MAPPING NEAR SHORE BATHYMETRY USING WAVE KINEMATICS IN A TIME SERIES OF WORLDVIEW-2 SATELLITE IMAGES

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ABSTRACT

The near shore bathymetry can be mapped with remote sensing of the motion of shoaling gravity waves. This method can be used with satellite imaging systems that can image a series of images with high resolution. Previous validation of this technique used two satellite images taken 10 s apart.. This paper reports on another validation with images in the vicinity of Newport, Oregon, USA, acquired on December 30, 2012 with the WorldView 2 satellite. The new results are obtained. First, demonstrating the benefits of averaging multiple (up to 10) image pairs. Second, significantly better spatial resolution than previously achieved. Third, increased maximum mapped depth. The Newport area bathymetry was mapped from just outside the surf zone out to a depth of 30 m, with a spatial resolution of 50 m. The result compares very favorably with the NOAA depth chart for this area.

Index Terms— shallow water bathymetry, shoaling waves, high resolution satellites

1. INTRODUCTION

There are two methods for mapping the near shore bathymetry from satellites. The first inverts the intensity of bottom reflected radiance into depth. This works in coastal waters with low optical attenuation in the blue-green bands. It is most often demonstrated in very clear tropical waters. Most implementations also include some form of in situ optical calibration and are thus not entirely based on remote sensing. The second method, which is the focus of this paper, inverts shoaling waves motion into depth. This method requires only imaging light reflected from the ocean surface. It is thus suitable in both clear and turbid waters. No in situ calibration is needed. Thus the method offers a more robust means of mapping bathymetry with satellite imaging systems. The validation of this method was previously reported. This paper adds an important additional validation test case.

There is a long history in using wave motion with coastal shore-based X-band radars, shore-based video, and airborne imaging. Hoogeboom et al. IGARSS'86 paper [1] introduced the modern, fully digital, Fourier transform based algorithm for depth inversion.

Many investigators followed Hoogeboom et al. with various refinements in implementation. A comprehensive summary of the key works can be found in [2,3]. Piotrowski and Dugan [3] provide an excellent account of their algorithm, which is similar to most other works in this area. They start with a 250 m x 250 m x 100 s cube of orthorectified and well registered images of the ocean surface. The cube is Fourier transformed into a wavenumber-frequency spectrum. A least-squares fitting of the theoretical gravity wave dispersion equation to the power spectrum determines a single depth value for the area spanned by the cube data. The cube dimensions define the spatial resolution, or 250 m. As shown in [3] the depth accuracy quickly degrades with smaller cube dimensions and is thus unsuitable for high resolution depth mapping. Another limitation of the method is the requirement of ~100 s of image data with a constant (or very little change) in sensor-surface geometry. This can be achieved with a fixed sensor or a slow flying aircraft circling the area of interest, but not from a satellite where the sensor view geometry changes rapidly.

2. HIGH RESOLUTION BATHYMETRY

A new algorithm was developed [2] to address the above limitations. The algorithm requires only two images, and depth is estimates at a pixel resolution, at least in theory. In practice the resolution is limited by the image interval time and noise, but is still better than previous methods.

Conceptually the algorithm is very simple. Let $I_1(x,y)$ and $I_2(x,y)$ represent the first and second images, respectively. Let $\Phi z, \tau$ represent an operator that propagates ocean waves for τ seconds, assuming a water depth z. The depth at any location x,y can than be estimated by minimizing the cost function, J, the difference between image 1 propagated forward $\tau/2$, and image 2 propagated backwards $\tau/2$,

$$J(x, y) = \ldots$$
$$\left\langle \left| \Phi^{z,\tau/2}(I_1(x, y)) - \Phi^{z,-\tau/2}(I_2(x, y) \right|^2 \right\rangle_A$$

with respect to z. The brackets $\langle..\rangle_A$ indicate noise averaging over an area A, which then defines the effective spatial resolution. The implementation uses Fourier transforms for efficient application of the Φ operator. The algorithm also includes shifting images to correct for ocean drift, which is also estimated in the process. Full details are in [2]. Without noise, and with $\tau \to 0$ the algorithm can be shown to produce exact bathymetry at single pixel resolution.

3. EVALUATION OF METHOD WITH WORLDVIEW-2 IMAGERY

The WorldView-2 satellite is well suited for this technique. By repeated camera re-pointing a time series of images at ~10 s intervals can be acquired of the same area during a single overpass. Image data is provided in both Panchromatic (1/2 m pixel resolution) and in eight Multispectral bands (2 m). The bathymetry inversion can use either Pan or Multi-spectral, or combination of the two. The higher resolution of Pan is useful to estimate the surface currents accurately. The IR bands are better for imaging ocean waves when there is strong reflection of the visible bands, including Pan, from the ocean bottom.

An earlier test with WorldView-2 imagery used a 7-image time series of Waimanalo Beach area, Oahu, Hawaii. The analysis is in Mancini's 2012 thesis work at the Naval Postgraduate School, Monterey, California, and also published in SPIE proceedings [4].

The latest data acquired for testing this method is a time series of 17 images on December 30, 2012, of a stretch of the Oregon coast between Newport Inlet and Yaquina Head. The area includes Agate Beach which Oregon State University researchers use as a laboratory for wave dynamics studies including Bathymetry inversion [5]. NOAA conducted a ski jet fathometer survey of Agate Beach. The bottom morphology includes small depressions, ridges, and submerged rocks to test the ability to resolve depth variations.

In the 17-image data series the wave visibility is noticeably degraded towards the end, due in part to intervening thin clouds. Images 2-12 were considered to have adequate wave imaging quality. Hence the analysis was limited to image pairs in this range, with up to 10 image pairs. In this data the Pan band was better than the Multispectral bands for imaging waves. Pan was less affected by the thin clouds. And due to high water turbidity bottom reflected radiance is not an issue.

Figure 1 is the bathymetry with 300 m resolution, and Figure 2 is 50 m resolution, with depth color coded for the range 0 to 30 m. A +1.1 m tide level correction has been applied. Contours for 10, 20, and 30 m depth are

superimposed for easier comparison to the same contours in the NOAA chart shown on the right.

In the left panel in Figure 1 is the bathymetry obtained with one image pair, the center panel is with 10-pair averaging. There appears to be only a small benefit from using more than two images for 300 m resolution.

In Figure 2 the method is tested with 50-m resolution. One image pair produces noisy depth estimates (rmse 3m). The 10-pair average produces marked improvement (rmse < 1m). Figure 3 is a zoom into a small area to illustrate that averaging succeeded in resolving a ridge and narrow feature delineated by a 10 m depth contour, just below the 'dumpsite' label.

The range of depths reliably estimated by this method depends on wave conditions, in particular the dominant wavelength, L. In the previously cited Waimanalo Beach case L=50 m and maximum reliably estimated depth was 16 m. In the Newport case the L=100 m and the maximum reliable depth appears to be at least 30 m. Based on these observations a rule of thumb for maximum depth is ~1/3 L. The low end limit is determined by the location where wave crests steepen to the breaking point and then transform into surf. The processing automatically detects and blacks out depth estimates in or near surf. Longer waves reach to greater depth, but shorter waves would are better for mapping the shallower depths nearer to shore.

Not available at the time of this writing but expected for the final truth data comparison are the LIDAR and fathometer depth surveys available for this area.

4. ACKNOWLEDGEMENTS

5. REFERENCES

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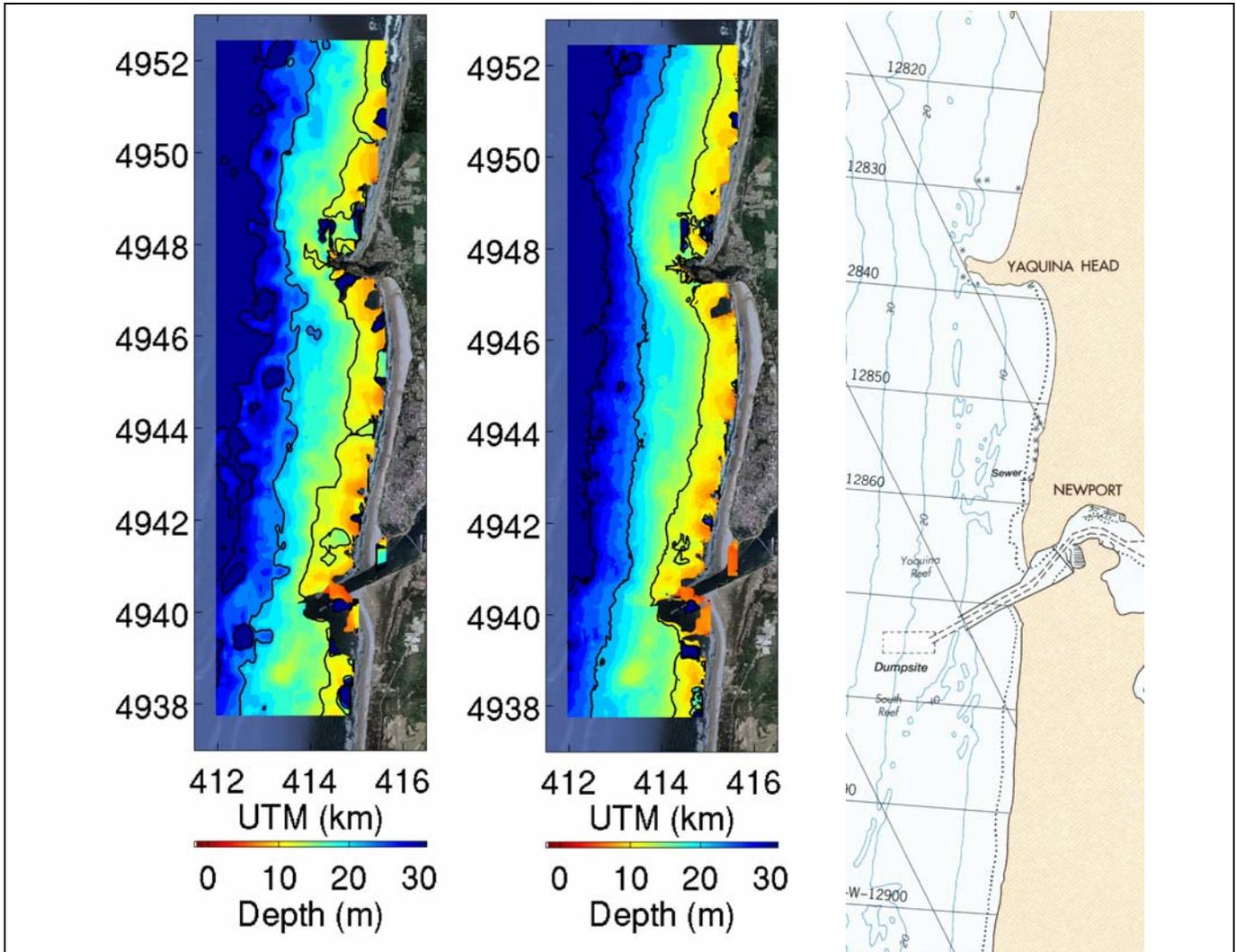
Figure 1 Satellite derived bathymetry with 300 m resolution. Left: Using one image pair. Center: Average of 10 image pairs. Right: NOAA chart for comparison.
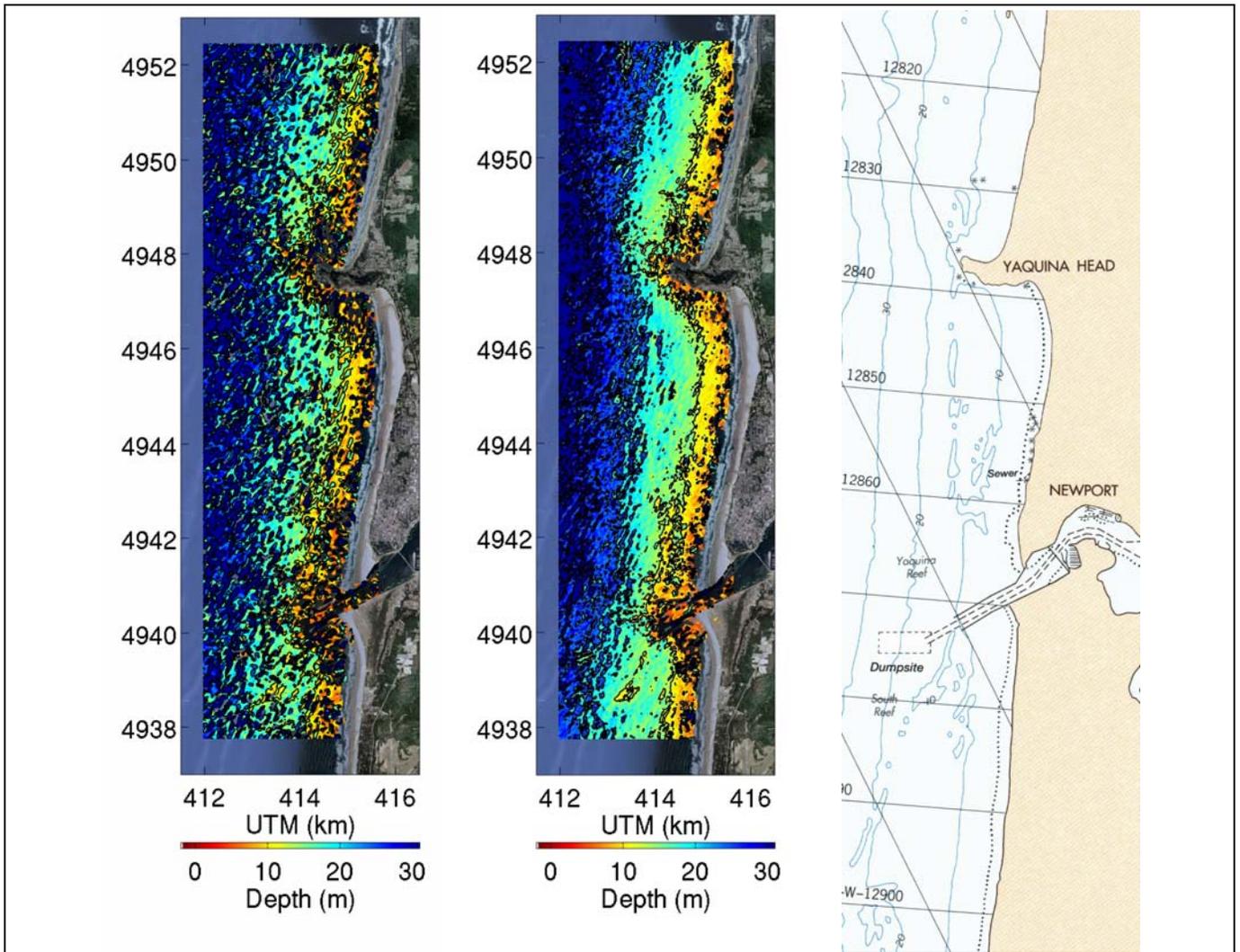
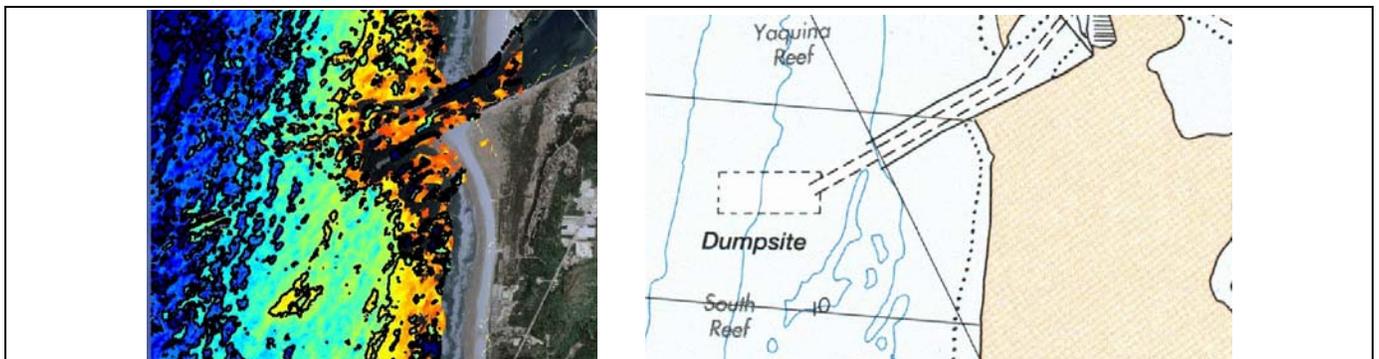**Figure 2 Satellite derived bathymetry with 50 m resolution.**

Figure 3 Detail in vicinity of Newport Inlet.