Real-Time Monitoring of Structure Movements Using Low-Cost, Wall-Mounted, Hand-held RTK-GNSS Receivers

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BIOGRAPHY (IES)

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ABSTRACT

It is useful and innovative to monitor the displacement of structures caused by seismic shaking and landslides irrespective of observation points by using a single piece of equipment to collect data for some construction companies, research institutes and so on. Global Navigation Satellite System (GNSS) receivers and antenna on the roof of a steel tower to monitor the displacement of a structure (caused by wind, other natural elements, etc.) have already been reported in Japan, but our study is the first study on low-cost GNSS systems that can be attached to the walls of a building to monitor movement. Specifically, this research focuses on the real-time monitoring of structure movement using wall-mounted, hand-held Real-Time Kinematic GNSS (RTK-GNSS) receivers. Generally, it is not easy to set the antenna on the roof of buildings, so this approach attempting to attach the antenna to the wall has an advantage of the aspect of the readily installing. RTK positioning is normally performed using expensive, dual-frequency, geodetic-level receivers and antennas because it is commonly used in surveying world. However, aside from its high cost, this type of equipment is not easy to procure. This study addresses this problem using a low-cost, single-frequency, consumer-level receiver, which produces comparable centimeter-level results. The methods presented use horizontal spread and statistical values to determine positioning results. Our work on the proposed monitoring system, with its robust RTK improvement method, will serve as a reference for monitoring the fluctuations and movements of structures in the fields of architecture, construction and so on.

I. INTRODUCTION

The need for accurately identifying locations is increasing because of the advent of a variety of smartphone applications that use location information. Multi- Global Navigation Satellite System (GNSS) positioning is now possible owing to progress in the deployment of positioning satellites and the high quality of firmware supplied by GNSS receiver manufacturers around the world. Therefore, real-time kinematic (RTK) positioning in open-sky environments (without structural barriers that affect positioning) is no longer a problem. However, it is also well known that the presence of urban buildings, trees and other obstacles decreases the performance of RTK positioning markedly in that area, which is a problem that needs to be addressed.

In open-sky environments, RTK positioning is often used for surveying on construction sites owing to its high performance. The Ministry of Land, Infrastructure, Transport and Tourism in Japan launched a project called “i-Construction” that encourages using and adapting ICT in its entirety on construction sites. However, dual-frequency receivers that can be used in such situations are expensive; therefore, in the future, systems will emerge that use single-frequency low-cost handheld receivers that are easy to produce and operate.

In this research, we affixed a low-cost, handheld GNSS receiver’s patch antenna to the wall of a building in a suboptimal environment (*i.e.*, partially shielded by trees or other structures). RTK positioning was performed with the antenna, which received the radio waves from the satellite and was perpendicular to the surface of the wall. This innovative system, which we are the first to propose, monitors a building’s shaking using centimeter-level information from positioning epochs. In Japan,

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which is a highly seismic country, the above system, which can detect the shaking of a building, is extremely useful. This study presents a system that can detect fluctuations in existing structures, as well as in buildings that are under construction, and important structural measurements can be obtained from the data. In contrast, the conventional method requires expensive measuring instruments and many employees to measure the movements of buildings. Our proposed method requires only three elements: power supply (lithium-ion mobile battery, PC, etc.), a handheld receiver, and an antenna (shown below in Fig. 1). The equipment is installed on the wall of a building where measurements need to be taken. The logged observational data is analyzed using software, which has considerable advantages in terms of personnel and cost. In the case of real-time application, we just put 3G SIM card and small computer which is Raspberry Pi. We have already developed them and the raw GNSS data of GNSS receiver installed on the surface of the wall is automatically transmitted to our PC server including RTK software.

Several challenges exist in developing the above system. First, as it is a single-frequency receiver, the number of satellites for RTK positioning is sometimes severely restricted. Therefore, it is very important to know if the number of satellites required will be available (due to limited sky view). Factors that significantly influence performance include the time zone with optimal satellite arrangement (BeiDou satellites in China tend to concentrate from the northeast to the southwest in the sky above Tokyo), dilution of precision caused by the geometrical arrangement of satellites, and the direction of the place where the experiment is conducted in relation to the above factors. Moreover, compared to that of dual-frequency receivers the RTK position information obtained by single-frequency receivers is low in terms of reliability and availability, so technologies for improving these metrics are also important.

Such systems will be easier to handle if the existence of the structures that shield radio wave propagation paths (hence deteriorate the surrounding environment) are known in advance. One way to cope with such environmental obstacles is to optimally apply the elevation mask and make it easy to receive more than 10 direct signals. With this technique, the influence of diffracted wave signals and reflected wave signals (multipath waves) from non-line-of-sight satellites can be reduced, and epochs obtained at the centimeter levels will increase. In existing research, the “GPS-Studio” (by KOZO KEIKAKU ENGINEERING Inc., Japan), which is a radio-wave propagation simulation, uses both the ray tracing and 3D map methods to provide precise positions of buildings, but it has not been widely used practically yet. Accumulation of these kinds of environmental data over time provides an advanced arbitrary measurement using AI.

The easy-to-obtain around low-cost ($100) handheld receiver can achieve an accuracy of a few centimeters at many measurement points, and it is possible to introduce several receivers at many places. In this paper, we propose a low-cost RTK system, which has not been designed earlier, as a monitoring system for building shaking, intended for practical applications.

Moreover, previous studies such as the monitoring of a steel tower’s displacements caused by the wind using RTK positioning [1][2][3] and the monitoring of a landslide caused by rain on the land near the river [4][5] do not employ these systems in an extreme environment. The aim of this research is to implement the RTK monitoring system in this type of environment to test its efficiency and accuracy.

Fig. 1. Low-Cost Rover Equipment

II. RTKLIB AND ROBUST RTK METHOD

Before we discuss about algorithm of RTK, it is quite important to discuss about satellite selection to remove the bad quality carrier-phase. First of all, we check LLI flag of the output from u-blox receiver to eliminate bad quality carrier-phase causing cycle-slip and so on. Generally, when the antenna is installed on the surface of the wall, the sky view is obstructed in half by the structure, so the influence of the diffracted wave from NLOS satellites should be taken into consideration in particular. On the other hand, the reflected wave can be ignored as there is almost no influence of the code/carrier phase multipath because the delay of the multipath is almost zero. We still need to check the effect of carrier phase multipath carefully because there is a few cm distance between the wall and antenna. Although the effect of DOP value may increase significantly but we just need to set the threshold of DOP according to our expected accuracy. Previous studies have shown that some diffracted signals from NLOS satellites can be almost completely eliminated using the picture of fisheyes lens [6]. Based on this satellite selection method, as a result, RTK performance dramatically improves using the standard method mentioned in the above. Fig. 2 shows the picture of the fisheyes lens and the transition of SNR (PRN24 of GPS). It can be confirmed that we need to adopt appropriate SNR mask to make RTK successful. Based on a lot of test data using u-blox M8 series, we found the suitable threshold of SNR which is 35 dB-Hz.

In the concept of normal installation of the antenna, the most common way is to set antenna upward. However, for this research, we did an initial test to check the performance according to the degree pattern of 0°, 45°, and 90° with respect to the ground (Fig. 3). From these results, we adopted the 0° orientation since the RTK performance was the best.

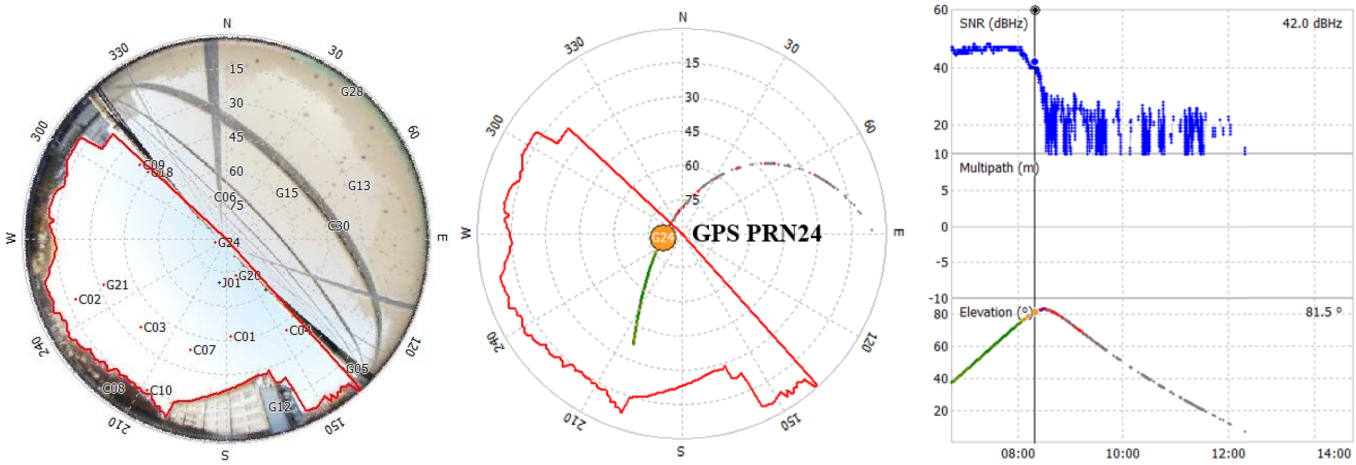

Fig. 2. Pictures of Fisheyes Lens (southwest) and Transition of SNR (PRN24 of GPS)

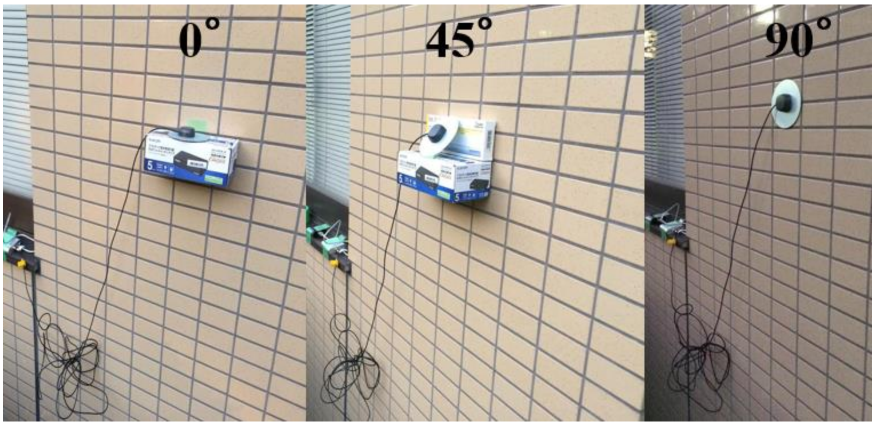

Fig. 3. Initial Experiment (0°, 45°, and 90°)

A. Using RTKLIB

To process the raw data logged by the receiver, we used RTKLIB (ver. 2.4.3 b29), which is an internationally famous, free software, developed by Mr. Tomoji Takasu who is a visiting researcher at our university. The results of this experiment seemed to be best when adjusting “Options” for RTKPOST, which is a post-processing function in RTKLIB; the improved results from our CUI post-processing software using Microsoft Visual Studio incorporating the proposed method.

Once we had the raw data, we had to search for the best “Options” while manually changing some parameters. This method will not be needed unless we employ the use of skyward angular range of view using fisheyes lens. Normally this process would be a difficult and laborious task. However, we do not have to change some parameters when using our proposed method.

Therefore, the proposed method has an advantage in this part. The below settings (Fig. 4 – Fig. 7) are for the southwest antenna, which will be discussed in Sections III and IV.

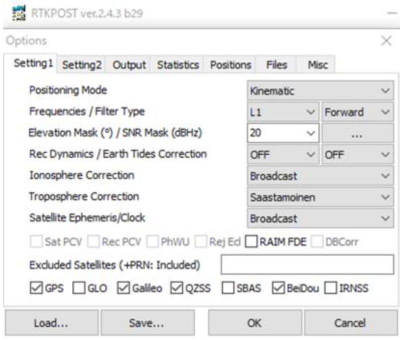

Fig. 4. Setting1

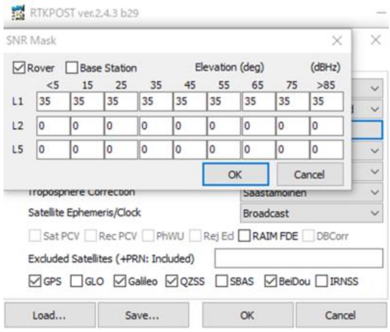

Fig. 5. SNR Mask

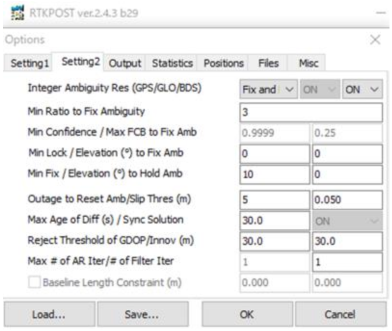

Fig. 6. Setting2

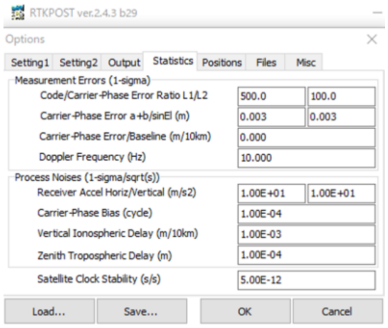

Fig. 7. Stats

Detailed setting in "Options" of RTKPOST is shown (in above Fig. 4 – Fig. 7). Currently, favorable results are obtained using these settings. The results of RTKLIB are presented in Section IV.

B. Using Robust RTK method

This section briefly introduces the proposed RTK method under severe environments. The most part is similar to the normal algorithm of RTK which means that we use LAMBDA method to resolve correct integer ambiguities and ratio test to enhance the reliability of RTK fixed solutions.

(a) Float Solution and Ambiguity Resolution

The RTK-GNSS uses a double difference (DD) code and phase observation. The DD measurements efficiently cancel the receiver and satellite-dependent biases. In addition, the atmospheric reflection errors that occur when two receivers are close are so similar that they can be eliminated. The DD observation models can be written as follows [7]:

(1) $$DDP = (P^{sv1}_{ref} - P^{sv2}_{ref}) - (P^{sv1}_{rov} - P^{sv2}_{rov33}) = \rho_{code} + \varepsilon_{code}$$

(2) $$DD\varphi = (\varphi^{sv1}_{ref} - \varphi^{sv2}_{ref}) - (\varphi^{sv1}_{rov} - \varphi^{sv2}_{rov}) = \rho_{phase} + \lambda N + \varepsilon_{phase}$$

where P and φ are the code and phase observations, respectively, ρ is the DD geometric distance, λ is the wavelength, N is the DD integer ambiguity, and ε is the DD measurement noise including the multipath error.

First, the DD observations are used to determine the 3D position solution (i.e., float solution) and real number ambiguity solutions at the same time. The details of the estimation of the float solutions can be referred to part (c) in the following. Then, the ambiguity resolution (AR) method is used to optimize the integer ambiguity solution. The AR method searches for the integer ambiguity that minimizes the cost function, which is given by

(3) $$C(N) = (N - N^{\wedge})^T W_N (N - N^{\wedge})$$

where N is the minimized integer ambiguity in the cost function, N^ is the float solution ambiguities, and W_N is the inverse of its covariance matrix.

The LAMBDA method is a well-known and efficient integer AR method based on the least-squares method [8] and was used to determine the optimal integer ambiguities.

(b) Ambiguity Validation Test

A test was performed to validate the integer ambiguities determined by the LAMBDA method. Several tests are available for ambiguity validation [9]. A ratio test based on integer least-squares is a clean and effective method to vilification tests. In this study, the ratio test with a fixed value is used for short base line RTK. According to the ratio test, the ratio of the differences from float ambiguity solution residuals (computed by the cost function) is compared.

The ratio value of the ratio test is defined as

$$\text{Ratio} = C(N_2) / C(N_1) > \text{Threshold} \quad (4)$$

where $C(N_1)$ is the cost function value of the best integer vector and $C(N_2)$ is the cost function value of the second-best integer vector. If this ratio is large enough, these ambiguities are acceptable. The threshold value is determined from the empirical results. The ratio test threshold is usually 2–3 depending on the environment. In this study, the ratio test threshold was set to 3.

(c) Robust RTK under severe condition

We need to modify the algorithm to find correct ambiguities to enhance the RTK performance under severe conditions. In addition to that, selecting high-quality satellites is important. Generally, Kalman-filter-based RTK has been used for this purpose because it can reduce the noise of float solutions, and it uses signal strength-based satellite selection. We use a similar satellite selection method according to the suitable threshold of the expected signal strength. However, we do not use the Kalman filter to reduce the error and noise of float solutions. In some applications such as determination of the structural deformation of the building, the movement of the structure is very slow and small. Even in the case of a bridge, the amount of displacement could be less than 10 cm per day. In such situations, we can tighten antenna movement constraint according to the dynamics of the target position. Furthermore, the initial position of the target is very important, and we can know the precise target position beforehand. Even without previous target position information, once we resolve the reliable precise position, we will use this information as an initial position. The difficulty in RTK under severe conditions is that large code multipath errors deteriorates the float solutions, as a result, RTK fix rate as well as reliability of RTK decreases. If we know the approximate precise position within 10 cm, we don’t have to use code measurements to resolve the carrier phase ambiguities. By doing so, the performance of RTK-GNSS under very severe conditions, such as almost half masking of the sky, is improved dramatically, even when compared to the RTK engine of geodetic-level GNSS receiver that cost over $10,000.

In parallel with the above robust RTK, resolved ambiguities of each satellite are saved and held. Based on the cycle slip information of the carrier phase, the RTK positions are produced using the saved ambiguities separately. Two RTK positions are checked weather they match within about 10 cm to enhance the reliability. Furthermore, we rely on the RTK positions deduced from the saved ambiguities in the case of large deformation due to big earthquake that the speed of the deformation exceeds over a few cm/s as long as we have enough satellites without cycle slips. If we don’t have usable satellites at least 5-6, it is impossible to estimate the position. The reason why we don’t use the above robust RTK solutions is that it does not cover the movement over approximately 20 cm in total because of the limitation of the ambiguity search space. In reality, the fluctuation of the building in big earthquake exceeds over 50 cm on higher floors. The brief flowchart of our proposed method is shown in Fig. 8.

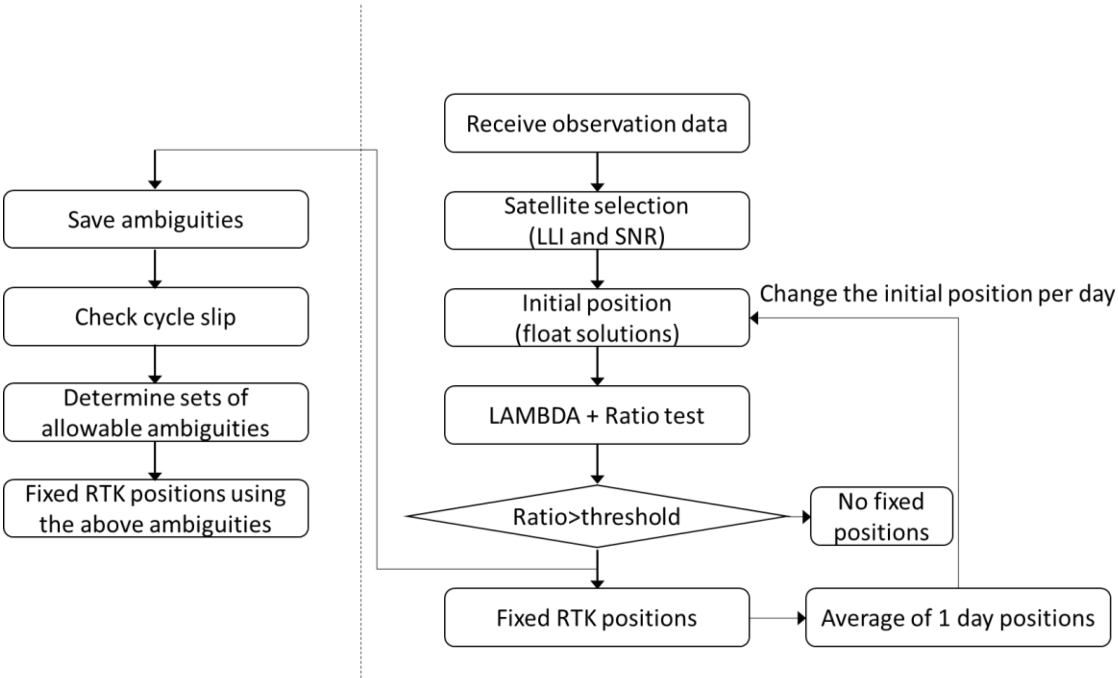

Fig. 8. Flowchart of Our Proposed Method

III. EXPERIMENTS

Over several days during November 2017, we conducted the positioning experiments mentioned in Section I, on various walls of a building at Tokyo University of Marine Science and Technology for about 24 h and 23 h. The equipment used in the experiment, installation location, and installation status are given below (Table 1, Fig. 9 – Fig. 13).

Table 1. Equipment Used

Observation period	1 Hz
GNSS receiver	Rover: NEO-M8T SCR-u2C (u-blox) Base station: NEO-M8T SCR-u2C (u-blox)
Satellite system	RTKLIB: GPS/QZSS/BeiDou/Galileo Proposed method: GPS/QZSS/BeiDou/Galileo or GPS/QZSS/BeiDou
Antenna	Rover: Patch-antenna TW4721 (Tallysman Wireless) Base station: Zephyr2 Geodetic (Trimble)
Others	Lithium ion mobile battery, Bookend, and so on

Fig. 9. Installation Location


Fig. 10. Installation Status (southwest)

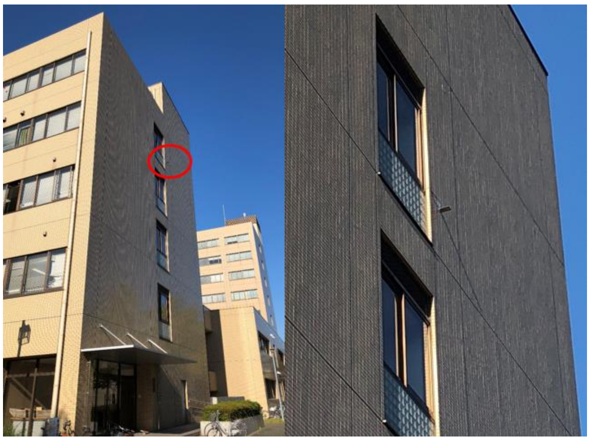
Fig. 11. Installation Status (southeast)


Fig. 12. Installation Status (northwest)


Fig. 13. Installation Status (northeast)

This experiment makes use of Trimble Inc., (an expensive antenna) for reference, but it is possible to replace the antenna with a patch antenna to minimize the cost of the project without performance deterioration. To investigate building movement, it is desirable to analyze data spanning months or years. However, for this experiment, we processed 24 h and 23 h of data. Post-processing of RTK positioning was performed using observation data at the rover station obtained by positioning, the observation data from the reference station, and the navigation message. We will investigate long-term data over one month in the near future.

IV. RESULTS AND EVALUATION

(i) Results of the Proposed Method

The experimental results are presented in the following tables and graphs: (Table 2 – Table 5, Fig. 14 – Fig. 17). The standard deviation and average represent the two-dimensional horizontal gap from the true value, and the epoch number represents the number of times RTK positioning was possible during 24 h (southwest) or 23 h (excluding southwest). The total number of epochs was 86,400 in the southwest, and 82,800 in all other cases. However, as it is important to judge whether the solution determined as the "fixed state" is a really correct solution, the reliability (%) is also included in these tables.

The reliability of RTK is defined as follows:

$$\text{Reliability (\%)} = (\text{Number of Reliable solutions} / \text{Number of Fix solutions}) \times 100$$

RTK Fix rate is defined as follows:

$$\text{RTK Fix rate (\%)} = (\text{Number of Fix solutions} / \text{Number of all epochs}) \times 100$$

Table 2. Southwest Results

Southwest	RTKLIB	Proposed method
RTK Fix rate (%) Number of epoch	91.8% 79314 (GBQE)	98.2% 84822 (GBQE)
Horizontal reliability (%) Number of epoch	99.15% 78638 (GBQE)	99.77% 84622 (GBQE)
Average of gap[m]	0.0214	0.0117
Standard deviation of gap [m]	0.173	0.0117

Table 3. Southeast Results

Southeast	RTKLIB	Proposed method
RTK Fix rate (%) Number of epoch	97.5% 80697 (GBQE)	96.4% 79805 (GBQE)
Horizontal reliability (%) Number of epoch	99.66% 80426 (GBQE)	99.85% 79682 (GBQE)
Average of gap[m]	0.0115	0.0081
Standard deviation of gap [m]	0.0132	0.0222

Table 4. Northwest Results

Northwest	RTKLIB	Proposed method
RTK Fix rate (%) Number of epoch	93.9% 77739 (GBQE)	97.4% 80681 (GBQ)
Horizontal reliability (%) Number of epoch	99.06% 77006 (GBQE)	99.99% 80676 (GBQ)
Average of gap[m]	0.0165	0.0119
Standard deviation of gap [m]	0.0186	0.0085

Table 5. Northeast Results

Northeast	RTKLIB	Proposed method
RTK Fix rate (%) Number of epoch	29.1% 24133 (GBQE)	12.5% 10331 (GBQE)
Horizontal reliability (%) Number of epoch	35.92% 8669 (GBQE)	99.40% 10269 (GBQE)
Average of gap[m]	20.2	0.0461
Standard deviation of gap [m]	254	0.0173

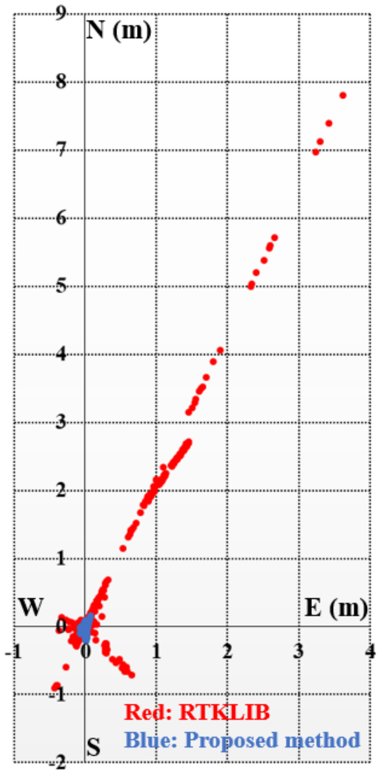

Fig. 14. Horizontal Results (southwest)

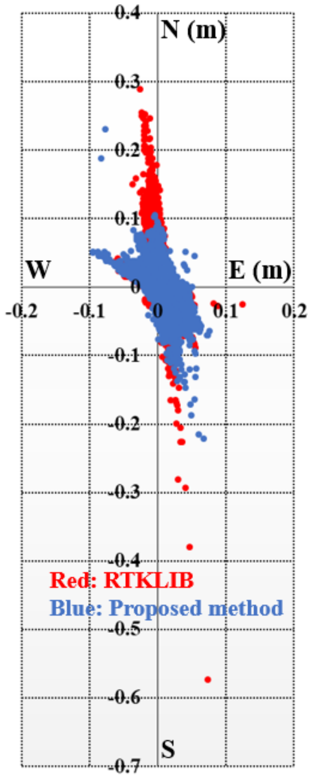

Fig. 15. Horizontal Results (southeast)

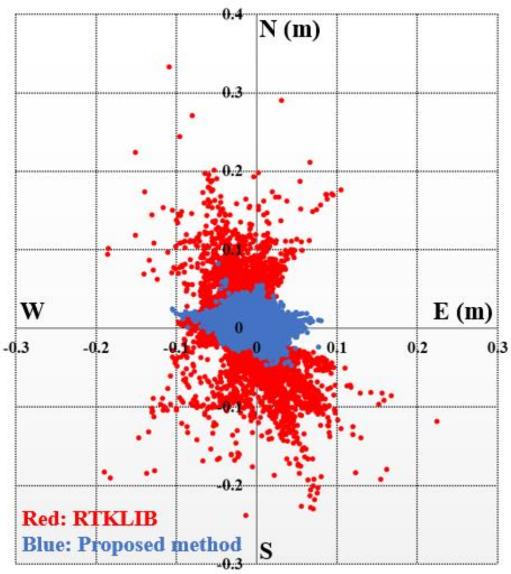

Fig. 16. Horizontal Results (northwest)

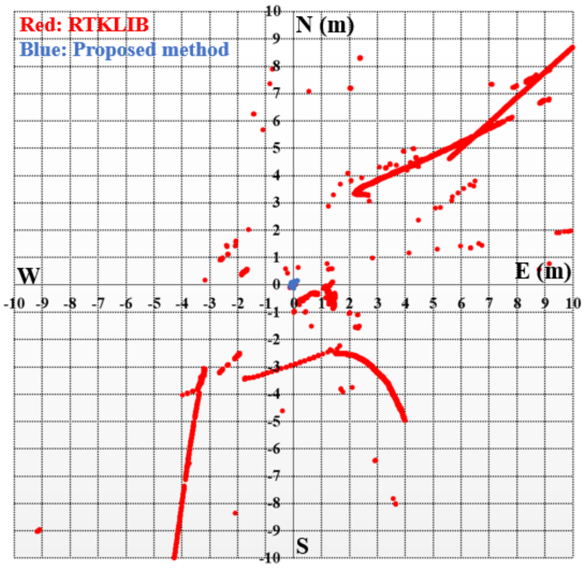

Fig. 17. Horizontal Results (northeast)

In any direction of these tests, the results from the proposed method were better than those of RTKLIB. The number of epochs that have the RTK flag set also increased. As for the reliability of the southwest and southeast results, which had a relatively good satellite constellation because of several BeiDou satellites, the horizontal results (within ±10 cm of the true value) can be obtained with high reliability at a rate of more than 99%. As can be seen from the horizontal results, as the satellite constellation and direction in which radio waves can be received were biased, RTK fixed solutions were elongated in the direction perpendicular to the surface of the wall. However, in the northeast, RTK fix rate was lower than the other three cases, simply because of the shortage of the number of usable satellites. With more visible satellites soon becoming available—like QZSS and Galileo—and the appearance of low-cost, dual-frequency receivers, performance will improve further. On the other hand, determining the position of northeast using the RTKLIB has been difficult due to limitations in lack of satellites. As a workaround, we used SPS855 receiver of Trimble Inc. to get the precise position. This confirms that the accuracy of the proposed method is relatively better than the result of RTKLIB, regardless of the fact that the RTK fix rate of proposed method is lower than RTKLIB.

Based on these test results, it is possible to detect a vibration of at least 3–4 cm of a wall in the case of the southern direction. In high-rise buildings, the walls vibrate even more, and when an earthquake occurs, large shakes can be detected, and it is possible to precisely determine the occurrence time and amplitude of shaking. This information is very important for construction companies. Almost all RTK fixed solutions are within 10cm in horizontal. This can be very useful for detection of long term transition of positions and movement of buildings if the day by day average is taken from those data. However, there is still a need to adapt an algorithm that can deal with a big seismic shakings such as a few decimeters moving in the near future.

(ii) RTK Performance of Commercial Receivers on the Wall

To investigate the performance of the low-cost commercial receivers with RTK, we obtained 1 hour data of NEO-M8P with the newest firmware (u-blox), which can obtain the receiver's calculated output (NMEA-format) of low-cost RTK and compare it to the corresponding data obtained with the proposed method. Sampling rate was 5 Hz and the installation point was southeast. Horizontal results are shown below (Fig. 18).

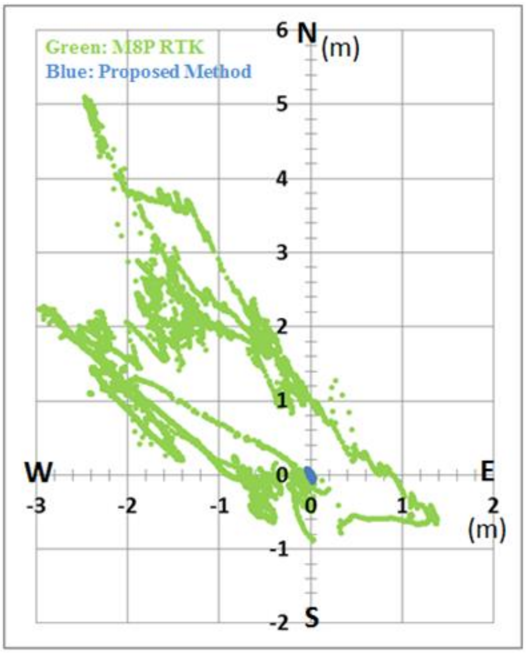

Fig. 18. Horizontal Result (u-blox NEO-M8P)

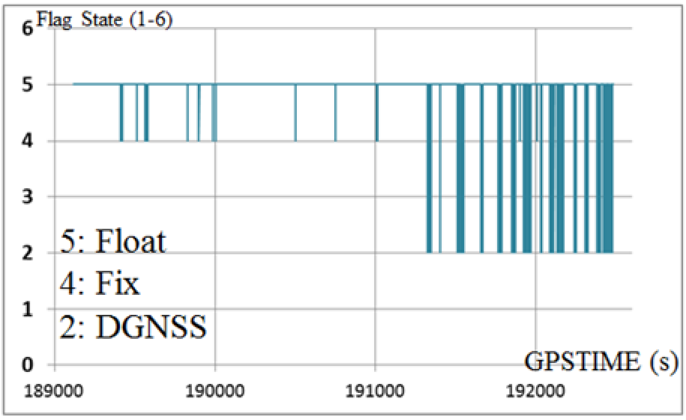

Fig. 19. Quality Flag

Based on the results, NEO-M8P could not properly obtain RTK fixed solutions in this environment. In addition, Fig. 19 shows the quality flag in a time series. It turned out that there were almost no RTK fixed solutions, and most of the solutions were float solutions; hence, in this kind of severe environment, RTK positioning of NEO-M8P was not good. Therefore, the effect of the proposed method was also confirmed from this experiment.

In addition to the above test, the geodetic-level GNSS receiver SPS855 manufactured by Trimble Inc. was also checked. We obtained 1 hour data on the southwest wall and sampling rate was 10 Hz. Horizontal and height results are shown below (Fig. 20, Fig. 21).

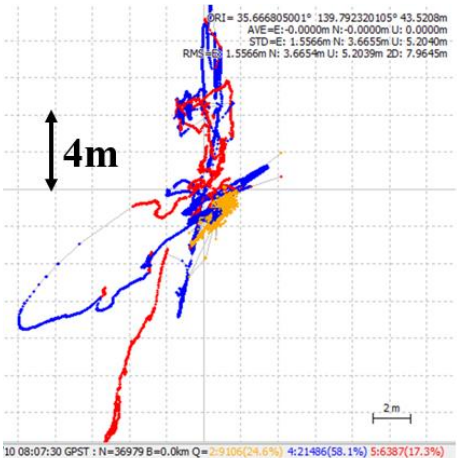

Fig. 20. Horizontal Result (Trimble SPS855)

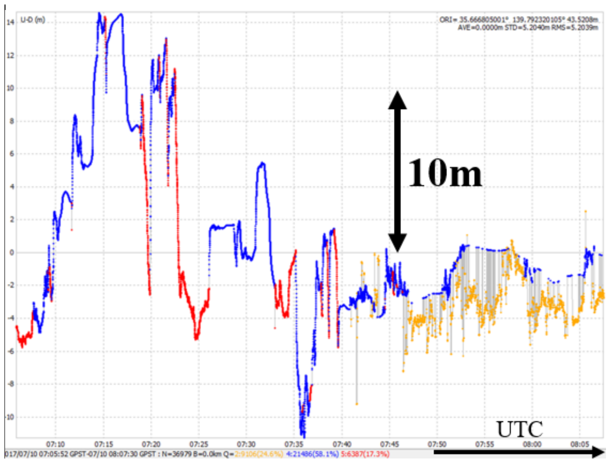

Fig. 21. Height Result (Trimble SPS855)

Based on the test results, there were no RTK fixed solutions in this environment using SPS855. Red plots are standalone, blue plots are DGNSS, and yellow plots are RTK float in Fig. 20 and Fig. 21. Therefore, even two very famous companies of GNSS receiver, they do not support these severe situations, hence the effect of the proposed method was also confirmed from this experiment. We actually don't think that these commercial receivers are not good. We can say that it is quite important to customize the RTK software to achieve the better performance in the very severe condition.

(iii) Further Experiments

Furthermore, the following horizontal results were those obtained when the antenna was manually moved on the southwest wall's surface to simulate shaking. As it is difficult to perform positioning experiments involving considerable outdoor shakings, we decided to manually move the antenna very close to the wall. It was moved in the lateral and vertical direction with respect to the wall's surface, every minute, from left to right and from top to bottom. The installation status as shown below (Fig. 22).

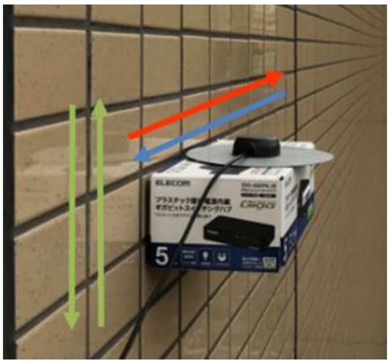

Fig. 22. Box for a Patch Antenna

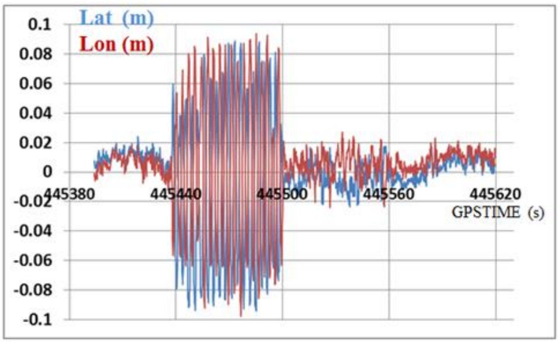

Fig. 23. Horizontal Result (southwest)

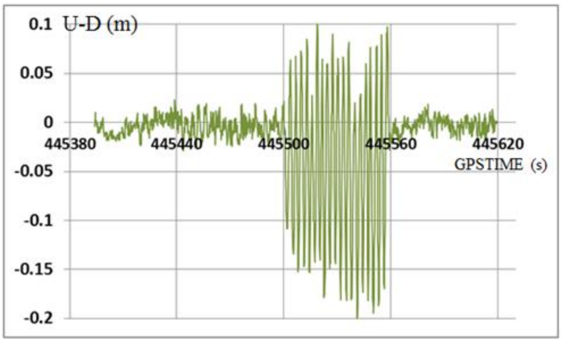

Fig. 24. Height Result (southwest)

The above figures (Fig. 23, Fig. 24) were the results of sampling at 5Hz, and it is assumed that it was shaken similar to when an earthquake occurs, in a short time and moving approximately 10 cm from the true position at a constant speed from left to right. The elongation of the solution shows that RTK fixed solutions can firmly follow the direction of the antenna. RTK fixed rate was almost 100%. Even if an external dynamic force works under such circumstances, it can detect several centimeters of motion, so it was found that it is a method that can be used for monitoring.

Moreover, following two results (Fig. 27, Fig. 28) were also obtained from a similar experiment considering a very big earthquake with a magnitude of 5 or more analyzed by RTKLIB and the proposed method. The antenna with a pole was moved approximately 40 cm from the true position at a slow and fast speed from left to right. The pole used in the experiment and installation status are given below (Fig. 25, Fig. 26).

Fig. 25. Pole Used in the Experiment

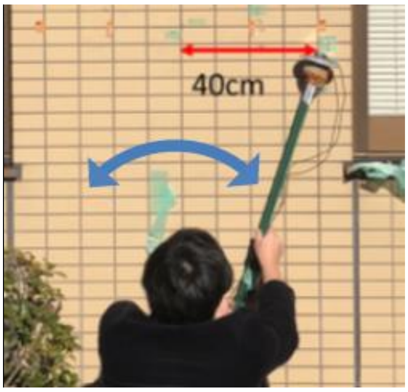

Fig. 26. Installation Status (southwest)

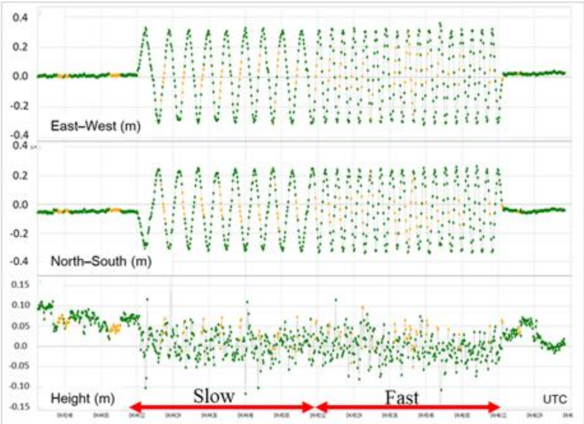

Fig. 27. Result of RTKLIB (southwest)

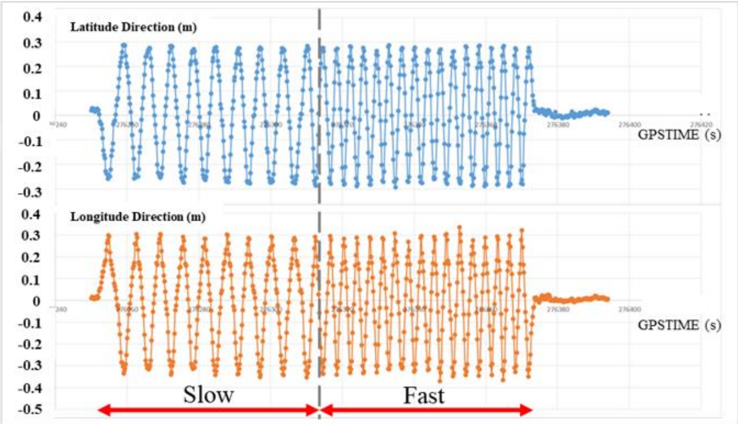

Fig. 28. Result of the Proposed Method (southwest)

There are some float solutions and wrong RTK fixed solutions in the result of RTKLIB, on the other hand, 100% RTK fixed solutions were obtained by the left part of the flowchart of the proposed method shown in Fig. 8.

In conclusion, from the above results, in an environment that satisfies conditions such as the number of satellites and the surroundings not being completely closed by buildings, it is possible to monitor the shakings of buildings inexpensively using the proposed method.

V. SUMMARY AND FUTURE SUBJECTS

In this paper, we proposed a method for structure movement detection with a low-cost, handheld RTK in severe environments. Although only one building at Tokyo University of Marine Science and Technology was shown as an example, we plan to include the following in our research: experimental results of low-cost handheld receivers on other buildings and skyscrapers in other areas, and methods to obtain more accurate positions, and applications in real-world scenarios.

RTK fix rate was as high as 90% or more in the southwest, southeast and northwest, which can be considered a practical level. Regarding the northeast wall, if the antenna is surrounded by buildings, securing a sufficient number of satellites is difficult. However, as the availability increases owing to the soon-increasing number of usable satellites, it is expected that performance will improve regardless of the direction.

Currently, as a post-processing step of RTK, "forward" (which is processing from the front in time series), is regarded as real-time performance. We need to develop the real-time software and it is necessary to obtain long-term data (taken over several months) to put this system into practical use.

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