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Original Article

Real-time wireless marine radioactivity monitoring system using a SiPM-based mobile gamma spectroscopy mounted on an unmanned marine vehicle

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ABSTRACT

Marine radioactivity monitoring is critical for taking immediate action in case of unexpected nuclear accidents at nuclear facilities located near coastal areas. Especially when the level of contamination is not predictable, mobile monitoring systems will be useful for wide-area ocean radiation survey and for determination of the level of radioactivity. Here, we used a silicon photomultiplier and a high-efficiency GAGG crystal to fabricate a compact, battery-powered gamma spectroscopy that can be used in an ocean environment. The developed spectroscopy has compact dimensions of 6.5 × 6.5× 8 cm^3 and weighs 560 g. We used LoRa, a low-power wireless protocol for communication. Successful data transmission was achieved within 1.4 m water depth. The developed gamma spectroscopy was able to detect radioactivity from a ^{137}Cs point source (3.7 kBq) at a distance of 20 cm in water. Moreover, we demonstrated an unmanned radioactivity monitoring system in a real sea by combining unmanned surface vehicle with the developed gamma spectroscopy. A hidden ^{137}Cs source (3.07 MBq) was detected by the unmanned system at a distance of 3 m. After successfully testing the developed mobile spectroscopy in an ocean environment, we believe that our proposed system will be an effective solution for mobile real-time marine radioactivity monitoring.

1. Introduction

Marine radioactivity monitoring is important in relieving public anxiety and taking immediate action when unexpected nuclear accidents occur at nuclear facilities located in coastal areas. Especially, for the effective decision making for nuclear or radiological emergency, in-situ gamma ray monitoring has to be conducted prior to the environmental sampling and in-laboratory radionuclide analysis [1]. In-situ gamma ray monitoring measures energy spectrum of the environmental radiation and assess existing radionuclides. However, in-situ radioactivity monitoring in an ocean environment is very challenging unlike terrestrial environment due to several reasons. First, gamma rays lose most of their energy in aquatic environments. Based on our simulation study, in which 2 kBq/m^3 of ^{137}Cs was uniformly distributed in 1 m^3 of seawater, we were able to detect gamma rays within 30 cm using a 50 × 50 × 30 mm^3 GAGG:Ce scintillation detector. Second, it is difficult to supply stable power in an ocean environment. Finally, data communication in an ocean or underwater environment is extremely challenging. Acquiring real-time data away from the coast is difficult and acquiring real-time data in underwater is even more challenging.

As a customary practice, real-time marine radioactivity monitoring is being conducted using a scintillation-based gamma-ray detector (e.g. NaI(Tl) coupled with photomultiplier tube (PMT)) installed underwater at specific fixed sites in coastal areas [2–7]. For example, Byun et al. [6]developed real-time large buoy-based radioactivity monitoring system that consists of a 3″ NaI(Tl) scintillator coupled with a 3″ PMT and powered by using solar power generator. The 3G cellular data communication was used for data communication. Such a fixed radioactivity monitoring system is

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useful for continuous long-term radioactivity monitoring in specific areas where level of radioactivity is predictable. Moreover, fixed system may have low minimum detectable activity (MDA) by using large detector geometry and adequate measurement time to measure low radioactivity level in the ocean.

On the other hand, mobile radioactivity monitoring systems may be necessary for wide-area ocean radiation survey to immediately deal with an emergency situation. Mobile system allows rapid monitoring in the wide-area ocean. Especially when the level of contamination is not predictable, mobile system will be useful to determine the level of radioactivity and the range of contaminated area. Marine vehicles, such as large or small ships [8], underwater robots, underwater drones, and unmanned surface vehicles combined with the radioactivity monitoring systems can be a good option to develop the mobile radiation survey system. Moreover, using unmanned remote vehicles will be even more helpful to avoid radiation exposure rather than the manned radiation survey system. Several considerations have to be taken into account to develop and operate mobile radioactivity monitoring system in the ocean environment. First, compact system geometry may be required to have high mobility and to be combined with unmanned vehicles. Second, the battery-powered system with low power consumption may be required for long-term monitoring in the ocean environment, because the ocean environment is hard to provide stable power supply. And finally, the wireless data communication may be helpful to transfer real-time data from the ocean to the land.

Hence, in this study, our strategy is to develop a mobile silicon photomultiplier (SiPM)-based gamma spectroscopy that can be mounted on an unmanned surface vehicle and allows real-time wireless data acquisition and transmission in underwater and water surface environments. To construct a mobile gamma spectroscopy, we used a SiPM, which consists of silicon photodiodes, and has a compact size compared to PMT-based systems. Several researchers have proposed the use of SiPM-based gamma spectroscopy in water environments [9–11]. However, Kim et al. (2019) [9] and Kim and Joo (2020) [10] used wired data transfer instead of wireless data communication. Data communication in aquatic environments is more challenging than in terrestrial environments because of the high permittivity and conductivity of water [12]. Acoustic communication is a good option for underwater data communication owing to its long range of over 20 km [13]; however, its high latency and low bandwidth, makes it unsuitable for real-time applications. Optical communication is another good option as it supports a large bandwidth and consumes low power. However, light scattering and interference from particles or objects in the water makes it unsuitable for long-range use. Radio frequency (RF) can be used in water-surface-to-terrestrial communication as RF protocols, such as Bluetooth, Wi-Fi, and ZigBee and cellular networks such as LTE, are extensively used in terrestrial environments and they offer low latency and high bandwidth, making them suitable for real-time applications. However, most RF communications show a high attenuation in a water environment and offer a limited range in underwater transmission. Several groups have developed mobile SiPM-based gamma spectroscopy with RF data communication, including Wi-Fi, which could be used in terrestrial or aerial environments [14,15]. However, they have not been tested in a water environment. Kim et al. (2018) [11] developed a mobile 6 × 6 × 30 mm^3 SiPM-based gamma radiation detector using Bluetooth. However, this study only covered an experimental evaluation of a single-pixel SiPM-based gamma detector contained in a small water box that did not represent a real underwater environment.

In this study, we evaluated the underwater performance of a mobile SiPM-based gamma spectroscopy system in a large water tank as well as in a real sea environment. The developed mobile gamma spectroscopy can be used in a stand-alone mode or in combination with unmanned vehicles to conduct real-time active radiation monitoring by moving in the water environment and identifying the contaminated area.

2. Materials and methods

2.1. Low-power wireless SiPM-based gamma spectroscopy

2.1.1. SiPM-based gamma spectroscopy

To construct a radioactivity monitoring system that can be utilized in marine environments, we developed a compact gamma spectroscopy system, a low-power battery-operated system, and wireless data communication. We used a SiPM and a high-efficiency scintillation crystal to construct the compact system. The gamma spectroscopy consisted of a 48 × 48 × 20 mm^3 GAGG:Ce ($Gd_3Al_2Ga_3O_{12}$, d = 6.6 g/cm^3, light output:50,000 photons/MeV) scintillation crystal (Epic Crystal, China) coupled with an 8 × 8 SiPM array (ArrayJ-60035-64P-PCB, OnSemi, USA). The analog SiPM signals from the 8 × 8 channels were summed and fed into a gain amplifier and a shaper. The peak-and-hold method [16] was used in the front-end circuitry to acquire the pulse height information of the incident gamma-ray signal. Front-end electronics, including a SiPM biasing circuit, were configured using a digital-to-analog converter (DAC, DAC7574, Texas Instruments Inc., USA). The output of peak-and-hold circuit was fed into a low-power 12-bit analog-to-digital converter (ADC, AD7492, Analog Device, USA) to acquire the pulse-height spectrum. In addition, a temperature and pressure sensor (MS5803-14BA, TE Connectivity, Switzerland) was installed on the board to acquire temperature and water depth information within the water environment. These environmental data were combined with radioactivity measurement data for the further data analysis. All the data were sent to a low-power microprocessor unit to conduct serial or wireless data communication to the acquisition PC. The developed SiPM-based gamma spectroscopy system was operated using a 3500 mA h Li-ion battery. Table 1 and Fig. 1(a) and (b) summarizes the specifications of the developed system. Energy calibration was conducted using five photon energies from standard point sources ^{133}Ba (356.02 keV), ^{22}Na (511 keV, 1275 keV), and ^{137}Cs (662 keV), and naturally occurring isotope ^{40}K (1460 keV). The SiPM photopeak values were plotted with the real energy value and fitted with a linear function as shown in Fig. 1(c).

2.1.2. Low-power underwater wireless data communication

Wireless data communication takes a significant portion of device power consumption [17]. Therefore, one of our strategies to develop a low-power gamma spectroscopy system was to use low-power wireless network configurations. Here, we used LoRa (from "Long Range") for data communication. LoRa is a low-power wide-area network protocol operated in the industrial, science, and medical (ISM) sub-giga-frequency RF range (800–900 MHz). LoRa offers long-range transmission (10 km range using speeds of 0.3–27 kbps) in terrestrial environments [18]. Compared to high-throughput network protocols such as Wi-Fi, cellular, or ZigBee, LoRa has a slow data rate; however, we chose LoRa because it supports long-range communication. Moreover, South Korea has developed a nationwide LoRa network. Using a customized LoRa antenna design, Dala and Arslan 2021 demonstrated that LoRa could support data transmission up to 6 m underwater and from 160 m above the water surface [19].

In this study, we used a 915 MHz LoRa for underwater or surface water wireless data communication. For device compactness, a very small omnidirectional monopole antenna of size 28 mm × Φ 9 mm was used (VSWR < 1.5 at 920 MHz). To overcome the low data

Table 1
Specifications of the SiPM-based gamma spectroscopy.

Specifications	
Scintillation crystal	GAGG:Ce 48 × 48 × 20 mm^3
Photosensor	8 × 8 SiPM array (ArrayJ-60035-64P-PCB)
Detector weight	560 g (including battery)
Detector size	6.5 × 6.5 × 8 cm^3
Energy range	20 keV–1.8 MeV
Energy resolution	8.75 ± 0.21%
Operation time	Up to 24 h
Other	Temperature, water/air pressure, and altitude sensor

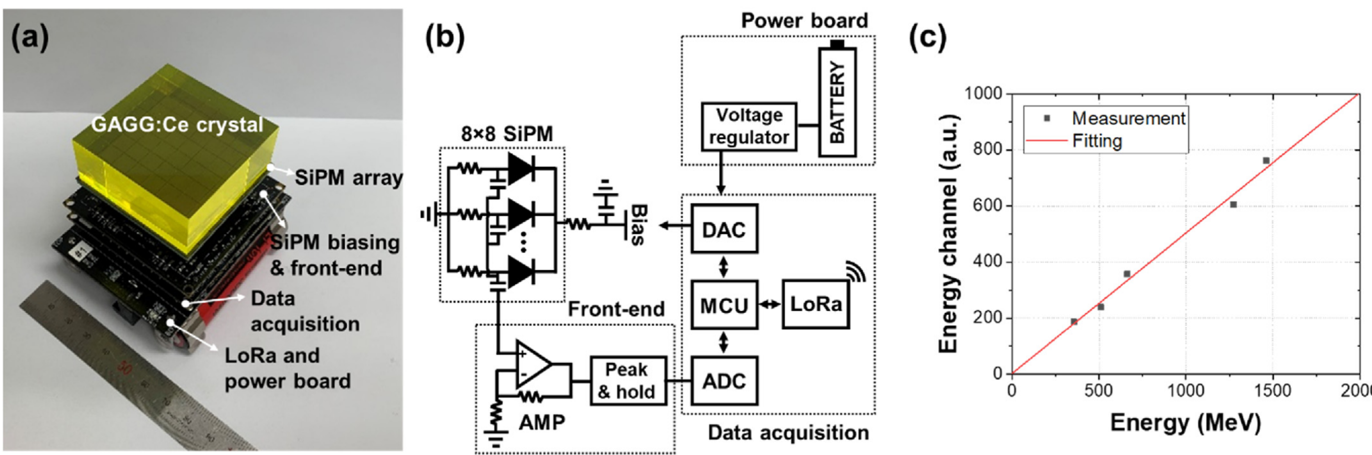

Fig. 1. (a) A real photograph and (b) a schematic of the developed low-power wireless SiPM-based gamma spectroscopy using 48 × 48 × 20 mm^3 GAGG:Ce scintillation crystal coupled with SiPM. (c) The calibrated energy spectrum of the develop gamma spectroscopy.

rate of LoRa, the real-time gamma energy was stored in an Electrically Erasable Programmable Real-Only Memory, and the cumulated energy spectrum was sent at once at the end of the data acquisition.

2.2. Underwater performance evaluation

In contrast to the terrestrial environment, it is challenging to conduct data measurements and transmission in the underwater environment. Therefore, the underwater performance must be validated prior to regular system operation. In this study, we evaluated the underwater performance of the developed wireless gamma spectroscopy system in a large water tank. All underwater evaluations were conducted inside a 35 × 20 × 9 m^3 water tank located at the Maritime Robotics Test and Evaluation Center of the Korea Institute of Ocean Science and Technology (KIOST) in Pohang, South Korea.

2.2.1. Wireless data communication evaluation

First, we evaluated the underwater data communication performance of the developed system. The wireless SiPM-based gamma spectroscopy and the 3.7 kBq ^{137}Cs point source were enclosed in the IP67 waterproof box and located inside the water tank. The waterproof box was tied to a crane to control the depth of the gamma spectroscopy inside the water. The detector was moved from a depth of 0 cm (water surface) to 160 cm with a 20 cm step size as shown in Fig. 2. The receiver was placed outside the water tank and measurements were conducted for 15 min at different water depths. Data transmission was tested for two trials, and communication success/failure was evaluated to determine the communication performance. In order to avoid rapid temperature change during the measurement, we placed the detector within the water about 15 min before the measurement to reach the stable temperature range. The temperature change during the measurement was insignificant which ranged from 1 to 3 °C.

2.2.2. Detector performance evaluation

To evaluate the gamma- ray detection sensitivity in the water environment, we performed wireless gamma spectroscopy at a water depth of 20 cm by tying it to a fixed structure. The 3.7 kBq ^{137}Cs point source was tied to a crane and the source-to-detector distance was modified from 0 cm to 100 cm with a 20 cm step size. Fig. 3(b) shows that the point source and the detector were not aligned because of the interference between the waterproof box and the rope tied to the crane. The measurements were conducted for 15 min at different source-to-detector distances.

2.3. Real-time unmanned marine radioactivity monitoring system in real-sea environment

As discussed earlier, mobile radiation monitoring devices may be advantageous compared with site-specific devices, especially in terms of contamination identification, because they can actively conduct radiation monitoring by exploring a larger ocean environment. In this study, we developed an unmanned marine radioactivity monitoring system by combining wireless gamma spectroscopy with an unmanned surface vehicle (USV), which was developed by KIOST [20]. The USV enables automated and manual operations along the predefined paths in water at a maximum speed of 16 km/h with two motors equipped at the rear. In addition, it offers a wireless data transmission system with a range of 8 km and a 4 h battery capacity. The size of the USV body was 170 × 38 × 28 cm^3, and the material of the body was carbon fiber reinforced polymer (FRP). To test the possibility of real-time

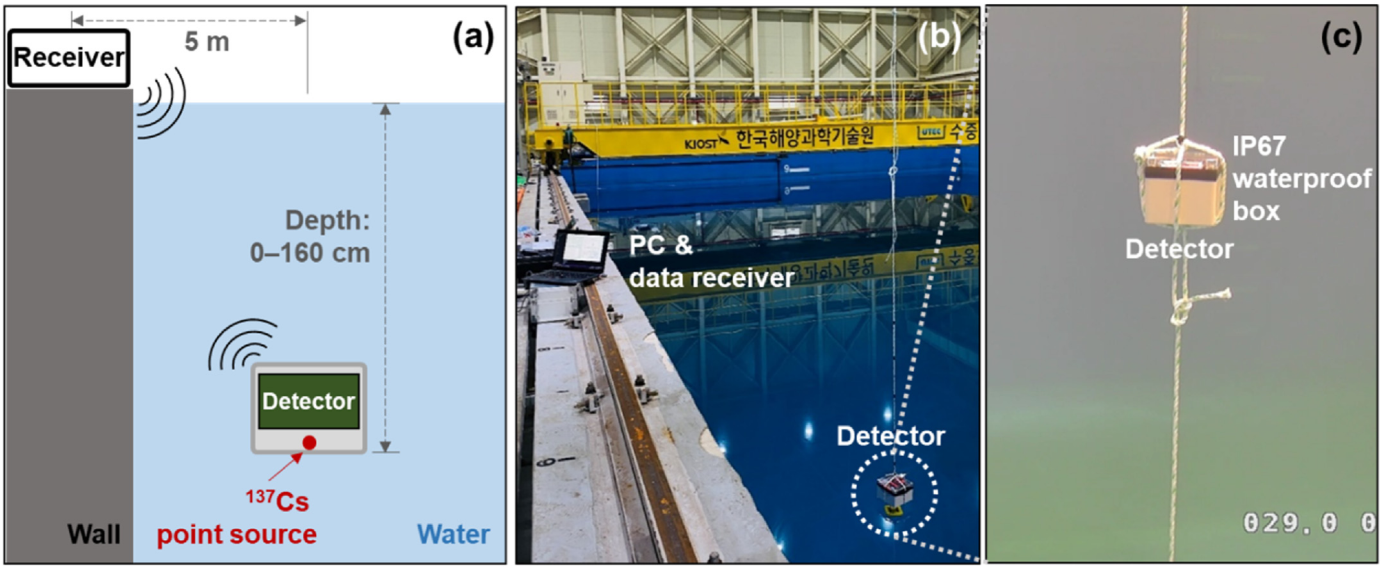

Fig. 2. Underwater wireless data communication evaluation. (a) Schematic of underwater wireless data communication evaluation experiment and (b) & (c) actual photographs.

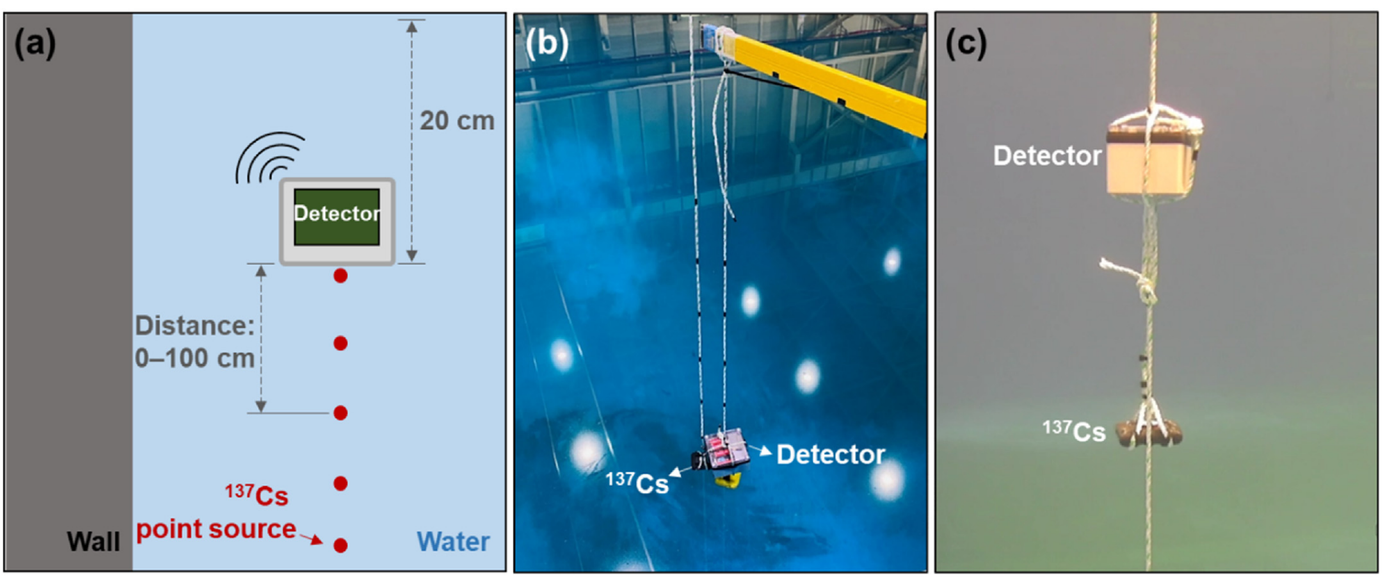

Fig. 3. Underwater detector performance evaluation. (a) Schematic of underwater wireless detector performance evaluation experiment and (b) & (c) actual photographs.

radioactivity monitoring in a real sea environment using the developed unmanned system, we conducted a hidden source tracking experiment in the ocean by hiding a sealed point source (3.07 MBq ^{137}Cs) located at 30 cm water depth near the landside (red point in Fig. 4(a)). The unmanned gamma spectroscopy was placed 10 m away from the source, and source tracking was started. The USV traveled along the dotted line in Fig. 4(a), and at each point (0.5, 2, 3, 5, and 10 m from the source), measurements were conducted for 5 min to acquire the gamma energy spectrum.

2.4. MDA (minimum detectable activity) evaluation

Here, MDA performance of the developed unmanned marine radioactivity monitoring system in the ocean environment was analyzed. MDA at 662 keV ^{137}Cs peak was calculated using the below equation [21] by taking into account of detection efficiency (ε), sample amount (m [L]), measurement time (t_s [sec]), gamma emission probability (I_r) of ^{137}Cs 662 keV peak, and background counts (μ_B).

$$\mathrm{MDA} = \frac{2.71 + 4.65 \times \sqrt{\mu_B}}{\varepsilon \times m \times I_r \times t_s}$$

The detection efficiency (ε) of the system was calculated using Geant4-based GATE Monte Carlo simulation [22] that includes SiPM-based gamma spectroscopy combined with USV on the seawater as shown in Fig. 5. Sample amount was determined to be a half-sphere with 50 cm radius filled with uniform ^{137}Cs. Background counts (μ_B) was measured from real background measurement data from 2.3 section which was measured for 15 min.

3. Results

3.1. Underwater data communication performance

To evaluate the underwater data transmission performance

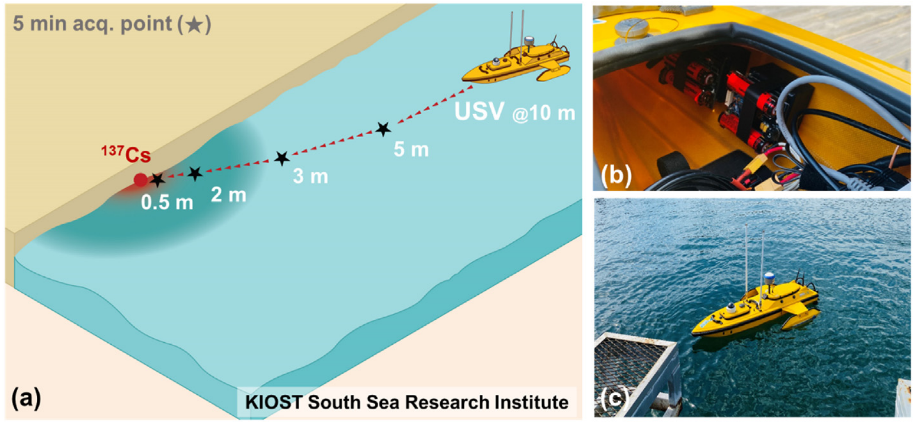

Fig. 4. (a) Schematic of real-time marine radioactivity measurement and source tracking experiment. Real-time unmanned active gamma spectroscopy system developed in this study where (b) & (c) show the wireless gamma spectroscopy installed inside the USV.

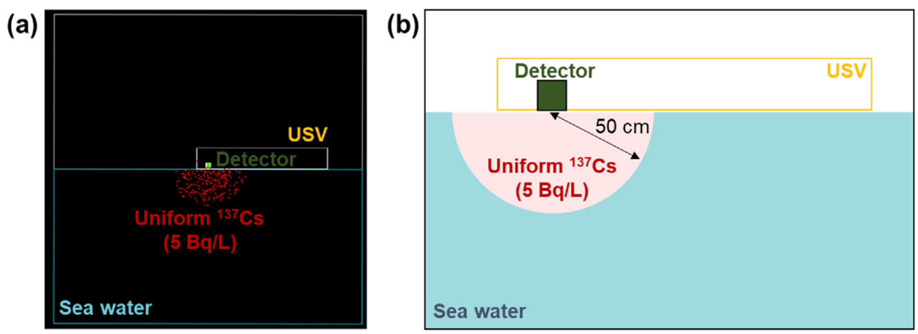

Fig. 5. (a) Simulated marine radioactivity monitoring system in the ocean environment using GATE simulation toolkit and (b) shows schematic of the simulated geometry.

using LoRa, the wireless gamma spectroscopy was placed in the water tank; the measured energy spectrum was transmitted to the receiver at the end of each measurement. LoRa successfully transmitted the spectrum data from under the water to the receiver placed outside the water tank until 1.4 m water depth. Once the gamma spectroscopy moved deeper than 1.4 m water depth, we were not able to get the transmitted data using LoRa communication. Fig. 6(a) shows the LoRa-transmitted energy spectrum at a water depth of 100 cm, while Fig. 6(b) shows LoRa-transmitted energy spectrum in the lab where the transmitter and receiver was located 3 m apart. The ^{137}Cs photopeak was clearly resolved, and the ^{40}K peak was observed as well. However, ^{40}K peak was insignificant compared to that of the terrestrial environment because the water environment acted as a natural shielding material and suppressed natural radioactivity. With a 3.7 kBq ^{137}Cs point source, the count rate was approximately 350 cps over the entire energy range, whereas the background count rate ranged from 15 to 20 cps.

3.2. Underwater detector performance

To evaluate the gamma detection performance within the water

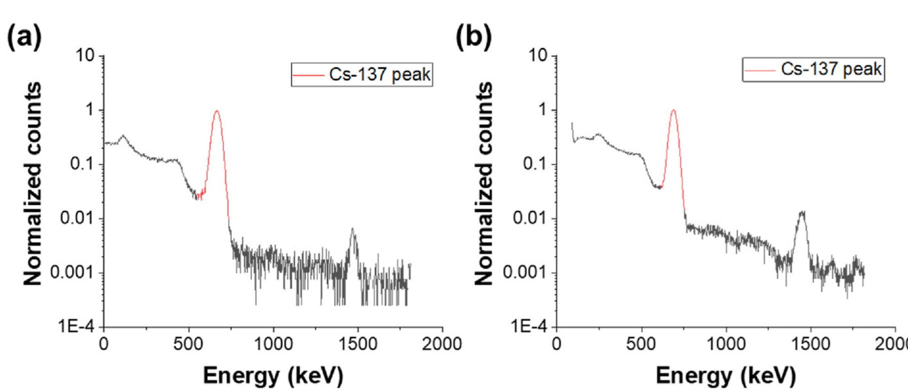

Fig. 6. (a) Normalized energy spectrum acquired from the wireless gamma spectroscopy using LoRa communication at 100 cm water depth. (b) Normalized energy spectrum acquired in the lab where transmitter and receiver were 3 m apart. The red line shows the ^{137}Cs peak region. All the data were acquired for 15 min using 3.7 kBq ^{137}Cs point source.

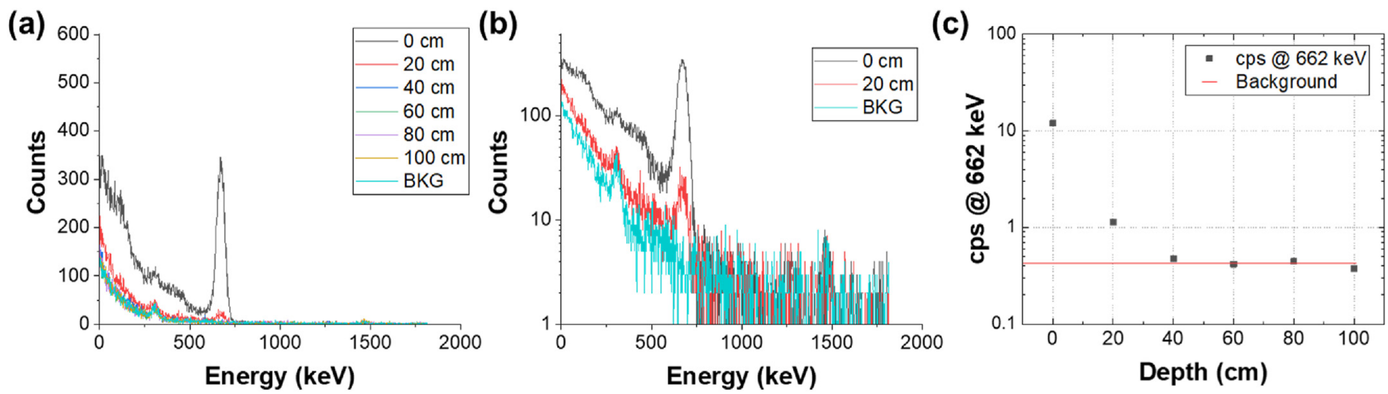

Fig. 7. (a) Energy spectra measured within water environment at different source-to-detector distances. (b) Energy spectra acquired measured at 0 cm, 20 cm, and in background shown in log-scale. (c) Count rate at 662 keV photopeak at different source-to-detector distances. All the data were acquired for 15 min using 3.7 kBq ^{137}Cs point source.

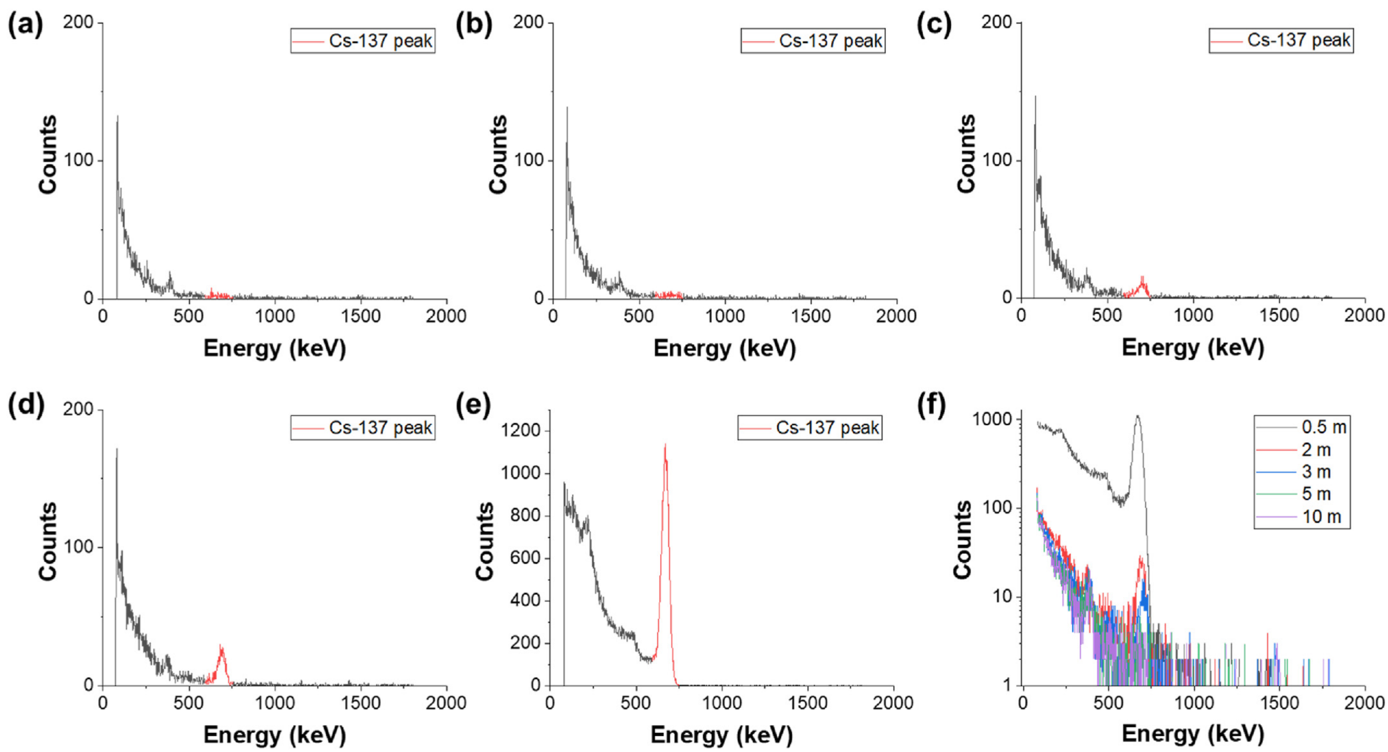

Fig. 8. Energy spectra acquired from the unmanned radioactivity monitoring system measured for 5 min at (a) 10 m, (b) 5 m, (c) 3 m, (d) 2 m, and (e) 0.5 m distance from the hidden ^{137}Cs source. The red line indicates the ^{137}Cs peak region. (f) Combined energy spectra at all distances. All the data were acquired for 5 min using 3.07 MBq ^{137}Cs point source.

environment, the gamma spectroscopy was placed at a water depth of 20 cm and the source-to-detector distance of the low-activity hotspot source (3.7 kBq) was modified from 0 cm to 100 cm. Fig. 7(a) and (b) show the energy spectra measured in the water environment. Fig. 7 (c) shows the count rate measured within the 662 keV photopeak at each water depth. At 0 cm source-to-detector distance, a 662 keV photopeak was clearly observed. However, as expected, a large portion of gamma rays went through Compton scattering in the water. Once the source and detector were placed more than 20 cm apart, it was challenging to identify the ^{137}Cs peak as we observed a similar count rate as the background. Because the ^{137}Cs source and the detector were not aligned in the same line owing to interference between the waterproof box and the rope tied up to the source, we observed a lower count rate than expected.

3.3. Real-time unmanned marine radioactivity monitoring

In this study, we demonstrate radioactivity monitoring in a real sea environment using the developed unmanned marine radioactivity monitoring system. Fig. 8(a) and (b) shows that the system did not detect any radioactive contamination when the system was located 10 m and 5 m away from the hidden hot spot source; the background level energy spectra were observed. The unmanned system drifted around the ocean until a higher level of radioactivity was detected. Once the system moved closer (~3 m) to the hidden hot spot source, the wireless gamma spectroscopy started to detect ^{137}Cs peak, as shown in Fig. 8(c), and we identified the area as contaminated. Moving closer, the system detected higher levels of ^{137}Cs peak radioactivity, identified the hotspot, and defined the contaminated area.

3.4. MDA evaluation results

Based on the simulation results, the detection efficiency of the developed system for 662 keV energy peak of ^{137}Cs was 3.0E-4. The MDA calculated for the developed system was 1.48 Bq/L for 15 min measurement, while we can achieve better MDA of 1.04 Bq/L, 0.73 Bq/L and 0.15 Bq/L for 30 min, 1 h and 24 h measurement, respectively.

4. Discussion

In this study, we developed an SiPM-based wireless gamma spectroscopy system. Compactness and battery operation were the key features of mobile gamma spectroscopy. For compactness, a SiPM photosensor and high-efficiency GAGG scintillation crystal (high Z and high light output) were used. Customized front-end electronics and a low-power ADC board were developed for battery operation. In addition, the developed gamma spectroscopy system supports real-time wired data transmission and semi-real-time wireless data transmission. LoRa was chosen for wireless data transmission because it offers low-power operation with long-range transmission of up to 10 km that would be advantageous in a large and powerless ocean environment.

Underwater performance was evaluated using the gamma spectroscopy in a large water tank environment. Good wireless data transmission without packet loss was observed within 1.4 m depth from the water surface. We did not test the device in a deep-water environment, since our target was water surface level. A recent study by Dala and Arslan 2021, reported successful transmission from a depth of 6 m underwater using a customized LoRa antenna. Therefore, we expect that our system would be more effective at deep underwater once we use the customized antenna. However, the developed system does not support event-by-event real-time data transmission due to the limitation of the low LoRa data rate (~27 kbps). Hence, we implemented a communication protocol to send the accumulated energy spectrum data at the end of the acquisition. Real-time event-by-event data transmission could be implemented using the built-in RF transmission capability of the USV system that supports data transmission up to 8 km. As a future work, we plan to develop an integrated unmanned marine radioactivity monitoring system that allows for real-time radiation detection and source tracking.

Moreover, we successfully demonstrated the feasibility of a mobile real-time marine radioactivity monitoring system in the real ocean environment. One of the difficulties of marine radioactivity monitoring is that radioactive contamination is not likely to exist as a small hotspot in the ocean. The background level of ^{137}Cs activity concentration in the East Sea of Korea ranges from 2.6 to 3.5 mBq/L [23]. At the initial stage of radioactive material release, the contamination area may exist as a small hot spot, but it will immediately disperse into the water. Hence, our strategy for marine radioactive monitoring is to monitor around the nuclear facility sites by moving the monitoring system itself on a regular basis and continuously measuring the background level of radioactivity. If there is an unexpected accident, the system will immediately identify the higher contamination area immediately after the radioactive material is released. With further efforts to lower MDA the developed gamma spectroscopy system, we believe that our proposed system is an effective solution for monitoring marine radioactivity.

5. Conclusion

In this study, we developed a mobile SiPM-based gamma spectroscopy for marine radioactivity. The mobile gamma spectroscopy enables low-power operation (~24 h using battery), has a small and compact geometry (<600 g, 6.5 × 6.5× 8 cm^3), and offers wireless data communication (real-time or cumulated data transfer). We evaluated the underwater performance and demonstrated a real-time marine radioactivity monitoring in a real-sea environment. In conclusion, we successfully proved the feasibility of a real-time marine radioactivity monitoring system using the developed mobile gamma spectroscopy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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