# MAPPING SHALLOW WATER DEPTH FROM SATELLITE

**Ron Abileah**
jOmegak
San Carlos, CA 94070
info@jOmegak.com

## ABSTRACT

Wave Kinematics Bathymetry (WKB) determines the water depth from ocean waves velocity. This method has been intensely researched over the past 20 years for remote sensing bathymetry. There are several successful implementations with nautical radars and aerial videography. Here we report on the first attempt to use high resolution satellite imagery. A successful test was made in a 60 $km^2$ area adjacent to the San Diego bay inlet with high resolution (~1 m) images taken by the IKONOS satellite. Comparing results with a multibeam sonar survey we determined that the following can be achieved with satellite WKB: one sigma depth errors in the range of 5-10%, horizontal resolution proportional to depth (100 m at 10 m depth), for up to a maximum depth of 25 m. The paper also discusses the strengths and weaknesses of WKB relative to other methods.

## INTRODUCTION

Several methods exist for charting shallow water bathymetry by remote sensing. The most advanced is the Airborne Lidar Bathymetry (ABL) method (Gunther 1996; also see other paper at the official SHOALS ABL web site http://shoals.sam.usace.army.mil/ ). Other technologies are based on: multispectral imaging of bottom reflected sunlight, a.k.a. photobathymetry (Lyzenga, 1978); sensing ocean currents-waves-bottom interaction with Synthetic Aperture Radar (Alpers, 1984); ocean wave refraction (Kasischke, 1986; Bennett 1986); and ocean wave velocity, which we call wave kinematics bathymetry (WKB) and will say a lot more about in this paper.

Table 1 compares the various methods. Depth accuracy is defined as a percentage of depth. Horizontal resolution is also known as the "sounding density" and defines the smallest navigational obstruction that can be detected. Accuracy and resolution standards for navigation charts are set by the International Hydrographic Organization (IHO) and "IHO order 1" is the goal for charts used in coastal navigation.

**Table 1. Comparison of remote sensing methods**

| | Depth accuracy | Horizontal resolution | Airborne/Satellite | Turnaround (months)[1] | Cost / sq km[1] | Turbid waters | Day/ night |
|---|---|---|---|---|---|---|---|
| Airborne Bathymetric Lidar | IHO-1 | IHO-1 | Airborne | 6-12 | >$1000 | X | ✓ |
| Photobathymetry | Variable | 10-30 m | Both | 1-2 | $50 | X | X |
| Currents interaction | Variable | 25 $m^2$ | Both | 1 | $10 | ✓ | ✓ |
| Wave refraction | 10-20% | 1 km | Both | 1 | $10 | ✓ | ✓ |
| WKB | 5-10% | 50-200 m | Both | 1-2 | $50 | ✓ | ✓[3] |

Notes: [1]Rough-order-of-magnitude assuming satellites, except ABL, which is on aircraft. [2]Ref: Argoss website (www.argoss.nl ). [3]WKB with the satellite imagery described in this paper is daytime only. However nighttime is possible with long wave IR (Farber, 1995), nautical X-band radars (see text), and theoretically possibly with space SAR.

The best method depends on circumstances and requirements. There is no substitute for ABL if the customer requires IHO-1standard. However other methods compete favorably in one or more of the other criteria. Possibly the most important motivation for the other methods is that all can be implemented with existing commercial low Earth orbit satellites. ABL is implemented on helicopters and twin-engine aircraft. It would be prohibitively expensive (because of the required laser power) to place it in space. Other benefits in the alternative methods are significantly lower cost and faster turnaround. Also note that ABL does not work in turbid waters. So in turbid waters, which is not an uncommon situation on the world's coastlines, an alternative method is needed.

Among the satellite based methods there are several considerations beyond the factors mentioned in the table. For instance, the current interaction method requires tidal currents > ½ m/s exactly at the time that the sensor is overhead. Both the current interaction and photobathymetry methods require calibration of nuisance parameters in the data reduction. For example, the photobathymetry method requires knowledge of the water attenuation to convert radiance into depth. There are several approaches for calibration but the only reliable method uses a handful of *in situ* depth measurements in the survey area. This implies that some bathymetry data must be acquired with ship sonar or ABL simultaneously with the remote sensing data. This is not always practical and adds time and costs (which are not included in Table 1). WKB does not need calibration and so is better for remote or inaccessible areas. On the other hand WKB requires ocean waves and so would not be suitable for harbors, estuaries, lakes, etc.

Photobathymetry, current interaction, and wave refraction have already been demonstrated from satellites. Results with photobathymetry has been widely reported on with data from the SPOT, LANDSAT, IKONOS, and QuickBird satellites. Bathymetry based on current interaction uses space based SAR and is offered as a commercial service (www.argoss.nl). There have been several operational implementations of WKB over the past 20 years, but not from satellite. In this paper we describe the first test of WKB with satellite imagery.

### How WKB works

WKB uses the fact that ocean waves slow down in shallow water. For example, the speed of a 50 m wave changes from 8.8 m/s in infinite depth, to 8.2 m/s at 10 m depth, 6.6 m/s at 5 m depth, and so forth. Longer (shorter) waves travel faster (slower). The trick than is to measure wave speed. WK use a sequence of two or more images which are taken at precisely known intervals, usually between 1 to 20 seconds. The images are orthorectified and georeferenced and a computer algorithm fits a "depth solution" to the data based on the wave motion.

In practice the analysis is a bit more complicated because the ocean surface is a composite of an infinite number of wavelengths, and each wavelength responds differently to depth. Another complication is that there is an ocean current superimposed on the depth dependent velocity. Sophisticated processing is required to determine a depth fit to the data. The fitting algorithm most commonly used today was developed in the 1980s at two European research organizations, the Netherlands Organization for Applied Scientific Research (TNO) and the German GKSS. Detailed explanation of the algorithms can be found in papers from these organizations (Hoogeboom, 1986; Seemann 2000; Senet, 1987; Van Halsema, 1986) and others (Dugan, 2000; Pieotrowski, 2002). A brief explanation follows.

The images $I_t(x,y)$ represent the ocean surface in georeferenced coordinates (*x*,*y*) at time *t*. The images are Fourier transformed into wavenumber spectrum $S_t(k_x,k_y)$. Ocean waves propagate according to the gravity wave dispersion relation such that the spectrum at time *t* is related to the spectrum at *t=0* as follows

$$S_t = S_0 e^{-i(\sqrt{g|k|\tanh(|k|d)} + [U_x, U_y]\bullet[k_x, k_y]')t},$$

where *d* is depth, *g* is the gravitation constant, and *U* is ocean current. Thus the spectrum phase (the term in the exponential) depends on depth and current. Depth and current are derived from the phase change ( $\arg(S_t/S_0)$ ) between two or more image transforms. One trick for a quick solution is to recognize that long waves "feel" the bottom, but short waves do not. Thus we first estimate the current velocity with short waves, i.e., wavelength < 10m, |*k*| > 0.1 c/m, and then fix the current velocity and solve for depth with the long waves, i.e., wavelength > 10m.

The above gravity wave dispersion equation is actually an approximation, but a very good one for depths > 2 m and generally works even at 1 m with moderate wave heights. In shallower depth the wave propagation physics changes significantly and different algorithms are required.

### Prior implementations

Although the physics underlying WK bathymetry were know for over 100 years, the practical use of the method required two crucial technological developments that did not exist until recently. The first: sensors that provide high resolution digital images of the ocean surface. The second: computers and Fast Fourier transforms for the calculations. These elements came together in the mid 1980s and several implementations began in Europe and the US. The European organizations used nautical X-band radars situated on bluffs (van Halsema 1986; Hoogeboom 1986; Senet 1997; Bell, 1998; Seeman, 2000). These systems are useful for continuous monitoring of coastal dynamics at a fixed location, but not for general surveying. US organizations pursued WKB with aerial photogrametric and aerial videography, which have a greater geographical reach. All prior implementations have been terrestrial. However, the earlier aerial photogrametric and videography work naturally evolved into WKB with satellite imagery as described later.

The first photogrametric implementation was by a research group at the Naval Ocean Research and Development Activity. They used images taken at six second intervals with an aerial reconnaissance camera overflight at Camp Pendelton beach, CA (Caruthers, 1985). Another group at Arete Inc. demonstrated WKB with the imagery from a high altitude military long-wave IR camera (Farber, 1995). This was the first instance of bathymetry at very long range (70 km). Later the same group developed a visible videography system in a stabilized turret for low altitude aircraft (Dugan 2000) and ran extensive tests at the US Army Coastal Engineering Research Center Field Research Facility (FRF) at Duck, NC. Their WKB depths were within 5% of ground truth (Piotrowski, 2002).

Another approach to ocean wave sensing used the airborne topographic Lidar (ATL). (Not to be confused with ABL. ABLs measure depth by lidar ranging to the ocean bottom. ATLs map the water surface topography.) Most ATL systems, however, are not designed to image the same surface two or more times in rapid succession and are thus not suitable for WKB. One exception is the NASA Airborne Topographic Mapper (ATM) which use an elliptical scan pattern producing two images of a 200 m swath separated by 2-3 seconds – an ideal interval for WKB. In 2001 the author tested the WKB on ATM data provided to him by Paul Hwang who had acquired the data for another and unrelated ocean waves research program (Hwang, 2000). The WKB depths were in qualitative agreement with charts and self consistent. Theses WKB results are not published but interested individuals can contact the author for further information.

## SATELLITE WKB

The motivation for using satellite is speed and access to remote areas. And with satellites it is easier to take the images under favorable meteorological and ocean wave conditions. You do not need to deploy sensor assets to location and than wait for the optimum conditions. Instead you checkup on the location at every opportunity. Typical satellites can revisit any spot on Earth at intervals of 3-4 days.

The implementation of WKB from satellite, however, had to await the arrival of satellites that can produce imagery for WKB. All commercial satellites use pushbroom imaging. To acquire two images requires one pushbroom scan, then re-pointing the camera to re-scan the same ground area, all within a few seconds. This requires pointing agility. WKB also requires 4 m or better ground resolution. Early imaging satellites did not have the needed capabilities. LANDSAT can only stare at nadir and did not have sufficient resolution. SPOT satellites have side-to-side pointing, which is not enough. Satellite WKB became feasible only with IKONOS, which was placed in orbit in 1999 by Space Imaging (recently renamed GeoEye). IKONOS was followed by other similar agile and high resolution satellites: EROS A1 (ImageSat, 2000), QuickBird (GlobalEarth, 2001), and OrbView-3 (OrbImage, 2003). OrbImage is planning the launch of OrbView-5 in 2007.

In 2004-2005 the National Geospatial-Intelligence Agency sponsored a test of WKB with commercial satellites. In the following we describe the results of that test.

### Special considerations

The basic approach for WKB depth estimation is the same whether the ocean waves are imaged with nautical radar, aerial videography, or satellite. However there are several special considerations with satellite imagery that should be mentioned.

All the modern commercial satellites, with exception of EROS, take simultaneous images in panchromatic (typically covering 0.5-0.9 µm) and in four narrow spectral bands (near IR, red, green, blue). Since panchromatic has higher resolution than the multispectral (1m versus 4 m in IKONOS), it would seem logical to use pan as the primary data in WKB. However there are some important advantages to using multispectral images. The near IR and red bands exclude light from below the ocean surface, specifically from the bottom, and they have less atmospheric path radiance. These factors increase contrast for surface waves. Higher wave contrast results in better WKB depths estimates. Also, multispectral images can be used to flag image pixels that are contaminated by clouds, whitecaps, ocean vessels and their wakes, flotsam, buoys, etc. These features cause spurious errors in WKB if not removed. Algorithms for multispectral discrimination of water and objects in water are described in (Silva, 1999).

We concluded that both pan and multispectral should be used in WKB processing. The ocean current is most accurately measured with the high resolution provided by panchromatic. The multispectral is best for depth estimation.

Another consideration is the sun angle. All the modern high resolution satellites can image up to $50^o$ off nadir look. The sun angle can thus be precisely optimized. The optimum imaging of ocean waves is in the direction of the sun but avoiding the $20\text{-}30^o$ sunglint cone, which is centered on the solar specular reflection point.

Lastly, suitable wave conditions are needed when the images are taken. The optimum conditions are significant wave height (SWH) in the range of 0.5 - 1.5 m, winds in the range of 5 - 15 kts. These conditions are fairly typical. There are 24 - 72 hour wave and wind forecasts that can be used to schedule satellite image capture.

## Test data

The IKONOS satellite was chosen for the 2005 test because of its re-pointing agility and simultaneous panchromatic and multi-spectral images. Another advantage for the study was that suitable images were available in the IKONOS image archive, so a special satellite tasking was not required. We used a series of seven pan-multispectral image sets of the inlet into San Diego harbor, taken in one overpass on April 8, 2002. The images were spaced ~13 seconds, at off-nadir angles from $7^o$ to $45^o$. For the middle image in the series the sensor-sun parameters were: Sun azimuth/elevation $146^o/61^o$, satellite azimuth/elevation $1^o/63^o$. Thus the camera pointing was $36^0$ from the sun specular point which is optimum for wave contrast. The total image area was 15 x 20 km. In this paper we focus on results in a 60 $km^2$ subset.

Figure 1 is one of the IKONOS images. Several key landmarks are indicated on the image on the left: the Pt. Loma peninsula, the harbor inlet, the Naval Air Station, and Silver Strand Beach. The harbor inlet is dredged. The distinct dark area in the water west of Pt. Loma is associated with a kelp forest. The image blowup on the right is a section of Silver Stand Beach and is intended to illustrate how well we see ocean waves in IKONOS images.

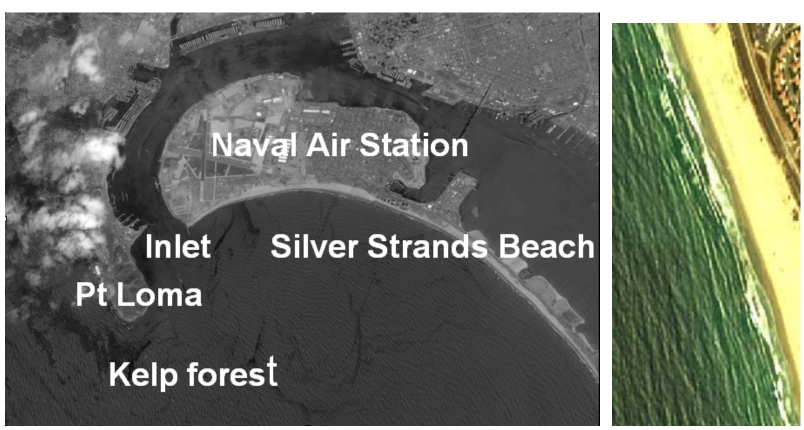


**Figure 1**. Left: IKONOS image and key landmarks discussed in the text. Right: a blowup of a small section of Silver Stands Beach. Image credit: Space Imaging.

The images were delivered by Space Imaging orthorectified and geo-registered. Several preliminary processing operations are done before depth estimation. First the image area is segmented into land + clouds and water. We also do noise filtering and flagging bad pixels in the water area using multispectral discrimination. The standard geo-registration done by the vendor is 25 m absolute. In WKB the geo registration between images (relative accuracy) is more important and the goal is 1 m. The WKB processing achieves this accuracy very easily, using landmarks (buildings, roads) or the short waves (ocean current and image mis-registration are indistinguishable: both offset the short waves). These operations and all the wave speed measurement and inversion into depth estimates are fully automated.

At the time the images were taken the SWH was 0.9 m (based on measurements of Scripps wave buoy 091, 20 km west of Pt Loma). This is a very mild sea. In fact the time history of several months before and after shows that on the image date San Diego was in a calm period in between major surf activity. The relative calmness of the waves is also confirmed by the very little white capping in the image. Despite the small waves, WKB did very well, as we show next.

### Test Results

There are two parameters in the process that can be adjusted to give varying accuracy: the horizontal resolution and number of image frames. WKB breaks the image area into square tiles. One tile is equivalent of one depth sounding. Our experience with WKB suggests that a tile dimension 10x the depth provides very good depth accuracy. Thus at 10 m depth we use 100 m x 100 m tiles, implying that depths are estimated on a grid of points spaced 100 m. The WKB process can derive depth estimates on several tile dimensions simultaneously. A good choice set is 50, 100, and 200 m. The final bathymetry product is then a fusion of high and low resolution tiles, depending on depth.

The number of image frames also affects depth accuracy. An increase in accuracy is theoretically possible with three or four images vice two images. (The main cost for satellite vendors is the setup and tasking; cost of taking a few more images after the first is not great and the cost of increased processing is insignificant. So multiple images should be taken if conditions permit.)

The aim or our test with the IKONOS San Diego images was to establish that WKB can work with satellite images, and to quantify the accuracy obtained with various choices of tile dimensions and number of images.

The basis of assessing WKB is comparing its depth with depths from a Fugro West multibeam sonar survey, which was conducted in October 2002, only 6 months after the satellite imagery. The comparison assumes that there had been no significant change in the bathymetry in the 6-month interval. The multibeam data is taken as absolute ground truth. The errors that will be reported for WKB are actually the sum of three errors: errors in the Fugro data, errors due to change in bathymetry in the 6 month interval, and errors in the WKB method. We believe the first two are small, so comparison reflects on the accuracy of WKB. The multibeam survey data was at 5 m resolution. For comparison the multibeam data was spatially averaged to correspond to the tiles used in WKB.

Figures 2 and 3 illustrate the results of WKB and comparison with ground truth. The WKB results are reported for depth range 5-20 meters. The Fugro ship generally stayed outside the 10 meter depth contour so direct comparison between WKB and Fugro survey is limited mostly to the range of 10 to 20 m.

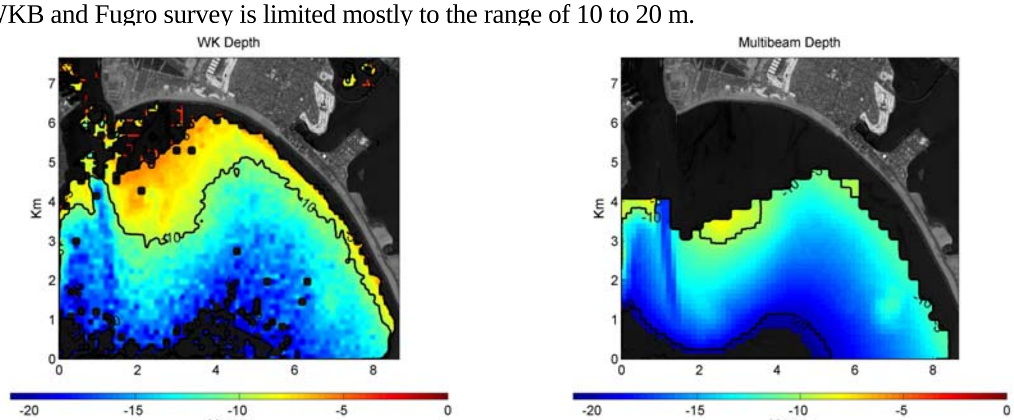


**Figure 2**. Left: WKB depths with 128 m tiles, 2 images. Right: Comparable Fugro multibeam depth. The color scale is depth in meters. A contour is drawn at the 10 m depth.

WKB results are shown on a color scale, from dark red (5 m) to dark blue (20 m). In the WKB plot a tile is blank when WKB failed to converge on a solution. The most common reason is insufficient short wind waves to estimate ocean current. As mentioned earlier knowing the surface current is important for WKB depth estimation. The depth will not be estimated unless the current can be accurately measured. In the San Diego image there were several patches of water where the short waves were deficient: in the area blocked by the Zuniga Jetty (at the tip of the Naval Air Station and inlet), an area where wind and waves are blocked by Pt. Loma, and inside the San Diego harbor. Another area (outside the area shown in Figure 2) was the kelp forest (pointed out in Figure 1). This was not surprising since it is well known that kelp damps out the ocean surface roughness that makes imaging the ocean surface possible.

In comparing the left and right plots in Figure 2 we see that WKB captured fine details of the bathymetry. For instance, WKB delineates the dredged channel leading into San Diego harbor. WKB also captured the 200 m mount in the lower right area. These features are even better represented in a four-image solution shown in Figure 3. The four image bathymetry is more accurate because the waves phase speeds are estimates with three time lags, versus one time lag with two images (Figure 2).

Figure 3 also provides comparison of the WKB bathymetry with depths contours in a USGS topographic map. The data in the map is over 30 years old. Comparison of bathymetry so many years apart must be treated with caution, but the comparison is a further indication that WKB is accurate, and especially at shallower depths that were not covered by Fugro.

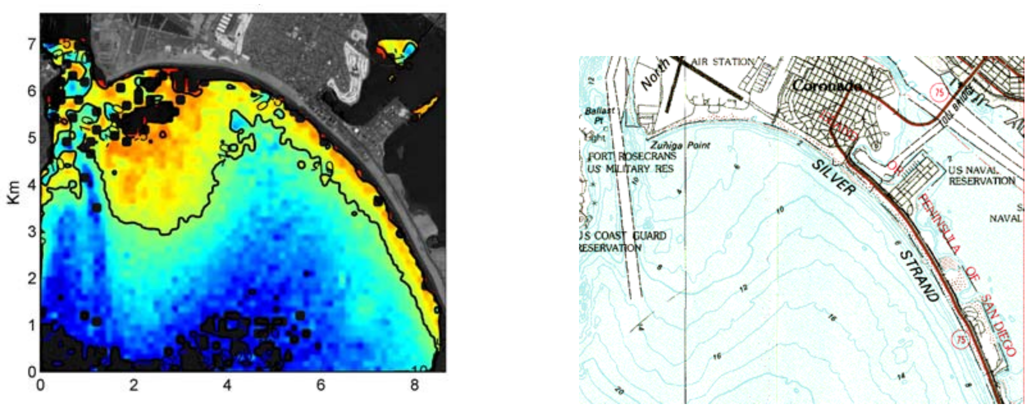


**Figure 3.** Left: WKB depths with 128 m tiles, four images; Right: corresponding USGS 1:24000 topographical map

The 1-sigma depth errors for various combinations were as follows

| | |
|---|---|
| 2 images, 256 m tiles | 4% |
| 2 images, 128 m tiles | 7% |
| 4 images, 128 m tiles | 5% |

The percent errors are for 10-15 m depths. Errors are slightly greater in the 15-20 m range. The results confirm that depth errors are reduced by either increasing the tile dimension (lowering resolution) or increasing the number of images. The two image processing produced good depth to 20 m. The four-image solutions extended to 25 m.

## CONCLUSIONS

WKB has been successfully demonstrated with satellite imagery. The resolution (nominally 100 m at 10 m depth) and depth accuracy (~5 %) are similar to results published for airborne videography. The horizontal resolution can be varied proportionally to depth. The 5% error applies to horizontal resolution 10x depth.

WKB is very fast compared to ABL. One satellite overpass can cover 300 km$^2$. The processing to convert images of 300 km$^2$ into bathymetry takes several days. Satellite revisit interval to a given area are 3-4 days. Thus an area of 1000 km$^2$ can be surveyed in less than one month. The actual turnaround time will be dictated by clouds and oceanic conditions, and by image acquisition priority. The estimated cost for WKB is < \$50/km$^2$, including the imagery at normal priority and WKB processing. Satellite vendors offers higher priority (faster turnaround) for additional cost.

WKB does not meet the IHO-1 standard for navigation safety charting. For that purpose there is no substitute for ship sonar and LIDAR surveys. But WKB does have a clear advantage in cost, speed, and access to remote areas.

Potential uses of WKB include coral reefs mapping, post storm assessment, and military amphibious planning. WKB should be useful for preliminary survey of large swath of coastline for planning ABL surveys. WKB, even without meeting IHO-1 standards , is clearly better than most existing outdated coastal charts.

## ACKNOWLEDGEMENTS

The author is indebted to Dr. Richard Brand, NGA, for his continued interest and encouragement of the research, and to Mr. Gene Dial of GeoEye (formerly Space Imaging) for immensely helpful technical advice on IKONOS imagery.

## REFERENCES

Alpers W. and I. Hennings (1984).A theory of the imaging mechanism of underwater bottom topography by real and synthetic aperture radar. *J. Geophys. Res.* , Vol. 89, 10,529-10,546

Bell, P. S. (1998). Bathymetry derived from an analysis of X-band marine radar images of waves. Proc. Oceanology '98, vol. 3, Brighton, U.K., 1998, pp. 535–543.

Bennett, J. R. (1986). An improved method for the determination of water depth from surface wave refraction patterns. Proc. of IGARSS'86 Symposium, Zurich (8–11 September).

Caruthers, J.W., R.A. Arnone, W. Howard, C. Haney, and D.L. Durham. (1985). Water depth determination using wave refraction analysis of aerial photography. Report 110, Naval Ocean Research and Development Activity.

Dugan, J.P., G.J. Fetzer, J. Bowden, G.J. Farruggia, J.Z. Williams, C.C. Piotrowski, K. Vierra, D. Campion, and D.N. Sitter (2000). Airborne Optical System for Remote Sensing of Ocean Waves. J. Atmospheric and Oceanic Technology.

Dugan, J. and C. Peiotrowski (2000). Developmental System for Maritime Rapid Environmental Assessment Using UAVs. Oceanology International 2000 Conference (7–10 March).

Farber, M., H.H. Suzukawa, Jr., and J. Dugan (1995). Long range airborne IR detection of ocean waves. *Proc. Targets and Backgrounds: characterization and Representation*, Vol. 2469, pp. 526-536 (17–19 April).

Fuchs, R. A. (1953). Depth estimation on beaches by wave velocity methods. Institute of Engineering Research Wave Research Laboratory

Guenther, G.C., Thomas, R.W.L., and LaRocque, P.E., (1996). *Design Considerations for Achieving High Accuracy with the SHOALS Bathymetric Lidar System*, SPIE: Laser Remote Sensing of Natural Waters From Theory to Practice, Vol. 2964, 26-37

Hoogeboom, P., J. C. M. Kleijweg, and D. van Halsema (1986). Seawave measurements using ship's radar. Proc. IGARSS Symp. (8–11 September)

Hwang, P., W. Krabill, W. Wright, R. Swift, and E. Walsh. (2000). Airborne Scanning Lidar Measurement of Ocean Waves. Remote Sensing of Environment, Vol. 73, pp 236–246.

Kasischke, E.S., G.A. Meadows, and P.L. Jackson (1986). The use of synthetic aperture radar imagery to detect hazards to navigation. ERIM Report 169200-2-F, for Defense Mapping Agency.

Lyzenga, D. (1978). Passive remote sensing techniques for mapping water depth and bottom features. Applied Optics, 17, No. 3, pp 379–383.

Piotrowski, C. C., and J. P. Dugan (2002). Accuracy of Bathymetry and Current Retrievals From Airborne Optical Time-Series Imaging of Shoaling Waves. IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 40, NO. 12, December 2002

Seemann, J., C. M. Senet, U. Wolff, H Hatten, and F. Ziemer, F (2000). Hydrographic parameter maps retrieved from nautical radar image sequences of inhomogeneous water surfaces. IGARSS2000, Conference Proceedings, Volume V, pp. 1898-1900

Senet, C. M. and J. Seemann, and F. Ziemer, (1997) "An iterative technique to determine the near surface current velocity from time series of sea surface images," in Proc. MTS/IEEE Oceans '97, Halifax,Canada, pp. 66–72.

Silva, D. M., and K. M. Tao, R. Abileah, and D.E. Moellman (1999). Multispectral and Hyperspectral Imagery For

Ocean Search and Rescue: Detection and Identification of Background Anomalies. International Symposium on Spectral Sensing Research, ISSSR 1999, Las Vegas, USA, 1-4 November
van Halsema, D., and J.C.M. Kleyweg (1986). The measurement of wavefields with a simple ship's radar. Fysisch En Electronisch Laboratorium, TNO, Report FEL (20 April 1986).