1. Introduction

Airborne lidars have been developed since 1980s and recently a new generation of airborne aquatic-terrestrial lidars is under the operational use that can penetrate water and map the submerged topography inside a stream (McKeen and Issak, 2011). As streams and rivers are arguably the most dynamic components of natural landscapes, of which physical characteristics are over a wide range of spatiotemporal scales as they respond to both natural and anthropogenic forcing (McKeen et al., 2009). Knowledge of water depth is valuable for computing river discharge and estimating bed material transports by the water surface slope (Legleiter and Overstreet, 2012). Airborne laser bathymetry (ALB) is an established operational technique which has been proven to be an accurate, efficient, cost-effective, save, and flexible method for rapidly charting near-shore water, adjacent beaches and coastal engineering structures (Gunther, 2000, Longenecker, 2002). The ALB collects bathymetry and topography over very shallow or environmentally sensitive waters that are unreachable using conventional survey methods (Irish and Lillycrop, 1999). The ALB provides accurate digital depth model in a 1 to 50 m vertical range with a 25 cm height precision (Collin et al., 2007). At water depths less than about 10 to 20 cm, laser reflections from the water surface can become convolved with channel bed reflections (McKeen and Issak, 2011). Researchers are under way to explore the range of water conditions that might limit the use of the ALB over the water with entrained air bubbles in turbulent flows and sediment suspended which reduces laser penetration in the water column and some organic contaminants absorbing laser energy (McKeen and Issak, 2011).

In this study, as the diffused attenuation coefficient, K, determines the detection limit of the ALB, Kd is discussed as a function of SS, CDOM and Chl-a with traditional optical measurements. The limit of Kd for ALB is presented.

2. Lidar equation

Although ALB is a measure of a time difference between a laser beam signal penetrating water column and a volume scattered return from the water bottom (Gunther, 2000), a simple lidar equation was considered (Collin et al., 2002;2007);

\[ P_{\text{received}} = P_{\text{transmitted}} \times \exp(-2KD) \]

where \( P_{\text{received}} \) is the received power by the bathymetry system as a signal, \( P_{\text{transmitted}} \) is the transmitted power of laser pulse, \( p \) is the bottom reflectance, \( K \) is the diffused attenuation coefficient, \( D \) is the water depth, and \( F_{\text{os}} \) is a performance of ALB detector system (Kuns, 2008). K is determined as a sum of scattering parameters of SS and Chl-a as a proxy of phytoplankton, and the absorption parameter of CDOM as Eq.2:

\[ K = K_{\text{SS}} + K_{\text{Chl-a}} + K_{\text{CDOM}} \]

Based on this lidar equation, a limit of bathymetry measurement is discussed on the various SS, Chl-a, and CDOM from the shallow waters around Japan.

3. In-situ measurements

Fig. 1 (Left) shows the location of in-situ measurements in Japan including the Yubari River, the Kushiro River, the Mogami River, the Tone River, the Yoshino River, the Ibo River, the Chikugo River and the Tatsuyama Bay.

The bathymetry measurement by the ALB off the Tone River and on the Tatsuyama Bay were referred to discuss the limit of ALB measurement (Fig.1 Right).

Through the in-situ measurements, K was obtained with the measurements of down-welling irradiance using PAR sensor (Biophotical) attached to CTD (XR-620D, RBR) from surface to bottom with a linear regression in the logarithm scale of irradiance. SS was determined with the dry weight measurement of filtered particles on 1.0 and 0.2 µm pore size filter as SS and SS-a. SS is discussed as a sum of SS and SS-a in this paper. CDOM was determined as the absorption coefficient of filtered water at 350 nm by the UV spectrometer (U-2900, Hitachi) (Vecchio and Subramaniam, 2004). Chlorophyll-a contained in phytoplankton was extracted and its concentration was determined by the fluorometric measurement using the Fluorometer (Turner).

4. Results

4.1. Limit of depth to be measured by ALB estimated with a simple lidar model

From the typical parameters of ALB and the simple lidar model, Eq.1, the limit of depth measurements by ALB was simulated as a function of K and the bottom reflectance. The limit of depth measurement is defined as the signal detection limit by ALB as a difference between the surface and bottom return, which could be ingested by a log amplified signal.

The bottom reflectance was determined from the in-situ measurement of albedo between the down and up-welling irradiance in the Tatsuyama Bay. Table 1 indicates the detection limit of water depth for each K. The bottom reflectance, \( F_{\text{os}} \), exhibited a slightly lower detection limit. Although the various combination between K and water depth, K>3 could be selected as the limit of ALB measurements where the water depth is 0.9 to 1.0 m. This detection limit showed a slightly deeper depth than the ALB measurements carried out off and the Tone River.

Table 1. Simulated detection limit by ALB as a function of K and bottom reflectance

<table>
<thead>
<tr>
<th>( F_{\text{os}} )</th>
<th>( R_1 )</th>
<th>( R_2 )</th>
<th>( R_3 )</th>
<th>( R_4 )</th>
</tr>
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<tr>
<td>1</td>
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<td>1.06</td>
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<td>1.15</td>
<td>0.95</td>
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<td>1.70</td>
<td>1.40</td>
<td>1.20</td>
<td>1.00</td>
</tr>
</tbody>
</table>

4.2. Estimate of K from optical parameters

As the in-situ data covers a wide range of Chl-a, SS, CDOM, and K, the in-situ data were ordered by K and the higher dataset of K more than 3.0 m

\[ y = 1.540x \]

SS, Chl-a, and CDOM exhibited the correlation coefficients with K as 0.545, 0.417, and 0.625 respectively. Although SS and Chl-a work as the scattering components, a further study is necessary on the contribution of Chl-a, which partly works as the absorption component CDOM, which works as the absorption component, exhibited the most highest correlation coefficient with K, which suggests a significant contribution to K and CDOM determines the optical properties of water.

5. Discussion

The implementations of ALB to the turbid water regions including coastal waters and rivers need the cost sensitive decisions based on the scientific background to measure the bottom profiles. The diffused attenuation coefficient, K, is one criterion to decide the possibility to measure bathymetries. Two methods to estimate K were studied and the use of a nephelometric turbidity unit was suggested to be one simple decision tool to decide the ALB flight.

6. Acknowledgements

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