Development of Mapping System for Airborne Radiation using Single-Frequency GNSS Positioning

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Measurement of airborne radiation must be performed before and after decontamination work to confirm whether decontamination has actually been performed. Conventional measurement procedures require enormous amounts of work. Without using a specific mark, it is difficult to find the same measurement location before and after the decontamination work. To overcome these problems, we developed an airborne radiation mapping system that can perform measurements precisely and quickly. The system enables the simultaneous measurement of airborne radiation at multiple heights by utilizing multiple measurement units. In addition, we developed a new navigation system to reduce workload. The airborne radiation mapping system facilitated quick measurement and easy movement.

Keywords: Airborne radiation, Mapping system, Global positioning system, Global navigation satellite system

1. Introduction

A large amount of radioactive material was released in the Fukushima Nuclear Power Plant accident on March 11, 2013, which was caused by the Tohoku-Pacific Ocean Earthquake. Much of the radioactivity released into the atmosphere was scattered widely inland on the west-northwest wind. As a result, air dose rates far exceeding the normal were confirmed in various places. In response to this situation, the government has designated 104 municipalities that observe air dose rates of 0.23 μSv or more per hour as priority areas for pollution status surveys based on the Act on Special Measures Concerning Radioactive Pollution (1) (2). In the designated area, the pollution status in the priority survey area is surveyed and measured for pollution status based on the method specified by the Ministry of the Environment, and the area recording 0.23 μSv or more per hour based on the results is the decontamination area (3). In the decontamination area, a pilot project was implemented to establish a decontamination method to reduce the air dose rate in living space, and decontamination work was started sequentially based on the results.

To confirm the efficacy of the decontamination work, measuring the air dose rate before the start of and after the end of decontamination work in the same place using the same method is necessary. However, because the decontamination area is large and all measurements are performed manually, it is difficult to complete the air dose rate measurement in a short time. In addition, to ensure the measurement points are the same before and after the decontamination work, guidance to the measurement points must be performed accurately.

As a method for confirming the current position accurately and in real time, Global Navigation Satellite System (GNSS) positioning is available. The authors have been working on saving labor (4), (5), (6) for soil pollution surveys by applying the GNSS and evaluating the accuracy of its receivers (5), (7).

By applying this technology, we developed a three-point simultaneous air dose rate measurement system that can measure air dose rates at multiple points in a short period of time without using application reports, in collaboration with industry and academia, and commercialized it at construction sites. This paper reports the design requirements of the developed system, specific design and evaluation, and verification results.

In this paper, Chapter 2 describes the air dose rate measurement associated with the decontamination work including problems. In Chapter 3, we describe the satellite positioning system in relation to the air dose rate measurement, initialization time evaluation, FIX solution maintenance performance evaluation, and positioning accuracy evaluation results. Chapter 4 describes the configuration, work methods, and demonstration of measurement results with the development system. Finally, Chapter 5 concludes the study.

2. RTK positioning

2.1 Positioning principle

RTK (Real Time Kinematic) is one of the satellite positioning technologies. It is a relative positioning that can determine the three-dimensional position of the positioning point in cm class as a relative position from the reference point.

Figure 1 shows the block diagram of the RTK. The three-dimensional position of the phase center of the reference point receiver antenna is obtained in advance by surveying or the like with an accuracy of mm level. At the reference point and the positioning point, the phases of radio waves (carrier waves) emitted from a plurality of positioning satellites that are receiving at the same time are measured. At the same time, the navigation message including the satellite position parameter broadcast from the satellite is received, and the satellite position can be treated as known. At the positioning point, the double phase difference is calculated by performing two subtractions of the inter-satellite phase difference of the measured carrier wave phase and the receiver phase difference. By this calculation, the phase error due to the ionosphere, the troposphere, the atomic clock mounted on the satellite, and the clock built into the receiver, which affects the distance measurement to the satellite, can be canceled. Then, the
distance difference between the two satellites used for the calculation of the double phase difference and the positioning point receiver can be measured in mm class.

At this time, as shown in figure 2, geometrically, by connecting points with a constant distance difference from the two satellites for which the double phase difference has been calculated, a rotating hyperboloid with two satellites as the focus can be defined. Therefore, if a plurality of satellites are being received, the phase center three-dimensional position of the positioning point receiver antenna is obtained in cm level as the intersection of the plurality of rotating hyperboloids. Furthermore, if the carrier phase measured at the reference point is transmitted to the positioning point in real time using some data transmission system, RTK positioning can be realized.

2.2 FIX and FLOAT solutions At the stage of calculating the distance difference from the double phase difference, the distance from the satellite to the positioning point is actually unknown. Therefore, it is unknown what the number of waves is, in terms of the wavelength of the carrier wave (L1: 1.57542 GHz approximately 19.03 cm, L2: 1.22760 GHz approximately 24.42 cm), and this is also an unknown number. This is a so-called uncertain wave number, an integer ambiguity. If this integer ambiguity is not confirmed, the distance difference cannot be obtained from the double phase difference. If the receiver continues to receive radio waves, the wavenumber integer value does not change, and the state in which the integer value is obtained by a statistical analysis method is called initialization, and it is calculated in this initialization state. The positioning result is called FLOAT solution (positioning). The state (convergence) in which the integer ambiguity is obtained is called the FIX solution (positioning), and the positioning result without the determination error of the integer ambiguity is obtained. FIX solution positioning rate is defined by FIX rate = N_{FIX} / N_{Total} × 100%. Here, N_{FIX} is the number of FIX positioning (normally once per second), and N_{Total} is the total number of positioning (normally once per second).

2.3 Dual-frequency positioning In the case of single-frequency of L1, the wavelength is about 19 cm as described above. Furthermore, if L2 is also used to perform positioning calculation at dual-frequency, the L2 wavelength will be about 24 cm, which is the least common multiple of about 86.2 cm. Since the number of searches for integer ambiguity can be reduced, the initialization time can be shortened. This is called Wide Lane.

Further, the influence of the ionosphere, which is one of the major causes of the phase error, has frequency dependence. Therefore, by using dual-frequency, errors in the ionosphere can be reduced.

3. Air dose rate measurement associated with decontamination work

3.1 Outline of air dose rate measurement The position of the dose rate measurement point differs depending on the concept of the ordering organization, such as the local government that performs the decontamination work. Figure 3 shows an example of air dose rate measurement points on a road. The airway dose rate is measured at one point on the road every 100 m and at a height of 1 m from the ground. For the sidewalk, the air dose rates are measured at three points at the right and left sides of the road at a height of 1 m, 50 cm above the ground, and directly above the road at 20 m every 20 m, respectively (8), (9).

3.2 Problems in air dose rate measurement For example, the number of road air dose rate measurement points on the road is 21 fixed points every 100 m, and 61 points when the measurement of each point in the height direction (1 m above the ground at 4 sidewalks, 50 cm, directly above) is added. When applied to 1 km of road, it is 610 points, which is a large number.

Generally, air dose rate measurement measures the gamma rays emitted when cesium-137 released in large quantities in the accident at the Fukushima Daiichi Nuclear Power Plant collapses, using a scintillation-type survey meter or other radiation measuring instrument. The operator manually measures and records all measurement points sequentially using a radiation measuring instrument. In addition, the time required for air dose rate measurement depends on the strength of the air dose rate, required accuracy, and performance of the radiation measuring instrument.
The air dose rate measurement, an aerial photograph or drawing, such as an orthochromatic photo, to which an aerial photograph is converted into an image with less distortion and a correct coordinate value is given is used. However, it is difficult to obtain a post-earthquake drawing of a scale that can be used for decontamination work.

Considering the accuracy of the available maps and human work, the required relative position accuracy is about 10 cm, initialization time is about 30 s, and the FIX rate is 70%. Although it is thought that it can be realized with a dual-frequency receiver, we studied a cheaper single-frequency receiver for early spread.

4. Accuracy evaluation of satellite positioning system

4.1 GNSS positioning and air dose rate measurement

In the air dose rate measurement system to be developed, the function of guiding the worker to the measurement point is an important factor that affects the evaluation of the system. For this reason, GNSS positioning, which measures the current position on the ground using artificial satellites, was adopted to guide the workers to the measurement points to increase the degree of freedom of the measurement work and achieve high efficiency (6).

In the field of surveying, as a similar operation, a backlass surveying method for associating a point with another point based on the coordinate values calculated from conventional tacks, piles, paint, and the like is used, and a surveying system that supports this operation is already on the market. When applying this to the air dose rate measurement system, it is necessary to first determine the measurement points on the drawing, read the coordinate values from the drawing, and register them in the surveying software.

In the air dose rate measurement in living spaces, structures such as houses and surrounding trees act as shields, and there are many severe environments for performing satellite positioning.

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environment were compared: one where the influence of obstacles is small and the other where the influence of obstacles is easy. In particular, an environment that is easily affected by obstacles simulates an environment in which use conditions are worse than the actual measurement environment, and is thus sufficient for an evaluation experiment.

The experiment was conducted with a mobile station installed on the roof of the MSE building of the Ibaraki National College of Technology, similar to the reference station, to perform comparisons in an environment with few shields. In the experiment, the positioning was started simultaneously with the single-frequency receiver and the dual-frequency receiver, respectively, and the solution converged from the first time when the RTK positioning results began to be outputted as a FLOAT solution, and the time elapsed from the time at which the first FIX solution was outputted. The process of measuring the time was performed for about 30 times. The baseline length between the reference station and the mobile station (fixed point) was about 10 m.

Table 2 shows the average, standard deviation, maximum value, and minimum value of the initialization time. Figure 4 shows the distribution of initialization time in a single-frequency receiver, and Figure 5 shows the distribution of initialization time in a dual-frequency receiver. The average value of initialization time was almost the same, i.e., 16.4 s for the single frequency receiver and 15.7 s for the dual frequency receiver. From the standard deviation, it can be seen that the variation of the dual-frequency receiver is smaller than that of the single-frequency receiver. In an environment with few obstructions in the surroundings, the difference in the average value of the single-frequency receiver was 0.7 s compared with the initialization time of the dual-frequency receiver, and the result was as good as 0.7 s. However, the standard deviation was 5.8 s for the single-frequency receiver and 3.1 s for the dual-frequency receiver, indicating that the variation in initialization time is slightly large. With RTKLIB, you can freely change the elevation angle mask, SNR mask, and the setting values of parameters that affect initialization according to the positioning environment. Therefore, by changing each setting value by trial and error and determining an appropriate setting value, it was possible to obtain a higher performance result than a dual-frequency receiver that cannot change various parameter values as a result.

Considering that the air dose rate measurement work is performed by humans, it is considered that the initialization time until the FIX solution is outputted for the first time is about 30 s. There is virtually no significant difference between them, and is applicable to either receiver.

4.3 FIX solution maintenance performance evaluation

In satellite positioning, maintaining the FIX solution in an environment with many obstacles such as structures and trees is an important index for evaluating the performance of the receiver. In this experiment, a single-frequency receiver and a dual-frequency receiver are compared and evaluated for maintaining the FIX solution around the structure and the ease of returning to the FIX solution in the case of a FLOAT solution.

In the experiment, after confirming the FIX solution of the receiver, we performed a four-minute journey around the structure from the western end of the one-story structure (20 m x 50 m) along the wall surface. During the experiment, each antenna was
while moving. Because the west side is sandwiched between the environment that restricts the structure and the top of the antenna, it is difficult to maintain the FIX solution. The south side of the training plant is very harsh for satellite positioning because it is completely covered by some trees. The eaves are overhanging toward the north, which is a severe positioning because it is completely covered by some trees. The south side of the training plant is very harsh for satellite positioning because it is completely covered by some trees. The eaves are overhanging toward the north, which is a severe positioning because it is completely covered by some trees.

The environment around the tree, which is the experimental site, is a three-story structure on the west side and a one-story structure on the east side, making it difficult to secure the required number of satellites depending on the time of day. The slide rail was installed so that the southern edge entered under the tree. In this experiment, the same antenna that can be used for both single-frequency and dual-frequency receivers was used to prevent errors in positioning accuracy due to antenna performance. The single-frequency and dual-frequency positioning experiments were conducted simultaneously.

Figure 6 and 7 show also the positioning results of a single-frequency receiver and dual-frequency receiver, respectively. In each figure, the blue line indicates the FIX solution, and the yellow line indicates the FLOAT solution. For the single frequency receiver, the FIX rate was 95.7% the first time and 82.6% the second time. When using a mobile object such as a car for positioning, the difference in FIX rate makes it difficult to obtain the position of the user, which changes every moment; thus, there is no effect on use. Near the tree on the south side of the structure, the single-frequency receiver showed a FLOAT solution similar to the dual-frequency receiver. However, it returned to FIX solution in a shorter time than the dual-frequency receiver. Similar results were obtained for the west side of the structure. From the experimental results, it is possible to perform positioning with a single-frequency receiver using the RTKLIB for positioning calculation even in an environment where positioning is difficult with the conventional method using a dual-frequency receiver. It was confirmed that it could be applied to the dose rate mapping system.

### 4.4 Positioning accuracy evaluation

To confirm the efficacy of decontamination work in air dose rate measurement, it is necessary to perform air dose rate measurement at the same point before and after the decontamination work. When satellite positioning is used to guide workers to measurement points, high-precision positioning with little variation and high reproducibility is required. In this experiment, the magnitude of variation of the positioning points is compared and evaluated between a single-frequency receiver and a dual-frequency receiver.

The experiment was performed with a slide rail with a movable range of about 3 m, which is installed horizontally around a tree adjacent to the MSE building of Ibaraki National College of Technology. The trolley equipped with the antenna is placed on the slide rail and manually reciprocated 20 times. Then, the trajectory of the antenna was recorded and the positioning accuracy was evaluated from the reproducibility of the trajectory.

The environment around the tree, which is the experimental site, is a three-story structure on the west side and a one-story structure on the east side, making it difficult to secure the required number of satellites depending on the time of day. The slide rail was installed so that the southern edge entered under the tree. In this experiment, the same antenna that can be used for both single-frequency and dual-frequency receivers was used to prevent errors in positioning accuracy due to antenna performance. The single-frequency and dual-frequency positioning experiments were conducted simultaneously.

Figure 8 and 9 show also the positioning results, respectively. In each result, the horizontal axis is the north-south direction, the vertical axis is the east-west direction, each cell is 10 cm × 10 cm, and the left side (south side) of the trajectory is below the tree. The green marks represent the FIX solution, and the red crosses represent the FLOAT solution. The FIX rate during the 20 round trips was 91% for the single-frequency receiver and 100% for the dual-frequency receiver. The maximum displacement in the direction perpendicular to the direction of movement was 3 cm at the southern end below the tree and 2 cm at the northern end. FLOAT solutions were obtained at several locations during the experiment, but returned to the FIX solution in a short time, and the measured values did not deviate by more than 5 cm around the average value during the FLOAT solution. From the experiment, it was confirmed that when using a single-frequency receiver for positioning, it was possible to obtain a positioning accuracy with a deviation of 5 cm or more around the average value compared with that of a dual-frequency receiver.

To confirm whether the single-frequency receiver can be used in the developed system, we conducted an experiment to compare the dual-frequency receiver and the single-frequency receiver that have been used so far. By using RTKLIB for positioning calculation, it was confirmed that the single-frequency receiver can obtain results comparable to those of the dual-frequency receiver. We also confirmed that positioning was possible using the single-frequency receiver around structures and under trees where positioning was difficult with a dual-frequency receiver. Therefore, it was determined that a single-frequency receiver can be used for the developed system.

### 5. Demonstration of development system

#### 5.1 Configuration of development system

In the developed air dose rate mapping system, a single-frequency receiver was adopted as the satellite positioning system that has never been adopted, based on the results of evaluation experiments. Table 3 shows the specifications of the adopted single-frequency receiver.
receiver. The kinematic method is used for positioning, and the GNSS positioning program package RTKLIB is used for positioning calculation. The transmission means for transmitting the reference station data to the mobile station uses an inexpensive packet communication service provided by a mobile phone company, considering convenience and cost.

Figure 10 shows the equipment configuration of the developed system, and Table 4 shows the specifications of the radiation measurement instrument. The dosimeter measures every second, and the averaged value is output and saved. The development system consists of two GPS/GLONASS receivers for the reference station and mobile station, as well as a GNSS antenna, antenna pole, packet communication device, personal computer, and radiation measurement device. The radiation meter uses a high-sensitivity CsI scintillation counter. Conventionally, since the radioactivity measuring instrument also had no external output, the measurement results were handwritten, and it was a relatively large and heavy device. Therefore, it was rare to measure at three points at one place. To complete the air dose rate measurement at three points in the height direction in a short time, the newly developed system fixed three radiation measuring instruments at the respective heights of the poles and achieved simultaneous measurement at three points. Other than the personal computer, it is integrated with the antenna pole, so that air dose rate measurement can be performed by one person. The software is compatible with touch operation that can be operated by directly touching the monitor screen, thereby eliminating difficult keyboard operations during on-site work. In addition, it is difficult to use the coordinate values given to the aerial photographs and drawings such as orthochromatic photographs because of crustal deformation and the like. A new function has been newly added that allows for accurate coordinate values to be added to drawings by measuring the target at the site at multiple points without using values.

5.2 Working with the development system Figure 11 shows the working procedure of the developed air dose rate measurement system, and Figure 12 shows the usage status. As a preliminary preparation, first, as shown in Figure 11 (1), the measurement points are marked in drawings such as aerial photographs using CAD or image editing software, and an image file is created. Next, to add coordinate values to the drawing at the site, GNSS positioning is performed at any two points that can specify the same position in both the drawing and the site, as shown in Figure 11 (2), and registered in this system. This preliminary preparation enables calibration processing to embed the coordinate values in the drawing from the registered positioning values, and it is possible to display the positional relationship between the worker's position and the measurement points, as shown in Figure 11 (3). As a result, the distance between the worker's current position and the measurement point can be confirmed on the PC, and the worker can be guided. After moving to the measurement point, the operator presses the record button (Figure 11 (4)) and records the measurement point data. At this time, the radiation measuring instrument

Table 3 Specifications of GNSS receiver

| Receiver          | Sensor Com GPS/GLONASS with L1 single GOSTAR |
|-------------------|---------------------------------------------|
| GNSS Antenna      | GPS/GLONASS with L1 single-frequency        |
| Satellite Channel | 14ch  (GPS 8ch, GLONASS 6ch)                |
| Software          | RTKLIB                                      |
| Precision         | cm level (Kinematic Mode, FIX)              |

Table 4 Specifications of airborne radiation measurement device

| Radiation Sensor   | CsI Scintillation Counter of PIN diode with energy corrected |
|--------------------|-------------------------------------------------------------|
| Dose Range         | 0.01 μSv/h - 9.9 Sv/h                                       |
| Measurement Frequency | 1 time/1-3600s (variable)                                |
| Data Log           | 30,000 points                                              |
| Communication      | Bluetooth                                                  |

Fig. 10 Schematic of measurement system for airborne radiation
automatically records the data measured every second together with time information in an internal memory. After the measurement at the site is completed, the air dose rate data is collected from the internal memory of the radiation measuring instrument and automatically combined with the measurement point data by GNSS positioning by the combining software. At this time, the data is combined based on the measurement time. By transferring the measurement data combined with the air dose data to GIS, it becomes possible to develop it on a map.

As described above, in the development system, the operator can use the coordinate value without knowing the coordinate value. Calibration can be performed with simple operations. Using a single-frequency receiver, which is less expensive than a dual-frequency receiver, allows the drawing on the screen to scroll as the operator moves, similar to that in car navigation. By moving the survey point displayed on the screen so that the pointer indicating its position overlaps, it is possible to guide to the measurement point.

5.3 Demonstration of Measurement results with the development system

The developed system was applied to measure the air dose rates in the premises of Ibaraki National College of Technology, and the effectiveness of this system was verified. Figure 13 shows an example of the measurement results. As a preliminary preparation, the drawings on the premises of Ibaraki National College of Technology were divided into 10 m x 10 m intervals, which are represented by the thin grid-like straight line in Figure 13. Drawing a point at the center of the divided frame can determine the measurement point. Measurements were performed at three points in the height direction (directly above the ground, 50 cm, 1 m) at 10 m x 10 m intervals. The area of the premises of National Institute of Technology, Ibaraki College was about 100000 m² and the number of measurement points was about 1000. Conventionally, several workers took several months to measure, with the developed system, this work could be completed in about two and a half days, confirming its effectiveness. This is one-tenth of the working time when using a conventional optical surveying instrument.

6. Conclusion

As an example of the use of GNSS positioning to improve the degree of freedom of decontamination work and improve work efficiency, an outline of air dose rate measurement required for decontamination work was explained, and the developed air dose rate measurement system was introduced in this paper. The newly developed system achieves high speed by simultaneous measurement of air dose rate at three points, easy operation by worker guidance method, and low cost by adopting single frequency GPS/GLONASS positioning, which was difficult with conventional optical surveying. In the future, we plan to expand its use for realization of decontamination work in places.
The combination of the single-frequency GPS/GLONASS receiver used in the positioning system and the RTKLIB, which allows for fine-tuning of settings, allows the selection of satellites used for positioning calculations. It is now available in the surrounding area. The concerned positioning accuracy is equivalent to that of dual-frequency GPS positioning, and further expansion is expected in the future.

In addition, MADOCA, CLAS (cm-Level Augmentation Service), and many others, currently being broadcast from the “Michibiki” satellite of the quasi-zenith satellite system, which is the first domestic satellite positioning system in Japan, officially launched on November 1, 2018. Cm-class positioning reinforcement service is available, which eliminates the necessity of separately constructing an RTK reference station and augmented data transmission means, which were some of the factors that became an indispensable, expensive, and complicated. It is considered that a system with high performance can be constructed. In addition, enhanced positioning accuracy by improving the satellite constellation by Michibiki can be expected.

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