Mapping Ocean Currents With IKONOS

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***Abstract*—The velocity of sea surface gravity waves depends on the wave wavenumber, *k*, and the surface current, *U*. The surface current can thus be inferred from the displacement of waves in as sequence of ocean surface images. This has been demonstrated using both marine radars and aerial video to image the ocean waves. In this paper we describe the implementation with IKONOS satellite images. We discuss special considerations for obtaining and processing satellite images: the need for precise co-registration of the images; the optimum sun angle for imaging ocean waves; the optimum oceanographic conditions; and the use of multi-spectral bands to edit non wave surface features (e.g., whitecaps). In the test case a current velocity map was produced at 200 m grid spacing. The rms error in the velocity estimates is 10 cm/s.**

***Index Terms*—Remote sensing, satellite applications, sea measurements, sea surface.**

I. Introduction

SEA surface currents can be determined from the apparent velocity of surface gravity waves. This has been demonstrated using marine X-band radars [1]-[3] and video [4]-[6] to image ocean surface waves. (The cited references are a *very* small subset of all the experiments and papers on this technique.) In this paper we demonstrate a similar technique using images taken by the IKONOS satellite.

The principle idea in using waves to measure current is as follows: the deep water dispersion velocity of surface waves is $1.25\ k^{-1/2}$ m/s, where k is the wave wavenumber in units of cycles/meter. (The deep water assumption is reasonable if the depth is > $1/2k$.) For example, the speed of a 10-m wave is 3.9 m/s. A current simply adds to the velocity. So if 10-m waves (k = 0.1 c/m) are observed to travel at 4.4 m/s one can deduce that there is a 0.5 m/s current in the wave direction.

The ocean surface is a continuum spectrum of long and short waves. With current radar and optical imagers we typically observe waves in the range 1 to 100 m (1 to 0.01 c/m). . The wavenumbers are decomposed by Fourier analysis. Each resolved wavenumber provides an independent estimate of current in one direction The phase shift in the Fourier transform coefficients is a measure of displacements (and velocity). There are tens to thousands of resolved wavenumbers, depending on the wave spectrum and Fourier transform resolution. A least-squares approach is used to estimate the velocity vector $\boldsymbol{U} = \{U_x, U_y\}$.

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The main difference between the earlier implementations ([1]-[6]) and the foregoing results with satellite imagery is that the previous work performed the Fourier analysis on a cube of ~100 images whereas with the IKONOS satellite there are only two to four images. Also, in previous work the time between images was typically ~1 s, whereas the interval between IKONOS images is ~13 s. These are significant differences and required a different processing algorithm (described later). The main result reported here is that two satellite images can provide good current velocity measurements.

II. The Satellite Imagery

The results presented here use the first four of a seven images sequence obtained in a single satellite pass over San Diego on April 8, 2002. These four images appear to have the best view geometry. The utility of the other three images is still under study.

TABLE I. IKONOS Images

ID	Time*	Collection Azimuth	Collection Elevation
178113	18:46:23.4	3.6^o	56.4^o
178116	18:46:36.7	0.9	62.8
178114	18:46:49.4	356.1	69.8
178117	18:47:2.7	345.3	77.0

*Time refers to the 1st line in the image. Images are take at approximately 13 s intervals.

Table I is a summary of time and view geometry parameters for the four images. Collection azimuth and elevation refer to the camera view direction. The sun azimuth was 146^o and sun elevation was 61^o.

The IKONOS, and other similar commercial satellite (e.g., QuickBird, EROS, SPOT, etc) work as pushbroom imagers. The IKONOS and EROS are the most agile and can "snap" multiple images of an area as long as it is within 50^o of nadir. One IKONOS image, as for example Fig. 1, is a strip of 12000 scan lines. Each scan line is ~1 m in panchromatic. (Four multi-spectral image bands are also collected near simultaneously at 4 m resolution.) To capture a sequence of images the satellite rescans the same ground footprint in a forward and reverse scan pattern: the first image is scanned in one direction, say South to North, the next in reverse, North to South, the third in reverse again, South to North, and so forth. The sweep rate is 6000 lines per second, so one image strip takes two seconds. The next images starts approximately 11 seconds later, after a delay for image data recording and camera re-pointing. Successive images are thus at 13 second intervals.

The example in Fig. 1 is typical of the four images. North is up. The coastline is at the top, the open ocean is below. Some of the key geographical features along the coastline (from left to right) are the Point Loma peninsula (partially obstructed by clouds); the inlet into the San Diego harbor, the Naval Air Station, and Coronado. The coastline arcing from center to the right is Silver Strands Beach.

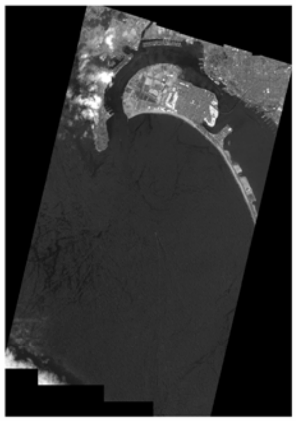

Fig. 1 An image strip. North is up. Credit: IKONOS image by GeoEye.

III. Special Considerations for Satellite images

IKONOS images can be purchased from an online archive or special ordered to meet specific customer needs. Special orders are fulfilled by tasking the satellite at some future date. Ocean surface current mapping is in the special order category because it requires at least two images in a short time interval, which is atypical of the way most imagery is collected. The following discussion covers several other considerations for the image collection that are unique to this application.

A. Camera-sun angle

The camera-sun angle is an important parameter in imaging ocean waves. In the ideal situation the sea surface radiance would be both very high (relative to camera noise) and linear with respect to wave slope. Unfortunately both conditions can not be met simultaneously. The surface brightness increases towards the sun specular point. The linearity improves further away from the sun specular point. The best compromise is 10 to 20^o from the sun specular point, avoiding the sun glint cone. The sun glint cone depends on wind speed; the greater the wind speed the wider the glint area. In the test case the pointing was ~35^o from the sun specular point, which was comfortably out of the glint.

The agility of the satellite to point anywhere within 50^o of nadir allows a near optimum sun angle to be achieved in almost every overpass.

B. Wave conditions

The wave spectrum is another important consideration. Wind waves on the scale of 4-20 m are very desirable. (Longer waves will not provide accurate velocity estimates; shorter waves will not be resolved.) The current can not be measured in dead calm sea, or in a short fetch, or even with large swell waves. If possible the image collection should be scheduled for a time period when short wind waves will be present in the area of interest. Otherwise leave it to chance – the same as with cloud cover – and hope for useful images in two or three retakes. If there is an opportunity to schedule the image capture the best time can be suggested by wave forecasts. There are several wave forecast services such as NOAA’s 180-hour WaveWatch III [7]. Wind shadowing by land mass should also be considered. The area to be surveyed should be open to sea and wind.

C. Geo registration

Since the current will be estimated from the wave travel distance between successive images it is essential that images are accurately geo-rectified and referenced to a UTM grid.

The satellite imagery vendor (GeoEye for IKONOS images) delivers the image data to varying degrees of registration accuracy, depending on customer need and budget. There are several grades of UTM registration from “Reference” with 25 m error to “Precision Plus” with 2 m [8]. The cost of the imagery goes up with precision.

Even “Precision Plus” is not as good as needed for current velocity. A 2 m error between successive images translates to 15 cm/s bias in current velocity. This is not too bad in itself but there will be additional errors from other sources, so this error should be avoided if possible. In other words we would like better than “Precision Plus” registration.

It is thus desirable to include some flat, sea-level land in the image collection. The land should have sufficient fiducials for image registration..

In the San Diego scene we found excellent registration fiducials on the airfield, on the beach, and in city streets. For the results reported here we used the markings spelling out “Coronado” on a stretch of Silver Stands beach (Fig. 2). The sharp edges in these markings were ideal for registration and provided better than ½ m accuracy.

The technique is thus most useful for mapping near-shore currents. It may not be feasible to include land in the image when the survey area is more than 20 km from the coast.

Fig. 2 Close-up on shoaling waves and "Coronado" imprint on beach. Credit: IKONOS image by GeoEye.

IV. Algorithm

This Section provides a brief explanation of the algorithm used to reduce two images into a current velocity map. The images have been previously co-registered as explained in Section III.C.

All previous algorithms, [1]-[6], used the Fourier transform of ~100 images, and determined the current velocity, ***U***, by searching for the wave energy concentration in wavenumber-frequency space. Our algorithm for satellite imagery is similar in concept but adapted to work with only two images, since usually only two (and at most four) satellite images can be obtained.

A. Image cleaning

Not all the radiance from the sea is ocean waves. There can also be whitecaps, surfactants, radiance from the ocean bottom (in the shallow areas), ships, buoys, and clouds. Such features can introduce errors in the measurement of current velocity. We use several techniques to flag or filter such features. The Near IR and red multispectral bands are used in shallow water (especially in depth < 10 m) to avoid contamination from ocean bottom. High intensities in near IR are used to flag clouds, whitecaps, ships, and buoys. Surfactant streaks can be minimized with a suitable wavenumber highpass filter.

B. Tiling

The image area is divided into square tiles of dimensions *D* m x *D* m. Each tile is processed independently of its neighbors and produces one current vector ***U*** = *{Ux, Uy}*. There is a tradeoff between resolution (tile size) and accuracy of the result. The larger the tile the greater the number of resolved wavenumbers, and the greater the accuracy of the estimated current velocity. The dimensions used in practice also need to consider the imaging resolution and the wave spectrum. All factors considered, tile dimensions of 100-200 m are found to be practical.

C. Exact time

The time difference between the images, Δ, should be known to 0.03s. Some care is needed to calculate the image time to this precision. Recall that the image is created by a pushbroom. The actual image time varies from the first to last scan line. A time correction is computed for the center of each tile, based on the distance of the tile center from the first scan line and knowledge of the pushbroom scan rate. The correction is between zero and two seconds. The change in time within a tile can be ignored.

D. Ocean current velocity

The two image tiles are Fourier transformed into wavenumber space, $F_1(\mathbf{k})$ and $F_2(\mathbf{k})$. Note that these are 2D rather than the 3D Fourier transforms. The current, U, can then be found by one of following: from the maximum of the correlation operator,

$$G(k) = \left| \sum_k H(k)\overline{F_1(k)}F_2(k)e^{-(j\omega(|k|)+U\bullet k)\Delta} \right|,$$

or from the minimum in the difference operator,

$$G(k) = \sum_k H(k)\left| F_1(k) - F_2(k)e^{-(j\omega(|k|)+U\bullet k)\Delta} \right|.$$

These achieve the same result as the 3D Fourier transform methods in [1]–[6] but with only two images. ***H(k)*** is wavenumber filter, usually a highpass filter that will emphasize short wind waves and reduce non wave features such as surfactant streaks; ω(k) is the deep water wave dispersion frequency at wavenumber *k*; Δ is the time difference explained above.

V. Results

Fig. 3 and Fig. 4 show current velocity maps. Fig. 3 is the result for images 178113 and 178116. Fig. 4 is the result for images 178114 and 178117. For brevity we show only an 8 km x 8 km area just outside the San Diego harbor. This is the most interesting area of the image because of strong outflow currents that can be found in the vicinity of the inlet.

Each vector represents the current averaged over 200 m x 200 m. For clarity only a subset of all the vectors are actually shown in the plot.

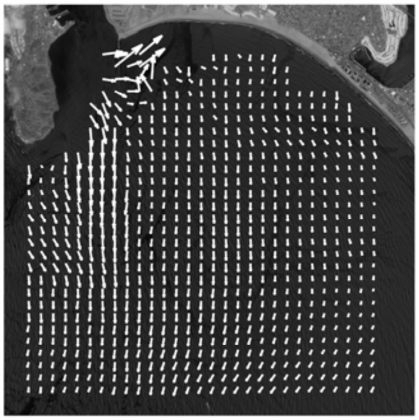

Fig. 3 Current vectors from image pair 178113-178116

There are some internal checks for validity. The algorithm checks there is sufficient short waves energy and sufficient number of resolved wavenumbers (both conditions are critical to getting good estimates). Some current velocity results are suppressed because of insufficient wave energy. This is especially apparent in the inlet area where the wind is blocked by the high bluffs of Point Loma. To the East

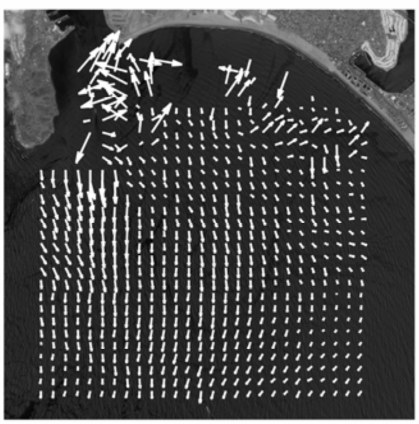

Fig. 4 Current vectors from image pair 178114-178117

of the inlet the Zuniga Jetty is effectively blocking waves. To the West is a large kelp forest (not shown here) that also damps wind waves.

Current velocity measurements are also eliminated in tiles with excessive bad data flagging. This occurs in and near the surf zone along the entire stretch of Silver Strands Beach.

However, good velocity estimates are obtained over most of the sea surface in this image. Surfactant streaks, although prevalent over the entire area, were not a problem. We attribute this success to the highpass filter.

The most prominent feature in the current velocity map is the jet outflow at the inlet, which is apparent by large downward velocity arrows starting at a location 2 km South of the mouth of the inlet (i.e., approximately at the tip of Pt. Loma). The peak flow at this point is 80 cm/s and tapers down to 20 cm/s further out and to the East and West of the inlet.

VI. Assessment of Accuracy

There are no *in situ* measurements of the current velocities to verify these results. However we can get some idea about the accuracy from internal consistencies.

The average difference between adjacent independent estimates (i.e., samples of estimated current velocity separated by 200 m) is 10 cm/s. This represent the upper bound on errors in velocity measurements. The actual error may be less if some fraction of the 200-m scale variation is real. We conclude that the rms error is 10 cm/s or better.

The two image pairs are independent. Comparing the two plots provides another indication of accuracy. The large outflow jet is present in both. However, the currents in the Fig. 3 are about 10 cm/s higher on average than the corresponding values in Fig. 4. The real current could not have changed appreciably in the 26 second time difference between the two estimates. Some unidentified bias is present in one or both results. As mentioned in Section III.C, we eliminated image mis-registration as a possible source of error. The cause of the 10 cm/s bias is a mystery.

Two other observations are (1) that the outflow is consistent with the fact that "currents in the San Diego Bay are predominately produced by tides" [9] and the tide was near maximum ebb flow at this time; and (2) the outflow velocity tapers down further away from the mouth as predicted by various tidal flow models.

In summary the current velocity rms is ~10 cm/s or less and there is a possible 10 cm/s bias.

VII. Comparison to other remote sensing techniques

Even with the uncertainty in the above evaluation, the IKONOS results compare favorably with other remote sensing ocean current mapping techniques.

For instance: HF Coastal Ocean Dynamics Applications Radars (CODAR) map currents with rms errors of ~20 cm/s on grid spacing of ~2 km [10]. CODAR installations are fixed at coastal sites and provide continuously cover ~2000 km^2 footprint. The IKONOS measurement error is about the same but with 10x as much resolution, 200 m vs. 2 km.

Space based SAR (e.g., RADARSAT) can estimate the sea current component perpendicular to the radar heading with rms errors of ~30 cm/s with 200 m resolution [11]-[13]. RADARSAT and IKONOS accuracies appear to be similar. It would be interesting to collect simultaneous data with RADARSAT and IKONOS for further comparison.

Another space based method tracks sea surface thermal and color features with the Advanced Very High Resolution Radiometer (AVHRR) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellites. The demonstrated rms error is ~10 cm/s on 24 km grid, with large coverage gaps where the sea surface is featureless [14]. Again, IKONOS errors are about the same, but with much better resolution (200 m vs. 24 km).

Piotrowski and Dugan [6], using aerial video, achieved an rms error of 3 cm/s in 256 m tiles. This accuracy is for two frames per second for two minutes (a total of 240 images). Their analysis also included the dependence of the error on tile size and number of images and time. The results in their analysis that are closest to a pair of IKONOS images suggest an rms of 15 cm/s. This is consistent with analysis in Section VI.

Acknowledgment

This work described in this paper evolved from an earlier study [15] that used the same satellite image data to map bathymetry. The data was obtained with the support of the Department of Defense National Geospatial-Intelligence Agency (NGA). Dr. Richard Brand of NGA provided much appreciated guidance and encouragement for this research. Mr. Gene Dial, GeoEye, provided a method for calculating accurate image time and other useful advice on IKONOS data.

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