Remote Synoptic Surface Current Measurements by Gravity Waves; A Method and its Test in a Small Body of Water

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(Manuscript received 16 June 1981, in final form 13 November 1981)

ABSTRACT

Synoptic surface current data in a lagoon have been obtained utilizing a new approach that evolved from the kinematics of wave-current interaction. Surface current at a position was determined from wavelength and direction of two monochromatic wavetrains with known frequency; these wave data were required only at the position of current determination. The data, collected by aerial photography, were processed optically by two-dimensional Fourier transforms. Possible extension to surface flow measurements in the open ocean is discussed.

1. Introduction

This report presents a new approach to synoptic surface flow measurements based on remote imaging of surface waves with known frequency.

The need for surface-current measurements and the limitations of available techniques is well known; for a brief discussion see, for example, Barrick *et al.* (1977). The only new synoptic surface-current measuring approaches that have appeared in recent years are based on Doppler scattering of microwaves or acoustic waves. The radar scattering method (Stewart and Joy, 1974; Barrick *et al.*, 1977) uses the Doppler shift in single-frequency radar waves resonantly scattered by ocean waves (with half the wavelength of the radar waves) to determine the synoptic surface-velocity field over a large area. The current vectors obtained by Barrick *et al.* (1977) were averages of areas a few kilometers on the side (radar system constraint), and ~20 min in time. The acoustic technique (Pinkel, 1981) is similar in concept to acoustic radar for ranging. The Doppler shift of the backscattered acoustic signals in water determines flow velocity in the beam direction. This nonresonant scatter is produced by living and nonliving acoustic scatterers in the water. The radius of the area covered by such an instrument is ~1 km, one limitation being the weak acoustic backscatter. The method has been successfully applied to measurements of the internal wave field in the upper ocean.

The approach presented here utilizes the unique property of surface water waves, lacking in most other wave systems, that they can be easily observed over a relatively large spatial region containing many waves. The waves are assumed to be linear, and the flow to be measured is assumed uniform with depth; the nonuniform case is briefly discussed.

2. Current determination

The wavelength and direction of monochromatic surface wavetrains depends in part on the velocity field of the water in which they propagate; hence, the distribution of wavelengths and direction in a region contains information about the surface flow there. Also, as waves propagate through a steady (or slowly varying) flow field, their angular frequency with respect to a stationary observer, σ_0, remains constant; this is a consequence of the conservation of wave crests and can be obtained directly from the ray equations. [See, for example, Kenyon (1971) who discusses the application of ray theory to surface waves.]

From linear wave theory

$$\left[\left(\frac{C}{C_0} = \left(\frac{L}{L_0}\right)^{1/2}\right]\right.,$$

the constancy of σ_0, and kinematic considerations (Johnson, 1947)

$$\left(\frac{\sigma_0}{2\pi} = \frac{C_0}{L_0} = \frac{C}{L} + \frac{U \sin\alpha}{L}\right),$$

we obtain

$$U \sin\alpha = C_0[L/L_0 - (L/L_0)^{1/2}].$$

This is valid for deep-water waves in a steady homogeneous flow. U is the current speed, and α is the angle between the current direction and the wave

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0022-3670/82/020200-08$06.00

crest at the position of current determination. L_0 and C_0 are the wavelength and phase speed of the wave-train in stationary water with respect to a stationary observer. L is the wavelength in the flow region. This equation determines the value of a current velocity component $U \sin\alpha$ in the direction normal to the wavecrest at a particular position, from measurements of wavelength in that position; also required is knowledge of L_0 (which is equivalent to knowledge of C_0 or σ_0). The flow velocity at a position on the water surface can thus be determined from the wavelength and direction data of two monochromatic water-wavetrains in that area. The interesting result here is that information about the propagation "history" of the waves is not required. Only local wave data (and C_0) is necessary for current determination. A single aerial image (be it photographic or radar) of monochromatic surface wave trains in a body of water contains synoptic data on the surface flow velocity, at every position that is "illuminated" by these water waves.

3. Experimental verification

In the experiment, wavelength and direction data were obtained from aerial photos of monochromatic wavetrains generated in the Agua Hedionda lagoon, Carlsbad, California. The test was conducted in the western section of the lagoon (see Fig. 1) during ebb tide; this section is connected to an eastern section via a narrow passage, through which water flows westward during ebb tide. At the southern end of the lagoon is an electric power plant that pumps water out of the lagoon for cooling purposes. Tidal flushing of the lagoon with Pacific Ocean water occurs from the northern entrance. The wind was blowing fairly steadily during the experiment from west to east. (Wind velocity data is not available due to instrument failure.) The resulting determinations of current velocity were compared to values obtained simultaneously from three Savonious-type current meters deployed in the region, at a distance of 0.6 m below the surface. At that depth, the effect of the surface waves on the current meters in the lagoon

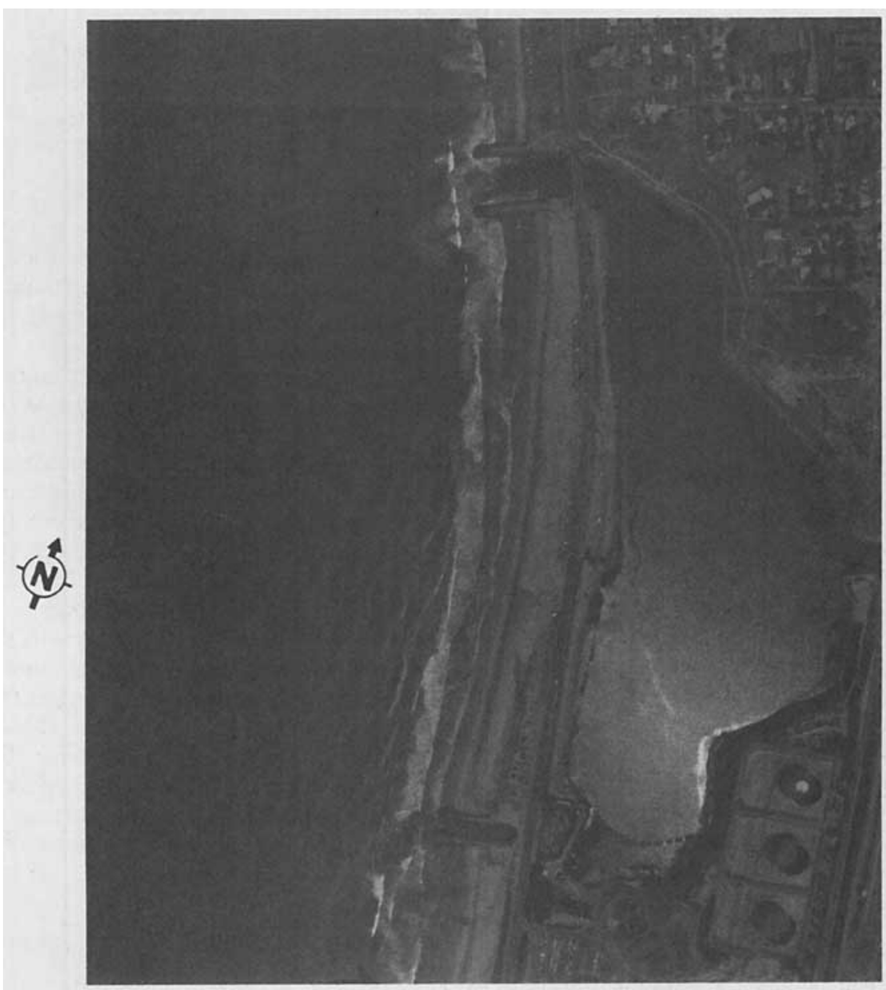

FIG. 1. The western part of the Agua Hedionda Lagoon.

FIG. 2. Aerial photo of monochromatic waves containing surface flow data. Distance between wave paddles on the left is about 61 m. Current meters are deployed by the wave generators, 45–75 m offshore.

was negligible. The monochromatic wavetrains were generated by two wave paddles, about 61 m apart at the lagoon shore. The period of waves produced by both paddles, T_0 = 0.76 s, (L_0 = 0.92 m) was accurately controlled. Fig. 2 is an aerial photo of the waves propagating in the lagoon; it contains synoptic surface flow data at every point in the photo that is "illuminated" by the waves.

The data processing required to obtain wavelength and direction data from the aerial photo is performed optically by a two-dimensional Fourier transform of the region of interest. In this type of processing, a transparency of the aerial photo diffracts a coherent light beam very much like a superposition of diffraction gratings; a lens behind the transparency focuses the diffracted beams on its focal plane (also called the Fourier plane). A photographic plate placed there records the Fourier transform (see Fig. 3). In addition to enabling simple determination of wavelength and direction, the Fourier transform improves the signal-to-noise ratio by concentrating the coherent wave signal at a definite spatial location in the 2-D Fourier transform; any random wavefield (noise in this case) will appear as a signal distributed over a large area in the Fourier transform. Fig. 3 is a Fourier transform of a lagoon region illuminated by two monochromatic wavetrains. This transform, together with distance and direction references incorporated in the aerial photo, contains the data required for determining the surface flow in that region.

Twelve high-contrast aerial photos of monochromatic wave-trains in the lagoon were taken during ~20 min. Each photograph contains a very large number of surface current readings; every region where both coherent wavetrains are visible in the photo contains the data necessary for determining the surface current there. The pictures were processed to obtain surface-flow velocities in the vicinity of the current meters. The processing included calculation of two flow components—$U \sin\alpha_{1,2}$ from two wavelength (or wavenumber) values measured in pictures like Fig. 3, as described at the beginning of this report. The wavelength of these waves in stationary waters was L_0 = 0.92 m. Figs. 4, 5 and 6 show a comparison between these values, processed at the region of a deployed current meter, and the flow values measured simultaneously by the current meter.

The scatter in measured-flow values

The scatter in the data points is due to a number of reasons. A part of the discrepancy arises when the

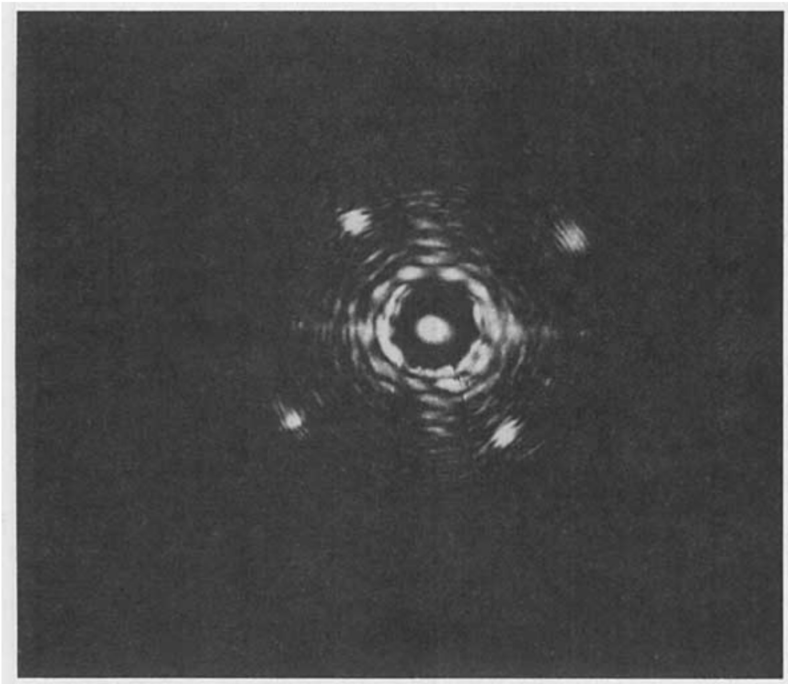

FIG. 3. Fourier transform of a lagoon region illuminated by two monochromatic wavetrains; there are ~15 waves of each wavetrain in this region. Each bright spot pair, situated symmetrically around the center, represents one wavetrain. The distance between bright spots in a pair is proportional to the wavenumber. This distance between the lower left to the upper right spot—44.5 mm in this picture, corresponds to the wavelength of the waves when there is no flow—$L_0 = 0.92$ m. Hence, the wavelength of this particular wavetrain was not modified by the current; this means that the propagation direction of the waves represented by this spot pair is perpendicular to the flow direction. (Thus, the flow velocity can be determined from its direction and the magnitude and direction of its component.) This transform was obtained from a region ~50 m offshore, midway between the paddles (see Fig. 2). The faint horizontal line is a directional reference. The dark area at the center is a filter to attenuate the zero-order diffracted light.

wave image (in the aerial photo) at the position of the current meters is poor, so that flow determinations must be made near (~15 m from) the current meter rather than at it.

The effect of vertically-nonhomogeneous flow on the phase velocity of codirectional linear waves was calculated by Stewart and Joy (1974), for $u/C_0 \ll 1$, as

$$U(k) = C - C_0 = 2k \int_{-\infty}^{0} U(z)\exp(2kz)dz,$$

where C is the wave velocity on the flow, C_0 is the wave velocity when there is no flow, k is the wavenumber, and $U(k)$ is the measured current speed; the surface is at $z = 0$ and deep water at $z = -\infty$.

Here, flow values are obtained from the measured wavelength L that is proportional to the phase velocity C for a constant frequency. The above expression suggests that for vertically-nonhomogeneous flows, these flow values are a weighted average of the flow with depth, strongly favoring flows that are closer to the surface; these measured values are, in general, below the maximum flow values in the water column. Also, the above expression suggests that the vertical velocity profile could be inferred from a number of velocity values $U(k)$, measured with wavetrains of different frequencies, σ_0, each probing the flow to different depths.

The scatter in flow values due to scatter in measured wavelength values can be estimated directly from the expression for $U \sin\alpha$, i.e.,

$$\frac{\partial U \sin\alpha}{\partial L} = C_0\left[1 - \frac{1}{2}\left(\frac{L_0}{L}\right)^{1/2}\right]\frac{1}{L_0}$$

for a rough approximation

$$\left(\frac{L_0}{L}\right)^{1/2} \approx 1.$$

Also, the wave velocity is approximated as M times faster than the flow velocity $C_0 \approx MU$. Hence,

$$\frac{\Delta(U\sin\alpha)}{U} \approx \frac{M}{2}\frac{\Delta L}{L_0},$$

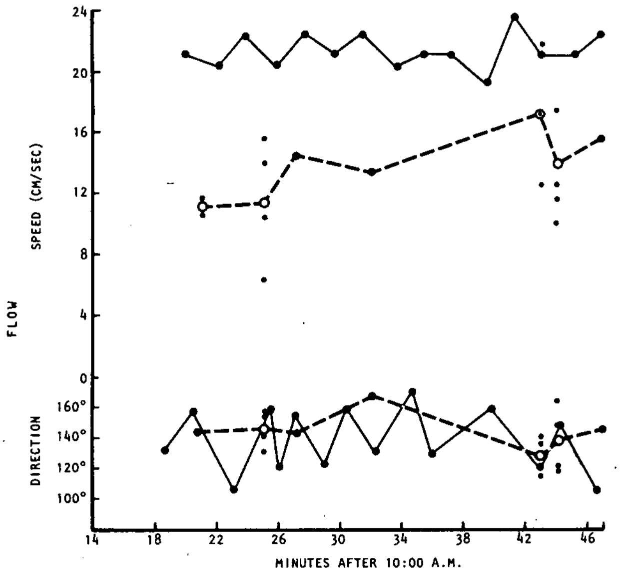

FIG. 4. Comparison of flow measurements from current meter No. 1 (solid line), and from wave data obtained by 2-D Fourier transforms of aerial photos of the same region (broken line). Open circles are averages of the readings indicated by black dots.

where ΔL is the scatter in wavelength measurement. Thus, measuring a 2 kt current ($\sim$1 m s^{-1}) with 6.5 s waves gives $M \approx 10$, and $\Delta(U \sin\alpha)/U = 5 \times \Delta L/L_0$; a 20% accuracy in the value of the velocity component requires a 4% accuracy in wavelength measurement. Physically, the velocity and wavelength of the fast-moving waves is not affected much by the relatively slow-moving current. Clearly, a smaller M or a better match between wave and current velocities will enhance accuracy. These considerations are closely related to the spatial variability of the current, via the resolution of the Fourier transform. An often-used estimate for transform resolution is $\Delta L/L = L/A$, where A is the diameter of the transformed area. To obtain high accuracy in wavelength measurements for high-M values, large areas of the wave-covered water have to be Fourier transformed. One limit to the utility of large-area Fourier transforms is the horizontal variability of the current. Increasing the area beyond the spatial scale of current variability only decreases resolution. (The bright spots in Fig. 3 will increase in size in the radial direction.) It is clear that the spatial variability of the flow has an important effect on flow measurement accuracy; this is in addition to other parameters influencing measured ΔL values, such as camera alignment and wave slope variability. In the experiment described here, $M = 5$ and $\Delta L/L = L/A \approx 6\%$. In practice, the Fourier transform resolution $\Delta L/L$ is better than that indicated by L/A, when the flow is spatially homogeneous in the area being transformed. The scatter in $\Delta L/L$ measurements due to other factors is estimated to be small (Sheres, 1980).

4. Discussion of the results

A number of features are immediately obvious from the data presented in Figs. 4, 5 and 6. The current speed, as determined by the wave data, is consistently lower than the readings obtained from the respective current meters that were deployed 0.6 m below the surface. (It is very difficult to deploy

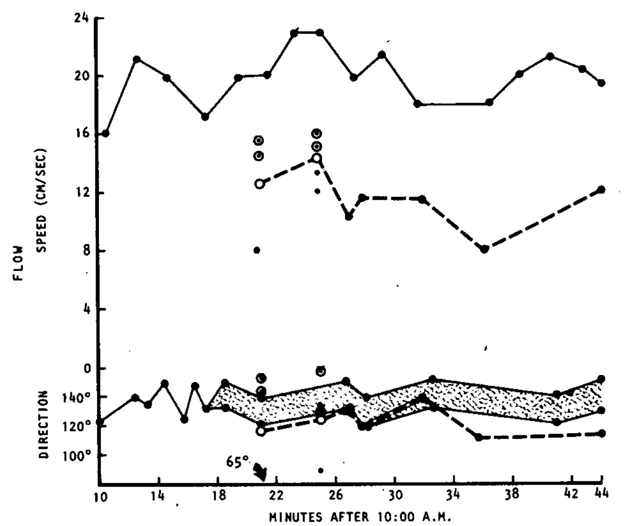

FIG. 5. Comparison of flow measurements from current meter No. 5 (solid line), and from wave data obtained by 2-D Fourier transforms of aerial photos of the same region (broken line). Open circles are averages of the readings indicated by the black dots. Black circles around the dots indicate data processed by measuring wavelength with the aid of a magnifier. The shaded area indicates the ambiguity in current meter data.

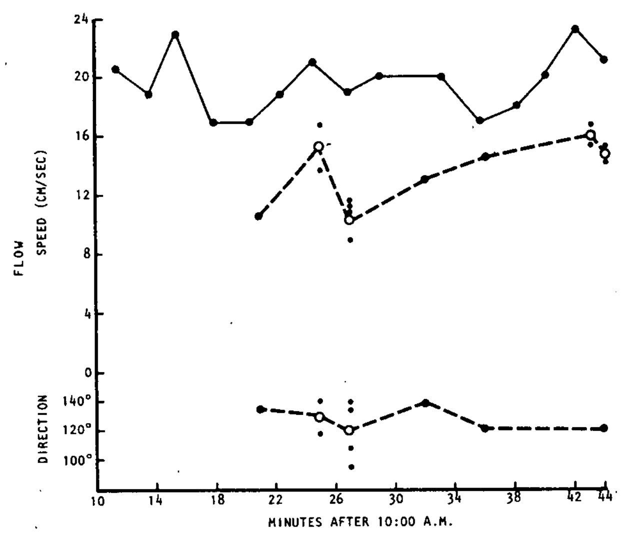

FIG. 6. Comparison of flow measurements from current meter No. 1002 (solid line), and from wave data obtained by 2-D Fourier transform of aerial photos of the same region (broken line). Due to a malfunction, directional data was not obtained from this current meter. Open circles are averages of the readings indicated by black dots.

them any closer to the surface.) The directions of flow determined by the current meters and the wave data (at the current meter position) are consistently very close in value.

As discussed in the previous section, a depth-integrating flow measurement, such as this one, is expected to give flow values that are below the maximum flow in the water column. Usually, with wind-generated currents, the maximum value of the resulting vertically sheared flow is at the surface. The higher flow values measured by the deployed current meters at a depth larger than half a wavelength suggests that the maximum flow was below the surface; this is possible when the vertical flow profile is dominated by processes other than wind. At the area of the measurement, ~60 m off the western lagoon shore, the wind coming from the west over a 2 m embankment would not be the dominant shearing force. The flow in the lagoon, as described in the previous section, is dominated by tidal flushing with cold ocean water, tidal exchanges between the eastern and western lagoon sections with their accompanying temperature and salinity stratifying effects (that were, unfortunately, not measured), and the pumping out of lagoon water for cooling the electric power plant.

Indeed, a few spot measurements with a hand-held bongo-type flow meter (from an anchored boat in the general area of the experiment) showed that the flow is sometimes faster at a depth of 60 cm than above it (see Table 1).

In addition, the direction of the flow, as determined by the wave method, is consistently in very good agreement with current meter data. The flow is determined, in the wave method, by the vector addition of two flow components; any errors, or noise, in the determination of either one or both of the two vectors, would have led to significant errors in the resultant flow direction. This is particularly true when one of the two sets of probing waves is directed with the current, and the other against the current (as was the case in this experiment), and both measured wavelengths have the same error; e.g., both are larger.

TABLE 1. Measurements by hand-held Bongo-type flow meter values in cm s^{-1}.

Depth (m)	Measurement number 1	2	3	4
0.15			Below Calibration Range*	
0.3	10–11	26	10	Below Calibration Range*
0.6	10–11	32, 24, 30	10	8.5–9.5
0.9	5 or less			

* If calibration curve were extended, it would read 5 cm s^{-1}.

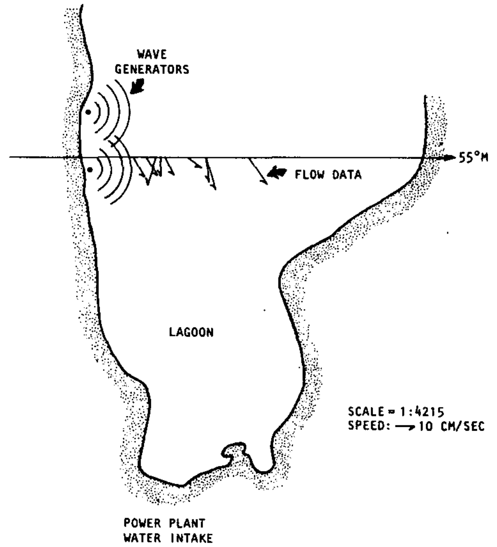

FIG. 7. Current determinations along a transect directed towards 55°M, obtained from a single aerial photo.

The surface flow measuring system described above offers a remote and synoptic way to determine the flow on the 2-D surface. The synoptic character of this flow measurement is evident in Fig. 7. The flow vectors presented in that figure were processed from one aerial photo, along the line directed toward 55° magnetic. This line was arbitrarily chosen; the flow vectors could have been determined along any other line, or in any region, provided that the region was illuminated by the monochromatic wavetrains. All the necessary information is contained and *compactly stored* in one aerial photo.

An obviously interesting extension of this work would include surface-flow measurements in the open ocean. A variety of high-flying platforms, e.g., satellites, have imaging instruments on board such as cameras and synthetic aperture radars which potentially could be used for surface-flow determination. Monochromatic swell could perhaps be used as the wave probe, provided information about their frequency could be obtained. An independent determination of the surface flow in one region that is "illuminated" by the waves (with a single current meter, for example), combined with wavelength data from the photo, would supply equivalent information that would enable synoptic flow measurement.

From the discussion in the previous section, it is clear that surface current measurement with swell has inherent low accuracy due to large M. Better accuracies can be expected if a way is found to isolate the shorter waves of the surface-wave spectrum and use them as the wave "probe" for the current measurements. For large-scale flows, L can be deter-

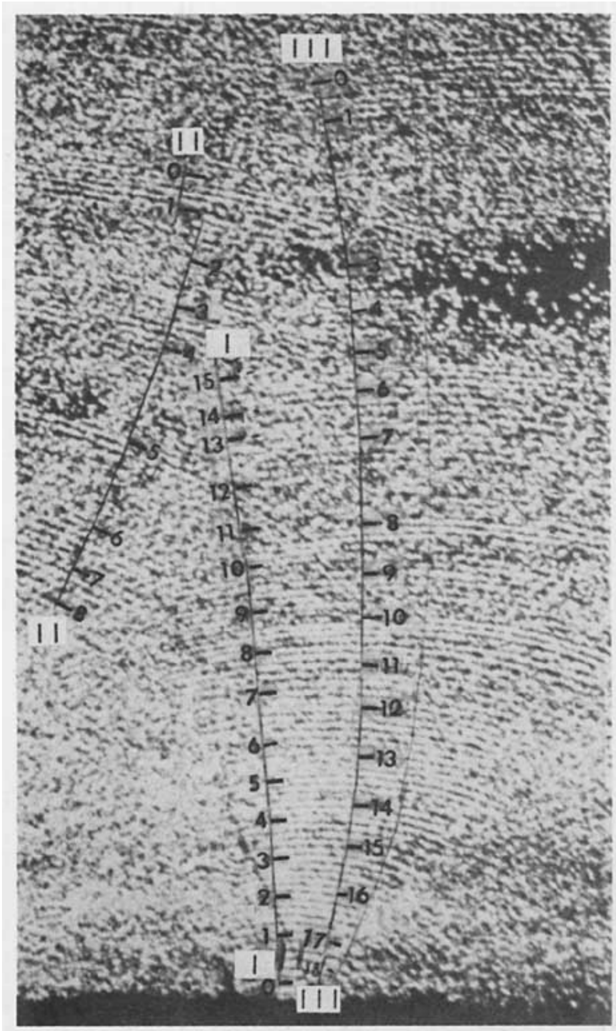

FIG. 8. Waves propagating in the lagoon from two wave generators on shore. Path II is traced along waves originating in the northern wave generation: Paths I and III are traced along waves originating in the southern wave generator. Both generators operate at the same frequency of 1.5 cycles per second.

mined accurately, even for swell, with Fourier transforms of large areas. The result is smaller ΔL and corresponding better accuracy.

In the open ocean, even low-accuracy synoptic surface flow information is not generally available, e.g., satellite infrared images routinely show patterns of eddies in the ocean but lack direct velocity values. These large-scale velocity patterns have an effect, albeit small, on the wavetrains passing through. Processing of surface-wave images for the wavelength variation in the dominant wavetrains is likely to be a worthwhile initial approach. As an example, a wave image from the lagoon has been processed to monitor the wavelength variations along three wave paths. Fig. 9 shows the result of careful wavelength measurements along these paths in Fig. 8. The wavelength variations show a coherent pattern with wavelength ~30 m; the bathymetry in that region did not show any correlated variations. The cause of these variations is not clear (unfortunately, I did not have the opportunity to explore it), but it is conceivable that they reflect surface velocity variation. Similar measurement in ocean-surface images, photographic or radar, could reveal patterns due to surface currents. These patterns can supply synoptic velocity data if additional wave or current information can be obtained at only one point.

Other potential sources for coherent waves are boats, particularly in harbors, bays, and coastal waters; they produce coherent wavetrains that cover large areas. The frequency of the waves depends on the speed of the boat with respect to the surface water it sails through. These waves can be useful for flow measurements in areas that are inaccessible for deployment of conventional current meters and sustain a lot of boat traffic. Fig. 1 shows a coherent wave train generated by a passing boat that can be clearly seen in the active nearshore region of the Pacific Ocean.

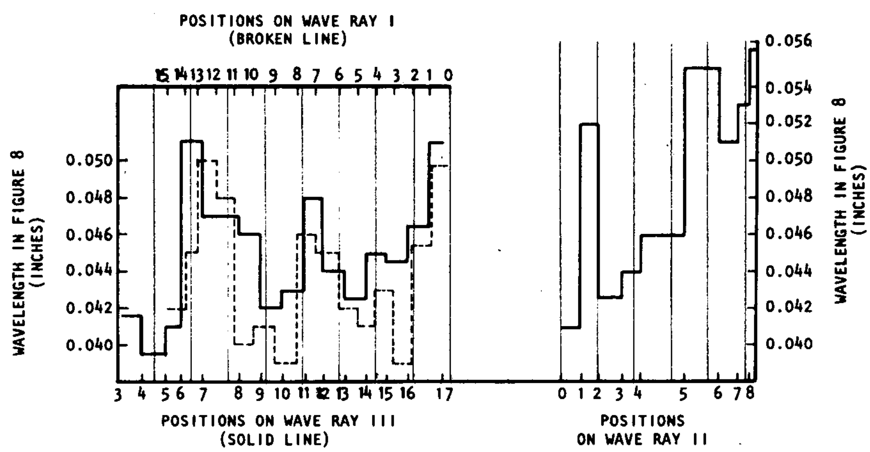

FIG. 9. Wavelength as a function of position for three different wave rays in Fig. 8. Each vertical line on the abscissa represents ten wavelengths.

Acknowledgments. I am indebted to the late John D. Isaacs for actively participating in this research and for contributing many valuable ideas to it. John Lyons was instrumental in the experimental work. Discussions and comments by Robert S. Arthur, Myrl C. Henderscott, and Kern E. Kenyon were most helpful. Larry Ford did the demanding aerial photography. Joseph E. Dietz of San Diego Gas and Electric Company provided access to and support in the company's facility at the Agua Hedionda Lagoon. Funding was provided by the Office of Naval Research, Coastal Sciences Section, and the Foundation for Ocean Research.

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