Generation of ^{137}Cs surface distribution maps using dense measurement transects of a towed gamma-ray spectrometer

Kosuke Murata[1], Blair Thornton[1], Kazunori Nagano[1], Seiki Ohnishi[2]
(1) Institution of Industrial Science, the University of Tokyo4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505 Japan
(2) National Maritime Research Institute, 6-38-1, Shinkawa, Mitaka-shi, Tokyo, 181-0004 Japan

***Abstract*— In this paper, we describe a method to generate surface distribution maps of seafloor ^{137}Cs levels. The method interpolates the measurements of a towed gamma-ray spectrometer, which are made along intersecting line transects, by modeling the spatial variations between each observation. Since it is known that sediment type has an influence on the distribution of ^{137}Cs, the proposed method aims to improve the spatial auto correlation of the models by segregating the surveyed area into continuous regions in which the sediment types are judged similar. This is achieved based on the back-scatter intensity of side scan sonar images taken in the surveyed region. The method is applied to data obtained at the Abukuma river mouth located approximately 80km north from F1NPP on October 2013. The accuracy of the proposed method was evaluated by correlating the levels of ^{137}Cs in the generated maps with samples that were obtained in the same area. The results demonstrate that the proposed method of interpolation improves the correlation compared to conventional methods that do not account for sediment type.**

Keywords—Spatial interpolation; ^{137}Cs; Kriging; Seafloor sediment;

I. INTRODUCTION

The aim of this work is to develop a method to map the continuous distribution of ^{137}Cs on the seafloor based on the measurements of a towed gamma-ray spectrometer. Following the earthquake and the tsunami that hit the east coast of Japan on March 11, 2011, a significant quantity of ^{137}Cs was released from the Fukushima Daiichi Nuclear Power Plant (F1NPP). The F1NPP disaster was designated as a level 7 accident on the International Nuclear Event Scale (INES), and the total amount of ^{137}Cs discharged directly into ocean between March 26 and the end of May 2011 has been estimated to be in the order of $3.5 \pm 0.7\times10^{15}$ Bq [1]. While a large portion of this is thought to have remained in solution and been dispersed by ocean currents [2], some proportion has accumulated in marine sediments and is expected to remain on the seafloor for several decades due to its 30 year half-life. Therefore it is necessary to monitoring the detailed distribution of seafloor radiation in the affected region off Tohoku.

II. BACKGROUND

Traditionally, radiation in seafloor sediments is surveyed by obtaining samples using a core-sampling device. This approach is suitable for collecting detailed information concerning the sediments and monitoring of seafloor radiation at Fukushima using this approach has been reported [3][4]. However, sampling points in the ocean are often separated by several kilometers and at these resolutions, it is not possible to capture the complex, local scale variations in the distribution of radioactive material on the seafloor. The authors previously described an in situ instrument [5] that has been developed and successfully deployed to measure the distribution of seafloor gamma-radiation continuously along linear transects [6]. The instrument consists of a gamma-ray spectrometer contained in a pressure hull covered with a flexible rubber hose. During operation, system is attached to a tether cable and towed along the seafloor by a ship. The towed gamma-ray spectrometer detects the photoelectric peak counts per second (cps) of 137Cs during survey. The count rates can be converted to radioactive concentration (Bq/kg-w) using conversion factors derived from Monte Carlo simulations that take into account the vertical profile of core samples obtained in the surveyed region. To date, the system has obtained data along transects that total more than 3000 km in length, with multiple datasets obtained near the F1NPP and Abukuma river mouth located approximately 80 km north from F1NPP. Fig.1 shows an example of data obtained using this system at the Abukuma river mouth on March to July 2013 and October 2013. Through comparing these data it is possible to determine temporal changes in the distribution patterns. However, while the datasets are measured along the same transect and can be geo-referenced to within a few tens of meters in post-processing [5], the exact location of the instrument on the seafloor may vary by several tens or hundreds of meters between different surveys (Fig.1) due to the nature of its operation. Since local scale variations in radiation levels are known to occur [3][6], it is therefore difficult to determine whether the differences in the data obtained are temporal effects or due to the difference in location of the measurement.

978-0-933957-43-5 ©2015 MTS

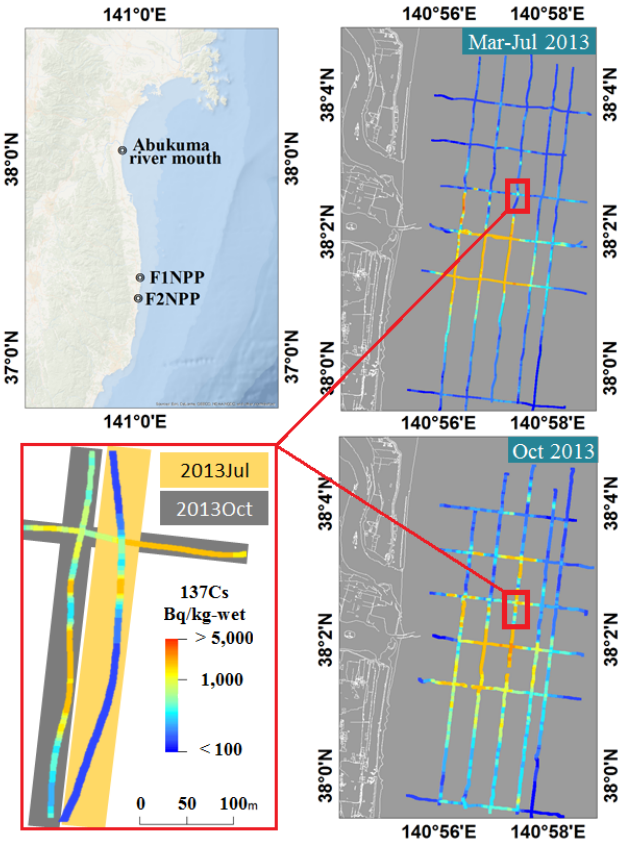

Fig. 1. Distribution of seafloor radiation at Abukuma river mouth in March to July 2013 and October 2013.

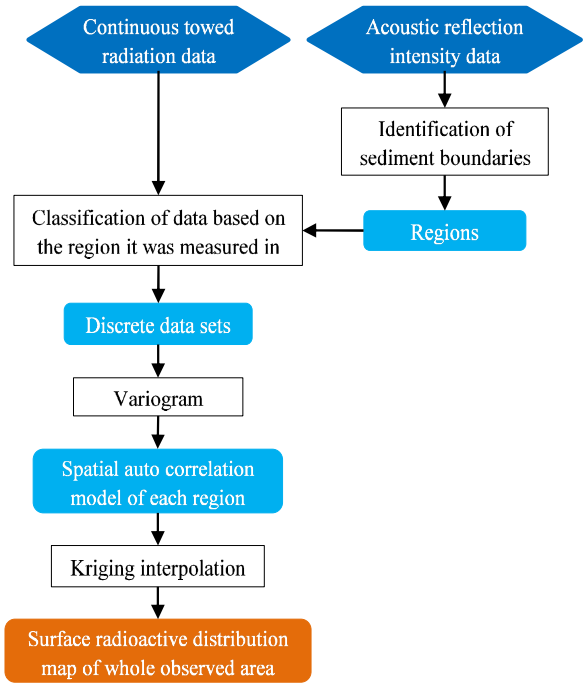

Fig. 2. Flow chart of proposed method

In order to overcome this problem, this paper proposes a method to generate surface distribution maps by interpolating the continuous towed data obtained using the towed spectrometer. The development of such a method can enable more meaningful comparison of geo-registered datasets and lead to a better understanding of the changes that can reliably attributed to time.

III. Methods

The method developed (Fig.2) is based on spatial interpolation using Kriging [7][8]. Kriging is a method to estimate the value $z(\boldsymbol{x}_0)$ at an arbitrary location by weighting and averaging the surrounded observed values $z(\boldsymbol{x}_i)$.

$$z(\boldsymbol{x}_0) = \sum_i w_i z(\boldsymbol{x}_i) \tag{1}$$

The weighting coefficients w_i depend on the distance from an arbitrary location, and the threshold of distance can be decided by fitting a variogram. A variogram γ, represents the continuity of data distribution

$$\gamma(\boldsymbol{h}) = \frac{1}{2N(\boldsymbol{h})} \sum_{i=1}^{N(\boldsymbol{h})} \{z(\boldsymbol{x}_i) - z(\boldsymbol{x}_i + \boldsymbol{h})\}^2 \tag{2}$$

Equation (2) calculates covariance of each pair of observed data as function of distance $\boldsymbol{h}$ between the data points to model their spatial correlation. The threshold of the distance for estimation is obtained by the fitting a theoretical model to calculated variogram plots.

In this work, we use Kriging to estimate the value and associated uncertainty of ^{137}Cs count rates at locations that are not observed from the data observed using a toed gamma-ray spectrometer. Kriging is frequently used as an optimal solution for spatial interpolation, and has been previously applied to generate ^{137}Cs surface distribution maps by interpolating distribution data measured on land using airborne measurements [9]. It has also been reported that the IAEA-MEL mapped the distribution of ^{137}Cs in sediment offshore Sellafield nuclear fuel reprocessing plant where total of 41×10^{15}Bq of ^{137}Cs was released into the Irish Sea. Here, Kriging was applied to data obtained using a gamma-ray spectrometer similar to the one used in this work [10]. However, while Kriging can be considered an optimal solution to problems where the spatial distribution is only a function of distance between data points, it cannot provide a robust solution in cases where some other factors influence the spatial distribution patterns. Previous studies have shown that Cs is strongly adsorbed to fine particles, especially to clay minerals [11] and this factor is known to have a large influence on the distribution of ^{137}Cs in marine sediments. Therefore in order to improve the model, we modify conventional Kriging interpolation by creating discrete sets of models for different sediment types.

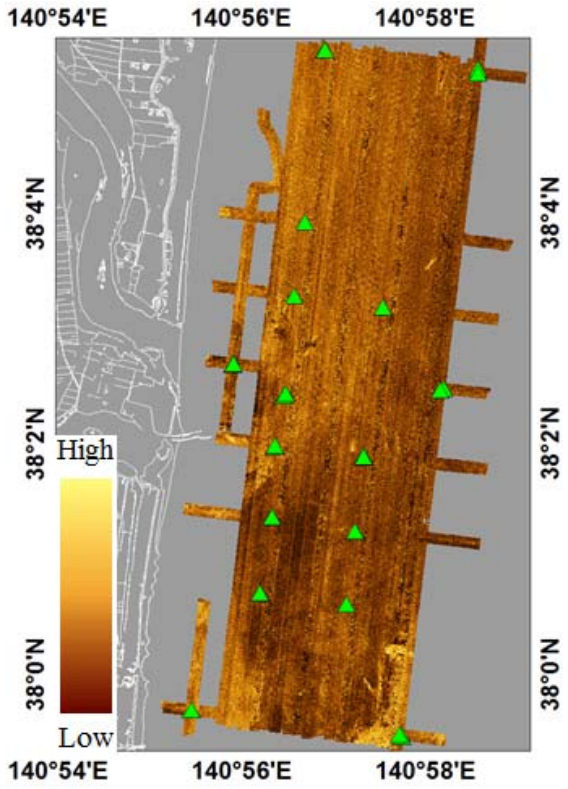

Fig. 3. Acoustic backscatter intensity data obatained at Abukuma river mouth.

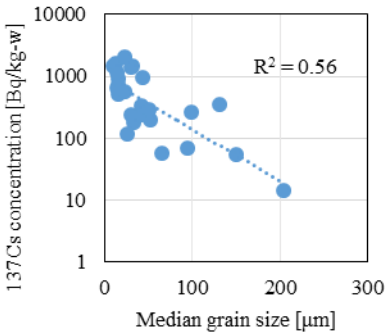

Fig. 4. Comparison between median grain size and concentration of 137Cs

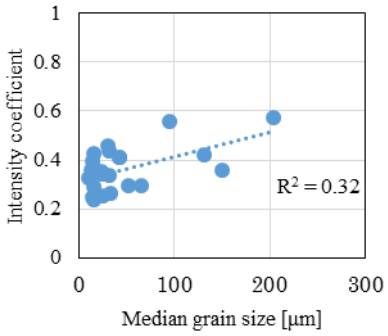

Fig. 5. Comparison between median grain size and acoustic intensity coefficient

The observed area (Fig.3) contains different type of sediment and each can be expected to have different distributions of 137Cs, and will not follow a simple spatial relationship across sediment boundaries. Fig.4 shows a scatter plot comparing median grain size and 137Cs concentration of the upper 0-3cm seafloor sediment of 29 samples obtained at Abukuma river mouth between March 2013 and January 2014.A correlation exists between the two parameters and there is a trend for smaller grain size sediments like clay and silt to have higher concentration.

It is not possible to directly measure the type of sediment over continuous areas. Therefore, in this work we use acoustic backscatter intensity data obtained at Abukuma river mouth using a side-scan sonar (Klein system 3000, 445 kHz), shown in Fig.3, to infer the location of sediment type boundaries. The strength of acoustic backscatter is related to the sediment types [12][13]. Fig.4 compares the median grain size of the top 3cm layer and the reflection intensity coefficient at the sampled location. Each sample's location is shown by a green triangle plots in Fig.3.Areas with high intensity acoustic reflections tend to represent areas with large grain sizes, i.e. sediments such as sand or rock, and low intensity areas represent a smaller grain size area like silt or clay. For the purpose of this study, it is not necessary to identify the specific type of sediment from the acoustic data, but just identify the boundaries between continuous sediment regions. These boundaries are used to segment the survey area and the data obtained by the towed spectrometer adopts the label of the segment that it was measured in. The spatial auto correlation model of the radioactivity distribution in each segment is considered using a variogram to model the spatial relationship within each segment. Each discrete model is used to generate the surface radioactive distribution map within each segmented area, and the segments are combined to generate a surface distribution of 137Cs over the entire surveyed area.

IV. Results

The proposed method is applied to the continuous radioactive data obtained during October 2013 at Abukuma river mouth. The sediment boundaries, for this work, have been identified manually based on the acoustic backscatter data in Fig. 3. The segmented regions are illustrated in Fig.6, where each segment is represented by a different color. To evaluate the generated radioactive distribution, results estimated through conventional Kriging and the proposed method are compared based on the level of 137Cs measured in sediments sampled in same area during the same period as the towed survey. The Sampled points are shown by blue triangles in Fig.6 with their numbers labels. The values interpolated using the proposed method are in units of cps and so it is necessary to convert these to Bq/kg-w of 137Cs using conversion factor that can be determined at each sample's location. Since the samples were obtained in regions near the towed-transects, in order to evaluate the accuracy of the interpolation method, data measured using the towed spectrometer within a 500m radius of each sample was removed and the results were compared. Table 1 shows the conditions under which conventional kriging and the proposed method were compared.

Generated maps are shown in Fig.7. In the conventional method, the spatial correlation determined was a zero order correlation and so the map generated is basically an average of measurements made over a wide area. Compared to the conventional method, the proposed method identifies stronger spatial correlations within the different segments. The Comparison of estimated values and observed values is shown in Fig.8 and correlation values between them are shown in Fig.9. In both data conditions, the proposed method improves the correlation. In the case of the estimation where measurements near the samples were removed, the proposed method was capable of providing significantly better estimates of the 137Cs levels. However, while the propose method resulted in significant improvements of the estimates for the data set shown in this work, the correlation values between the estimations and the results of sampling have a R2 value of < 0.4. This is due to the influence of two outliers. Sample No. 5 represents the peak of a region that has a locally high level of 137Cs. This is most accurately modeled by the proposed method using all of the data points (condition B), but since it represents a local maximum in 137Cs, it cannot be interpolated from the surrounding data in the data where points have been removed (condition D). For conventional Kriging (conditions A and C), the spatial scale of the locally high area is too small to be modeled by the derived spatial relationship, and so the information is lost. When all points are considered the proposed method can model the relevant spatial relationship.

However, while the propose method resulted in significant improvements of the estimates for the data set shown in this work, the correlation values between the estimations and the results of sampling have an R2 value of 0.4. This is due to the influence of by two outliers. The one Sample No.5 represents the peak of a region that has a locally high level of ^{137}Cs. Estimation of value that is higher than surrounding observed value may resulted with under estimated value in kriging, and this is the possible reason of Sample No.5 became outlier. The other outlier is sample No.10. In this case, all models performed poorly. Since the sample is located at near a sediment boundary, it can be expected that region has high spatial variability. This is combined with spatial uncertainty in the location from which the sample was retrieved (which could well vary by several tens of meters) making inherently unfavorable conditions for data interpolation.

TABLE I. COMBINATION OF METHOD AND DATA CONDITIONS

Data condition	**Method**	
	Conventional Kriging	***Proposed method***
Normal	A	B
Partially removed	C	D

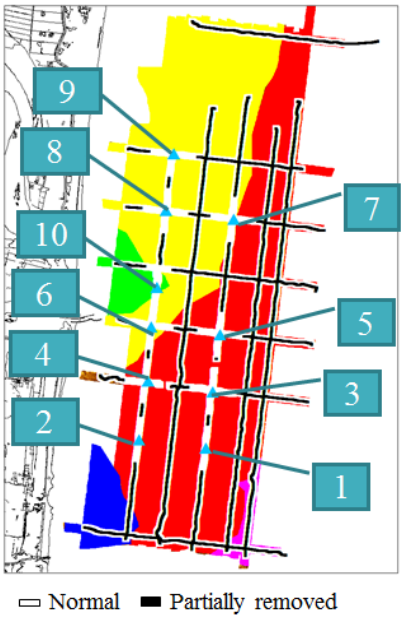

Fig. 6. Segmented regions.

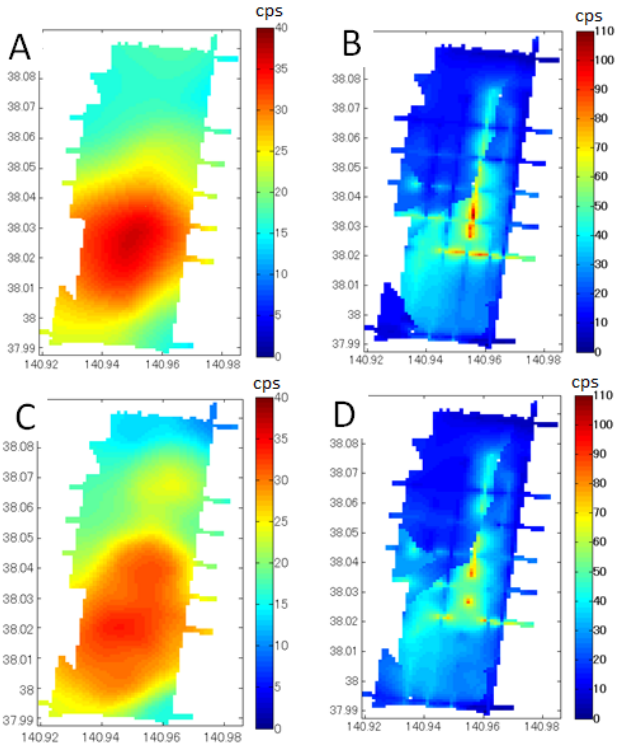

Fig. 7. Generated 2D surface distribution maps of ^{137}C cps

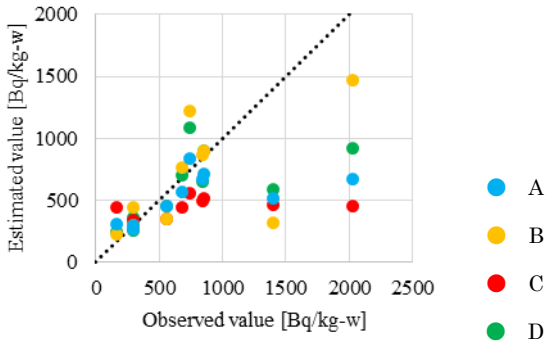

Fig. 8. Comparison between estimation and observation

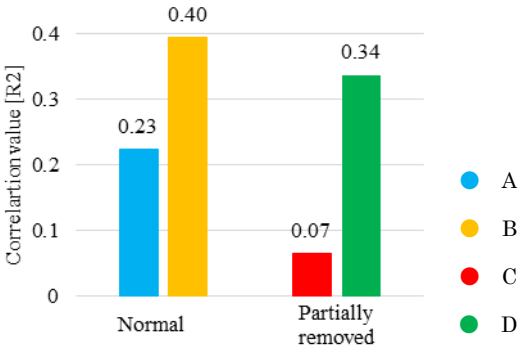

Fig. 9. Correlation between estimation and observation

V. Conclusions

This work proposes a method to interpolate the measurements of a towed gamma-ray spectrometer and generate 137Cs surface distribution maps for marine sediments. Acoustic backscatter intensity data from side-scan sonar images of the survey region were used to segment the data, and Kriging was used to interpolate the data within each segment by modeling the spatial correlation of the observed data. It is demonstrated that the overall accuracy can be improved by accounting for boundaries in sediment types when modeling the spatial correlation between observed data points.

In our future work, the authors will automate the segmentation of the acoustic data using image processing techniques to improve the objectivity of the method. Finally the method will be applied to data sets from different time periods and also before and after events such as typhoons in order to help understand the spatial redistribution of radioactivity on the seafloor.

Acknowledgment

The analysis in this work was performed on data obtained by the Nuclear Regulation Authority of Japan.

References

[1] D. Tsumune, T. Tsubono, M. Aoyama,K.Hirose, "Distribution of oceanic ^{137}Cs from the Fukushima Dai-ichi Nuclear Power Plant simulated numerically by a regional ocean model," J. Environ. Radioactiv., vol.111, pp.100-108, 2012.

[2] Y.Masumoto, "Oceanic dispersion simulation of 137cs released from the Fukushima Daiichi Nuclear Power Plant," Elements, vol.8, pp.207-212, June 2012.

[3] M.Kusakabe, S. Oikawa, H. Takata, and J. Misono, "Spatiotemporal distributions of Fukushima-derived radionuclides in nearby marine surface sediments,"Biogeoscience, vol.10, pp.5019-5030, 2013.

[4] D. Ambe, "Five-minute resolved spatial distribution of radiocesium in sea sediment derived from the Fukushima Dai-ichi Nuclear Power Plant," J. Environ. Radioactiv., vol.138, pp.264-275, 2014.

[5] B. Thornton, S. Ohnishi, T. Ura, N. Odano, and T. Fujita, "Continuous measurement of radionuclide distribution of f Fukushima using a towed sea-bed gamma ray spectrometer," J. Deep-Sea Reserch I, vol.79, pp.10-19, 2013.

[6] B. Thornton, "Distribution of local ^{137}Cs anomalies on the seafloor near the Fukushima Dai-ichi Nuclear Power Plant," J. Marine Pollution Bulletin, vol 74, pp.344-350, 2013.

[7] G. Matheron, "Principles of geostatistics," Economic Geology, vol. 58, pp.1246-1266, December 1963.

[8] H. Kohsaka, "Kriging and its geographic applications," J. Institute of Natural Sciences Nihon University Japan, vol.34, pp.27-35, 1999.

[9] T. Torii, "Investigation of radionuclide distribution using aircraft for surrounding environmental survey from Fukushima Dai-ichi Nuclear Power Plant," JAEA-Technology 2012-036, December 2012.

[10] I.Osvath, P.P.Povinec, M.S.Baxter, and L.Huynh-Ngoc, "Mapping of the distribution of ^{137}Cs in Irish sea sediments," J. Radioanal. Nuc. Chem., vol.248, no.3, pp.735-739, 2001.

[11] B.C.Bostick, M.A.Vairavamurthy, K.G.Karthikeyan, and J. Chorover, "Cesium adsorption on clay minerals: An EXAFS spectrosopic investigation," Environ. Sci. Technol., vol.36, pp.2670-2676, 2002.

[12] R.W.Faas, "Analysis of the relationship between acoustic reflectivity and sediment porosity," Geophysics, vol.34, no.4 pp.546-553, August 1969.

[13] J.S.Collier, and C.J.Brown, "Correlation of sidescan backscatter with grain size distribution of surficial seabed sediments," Marine Geology, vol.214, pp.431-449, 2005.