UTILITY OF WAVELET AND REGRESSION ANALYSIS WITH LAND COVER MAP FOR DTM EXTRACTION FROM ASTER GDEM

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ABSTRACT: Digital elevation model (DEM) is one of the most basic and important information for a range of spatial applications on the earth. DEM falls into digital terrain model (DTM) and digital surface model (DSM) based on whether they include the height of surface objects or not. For some of the applications such as hydrology, geomorphology, and studies on the gravity field, global-scale DTM is necessary in particular. There are various types of existing DEMs, but we do not have any global DTMs that are useful in terms of data openness, reliability, spatial uniformity, resolution, and accuracy. Although ASTER GDEM is of high quality, it is also not useful for a kind of applications because it describes the upper surface of the landscape. Therefore, to create global DTM is a very significant challenge. With a background like that, we set our goal of generating global DTM from ASTER GDEM. We assumed that the spatial frequency characteristics of DTM and that of curves from surface features differ from each other. Based on this assumption, ASTER GDEM was decomposed into hierarchical wavelet components, and then DTM was regressed on them. As a result of regression, standard deviations for some of estimated coefficients were relatively large. This means that these coefficients are controlled by other elements. Therefore, we carried out regression considering land cover that is thought to affect the frequency characteristics of DEM and DTM.

1. INTRODUCTION

1.1 Digital Elevation Model

Digital elevation model (DEM) is one of the most primary and important geospatial information that contributes to all kinds of scientific fields for public's benefit. Major application fields are hydrological simulation, meteorological simulation, biomass estimation, urban stock volume estimation, topographic cartography, gravity field modeling, and topographic correction for remote sensing data. Group on Earth Observations (GEO) regards DEM as basic information required for all the nine social benefit areas in 10-year implementation plan (Muller, 2008).

Many application fields of DEM deal with global-scale phenomena. Even if the subject matter itself is on just one-religion scale or smaller, it is valuable that the same manner can be applied in any other regions around the world for comparison or accumulation of information. To do this, fundamental data used in the process should be on the same quality globally. Therefore, to be developed uniformly on the global scale is one of the most important specifications required for DEM.

DEM falls into digital terrain model (DTM) and digital surface model (DSM) based on whether they include the height of surface objects or not. For some of the applications such as hydrology, geomorphology, and studies on the gravity field, global-scale DTM is necessary in particular.

In this study, we use the term "DTM" as the ground elevation data, "DSM" as the surface elevation data, and "DEM" as the general term for "DTM" and "DSM".

1.2 Existing DEMs and Their Problems

There are various kinds of existing DEMs. Representative ones are GTOPO30, SRTM3, ASTER GDEM, and original DEMs developed by each country. GTOPO30, DTM completed by U.S. Geological Survey's EROS Data Center in 1996, covers all of the earth surface and is open for public, but it has problems with data source reliability, spatial uniformity, and data freshness (Une, 2008). SRTM3 and ASTER GDEM are superior at data openness, reliability, spatial uniformity, data freshness, resolution, and coverage, but they are not useful for a kind of applications because they include the height of buildings and vegetation. Furthermore, original DEMs of each country are not useful because of the openness and coverage. So it is said that we do not have any useful global DTMs. Therefore, to create global DTM is a very significant challenge.

Table 1 Existing DEMs

	GTOPO30	SRTM3	ASTER GDEM	Original DEMs
Openness	Good	Good	Good	Bad
Reliability	Bad	Good	Good	Excellent
Uniformity	Bad	Good	Good	Excellent
Freshness	Bad	Good	Excellent	Good
Resolution	Bad	Good	Excellent	Excellent
Coverage	Excellent	Good	Excellent	Bad
DTM/DSM	DTM	DSM	DSM	DTM

1.3 Concept of This Study

The problem of SRTM3 and ASTER GDEM is only that they are not DTM but DSM. Between these two DEMs, ASTER GDEM is better than SRTM3 in terms of data freshness, resolution, and coverage. So we aimed to extract DTM from ASTER GDEM. One of the differences between DTM and DSM is the spatial frequency characteristics. Curves of ground elevation are formed by internal and external geomorphic agent, so it is relatively gentle. On the other hand, curves of the surface of objects on the ground are relatively radical because the height of buildings and vegetation changes with every short distance.

Wavelet transform is useful for analyzing the spatial frequency characteristics of images because it decomposes an image with the axis of spatial frequency and spatial location while Fourier transform does not have the axis of spatial location. DSM image is decomposed into images with each frequency level, but we have no knowledge that explains that to which frequency the surface objects height affects. This problem is solved by regression analysis with DTM as dependent variable and wavelet components of DSM as independent variables. Furthermore, land cover type is possible to affect the frequency characteristics of DSM. So the accuracy is expected to improve by carrying out regression analysis with every land cover type.

1.4 Objective

The final goal of our study is generating global DTM from ASTER GDEM. For this purpose, in this study we examine the utility of wavelet analysis, regression analysis, and land cover map in DTM extraction from ASTER GDEM.

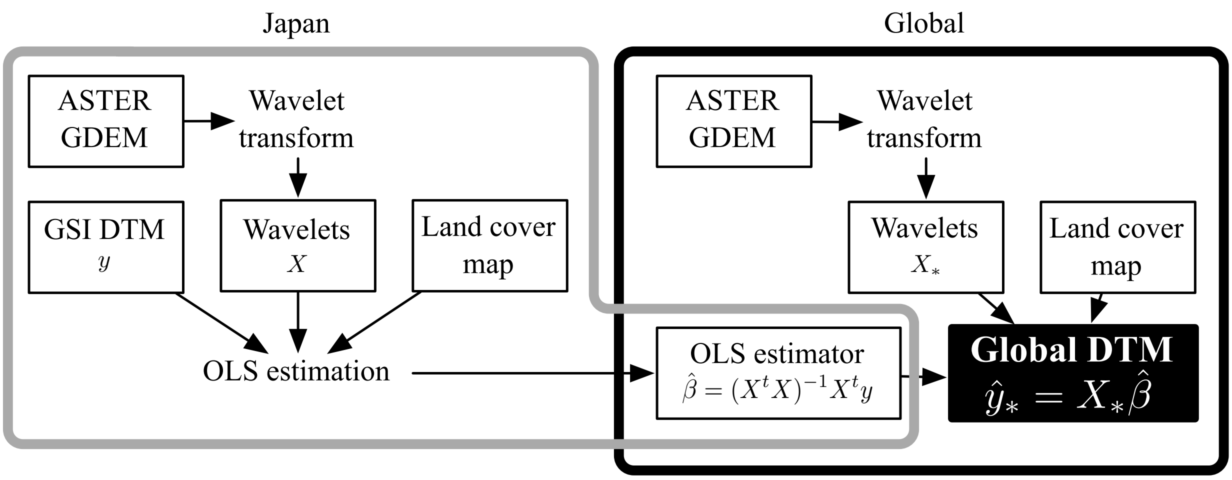

Fig 1 Overview of this study

2. METHODOLOGY

2.1 Data Used in This Study

2.1.1 ASTER GDEM: ASTER GDEM is a free global DEM which was released in 2009 by Ministry of Economy, Trade and Industry (METI) in Japan and the National Aeronautics and Space Administration (NASA) in United States. Elevation data is derived by photogrammetry using two directions images from ASTER sensor on Terra. Spatial resolution of ASTER GDEM is 1 arc-second (approx. 30m) and elevation accuracy is 10.87 m (standard deviation to NED). Terra is still on the orbit and continuing taking photos, so data update and accuracy improvement is available (ASTER GDEM Validation Team, 2009).

2.1.2 GSI DTM: For reference DTM, we used a DTM developed by Geographical Survey Institute (GSI) in Japan, which covers some parts of Japan. GSI generated it by photogrrammetry using aerial photos and objects filtering, therefore it is regarded as a DTM. Resolution is 5 m and accuracy of elevation is better than 0.7 m (standard deviation to ground survey). Spatial resolution is fitted to that of ASTER GDEM by bilinear resampling.

2.1.3 Land Cover Map: So far, we do not have global land cover map with 1 arc-second resolution. So in this study 30 arc-seconds global land cover map from the Moderate Resolution Imaging Spectroradiometer (MODIS) was used. One pixel of MODIS land cover map was divided into 30x30 pixels.

2.2 Wavelet Transform

Wavelet transform is one of the frequency analysis techniques. Although it seems like Fourier transform, they differ from each other in temporal analysis. While Fourier transform only focuses on frequency, wavelet transform analyses both frequency and time (Nakano et al., 1999). Time for signal is space for DEM profile. So, spatially localized wave can be separated from DEM profile by wavelet transform.

One-dimensional discrete wavelet transform separates one signal into two signals.

$$s_0 = d_1 + s_1 \tag{1}$$

s_j is called "wavelet smooth level j" and d_j is "wavelet detail level j". s_0 is the original signal; in case of this study, it is one-dimensional profile of ASTER GDEM. d_1 and s_1 are high- and low-frequency component of s_0, respectively.

The same calculation can be applied to s_1.

$$s_1 = d_2 + s_2 \tag{2}$$

From equation (1) and (2),

$$s_0 = d_1 + d_2 + s_2$$

If the original signal length is 2^J, the same operation can repeats J times. After that, s_0 is expressed as below.

$$s_0 = d_1 + d_2 + d_3 + \cdots + d_J + s_J = \sum_{j=1}^{J} d_j + s_J$$

Calculation of wavelet transform is just a convolution of wavelet filter and wavelet coefficients. For the filter function, we chose Daubechies' one (N=2) for simplicity.

For more detailed about calculation above, see (Nakano et al., 1999). We followed the method that is introduced in this book.

In two-dimensions, one image is decomposed into four images. At first, one-dimensional wavelet transform is carried out to each row of the original image. So the original image is decomposed into two images (name "A" and "B", temporary). And then, one-dimensional wavelet transform is carried out again to each column of image A. So image A is decomposed into two images. The same for image B. After that, we get four images.

$$LL_0 = HH_1 + HL_1 + LH_1 + LL_1$$

LL_0 is the original ASTER GDEM image. Here, “L” and “H” means low- and high-frequency, respectively. So, for example, HL_j is a level j image with high-frequency rows and low-frequency columns. After the same processes of the case of one-dimension, the original image can be expressed as below.

$$LL_0 = \sum_{j=1}^{J} (\, HH_j + HL_j + LH_j \,) + LL_J$$

2.3 Regression Analysis

In this study, we regarded it as the problem of estimating the beta of equation below (in one-dimension, for simplicity). So for example, if the surface objects height in ASTER GDEM image affects only the d_1 component, beta 1 must be equal to zero and others are one.

$$\begin{pmatrix} DTM(1) \\ DTM(2) \\ \vdots \\ DTM(N) \end{pmatrix} = \begin{pmatrix} 1 & d_1(1) & d_2(1) & \cdots & d_J(1) & s_J(1) \\ 1 & d_1(2) & d_2(2) & \cdots & d_J(2) & s_J(2) \\ \vdots & & & \ddots & & \vdots \\ 1 & d_1(N) & d_2(N) & \cdots & d_J(N) & s_J(N) \end{pmatrix} \begin{pmatrix} \beta_0 \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_J \\ \beta_{J+1} \end{pmatrix} + \begin{pmatrix} \varepsilon(1) \\ \varepsilon(2) \\ \vdots \\ \varepsilon(N) \end{pmatrix} \qquad (3)$$

The index 1, 2, … , N inside parentheses represents position in a profile signal. In case of image, N is equal to the product of x size and y size of the image.

For estimate the beta of equation (3), the ordinary least squares (OLS) estimation was carried out. Equation (3) is simply written as

$$y = X\beta + \varepsilon \qquad (4)$$

The OLS estimator for linear regression model (4) is

$$\hat{\beta} = (X^t X)^{-1} X^t y \qquad (5)$$

The OLS predictor for DTM is calculated as

$$\hat{y} = X\hat{\beta} \qquad (6)$$

2.4 Regression with Land Cover Map

The frequency characteristics of DEM and DTM are changes if the land cover condition at that location changed. So the vector beta in equation (3) takes different values on different land cover type. Therefore, we separated the original ASTER GDEM image into images of each land cover type and calculated (5) and (6) for each image.

3. APPLICATION AND RESULTS

3.1 Application

Regression analysis was carried out on a test area in Saitama, Japan (Fig 2 - 6). Regression considering land cover was also done and the results were compared.

Two-dimensional discrete wavelet transform was applied to 1024x512 image at first. This image was decomposed up to level 6.

Because of the feature of calculation method, some pixels on the edge of the image are sacrificed. Values of victim pixels are not available, so they should not be used for regression. The image size without sacrifice is 770x258.

Land cover types that are included in the area were mixed forests, evergreen needleleaf forest, urban and built-up, and woody savannas. For simplicity, we summed up mixed forests, evergreen needleleaf forest, and woody savannas into one land cover type, and then DTM was regressed at each of forest area and urban built-up area.

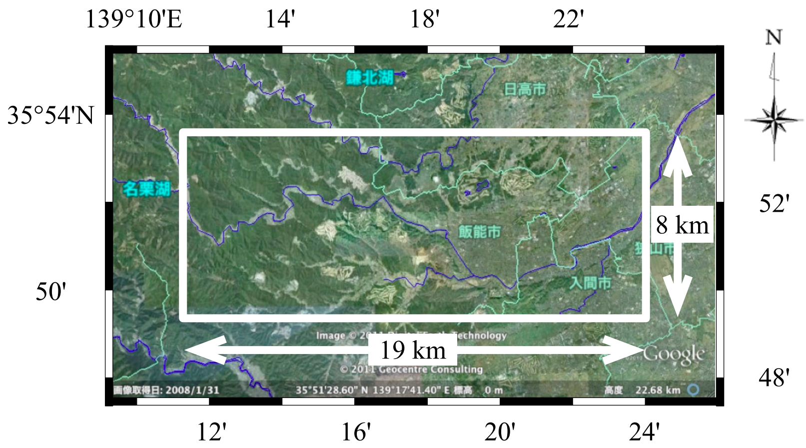

Fig 2 Test area (inside the white square)

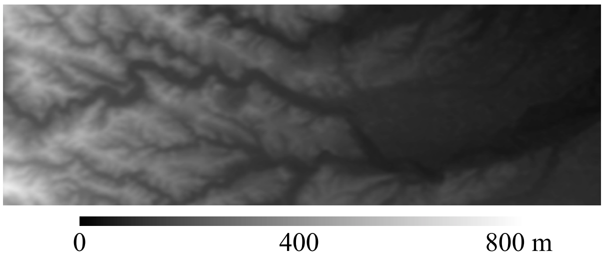

Fig 3 ASTER GDEM

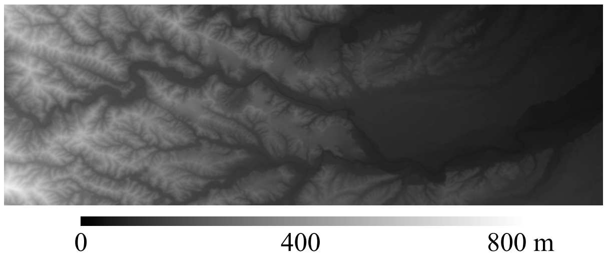

Fig 4 GSI DTM

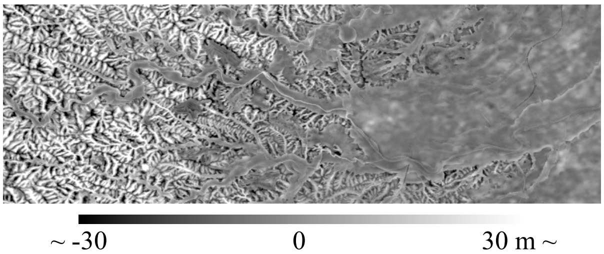

Fig 5 ASTER GDEM minus GSI DTM

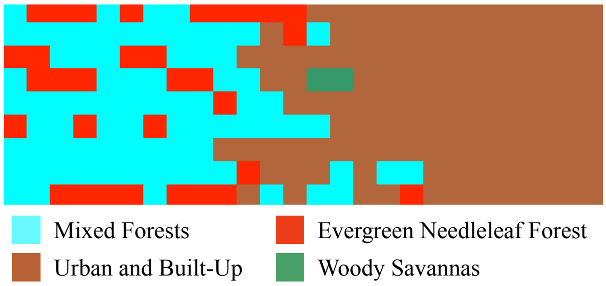

Fig 6 Land cover map

3.2 Results

Figure 7 and 8 shows residuals of estimated DTM images. Table 2 shoes RMSEs of to GSI DTM.

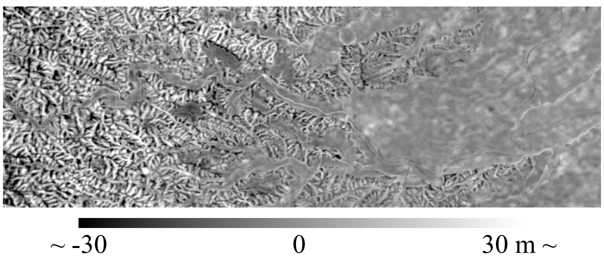

Fig 7 OLS predictor without LC minus GSI DTM

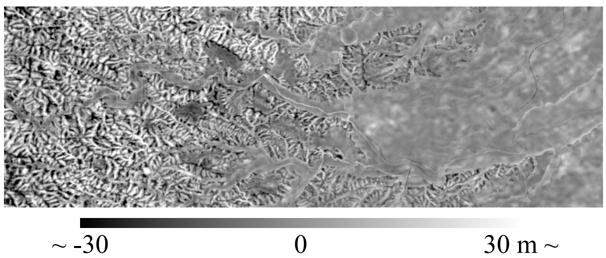

Fig 8 OLS predictor with LC minus GSI DTM

Table 2 RMSEs to GSI DTM

	RMSE to GSI DTM (m)
ASTER GDEM	10.85
OLS predictor without land cover	9.69
OLS predictor with land cover	9.65

As the result of OLS estimation without land cover, Student's t-value for the coefficient value of beta corresponding to HH_1 component took 0.71, with null hypothesis of "coefficient is equal to zero" (table 3). This means HH_1 images of ASTER GDEM and GSI DTM have no correlation with each other. Of course, the same for OLS estimation with land cover type.

From comparison between figure 5 and figure 7, we can find that global errors of ASTER GDEM were removed by applying wavelet and regression analysis. Especially, the accuracy was improved in the urban area; right side of the image. However, in forest area, it is difficult to see visible accuracy improvement. As a result, RMSE of OLS predictor without considering land cover to GSI DTM is 1.2 m less than that of original ASTER GDEM image.

Table 2 and a comparison of figure 7 and 8 show us that the estimation accuracy did not improved by considering land cover type. It means that land cover type doesn't affect the spatial frequency characteristics of ASTER GDEM, or other kinds of factors affects. Slope is one of the candidates for this unknown element. In the forest area of figure 7 and 8, we can see defined influence of terrain. So some information about terrain such as slope or aspect need to be considered. Additionally, the problem of spatial resolution of land cover map is to be solved. The roughness of land cover map is possible to derive bad result in this analysis.

Table 3 Result of regression

	OLS without land cover			OLS with land cover					
				Forest			Urban and built-up		
	coef.	stdev.	t-value	coef.	stdev.	t-value	coef.	stdev.	t-value
const.	7.27	0.0431	168.93	6.15	0.1278	48.09	5.61	0.0522	107.37
HH_1	0.10	0.1483	0.71	0.17	0.2712	0.63	0.04	0.1231	0.29
HL_1	1.60	0.0503	31.77	1.75	0.0727	24.08	0.94	0.0674	13.93
LH_1	1.45	0.0301	48.11	1.51	0.0422	35.75	1.07	0.0468	22.75
HH_2	2.18	0.0758	28.78	2.45	0.1109	22.09	1.17	0.0970	12.02
HL_2	1.65	0.0153	107.92	1.69	0.0214	79.10	1.38	0.0242	56.85
LH_2	1.36	0.0090	150.67	1.38	0.0125	110.62	1.18	0.0154	76.69
HH_3	1.70	0.0130	130.23	1.73	0.0181	95.48	1.46	0.0215	67.86
HL_3	1.36	0.0055	247.54	1.37	0.0076	180.30	1.26	0.0093	135.82
LH_3	1.16	0.0033	351.98	1.17	0.0045	259.18	1.06	0.0061	173.30
HH_4	1.19	0.0046	259.83	1.19	0.0063	190.29	1.16	0.0086	134.27
HL_4	1.10	0.0030	373.10	1.12	0.0041	271.72	1.02	0.0050	205.50
LH_4	1.02	0.0019	543.73	1.03	0.0026	394.69	0.99	0.0033	304.52
HH_5	1.02	0.0028	364.57	1.03	0.0038	267.79	0.98	0.0053	185.05
HL_5	1.00	0.0019	529.98	0.99	0.0026	389.08	1.02	0.0038	270.50
LH_5	0.97	0.0011	881.08	0.96	0.0015	634.04	0.99	0.0019	527.47
HH_6	0.98	0.0021	462.90	0.98	0.0029	337.14	0.97	0.0038	255.60
HL_6	0.95	0.0019	508.13	0.95	0.0025	374.36	0.97	0.0040	240.78
LH_6	0.96	0.0010	944.00	0.96	0.0015	658.12	0.97	0.0014	678.26
LL_6	0.97	0.0002	4851.36	0.97	0.0004	2190.46	0.98	0.0005	2106.06

3.3 Future Works

At first, we need to examine the result of regression, especially the coefficient values, and compare each frequency components. Then, the reason why estimation with land cover did not work well should be discussed. Alternate available land cover map is necessary. About wavelet transform, other wavelet base functions are worth trying and comparing, because different combination of input signal waveform and base function makes different results. Finally, in this research we applied OLS estimation, which ignores the covariance of elevation. Actually the elevation values of two points close to each other have some correlation, so the accuracy is expected to be improve by introducing kriging, which is a estimation and prediction considering the covariance.

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