Development and Application of Vehicle-mounted Soil Gamma Spectrometer

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Date: 2025-08-27T00:00:00+00:00

Abstract

In agricultural soil radioactivity research, the specific activities of radionuclides such as U-238, Th-232, and K-40 are primarily analyzed in laboratories after sampling, a process that is time-consuming and costly, rendering it unsuitable for large-scale agricultural applications. This paper establishes a mathematical model correlating soil radionuclide specific activity with gamma-ray intensity for the on-site rapid detection of soil radioactivity. Based on MCNP simulation calculations, a vehicle-mounted soil gamma spectrometer was developed using a NaI(Tl) detector measuring 5.7$×11×$40 cm. The instrument, mounted on the rear of an agricultural machine, can detect the content of radioactive elements in soil during plowing. It features real-time positioning and display of radionuclide specific activity, with a measurement capability of up to 88089 centiare per hour. The instrument was deployed in a 264267 centiare experimental field, yielding distribution maps of the specific activities of U-238, Th-232, and K-40 within the experimental field. Compared with laboratory analysis results, the relative deviations of the specific activities of U-238, Th-232, and K-40 measured by the vehicle-mounted soil gamma spectrometer were within $±$16%, $±$15%, and $±$10%, respectively. This device can improve the efficiency of measuring soil radionuclide specific activity and reduce the cost of investigating the distribution of agricultural soil radioactivity.

Full Text

Preamble

Development and Application of a Vehicle-Mounted Soil Gamma Spectrometer

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In agricultural soil radioactivity research, the specific activities of radionuclides such as ^{238}U, ^{232}Th, and ^{40}K are typically analyzed in laboratories after sampling—a process that is time-consuming and costly, making it unsuitable for large-scale agricultural applications. This paper establishes a mathematical model correlating soil radionuclide specific activity with gamma-ray intensity for on-site rapid detection of soil radioactivity. Based on MCNP simulation calculations, a vehicle-mounted soil gamma spectrometer was developed using a NaI(Tl) detector with dimensions of 5.7$×11×40*cm.Theinstrument,mountedontherearofanagriculturalmachine,candetectthecontentofradioac*
*timepositioninganddisplayofradionuclidespecificactivity,withtheabilitytomeasureupto*88089*m*^{2}$ per hour. The instrument was applied in a 264267 m^2 experimental field, and distribution maps of the specific activities of ^{238}U, ^{232}Th, and ^{40}K in the experimental field were obtained. Compared with laboratory analysis results, the relative deviations of the specific activities of ^{238}U, ^{232}Th, and ^{40}K measured by the vehicle-mounted soil gamma spectrometer were within $±$16%, $±$15%, and $±$10%, respectively. This device can improve the efficiency of measuring soil radionuclide specific activity and reduce the cost of investigating the distribution of agricultural soil radioactivity.

Keywords: Agricultural soil, MCNP simulation calculations, Vehicle-mounted gamma energy spectrum, On-site detection, The specific activity distribution of radionuclides

INTRODUCTION

The measurement of radionuclide specific activity in agricultural soils typically involves on-site sampling followed by analysis in a low-background laboratory [**?**], which is time-consuming and expensive, limiting its application in large-scale agricultural areas. Vehicle-mounted gamma spectrometry offers advantages such as strong mobility, wide coverage, fast measurement speed, and high sensitivity [**?**]. Current research on vehicle-mounted gamma spectrometry systems mainly focuses on environmental pollution assessment due to nuclear accidents, mineral resource exploration, and radiation emergency monitoring [**?**, **?**], with limited studies on agricultural soil radioactivity characteristics. The distribution of radionuclides such as ^{238}U, ^{232}Th, and ^{40}K in the soil can be used to assess soil properties and conditions \cite{5-7}. Utilizing vehicle-mounted gamma spectrometry to measure the specific activities of these radionuclides in agricultural soils can improve measurement efficiency, reduce the cost of investigating soil radioactivity distribution, expand the application scenarios of vehicle-mounted gamma spectrometry, and promote the development of agricultural production technologies.

In 2018, Xu Lipeng et al. developed an improved BP neural network model based on the Fast Fourier Transform (FFT) background subtraction method for accurate determination of radiation dose rates by vehicle-mounted gamma spectrometers [?]. In 2020, Adam Varley et al. used a large-volume NaI(Tl) detector to identify concentration changes of ^{137}Cs in the arable soil layer at high spatial resolution, thereby quantifying soil erosion processes [?]. In the same year, Young-Yong Ji et al. developed an airborne radiation measurement system based on a hexahedral large-volume NaI(Tl) detector for large-scale assessment of ground-deposited radionuclide dose rates [?]. In 2022, Robert Finck et al. studied a mobile gamma-ray in-situ detection system for lost sources (^{137}Cs and ^{60}Co) and developed an algorithm to calculate the maximum detectable distance of the system, which can be used to recommend the best combination of detector, vehicle speed, and instrument settings during mobile searches for lost gamma-ray sources [?]. SoilOptix, a Canadian company, developed a soil detection system based on a 2L CsI scintillation crystal using gamma spectrometry, relying on artificial intelligence and big data mining algorithms to analyze soil texture and nutrient data [?].

This paper presents the development of a vehicle-mounted soil gamma spectrometer for measuring the radioactive characteristics of farm and agricultural soils. A mathematical model correlating soil radionuclide specific activity with gamma-ray intensity was established. The effective detection range of gamma rays with energies of 1460 keV, 1765 keV, and 2614 keV in the soil was assessed for NaI(Tl) detectors with dimensions of $ 7.5×7.5*cmand*5.7×11×$40 cm. Using MCNP simulations, the minimum measurement time and distance required for the NaI(Tl) detectors (with dimensions of $ 7.5×7.5*cmand*5.7×11×$40 cm) to achieve a relative standard error of no more than $±$15% in the energy window count were calculated based on the average specific activities of ^{238}U, ^{232}Th, and ^{40}K in Chinese soils. The instrument was applied in a 264267 m^2 experimental field, covering an area of 88089 m^2 per hour. Distribution maps of ^{238}U, ^{232}Th, and ^{40}K specific activities were obtained. Sixteen soil samples were collected on-site for laboratory analysis. The comparison showed that the relative deviations of the specific activities of ^{238}U, ^{232}Th, and ^{40}K measured by the vehicle-mounted soil gamma spectrometer from the laboratory analysis results were within $±$16%, $±$15%, and $±$10%, respectively. In the absence of extremely high precision requirements, the vehicle-mounted soil gamma spectrometer can significantly save measurement time and sampling analysis costs.

II. PHYSICAL PRINCIPLES

A. Gamma-Ray Spectrum Distribution at the Soil Surface

Natural radionuclides have existed in the Earth' s crust since its formation. The decay of uranium and thorium series and ^{40}K radionuclides typically involves the emission of gamma rays [?]. Each radioactive source produces gamma rays with characteristic energies that can be used as identifiers. The activity of a radioactive source can be determined by measuring the number of gamma rays emitted per unit of time. The gamma-ray spectrum of a natural-environment-based scintillation detector is shown in Fig. 1 [Figure 1: see original paper]. The device developed in this paper primarily measures the gamma rays with energies of 1765 keV, 2614 keV, and 1460 keV emitted from the decay of ^{214}Bi (a uranium series progeny), ^{208}Tl (a thorium series progeny), and ^{40}K, respectively, to determine the specific activities of ^{238}U, ^{232}Th, and ^{40}K in the soil [?]. According to survey data, the average specific activities of ^{238}U, ^{232}Th, and ^{40}K in Chinese soils are 39.5 Bq/kg, 49.1 Bq/kg, and 580.0 Bq/kg, respectively [?].

B. Mathematical Model of Soil Radionuclide Activity and Gamma-Ray Intensity

The mathematical model correlating the gamma-ray intensity received by the detector with the soil radionuclide activity can be established using a spherical coordinate system with the center of the detector' s bottom surface as the origin O and the positive direction of the Z-axis pointing downward. The detector' s measurement range can be considered as a conical frustum. The full-energy peak count rate received by the detector can be expressed as follows:

$$D = \int\int\int Sq\rho f \varepsilon_E e^{-\mu(r-h\cos\theta)} e^{-\mu_0 \frac{h}{\cos\theta}} \sin\theta \, d\theta \, d\phi \, dr \tag{1}$$

where D is the full-energy peak count rate received by the detector; S is the equivalent area of the detector receiving gamma rays; q is the content of the radioactive element; ρ is the density of the radioactive material; f is the branching ratio of the radionuclide; ε_E is the intrinsic detection efficiency of the detector for gamma rays of a specific energy; h is the distance between the detector and the surface of the radioactive material; μ and μ_0 are the linear attenuation coefficients of gamma rays of a specific energy in soil and air, respectively; θ is the angle between the detector and the unit volume element; ϕ is the angle between the unit volume element and the X-axis; r is the distance from the detector to the unit volume element, as shown in Fig. 2 [Figure 2: see original paper].

The intensity of gamma rays contributed by the conical frustum-shaped detection range can be projected onto the plane $z = h$ by integrating over r (where $r \in (h/\cos\theta < r < \infty)$). In a uniform field, the rate of irradiation dose contributed by volume elements within the same R is equal, and the weight factor can be expressed as follows:

$$\omega = \frac{\mu}{(h^2 + R^2)^{3/2}} e^{-\mu_0 \sqrt{h^2+R^2}} \tag{2}$$

The lateral truncation ratio coefficient is defined as:

$$p_h = \frac{\int_0^{R_{tr}} 2\pi\omega R\, dR}{\int_0^{\infty} 2\pi\omega R\, dR} = \frac{\int_0^{R_{tr}} \frac{R}{(h^2+R^2)^{3/2}} e^{-\mu_0 \sqrt{h^2+R^2}}\, dR}{\int_0^{\infty} \frac{R}{(h^2+R^2)^{3/2}} e^{-\mu_0 \sqrt{h^2+R^2}}\, dR} \tag{3}$$

where R_{tr} is the lateral truncation distance, defined as the distance at which the irradiation dose rate from the medium to the detector reaches a fraction p_h of the total dose rate at a height h above the ground. The corresponding detector opening angle is defined as the truncation angle θ_{tr}. The relationship between the lateral truncation ratio coefficient p_h, the detector measurement height h, and the truncation angle is shown in Fig. 3 [Figure 3: see original paper] for h values of 0.5 m, 1.0 m, 1.5 m, and 2.0 m.

C. Mathematical Model of Soil Radionuclide Activity and Gamma-Ray Intensity

Based on the empirical formula recommended by the International Atomic Energy Agency:

$$L = v \cdot \Delta t \cdot t \tag{4}$$

where L is the size (width or diameter) of the detection target (m), v is the detector movement speed (m/s), Δt is the number of samples within the range L, and t is the sampling time interval (s).

In actual measurements, measurement precision must be considered. The relative standard error of the net count rate of the radiation sample can be expressed as Equation (5) [**?**]:

$$\varepsilon_n = \sqrt{\frac{n_c}{t_c} + \frac{n_b}{t_b}} \Bigg/ \left(\frac{n_c}{t_c} - \frac{n_b}{t_b} \right) \tag{5}$$

where ε_n is the relative standard error of the net count rate of the radiation sample, n_c is the total count rate of the radiation sample, t_c is the measurement time, n_b is the background count rate, and t_b is the background measurement time. Since the background count rate of NaI(Tl) is low and the background measurement time can be as long as possible, Equation (5) can be simplified to Equation (6):

$$\varepsilon_n = \frac{1}{\sqrt{n_c \cdot t_c}} \tag{6}$$

Therefore, under the premise of ensuring measurement precision ε_n, the minimum measurement distance can be expressed as Equation (7):

$$L_{min} = \frac{v}{\varepsilon_n^2 \cdot n_c} = \frac{v}{\varepsilon_n^2 \cdot V \cdot \rho \cdot Q \cdot B \cdot \varepsilon_E \cdot K} \tag{7}$$

where v is the vehicle speed (m/s), ε_n is the maximum relative standard error allowed during the measurement process, V is the effective detection volume (m^3), ρ is the soil density (taken as 1800 kg/m^3), Q is the average radionuclide content (Bq/kg), B is the branching ratio for the corresponding gamma-ray energy, ε_E is the full-energy peak detection efficiency, and K is the proportionality constant between the activity of the progeny nucleus and the parent nucleus in long-term equilibrium (for ^{208}Tl, 0.337; for ^{40}K, 1; for ^{214}Bi, 0.999 [**?**]).

III. PROBE DESIGN OF THE VEHICLE-MOUNTED SOIL GAMMA SPECTROMETER

A. Detector Selection

The gamma spectrometry probe is used to detect gamma rays emitted from radioactive nuclides in the soil. The selection of the detector must be based on practical considerations. Taking into account the intrinsic energy resolution, background count rate, relative light output, detector cost, and maximum sensitive volume, a NaI(Tl) detector was chosen. The main parameters of common scintillation detectors are shown in Table 1 . Generally, increasing the detector volume can improve the accuracy of the measurement, as larger volumes yield higher detection efficiency [**?**]. However, this also increases the detector cost. To ensure measurement accuracy while controlling instrument costs, simulations must be performed for detectors of different volumes.

B. Detection Efficiency Simulation

The MCNP program has a very flexible geometric processing capability. It can solve the transport equation without direct solution by simulating the behavior of a large number of particles and recording certain characteristics of their average behavior. The Monte Carlo method can truly simulate the actual physical process and provide accurate results that closely match reality. In this study, the GEANT4 simulation was used to calculate the detection efficiency. The GEANT4 platform, developed by CERN (European Organization for Nuclear Research), is an open-source MCNP program that provides a complete set of tools for detector simulation in all fields, including geometry, tracking, detector response, operation, event and track management, visualization, and user interface. The platform also includes a comprehensive set of physical processes to handle different interactions of particles with matter over a wide range of energies [**?**].

The geometric model for the simulation is shown in Fig. 4 [Figure 4: see original paper], where d is the soil thickness, θ is the half-angle of the detector, and H_0 is the distance between the detector and the ground. It should be noted that the soil thickness should decrease with increasing θ. For simplicity in constructing the geometric model, the soil thickness directly below the detector was used uniformly. Considering the soil thickness, the thickness d was taken at $I/I_0 = 0.05$ according to Equation (8), with θ taken as the half-angle of the detector corresponding to the truncation distance when $p_h = 0.9$, and the distance between the detector and the ground $H_0 = 50$ cm.

$$I = I_0 e^{-\mu d} \tag{8}$$

The linear attenuation coefficients μ and μ_0 for gamma rays with energies of 1460 keV, 1765 keV, and 2614 keV in soil and air were fitted from tables [**?**, **?**]. Combined with Equations (3) and (8), the detector' s half-angle (θ) and the soil frustum thickness (d) were calculated. Based on the previous calculation results of θ and d, the effective detection volume of different-sized NaI(Tl) detectors was calculated as parameters for the MCNP model. Table 2 shows the parameters for constructing the MCNP model.

Simulations were conducted for cylindrical and rectangular solid NaI(Tl) scintillation detectors with dimensions of $ 7.5×7.5*cmand*5.7×11×$40 cm, respectively. The statistical error of the detection efficiency simulation results was controlled within 5%. The simulation results are shown in Table 3 . In cases where the on-site measurement precision requirement is not high, a value of $±$15% can be taken for ε_n. Based on Equation (6) and the values in Table 4 , with the uranium window count rate as a reference, the $ 7.5×7.5*cmcylindricalNaI*(*Tl*)*detectorrequiresameasurementtimeofatleast*80.82*seconds*, *whilethe*5.7×11× *mountedsoilgammaspectrometerusingthe*5.7×11×$40 cm rectangular NaI(Tl) detector, with a measurement precision better than $±$15%, is 16 m.

IV. ELECTRONICS AND MEASUREMENT SOFTWARE

A. Hardware Composition

Fig. 5 [Figure 5: see original paper] shows the hardware composition diagram of the vehicle-mounted soil gamma spectrometer. The detector used is a 5.7$×11×$40 cm rectangular NaI(Tl) detector produced by Beijing Zhongguang, with an energy resolution of 8.13% @ 662 keV. The nuclear electronics part uses self-developed components by the research group, including an active voltage divider circuit, a programmable high-voltage power supply, a preamplifier circuit, and a digital multi-channel pulse processor. The main technical parameters of the nuclear electronics components are: ADC resolution of 14 bits with a maximum sampling rate of 65 Msps; signal acquisition signal-to-noise ratio of 70 dB; pulse shaping using a double Gaussian smoothing filter [**?**, **?**].

The positioning component uses the UM982 positioning and orientation module developed by BDstar Navigation, which supports dual-mode Beidou and GPS positioning, suitable for high-precision navigation and positioning in drones, precision agriculture, and autonomous machines. The maximum refresh frequency is 20 Hz. Currently, differential positioning technology is used to achieve a positioning accuracy of 0.4 m, and RTK positioning can reach an accuracy of 0.8 cm. The main controller uses an embedded microprocessor i.MX6ULL based on the Cortex-A7 MPCore core, with a clock frequency of up to 800 MHz, 512 MB of external expanded memory, and 8 GB of EMMC (Embedded Multi Media Card) for storing measurement data. Using a 2048-channel spectral resolution and a 1 Hz sampling frequency, it can store continuous measurement data for 20 days. The system uses WiFi/4G/serial port communication and other data transmission methods to send measurement data to the control end in real-time. The control end selects a CF-33 type military computer installed with control software, with a waterproof and dustproof rating of IP65. The software interface is shown in Fig. 6 [Figure 6: see original paper].

B. Software Development

The human-machine interaction software adopts a three-layer architecture and dual-thread design. The hardware control layer uses C++ programming to implement hardware device control and interface functions to ensure the real-time performance of gamma-ray spectrometry and data processing. The data processing layer uses the ultra-fast small database SQLite to improve data storage management capabilities. To ensure good human-machine interaction, software modularization, and reliability, the interface programming uses C#. The main thread is responsible for the main work of the software, while the auxiliary thread monitors the operating status and can perform fault diagnosis and recovery in case of abnormal situations. The software realizes functions such as dose mapping, radionuclide identification, GIS map, data import and export, historical playback, trend display of regions of interest, color difference spectrum display, database storage management, and hardware offline alarm.

V. FIELD APPLICATION

A. Field Measurement

The field measurement area for the vehicle-mounted soil gamma spectrometer was a part of an experimental field in Inner Mongolia. The experimental field is located in the Inner Mongolia Autonomous Region' s plain area, with an area of 264267 m^2. According to the data, the average specific activities of the natural radionuclides ^{238}U, ^{232}Th, and ^{40}K in the soil of the Inner Mongolia Autonomous Region' s plain area are 20.86, 34.89, and 624.63 Bq/kg, respectively [?]. Based on the actual situation of the measurement area, several measurement lines with a spacing of 20 meters were drawn in the farmland, and the vehicle-mounted soil gamma spectrometer performed reciprocal measurements along these lines, taking a total of 3.05 hours, with an operational area of up to 88089 m^2 per hour. Fig. 7 [Figure 7: see original paper] shows the measurement route map of the experimental field. Before starting the measurement, the vehicle-mounted soil gamma spectrometer was installed at the rear of an agricultural tractor, and the device was calibrated to maintain a fixed distance of 50 cm between the probe and the ground. The sampling cycle was set to 1 second. The device was pre-heated on-site until the peak position and count rate of ^{40}K stabilized, and then the vehicle was started for actual measurement, maintaining a speed of 5 km/h. Fig. 8 [Figure 8: see original paper] shows the starting point of the vehicle-mounted soil gamma spectrometer measurement.

B. Comparison of Field Measurement Results with Laboratory Sampling Analysis Results

To evaluate the accuracy of the vehicle-mounted soil gamma spectrometer measurement results, 16 soil samples were taken using the 5-point method [**?**] and sent back to the laboratory for gamma-ray spectrometry analysis. The distribution of sampling points is shown in Fig. 9 [Figure 9: see original paper]. The comparison between the field measurement results of the vehicle-mounted soil gamma spectrometer and the laboratory soil sample gamma-ray spectrometry measurement results is shown in Table 5 . As shown in Table 5, the relative deviations of the specific activities of ^{238}U, ^{232}Th, and ^{40}K measured by the vehicle-mounted soil gamma spectrometer from the laboratory analysis results are within $±$16%, $±$15%, and $±$10%, respectively. In the absence of extremely high measurement precision requirements, the vehicle-mounted soil gamma spectrometer can significantly improve the efficiency of measuring the distribution of ^{238}U, ^{232}Th, and ^{40}K specific activities in agricultural soils and reduce survey costs.

VI. DATA ANALYSIS AND DISCUSSION

The vehicle-mounted soil gamma spectrometer obtained 10,615 effective measurement data points in the experimental field. The specific activities of ^{238}U, ^{232}Th, and ^{40}K were statistically analyzed, and the frequency distribution histograms of the specific activities are shown in Fig. 10 [Figure 10: see original paper]. The statistical results of the specific activities are shown in Table 6 . From the statistical analysis, the specific activity distribution of ^{238}U is relatively uniform, with a flat and symmetrical normal distribution and a low probability of extreme values. The specific activities of ^{232}Th and ^{40}K have a more peaked normal distribution, with a higher probability of extreme values on the left side of the distribution. The average specific activities of ^{238}U, ^{232}Th, and ^{40}K in the experimental field are 1.38, 1.38, and 1.21 times the average values of the Inner Mongolia plain area, respectively, indicating a significant increase.

Studies have shown that the application of phosphate fertilizer can significantly increase the specific activity of ^{238}U in the soil \cite{25-27}. The specific activity of potassium in agricultural soils is also affected by soil moisture and fertilizer application [?]. Therefore, the application of phosphate and potassium fertilizers is likely the main reason for the higher average specific activities of ^{238}U and ^{40}K in this area compared to the Inner Mongolia plain area. There is currently insufficient evidence to suggest that plowing increases the specific activity of ^{232}Th in the soil. The natural environmental radionuclides in the soil mainly depend on geological and geographical conditions and are controlled by the parent rock mineral composition [?]. It is speculated that the higher specific activity of ^{232}Th in the survey area compared to the Inner Mongolia plain area may be more influenced by the parent rock mineral composition.

Natural radionuclides are unevenly distributed in rocks and soils. To compare the specific activities of materials containing variable amounts of ^{238}U, ^{232}Th, and ^{40}K, the equivalent radium activity is generally used to represent the total radiation dose of natural radionuclides [?]. The average equivalent radium activity calculated for this area is 156.24 Bq/kg, which is far below the permissible limit of 370 Bq/kg recommended by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) [?]. This indicates that natural radionuclides will not pose a hazard to people working and living in this area.

The natural radioisotope ^{238}U, ^{232}Th, and ^{40}K activity distribution in this experimental field is shown in Figure 11 [Figure 11: see original paper]. From Figure 11a, it can be seen that ^{238}U is mainly distributed in the upper left area of the experimental field, presenting an irregular cluster-like pattern, with sporadic aggregations in some areas. From Figure 11b, it can be observed that ^{232}Th is more concentrated in the experimental field, with higher activity in the upper left and lower right areas, presenting a small irregular cluster-like distribution, while the middle part of the experimental field has less distribution, presenting a large irregular cluster-like pattern. From Figure 11c, it can be seen that the ^{40}K activity distribution is roughly opposite to that of ^{232}Th, with higher activity in the central area of the experimental field.

Natural uranium mainly exists in the oxidation states of tetravalent (U^{4+}) or hexavalent (U^{6+}). Hexavalent uranium has a higher solubility in water, while tetravalent uranium basically does not migrate in water [?]. Thorium is one of the least mobile elements in natural water systems and can be used in geology to distinguish the tectonic background formed by basic rocks [?]. The form of soil potassium can be classified based on the sites and exchange characteristics of potassium in the soil as water-soluble potassium, exchangeable potassium, non-exchangeable potassium, and mineral potassium, among which mineral potassium accounts for 90% to 98% of the total soil potassium [?]. Relevant researchers can conduct more in-depth studies on agricultural soil water and soil migration and soil formation parent materials based on the distribution of ^{238}U, ^{232}Th, and ^{40}K activity in the soil.

VII. CONCLUSIONS

This paper presents the development of a vehicle-mounted soil gamma spectrometer for on-site rapid detection of agricultural soil radioactivity. First, a mathematical model correlating soil radionuclide activity with gamma-ray intensity was established. Based on the model, the effective detection range of gamma rays with energies of 1460 keV, 1765 keV, and 2614 keV in the soil was calculated for NaI(Tl) detectors with dimensions of $ 7.5×7.5*cmand*5.7×11×$40 cm. The minimum measurement time and distance required for the detectors to achieve a relative standard error of no more than $±15×11×40*cmNaI(Tl)detectorwasdeveloped.Theinstrument,installedattherearofanagriculturalmac* *timepositioning,anddisplayofradionuclidecontent.Thedevicewastestedina*264267*m*^{2}$ field, generating distribution maps of ^{238}U, ^{232}Th, and ^{40}K specific activities. The operational time was 3.05 hours, with an operational area of up to 88089 m^2 per hour. Third, sixteen soil samples were collected on-site for laboratory analysis. The results showed that the relative deviations of the specific activities of ^{238}U, ^{232}Th, and ^{40}K measured by the vehicle-mounted soil gamma spectrometer from the laboratory analysis results were within $±$16%. In the absence of extremely high measurement precision requirements, the device can significantly improve the efficiency of measuring soil radionuclide-specific activities and reduce the cost of investigating the distribution of agricultural soil radioactivity.

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Note: Figure translations are in progress. See original paper for figures.