A Study on Micro-Scale Airborne Radiation Monitoring by Unmanned Aerial Vehicle for Rural Area Reform Contaminated by Radiation

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After Fukushima No.1 nuclear power plant accident in 2011, radiation monitoring in habitation area becomes one of the crucial issues of environmental risk assessment. Airborne survey is a valid technique to detect environmental data in broad area. In case of radiation monitoring, observed data should be calibrated by considering microtopography or heights/types of trees to estimate ground-level contamination. Recent UAV stereo-camera survey makes it possible to provide digital surface model (DSM). This study aims to develop a calibration method of airborne radiation monitoring data by using DSM by UAV.
First of all, the authors conducted airborne radiation survey in a rural area of Fukushima city where forests, rice fields and vegetation fields are contaminated by radiation after the accident. Here, we employed an UAV named “Robin-PARS” for airborne radiation, on which a stereo camera and radiation survey meter are mounted. In this study, UAV flies about 250m above the ground in order to make DSM data resolution about 5cm and to detect air radiation at intervals of one second. Here, midair of the following types of areas are selected as research fields; (1) flat rice field, (2) orchard field and (3) conifer forest. Ground features are categorized by using true ortho mosaic pictures.
Secondly, detected data are calibrated by estimating the difference between aviation altitudes and surface elevation that is calculated elevation and the ground feature height by using DSM. Here, air radiation at 1m from the ground is estimated by using the proposed calibration model. Finally, calibrated data are mapped and spatially interpolated on GIS. Grid cell size that is employed for interpolation is less than 1m. It is indicated that proposed techniques make it possible to detect micro hotspots of radiation in the fields where the ground survey is hard to be conducted.

Key Words : *radiation monitoring, air-bourne survey, UAV, digital surface model, Bayesian model*

1. RESEARCH BACKGROUNDS AND PURPOSES

(1) Backgrounds

After the Fukushima Nuclear Power Plant (NPP) accident aused by the great Earthquake of East Japan on

March 11^{th}, 2011, environmental radiation risk monitoring has been one of the crucial issues in Japan for the purpose of decontamination and health monitoring. Not only food contamination (e.g. rice, mushroom and fishes) but also contamination of rice fields and soilds have been surveyed by the government, local authorities and private enterprises.

Because the majority of lance spaces in Japan is covered by mountaneous area, it is necessary to conduct radiation surveys on the mountains. Air-borne survey of radiation is one of the effective method to show spatial distribution of radiation in the vast field[1), 2), 3)]. In case of air-borne survey of radiation, monitoring errors caused by elevation level and heights of surface objects such as trees and buildings have to be considered. However, it has been difficult to calibrate air-borne radiation survey results by considering these effects[4)]. This is mainly because spatial data on hights of surface objects cannot be calculated by using digital elevation model.

(2) Purposes

This study aims (1) to propose calibration methods of air-borne radiation survey, (2) to conduct radiation monitoring by using unmanned air vehicle (UAV) in Fukushima and (3) to apply the proposed calibration method to the survey data.

2. METHODOLOGIES

Outline of methodologies is shown in **Fig. 1**. In this study, first of all, environment radiation is measured by using UAV that install NaI scintillator in Fukusihma city. Secondary, measured data set is calibrated with a calibration model that estimate ground level radiation according to height of elevation and spatial objects. Here, precise digital surface mode (DSM) is employed for calibration. Finally, calibrated data set is visualized on a GIS map.

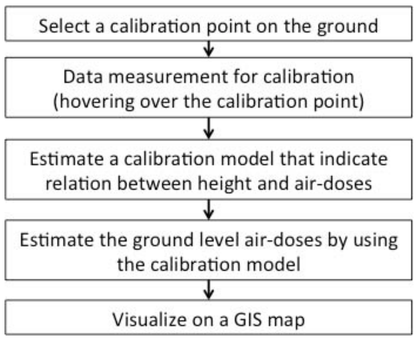

Fig 1. Analysis flow

(1) Unmanned air vehicle (UAV) survey

UAV is employed for detecting air-radiation in order to show spatial distribution of radiation in the narrow fields. In this study, a UAV (Robin PARS) shown in Pic. 1 is employed. Radiation monitoring devices (**Fig. 2**) and digital camera is mounted on the bottom of the UAV. NaI scintillator (TS100A) (**Fig. 3**) radiation survey meter (Techno AP Cpo. Ltd.) is installed on the beneath of the vehicle. With TS100A, such air doses are recorded at intervals of 1 second, three second and 10 seconds. In this study, three seconds average of air-doses is employed as the data that indicate radiation level.

Fig. 2 UAV employed in this study (left: front, right: back)

Fig. 3 NaI scintillator mounted on the beneath lack of UAV

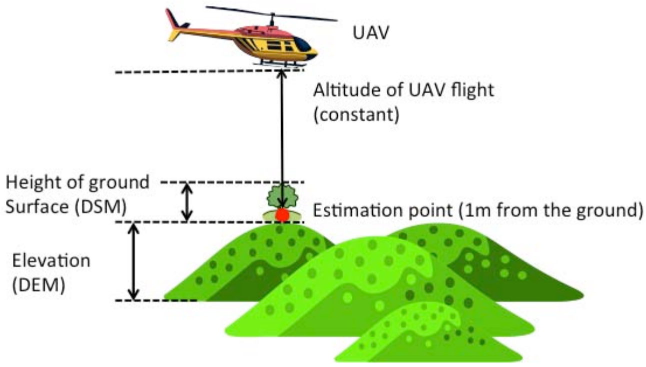

Fig. 4 Image of data measurement by a UAV survey

By combining these devices, it becomes possible (1) to measure radiation air doses, (2) to survey ground surface/features and (3) to model dogotal surface (its resolution is approximately 5cm). When combining these data set with digital elevation model (DEM), ground level radiation could be estimated by using a calibration model (shown in the next column) that indicate relationship between hight of UAV and environmental radiation (**Fig. 4**) .

In order to estimate a calibration model, hovering survey of radiation is also conducted. In this study, the UAV hovered from 50m to 200m by 10m pich on the calibration point (**Fig. 5**)

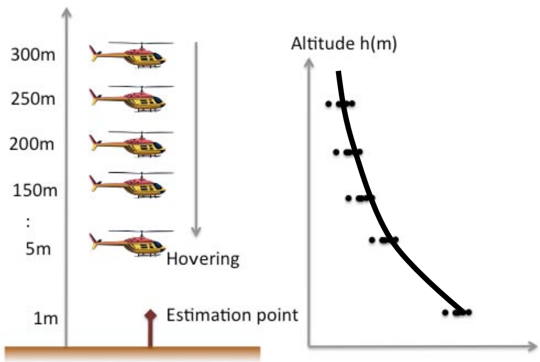

Fig.5 Image of Hoveing survey (left) and decay curve of calibration model (right)

As air-radiation is assumed to be stochastically distributed according to Normal distribution, we planned that UAV fly along quadrat center line (Fig. 6). In this study, the width of quadrat is configured to 10 meter.

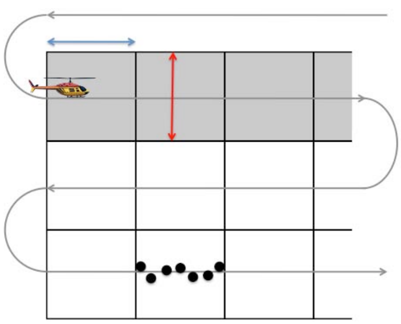

Fig. 6 Image of quadrat air-borne survey
(Squares indicate quadrats and dots mean sampling points)

(2) Outline of a calibration model

Calibration models are estimated by using (1) fixed point survey and (2) hovering survey. In this study, we decided hight of estimationpoint is 1m from the ground. Therefore, several points are selected for calibration and radiation air-doses are measured. In order to consider spatial eccentricity of radiation nuclear, five points (estimation point and spatial neighbors) are selected as caribration points (**Fig. 7**).

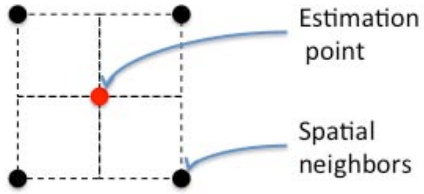

Fig. 7 Relation between stimation point and spatial neighbors for the ground level calibration

As environmental radiation is assumed to be distributed according to Normal distribution, posterior of Normal distribution of radiation is estimated by using Markov-chain Monte Carlo (MCMC). Here, observed radiation (air-doses) data of fixed-point and UAV hovering data are indicated as y1 (vector) and y2 (vector), respectedly.

$$\mathbf{y}_1 \sim N\left(\theta_1, \sigma_1^2\right),\ \mathbf{y}_1 = \left\{y_{1,1}, \ldots, y_{n_1,1}\right\} \tag{1}$$

$$\mathbf{y}_2 \sim N\left(\theta_2, \sigma_2^2\right),\ \mathbf{y}_2 = \left\{y_{1,2}, \ldots, y_{n_2,2}\right\} \tag{2}$$

Then, hierarchical prior of variance, precition and mean are expressed as equation (3a), (3b) and (3c).

$$1/\sigma^2 \sim \Gamma\left(\nu_0/2, \nu_0\sigma_0^2/2\right), \tag{3a}$$

$$1/\tau^2 \sim \Gamma\left(\nu_0/2, \nu_0\tau_0^2/2\right), \tag{3b}$$

$$\mu \sim N\left(\mu_0, \gamma_0\right) \tag{3c}$$

Hierarchical posterior of mean, variance and hyper-parameters are then expressed as from equation (4a) to (4f).

$$\mu \mid \theta_1, \theta_2, \tau^2 \sim N\left(\frac{m\bar{\theta}/\tau^2 + \mu/\gamma_0^2}{m/\tau^2 + 1/\gamma_0^2}, \frac{1}{m/\tau^2 + 1/\gamma_0^2}\right), \tag{4a}$$

$$1/\sigma^2 \mid \theta_1, \theta_2, \mathbf{y}_1, \mathbf{y}_2 \sim \Gamma\left(\left\{\nu_1 + \sum_{j=1}^{2} n_j\right\}/2, \left\{\nu_1\sigma^2 + \sum_{j=1}^{2}\sum_{i=1}^{n_j}\left(y_{i,j} - \theta_j\right)^2\right\}/2\right) \tag{4b}$$

$$1/\tau^2 \mid \mathbf{y}_1, \mathbf{y}_2, \mu \sim \Gamma\left(\left\{\nu_0 + m\right\}/2, \left\{\nu_0\tau_0^2 + \sum_{j=1}^{2}\left(\theta_j - \mu\right)^2\right\}/2\right) \tag{4c}$$

$$p\left(\theta_1, \theta_2, \mu, \tau^2, \sigma^2 \mid \mathbf{y}_1, \mathbf{y}_2\right) \propto p\left(\mu, \tau^2, \sigma^2\right) p\left(\theta_1, \theta_2, \mid \mu, \tau^2, \sigma^2\right) p\left(\mathbf{y}_1, \mathbf{y}_2 \mid \theta_1, \theta_2, \mu, \tau^2, \sigma^2\right)$$
$$= p(\mu) p\left(\tau^2\right) p\left(\sigma^2\right)\left\{\prod_{j=1}^{2} p\left(\theta_j \mid \mu, \tau^2\right)\right\}\left\{\prod_{j=1}^{2}\prod_{i=1}^{n_j} p\left(y_{i,j} \mid \theta_j, \sigma^2\right)\right\} \tag{4d}$$

$$\theta_1 \mid \mathbf{y}_1, \sigma^2 \sim N\left(\frac{n_1\bar{y}_1/\sigma^2 + 1/\tau^2}{n_1/\sigma^2 + 1/\tau^2}, \frac{1}{n_1/\sigma^2 + 1/\tau^2}\right) \tag{4d}$$

$$\theta_2 \mid \mathbf{y}_2, \sigma^2 \sim N\left(\frac{n_2\bar{y}_2/\sigma^2 + 1/\tau^2}{n_2/\sigma^2 + 1/\tau^2}, \frac{1}{n_2/\sigma^2 + 1/\tau^2}\right) \tag{4d}$$

In order to estimate hierarchical posterior of Normal distribution, Gibbs sampler is employed as MCMC sampling method. In this study, we employed 11,000 MCMC iteration and 1,000 burn-in for one chain with single thinning interval.

A decay curve model of radiation according to height from the ground can be expressed as equation (5).

$$y = \exp\left(ax + b\right) \tag{5}$$

Here, y and x mean air radioactivity and height from the ground. a and b are unknown parameters and $a < 0$. When estimating the model, posterior mean of y and x are employed calculated according to equation (1) to (4).

3. RESULTS OF UAV SURVEY

(1) Study area

In this study, Hiraishi district in Fukushima prefecture is selected as sampling area (**Fig. 8**). This district locates at the southwest of the center of Fukushima city. Majority of the residents in this area is farmars and they are prohibited to cultivate rice field, fruits trees and to sell the locally grown vegitables (**Fig. 9**). A pilot survey is conducted on September 1st 2012, and the main survey is conducted on February 11th 2013.

(2) Results of UAV radiation measurement

Fig. 10 shows the result of the airial ortho photo that is taken by a digital camera on the UAV and modified geometrically.

Fig. 11 indicates the result of radiation measurement. As shown in this figure, it is considered that features on the ground.

Fig. 12 shows elevation at sampling points of UAV.

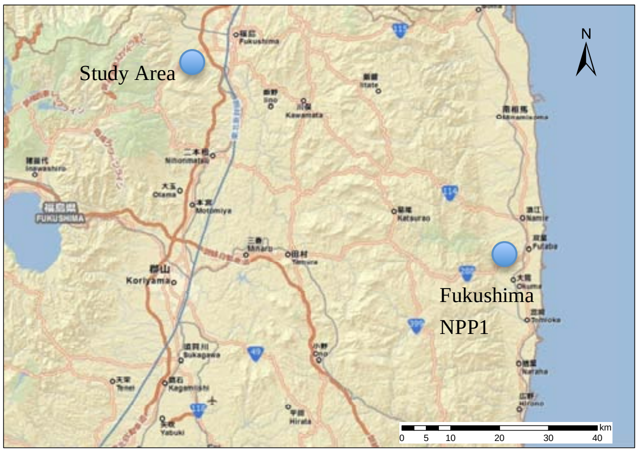

Fig. 8 Location of the study area

Fig. 9 Scenary of the study area

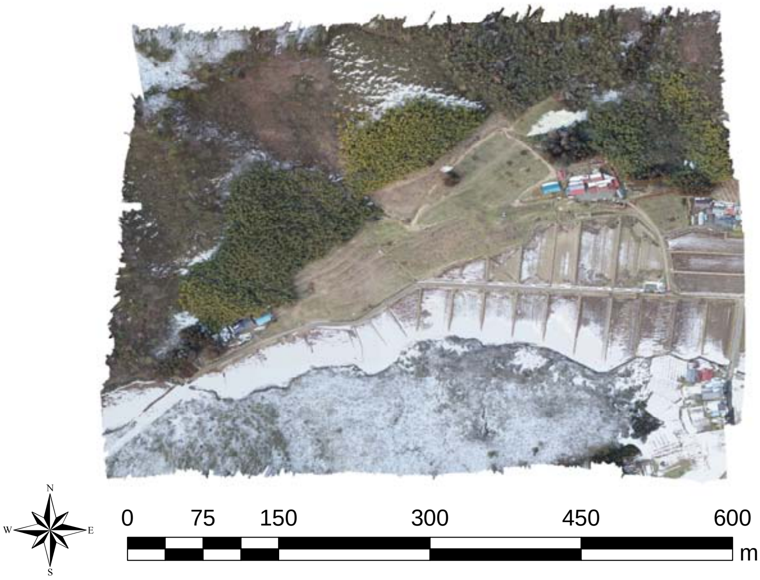

Fig. 10 Airial ortho photo of the study area by the UAV

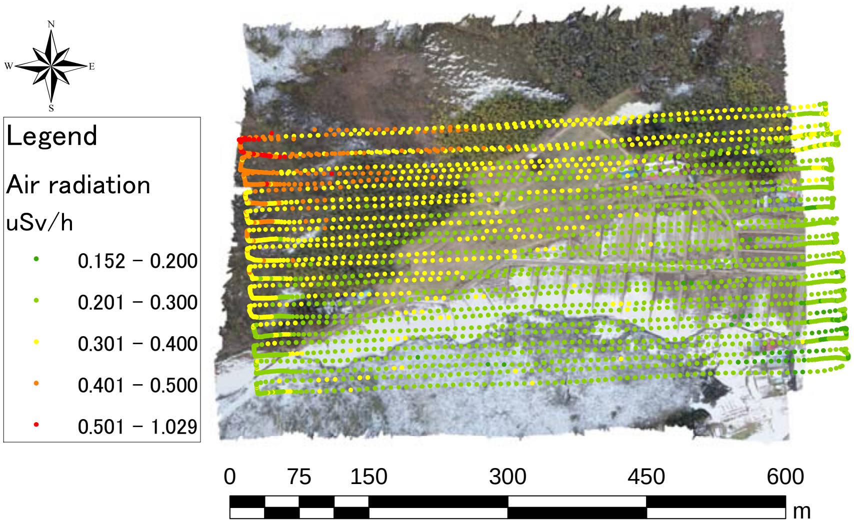

Fig. 11 UAV air-borne radiation survey result (before calibration)

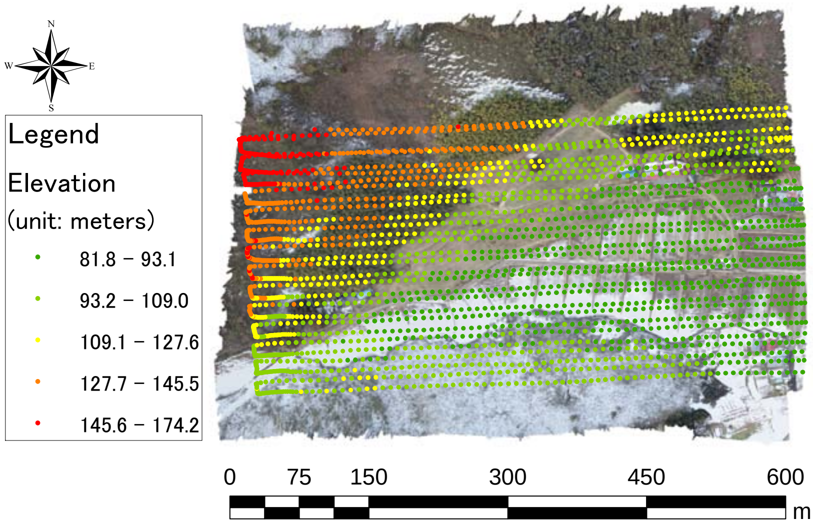

Fig. 12 Surface elevation at sampling points of UAV

4. ANALYSIS RESULTS

(1) Calibration model

MCMC posterior distribution of radiation air-doses at the calibration (fixed-point) is shown in **Fig. 13** and decay curve according to UAV height is estimated as shown in **Fig. 14**. Calibration model is estimated as indicated in equation (5).

$$y = \exp\left(-0.008556x - 0.285962\right) \tag{5}$$

Here, x and y mean height of UAV (unit: meter) and air-doses (unit: uSv/h), respectively.

Using equation (5), air radioactivity at the grould level y_g can be calculated as following.

$$y_g = \alpha\left\{y_{x=1} + y_{obs} - y_k\right\} \tag{6a}$$

$$y_k = \exp\left\{a\left(x_{UAV} - x_{DEM}\right) + b\right\} \tag{6b}$$

Here, $y_{x=1}$ means model based air radioactivity at the ground level (height = 1m) as calculated in equation (7).

$$y_{x=1} = \exp(-0.008556 \cdot 1 - 0.285962) = 0.7444 \quad (7)$$

y_{obs} is observed air radioactivity. x_{UAV} and x_{DEM} mean UAV flight altitude and altitude obtained from digital elevation map at the correspondant point of x_{UAV} .

(2) Estimation of air-doses at the ground level

Fig. 15 indicates calibrated result of air-doses by using equation (5). As shown in this figure, micro hot-spots of radiation are detected in the midst of the forest. Besides, radiation in the area framed by black dot line (fruit trees on southern slopes) are comparatively higher. When comparing with **Fig. 11** and **Fig. 15**, it is indicated that both elevation and feature height should be considered when estimating ground level contamination when air-borne survey is conducted.

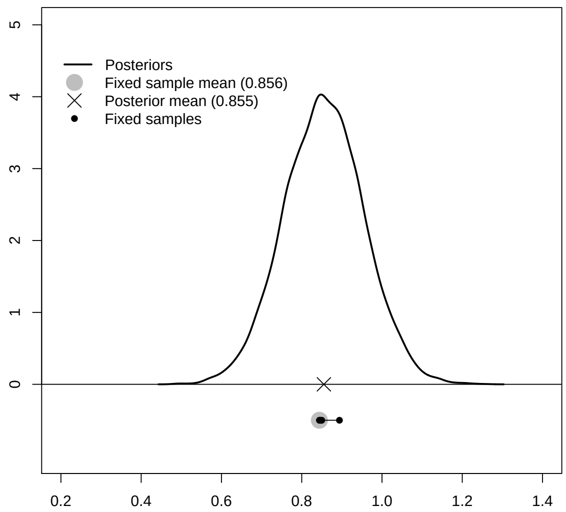

Fig. 13 Prior (observed) sample and posteriors of radiation at the fixed calibration points

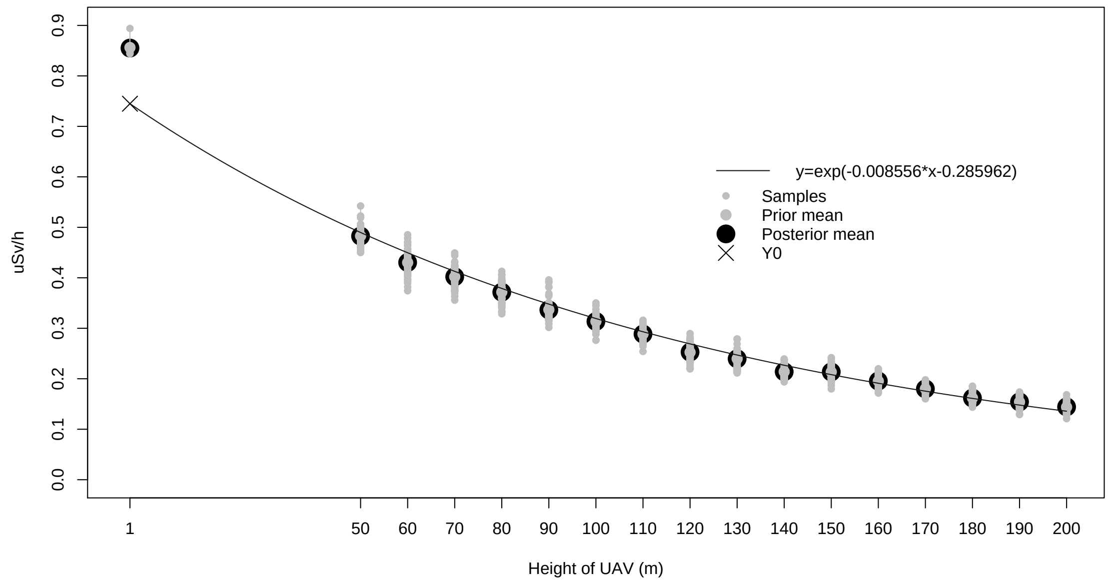

Fig. 14 Airial ortho photo of the study area by the UAV

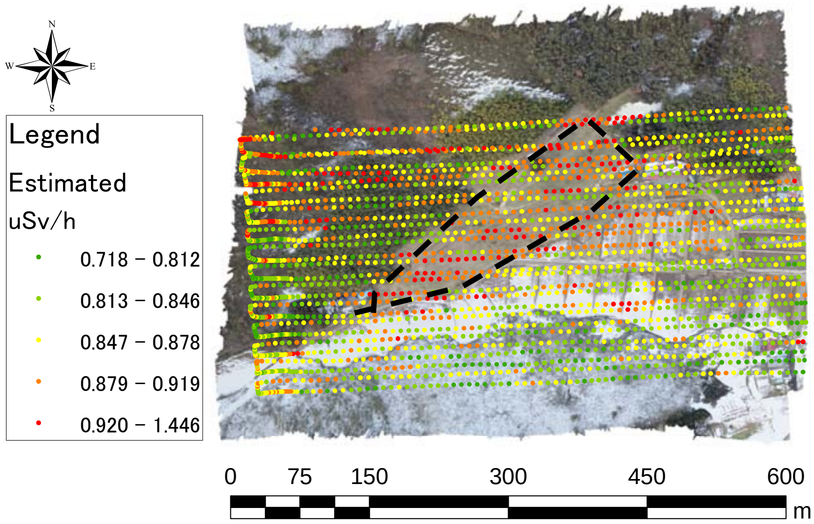

Fig. 15 Caribrated radiation air-doses in the study area

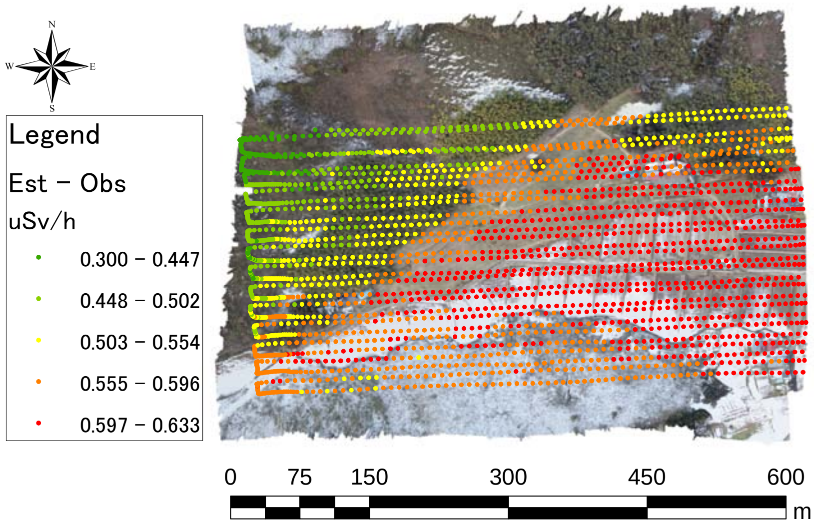

Fig. 16 Difference between estimated and obsereved air radioactivity

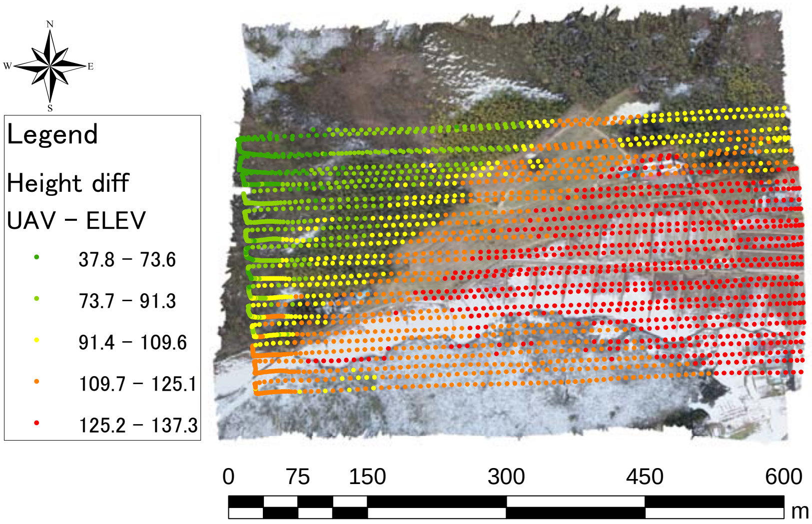

Fig. 17 Difference between UAV flight height and surface elevation (unit: meters)

Fig. 16 indicates difference between estimated radioactivity at the ground level and observed radioactivity by UAV air-borne survey (before calibration). This results basically corresponds to defference between UAV flight height and elevation as shown in **Fig. 17**.

5. CONCLUSIONS

In this study, the authors proposed methodology to calibrate air-radioactivity that is obsereved by UAV air-borne survey. Because the number of sampling points is limited, posterior mean of Normal distribution on air-radiation is estimated by MCMC. A decay model for calibration corresponds to UAV flight altitude, surface height and elevation is also estimated by Bayesian approach. It is indicated that calibrated result of air-doses at the ground level seem to reprecate actual surface air-doses well.

In the future, the authors plan to conduct air-borne radioactivity suevey with UAV in forestery area where radiation contamination seems to be high, such as Iitate-village. It is also a crucial issue to make UAV air-borne survey reasonable. Air-borne survey combined with manned air vehicle is also remained research field.

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