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Instruments and Methods

Continuous measurement of radionuclide distribution off Fukushima using a towed sea-bed gamma ray spectrometer

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ABSTRACT

Instrumentation and data processing methods to continuously map the distribution of radionuclides on the seafloor have been developed and applied to survey radioactive discharge from the Fukushima Dai-ichi Nuclear Power Plant following the M9.0 earthquake and tsunami that struck the east coast of Japan on March 11 2011. The instrument consists of a flexible rubber hose with an integrated gamma ray spectrometer that measures the full gamma spectrum between 0.1 and 1.8 MeV while being towed along the seafloor by a ship. The data processing methods described allow for quantification of ^{137}Cs and ^{134}Cs concentration in marine sediments, and a technique has been developed to optimize the spatial resolution of the measurements for each radioactive species for a given level of statistical uncertainty. The system was deployed during August and November 2012 to measure the distribution of radionuclides along three transects within an 80 km radius of the plant. Increased levels of ^{137}Cs and ^{134}Cs were recorded and their distributions mapped continuously over distances of 1.6, 12.5 and 22 km respectively. The levels of ^{137}Cs and ^{134}Cs were found to vary significantly with location. The in situ measurements show good agreement with laboratory analyzed samples obtained during the surveys. The results demonstrate that the instrument and data processing techniques described enable high resolution, quantitative measurements of ^{137}Cs and ^{134}Cs in marine sediments, and provide an effective solution for rapid, low cost monitoring of radioactive material on the seafloor.

1. Introduction

The M9.0 earthquake and subsequent tsunami that struck the east coast of Japan on March 11 2011 triggered a series of events that resulted in discharge of radioactive material from Fukushima Dai-ichi Nuclear Power Plant (F1 NPP) into the environment. The event has been rated at Level 7 on the International Nuclear Event Scale, with an estimated $3.5 \pm 0.7 \times 10^{15}$ Bq of ^{137}Cs thought to have been discharged into the ocean between March 26 and the end of May 2011 (Tsumune et al., 2012). While a concerted effort has been made to monitor the distribution of radioactive material in the environment, survey of radionuclides on the seafloor remains one of the most challenging areas of monitoring. In this communication, we describe an instrument developed to measure the continuous distribution of radionuclides on the seafloor together with methods to process the data it obtains in a quantitative manner. The system consists of a gamma ray spectrometer built into a flexible hose that is towed along the seafloor by a ship. While similar systems have been developed previously, the main emphasis of this work lies in the development of data processing techniques that allow for direct quantification of ^{137}Cs and ^{134}Cs concentration with bounded error margins, and optimizes the spatial resolution of measurements made for each radioactive species for a given level of statistical uncertainty. Monitoring surveys were performed at two sites located within an 80 km radius of F1 NPP during August and November 2012, about one and a half years after the discharge. The continuous distributions of ^{137}Cs and ^{134}Cs were mapped along three transects of distances 1.6, 12.5, and 22 km, respectively. The results have been verified through comparison with laboratory analyzed samples obtained during the surveys, demonstrating that continuous mapping using in situ measurement techniques forms an effective tool to rapidly build a picture of the distribution of radionuclides on the seafloor.

1.1. Background

Monitoring of seafloor radiation is typically carried out through sampling (Ilus et al., 2007; MEXT, 2011, 2012; TEPCO, 2012; Fukushima Prefecture, 2012a, 2012b). However, wide area surveys in regions with

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strongly varying radionuclide concentration require a density of sampling that exceeds the practical capabilities of standard techniques. The costs associated with dense sampling surveys are prohibitive, and wide area surveys can often only be sampled sparsely with points typically separated by tens of kilometers (MEXT, 2011). Data obtained from such sparse sampling surveys cannot capture local scale variations in the distribution of radionuclides on the seafloor. Furthermore, the traditional methods employed for seafloor sampling are not effective in regions of rocky outcrops (Jones et al., 1984; Ilus et al., 2007; MEXT, 2011, 2012; TEPCO, 2012; Fukushima Prefecture, 2012a, 2012b) or in steeply sloped areas, which are common in coastal areas.

In situ measurement of radioactivity offers an efficient, low cost alternative to sampling of the marine environment. Numerous oceanographic instruments have been developed to monitor temporal variations of radionuclide concentration in the water column (Aakenes, 1995; Wedekind et al., 1999; Van Put et al., 2004; Bagatelas et al., 2010; Tsabaris, 2008; Tsabaris et al., 2012), and on the seafloor (Kostoglodov, 1977; Povinec et al., 1996; Yoshida and Tsukahara, 1991; Kobayashi et al., 1999). In situ radiation sensors typically use passive gamma ray spectroscopy, and can in theory detect any gamma ray emitter present in sufficient quantities. However, rapid absorption of gamma rays by the pressure tight vessels used to house underwater instruments, and moreover the absorption of water itself limits in situ measurements to emission energies in excess of 0.1 MeV (Jones, 2001). In addition to limiting the range of detectable emission energies, for measurement of seafloor radiation, the strong absorption by seawater requires the detectors to be within a few centimeters of the seafloor (Kostoglodov, 1977; Jones et al., 1984). In order to perform measurements of seafloor radioactivity over long distances, dedicated seafloor towed gamma ray spectrometers have been developed by various groups since the 1960s, with separate systems being developed in the United Kingdom (Miller et al., 1977; Thomas et al., 1983; Jones, 1994), the United States (Noakes and Harding, 1971; Noakes et al., 1974, 1989), Belgium (Bastin, 1973), the Netherlands (de Meijer et al., 2002), Monaco (Povinec et al., 1996; Osvath and Povinec, 2001) and Russia (Aksenov et al., 1976; Nevesskiy and Kostoglodov, 1976). A review of the development of these systems can be found in Jones (2001). Towed gamma ray spectrometers typically consist of a gamma ray spectrometer in a flexible hose that is attached to a ship by a wire or tether cable as illustrated in Fig. 1. The hose is towed along the seafloor by a ship, allowing the detector to maintain continuous contact with the seafloor over long distances. Surveys using towed systems are not selective in the types of seafloor where they can be deployed, and the continuous nature of the measurements can reveal variations in radionuclide concentration on spatial scales that cannot be captured through traditional sampling techniques.

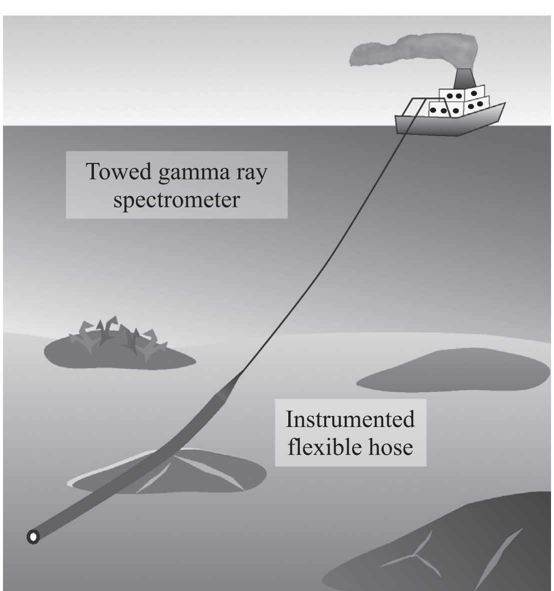

Fig. 1. Illustration of a ship towed gamma ray spectrometer (adapted from Jones (2001)).

While the earliest towed systems, developed in the 1960s, measured total gamma ray count rates regardless of the emitting radionuclides (Bastin, 1973), the development and applications of spectroscopic techniques in the 70s allows modern towed systems to measure the full gamma spectrum. The distributions of radionuclides can be determined through analysis of the gamma spectrum, where values are typically quantified through calibration with laboratory analyzed samples obtained in the surveyed area (Jones, 2001) or through Monte Carlo simulations (Osvath and Povinec, 2001; Maucec et al. 2004). One obvious requirement for measurements to be performed is for the instrument to maintain contact with the seafloor. For this, towed systems are often equipped with accelerometers, underwater microphones and depth sensors to verify that the system is in contact with the seafloor at any given time. The radioactive count rate of the spectrometer itself can also be used for this purpose, since the concentration of ^{40}K is significantly higher in sediments than in seawater. Even when proper contact is maintained, sources of uncertainty in the measurements include non-uniform vertical distributions of radionuclides, variable seafloor geometries and changes in the density and porosity of the sediments. In addition to these physical factors, the energy resolution of the detector is also limiting since it may not be possible to completely resolve radioactive emissions with similar energies, e.g. ^{137}Cs at 0.662 MeV and ^{134}Cs at 0.607 MeV. However, despite these challenges, it is generally accepted that the total error in measurement is usually no greater than 30% of the recorded values (Jones et al., 1984).

For towed surveys, in addition to measuring the concentration of radionuclides, it is also necessary to determine the location on the seafloor where the measurements were made. The position of the instrument can be estimated using dynamic catenary models that take as input shipboard GPS, measurements of ship velocity, the depth of the instrument, and the length of cable used to tow the system. While improvements in the accuracy of position estimates can be achieved by including cable tension and underwater current profile measurements into the models, for shallow water applications, less than 200 m depth, a simple dynamic model can provide position estimates with errors in the order of a few tens of meters, which is considered sufficient since the main interest is in mapping the distribution of radionuclides over several kilometers. In order to extend the method to deeper water applications, the use of acoustic localization techniques may become necessary to achieve sufficient positional accuracy.

1.2. Study area

In this work, we describe the development of a compact towed gamma ray spectrometer together with algorithms to process the data it measures. The targets for detection are the artificial radionuclides ^{137}Cs and ^{134}Cs, discharged from the F1 NPP, whose levels prior to the accident ranged from 0.68 to 1.7 Bq/kg (dry) for ^{137}Cs in sediments off the east coast of Japan (MEXT, 2011). These, together with the natural background emitter ^{40}K (Ilus et al., 2007), emit gamma rays of sufficient energy for detection, and are known to be present in marine sediments off Fukushima in sufficient quantities for in situ measurements to be possible (MEXT, 2011, 2012). Measurements of the instrument are quantified using Monte Carlo radiation transport models (Maucec et al., 2004), and a detailed analysis has been performed to evaluate measurement