun-flare spots for afternoon hours at Lituya Bay on 13 August.

size of the sun spot on a 9- × 9-inch aerial photograph made with a 6-inch focal-length lens. The sun spot is reduced considerably by using an infrared emulsion instead of the usual panchromatic emulsion. The preparation of this diagram is a standard flight-planning procedure at the Coast and Geodetic Survey. It is prepared by plotting the trace of the image of the sun at photograph scale for the latitude and longitude of the area and the approximate date of the planned photography. The Air Almanac (4) and Sight Reduction Tables for Air Navigation (5), are used to compute points on this curve. The trace of the sun's image frequently passes near

(4) The Air Almanac, Her Majesty's Stationery Office in London, or United States Naval Observatory, Washington, D.C.

(5) Sight Reduction Tables for Air Navigation, H.O. Publication No. 249, United States Navy Hydrographic Office.

the center of the photograph at noonday making it necessary to photograph before 0800 or after 1600. The half-ellipses which show the probable area of sun-spot flare are centered on the image of the sun at two-hour intervals beginning at noon and are defined as the line of intersection between a horizontal surface and a circular bundle of rays which is 7 inches in diameter. The diameter of this bundle of rays is a function of the smoothness of the water surface. If it were as smooth as a mirror, the bundle would have a diameter of only 25 microns at photograph scale. On a calm day a photograph of sheltered harbor water would image a sun-flare spot about 1½ inches in diameter and on a windy day a photograph of open sea along the coastline would image a sun spot nearly 7 inches in diameter. For this project, the direction of flight was chosen along a northwesterly-southeasterly line parallel with the coastline and slightly offshore, so that the inlet would not be obscured by the sun spot on any of the photographs made along this flight path, providing the photographic hours were restricted to the interval between 1300 and 1700.

The third restriction on the floating-target photography was that the maximum current velocity for the day had to be at least as great as the average maximum for the tidal period. The Tidal Current Tables, published by the Coast and Geodetic Survey, were used to select the days on which currents of greater than average maximum would occur at the reference station at Wrangell Narrows. Observing all previous restrictions, it was determined that the photography would have to be made between 1300 and 1700 on one of the following dates for the ebb current; 17, 18, 19 July, 3, 4, 15, 16, 17 August; and for the flood currents on one of the following dates : 9, 10, 11, 22, 23 August.

The fourth restriction, that of minimizing the cost without jeopardizing the success of the program, was accomplished by determining the approximate time of maximum current and limiting the photography to one hour each day. Photographic flights were made over the inlet at the expected time of maximum current, one-half hour before maximum current and one-half hour after. For each photographic flight the hydrographic vessel released a set of eight floating targets in sequence with a time spacing of one minute so that the fourth target of the set would arrive at the inlet at the same time the airplane passed over. With each pass of the airplane, the photographer obtained 6 overlapping photographs of the inlet (see figure 4). The time spacing of the photographs was 5 seconds giving a total observing time of 25 seconds for the six photographs of the sequence. The coverage of each set of photographs can be visualized by looking at figure 4 and realizing that each target image moved one-twelfth of the distance toward the next target before the second photograph was exposed, another twelfth before the third photograph and so on, until five-twelfths of the distance to the next target image have been traversed and 6 photographs have been taken.

The two remaining restrictions were unpredictable. The weather had to be unusually good for summertime at Lituya Bay in order to obtain the photographs, and the water had to be calm enough for the hydrographic vessel to hold position in open sea within the tidal-current stream into the bay.

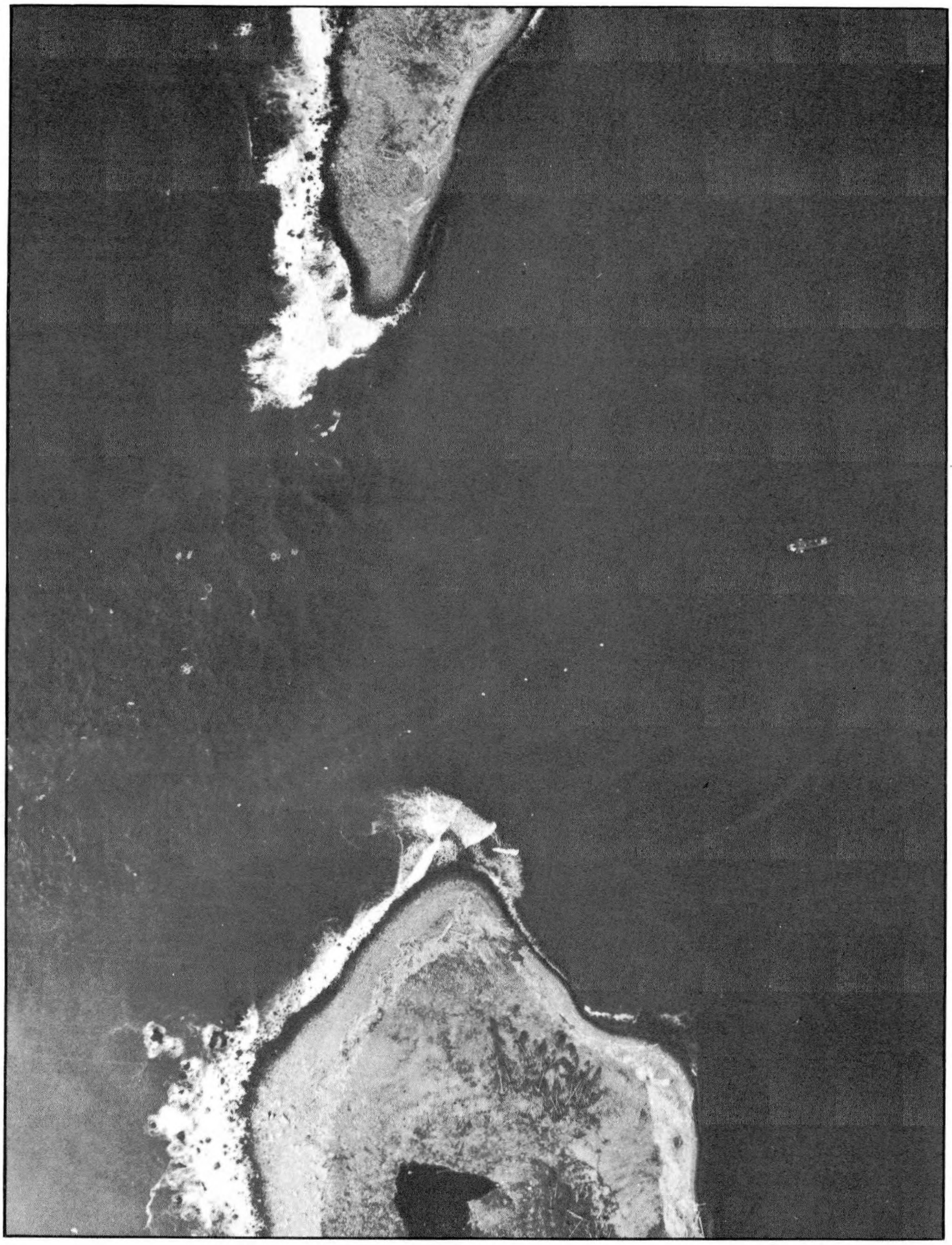

Figure 4. — Portion of an aerial photograph showing free-floating targets passing through the entrance at Lituya Bay.

As it happened, the weather was too poor for either of the parties to accomplish their work on all but 4 of the days listed. However, we were fortunate enough to photograph all three sets of floating targets on flood currents on 10 August and again on 11 August and on ebb currents on 15 and 16 August. By coincidence, a minimum of two flood and two ebb currents were considered a minimum for a current determination.

The first step of the photogrammetric-data reduction consisted in leveling each photograph to sea-level datum and scaling it to a base map of the area by standard photogrammetric methods after which each target image was plotted on the base map. Then by scaling the distance traveled by each target during each 5-second photographic interval, we were able to obtain an almost instantaneous velocity for each segment of the current stream from the position of the first target to the last.

The maximum flood current measured was 5.4 knots and the maximum ebb current was 4.7 knots. The velocity ratios, with respect to the reference station at Wrangell Narrows, were 1.4 for both flood currents and 1.2 for both ebb currents. There was some doubt that the targets always got into the center of the current stream. This would make the observed values slightly lower than the true velocities. It was interesting to note that on the flood currents small eddies were created which would occasionally catch one of the targets and slow its progress. The influence of these eddies, if not eliminated, would have caused errors that would probably not have been detected by any other method of current measurement. This set of measurements was concerned only with surface currents, but currents could be measured at any or several depths by using floats with depth vanes attached beneath them.

The photogrammetric method accurately determined surface-current velocities and provided an appreciably greater coverage than can be achieved with anchored equipment. However, inasmuch as continuous observations at various depths are needed for prediction purposes, the method does not replace conventional methods, except for situations similar to Lituya Bay where submerged rocks and strong currents prevent the use of standard methods.

IHB NOTE. — Mr. Charles B. Taylor, Jr. was born in New Jersey and attended public schools there. In 1941 Lehigh University of Bethlehem, Pennsylvania, conferred the degree of B. S. in Civil Engineering on him. He joined the Coast and Geodetic Survey in 1942 and since 1944 has been assigned to the Tides and Currents Division where he is now Assistant Chief, Currents and Oceanography Branch. Mr. Taylor is the author of papers having to do with anomalies of ocean water temperatures and salinities.

Mr. William D. Harris was born in Iowa and received his formal education there and at Iowa State College, School of Electrical Engineering. His entire professional career has been with the Coast and Geodetic Survey. Since 1952 he has been assigned to the Research Branch of the Photogrammetry Division, of which he is now Acting Chief. He is the author of papers on the nine-lens mapping system, the exposure and development of aerial photography, the adjustment of strip aerotriangulation by electronic computers, and the use of infrared and color emulsions for aerial photography.