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Real-time Monitoring for Structure Deformations Using Hand-held RTK-GNSS Receivers on the Wall

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***Abstract*— Monitoring the displacements of structures caused by slight or big seismic shakings and landslides the irrespective of observation points by simply taking the data using a single equipment is useful. GNSS antennas and receivers on the roof of a steel tower to monitor the displacement of the structure caused by the wind etc. has already been reported, but ours is the first study on a low-cost GNSS system attached to the wall of a building to monitor structure deformations. More specifically, this research focuses on real time monitoring for structure deformations using hand-held RTK-GNSS (Real-Time Kinematic Global Navigation Satellite System) receivers installed on building wall. RTK positioning is normally carried out using expensive receivers and antennas compatible with dual frequencies. However, aside from its high cost, this type of equipment is also not easy to procure. This study addresses this problem by using a single-frequency low-cost receiver, with comparable results in centimeter level. The methods presented make use of horizontal spread and statistical values to come up with the positioning results. Our work on the proposed revolutionary monitoring system with a robust RTK improvement method will serve as basic research for monitoring the fluctuations and deformations of structures in the fields of architecture and construction.**

Keywords—RTK-GNSS; hand-held GNSS receiver; structure monitoring

I. Research Background and Objective

With the advent of a variety of smartphone applications that use location information, the need for accurately identifying location is increasing. Multi-GNSS positioning is now possible due to the 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 structures that affect positioning is no longer a problem. However, it is also well known that if the surrounding environment deteriorates slightly due to the presence of urban buildings, trees and other obstacles, the performance of the RTK positioning drops markedly in that area and problems to be addressed are highlighted.

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 of Japan launched a project called “i-Construction” that encourages using and adapting ICT in its entirety under construction sites. However, receivers compatible with dual frequencies and can be used in such situations are expensive; in the future, therefore, systems will be emerging 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 an adverse environment shielded to some extent by trees or other structures. RTK positioning was performed with the direction of the antenna receiving the radio waves from the satellite oriented perpendicular in regard to the surface of the wall. An innovative system that has been proposed for the first time monitors the building’s shaking using information of positioning epochs obtained at the centimeter level. In Japan, which is a highly seismic country, the above system that can detect the shaking of a building is extremely useful. This study presents a system which can detect the fluctuation of the existing structure as well as the building in construction site and can lead to significant structural measures from the obtained data. In contrast, the conventional method requires expensive measuring instruments and many personnel to measure the shaking and deformation of buildings. On the other hand, in our proposed method, only three elements, namely power supply (lithium-ion battery, PC etc.), handheld receiver, and antenna (shown in Fig. 1.), are required. The equipment is installed on the wall of a building where measurements need to be performed at a set hour (or long term). The logged observation data is analyzed by using software, and this approach has great advantages both in terms of personnel and cost.

Fig. 1. Rover equipment

Several challenges exist in realizing the above system. First, since it is a receiver of single frequency, the restriction of the number of required satellites for RTK positioning is sometimes severe. Therefore, it is very important whether the number of satellites required in the limited sky view is satisfied or not. The time zone with the optimal satellite arrangement (BeiDou satellites in China tend to concentrate in the direction from the northeast direction to the southwest direction 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 items are also factors that greatly influence the performance. Moreover, as compared with receivers compatible with dual frequencies, since the solution (position information) of RTK obtained by receivers compatible with single frequency has a characteristic that reliability and availability are low, technologies that ensure these requirements are also important.

Such systems will be easier to handle if the existence of structures that shield radio wave propagation paths (and hence deteriorate the surrounding environment) are known in advance and are available on the database. 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 at all times. With this kind of 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 centimeter levels will increase. In the existing research, we can point out the "GPS-Studio" made by KOZO KEIKAKU ENGINEERING Inc. (Japan), which is a radio wave propagation simulation that uses both the ray tracing and 3D map methods and provides precise positions of buildings, but it has not been widely put into practical use yet. Accumulation of these kinds of environmental data through time provides an advanced arbitrary measurement using AI.

The easy-to-obtain $100 low-cost 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 is not found in existing research, as a monitoring system of building shaking, as a basic research toward practical applications.

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

II. Post-process by RTKLIB and Robust RTK Method

A. Using RTKLIB

To process the raw data logged by the receiver, we used RTKLIB, which is internationally famous as existing free software, developed by Mr. Tomoji Takasu who is a visiting researcher in our university. We compared the results of this experiment that seem to be best set by "Options" of RTKPOST, which is a post-processing function in RTKLIB, with the improvement results by CUI post-processing software incorporating the proposed method.

Detailed setting in "Options" of RTKPOST is shown (in Fig. 2.–Fig. 5.). Currently, it is considered that the favorable results are obtained with this setting.

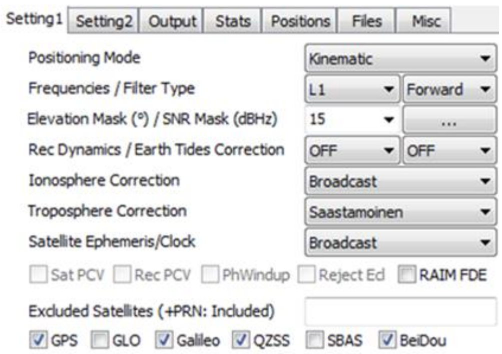

Fig. 2. Setting1

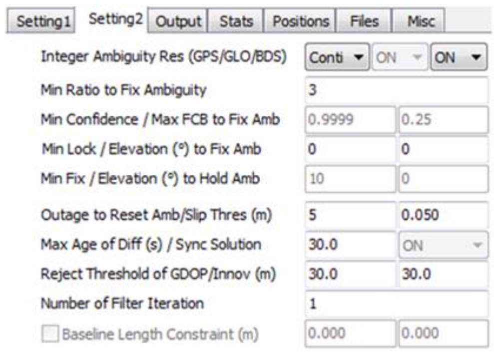

Fig. 3. Setting2

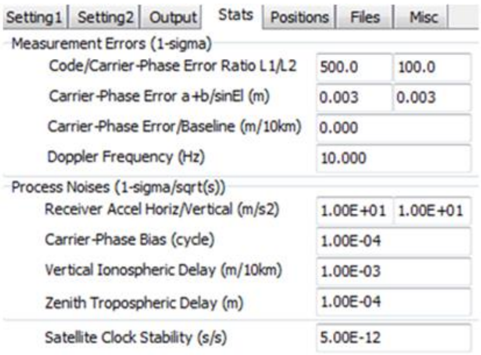

Fig. 4. Stats

The signal strength mask is as shown in Fig. 5.

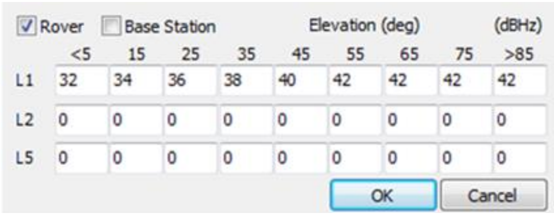

Fig. 5. SNR Mask

The results of RTKLIB are shown in Section IV.

B. Robust RTK Method

This section briefly introduces the proposed RTK method under severe environments.

- 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 [3]:

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

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

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. Then, the AR (Ambiguity Resolution) method is used to optimize the integer ambiguity solution. The AR method searches for the integer ambiguity that minimizes the cost function. The cost function of the integer vector is given by

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

where N is the minimized integer ambiguity in the cost function, is the float solution ambiguities, and W 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 [2] and was used to determine the optimal integer ambiguities.

- Ambiguity Validation Test

To validate the integer ambiguities determined by the LAMBDA method, a test was performed. Several tests are available for ambiguity validation [4]. 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 difference from float ambiguity solution residuals computed by cost function is compared.

The ratio value of the ratio test is defined as

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

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 set from 2 to 3 depending on the environment. In this study, the ratio test threshold was set to 3.

- Robust RTK under severe condition

To enhance the RTK performance under a severe condition, we need to modify the algorithm to search correct ambiguities. In addition to that, selecting the satellites with good quality is quite important. Generally, Kalman-filter based RTK has been used for this purpose because we can reduce the noise of float solutions, and the signal strength-based satellite selection is used. We use the 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 structure deformation of the building, the movement of the structure is usually very slow and small. Even in the case of a bridge, the amount of displacement will be less than 10 cm or more. In such situations, we can tighten the condition of constraint of the antenna movement 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 the previous target position information, once we resolve the reliable precise position, we will use this information as an initial position. By doing so, the performance of RTK-GNSS under very severe conditions like as almost half masking of the sky view is improved dramatically even compared with the geodetic-level GNSS receiver that cost over $10,000.

III. EXPERIMENTS

Over several days during April 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 12 hours. The equipment used in the experiment, installation location, and installation status are shown below (Table I., Fig. 6.–Fig. 9.).

TABLE I. EQUIPMENT USED

Observation Period	1Hz
GNSS Receiver	Rover: NEO-M8T SCR-u2C (u-blox) Basestation: NEO-M8T SCR-u2C (u-blox)
Satellite System	GPS/BeiDou/QZSS/Galileo
Antenna	Rover: Patch-antenna (Tallysman Wireless) Basestation: Zephyr Geodetic (Trimble)

Fig. 6. Installation location

Fig. 7. Installation status (SW)

Fig. 8. Installation status (SE)

Fig. 9. Installation status (NW)

This particular experiment makes use of Trimble Inc., an expensive antenna of the reference, but it is possible to replace the antenna to a patch antenna to minimize the cost of the project without the deterioration of the performance. For the purpose of investigating building movement fluctuations, it is desirable to be able to analyze data over a span of months or years. However, for this experiment, we processed 12 hours of data. Post-processing of RTK positioning on software was performed using three of the observation data of the reference station obtained by positioning, the observation data of the reference station, and the navigation message. We will investigate the long-term data over one month in the near future.

IV. RESULTS AND EVALUATION

The experimental results are shown in the following tables and graphs: (Table II.-Table IV., Fig. 10.-Fig. 11.). The standard deviation and the average represent the three-dimensional gap from the true value, and the epoch number represents the number of times RTK positioning was possible during about 12 hours. The total number of epochs was 43572 in the southwest, 43386 in the southeast and 43676 in the northwest. However, since it is important to judge whether the solution decided as “Fix state” is a really correct solution, the item of reliability (%) is also included in these tables.

The reliability of RTK is defined as follows:

Reliability = Number of Reliable solutions / Number of FIX solutions

RTK Fix Rate is defined as follows:

RTK Fix Rate = Number of FIX solutions / Number of all epochs

TABLE II. THE RESULT OF SOUTHWEST

[RTK Fix Rate] RTKLIB: 69%, Proposed Method: 88%

Southwest	RTKLIB	Proposed Method
Standard Deviation (m)	0.743	0.018
Average (m)	0.103	0.024
Number of epoch	29975	38151
Horizontal Reliability(%)	97.58	99.86
Height Reliability (%)	98.44	100

TABLE III. THE RESULT OF SOUTHEAST

[RTK Fix Rate] RTKLIB: 58%, Proposed Method: 81%

Southeast	RTKLIB	Proposed Method
Standard Deviation (m)	0.807	0.018
Average (m)	0.119	0.028
Number of epoch	25077	34955
Horizontal Reliability(%)	98.50	99.98
Height Reliability (%)	98.23	99.99

TABLE IV. THE RESULT OF NORTHWEST

[RTK Fix Rate] RTKLIB: 19%, Proposed Method: 34%

Northwest	RTKLIB	Proposed Method
Standard Deviation (m)	31.313	0.047
Average (m)	5.034	0.026
Number of epoch	8463	14655
Horizontal Reliability(%)	0.41	98.73
Height Reliability (%)	16.37	98.79

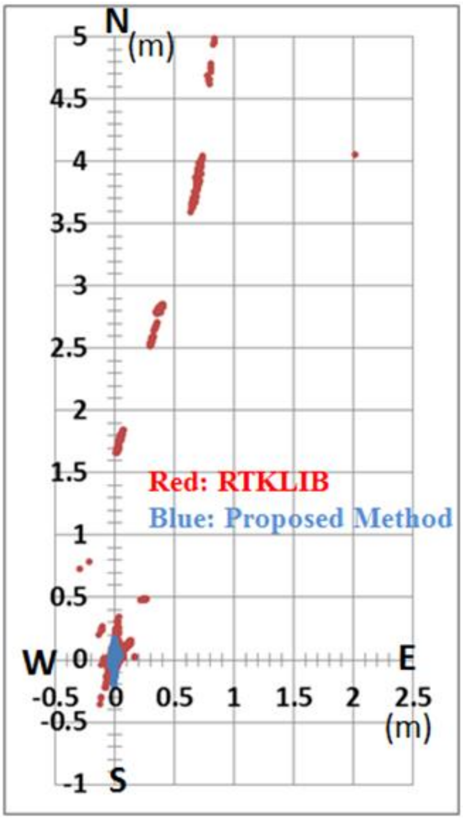

Fig. 10. Horizontal result (southwest)

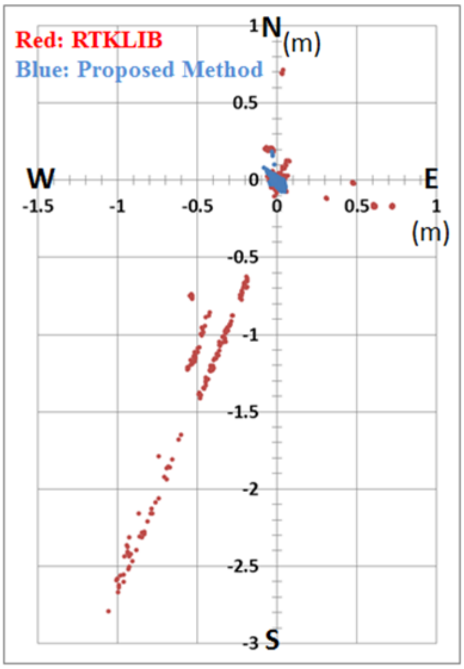

Fig. 11. Horizontal result (southeast)

In any direction of these tests, it can be seen that the proposed method was better than the results of RTKLIB. The standard deviation and the average were both better by more than one digit, and the number of epochs that have the RTK flag set also increased. As for the reliability of the southwest and southeast results with relatively good satellite constellation because of several BeiDou satellites, the horizontal results (within ±10 cm from the true value) and the height result (within ± 20 cm from the true value) can be obtained with a high reliability at a rate of more than 99%. As can be seen from the horizontal results, as the direction in which radio waves can be received and the satellite constellation were biased, the fixed solutions were elongated in the direction perpendicular to the surface of the wall compared to the horizontal direction. On the other hand, in the case of northwest, the fix rate was lower than the above two cases because of the shortage of the number of usable satellites simply. With more visible satellite in the near future like as QZSS and Galileo, the performance will be improved more.

Based on these test results, it will be possible to detect the vibration of the wall over at least 3-4 cm in the case of south direction. In a high-rise building, the walls vibrate even more, and when an earthquake occurs, large shakes can be detected, and it is possible to know the occurrence time, the amplitude of shaking precisely. These data are very important for the construction company.

To investigate the performance of the low-cost commercial receiver with RTK, we took one hour data of NEO-M8P with the newest firmware (u-blox) which is able to obtain the receiver's output (NMEA format) of low-cost RTK, and compared them with the corresponding data obtained with the proposed method. Horizontal results were shown below (Fig. 12.).

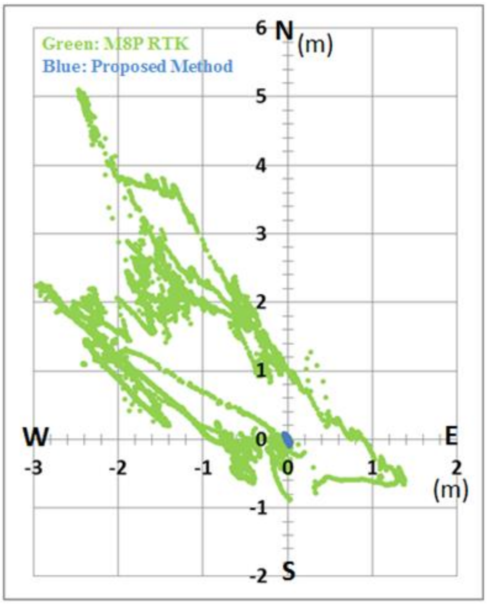

Fig. 12. Horizontal result (southeast)

From the results, it was found that M8P couldn't obtain a fixed solution in this environment. In addition, Fig. 13. below shows the quality flag in time series. It turned out that there were almost no fixed solutions and most of them were float solutions, and hence in this kind of severe environment, RTK positioning of M8P was not good. Therefore, the effect of the proposed method was also confirmed from this experiment.

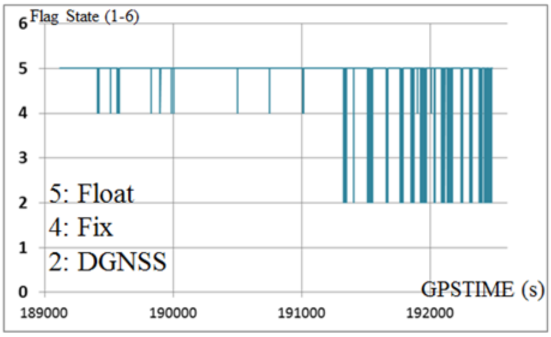

Fig. 13. Quality flag

Furthermore, the following horizontal results were those obtained when the antenna was manually moved on the southwest wall's surface to simulate a shaking. Since it is difficult to perform positioning experiments of big 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 up to down.

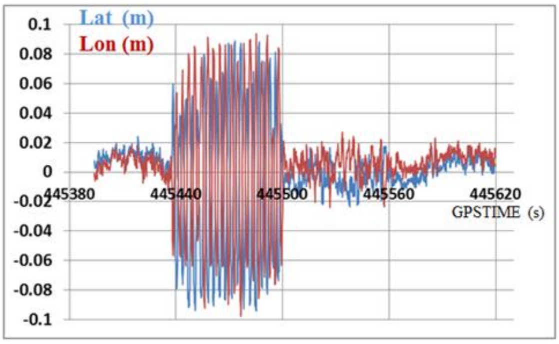

Fig. 14. Horizontal result (southwest)

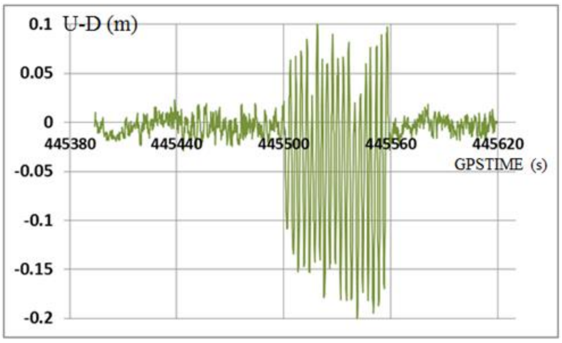

Fig. 15. Height result (southwest)

Above figures were the results of sampling at 5Hz and it is assumed that it shakes as it does when an earthquake occurs, in a short time and moving approximately 10 cm at a constant speed to the left and right. From the elongation of the solution, it can be seen that the fixed solutions can firmly follow the direction of the antenna. The fix rate was almost

100%. Even if an external dynamic force works under such circumstances, it can detect exactly several centimeters of motion, so it was found that it is a method that can be used for monitoring.

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 deformations and shakings of buildings at low cost by using the proposed method.

V. Summary and Future Subjects

In this paper, we proposed a method of structure deformations detection with the concept of low-cost handheld RTK under severe environments. Although only one building at Tokyo University of Marine Science and Technology was shown as 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 of improvement to obtain more accurate positions and applications to demonstrate its real world applications.

The fix rate was as high as 80% or more in the southwest and the southeast, and can be considered to be a practical level. Regarding the direction of northwest, if the antenna is surrounded by buildings, securing the sufficient number of satellites is difficult. However, as the availability increases due to the increase of the usable satellites in the near future, it is highly expected that the performance will be improved regardless of the direction.

Currently, as a post-processing step of RTK, “forward” which is processing only 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 such as that for several months to put into this system to practical use.

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