Determination of Coral Depth with Formosat-2 Multispectral Image

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Abstract  
Water depth is usually measured along a cruise with ship-board echo sounder. For navigational safety, the electronic nautical chart displays the shallower depth from above method, therefore it may not reflect the true topography of the sea bottom which is required by users like divers, aquaculture, coastal engineering, etc.. In the remote area or non-accessible regions, depth information is even less than the nautical chart. Formosat-2 multispectral image was used to derive the detailed bathymetry of Nawan region, without requiring optical data of water. The light is attenuated exponentially in passing through the water, either downward from sea surface, or upward from bottom reflection. The total radiance received by satellites includes scattered light from the atmosphere and water column, and reflected light from the sea surface and the sea bottom. The optical property of Nanwan water is clean and homogeneous. The ratio of reflected blue light to green light depends mostly on the water depth, and is much less by the change in bottom albedo. The surface wave-induced reflectance is a systematic error that may be estimated by near infrared band. The water depth therefore can be calculated from three bands (Blue, Green, and near Infrared) of Formosat-2 images. The maximal derivable depth from this method is 35 m in Nanwan area, which is better than the methods of two bands (Blue and Green). Because remote sensing data are average values within a pixel, and radiance decays exponentially, reflected radiance is much more in shallower part of the pixel, than in the deep. Most of the depth data calculated with three bands are shallower than in situ data. This method can easily be extended to regions without in situ depth data. The limitation of this method is clarity of water, i.e. low concentration in suspension material for least influence on water spectrum that varies with suspension material.

Keywords: Formosat-2, multispectral, bathymetric mapping, coral, water reflectance

1. Introduction
The traditional method for measuring water depth uses shipboard echosounder. It is difficult to impossible to make such measurements in regions that are either too remote, or too shallow to be accessible to ships. Without sufficient depth data from echo sounders, the electronic nautical charts can hardly provide accurate data to show the real shape of coral system that are shallow in most regions.

Fig. 1. In regions of corals, the detailed bottom topography can hardly represented by nautical charts. For example, (a) is the nautical chart in paper or in electronic format, (b) is a satellite image from Google Earth that shows abundance of knolls of coral in a region that nautical chart (c) provides only three depth data. Less than 1% of the real change of bathymetry can be found in the nautical chart.

The density of depth data from echo sounders is limited by the distance \( d \) between cruise tracks for single beam echo sounders, and by the ratio of depth \( h \) to \( d \) \((h/d)\) for multi-beam echo sounders. For the safety of navigation, the shallower depth data has higher priority on the nautical chart, and the users can only estimate the water depth by interpolation between the data on the chart.

This practice is acceptable for navigation purpose or for regions of smoothly varying sea bottom, but it is far from real bottom topography, especially in regions of corals, like Dongsha Atoll (Fig. 1). Inside of Donsha Atoll, there are many knolls of coral (Fig. 1b). It is more than 100 times complicate than what the nautical chart shows. (Fig. 1c). Detailed real topography is often required for planning diving, recreation, ocean engineering etc..

In regions of homogeneous clear water, remote sensing method may be applied to acquire a first glance of the distribution of water depth in a fast and safe manner.

The water body will either absorb or scatter most of the solar radiation that passes through sea surface. Because the scattering of light by air or water molecules is proportional to the fourth power of frequency of light, we see blue sky above us, and blue water in the ocean, and we use yellow light in the fog to see farther. In the sea water, most of sunlight in the near infrared (IR) band is absorbed near sea surface, and the ultraviolet light is scattered back without reaching the sea bottom, on the visible band can penetrate the water body and reach the sea bottom (Blyth,1981).
After entering sea water, the visible light will be attenuated exponentially, and the intensity of light at depth \( z \), \( (L(z)) \) may be represented as (Stumpf et al., 2003):

\[
L(z) = L(0) e^{-k_d z}
\]  

\( L(0) \) is the light intensity just below sea surface \((z=0)\), \( k_d \) is the attenuation coefficient.

Lyzenga (1978) developed an empirical formula to map the water depth and benthic type. For example, the satellite-received light intensity varies with corals, macro algae and sandy bottom, so is the ratio of light intensity of different bands.

Single band method requires too many empirical coefficients and is difficult to use and the accuracy of estimated water depth is susceptible to the change of bottom material. The estimated water depth increases with the albedo of bottom material, and the maximal applicable depth is about 15 m (Stumpf et al., 2003).

Leu (2004) applied linear regression equation to derive the water depths in Nanwan (South Bay off southern coast of Taiwan island). He found that no single equation gives satisfactory accuracy of estimated water depth, so he derived three linear regression equations for each of \(0–10 \) m, \(10–20 \) m and \(20–30 \) m depths. Again, he needed many depth data for regression analysis and he could not remove the wave pattern in the estimated depths, like those in Fig. 2.

Here three-band method on remote sensing of water depth is proposed. Including near IR (NIR) band in the analysis may greatly reduce the wave influence on the estimation of water depth. Further including the ratio of scattering in blue band vs. in green band, will reduce the influence of bottom material on the accuracy of depth estimation and eliminate the need of massive amount of in situ measured depth data for generating empirical equation (Huang et al., 2008). Therefore, the application of this proposed three-band method will be least constrained by the shortage of in situ measurement.

The satellite data used here is from Formosat-2 Multispectral image that was provided by National...
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Formosat-2 is a sun synchronous remote sensing satellite that was launched on May 21, 2004. It flies at 891 km above sea level, passes Taiwan island twice per day, and may selectively observe 24 km swath with nadir angle ±45°. The mission of Formosat-2 is to take near real-time picture around the globe. The major payload is a camera system that has both panchromatic and multi-spectral function. At nadir view angle, the swath of images is 24 km, and 2m ground resolution for panchromatic and 8 m for multi-spectral images.

Multi-spectral images have 4 bands, three visible bands (blue, green, red) that may form a true color image, and a near-infrared band (NIR) as shown in Table 1.

<table>
<thead>
<tr>
<th>Bands (nm)</th>
<th></th>
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<tbody>
<tr>
<td>Panchromatic</td>
<td>450–900</td>
</tr>
<tr>
<td>Multispectral</td>
<td>450–520 (blue)</td>
</tr>
<tr>
<td></td>
<td>520–600 (green)</td>
</tr>
<tr>
<td></td>
<td>630–690 (red)</td>
</tr>
<tr>
<td></td>
<td>760–900 (near-infrared)</td>
</tr>
</tbody>
</table>

2. Region of study and data

2.1. Region of study

The study region is Nanwan region off southern coast of Taiwan island, with latitudes 21.9°~22°N, and longitudes 120.73°~120.8°E as shown in Fig. 3.

Kuroshio water branches into Nanwan region yearly around, and provides warm and clean sea water that is preferred by the coral. The coral community enhanced the biodiversity of the region and created a
rugged bottom that is ideal for diver, especially during the coral spawning season. But, the rugged bathymetry discourages investigation with research vessels, or large survey vessels. The available depth data can not represent 1% of the depth change in Nanwan region.

2.2. Data

Level 1A Multi-spectral image of Formosat-2 satellite were used for this analysis. Radiative calibration and Geolocation correction were applied with ground control points. The image has 3000 x 3000 pixel elements. It was taken at 10:09 local time of July 20, 2007.

Total 606 depth data from multi-beam measurements were used for the comparison with satellite-derived water depth. These data range from 4m to 56 m, with horizontal distance 10 ~ 12 m. WGS 84 map coordinates were used for in situ data and for Formosat-2 images in Fig. 3. The in situ depth data were corrected for the tide, and the difference between the mean sea level and the mean lower low water level that was used in tidal analysis.

3. Method of Analysis

Fig. 4 is a multi-spectral image of Formosat-2 satellite that is used to estimate the water depth. It has four bands, B/G/R/NIR. NIR image was used to separate ocean from land because it has the largest contrast at the land/water boundary.

![Fig 4. Formosat-2 images of Nanwan region in 4 bands, (a) red, (b) green, (c) blue, (d) NIR](image)

Equation (2) is used to convert digital number $DN(\lambda)$ of Formosat-2 image into total radiance $L_\lambda(\lambda)$:

$$L_\lambda(\lambda) = DN(\lambda) \cdot gain(\lambda) + bias(\lambda)$$

(2)

where $gain(\lambda)$ and $bias(\lambda)$ are provided in the satellite data file. After correction for atmospheric transmissivity, surface reflection and wave effect, the ratio of under water radiance in blue and in green bands is derived for estimating the water depth in Nanwan region.
The reflectance of water is the ratio between the reflected energy and the incident energy, therefore the remote sensing reflectance of the water just below sea surface ($R_w$) is defined (Stumpf et al., 2003) as:

$$R_w = \frac{\pi L_{wi}}{E_{di}}$$

($R_w$) is the reflectance of water body at the band of wavelength $\lambda_i$, '-' means that the parameter was measured just below sea surface, $L_{wi}$ is the upwelled radiance from water body at $\lambda_i$ band, and $E_{di}$ is the downward solar irradiance at $\lambda_i$ band.

For the scattering in the atmosphere, it includes the Rayleigh scattering ($R_r$) and aerosol scattering, where

$$R_r(\theta_d, \theta_v, \phi) = \frac{\tau^2}{4\cos(\theta_d)\cos(\phi)}$$

$\theta_d$ is solar zenith angle, $\theta_v$ is satellite viewing angle, $\phi$ is the azimuth angle between the Sun and the satellite, $\tau^2$ is about 0.235 at 0.45 μm band, $\Theta$ is the scattering angle, and $P(\Theta)$ is the phase function, or the angular dependence of scattering coefficient. Fresnel reflectivity is about 2% for small incidence angle of skylight at sea surface. The incidence angle is the sum of satellite viewing angle and the tilt-away slope $\beta$ of surface from the satellite. In deep sea zone where wave amplitude is low, so is $\beta$, and the Fresnel reflectivity is uniformly about 2%. Near the coast, wave amplitude increases with shoaling effect, $\beta+\theta_c$ can be large to have increased Fresnel reflectivity on sky light, and increased radiance at all bands of B/G/NIR.

The radiance of B and G band just below sea surface can be derived from satellite images after subtracting the atmospheric scattering radiance, and radiance from surface reflectance and wave-induced reflectance. Then, the ratio of the radiance of B and G is used to estimate the water depth. Comparison with in situ measured water depth requires correction on the difference of tidal elevation to compare the depth relative to mean sea level height. The flow chart of data processing is shown in Fig. 5.

**Fig. 5. Flow chart of data processing.**
The solar spectral irradiance reaching sea surface $E_{di}^+$ varies seasonally and it depends on the transmittance of the atmosphere and the incidence angle of sunlight at sea surface:

$$E_{di}^+ = E_{0i} \left( \frac{1}{r^2} \right) T_{di} \cos(\theta_d) \tag{4}$$

where $E_{0i}$ is the annual mean solar irradiance at the top of atmosphere, '+' means above sea surface, $r$ (in astronomical unit) is the distance between the Sun and the Earth that varies seasonally, $T_{di}$ is the transmittance of sunlight at $\lambda_i$ band, $\theta_d$ is solar zenith angle that varies daily and seasonally.

The shoaling effect on long waves makes the long wave having increasing wave amplitude with decreasing wavelength and wave speed. Increasing wave amplitude results larger slope and larger Fresnel reflectance on sea surface, and more sunlight is reflected to Formosat-2. This extra reflectance should be removed from the satellite measurement to get the correct spectral reflectance of the water body.

Because the scattering and reflection of NIR in the atmosphere is nearly uniform, and the reflectance of NIR in sea water is nearly zero, the extra NIR spectral radiance $L_{IR}(\lambda_i)$ in coastal region, as compared to NIR in the deep sea region, is mostly from the increased slope of sea surface while the wave. The breaking of waves and the foams may not be account for properly by this procedure. Since the Fresnel reflection is uniform across blue to NIR bands, we may use NIR to remove the influence of wave on the spectral radiance of blue and green bands.

$$L_{s}(IR) = L_{c}(IR) - L_{\infty}(IR) \tag{5}$$

$L_{s}$ is the radiance of NIR band in the deep sea where Fresnel reflectance is nearly uniform for low surface slope over swells, $L_{c}$ is the radiance of NIR near the coast where swell has larger amplitude due to shoaling effect, and $L_{\infty}$ is the swell-induced increase of NIR radiance. The increased reflectance can be computed with Eq. (3) and applied to blue and green band.

Under sea surface, the upward propagating radiance is composed of reflection of water body and of sea bottom:

$$\pi L_{wi} = E_{di} R_{\lambda_i} \left[ 1 - e^{-2k_{\lambda_i} z} \right] + E_{di} R_{bi} e^{-2k_{\lambda_i} z} \tag{6}$$

where $R_{\lambda_i}$ is the reflectance at $\lambda_i$ band from the water body in regions of optically deep, $k_{\lambda_i}$ is the attenuation coefficient at $\lambda_i$ band, $R_{bi}$ is the spectral reflectance at $\lambda_i$ band from the sea bottom. Substitute Eq.(6) into Eq.(3), one can get the reflectance of water body at each pixel of the image:

$$R_{\omega_i} = R_{\lambda_i} \left[ 1 - e^{-2k_{\lambda_i} z} \right] + R_{bi} e^{-2k_{\lambda_i} z} \tag{7}$$

In deep zone ($k_{\lambda_i} z \gg 1$), the reflection of sea bottom is so weak that is not discernable from the noise of the data, $R_{\omega_i} = R_{\lambda_i}$. Over the coastal shallow water, satellite may receive radiance that is reflected from sea bottom, along with scattering the atmosphere, reflection at sea surface and scattering of water body. From the change of reflectance, Eq.(7) may be rewritten into Eq.(8) to derive water depth of shallow region:

$$R_{\omega_i} - R_{\lambda_i} = \left[ R_{\omega_i} R_{\lambda_i} \right] e^{-2k_{\lambda_i} z} \tag{8}$$

Each benthic material has its own reflectance spectrum, but the mean reflectance in a pixel has nearly uniform reflectance over blue and green band. Hence, the influence on satellite received underwater spectrum is influenced more by the water depth, than the type of bottom material (Philpot, 1989).

Lubin et al. (2001) studied the ratio of reflectance of band-1 (450~520 nm) to that of band-2 (520~600 nm) of Landsat, as a function of bottom materials that include white sand (41% reflectance at 500 nm),
corals and sea weed (17% reflectance at 500 nm). He found that using the ratios among several bands gives similar estimation of water depth: in water depth of 0~20 m, the root-mean-square of differences is less than 0.4 m, either for white sand or dark algae regime.

In this study, NIR reflectance is used to remove the wave-induced reflectance in blue and green band, and the ratio of remaining blue and green light reflectance from water body is used to estimate the water depth over coral regime. From Eq.(8) for blue and for green light, the relation between water depth $z$ and reflectance may be derived:

$$ z = \frac{1}{2(k_\lambda - k_{\bar{\lambda}})} \ln \left[ \frac{(R_{\lambda_i} - R_{\lambda_j})(R_{\lambda_j} - R_{\lambda_i})}{(R_{\lambda_i} - R_{\lambda_j})(R_{\lambda_j} - R_{\lambda_i})} \right] $$

(9)

Subscript $i$ and $j$ are for spectral bands $\lambda_i$ and $\lambda_j$. From a few known depths in the region of satellite image, one may derive the attenuation coefficients for blue and green band. Assuming the water clarity is uniform across the region of satellite image, Eq.(9) permits one to derive the water depth at the time of satellite imaging. The accuracy of this computation may be verified by in situ measurement of water depth data that is adjusted to the tidal level at the time of satellite image.

4. Result and Discussion

4.1. Result and comparison

After removing wave interference with NIR band, and estimate water depth with the ratio of reflectance of water body in blue and green bands, the results are presented in Fig. 6~8 for offshore of Houbi Lake, Nanwan and Kenting, respectively. Fig. 6 shows that there is a shallow region east of Houbi Lake and the depth is mostly less than 5 m. It is also a surf zone off the harbor. To avoid the danger of grounding, larger boats from the east, will enter the harbor from the south for the last half mile.

Fig. 6 Estimated bathymetry offshore of Houbi Lake. The brown color represents either land or ships, the blue color represents that the bottom-reflected light is too weak to be discernable from noise.
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Fig. 7. Estimated bathymetry offshore of Nanwan. The brown color represents either land or ships, the blue color represents that the bottom-reflected light is too weak to be discernable from noise.

Fig. 7 shows a shallow region west of the Port of The Third Nuclear Power Plant, which is also the intake point of cooling water. The water depth here is within 5 m.

Fig. 8. Estimated bathymetry offshore of Kenting. The brown color represents either land or ships, the blue color represents that the bottom-reflected light is too weak to be discernable from noise.

From Fig. 8, one may find that the isobaths off Kenting are mostly parallel to the coast. The detectable water depth was up to 35 m. Beyond 35 m depth, the bottom reflected light is too weak to be recognizable from the satellite received radiance, and is considered optically deep water where remote sensing method is no longer applicable.

The above estimated water depths were compared against 394 in situ measured depth in the range of 1 ~ 35 m, as shown in Fig. 9. Three point moving average on in situ depth data to account for the difference between point-wise in situ data and area-mean remote sensing data.
Fig. 9. Estimated water depths (blue x) from 3-band remote sensing data is compared against in situ measured water depths (green circle, 3-point moving averaged).

The remote sensing depth is far more rugged than the in situ depth data, as shown in Fig. 9. From visual data (from photographs and by naked eyes), coral bathymetry has very quite rugged topography, the in situ measured data seems to have been over-smoothened, the rugged nature satellite-derived bathymetry seems to be more realistic.

The plot of estimated depths vs. measured depths are in Fig. 10, where the differences between the two decreases with depth. In general, the estimated depth is shallower than the measured depth with correlation coefficient 0.768 for 0~30 m depth range.

Fig. 10. Estimated depths from three-band satellite imagery vs. measured depths (horizontal axis)

Table 2 shows the statistics of standard deviation of estimated depths for three ranges of depths, 0~10 m, 10 ~ 20m and 20 ~ 30 m.
Table 2. The standard deviation (SD) of estimated depths with three-band method.

<table>
<thead>
<tr>
<th>Range of measured depths</th>
<th>SD of estimated depths</th>
<th>SD/range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ~ 10 m</td>
<td>1.5707 (m)</td>
<td>15.7%</td>
</tr>
<tr>
<td>10 ~ 20 m</td>
<td>2.7908 (m)</td>
<td>14.0%</td>
</tr>
<tr>
<td>20 ~ 30 m</td>
<td>4.5292 (m)</td>
<td>15.1%</td>
</tr>
</tbody>
</table>

4.2. Discussion

The errors in remote sensing of water depths have two major sources, first the meaning of depths are different, it is point data for in situ measured water depth along a line, while it is 8 m x 8 m averaged depth data for remote sensing method, besides, the shallower part in a pixel gets higher weighting due to its higher radiance. Large variation of water depth in coral community is common, or normal. Secondly, the push-broom type of satellite detector array suffers different degrees of ageing, therefore the computation of gain and bias suffers unknown degree of inhomogeneity.

5. Conclusions

Remote sensing water depths with the blue, green and NIR bands has been applied to Nanwan regions which is offshore of southern Taiwan island. The estimated water depths reveal more realistic topography of coral communities than the in situ measured depths, and they are far more realistic than the nautical chart. The point-wise accuracy of remote sensing depths are inferior than the in situ measured depths, with about 15% standard deviation, and the range of detectable depth is limited to 35 m.

For water depths deeper than 35 m in Nanwan region, the bottom reflected radiance and the change of spectral ratio are not discernable from noise in the radiance data. In the computation of water depth, there is assumption of homogeneous optical property from coastal water to deep seas where wave interference is near non-existing. This method of remote sensing of water depth gives better data if the water is more clear (less suspended particles in the water), the solar beam is more perpendicular to sea surface, and the wave amplitude is small. It is this reason that the tropical coral community is picked for demonstration, instead of the west coast of Taiwan island where coastal water is murky, or mid-latitude shallow region where density of suspended particles are much higher.

Near the coast, the shoaling effect on the long waves makes them increasing wave amplitude and surface slope as the waves approaching the beach. Fresnel reflection shows that the surface reflectance is nearly constant for small incidence angle, but it increases nearly exponentially with incidence angle. This increased surface reflectance in blue and green band will result error in computed water depths. Fortunately, NIR also has increased Fresnel reflection at sea surface by the surface waves, and NIR reflectance is independent of water depth. The wave induced error in depth computation is clearly visible as we compare the result of Fig. 2 and Fig. 8. Being able to reduce the wave effect makes the three-band method more accurate in the estimated depths, applicable to deeper water depth, and applicable to images with the presence of surface waves.

Remote sensing water depth is often criticized for its poor accuracy. In the sense of point measurement, in situ measurement is definitively a better choice. But, in the sense of two-dimensional coverage and density of data, remote sensing depths are far better choice in representing the topography of the sea bottom. Besides, the shallow portion of a pixel reflects more sunlight to the satellite, and is given higher weighting in the computation. Therefore, most remote sensing depths are shallower than the measured depths, as seem in Fig. 9 and 10.

The rugged topography in coral community can not be represented by the nautical chart (as shown in
Fig. 1), but the fast changing depths are clearly visible in the remote sensing depths (Fig. 6–8). This kind of information is useful to divers and researchers of coral communities in selecting their site before entering the water.

In mapping a new territory or a remote region, depths from remote sensing method should be able to provide the basic information for prioritizing the multi-beam survey of bathymetry, and for selection of sites for certain activities, e.g. diving, aquaculture, off-shore platform, etc.

6. Acknowledgment

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7. Reference