BATHYMETRIC MODULATION ON WAVE SPECTRA

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ABSTRACT Ocean surface waves may be modified by ocean current and their observation may be severely distorted if the observer is on a moving platform with changing speed. Tidal current near a sill varies inversely with the water depth, and results spatially inhomogeneous modulation on the surface waves near the sill. For waves propagating upstream, they will encounter stronger current before reaching the sill, and therefore, they will shorten their wavelength with frequency unchanged, increase its amplitude, and it may break if the wave height is larger than 1/7 of the wavelength. These small scale (~ 1 km) changes is not suitable for satellite radar observation. Spatial distribution of wave-height spectra *S*(x, y) can not be acquired from wave gauges that are designed for collecting 2-D wave spectra at fixed locations, nor from satellite radar image which is more suitable for observing long swells. Optical images collected from cameras on-board a ship, over high-ground, or onboard an unmanned auto-piloting vehicle (UAV) may have pixel size that is small enough to resolve decimeter-scale short gravity waves. If diffuse sky light is the only source of lighting and it is uniform in camera-viewing directions, then the image intensity is proportional to the surface reflectance *R*(x, y) of diffuse light, and *R* is directly related to the surface slope. The slope spectrum and wave-height spectra *S*(x, y) may then be derived from *R*(x, y). The results are compared with the in situ measurement of wave spectra over Keelung Sill from a research vessel. The application of this method is for analysis and interpretation of satellite images on studies of current and wave interaction that often require fine scale information of wave-height spectra *S*(x, y) that changes dynamically with time and space.

KEY WORDS: Backscattering, bathymetry, wave

1. INTRODUCTION

1.1 Modulation on Surface Waves

As surface waves propagate into region of varying depth, the successive wave crests propagate at different speed. As they propagate into region of changing surface current, the successive wave crests are carried by currents of different speed. In either of above two cases, the wavelength, or the distance between two successive wave crest changes with location and time.

In the case of shoaling or current with convergence, the wave energy converges, wave height increases, surface gets rougher, and surface wave may even start to break. Because the wave spectrum and tidal height changes constantly, the surf zone changes constantly. The same situation happens if the current patterns also propagate, just like the surface wave.

As non-linear internal waves (NLIW) propagate through the ocean, it will generate surface current that is not negligible with respect to the dominant waves. To those short gravity waves that are responsible to the Bragg scattering on satellite radar waves, the current speed of NLIW is too large for them to propagate against. These short gravity waves will converge or even break at the convergent side of NLIW, and results higher Bragg scattering, and bright pattern on synthetic aperture radar (SAR) images.

1.2 Bathymetric Effect

Non-uniform bottom depth is a good source for generating non-uniform current. Northeast of Taipei at northern Taiwan (Fig. 1), there is Keelung Sill between Keelung Harbour and Keelung Islet (KLY in Fig. 2).

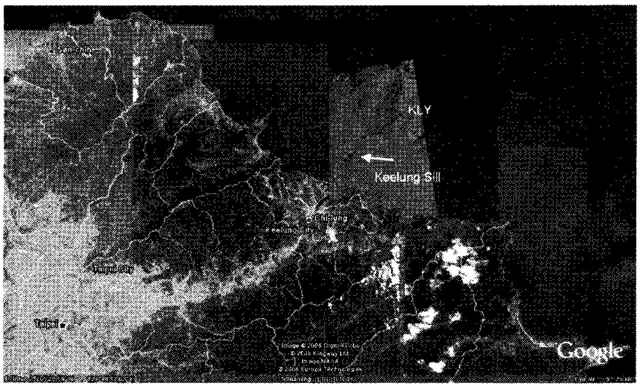

Figure 1. Geographic location of Taipei, Keelung Islet (KLY) and Keelung Sill. The sill top is indicated by the change of color of sea surface.

The hypothesis is that when the tidal current approaches a sill, it will speed up; and slows down as it leaves a sill. Surface waves will be modulated as it propagates into this region of different current speed. In the normal case, there is Dispersion Relation among the wave frequency ω, wave number κ and water depth d:

$$\omega = \sqrt{g\kappa \cdot \tanh(\kappa d)} \tag{1}$$

where g is gravitational acceleration (9.8 m/s/s)

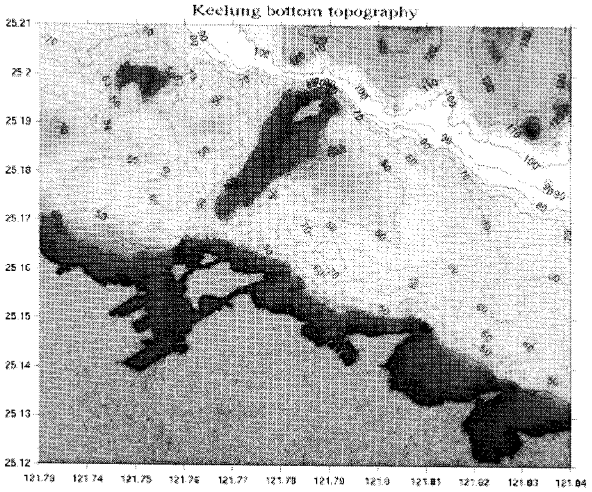

Figure 2. The bathymetry near Keelung Sill (yellow line), between Keelung Islet and Keelung Habor..

Waves will change its wavelength as they propagate through region of changing depth and changing current, but they will not change their frequency. This can easily be verified if we have a fixed sensor in the water tank, or a fixed station in the water.

Near the sill, the water depth is mostly above 40 m. It is unrealistic to have a fixed station. So, we will observe the waves from a ship, as in Fig. 3.

Fig. 3: Measuring surface wave over Keelung Sill with wave gauges on the starboard side of Ocean Researcher 2.

1.3 Doppler Effect

Because the ship drifts with the current, the observed wave frequency is Doppler shifted towards higher frequency if the waves are propagating upstream, and towards lower frequency otherwise. We are interested in the waves that propagated upstream because these are the waves that have higher energy and they cause bright pattern on SAR images (Fig. 4) of the meeting.

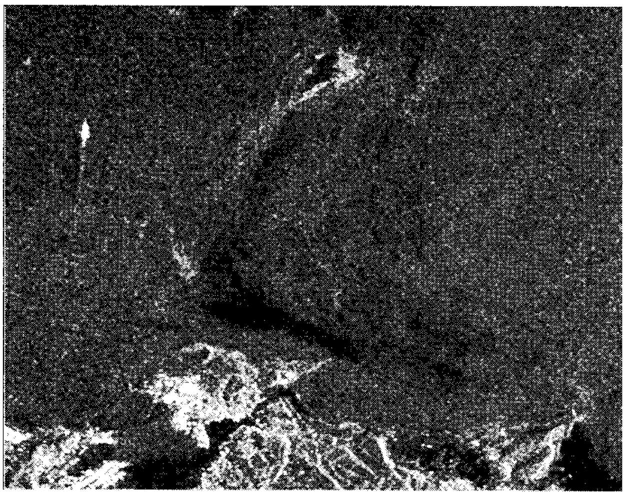

Figure 4. Satellite SAR image of surface roughness over Keelung Sill during northwestward flood tide. The brighter pattern was produced by surface waves propagating upstream and resulted higher density of surface waves.

The observed wave frequency ω_D is Doppler shifted and has a new Dispersion Relation:

$$\omega_D = \vec{\kappa} \cdot \vec{U} + \sqrt{g\kappa \cdot \tanh(\kappa d)} \tag{2}$$

where U is approaching speed of the ship towardst the waves.

2. METHODS OF OBSERVATION

2.1 Photographic Images

If the sea surface is illuminated by **diffuse sky light** that is uniform in all directions, then the reflected skylight increases with the viewing angle α (zero for looking down a flat surface), or reflectance $\rho(\alpha)$ increases with α.

For a camera with fixed inclination from horizontal plane, the viewing angle α increases when the sea surface is tilted away from camera, so is $r(\alpha)$, and the pixel is brighter.

2.2 Photos taken near the Bridge of R/V

Photos of sea surface were taken when R/V Ocean Researcher 2 drifted downstream, from region of smooth surface towards the sill top, and to the lee side of Keelung Sill

In the zone above the Keelung Sill, surface waves of 5~10 meter long dominate wave amplitude, vs. further downstream

These are not the short gravity – capillary waves that reflects satellite SAR energy by Bragg scattering

It is difficult to compare the wavelength, or change of wavelength if we do not view the waves from directly above sea surface. Fig. 5 shows the original and orthonormally projected images of surface waves before they reach the sill. It is clear that the surface reflectance image is more wave-like pattern after the projection.

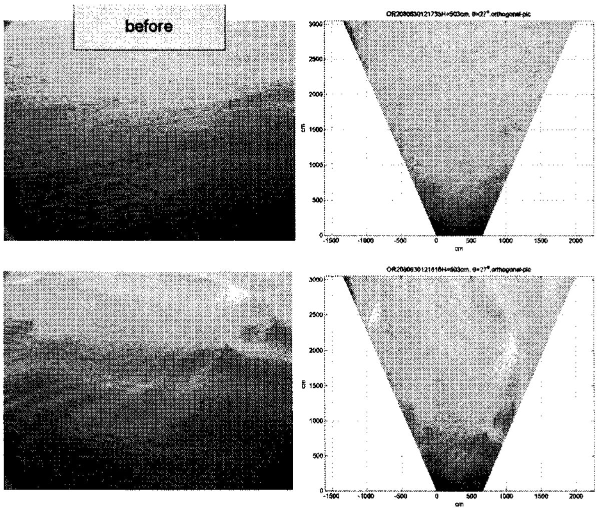

Figure 5. The original (left) and orthonormally projected (right) images of surface waves before they reach the sill.

Fig. 6 shows the change of surface roughness as the waves propagated into the region of influence by the sill, and after the waves passing the sill.

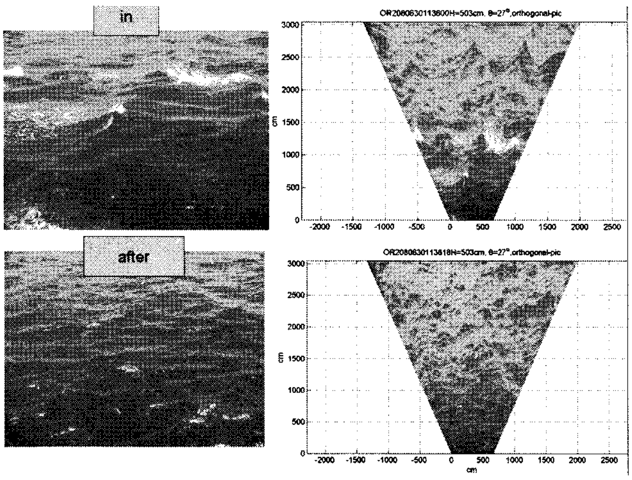

Figure 6. The original (left) and orthonormally projected (right) images of surface waves as they propagated into the region of influence by the sill, and after the waves passing the sill.

2.3 Photos from Hill Top

In order to continuous images of the same sea surface, one must stay at a fixed location. The only choice is taking photos from the hill top of Keelung Islet, Fig. 7.

Projecting above image to geographic coordinate (Fig. 7) is a necessary step for cross comparison of images from the ship, and from UAV.

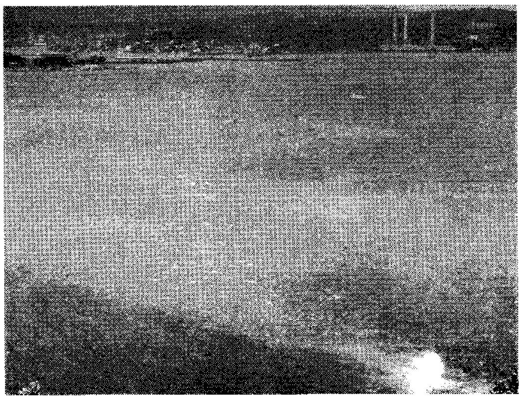

Figure 7. Surface roughness pattern that was observed from hilltop.

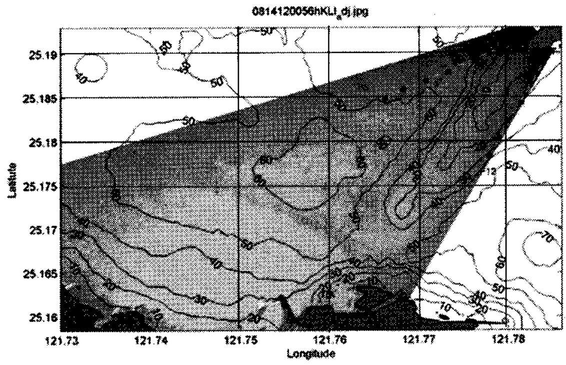

Figure 8. Photos from hill top is projected to geographic coordinate.

2.4 Photos from Unmanned Airborne Vehicle (UAV)

Viewing large area with high spatial resolution and medium viewing angle can only be down with Unmanned Airborne Vehicle (UAV).

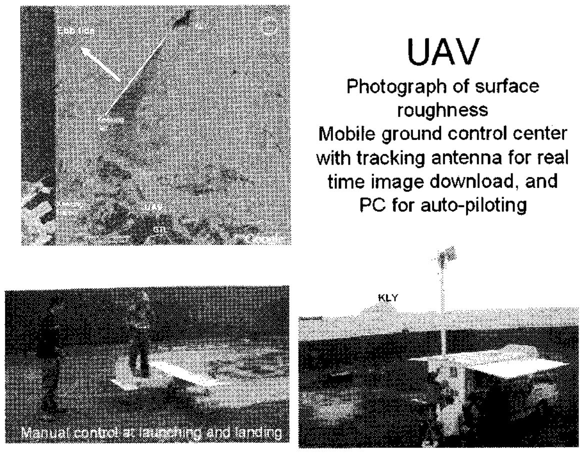

Figure 9. UAV operation from mobile ground station with tracking antenna (lower right), manual control for launching (lower left), and computer controlled flight over Keelung Sill (upper left)

A comparison of images taken by various methods is shown in Figure 10.

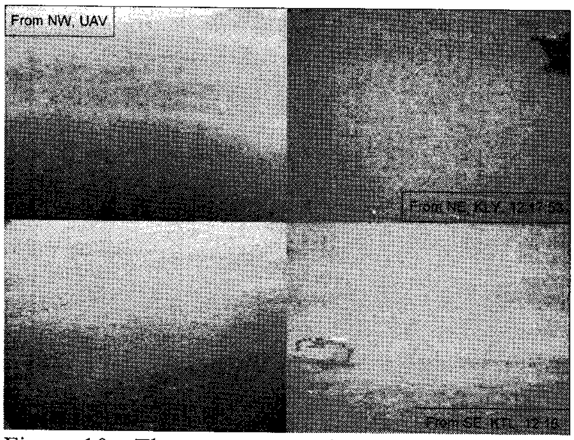

Figure 10. The same sea surface that was photographed from different angle and different methods.

3. DATA ANALYSIS

The processing procedure of images is shown on UAV photos:
(1) Select an image (Fig. 11);

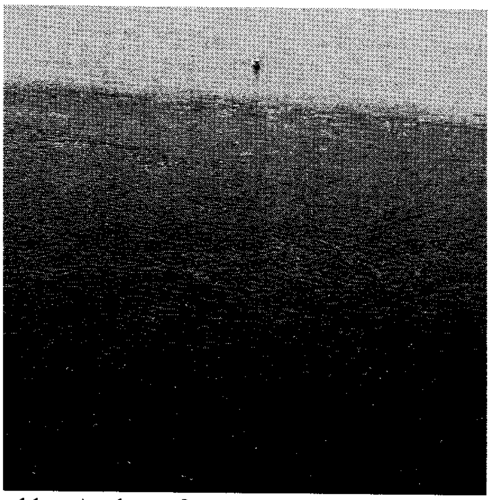

Figure 11. A photo from UAV when the ship passing Keelung Sill. (courtesy of 智飛科技)

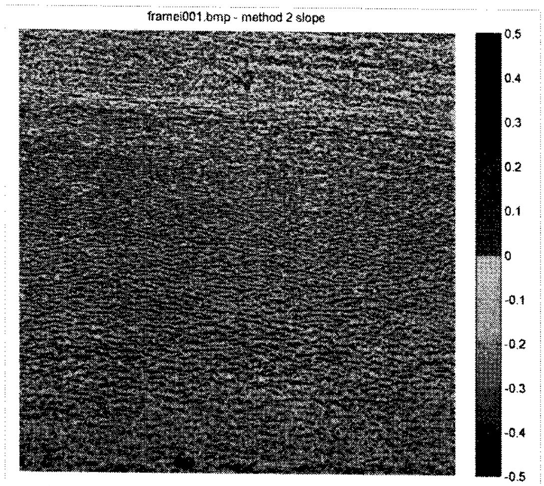

Figure 12. Slope of sea surface in the viewing direction of UAV.

(2) Derive image of slope in viewing direction (Fig. 12);
(3) Make orthonormal projection to correct x-y aspect ratio (Fig. 13)
(4) Take a slice of the image across the sill top
(5) Take Huber-Huang Transformation to derive power spectral density (PSD) as a function of distance and wavenumber (Fig. 14).

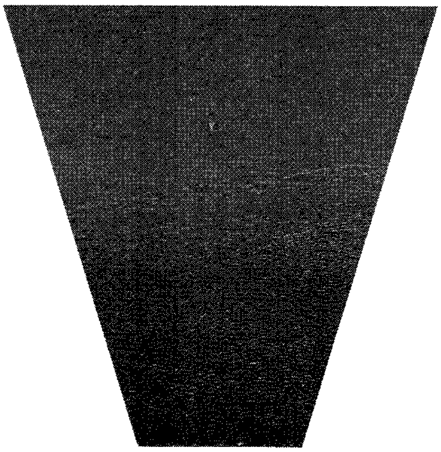

Figure 13. Slope of sea surface that is projected to geographic coordinate.

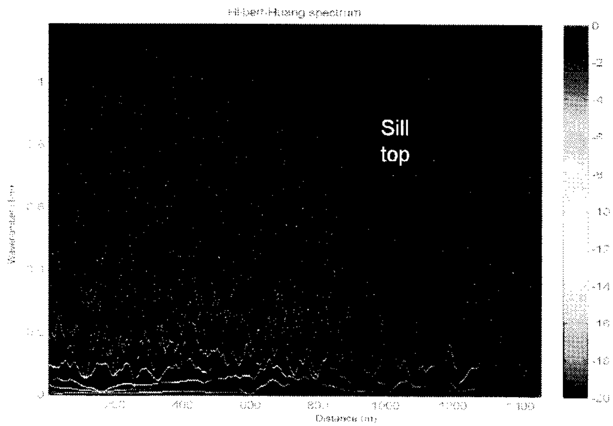

Figure 14. Power spectral density as a function of time as derived with Hilbert-Huang Transformation

4. DISCUSSION

The implication of PSD from HHT (Fig. 14) is that:
(1) PSD of 1~ 5m (k = 0.2~1 m-1) short waves dropped off near the sill, with 1-m long wave disappeared first;
(2) These are not the wavelength for Bragg scattering as shown in SAR images;
(3) PSD of 10 or 20 m long waves can pass over the sill, but they still loose some energy

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