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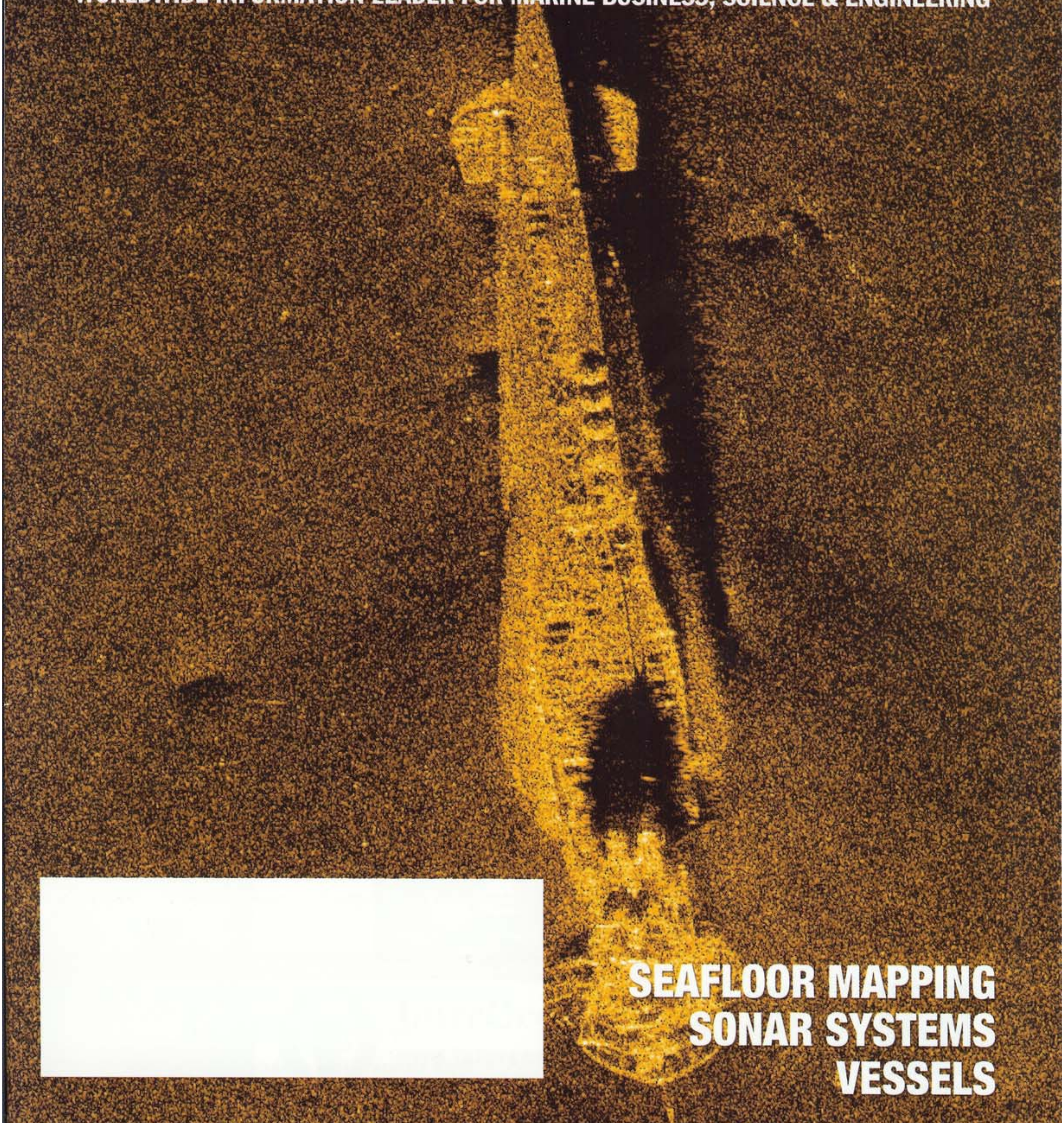

SEAFLOOR MAPPING
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Shallow-Water Bathymetry with Commercial Satellite

A Technique for More Than 100 Years Has Matured into a Capability for Rapid Shallow Water Depth Mapping

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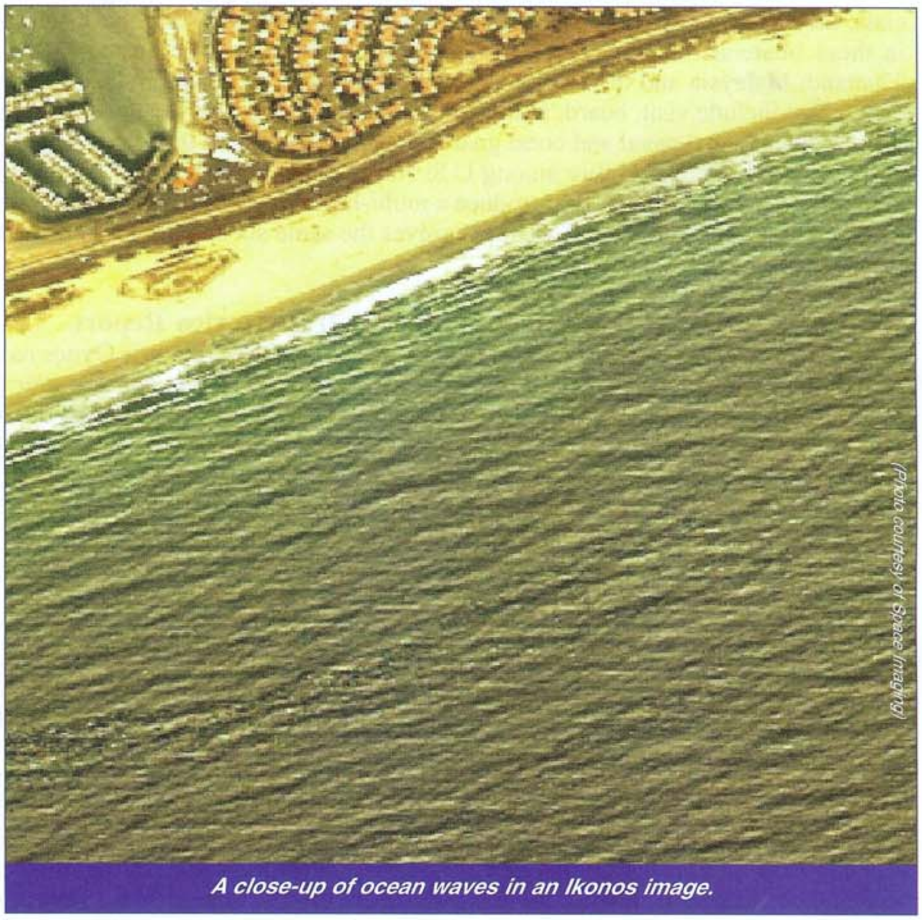
A technique based on waves kinematics (WK) uses two or more images of ocean waves taken a few seconds apart to measure wave velocities, and then inverts velocity into depth. The theory behind the technique has been known for more than 100 years. A crude version can be made by the visual observation of waves from a cliff or pier. One can fix his eyes on a point on the ocean near the shore and estimate the seconds (T) between successive crests—it is usually 10 seconds—and the distance (L) from crest to crest. The wave velocity is $C = L/T$; the depth is approximately $C^2/9.8$.

There has been considerable interest and research over the past 20 years in developing this technique as a remote sensing of bathymetry, and a commercially viable capability is now emerging. Several groups in Europe have experimental WK systems using X-band nautical radars.[1] In the United States, WK has been utilized with airborne optical imaging[2] and, as discussed in this article, most recently with optical imaging from satellites.

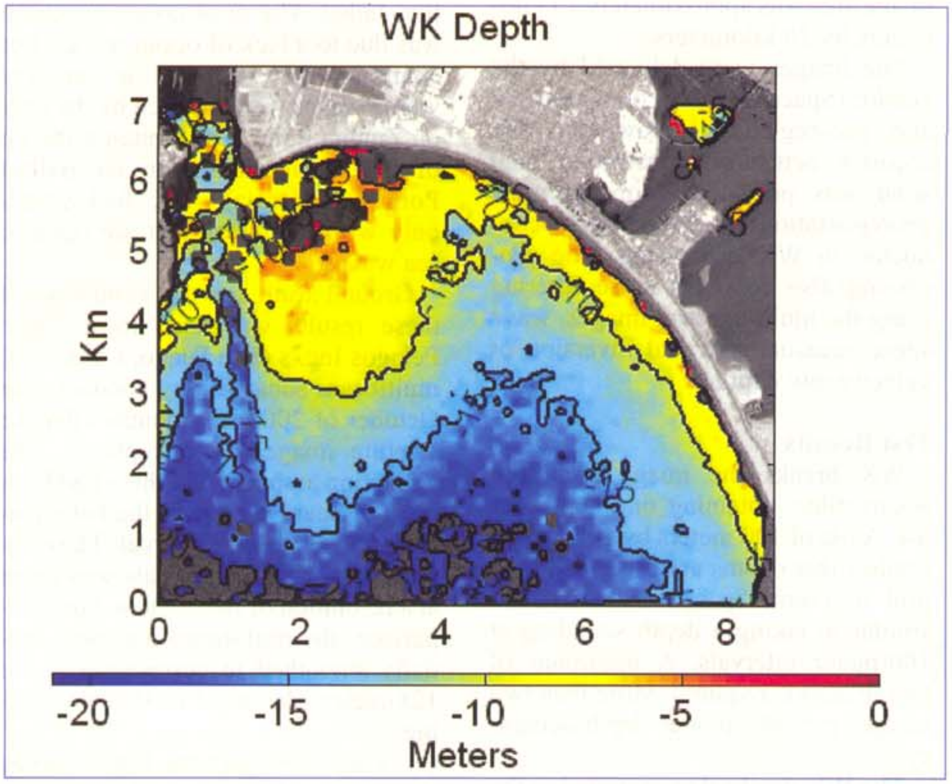

(Photo courtesy of Space Imaging)

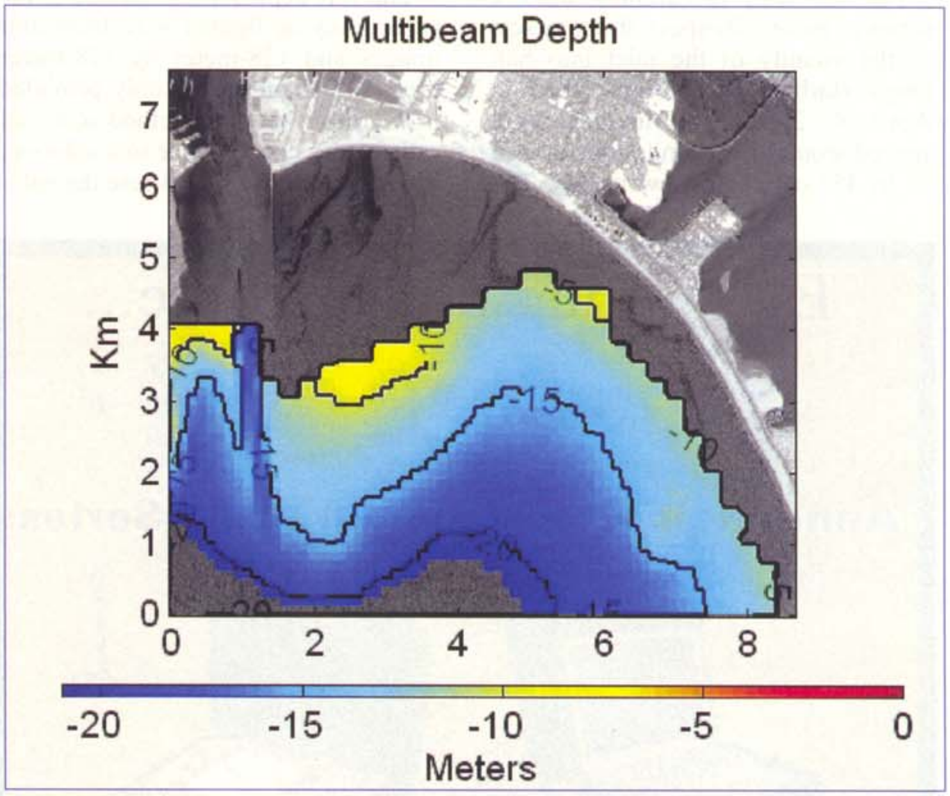
A close-up of ocean waves in an Ikonos image.

The Technique

For this technique, two or more images are taken some seconds apart (typically two to 20 seconds between consecutive images). The images are orthorectified and georeferenced, then a computer algorithm fits a depth solution to the data. The fitting algorithm most commonly used today was first developed in the 1980s by European research organizations.[1] The algorithms use the Fourier transform (FT) to measure phase shifts between consecutive images. Phase change is related to wave speed, which is then related to depth by a formula known as the linear gravity wave dispersion relationship. This is actually an approximation, but a very good one for depths greater than one meter. The speed of an ocean wave depends only on its wavelength and the water depth. For example, a 50-meter wave travels at 8.84 meters per second in infinite depth, slowing down to 8.15 meters per second at 10 meters' depth, 6.59 meters per second at five meters' depth and so forth. Longer (shorter) waves travel faster (slower).

The European groups applied this method with nautical X-band radars. Around the same time, experimenters in the United States began using optical imaging. The optical approach provides more resolution in a smaller package. The first optical imaging attempt was made in the 1980s at the Naval Ocean Research and Develop-





(Above) The WK depth superimposed on an Ikonos panchromatic image; north is up. Pt. Loma is on the upper left edge of the image. To the east of Pt. Loma is the dredged inlet into San Diego Harbor, the naval air station on Coronado and Silver Strand Beach. Constant depth contour lines are at 10, 15 and 20 meters.

(Right) Fugro ship multibeam bathymetry used for validating WK. Constant depth contour lines at 10, 15 and 20 meters are used for visual comparison with WK.

ment Activity (NORDA). Two images were taken with an aerial reconnaissance camera over Camp Pendelton Beach, California. The film images were digitized and the wave motion was manually tracked on a light table—a very tedious process. In the 1990s, a group at Arete Associates (Arlington, Virginia) implemented a more sophisticated approach with two important improvements over the NORDA effort—they used a charge-coupled device camera for imaging the ocean (so the data was already in digital form and ready for computer processing) and automated FT algorithms similar to those employed earlier by the Europeans. Tests were administered at the U.S. Army Coastal Engineering Research Center, Field Research Facility, in Duck, North Carolina, where excellent ground truth validated their results.[2]

Satellite WK

The author of this article was engaged in this technology from its earliest days, and was interested in the implementation of WK bathymetry with commercial satellite imagery. The motivation for using satellite was both speed and economics. Traditional technologies deploy ship or aircraft, and personnel to remote survey sites. These resources are then tied up waiting for favorable weather conditions. Satellites revisit all areas of the world every few days, taking data whenever and wherever the meteorological and ocean wave conditions are most suitable.

The implementation from satellite, however, had to await the arrival of suitable satellites. Early commercial satellites did not have the needed capabilities. Satellites use pushbroom imaging, and the acquisition of two images requires one pushbroom scan, then re-pointing the camera to re-scan the same ground area, all within a few seconds. The early commercial and civilian satellites SPOT and Landsat did not have sufficient re-pointing agility. WK also requires an image resolution of four meters or better, which was also not available in the early days of commercial satellites.

Satellite WK bathymetry became practical only when the Ikonos satellite—the first of several commercial high-resolution satellites—was placed into orbit in 1999 by Space Imaging (Thornton, Colorado). Ikonos was followed by EROS A1 from ImageSat International NV (Tel Aviv, Israel) in 2000, QuickBird from DigitalGlobe (Longmont, Colorado) in 2001 and OrbView-3 from OrbImage Inc. (Dulles, Virginia) in 2003. All of these satellites have a four-meter or better resolution and were designed to re-point and take multiple images in a single overpass.

The re-pointing capability was primarily intended for stereo imaging used to aid in the construction of 3D images of the Earth's surface, but it also fulfilled an essential requirement for the WK approach.

The feasibility of WK bathymetry from a satellite was established in a 2002 study for the National Reconnaissance Office.

The first test with real satellite imagery was undertaken in 2005 under the auspices of the National Geospatial-Intelligence Agency (NGA).

The First Test From a Satellite

Ikonos was chosen for the 2005 test because of its fast re-pointing and simultaneous capture of panchromatic and multi-spectral images. While panchromatic images are sufficient, better results are possible with multi-spectral images. Multi-spectral images can be used with a special algorithm to filter out non-wave features, such as ocean-bottom reflection, whitecaps, surfactant streaks, vessels and their wakes and clouds. These features cause spurious WK depth errors if not removed.

For the test, researchers used a series of pan-multi-spectral image sets of the vicinity of the inlet into San Diego Harbor in California, taken on April 8, 2002. The images were spaced around 13 seconds and covered 7° to 45° off-nadir view angles. The image area was approximately 15 kilometers by 20 kilometers.

The images were delivered by the vendor (Space Imaging) orthorectified and geo-registered. However, WK requires better georegistration than what was provided. More accurate georegistration is automatically conducted in WK processing. The processing also conducts noise filtering using the multi-spectral images, wave speed measurement and inversion of velocity into depth.

Test Results

WK breaks the image area into square tiles, obtaining one depth per tile. A tile of 100 meters by 100 meters implies that depths are estimated on a grid of points spaced 100 meters—similar to taking a depth sounding at 100-meter intervals. A minimum of two images is required. More than two images provide greater depth accuracy.

The WK depths demonstrated in the accompanying figures were from four images and 128-meter by 128-meter tiles. WK depths were only provided in the tiles where the method achieved satisfactory convergence to a solution. There were a few tiles where the solution failed. The most common reason was due to a lack of ocean waves. For example, this occurred in an area where waves were blocked by the jetty on Zuniga Point, California (at the tip of the naval air station on Ballast Point, California). WK bathymetry only works in areas that are open to sea waves.

Ground truth for the validation of these results was used from Fugro Pelagos Inc.'s (San Diego, California) multibeam sonar survey conducted in October of 2002, six months after the satellite imagery was captured. The validation assumed that there had been no significant change in the bathymetry in the six-month interval. The original multibeam survey data was taken at a resolution of five meters. For comparison, the multibeam data was spatially smoothed to correspond to the 128-meter tiles used in WK processing.

For the most part, the Fugro survey ship remained outside of the 10-meter depth contour and did not cover all of the area processed with WK. In the areas where WK and the multibeam data did overlap, the one-standard deviation difference was five percent.

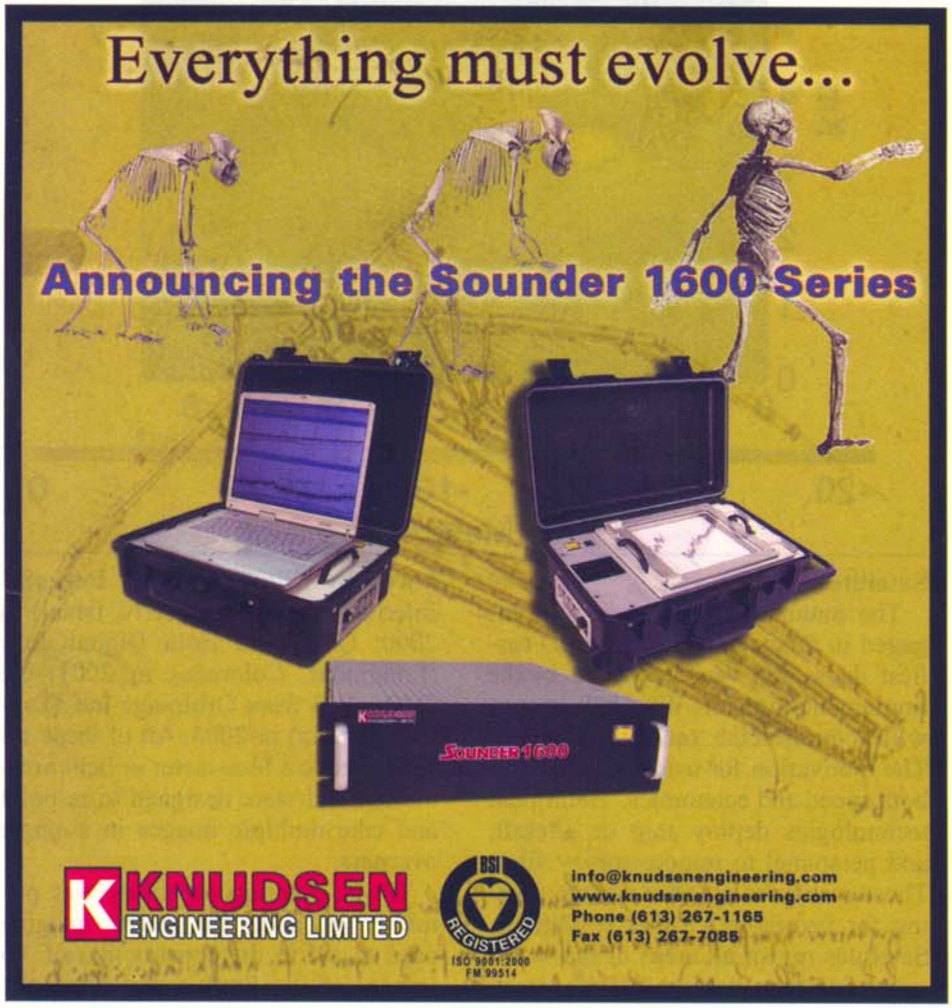
WK resolved the narrow-dredged channel into the harbor, the spit to the west of the dredged canal, a shallow mount on the east side, between the 10 and 15-meter contours and other important details of the bathymetry.

Where WK is Most Useful

Satellite WK bathymetry has been successfully implemented, and the computer algorithms have been validated against a ship multibeam survey. Satellite WK can now be added to a host of other bathymetric charting techniques and services. The following summary can help users understand and select from: ship multibeam, airborne light detecting and ranging (LIDAR) and three methods from satellite (photo-bathymetry, synthetic aperture radar (SAR) and WK).

The first item to consider is whether the intended use for the bathymetry requires International Hydrographic Organization order 1 (IHO-1)—the gold standard for navigation charts. Only multibeam and LIDAR methods deliver IHO-1.

Multibeam surveys are slow and expensive. LIDAR is a faster option. According to a recent article featured in *Sea Technology* magazine, LIDAR is 20 to 100 times faster than ship multibeam and even more cost effec-



tive.[3] However, LIDAR only works in clear and shallow-water depth, so a vital role for ship multibeam still exists.

Satellite techniques do not meet the IHO-1 standard, but do have clear advantages in cost and speed. They are more practical for remote areas (e.g., charting coral reefs and military amphibious planning). They would also be more practical in applications where frequent resurveying is needed (e.g., monitoring sandbar movement or the condition of dredged channels). Satellite bathymetry can be used as a preview of an area that will later be surveyed by multibeam or LIDAR. The satellite bathymetry would indicate where the ship or LIDAR need to concentrate.

The three satellite methods have complementary capabilities. The photometric bathymetry method determines depth from the intensity of light reflected back from the sea bottom. It requires ground truth datum to calibrate local water's optical properties and skilled photo-interpreters. If such calibration and expertise is available, photometric bathymetry can provide accurate depth and horizontal resolution comparable to LIDAR. However, getting ground truth points can be difficult (and cost extra). Photo-bathymetry only works in very clear water.

The SAR approach senses the interaction of a current with bottom bathymetry (another approach developed in Europe over the past 20 years). SAR does not depend on water clarity, but it does requires tidal current exceeding half-a-meter per second. It also requires ground truth calibration to invert SAR measurements into accurate depth.

WK offers a modest horizontal resolution (not as good as any of the above methods) but has several advantages: it works in turbid water (an important consideration for at least 50 percent of the world coastlines), it does not depend on strong tidal currents and it does not require ground truth calibration. In fact, WK bathymetry can substitute for ground truth in the calibration of the other methods.

> ***"Satellite WK can now be added to a host of other bathymetric charting techniques and services."***

The most important advantages of WK may be that it is a robust, fast and inexpensive method for surveying coastlines with very outdated charts. In very remote areas of the world, satellites offer the only practical option for maintaining up-to-date charts.

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Ron Abileah is engaged in remote sensing with satellite imagery, underwater acoustics and radar, earning a B.S. in mathematics from the University of Missouri in 1972. His technical interests include the use of commercial satellites for monitoring marine mammals and geophysical processes.