Study on modernizing the General Standard of Operation Specifications for Public Surveys (2)

Estimation of uncertainties regarding the proposed operation specification for control surveys

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Key words: Standards, modernization, total station, GNSS, CORS, public survey

SUMMARY

In our previous paper (Murakami, FIG WW 2023), we reported the overview of the study on the modernization of the General Standard of Operation Specifications for Public Surveys (GSOS). GSOS is provided by the Geospatial Information Authority of Japan (GSI), the national geospatial organization, served as a model for public organizations to conduct surveying and mapping and we, as a private sector, set up a study group and have been developing new specifications to modernize GSOS.

As the first step of progress, we proposed control surveys with a simpler structure of two tiers of control points instead of traditional four. The first-tier points are set up by using only GNSS and CORS, consisting of a regional network with the interval of about 200m-500m without referencing to any ground marker points. The second-tier points are set up by using total stations with reference to the first-tier points, consisting of narrow network with the interval of about 50m.

In this study, we examine the practical performances of total stations that are used most in public surveys and estimate uncertainties of angle and distance measurements in a short range of about 50m. We also examine the practical performances of double-frequency GNSS receivers and estimate uncertainties of baselines measurement for the variety of ranges from 200m to 18km. During this study, we find that the centering errors of a total station and mirrors, even if they are smaller than 1mm, affect much on the positional uncertainties in traverse surveys with short distances such as 50m. This can be applied to the measurements of local ties between space geodetic instruments/apparatus such as GNSS, SLR, and VLBI. Using estimated uncertainties of survey instruments, we can have the prospect that the positional uncertainties of the proposed control points be less than 20mm. It is equivalent to the positional uncertainties of 20mm of CORS at the reference epoch.

This leads to the prospect of conducting surveys with smaller uncertainties in a simplified manner compared to conventional control surveys.

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1. Introduction

In our previous paper (Murakami, FIG WW 2023), we reported the overview of the study on the modernization of the General Standard of Operation Specifications for Public Surveys (GSOS). GSOS is provided by the Geospatial Information Authority of Japan (GSI), the national geospatial organization, served as a model for public organizations to conduct surveying and mapping (GSI,2023), and we, as a private sector, set up a study group and have been developing new specifications to modernize GSOS.
As a first step, we proposed control surveys with a simple structure: a two-tier control point system, instead of the conventional four-tier one. The first tier consists of a regional network with approximately 200m to 500m intervals, using only GNSS with reference to GEONET, which is the nationwide CORS network in Japan consisting of more than 1,300 CORSs (Tsuji et al., 2017), and without reference to any ground markers. The second tier point will consist of a narrow network with intervals of about 50 m, based on the first-tier points, and will be established using only total stations (TS) (Figure 1).
In this study, the practical performance of TS and GNSS survey instruments is examined. And we estimate the uncertainty of the position of control points based on the examined performance of the instruments.

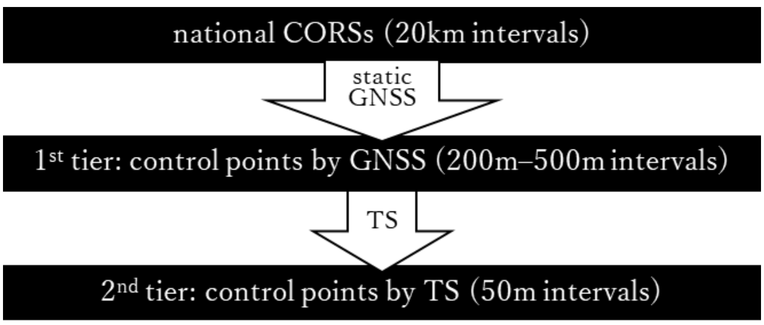

Figure 1. Proposed hierarchy structure of control points

2. Performance Classification of Surveying Instruments Defined by the GSI

GSI defines the criteria for performance classification of surveying instruments used for public surveys.

2.1 Performance Classification of Total Stations and its Criteria

In accordance with GSOS, TSs are classified into three classes. In this study, data derived from the class-2 TS (Table 1), which are employed the most in public surveys in Japan, were analyzed.

Table 1. Performance criteria of the class-2 total station

Performance of angle measuring section		Performance of distance measuring section	
Minimum reading of graduation		Nominal measurement accuracy	Minimum reading
Horizontal (arcsec)	Vertical (arcsec)		
10 or less	10 or less	$\pm(5\text{mm} + 5\times10^{-6}\cdot D)$ or less	1 mm

where D is the measurement distance

2.2 Performance Classification of GNSS and its Criteria

GNSS surveying instruments consist of a GNSS receiver and a GNSS antenna and are classified into two classes. In this study, data from the class-1 GNSSs (Table 2), which are employed the most in public surveys, were analyzed.

Table 2. Performance classification of the class-1 GNSS

Number of receiving bandwidths	Observation method	Nominal measurement accuracy	Nominal measurable distance	Minimum analysis value
2 bandwidths (L1, L2)	Double frequency static	$\pm(5\text{ mm} + 1\times10^{-6}\cdot D)$ or less	10 km or more	1 mm
	Single frequency static	$\pm(10\text{ mm} + 2\times10^{-6}\cdot D)$ or less	10 km or less	
	Double frequency rapid static	$\pm(10\text{ mm} + 2\times10^{-6}\cdot D)$ or less	5 km or more	
	Single frequency rapid static	$\pm(10\text{ mm} + 2\times10^{-6}\cdot D)$ or less	5 km or less	
	Kinematic	$\pm(20\text{ mm} + 2\times10^{-6}\cdot D)$ or less	---	
	RTK	$\pm(20\text{ mm} + 2\times10^{-6}\cdot D)$ or less	---	
	Network RTK	$\pm(20\text{ mm} + 2\times10^{-6}\cdot D)$ or less	---	

where D is the measurement distance

3. Validation of surveying instruments by the Japan Association of Surveyors

GSI and most public agencies require that surveying instruments that are employed in public surveys and categorized as performance classification shall be validated once a year by a third party in principle. The Japan Association of Surveyors (JAS) is one of the organizations competent to conduct this validation, and is commissioned by various surveying firms to conduct the validation of their surveying instruments.

3.1 Total Stations

We used the validation data from 1052 TSs that were validated by JAS in fiscal year 2019. Of these, the total number of 956 Class-2 TSs were tested for angle measurements, and among these, 585 had the minimum reading unit set at 5 arcseconds. As for the distance measurement test, there are 957 Class-2 TSs.
The following items are tested for the validation of surveying instruments.

- Horizontal angle measurements (Figure 2)
  The measurements consist of two sets of three paired observations in three directions (0°, 90°, 180°) each. The validation includes the test of set-to-set difference. Other tested items are the following quantities: the double angle difference; the observation difference; the deflection of the line of sight with focusing; and the vertical angle constant.

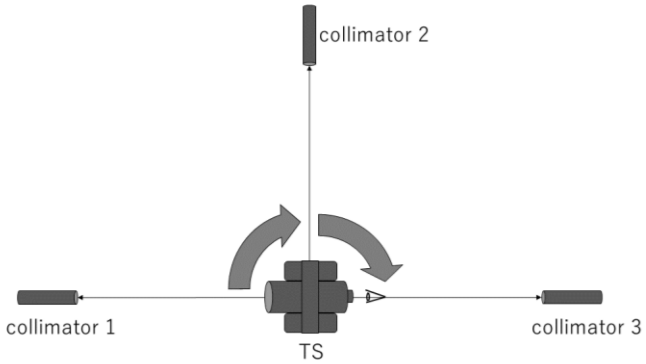

Figure 2. Schematic diagram of the test of horizontal angle measurements

- Distance measurements (Figure 3)
  A total of ten measurements are taken for the 400 m baseline and five measurements for the 2 m baseline, and the average of all measurements is compared to the reference value, which is determined by the reference instrument.

The items and methods of these tests are different from those described in ISO 17123-5 (2012) which requires the test of coordinates repeatability. Instead, in our validation the repeatability of the angle and the distance measurements are taken. Therefore, we can estimate the uncertainty of angle and distance measurements separately.

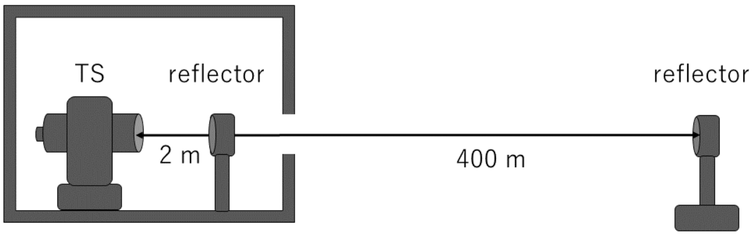

Figure 3. Schematic diagram of the test of distance measurements

3.2 GNSS Surveying Instruments

We used validation data from about 3,000 Class-1 GNSS surveying instruments in validations conducted by JAS from 2018 to 2022. Some of the data are missing records of observation date and site, so they are treated as preliminary data at the time of writing the paper, and will be subject to further examination. The baseline length ranges from about 200m to 18km.

4. Performance of Total Stations

The practical performance of total stations is investigated. To estimate the uncertainty of angle and distance measurements at short distances of about 50 m, we evaluated the performance of angle and distance measurements using the aforementioned validation data. On the other hand, since the performance evaluated from the validation data is not necessarily demonstrated in actual field measurements, experimental observations of angle and distance were conducted in the field and the performance was evaluated.

4.1 Performance of Angle Measurements

4.1.1 Results from the Validation Data

The total amount of 1170 samples (i.e., two included angles each for 585 instruments) of set-to-set differences were extracted from the validation data and analyzed. Assuming that the set-to-set differences are normally distributed with mean zero and standard deviation σ_d, the extracted samples show $\sigma_d = 1.4$ arcseconds.
Recalling that a set-to-set difference is the difference between the averages of two sets of the three paired observations, the standard deviation per sighting, σ_s , is derived from $\sigma_s = \sqrt{3/2}\,\sigma_d$. Thus, we estimated the uncertainty of the angular measurement per sighting as 1.7 arcseconds.

4.1.2 Results from the Field Experiment

Experimental observations were conducted by two observers using three different TS models in order to see the effects of instrumental and individual differences. The reflectors were set up in three directions (0°, 90°, 180°) (Figure 4) at the calibration site of baselines at GSI's premises, and 10 observations were made for each of the three TS models. 120 samples were obtained for each of the two included angles (90° and 180°). The average of each included angle was calculated for each TS, and the standard deviation from the average was determined. The standard deviation per included angle is estimated to be 3.5 arcseconds. Thus, the uncertainty of the angle measurement per sighting is 2.5 arcseconds, which is larger than the uncertainty obtained from the validation data.

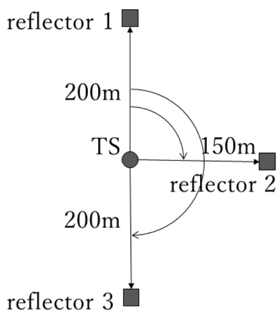

Figure 4. Schematic diagram of the field experimet for angle and distance measurements

In this observation, the instrument was set up on a concrete pillar without using a tripod. Therefore, the observation results are not affected by the centering error. In addition, the observation distances are 150 m and 200 m, implying that the influence of temperature and pressure as well as atmospheric disturbances are small. We speculate that the large difference of the angle measurement uncertainties between the validation and the field experiment comes from the fact that in the validation, the target was a thin scale line of the collimator and was carefully sighted, whereas in the field experiment, the target was a reflector of finite size and was sighted in a usual way of surveying, i.e., “quickly”.
Therefore, we decided to use the uncertainty obtained from the field experiment.

4.2 Performance of Distance Measurements

4.2.1 Results from the Validation Data

The test of distance measurement is performed independently from that of angle measurement. The average of ten measurements is adopted for the 400 m baseline, although most of ten measurements differ slightly by 1 mm, so there is little meaning in determining the standard deviation for each individual model. Analyzing the deviation of the average of each 957 TSs from the reference value, we obtained the mean value as -0.2 mm and the standard deviation as 1.3 mm, therefore the uncertainty of the distance measurement of the TSs was determined to be 1.3 mm in RMSE. In case of the 2-m baseline, the mean value was -0.2 mm and the standard deviation was 1.1 mm, therefore the uncertainty was determined to be 1.1 mm in RMSE. The term proportional to the distance in the uncertainty could not be obtained in this study due to the lack of data over wide range of distances, so we take the manufacturers' nominal value of 2ppm.

4.2.2 Results from the Field Experiment

Distance measurements were made simultaneously with the angular measurements described in section 4.1.2, using three models of TSs, with one set of three paired observations in three directions, and two sets of observations repeated 10 times. Thus, 120 distance measurements were made per model per direction. The distance between the TS and the reflector was 200 m

for the reference direction (0°) and the 180° direction, and 150 m for the 90° direction. Since the reference values of the distances had not been updated, the average of all models' distance measurements in each direction was substituted for the reference in the analysis. As a result, the standard deviation of 0.8 mm from the mean value was obtained.
The standard deviation of distance measurement of each TS is about 0.5 mm. On the other hand, the validation data shows the deviations from the reference with a range of 0mm-5mm, suggesting that large instrumental errors exist. The small uncertainty in the field experiment may come from the fact that the total number of three TSs are not enough to reveal the influence of instrumental errors. Therefore, we decided to use the distance uncertainty obtained from the validation data.

4.3 Centering Errors Derived from the Field Experiment

When aiming for the uncertainty of about 10 mm in a traverse survey with a side length of 50m each, the centering errors of TS and reflectors significantly affect the uncertainty of angle and distance measurements, so we estimated their magnitude based on the field experiment. In the observation of the centering error of TS, a single observer repeated the alignment of TS and the observation of the fixed reflectors. In the observation of the centering error of a reflector, one rod person repeated the alignment of a reflector and one observer made the observation of a reflector and then repeated the same process after switching the rod person and the observer to see the effect of individual differences. Since each instrument was mounted on a tripod during the experiment, the results may include uncertainty due to tripod distortion, which was not estimated in this study.

4.3.1 Centering of TS

In this experiment, TS was placed in the center and reflectors were placed at the distance of 11 m in four directions at 90° intervals (Figure 5). The process was repeated 30 times, with each set consisting of 3 paired angle and distance measurements, and the TS was re-aligned for each set. The observer was instructed not to pay any more attention than usual to the centering operation in order to reproduce realistic surveying operations. The results of the analysis show that the deviation of the instrument center from the reference point center is distributed as shown in Figure 6. One point has a deviation of more than 1 mm, while the other 29 points have the standard deviation of 0.24 mm. From this result, the uncertainty was evaluated to be 0.3 mm.

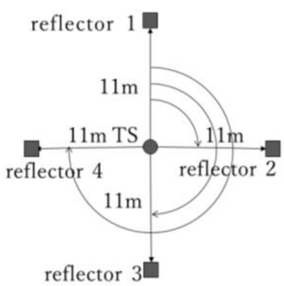

Figure 5. Schematic diagram of measurements of centering errors of TS

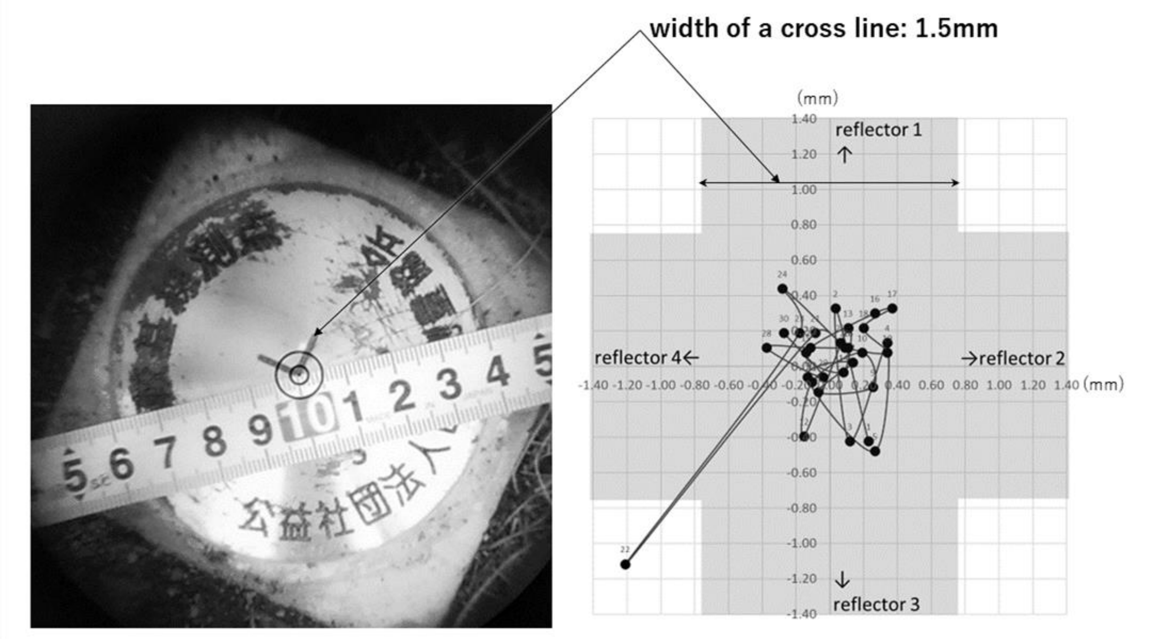

Figure 6. Centering errors of TS

4.3.2 <u>Centering of a Reflector</u>

In this experiment, two reflectors were placed in two directions at 90° intervals at 11 m from the TS (Figure 7), and three paired angle and distance measurements in two directions were made as one set of measurements. The process was repeated 30 times, with repositioning only the reflector in the 90° direction each time. This process was repeated after switching the observer and the rod person. As a result, the centering errors of the reflector was distributed as shown in Figure 8 (the observer and the rod person were switched in Case 1 and Case 2). In Case 1, the centering errors increased in the latter half of the process, and we speculate that part of this is due to the tripod distortion caused by sunlight and part of it due to individual human error. The uncertainty was evaluated to be 0.6 mm based on the combined results of the two cases.

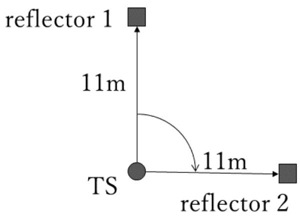

Figure 7. Schematic diagram of measurements of centering errors of a reflector

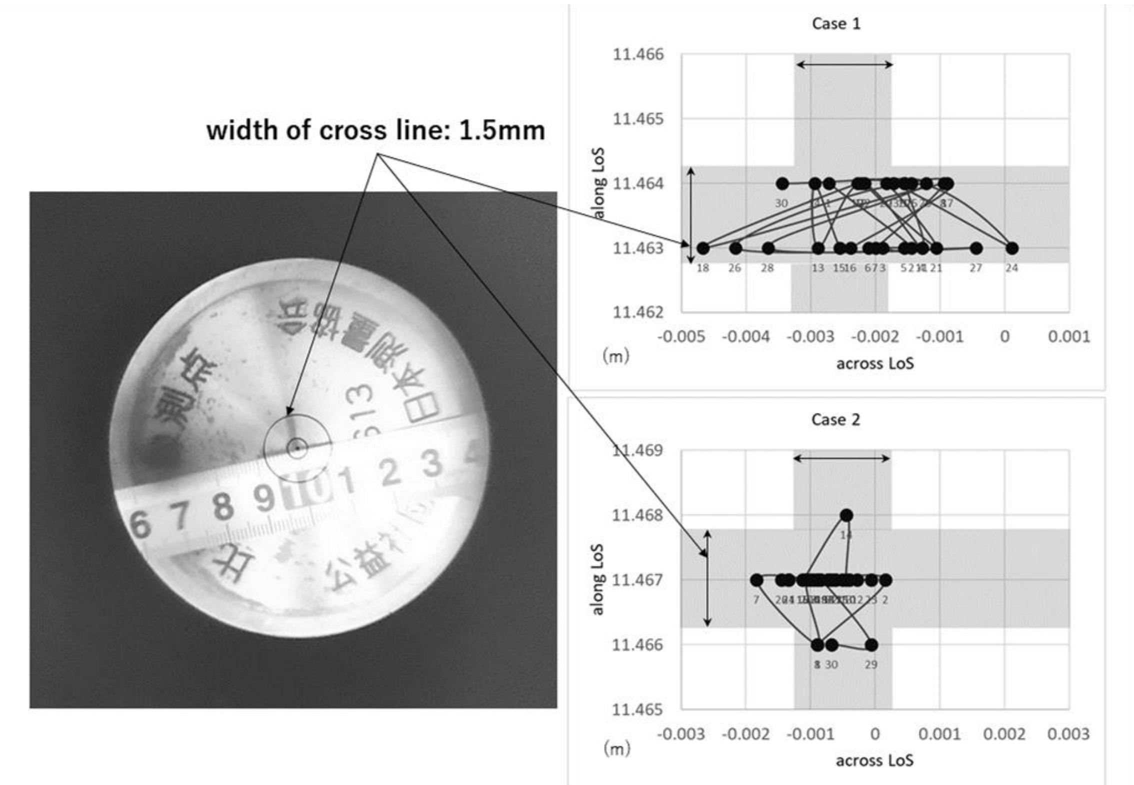

Figure 8. Centering errors of a reflector

4.4 Atmospheric Effects

As adopting the meteorological correction formula:

$$\frac{dD}{D} = (dt - 03.dp + 0.04de)\ ppm$$

where D: distance, t: temperature (°C), p: air pressure (hPa), e: water vapor pressure (hPa), then the uncertainty of distance measurement due to the uncertainty of air temperature, air pressure, and water vapor pressure are as follows:

dD/D < 1.2 ppm if *dt* < 1.2 °C (standard deviation of a rectangular distribution of ±2 °C),
dD/D < 1.2 ppm if *dp* < 4.0 hPa (standard deviation of a rectangular distribution of ±7 hPa),
dD/D < 1.2 ppm if *de* < 30hPa.

The combined uncertainty is 2 ppm, and with careful meteorological measurements, the uncertainty can be reduced to less than 1 ppm. We consider single route traverse surveys consisting of 10 sides with the length of 50 m and a total route length of 500 m. If the distance uncertainty caused by atmosphere is 1 ppm, it accounts for 0.05 mm for 50 m and 0.5 mm for 500 m.

4.5 Uncertainty of Position Obtained by Traverse Survey by TS

For the angle measurement uncertainty of TS, the result according to section 4.1.2 is adopted. For the distance measurement uncertainty, the result according to section 4.2.1 is adopted. The uncertainty due to the reflector constant (in unit of 1 mm) is $1/\sqrt{12}$ mm, which affects the distance uncertainty. The atmospheric influence is negligible in short distances. The centering errors shown in section 4.3 are added to the angle and distance measurement uncertainties assuming a side length of 50 m. The combined uncertainties of the angle and distance measurements are estimated as follows.
Distance uncertainty: 1.5 mm (combined uncertainty of distance measurement error, centering error, and reflector constant) + 2 ppm (manufacturers' nominal value).
Angular uncertainty per sighting: 3.5 arcseconds (combined uncertainty of angle measurement error and centering errors of TS and a reflector). Therefore, the uncertainty of the measurement of one included angle is 4.9 sec.
These values are applied to the following equation presented by Murakami (2023):

$$M_n{}^2 = n \cdot dS^2 + \sum_{k=1}^{n} k^2\, S^2 d\beta^2$$

Equation 1

where

M_n: horizontal root mean square error at point n,
n: number of unknown points (or number of sides),
S: distance between neighboring points,
dS: uncertainty in a distance measurement, and
$d\beta$: uncertainty in an angle measurement.

By substituting 4.9 arcsec for $d\beta$ and 1.5 mm for dS with S=50 m and n=10, the positional uncertainty at each measured control point along an open single-route traverse is obtained (Figure 9).

Assuming a connected single route traverse with given coordinates and no directional angle observation at both end points, the net adjustment using the weights derived from the above angular and distance uncertainties results in the improvement of the positional uncertainties at each measured point (Figure 10), which makes us to prospect that the positional uncertainty smaller than 10 mm can be obtained in a connected single-route traverse survey with a total length of about 500 m.

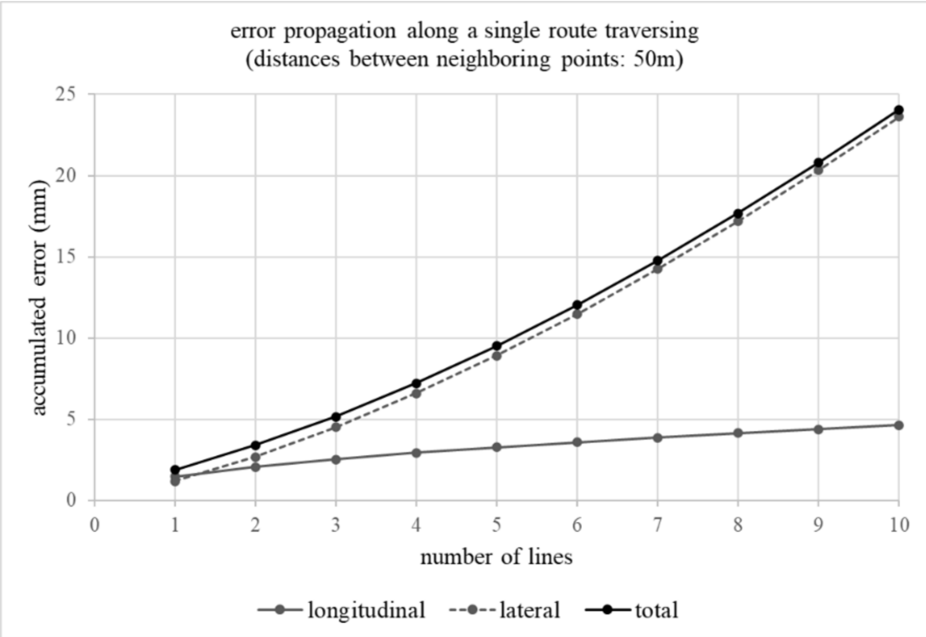

Figure 9. Uncertainty at each measured point along an open single-route traverse

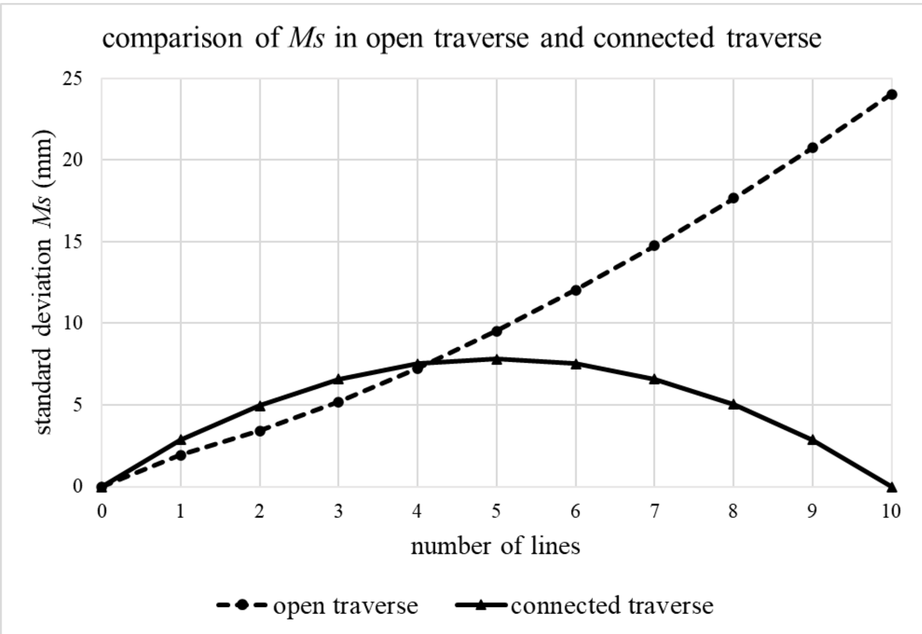

Figure 10. Improvement of positional uncertainties after net adjustment

4.6 Application of Uncertainty of Traverse Survey by TS to Colocation

The positional uncertainty of traverse surveys derived above is also applicable to the measurement of local ties between space geodetic equipment/instruments such as GNSS, SLR, VLBI, etc. For short traverse surveys of 50 m or so, centering errors of TS and reflectors, even if they are less than 1 mm, have a significant effect on the uncertainty of the

position. The following is an example of the application of this method to local tie measurements.
Assume that a 5-sided open traverse route with a side length of 10 m constitutes a local tie, and that TS with smaller uncertainties of angle and distance is employed, *i.e.*, TS with 1.0 arcsec and 0.4 mm uncertainties and calibrated more precisely than the one employed in usual public surveys.
Calculations with different magnitudes of the centering error using Equation 1 in section 4.5 yield the results in Table 3. As can be seen, when the centering error is set to zero (Case 1), that means, TS and reflectors are mounted on pillars fixed to the ground, the uncertainty of the local tie is 1 mm, but a small amount of centering error will cause the uncertainty of the local tie to exceed much more than 1 mm (Case 2, Case3).

Table 3. Effect of centering errors of instruments on positional uncertainty, assuming uncertainty of angle measurements as 1.0 arcsec and distance measurements as 0.4mm

	Case 1	Case 2	Case 3
Centering error of TS	0.0	0.3	1.0
Centering error of reflector	0.0	0.6	1.0
Standard deviation of position *Ms*	1.0	7.9	18.5

Unit: mm

5. Performance of GNSS Static Mode Observation

Although we reported in our previous paper (Murakami, 2023) that "the measurement uncertainties of static-mode GNSS for 10km baseline are 6mm for NS and EW components and 26mm for vertical component," it is also important to clarify the dependence of the uncertainty on distance, since the spacing of GNSS stations may range from 200m to 20km. In this study we estimate the uncertainties of baseline measurements for various ranges from 126 m to 17.8 km. As mentioned above, this is a preliminary assessment, as some of the data are missing observation date and site and require further scrutiny.
The results currently available are:

$$\Delta E, \Delta N \sim 2\ (mm) + 0.3ppm \times D, \Delta U \sim 5\ (mm) + 1ppm \times D$$

which are smaller than those reported previously for D=10 km, and we can prospect to obtain an uncertainty of about 10 mm in horizontal position of the proposed regional reference point. This is the same order of magnitude as the CORS position uncertainty of 20 mm at the reference epoch (Tsuji and Matsuzaka, 2004).
In contrast, the manufacturers’ nominal accuracy, though it varies from model to model, is described in general as follows:

$$\Delta E, \Delta N \sim 3(mm) + 0.5ppm \times D, \Delta U \sim 5\ (mm) + 0.5ppm \times D$$

The tentative results obtained are smaller than the manufacturers' nominal accuracy for the horizontal component, while the term proportional to distance D is larger than the manufacturer's nominal value for the vertical component. The results may change with further scrutiny.

6. Conclusion

In the proposed two-tier system of control surveys, the first tier consists of a regional network of approximately 200m to 500m spacing, using only GNSS instrument with reference to CORS and without reference to any ground markers. The second tier points consist of a narrow network with intervals of about 50 m, connected to the first tier points, and will be measured using only total stations. The position of the regional reference points of the first tier are expected to have the uncertainty of 10 mm with respect to the national CORS. Also, the narrow traverse surveys by TS are expected to have the uncertainty of 10 mm with respect to the first tier points. This leads us to the idea to conduct control surveys with the uncertainty of less than 20 mm by simpler surveying operations compared to conventional surveys.

Acknowledgement

The chairman and members of the study group for modernization of public surveys provided useful advices in this study. The author would like to express his gratitude to them. He also thanks the people involved in the instrument validation by the Japan Surveyors Association for their assistance in extracting validation data and for conducting the field experiments.

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BIOGRAPHICAL NOTES

Mr. MURAKAMI Masaki has been Vice President of the Japan Association of Surveyors since 2019. He worked for the Geospatial Information Authority of Japan and retired in 2015 as Deputy Director General. He works for Pasco corporation after the retirement.

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