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Tidal Current Surveys by Photogrammetric Methods

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This series of Technical Bulletins was inaugurated to present primarily to the personnel of the Coast and Geodetic Survey and incidentally to others technical information related to the Bureau's scientific and technical activities. Since many of the bulletins deal with new practices and new techniques, the views expressed are those of the authors and do not necessarily represent final Bureau policy.

Technical Bulletin No. 22 describes the application of photogrammetric techniques to the measurement of currents in bays and harbors and of the circulation in large water bodies. Included in this presentation are the principle on which the method is based, the equipment and materials used, the survey operation, the photogrammetric measurements and reduction of data, and the status of this type of surveys.

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Tidal Current Surveys by Photogrammetric Methods

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THE application of photogrammetric techniques to the measurement of currents in bays and harbors provides a feasible method for detailed current surveys and studies of the circulation in large water bodies. This bulletin describes the principle on which the method is based, the equipment and material used, the survey operation, the photogrammetric measurements and reduction of data, and the status of photogrammetric current surveys. The author gratefully acknowledges the assistance and support of Capt. Lawrence W. Swanson, Assistant Director for Physical Sciences, who conceived the idea of using photogrammetric measurements to supplement the Bureau's tidal current surveys, and the help rendered by both field and office personnel of the Marine Data Division. A particular word of appreciation is due Mr. William Shofnos, Assistant Chief of the Marine Data Division, and Mr. Charles B. Taylor, Chief of Currents Section, for their assistance.

INTRODUCTION

The mariners' 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. The Coast and Geodetic Survey has been making current surveys since 1844 as part of its service to maritime commerce. The Bureau publishes annual Tidal Current Tables that predict the times of slack water and the times and velocities of the maximum flood and ebb currents, as well as special publications containing observations of data for various waterways. Current charts that show the direction and velocity of the tidal current for each hour of the tidal cycle are also issued for some harbors.

Instruments and procedures for the measurement of currents and techniques for the reduction of current data have been developed and improved over the last century. Today the principal instruments for conventional current surveys are the Roberts radio current meter and the time-tested current pole. These instruments provide reliable measurements at the site of operation, but they cannot be placed in shallow water and the number of sites that can be occupied is usually limited by time and cost factors.

The rapid population expansion and industrial growth of the nation has brought demands for more detailed circulatory current surveys of harbors and bays in connection with water pollution, fisheries, silting, shore erosion, and coastal engineering problems. The Bureau's search for economically feasible methods of obtaining a great number of current measurements led in 1957 to the investigation of photogrammetric methods, the potential value of which has been known for many years.

The Bureau's first use of aerial photography specifically for the measurement of currents was the measurement of the maximum tidal current at the hazardous entrance of Lituya Bay, Alaska, in 1959.[1] The success of this project, the rapidly growing need for circulatory surveys, and the work of Prof. H. L. Cameron of the Nova Scotia Research Foundation and W. D. Forrester of the Canadian Hydrographic Service[2 3 4] gave impetus to the plan of Capt. L. W. Swanson, Assistant Director for Physical Sciences, to make an aerial photogrammetric survey of a complete tidal cycle for an entire harbor area. This was first done at Charleston Harbor, S. C., in the spring of 1962, in conjunction with a conventional tidal current survey using current meters and current poles.

CURRENTS DEFINED

For the pupose of this discussion, currents may be classified as tidal and nontidal, but the actual current experienced in any locality is usually a combination of both tidal and nontidal movements.

The tidal current is the horizontal movement of the water and is a part of the same general movement of the sea that is manifested by a vertical rise and fall of the water level known as the tide. Like the tides, tidal currents are periodic and arise from astronomical causes. Currents caused by meteorological conditions

[1] Measurement of Tidal Currents at Lituya Bay, Alaska, Introducing Aerial Photogrammetric Methods by Charles B. Taylor, Jr., and William D. Harris, *The International Hydrographic Review*. January 1961.

[2] The Measurement of Water Current Velocities by Parallax Methods by H. L. Cameron, *Photogrammetric Engineering*, March 1952.

[3] Plotting of Water Current Patterns by Photogrammetry by W. D. Forrester, *Photogrammetric Engineering*, December 1960.

[4] Water Current and Movement Measurement by Time-Lapse Air Photography. An evaluation by H. L. Cameron, *Photogrammetric Engineering*. March 1962.

that have a rough periodicity can also be classified as tidal currents for the purpose of reduction.

The tidal currents may be subgrouped as either rotary or reversing. Offshore and in the open ocean, where land barriers do not restrict the direction of flow, the tidal currents usually are rotary due to the deflecting force of the earth's rotation (Coriolis force). A characteristic feature of rotary currents is the absence of slack water. Rotary currents flow continuously with the direction of flow changing through all points of the compass during a tidal period. The tidal currents are of the reversing type in rivers and straits where the direction of flow is more or less restricted to certain channels. The water flows alternately in approximately opposing directions with a period of slack water at each reversal of direction. These cycles of current occur once each day (diurnally) or twice each day (semidiurnally) depending on their location.

Reversing tidal current cycles may be considered as beginning with slack water before flood. The current movement upstream increases in velocity until the maximum velocity of flood current is reached. It then decreases until the following slack water or slack before ebb. The current flow downstream now begins, increases to a maximum ebb velocity, and then decreases to the next slack or slack water before flood. On the Atlantic Coast of North America a complete cycle takes approximately 12 1/2 hours and is an example of the semidiurnal type of reversing current, see figure 1.

Nontidal currents are not periodic and may be considered under two classes—permanent and temporary. Permanent currents are those which flow more or less continuously in one direction and include such well-known features of the oceanic circulation as the Gulf Stream, Japan Current, etc. The primary generating force is wind. Other factors are density differences in the water, depth of water, underwater topography, and deflection due to rotation of the earth. The current in a river due to the fresh water discharge may also be considered as a permanent current. Temporary currents are caused principally by changes in meteorological conditions; the currents created by wind action are the most common example of temporary currents.[5 6 7]

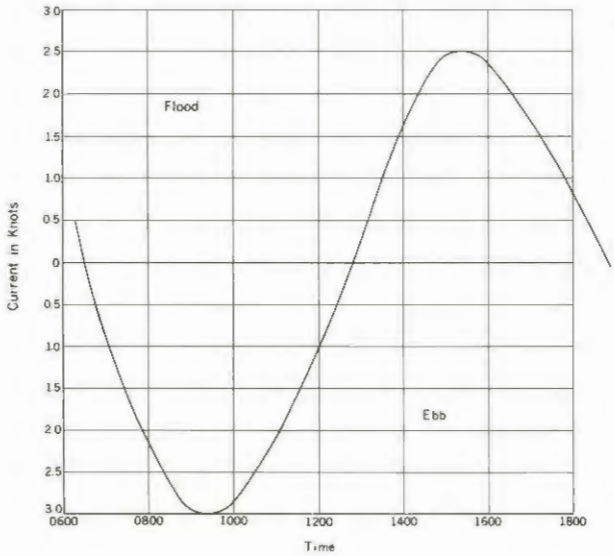

FIG. 1.—Current cycle at the Charleston Harbor, S. C., reference station on April 2, 1962.

PRINCIPLE OF PHOTOGRAMMETRIC MEASUREMENT OF CURRENTS

The principal feature and advantage of the photogrammetric method is that it can provide an instantaneous synoptic measurement of currents over a large area. The objective of the Coast and Geodetic Survey is to combine the photogrammetric measurements with the standard current meter surveys to obtain a more detailed circulatory current chart.

To apply photogrammetry to current surveys it is necessary to achieve absolute orientation on stereoscopic plotting equipment, as in normal practice, and to have the water surface marked, either artificially or naturally, to permit the identification of specific surface points stereoscopically. Natural markings result primarily from foam configurations. The number of such targets tends to be proportional to the magnitude of the current speed. As we are also interested in obtaining measurements of small velocities of less than 0.5 knot, as well as maximum velocities, we cannot depend on the availablity of natural targets. It is necessary to seed the area with suitable floating targets and to record their movement on aerial photographs taken throughout a tidal cycle.

Figure 2 illustrates the photogrammetric method in very general terms. The diagram shows a pair of photographs taken in line of flight from 1 to 2 with 60 percent endlap.

These two photographs, or glass plate diapositives of them, are placed in the projectors of the stereoscopic plotting instrument. The projectors of the plotter are analogous to the aerial cameras, and the perspective of rays from the camera stations are reproduced in the plotter at a reduced scale. Thus, the diagram may also be visualized as the reduced scale perspective in the plotting instrument.

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[5]Manual of Current Observations, Special Publication No. 215, Revised (1950) Edition, *U.S. Coast and Geodetic Survey.*

[6]An Introduction to Physical Oceanography by William S. von Arx, 1962.

[7]Oceanography, Part 6 of American Practical Navigator (1958), H. O. Publication No. 9, *U. S. Navy Hydrographic Office.*

Absolute orientation of this perspective, or model, from the overlap area of the two photographs is attained by leveling and scaling to ground control. We are then able to make measurements in three dimensions—*X*, *Y*, and *Z*; the *X* direction being parallel to the flight line or hase line, the *Y* direction normal to the base line, and the *Z* direction normal to the level surface (in this case normal to water level).

Let us consider a floating target that moved from *A* to *E* in the interval of time between the taking of the first photograph (*1*) and the second photograph (*2*). Since the target moved in a direction opposite to the movement of the aircraft, the target will appear in the stereoscopic view of the photographs to be above the water surface at *F*. If there had been no movement of the target, it would appear to float on the surface of the water at *A*. If the movement had been from *A* to *G*, the target would appear to be below the surface of the water at *H*.

The components *AX* and *AY* of the movement *AE* are measured separately in the plotting instrument and combined to obtain the direction and horizontal distance *AE*; this distance is converted to a velocity value in accord with the exposure interval (interval of time) between photographs *1* and *2*. A preliminary investigation of the errors inherent in the photogrammetric technique indicates a cumulative error of approximately 0.1 knot in the speed determination with the error decreasing as the time interval between exposures increases.

A numher of conventional current meter stations placed at strategic locations in the area serve to control the photogrammetric measurements and provide data for the reduction of those measurements. For example, the aerial photography for a complete tidal cycle (12 1/2 hours) usually cannot be taken on a single day; parts of the tidal cycle are photographed on each of several days and the photogrammetric measurements are then translated or reduced to the equivalent of measurements made continuously throughout a single cycle by comparison with the current meter station values.

One of the current meter stations in the area is used as a reference station; currents at this station can be predicted for any future time by means of the puhlished tidal current tables. It follows, therefore, that a current chart prepared with numerous photogrammetric measurements can be used to predict the currents at each place, that is, throughout the area, at any future time since the velocity relationships between the photogrammetric measurements and the current meter reference station are known for any phase of the tidal current cycle for which current charts have been constructed.

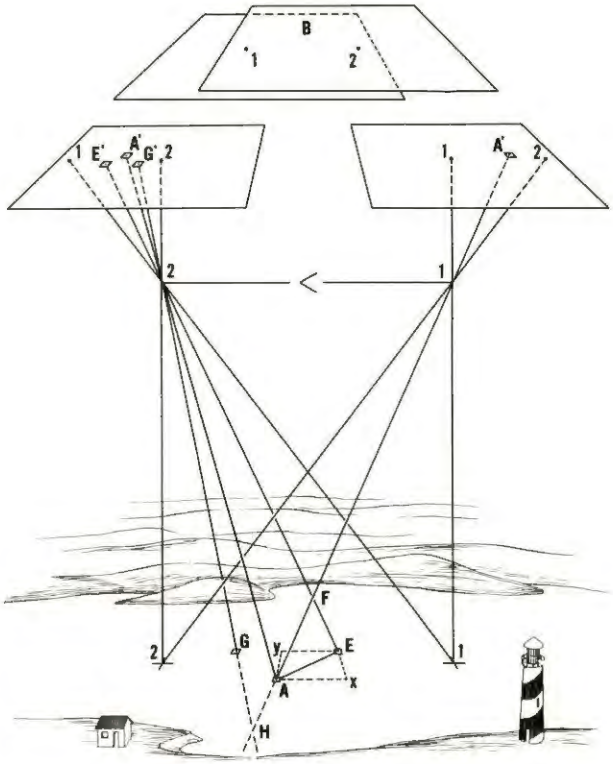

FIG. 2.—Photogrammetric current measurement.

PLANNING AND PREPARATION

There are many factors to be considered in preparing for a photogrammetric current survey. These include the choice of camera and film emulsion, target design, and method of seeding the targets in the water area.

Photography

Ideally, the date for scheduling aerial photography should be chosen so that the entire current cycle takes place during the daylight hours suitable for photography. It is normal practice in the Coast and Geodetic Survey to limit the taking of photography to the period hetween 1 hour after sunrise and 1 hour before sunset. The required time interval of 12 1/2 hours occurs when the sun reaches the summer solstice on June 21st. At that time of the year, however, the position of the sun is such that a relatively large sun spot reflection appears on aerial photographs of water areas which severely hampers the office identification of floating targets.

This situation can beavoided by taking photography on several days, photographing sections of the current cycle until a complete periodic coverage of the cycle has been obtained. The length of the period is determined by the time required to fly and secure photographic coverage

of the entire area. It is also desirable to select days on which the current velocities are near their maximum monthly values during daylight hours since the current meter observations are more reliable at the higher velocities.

An evaluation must be made of the parts of the photographs on which the target images will be obscured by the sun's reflection from the water surface. This study, which is a standard procedure in the Bureau, requires a plotting of the hourly trace of the sun's image at photographic scale for the dates on which photography is scheduled, see Figure 3. Flight line charts are then drawn for different periods of each day to preclude the appearance of sun spot in critical areas of the photography.

The need for land detail on two sides of each photograph to achieve absolute orientation of stereoscopic models, together with the desirability of reducing the volume of photogrammetric measurement, emphasizes the value of small-scale (high-altitude) photography. Large floats must be anchored at strategic locations prior to photography to aid in the orientation of the stereoscopic models where the body of water is too wide to be spanned. This is tedious and tends to be expensive, but, considering the time and cost of operating a large number of current meter stations by ship, the relative cost of anchoring floats is not always prohibitive.

Stereotriangulation may be employed to determine the geographical location of the floats and thereby position the photographs. As an alternative to triangulation, especially across large harbor and bay areas, the photographs can be positioned by selection of a proper end lap, flight altitude and a carefully laid out flight line prior to photography. A gross error in position will not be introduced if experienced aircraft personnel and quality equipment are used.

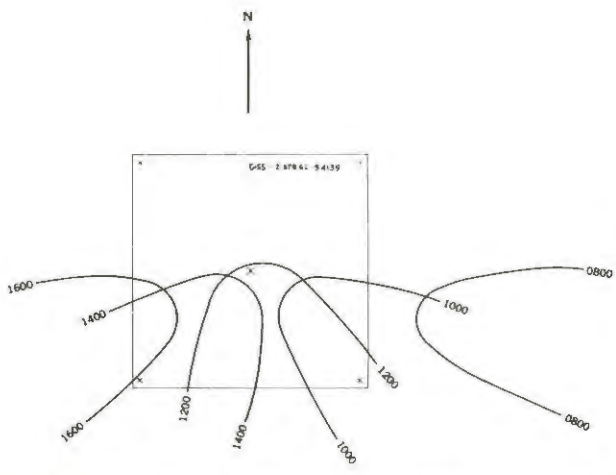

FIG. 3.—Sun spot study for Charleston Harbor, S. C., for April 1962, showing the trace of the reflected image of the sun on the water surface during the day of photography.

It is advisable to take the photography with 80 percent end lap; since only 60 percent end lap is required for measurement on stereoscopic plotters this permits a choice between two stereoscopic models covering any location in the survey area. This is desirable for various reasons, such as one model may be better for current measurements than the other.

Camera and Film Emulsion

High resolution, low distortion aerial cameras are necessary. The Coast and Geodetic Survey, at present, uses the Wild RC-8 (6-inch focal length) Aviogon and the Wild RC-9 (3.5-inch focal length) super-Aviogon cameras. A super-wide-angle camera, such as the RC-9, has the advantage of being able to obtain any desired photographic scale from a much lower altitude than is possible with a 6-inch focal length camera, the ratio of altitudes being about 0.6.

The choice of the proper emulsion to use in a current survey depends on the characteristics of the particular emulsion and the conditions surrounding the survey.

Infrared emulsion used with a suitable filter has the advantage of increased atmospheric haze penetration, reduced sun spot size, and yields a sharp waterline around the painted artificial targets. However, the screening out of most of the visible light spectrum by the filter and the absorption of infrared light rays by the water results in a dark to black tone of the water surface that makes it difficult to distinguish surface details produced by minor discolorations on the water surface. If these discolorations are not of major importance, infrared is to be recommended because the reduction in the size of the sun spot allows for greater flexibility in the selection of flight lines and of the time of day for the photography.

Color emulsion permits the use of a color coding system to denote different types of artificial targets in a current survey. Color also aids in model orientation on stereoscopic plotting equipment because it records some of the harbor bottom details in shallow waters. However, color does not record surface details produced by minor discolorations. Furthermore, color photography has the disadvantage of a larger sun spot size since nearly all of the reflected visible light rays from the water surface are recorded on the emulsion.

In view of these considerations, panchromatic film emulsion with a minus blue filter is often the best choice for the survey as it provides excellent overall results when trying to record both target and water surface details on a single emulsion. As the portion of the light spectrum recorded on the emulsion is larger than for in-

frared and smaller than for color, the sun spot resulting from use of this emulsion and filter is intermediate in size between that of infrared and color emulsions.

Target Design and Seeding

Extensive studies have been made over the years by numerous individuals and organizations to develop both current meters and drift-type current measuring systems to meet their needs and capabilities.[8] Drift-type current measuring target devices can be classified as surface, transsurface, and subsurface floats. The surface class consists of those which remain essentially at the surface, such as wooden targets, dye, foam, confetti, or oil slick. The transsurface group comprises those devices that measure the current in the top layers of the water body, such as current poles or current bottles. The subsurface class includes truly submerged floats dependent, for example, on a neutral buoyancy at some particular depth, and mixed-type devices such as a drogue attached to a surface float. All of these contrivances have their pertinent advantages and the choice of target to use is governed by the current information wanted.

The targets must be designed to meet certain specifications: they must present a minimum hazard to navigation; they must be relatively inexpensive as they may not be recovered; seeding of the targets in the survey area must be free from complexity; and the target movement must be readily recordable on the aerial photographs. The photogrammetric method may be used with any of the current measuring devices mentioned above provided they are built so as to show on the aerial photography.

To provide a thorough coverage of the survey area requires the placement of many targets. Launching the targets from selected shore points and depending on the predicted currents to transport them to the desired locations is not feasible. The seeding of a large water body by this method requires a substantial number of launching stations and a high degree of synchronization. A large number of targets are necessary to insure that some of them will drift into position in spite of eddies, obstacles, and wind. Further, erratic movement of the targets due to complex circulatory patterns makes it difficult to guarantee that the targets will be in position at the appointed time.

Consequently, seeding of targets by skiffs, or perhaps by helicopter, appears appropriate. Reseeding can be undertaken as needed to replace targets drifting out of the area and to fill in any gaps that may develop in the target distribution. A transmitting-receiving radio unit and walkie-talkies are essential to good coordination between the photogrammetric survey units.

Experience has shown that use of a helicopter is not too satisfactory. Direct radio communication with the helicopter from a central base office or skiff is difficult because of the high volume of noise generated by the rotor blades. Modification of a walkie-talkie for use with earphones did not, in our case, sufficiently improve hearing for ready communication. Reseeding by helicopter is not very efficient as the crew cannot see too well where additional targets are needed when flying at the low altitude necessary for proper seeding. This emphasizes the use of skiffs, and similar water craft, for target distribution. However, the use of a small aircraft as an observation platform for coordination of activities by radio communication is invaluable.

Surface Current Targets

The use of skiffs for target seeding requires compactly designed targets to facilitate handling and to increase the number that can be carried by the skiffs. Painted plywood targets provide excellent images for the measurement of surface currents but they are relatively expensive and are difficult to handle in volume due to their bulk and weight. This is particularly so for smaller scale photography where targets measuring some 10 feet across are required.

A comparison of velocity measurements obtained from natural foam targets with values determined from plywood targets shows that foam markings can provide accurate current velocity information. The foam movement represents an actual physical transportation of the water surface and is not merely a product of wave propagation through the water medium.

Natural foam markings cannot be used where they represent standing waves or breakers caused either by subsurface objects or by the clash of water bodies moving in opposing current directions. In most instances, a careful stereoscopic examination of the photography will permit distinguishing between these types of foam and moving currents.

The successful use of natural foam configurations as surface targets led us to investigate the use of an artificially produced foam in lieu of plywood targets. Both chemical and mechanical production of foam were studied. A chemical fire foam, formed by the interaction of two chemical solutions, is not satisfactory at the present due to the lack of a suitable container-distributing apparatus. Equipment is available, however, for the mechanical formation and distribution of fire foam. This technique employs a protein base liquid that increases the surface

[8]Investigation of Current Measurement in Estuarine and Coastal Waters, Publication No. 19, *State Water Pollution Control Board*, Sacramento, Calif.

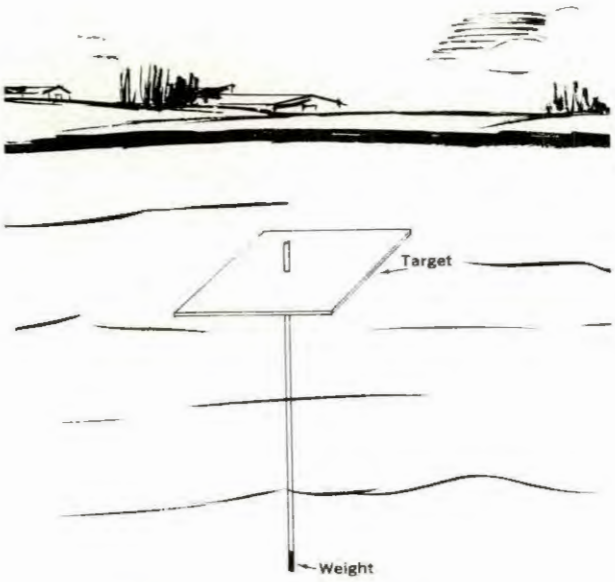

FIG. 4.—Target design to furnish an integrated current value over a specified depth.

tension of water similar to a detergent effect. Six gallons of liquid are mixed in the nozzle chamber of a special spray-pump with 94 gallons of water to produce 1,000 gallons of artificial foam at an optimum temperature of 70° F.

Seeding of the material can be accomplished by skiffs properly equipped to distribute the foam on the water surface in streaks. When sprayed on the water, the foam distributes itself in a thin even layer on the surface thereby presenting no significant bearing surface to the wind. The currents cause the artificial foam to assume distinctive patterns similar to that of natural foam that can then serve as the targets for current measurements. The passage of ships through the material only adds to the pattern formation. Larger targets can be easily formed to comply with the target size requirements of small-scale photography. The use of foam systematically distributed throughout the area also facilitates office recovery of target images.

Artificial foam has other advantages in that there is no danger posed to small boats plying the area and no pollution or littering of the beaches because the material dissipates within a few hours. The limited lifespan of the foam imposes no restrictions on the current survey as reseeding can be performed by the skiffs as necessary. Use of this technique makes detailed photogrammetric surface current surveys covering larger bodies of water feasible.

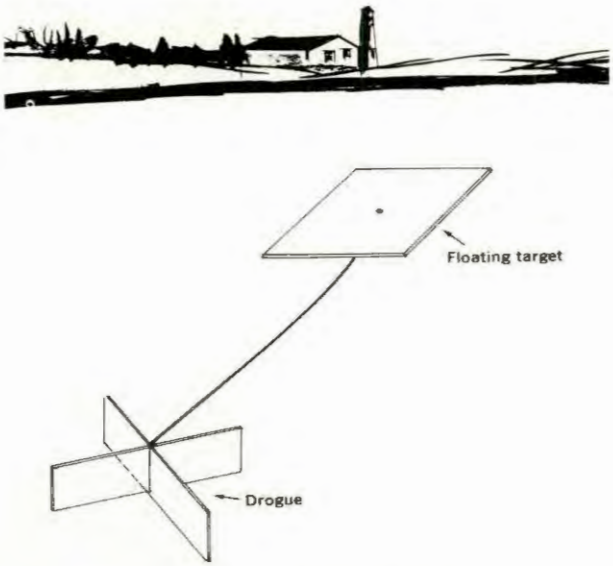

FIG. 5.—Drogue type of target.

Transsurface Current Targets

Current measurements in the top layers of a water body may be made by the use of current poles modified so that their movement can be recorded photographically. Though we have not yet tested it, such a device might consist simply of a pole weighted at one end to float upright with one or two feet protruding above the surface and a floating plywood target having a drilled center hole equal in diameter to that of the weighted pole. At the time of seeding, the pole would be placed in the water and the target fitted over the pole. A pin device might be advisable to fasten the assembly together and prevent disengagement, see figure 4. Fins could be fitted to the pole to emphasize the forces acting on the pole in comparison with those affecting only the surface target.

Under consideration is the testing of a weighted balloon-type target partially filled with water. Entrapped air causes the target, which is cigar-shaped, to float upright in the upper layers of the water. The top of the balloon target then serves as the target image on the photography.

Subsurface Current Targets

When the current survey requires the gathering of current information at one or more specific depths, the use of subsurface floats is necessary. A device that might be used to measure subsurface currents is a drogue suspended by cable from a floating buoy that also serves as a target for photography.

Drogues, which are a type of sea anchor, can be designed in numerous configurations. A simple drogue would consist of two sheets of an inexpensive material fastened together in the shape of a cross, see figure 5. The portions of the system at the surface must be kept relatively

small so that the drag forces are minor when compared with those acting on the drogue.

Open position-type drogues, having a large projected area, present difficulties in launching. The bulkiness of the system also limits the number that can be stored aboard a skiff. For this reason a collapsible-type drogue is favored in which the arms of the drogue assume the 90-degree position only on insertion in the water. Other possible designs include parachute or balloon devices adapted for use as subsurface drogues.

The photogrammetric measurement of current information at the surface, transsurface, and subsurface depths will require the simultaneous use of several different types of current measuring systems. The employment of color emulsion and color coding on the visible portion of the target devices will permit differentiation between the systems on the photographs.

Weather

Weather conditions present problems that are best met by providing for flexibility in the choice of survey equipment. Difficulties caused by atmospheric haze and sun spot size can be minimized by use of the proper emulsion and filter. The problem of clouds at altitudes that preclude the use of a 6-inch focal length camera may be solved by employing a shorter focal length, superwide-angle camera, such as the Wild RC-9, that provides the same scale photography from a lower flight altitude.

Temporary wind-induced water movement complicates the photogrammetric measurement of tidal surface currents. It is not practicable to delay the photography until no wind-induced movement is present and, while such movement can be recognized to a degree by stereoscopic examination, it cannot be readily separated from the tidal movement. Consequently, current meter control stations in the area of the survey provide the only means of correcting the photogrammetric measurements so as to remove the effects of temporary wind-induced movement. The current meter stations provide relatively long-period observations that tend to average out temporary water movements caused by wind action. In general practice, the ratio between the mean-value current meter surface velocity at a particular instant of the tidal cycle and a nearby photogrammetrically measured surface velocity is applied to all the photogrammetric measurements within the area controlled by that meter to correct them for wind-induced movement.

For purposes of discussion, wind-induced currents can be broken into three categories, though these are not separable in nature. Consider first the force of the wind blowing across the open seas for extended periods. This causes a stress that moves the surface layer of water.[9] [10] Surface currents are thereby developed and their effect is transmitted to succeeding layers below the surface. Due to internal friction within the water, the effect decreases with depth. The wind speed, the length of time it has blown, its constancy, the fetch, and other factors determine the speed of the current. In general, for deep water the speed of a wind-induced water surface current will average about two to three percent of the wind speed where the wind has been blowing steadily for at least 12 hours. The deflecting force of the earth's rotation (Coriolis force) causes a wind-induced current to flow in a different direction from the wind.[11] In the Northern Hemisphere the deflecting force is 90 degrees to the right of the direction of water movement while in the Southern Hemisphere the deflecting force is 90 degrees to the left of the direction of motion. The Coriolis force increases with latitude and speed. Studies reveal that the angle between wind direction and the wind-induced surface current varies from about 15 degrees along shallow coastal areas to as much as 60 degrees in the deep oceans. The angle increases with depth. Thus the current flow at several hundred fathoms may be opposite in direction to that of the surface current.[12] Such currents set up in the open sea will increase or decrease the movement of water in and out of a harbor or bay. This effect cannot be identified during the photogrammetric measurements and is compensated for only by means of the current meter stations mentioned above.

Strong steady winds within a harbor area can cause a movement of water and this effect may vary from one place to another within the area being surveyed. This temporary movement of water can be recognized by stereoscopic study of the photographs. The water surface tends to appear as a plane with a marked elevation change beginning directly at the shoreline if the movement is due only to wind. However, if tidal current movement is present in addition to that caused by the wind, the water surface will depart from a plane in the vicinity of the current action that is not wind-induced. Stereoscopic examination thus is helpful in determining the area affected by wind action and in applying corrections from the current meter control stations.

The problem is more complex when wind gusts prevail in addition to strong steady winds. The wind gusts produce a wave propagation rather than a horizontal movement of the surface water. This wave propagation has much the same ap-

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[9] See footnote 8.

[10] The Causes and Predictions of Surface Currents in Sea and Lake by T. Laevastu. *Department of Meteorology and Oceanography, University of Hawaii*, July 1962.

[11] See footnote 6.

[12] See footnote 7.

pearance under the stereoscope as the water movement discussed in the preceding paragraph and the two cannot be separated.

To date, the stereoscopic effect has not been found on photography taken at wind speeds of less than 10 to 12 knots. Furthermore, at this wind speed, tests with a number of targets constructed with 1-foot skegs, together with simple surface targets, have not revealed any noticeable discrepancy in current speed between layers of water within 1 foot of the surface.

MEASUREMENTS AND REDUCTION OF DATA

The photogrammetric measurement and reduction of data requires a highly skilled instrument operator since careful attention must be paid to the geometry of the problem and to the selection of office-identified natural targets in addition to the artificial targets that were especially seeded. Experience indicates that approximately one stereoscopic model can be measured and data reduced per day. Unusual models may require a longer time for reduction due to difficulty in achieving absolute orientation.

Photogrammetric Measurement

The measuring technique requires the absolute orientation of the stereoscopic models on stereoplotting equipment and the determination of the x- and y-parallax at each target. While all of the instruments provide elevation readings from which the x-parallax can be readily obtained, some of the plotters do not furnish a direct reading of the y-parallax due to lack of a specific "By" motion. In consequence, mensuration on these latter instruments, such as the Kelsh plotter and the Wild B-8 Aviograph, is decidedly different from the current measuring technique on stereoscopic plotters which do possess a specific "By" motion, such as the Wild Autograph and the Zeiss Stereoplanigraph.

After absolute orientation is achieved using fixed detail present in the stereoscopic model, the availability of a "By" motion permits the direct removal of y-parallax at each target separately. The change in the "By" motion, as read on the counter dial to 0.01 mm., represents the target movement perpendicular to the flight line at the scale of the model. The x-parallax, computed from the elevation reading for the model image of the target, represents the target movement parallel to the line of flight at model scale. The two components are combined to yield a resultant vector that defines the direction and speed of the target motion in the interval between the photographic exposures.

When no "By" motion is available, it is necessary to mark the position of the target on a map drawing as indicated by the earlier photograph, and then to mark the position of the same target as given by the later photograph. The target movement between photographic exposures is ohtained by scaling between the two marked positions on the drawing.

The precision attained by a proficient instrument operator in determining the current velocity depends largely on the quality of the target image and on the optical and mechanical properties of the stereoscopic plotting equipment. Normally, it would seem desirable to fuse the two target images directly into a single image in the stereoscopic model by removing the y-parallax with a "By" motion. However, the reduction of the same models on the Wild B-8 plotter and Zeiss Stereoplanigraph in the Bureau revealed excellent agreement between the two instruments despite the variation in the measuring technique. The maximum discrepancy noted was 0.2 knot.

In the presence of tilts and relief ranges likely to be encountered in production mapping, it is necessary to reduce photography on plotting equipment for which the principal distance can be set equal to the focal length of the taking camera in order to avoid the appearance of unacceptably large residual errors.[13] However, if the range of tilts and relief is small, the setting of the stereoplotter principal distance equal to the focal length of the aerial camera is not as critical. In this regard, it was found possible to reduce a number of RC-9 photography models on the Zeiss Stereoplanigraph despite the principal distance of the plotter being fixed at 6 inches. The achievement of a satisfactory parallax solution during absolute orientation and the attainment of high correlation in current velocity results, regardless of the plotter used to measure the photographs, is dependent to a large extent on the ability of the aircraft crew to minimize the amount of tilt present in the photography.

The procedure for measuring target movement on stereoscopic plotting equipment possessing a "By" motion is as follows:

1. Tape overlay on manuscript or base map.
2. Absolutely orient the stereoscopic model on the plotter.
3. Determine the base/height ratio of the instrument model.
4. Mark and label the position of the two photo centers on the drawing.
5. Mark the average position for a selected target as given by its two images. Note the type of target and its direction of motion according to its position on the earlier and on the later photographs.
6. Remove y-parallax at the target images by use of the "By" motion for the projector containing the earlier photograph.

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[13]The Conditions Necessary For Plotting Stereo Models In Which The Set Principal Distance Is Not The Same As That Of The Taking Camera by J. A. Eden, *Photogrammetric Engineering*, March 1962.

7. Note the change in the "By" motion as given by the dial counter (including the sign). Any targets examined later that exhibit a similar "By" motion change, relative to the "By" value obtained during absolute orientation, are moving in the same direction.

8. Draw an arrow from the target position normal to the line of flight and in the direction of the target movement. Note the change in the "By" motion alongside the arrow. This is the target motion in millimeters at model scale normal to the line of flight.

9. Read the elevation of the target model image (elevation at shoreline being zero). A minus elevation indicates a target movement parallel to the line of flight toward the later photo center. A positive elevation reveals a motion parallel to the line of flight toward the earlier photo center.

10. Draw an arrow from the target position parallel to the line of flight in the direction indicated by the sign of the elevation change. Note the elevation change alongside the arrow.

11. Proceed as above to all targets being used in the survey.

Errors inherent in photogrammetric mensuration include such items as stereoplotter model deformation, absolute orientation of the model, image displacement resulting primarily from irregular film shrinkage, operator pointing on targets, and the determination of the time interval between photographic exposures. A preliminary investigation of these factors indicates a cumulative error of about 0.1 knot in the speed determination with the error varying inversely as the time interval between exposures.

Data Reduction

After the photogrammetric measurements are completed, the reduction of data is accomplished as follows:

12. The target elevation is multiplied by the base/height ratio to determine the target movement parallel to the line of flight in millimeters at model scale.

13. The resultant target movement in millimeters at model scale and the direction of motion is computed from the two motion components (y component from step 8 and x component from step 12).

14. The target speed in knots is determined from the total horizontal movement and the time interval between exposure of the first and second photographs of the model.

15. The resultant speed and direction of movement are plotted on the drawing at each target. Arrows may be used to represent direction and the speed noted alongside the arrow.

Upon completion of the above computations and the plotting of current velocities, it is possible to interpolate surface current velocities between the target positions and thus fill in any gaps in the survey that may develop because of poor target distribution. The presence of surface discolorations gives the water surface a texture so that when a model is examined stereoscopically the water exhibits a relief effect depending on the velocity of the current. This requires that the model be rotated under a stereoscope so that the maximum relief effect possible exists for a particular area. A simple stereoscope and contact paper prints are used in preference to a stereoplotter because of the greater angular field of view and the ease with which the photographs can be rotated to simulate different lines of flight.

As a result of this orientation of the model, the water is flowing at its maximum speed in a direction parallel to the line represented by the axis of the stereoscope. An approximate interpolation of surface current velocities is then made by comparison with the relief shown at the measured targets which display a current flow in the same direction. If the target motion is not parallel to the axis of the stereoscope, the component of the current in the desired direction can be computed by simply multiplying the target speed by the cosine of the angle between the two directions. The interpolation technique may be rather crude and errors may approach 0.5 knot, but they do serve to fill in gaps in a surface current survey that might otherwise remain.

The next step is the production of a series of current charts showing the circulatory pattern throughout the survey area at various times of the current cycle on a selected day. Conventional current meter stations at strategic locations provide tidal current cycle curves that permit translation of photogrammetric data secured from photography taken on several different days to a single selected day.

The times of critical points such as maximum ebb, etc., for which current charts are desired, are taken from the current cycle curve for a specified reference current meter station and noted on the current curves of the other meter stations on the selected day. A ratio is obtained at these times between the current speed given by the curve for a meter station and the speed measured photogrammetrically from a target near the station at the same phase of the current on the day of photography. The ratio is applied to all the photogrammetrically measured velocities in the area of the meter station to translate them from the day of photography to the selected day. Similar relationships can be obtained at other meter stations to translate current velocities observed in their immediate area to the

selected day. The current charts will show either the actual or the predicted current flow pattern throughout the area on the selected day depending on whether actual or predicted current cycle curves are used for the translation.

From the series of current charts produced as described above, current velocity relationships can be obtained for numerous locations in the area that express the velocity at each location as a function of the velocity at the selected reference meter station. This relationship remains approximately the same at the same time of the current cycle on any other day. The current cycle curve generated at the reference meter station provides time differences and ratios for use with the Tidal Current Tables for the prediction of the expected average current velocity at the reference station on any desired future day. The prediction of expected average current velocities at any place in the area at any future time can be accomplished by applying the current velocity relationships to the predicted current velocity at the reference station.

The predicted current cycle curve derived from meter operation in the vicinity at another time is used for control of the photogrammetric survey when meter operation does not coincide with the photography. However, the operation of meters at the time of photography is highly desirable as a means of cross checking the accuracy of the photogrammetric measurements as well as the current meter readings. The results stated in this report are based on photogrammetric measurement of *surface* currents, but better agreement probably will occur when the photogrammetric current measurements are obtained at the same depth as the meter installation by the use of targets with subsurface extensions.

Current information charts can be displayed in several ways. For example, a contour type of chart can be made wherein continuous lines are drawn between current speeds of the same magnitude. Another series of continuous lines is then used to indicate the direction of current movement. The prevalent practice, however, is to employ arrows to represent the direction of current flow. The speed of movement can be either printed alongside the arrow or indicated by means of a coding symbolization. The preferable type of display depends largely on the use to be made of the current information depicted thereon.

PHOTOGRAMMETRIC CURRENT SURVEYS COMPLETED AND PLANNED

Charleston

The field work for the photogrammetric *surface* current survey of Charleston Harbor, S. C., was completed in April 1962. Panchromatic photography at 1:20,000 scale and an end lap of

FIG. 6.—Target seeding by skiff.

60 percent was secured at hourly intervals using both a 6-inch focal length Wild RC-8 camera and a 3.5-inch focal length Wild RC-9 camera. Painted plywood targets were seeded in the harbor by skiff and helicopter at approximately half-mile intervals. Reseeding was performed by the helicopter during the day to maintain the target density. This did not prove very satisfactory as the low altitude of the helicopter necessary for proper seeding hampered the search for previously seeded targets. A transmitting-receiving radio unit and walkie-talkies were employed to coordinate operations. Fourteen employees were assigned to the survey which required the seeding of approximately 500 targets weighing 3,000 pounds and occupying some 80 cubic feet, see figures 6 and 7.

In addition to simple 1' X 8' painted plywood targets, several 4' X 4' targets were constructed with one-foot skegs. Their purpose was to investigate wind effect on the surface layer of water. They were kept in the vicinity of a current meter installation by the skiffs. A flag was placed on these special targets to aid the skiffs in finding them when the currents carried the targets too far from the meter site.

Over 1,300 photographs were taken during a 2-day period covering the complete tidal cycle. Some 21 models from different crucial periods of the current cycle were chosen for immediate reduction, see tables 1 and 2.

The target images were indicated on contact paper prints by examination of the film under magnification. The glass diapositives were printed emulsion to emulsion with care being taken to minimize the presence of dust particles during the printing process. The stereoscopic

Table 1.—Predicted Tidal Current Cycle for Reference Station Off Ft. Sumter, Charleston Harbor, S. C.

(Speed in knots)

Date	Time	Phase	Speed
1962			
April 2.....	0018	slack	....
	0258	flood	2.6
	0630	slack	....
	0934	ebb	3.0
	1254	slack	....
	1529	flood	2.5
	1850	slack	....
	2156	ebb	3.1
April 8.....	0205	ebb	3.1
	0532	slack	....
	0800	flood	2.3
	1122	slack	....
	1423	ebb	2.7
	1742	slack	....
	2021	flood	2.5
	2353	slack	....

FIG. 7.—Target seeding by helicopter.

Table 2.—Photogrammetric Data for Current Survey of Charleston Harbor, April 2 and 8, 1962

Date, camera, and focal length in millimeters	Estimated time of photography	Stereoscopic model number	Interval between exposures (seconds)	C-8 Stereoplanigraph base/height ratio
April 2, 1962*.....	0824	62S4135-6	21	0.55
Wild RC-8	0825	36-7	22	0.56
(152.29)	0825	37-8	20	0.53
	0825	38-9	21	0.53
	0825	39-40	20	0.51
	0826	40-1	19	0.53
	1135	4369-70	28	0.54
	1232	4448-9	17	0.59
	1237	4456-7	27	0.54
	1237	57-8	29	0.57
	1242	4467-8	17	0.58
	1247	4474-5	30	0.54
	1247	75-6	27	0.56
	1500	4614-5	15	0.53
	1500	15-6	17	0.57
	1512	4634-5	21	0.59
	1512	35-6	21	0.56
	1516	4642-3	21	0.55
	1517	43-4	22	0.56
April 8, 1962.....	1228	62M235-6	18	0.64
Wild RC-9	1332	344-5	21	0.57
(88.2)				

*End lap for April 2, 1962, stereoscopic models ranged from 61 to 66 percent.

FIG. 8.—Roberts radio current buoy and surface target.

models were set on a Zeiss C-8 Stereoplanigraph and on a Wild B-8 Aviograph for measurement of the movement of each target. Following the computation of current velocities at the targets, the interpolation of additional current speeds was undertaken between the target positions to fill in any gaps in the survey coverage.

The photogrammetrically measured surface current velocities were then compared with the current velocities obtained by current meters. Some 50 meter stations were set between January and June of 1962, by the ship assigned to the survey, see figures 8 and 9. In general, each meter station consisted of three Roberts radio current meters suspended at different depths from a buoy. These depths averaged 1/6, 1/2, and 5/6 of the charted water depth. An approximation of the surface current speed was made by a linear extrapolation of the current velocity readings given by the three meters at the stations in operation at the time of the photography. The use of an extrapolation technique is controversial in harbors due to the interplay of a fresh water discharge from rivers abetting an outward flowing nontidal surface current with ocean water

flowing in and out of the harbor under the influence of astronomical and other forces.

Despite this, in all instances, save two, wherever the photogrammetric value and the extrapolated current velocity were in close proximity to each other, the velocities agreed within a maximum of 0.3 knot, see table 3. The first instance of major disagreement was due to water surface displacement caused by wind action in the vicinity of buoy No. 22 at 1245 hours on April 2, as revealed by a stereoscopic examination of the photographs. The other exception was due to an unsatisfactory linear extrapolation of the surface current speed resulting from a marked lack of alignment when the meter values were plotted for buoy No. 25 at 1332 hours on April 8. The photogrammetric current velocities noted in the table as approximate are either too far from the buoy site or are in shallow water and hence can be expected to differ from the surface current speeds extrapolated from the meter readings.

Table 3 reveals that, at any selected time in the tidal current cycle, the relationship between the photogrammetric surface current speeds and those derived by meter extrapolation remains approximately the same for each meter site. This indicates that the surface layer of water moves as a distinct and rather separate unit relative to the flow of the subsurface layers due primarily to the outward flowing nontidal surface current. It also indicates that the photogrammetric surface current values can be reduced to the true surface velocity values for various locations in the survey area by the methods described in preceding paragraphs.

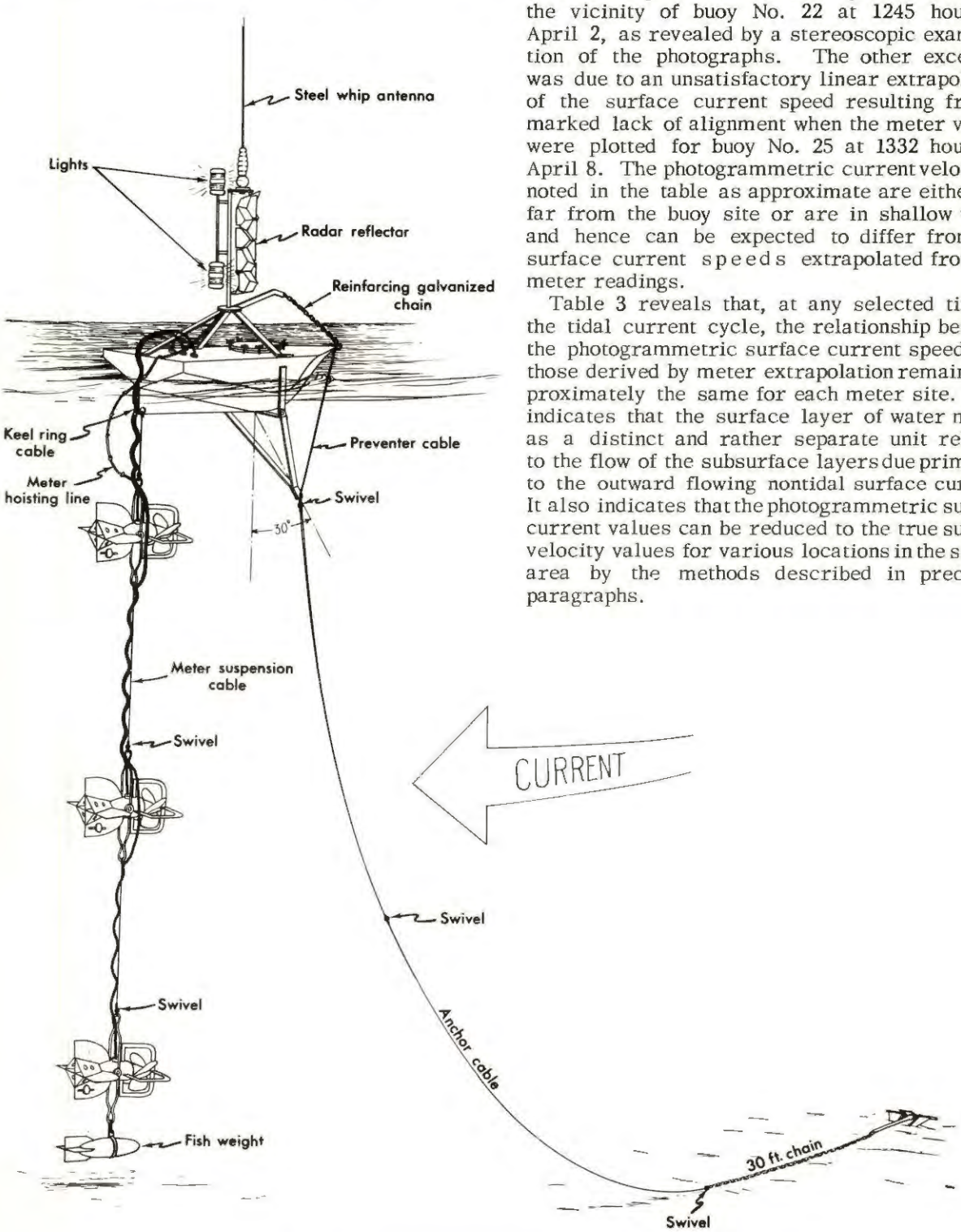

FIG. 9.—Radio buoy showing multisuspension of Roberts radio current meters.

Table 3.—Comparison of Surface Current Speeds in Charleston Harbor as Obtained From Photogrammetric Measurements and as Extrapolated From Current-Meter Readings on the Day of Photography

(Speed in knots)

Date and time	Buoy number	Surface speed extrapolated from meter readings	Surface speed obtained from photogrammetric measurements
April 2, 1962			
0825	22	[1] 3.5 e	[2] 3.5 e (approx.)
	28	3.4 e	3.3 e
	35	3.0 e	2.7 e
1135	22	2.1 e	1.8 e (approx.)
	28	1.9 e	1.7 e
	35	1.8 e	1.7 e
1245	22	0.7 e	[3] 1.2 e
	28	0.5 e	0.2 e
	35	0.4 e	0.2 e (approx.)
1516	22	1.3 f	1.0 f
	28	1.7 f	1.5 f
	35	[4] 1.1 f	1.0 f (approx.)
April 8, 1962			
1228	23	[4] 2.3 e	2.0 e
	24	2.0 e	1.7 e
	25	1.9 e	1.6 e
1332	23	2.9 e	.....
	24	2.7 e	2.5 e
	25	[4] 2.8 e	2.0 e

[1] e = ebb tide; f = flood tide.

[2] Approximate notations indicate target positions that are too far removed from buoy locations, or positions that are in water areas that are too shallow for reliable comparison.

[3] Wind effect present.

[4] Extrapolated values are uncertain.

Table 4 is a comparison of photogrammetric surface current speeds with the predicted surface current speeds for April 2, 1962, as derived by linear extrapolation of readings obtained from meters operating on days other than April 2nd. The prediction of the average current velocity to be expected at a current meter station at any time in the future is based on the mean of a large number of observations made by meters operating over a prolonged period of time. The actual current velocity at that location may depart somewhat from the predicted mean value for that time of the current cycle. A similar departure can be expected for surface current velocities determined photogrammetrically since they represent the actual current flow at the instant of photography. The difference between the surface current flow measured photogrammetrically and the predicted mean value should be fairly constant for various locations in the survey area for the same time of the current cycle provided the size of the area is not too large. The degree of difference is affected by an outward flowing nontidal surface current. Hence table 4, like table 3, shows the relationship between the photogrammetric surface current speeds and the extrapolated surface currents derived from meter predictions to be approximately the same for each buoy site at the same time of the current cycle. Furthermore, these relationships are nearly identical regardless of whether actual or predicted meter readings are used for the extrapolation, see table 5. This illustrates again the feasibility of using photogrammetric surface current measurements together with current meters to determine the true surface current velocity at various locations in an area.

Two large discrepancies are to be found in table 4. At 0825 hours the extrapolated surface

Table 4.—Comparison of Surface Current Speeds in Charleston Harbor as Obtained From Photogrammetric Measurements for April 2, 1962, and as Predicted From Extrapolated Current-Meter Readings Made on Days Other Than April 2, 1962

(Speed in knots)

Time	Buoy number	Speed predicted from meter observations on days other than April 2, 1962	Speed obtained from photogrammetric measurements for April 2, 1962
0825	3	[1] 2.8 e	3.1 e
	4	1.9 e	2.2 e
	5	[2] 3.1 e	3.2 e
	6	[3] 2.1 e	3.6 e
	10	[2] 3.4 e	3.2 e
	13	2.5 e	[4] 3.0 e (approx.)
	14	2.0 e	2.2 e (approx.)
	23	3.0 e	3.2 e (approx.)
	24	3.1 e	3.3 e
	25	3.1 e	3.5 e
	26	3.3 e	3.5 e
	27	2.6 e	2.5 e (approx.)
	29	2.2 e	2.2 e
1135	25	2.4 e	1.5 e
	26	2.4 e	1.7 e
	27	2.1 e	1.6 e
	34	2.5 e	1.7 e (approx.)
1245	24	1.1 e	0.4 e
	25	0.9 e	0.4 e
	26	1.2 e	0.6 e
	27	1.2 e	0.6 e
	29	0.7 e	0.3 e (approx.)
	30	0.4 f	0.2 f
1500-12	3	2.1 f	1.9 f
	4	1.9 f	1.0 f (approx.)
	5	1.1 f	1.1 f
	6	[2] 1.6 f	1.2 f
	10	[2] 2.0 f	1.5 f
	14	0.1 f	0.1
1516	23	0.8 f	0.8 f
	24	0.9 f	0.7 f
	25	1.7 f	1.4 f
	26	1.4 f	1.2 f
	34	[2] 1.3 f	1.0 f

[1] e = ebb tide; f = flood tide.
[2] Extrapolated values are uncertain.
[3] Meter reading questionable.
[4] Approximate notations indicate target positions that are too far removed from buoy location or positions that are in areas where current velocities change too rapidly for reliable comparison.

current from predicted meter readings at buoy No. 6 is 2.1 knots versus 3.6 knots measured photogrammetrically. The meter readings are suspect here as they do not agree with the current velocities recorded by other nearby meters in the same channel. In addition, the large number of photogrammetric current measurements in the immediate area confirms the photogrammetric velocity. The other discrepancy occurs at 1500-1512 hours at buoy No. 4 where the

Table 5.—Ratio of Photogrammetric Current Determinations for Charleston Harbor on April 2, 1962, to: (1) Extrapolated Values for Meter Observations on Day of Photography, and (2) Predicted Currents Based on Current Meter Observations for Days Other Than Day of Photography

Time of observation (April 2)	(1) Meter observations (April 2)	(2) Predicted currents for April 2 based on meter observations on days other than April 2
0825	0.96	1.06
1135	0.90	0.70
1245	0.45	0.46
1500-1516	0.85	0.86

photogrammetric velocity is 1.0 knot versus an extrapolated meter value of 1.9 knots. Buoy No. 4 is located at the entrance to Charleston Harbor and is close to the shore of Sullivans Island. The rapid change in current speeds that takes place as the shore is approached may account for the disagreement. In addition, the photogrammetric values in the immediate area are interpolated current velocities and were not measured directly.

Meter readings of current velocity are not as accurate at small velocities as at the larger speeds. Consequently, the surface current velocities determined by extrapolation of meter data observed near periods of slack water are subject to greater error. Table 5 reveals a large departure by the photogrammetrically measured surface currents from the extrapolated meter data at 1245 hours on April 2—slack water being predicted at 1254 hours—see table

Chart No. 1.—Current chart for Charleston Harbor, S. C., at one hour before maximum ebb current on April 2, 1962.

1. This may be due to the decreased accuracy of the meters and also to the fact that the current velocity ratios between meters and photogrammetric surface measurements are subject to greater error when the current velocities are small.

The ratio of the instantaneous surface currents measured photogrammetrically to the current speeds derived by extrapolation of meter data is nearly identical regardless of whether or not the meters were in operation on the day of photography. This is remarkable when it is realized that the meters were in their positions at different times extending from January through June of 1962.

The presence of the outward flowing nontidal surface current is suggested in table 5 by the larger ratio of photogrammetric current measurements to extrapolated meter readings at 0825 hours (approximately one hour before maximum ebb current) as compared to the ratio at 1500-1516 hours (approximately 20 minutes before maximum flood current).

The existence of a systematic relationship between the photogrammetric surface current speeds and the surface current speeds obtained by extrapolation from current meter data might imply that knowledge of the surface current speed alone would permit one to accurately deduce current flow information below the water surface. While this may be somewhat true as regards the speed of the subsurface current, indications are that a deduction as to the exact direction of the subsurface flow would be extremely hazardous in areas of limited size and depth. Consequently, specifically designed subsurface current measuring target systems are necessary for highly accurate photogrammetric measurement of subsurface currents.

Separate charts were used to display the surface

Chart No. 2.—Current chart for Charleston Harbor, S. C., just prior to maximum flood current on April 2, 1962.

circulatory pattern in Charleston Harbor at various hours of photography. Two of the charts for April 2 have been reproduced for insertion in this report. The charts show the position of each target and points of interpolation, the type of target, the speed and direction of the current, the time of photography, the stage of the tide, the photographs used and the location of the photograph centers. Employment of this type of display permits the showing of a large number of individual current observations. In some models the number of ohservations approaches a density of 125 surface current measurements per square mile.

Chart No. 1 shows the surface circulatory pattern at 0825 hours on April 2, 1962, at approximately 1-hour before maximum ebh current scheduled for 0934 hours at the Charleston Harbor reference station off Ft. Sumter. It is an example of the very complete type of current survey that can be accomplished by photogrammetric methods. The number of observations obtained from the artificial targets is but a fraction of those computed from the natural targets and by interpolation.

Chart No. 2 depicts the surface current pattern at 1500 to 1516 hours, or approximately 20 minutes before maximum flood current at the Charleston Harbor reference station. The photogrammetric analysis revealed the existence of unexpected complex current flow patterns at several periods in the tidal current cycle. These patterns are especially noticeable on this chart where large eddy formations can be seen in the vicinity of Ft. Sumter and around the bend of Hog Island. It is apparent that a very large number of meter installations and observations would be required to duplicate the information acquired photogrammetrically.

Though the photogrammetric surface current survey of Charleston Harbor was initiated originally as an experiment, the results have been so encouraging that additional models are being measured and reduced to provide more detailed information for a series of hourly tidal current charts for the harbor.

Ocracoke Inlet

Since the Charleston survey, a photogrammetric surface current survey, in conjunction with current meters, has been successfully completed at Ocracoke Inlet on the Outer Banks of North Carolina. This was a cooperative survey made by the Coast and Geodetic Survey for the Corps of Engineers in October 1962. Panchromatic photography at 1:30,000 scale, with an end lap of 80 percent, was secured with a Wild RC-8 camera at half-hour intervals throughout the tidal current cycle. Painted plywood targets, 4' by 4' and 4' by 8' in size, were seeded in the inlet by skiffs. The target density was maintained by reseeding the area periodically by skiffs. A better target distribution was obtained by using a helicopter only as an observation post than was the case at Charleston Harbor where the helicopter also assisted in the seeding of the targets. The survey of the 9-square-mile area comprising the inlet required the anchoring of several 4' by 8' plywood platforms on the Pamlico Sound side of the inlet, and the anchoring of launches on the ocean side to serve as fixed stations for absolute orientation of the models on the stereoscopic plotting instruments.

Twenty-three models were measured and the photogrammetric data translated to a selected datum day using the tidal current cycle curves generated at four conventional meter stations in the area. A series of current charts were produced showing the actual surface current flow in the inlet at critical times of the tidal current cycle. An example of one of these is Chart 3 which shows the surface current pattern on Sunday, October 14, 1962, at the time corresponding to maximum flood at meter station 1. The relationship between the observed current at any place on the chart and the current velocity at meter 1 remains approximately the same at the same time of the current cycle on any other day. The Tidal Current Tables permit the prediction of the current velocity at meter station 1 at a future time. The surface current velocity relationships existing between the various locations and meter 1, as revealed by the chart, can then be applied to predict the average current velocities to be expected throughout the area at the same time of the current cycle on any other day.

Tampa Bay

In April 1963, a photogrammetric surface current survey of Tampa Bay, Fla., was begun with the taking of 1:80,000 scale photography, using a Wild RC-9 camera, to cover 240 square miles of water. A mechanically produced fire foam was used to provide the necessary targets for the measurement of surface current velocities. The entire seeding and reseeding of the foam targets was carried out by skiffs and launches, see figure 10. A light single-engine Cessna aircraft was used as an observation post to inspect the quality and placement of the foam targets. Use of this aircraft avoided the radio communication problem encountered at Charleston Harbor and Ocracoke Inlet where a helicopter was employed.

Office measurement and reduction of data will be done in the near future. The size of the Tampa Bay survey makes it the most ambitious photogrammetric current measurement to date. The successful use of new techniques on this

project is a long stride forward toward the production of detailed charts covering the larger bays and harbors of the nation.

To permit the application of photogrammetric methods to the measurement of currents below the surface, a study was made of various subsurface current measuring target designs and of materials suitable for use in their construction. The results were encouraging and this study will be continued.

CONCLUSIONS

On the basis of results obtained to date, the application of photogrammetry to the field of tidal current surveys is warranted in many instances, especially where detailed circulatory information is desired. Consideration of the manpower and equipment requirements, the time and cost of the operations, and the final product obtained, serve to point out the advantages of the photogrammetric approach for detailed surveys.

The conclusions to be drawn from the results are:

1. Photogrammetric methods can provide accurate surface current measurements of large current velocities as well as smaller velocities down to 0.1 or 0.2 knot.

2. Photogrammetry can provide synoptic measurements of a large area and thereby obtain more detailed circulatory information than is feasible otherwise.

3. For the preparation of a current chart, photogrammetric measurements must be made in conjunction with current meter readings for proper reduction of the photogrammetric data. The data obtained from long periods of meter observation permit the removal of eccentricity introduced into the instantaneous photogrammetric observations by meteorological disturbances and the prediction of current velocities at future times.

The Coast and Geodetic Survey plans to apply photogrammetry to current surveys as a production operation in the future whenever more detailed information is needed than can be readily obtained by conventional methods.

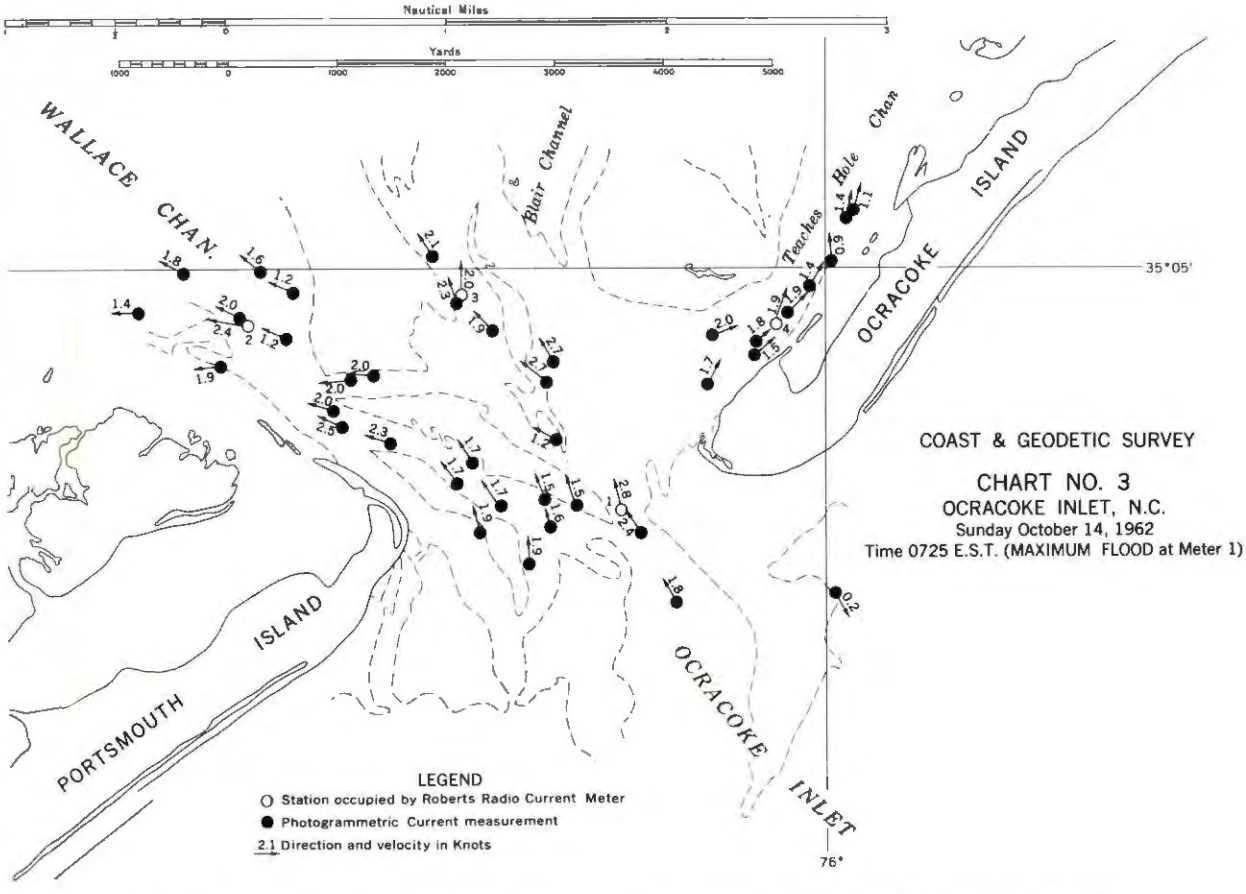

Chart No. 3.—Current chart for Ocracoke Inlet, N. C., at maximum flood current on October 14, 1962.

FIG. 10.—Sample distribution of artificial foam targets at Tampa Bay, Florida.

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