1. Waveform of spaceborne LiDAR

<table>
<thead>
<tr>
<th>Forest type</th>
<th>Height &amp; Biomass</th>
<th>Photo</th>
<th>ICESat/GLAS waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm plantation</td>
<td>H = 5 m, AGB = 44 t/ha</td>
<td></td>
<td><img src="image1" alt="Waveform" /></td>
</tr>
<tr>
<td>Sakhalin fir plantation</td>
<td>H = 18 m, AGB = 132 t/ha</td>
<td></td>
<td><img src="image2" alt="Waveform" /></td>
</tr>
<tr>
<td>Forest reserve</td>
<td>H = 28 m, AGB = 295 t/ha</td>
<td></td>
<td><img src="image3" alt="Waveform" /></td>
</tr>
</tbody>
</table>
2. Canopy height & forest biomass

Canopy height and forest biomass are the most fundamental parameters representing forest resources.

They can be easily converted to carbon stock using carbon fraction or allometric equation.

Monitoring and mapping are essential for carbon cycle study and REDD+ implementation.

Canopy height and forest biomass are fundamental MOLI-products.

3. Observation of ICESat/GLAS

Canopy height map

Aboveground biomass map

[Hayashi et al., Carbon management, 2015]
3. Observation of ICESat/GLAS

Forest disturbance observation (typhoon Songda)

[Hayashi et al., *Remote sensing of environment*, 2015]

4. MOLI footprint data product

- **MOLI level-2 product**
  - Footprint data product
  - Waveform clustering
  - Ground elevation
  - Canopy height
  - Aboveground biomass
  - Along-track 1 km-width product
  - Canopy height
  - Aboveground biomass

- **Specification of canopy height estimation**
  - Object: SNR > 10, ground slope < 30°
  - Accuracy: RMSE < 3 m

- **Specification of aboveground biomass estimation**
  - Object: SNR > 10, ground slope < 30°
  - Accuracy: RMSE < 20 t/ha
5. Canopy height estimation

Methodology in previous studies

- Direct method
  - RH100
  - \( \tan \theta \) correction
- Empirical method
  - DEM data
  - Edge extent

Pulse broadening according to ground slope affects the estimation accuracy greatly.

MOLI takes measures against this effect.

[Hayashi et al., ISPRS Journal of Photogrammetry and Remote Sensing, 2013]
6. MOLI’s measures against slope

**Measure 1 : Optimization of footprint size**

<table>
<thead>
<tr>
<th>Footprint size</th>
<th>Estimation accuracy</th>
<th>Ground detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>High</td>
<td>Insensitive</td>
</tr>
<tr>
<td>Large</td>
<td>Low</td>
<td>Sensitive</td>
</tr>
</tbody>
</table>

MOLI’s footprint size $= 25$ m

**Measure 2 : Measurement of ground slope**

- Footprints are located adjacently.
- Ground slope can be calculated.
- It can be used to correct canopy height estimates.
7. MOLI’s algorism for canopy height

**Direct method**

- Height difference between signal start and ground peak ⇒ canopy height.
- Ground peak detection: Gaussian-fitting or short-time Fourier transform (STFT).
- STFT is a robust method even for noisy waveform.

[Y. Sawada, private communication]

7. MOLI’s algorism for canopy height

**Empirical method**

- We will develop empirical models using waveform extent and some parameters.
- The models have an ability to correct pulse broadening in sloped area.
- We will develop the models based on field data, after MOLI launch.

<table>
<thead>
<tr>
<th>Area</th>
<th>Estimation model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>$H = 0.707 \ WE - 0.506 \ TI$</td>
<td>Xing et al., 2008</td>
</tr>
<tr>
<td>England</td>
<td>$H = 0.96 \ WE - 0.53 \ TI$</td>
<td>Rosette et al., 2010</td>
</tr>
<tr>
<td>United States: Mendocino</td>
<td>$H = 0.87 \ WE - 0.29 \ TI$</td>
<td>Chen, 2010</td>
</tr>
<tr>
<td>Santa Clara</td>
<td>$H = 0.64 \ WE - 0.27 \ TI$</td>
<td></td>
</tr>
<tr>
<td>Lewis</td>
<td>$H = 0.84 \ WE - 0.31 \ TI$</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>$H = 0.899 \ WE - 0.431 \ TI$</td>
<td>Hayashi et al., 2013</td>
</tr>
</tbody>
</table>

WE: Waveform extent, TI: Terrain index
8. Aboveground biomass estimation

Methodology in previous studies

- Using canopy height
- Using waveform parameters
- Multiple regression
- Machine learning

9. MOLI’s algorism for aboveground biomass

**Method of using waveform parameters**

- We will develop empirical models using waveform parameters.
- The models will be expected to provide accurate estimates.
- We will develop the models based on field data, after MOLI launch.

**Example of waveform parameter**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>WE</em></td>
<td>Waveform extent</td>
</tr>
<tr>
<td>RH10, RH20, …, RH100</td>
<td>Relative height</td>
</tr>
<tr>
<td>LE, TE</td>
<td>Edge extents</td>
</tr>
<tr>
<td>θ</td>
<td>Front slope angle</td>
</tr>
<tr>
<td>Skew, Var</td>
<td>Skewness and variance of waveform</td>
</tr>
</tbody>
</table>
10. Future plans

1. Sample waveform data collection using airborne LiDAR.

2. Algorithm development using the sample waveform data.

3. Ground-truth data collection by field measurements or airborne LiDAR observations.

Thank You for your attention!