An Intrinsic Characteristic in the Multiple Use of Mobile Phone Terminals with GPS and its Application to the Positioning Error Reduction

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***Abstract*—**In recent years, studies of location identification by mobile phone have been attracting a lot of attention. Especially, GPS contents of mobile phones are increasing for the purpose of various kinds of applications, such as games, navigations and so on. So far, many investigations have been carried out for the performance of conventional GPS devices, but few people study mobile phone GPS performance. In this paper, we measure and examine the performance of mobile phone GPS using various types of terminals of different venders under some environments. As for the performance improvement, we propose efficient methods and evaluate them for the methods including distance errors and direction errors of GPS. The reduction methods for such errors applying the group characteristics of mobile phones are also described.

***Keywords*—**Mobile phone GPS, distance errors, direction errors, noise reduction, impulse noise

I. Introduction

CURRENTLY, mobile contents using GPS have been rapidly increasing, and the mobile phone GPS has become a indispensable function for navigation, providing location information in the case of emergency, disaster, etc. In this regard, we measured and accumulated quantitative data of mobile phone GPS error characteristics under various conditions. For example, (1) the error characteristics under clear sky conditions, in buildings, etc., (2) the estimation of bias in the errors, (3) the reproducibility of the errors in time, have been investigated [1] - [3]. Compared to the previous research results on mobile phone GPS, it is revealed that significant errors can result under certain conditions. Additionally, we examine the mobile phone GPS error characteristics under a variety of conditions.

In particular, the characteristic among multiple terminals (hereinafter referred to as the group characteristics) are explored and methods of error reduction are examined based on the results.

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II. Overview of Experiments

In this study, by using eight mobile phones of five different types from four venders, GPS measurements were taken every minute. Three experiments described below were carried out. TABLE I and Fig. 1 show the number and the configuration of mobile phone models used in the experiments and outside view, respectively.

Experiment 1: The measurement of error characteristics with respect to directions of mobile phone's antenna.

Experiment 2: Out-of-sync error (impulse noise) analysis.

Experiment 3: The measurement of group characteristics of mobile phone GPS errors.

TABLE I. The composition of 8 mobile phone terminals of 5 different types used in experiments

Mobile Phone Type	①	②	③	④	⑤
Vender	A	B	C	C	D
Units	1	1	1	3	2

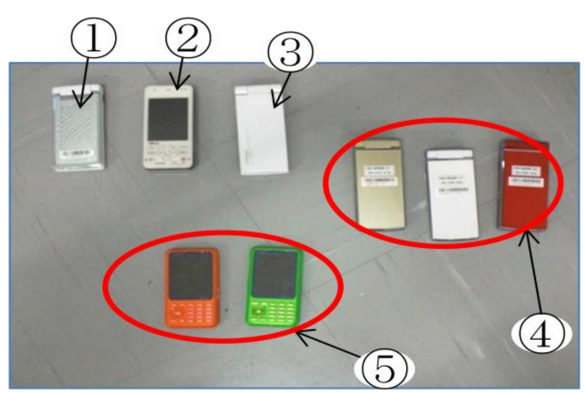

Fig. 1 8 mobile phone terminals used in experiments

As a method of calculating the errors, the difference between the measured value and the true value of measurement location was calculated by employing the Hubeny formula in Fig. 2 [4]. The detailed process is shown in Fig. 3. GPS error has two parameters (distance error and direction error [5]). X and Y of Fig. 3 mean the longitude error and latitude error. For the determination of the true value, the value from Google map service was used as the reference.

Hubeny's Formula for Distance Calculation

$$D = \sqrt{(M * \Delta P)^2 + (N * \cos(P) * \Delta R)^2}$$

$$M = a * (1 - e^2) / \sqrt{(1 - e^2 \sin^2(P))^3}$$

$$N = a / \sqrt{1 - e^2 \sin^2(P)}$$

$f = 1/299.152813$

$F = 1/f$

$e = \sqrt{2F - 1}/F$

$a = 6377397.155(m)$

D: Distance between 2 points (m)
P: Average latitude between 2 points
ΔP: Latitude difference between 2 points
ΔR: Longitude difference between 2 points
M: Meridian radius of curvature
N: Prime vertical radius of curvature

f: Ellipticity
F: Inverse ellipticity
e: Major eccentricity
a: semimajor axis

NB: The values of a and f are specified by reference to the ellipsoid value in Survey Law Section 2, Article 2.

Fig. 2 Hubeny's formula for distance calculation

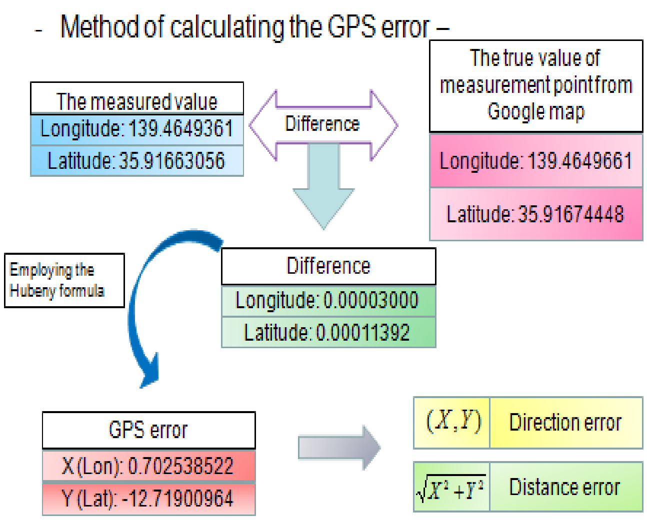

Fig. 3 Process of calculating the GPS error

As will be discussed shortly, Experiment 1 uses terminal 1-A (mobile phone type 1 by vender A), while Experiments 2 and 3 use all the 8 terminals of 5 different types.

III. Experiment 1

By considering the user convenience, the GPS antenna is generally placed around the top end of the display. Thus, when GPS measurements are taken by mobile phones, in order to determine whether the measurement directions has any effect. The direction of GPS antenna is changed from North, South, East and West. These measurements were performed under clear sky conditions. Next, we carried out the verification and the evaluation of the results of the experiment using the average and the variance of GPS errors. The results of the experiment are shown in TABLE II and Figs. 4-7.

TABLE II. GPS errors for the 4 directions

Direction	East	West	South	North
Average Error (m)	13	14	14	12
Maximum Error(m)	62	56	49	122
Minimum Error (m)	0	0	1	0
Variance (m^2)	94	109	99	97

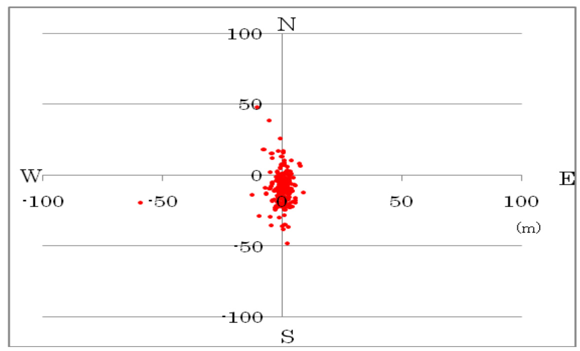

Fig. 4 Error variance diagram for the Eastern direction

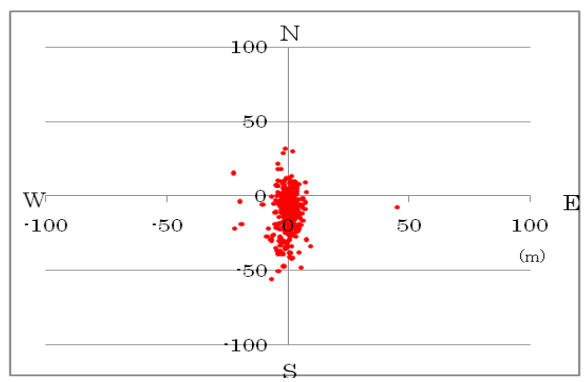

Fig. 5 Error variance diagram for the Western direction

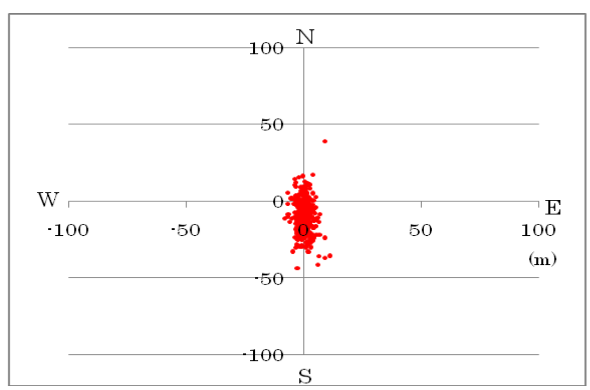

Fig. 6 Error variance diagram for the Southern direction

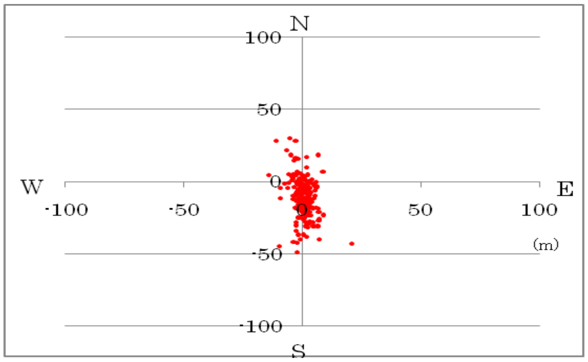

Fig. 7 Error variance diagram for the Northern direction

From the above results, it can be seen that there is a noticeable difference in the term of maximum error, but the average and the variance of errors are not so different and are actually very close. It is apparent that the direction characteristics do not exist and it can therefore be confirmed that the results of GPS measurements does not depend on the orientation of GPS antenna.

IV. Experiment 2

A. *Impulse Noise Characteristics*

In most of the results of mobile phone GPS measurements we have carried out in [1]-[3], large errors from the hundred to the thousand meter level rarely appears. Such a large error significantly decreases the utility of the GPS. We named such an error 'out-of-sync error' or 'impulse noise.' In this experiment, we investigate the indoor and outdoor impulse noise characteristics of the different mobile phone types using 8 terminals under the same environmental conditions for the same length of time. The measurements for each maker's mobile phone are recorded. Furthermore, we also consider a method of impulse noise reduction.

In order to find the cumulative probability distribution, measurements taken over a period of 24 hours were integrated and from these measurements the occurrence rate of impulse noises was determined. From these observations, an error greater than or equal to 100 meters was defined as impulse noise. A representative part of the results for impulse noise characteristics are shown in Figs. 8-11.

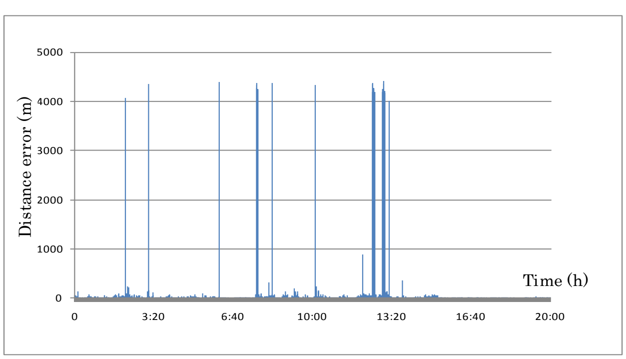

Fig. 8 Indoor impulse noise measurement results with terminal 4-C-1 (same terminal type as 4-C-2)

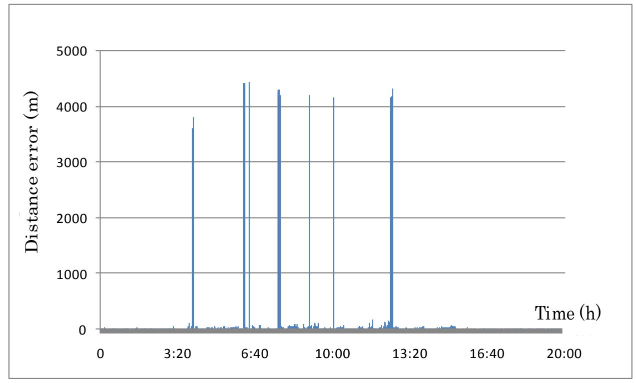

Fig. 9 Indoor impulse noise measurement results with terminal 4-C-2 (same terminal type as 4-C-1)

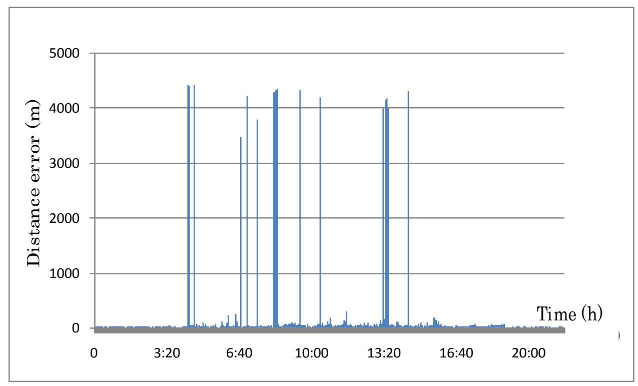

Fig. 10 Indoor impulse noise measurement results with terminal 4-C-3

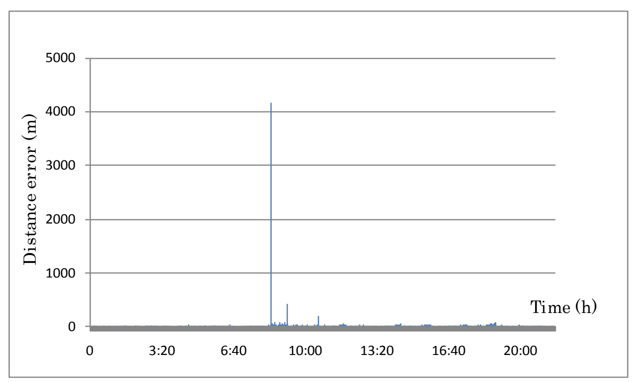

Fig. 11 Indoor impulse noise measurement results with terminal 3-C

The notation, X-Y-Z in Figs. 9-11 denote a mobile phone type X, by vender Y and Z is the unit number. We can also recognize that once impulse noise occurs, it occurs with high-rate.

As shown in Figs. 8-10, for mobile phones from the same maker, the impulse noise characteristics are almost the same. It can be confirmed from Fig. 11 that even if the same maker, different mobile phone types have different impulse noise characteristics.

B. A Method for Impulse Noise Reduction

We consider a N-point moving average method for impulse noise reduction. The noise reduction effectiveness for N=3 and N=5 are shown in Figs. 12-14. Fig. 12 is the basic measurement error result, while Figs. 13 and 14 are the results obtained from the result in Fig. 12 when N is set to 3 and 5, respectively.

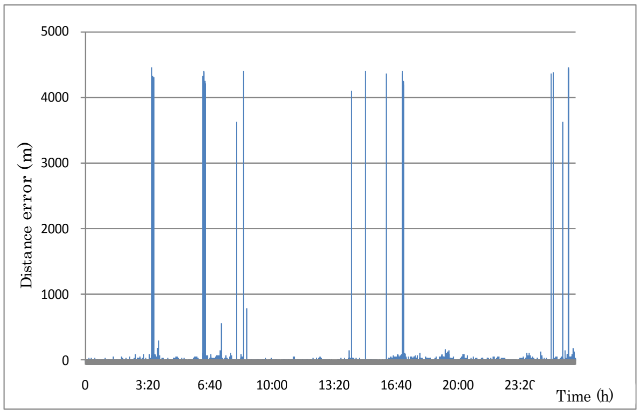

Fig. 12 Indoor impulse noise measurement results with terminal 4-C-3

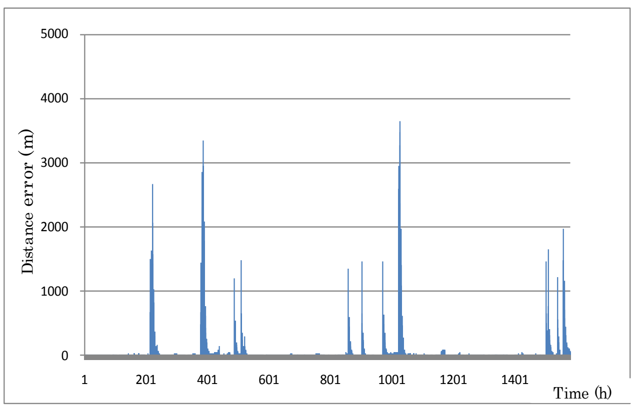

Fig. 13 The result when the 3-point average method is applied to the result in Fig. 11

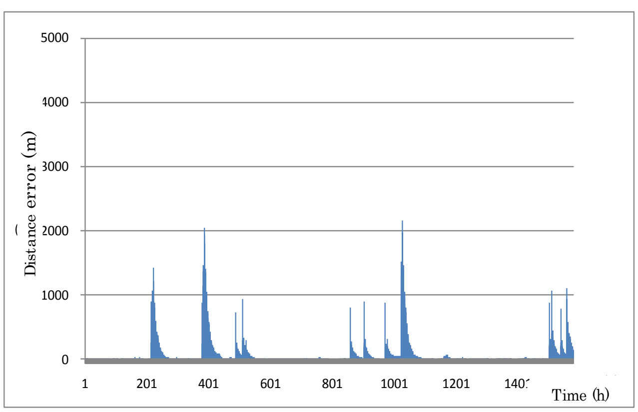

Fig. 14 The result when the 5-point average method is applied to the result in Fig. 11

By applying the N-point moving average method, the maximum value of the impulse noises can be reduced significantly as shown in Figs. 12-14. By increasing the value of N, it is possible to further reduce the impulse noise values but the errors spread in time. For this reason, if impulse noises occur continuously, the effectiveness of the moving average method is small.

C. Impulse Noise Occurrence Rate

Next, for the indoor and outdoor impulse noise occurrence rates, the measurement results for the cumulative probability distribution and the probability density are shown in Figs. 15 and 16, respectively.
The cumulative probability distribution results suggest that the percentages of impulse noise for outdoors and indoors in terms of the time rate are 0.2% and 3.5%, respectively. For outdoors, the occurrence frequency was as low as 0.2%, but for indoors, due to multipath and other error factors, the occurrence frequency was comparably higher than 10 times.

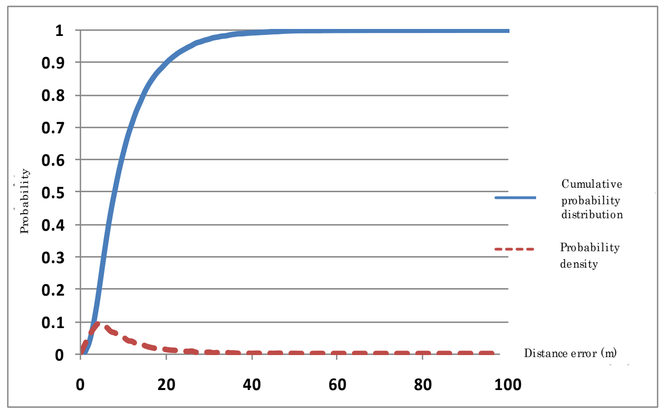

Fig. 15 Cumulative probability distribution of GPS errors (Outdoor)

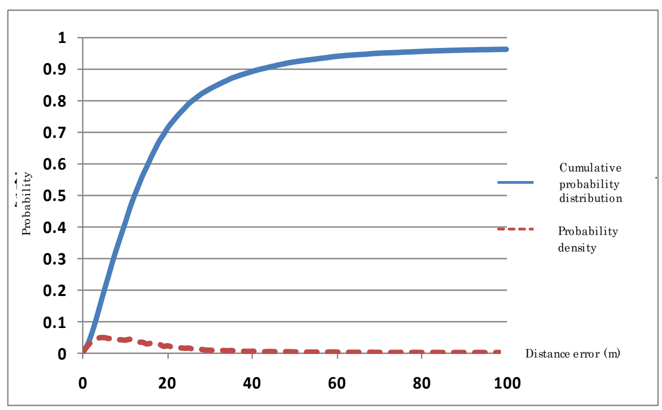

Fig. 16 Cumulative probability distribution of GPS errors (Indoor)

D. Formulation of the GPS Error Characteristics

Based on the outdoor measurements data obtained by using 8 mobile phones, the GPS error distribution is formulated. The following method is employed. First, the probability of GPS error frequency and distance error are found separately and then a graphical representation of their relationship is obtained. Next, the approximate curve is assumed to fit the gamma probability distribution function shown in Equation (1) and then the parameters α and β of the gamma distribution function are determined by the least squares method.

$$f(x,\alpha,\beta) = x^{\alpha-1}e^{-x/\beta}(1/\beta^{\alpha}\Gamma(\alpha)) \qquad (1)$$

The process of the calculation by the least squares method is as follows. Let x_k [m] be a the GPS error and y_k be the occurrence probability of it, then the difference between y_k and $f(x_k,\alpha,\beta)$, denoted by $d_k = (y_k - f(x_k,\alpha,\beta))^2$, is calculated for k=1, 2, 3, …, 100. The values of α and β that minimize S, defined below, are obtained.

$$S = \sum_{k=1}^{100} d_k = \sum_{k=1}^{100} (y_k - f(x_k,\alpha,\beta))^2$$

The partial derivatives of S with respect to α and β are calculated, and then the simultaneous equations $\partial S/\partial\alpha = 0$, $\partial S/\partial\beta = 0$ are solved to get values of α and β. The result is shown in Fig. 16

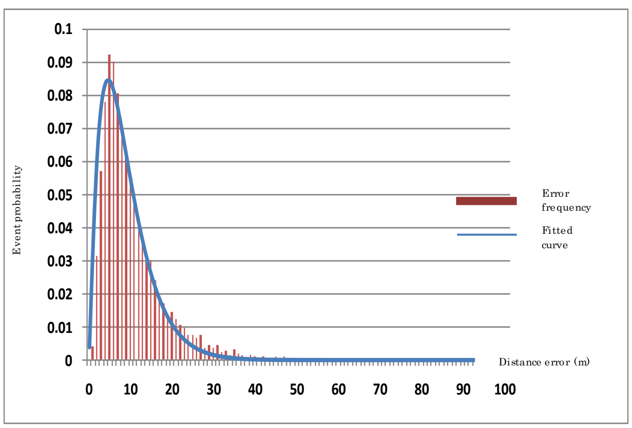

Fig. 16 The frequency of errors and the approximate Gamma curve (Outdoor example)

By using this least squares method, the outdoor GPS error characteristic parameters α and β in Equation (1) were 2.1 and 4.3, respectively. On the other hand, the indoor parameters α and β were 1.6 and 9.1 respectively.

V. Experiment 3

A. Verification and Evaluation of Group Characteristics

As a way of using GPS in the future, the following two scenarios can be envisaged. First, many mobile phone owners can use their mobile phones at the same time, in the same place. Second, a large number of GPS-equipped sensors can be densely placed in close vicinity. Based on these situations, the correlations between multiple GPS measurements can be calculated. We investigate characteristics between mobile phone types for a single maker. Also the characteristics from different mobile phone makers are investigated. As in the previous two experiments, 8 terminals are used but the measurement time is extended. All the terminals are placed with a circle of 1m radius.

The error data for the 8 terminals is shown in TABLES III and IV for outdoor conditions and in TABLES V and VI for indoor conditions. The reason why the measured data points differ is because of the difference in communication conditions during measurement and also due to the condition of the server. The measurement data is transmitted to the server automatically and hence the chances of unsuccessful transmissions exist. Terminal 2-B, which is stabilized in both the outdoor and indoor environments with little error, shows the best characteristics.

TABLE III. Outdoor experiment results (distance error)

Type Name	1-A	2-B	3-C	4-C-1
Average Error (m)	10	12	11	9
Maximum Error(m)	58	117	296	191
Minimum Error (m)	0	0	0	0
Variance (m^2)	59	83	646	72
Out of Syn Error (>100m)	0	1	13	1
Data points	1608	1348	1475	1590

TABLE IV. Outdoor experiment results (distance error)

Type Name	4-C-2	4-C-3	5-D-1	5-D-2
Average Error (m)	9	8	11	11
Maximum Error(m)	58	56	238	231
Minimum Error (m)	0	0	0	0
Variance (m^2)	50	46	180	253
Out of Syn Error (>100m)	0	0	2	8
Data points	1448	1367	904	1063

TABLE V. Indoor experiment results (distance error)

Type Name	1-A	2-B	3-C	4-C-1
Average Error (m)	283	13	19	140
Maximum Error(m)	4678	4169	4169	4414
Minimum Error (m)	0	0	0	0
Variance (m^2)	975352	118	19120	466226
Out of Sync Error (>100m)	317	0	5	82
Data points	2707	2617	1810	1594

TABLE VI. Indoor experiment results (distance error)

Type Name	4-C-2	4-C-3	5-D-1	5-D-2
Average Error (m)	85	86	50	22
Maximum Error(m)	23192	4458	4396	4134
Minimum Error (m)	0	0	0	0
Variance (m^2)	420428	266686	125164	19840
Out of Syn Error (>100m)	74	70	59	24
Data points	2637	2077	1716	2144

From these tables, it can be deduced that the error relationship among terminals of the same type with respect to the maximum error is a bit different from that of the previous results, including the impulse noise characteristics. Next, in order to investigate the correlations among errors of terminals, the cross-correlation coefficient over the same period for each error in the preceding experimental results was examined. TABLE VII shows the results.

TABLE VII. The correlation coefficients of distance error and direction error between mobile phones

		Indoors		Outdoors	
	Combination	DSEC	DREC	DSEC	DREC
[1]	1-A & 2-B	0.15	0.21	0.16	0.2
[2]	1-A & 3-C	0.16	0.22	0.06	0.13
[3]	1-A & 4-C-1	0.32	0.33	0.1	0.26
[4]	1-A & 4-C-2	0.11	0.13	0.2	0.29
[5]	1-A & 4-C-3	0.11	0.14	0.21	0.3
[6]	1-A & 5-D-1	-0.01	0	0.12	0.29
[7]	1-A & 5-D-2	0.1	0.12	0.09	0.09
[8]	2-B & 3-C	0.09	0.08	0.11	0.22
[9]	2-B & 4-C-1	0.05	0.1	0.26	0.41
[10]	2-B & 4-C-2	0.05	0.1	0.15	0.12
[11]	2-B & 4-C-3	-0.03	0.05	0.26	0.39
[12]	2-B & 5-D-1	-0.01	0.04	0.16	0.33
[13]	2-B & 5-D-2	-0.03	0.02	0.09	0.22
[14]	3-C & 4-C-1	-0.01	0.01	0.05	0.14
[15]	3-C & 4-C-2	0.22	0.23	0.03	0.2
[16]	3-C & 4-C-3	0.01	0.01	0.02	0.08
[17]	3-C & 5-D-1	0.01	0.02	-0.01	0.1
[18]	3-C & 5-D-2	0	0.01	-0.03	0.12
[19]	4-C-1 & 4-C-2	0.35	0.36	0.39	0.46
[20]	4-C-1 & 4-C-3	0.4	0.42	0.28	0.4
[21]	4-C-1 & 5-D-1	-0.01	0	0.14	0.34
[22]	4-C-1 & 5-D-2	-0.03	0	0.09	0.16
[23]	4-C-2 & 4-C-3	0.34	0.35	0.34	0.44
[24]	4-C-2 & 5-D-1	-0.01	0	0.16	0.3
[25]	4-C-2 & 5-D-2	-0.01	0	0.09	0.17
[26]	4-C-3 & 5-D-1	-0.01	0	0.2	0.31
[27]	4-C-3 & 5-D-2	-0.01	0	0.07	0.2
[28]	5-D-1 & 5-D-2	0.09	0.08	0.15	0.07
	Average	0.09	0.11	0.14	0.24

Key—DSEC: Distance Error Correlation, DREC: Direction Error Correlation

For each cross-correlation, the indoor distance error and direction error had average values 0.09 and 0.11, respectively. The correlations between different types of the same maker were rather high. In addition, the average outdoor distance and direction errors were 0.14 and 0.24, respectively. These values are higher than them for indoors, respectively. As with outdoor results, some indoor correlations between terminals of the same maker were slightly higher.

From the results, it can be confirmed that mobile phone models from the same vender have slightly high correlation in distance and direction errors. However, among the other venders, though the GPS chip used is the same (in all the experiments, the chip is from Qualcomm), the correlations are nearly zero. For each vender's terminals, the GPS positioning error is thought to be highly dependent on the antenna's location, structure and sensitivity.

B. Ideal Estimation of the True Value of Measurement Points

As mentioned in the results for mobile phone GPS error's group characteristics in TABLE VII, correlation coefficients between terminal models are generally low. Using this nearly zero cross-correlation and multiple mobile phones to reduce the measurement error, the true value of measurement points was estimated. The true value estimation method is as follows.

As the method of estimating the true value, the GPS error can be expressed as a sum of measurements as shown in Equation (2). The estimation at a point x is denoted by $\hat{f}(x)$.

$$\hat{f}(x) = F(x) + \sum_{j=1}^{k} n_j(x)/k \qquad (2)$$

Where,

$F(x)$**:** the true position

$n_j(x)$**:** error at terminal j

k **:** the number of devices used in the measurement of GPS

Taking account the fact that the mobile phone GPS error correlation coefficient is small, it is expected that the amount of noise term used to determine the GPS error in Equation (2) is closer to zero as $k \to \infty$.

In order to examine the effect of proposed true value estimation method of Equation (2), the following experiments were carried out. Actually, as a calculating method of the true value estimation, direction error derived as shown in Fig. 3 is used. The resulting mean value becomes the result of the true value estimation method for the direction error of the N mobile phones assuming a true position value of Google map.

Based on these concepts, first, the average of GPS errors for each terminal that would become the basis is calculated. Second, GPS errors *O* based on the concept of Equation (2) for different combinations of mobile phones from two to eight terminals are obtained. This calculation process of *O* is shown by the following Equation (3).

$$O = \sqrt{((1/N)\sum_{i=1}^{N} X_i)^2 + ((1/N)\sum_{i=1}^{N} Y_i)^2} \quad (2 \le N \le 8) \qquad (3)$$

Where,

X_i **:** the longitude direction error for terminal number i, when assuming a true value which is referred from the Google map

Y_i **:** the latitude direction error for terminal number i, when assuming a true value which is referred from the Google map

N **:** number of terminals used for true value estimation method

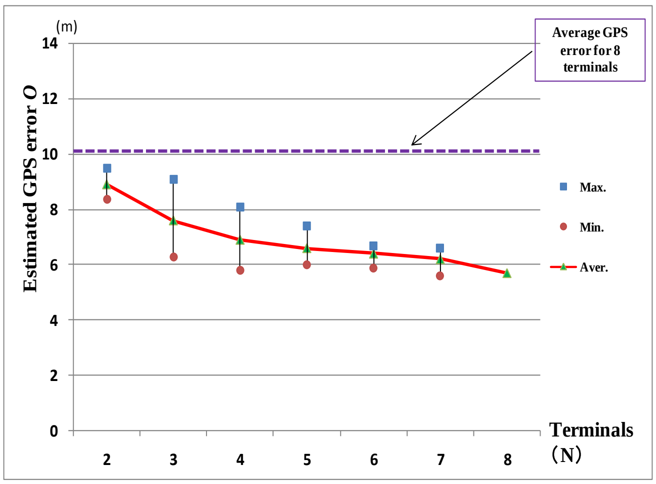

Fig. 17 The relationship between the number of terminals, N, and the estimated error in the case for true value position

The results of Equation (3) are shown in Fig. 17. The average GPS estimation error from the ${}_8C_N$ (N = 2 ~ 8) combinations of terminals as well as the maximum estimation error and the minimum estimation error are shown in Fig. 17. The dotted line shows average GPS error for 8 terminals.

Then we compared the average distance error for the 8 terminals before and after estimation. Fig. 18 and TABLE VIII show the results, respectively.

Through estimation of true value using 8 mobile phone terminals, it is possible to reduce the GPS measurement error to less than 44% when compared to the error obtained by using only one mobile terminal.

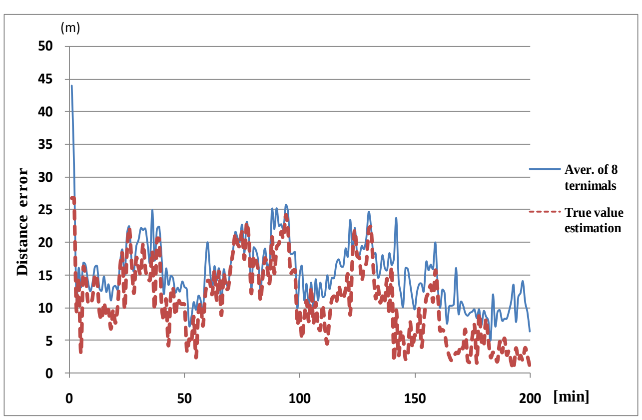

Fig. 18 Comparison of the average distance error of the true value estimation method using 8 mobile phone terminals

TABLE VIII. The error before estimation (average of 8 terminals) and after estimation by using proposed method

	Before Estimation	After Estimation
Average Error (m)	15	6
Maximum Error(m)	46	41
Minimum Error (m)	4	0
Variance (m^2)	35	37

C. Temporary True Value Estimation Method

It was confirmed to be able to reduce the GPS error considerably from the above-mentioned results. However, it is a precondition to know the true value of the measurement point to turn this method into useful. Then, we assumed the location information of one terminal of eight mobile phones to be a true value to calculate the GPS error $\hat{O}$, and carried out additional experiments of actual true value estimation method by combining ${}_7C_N$ (N=2 ~ 7) terminals. The result is shown in Fig. 19. This calculation process can be represented by following Equation (4).

$$\hat{O} = \sqrt{((1/N)\sum_{j=1}^{N}\hat{X}_j)^2 + ((1/N)\sum_{j=1}^{N}\hat{Y}_j)^2} \quad (2 \le N \le 7) \quad (4)$$

Where,

$\hat{X}_j$ **:** the longitude direction error for terminal number j, when assuming a value which is longitude of one from among eight mobile phones

$\hat{Y}_j$ **:** the latitude direction error for terminal number j, when assuming a value which is latitude of one from among eight mobile phones.

N **:** Number of terminals used for temporary true value estimation method

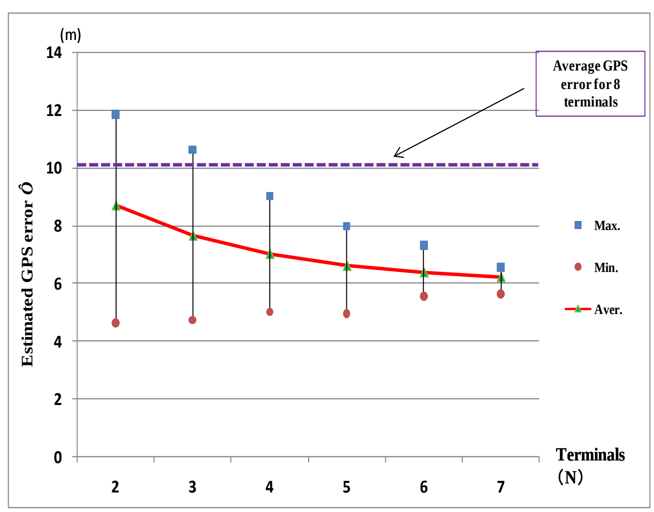

Fig. 19 The relationship between the number of terminals, N, and the estimated error in the case for temporary value position

Through estimation of actual true value estimation using 8 mobile phone terminals, it is also possible to reduce the GPS error to less than 40% when compared to the error obtained by using only one mobile terminal, while a little bit less than that of an ideal method of Equation (3).

VI. Conclusion

The results of the experiments can be summarized as follows.

1) The GPS error characteristics are independent of the orientation (N, S, E, W) of the mobile phone.
2) Out of Sync error (impulse noise) is rarely encountered, but causes very large errors when encountered. In clear sky conditions, the time rate of occurrence is about 0.2%, but in indoor conditions where the GPS satellites are hard to see, the occurrence rate increase to about 3% or 4%. The amount and timing of its occurrence is highly dependent on the type of mobile phone terminal.
3) Impulse noise reduction by the N-point moving average method (N=3-5) is very effective.
4) The GPS error distribution is well approximated by gamma distribution.
5) As for the group characteristics between multiple GPS mobile phones, the cross-correlation of the distance and direction errors for different terminals is small. Using this property, by a simple addition of GPS errors from multiple terminals, it is possible to estimate the true value of measurement points. For example, when we use eight mobile phones, the GPS error can be reduced to below 40% of that produced by a single mobile phone.

VII. Future Research

In future, for different types of mobile phones, a detailed investigation of mobile phone antenna characteristics [8], the sensitivity and the structure of the antenna is necessary. Analysis of the relationship between GPS radio waves and the base station is also required.

In addition, further development of advanced GPS systems are also required for GIS applications [9], [10].

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