Theory of Indoor GPS by Using Reradiated GPS Signal

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ABSTRACT

A novel positioning method based on GPS technology in a space where GPS signal can't be received is discussed. If positioning by using GPS receiver is possible even in such spaces, a seamless location on ground surfaces, inside buildings, in underground spaces and so on becomes possible. The merit may be significant. For this kind of purpose, pseudolites are used usually. In the present paper, a new method based on reradiation of GPS signals is proposed. In the present paper, the above mentioned reradiation approach is investigated theoretically. A method of experiment and experimental results are also discussed. In spaces similar to those mentioned above, there exist problems such as near-far and multi-reflection problems. The effects and solutions are proposed through experiments by wired transmission, those in a radio dark room and those in an actual environment. The phase distance is much more effective than the pseudo range.

1. INTRODUCTION

A novel positioning method based on GPS technology in a space where GPS signal can't be received is discussed. If positioning by using GPS receiver is possible even in such spaces, a seamless location on ground surfaces, inside buildings, in underground spaces and so on becomes possible. The merit may be significant.

For this kind of purpose, pseudolites are used usually. In the present paper, a new method based on reradiation of GPS signals is proposed. GPS signals are received on ground surface where a favorable environment is provided to receive them. The received GPS signals are demodulated and separated into channels corresponding to individual satellites. The separated signals are then modulated separately, transmitted to reradiation antennas placed at appropriate positions in the target space, and radiated from the antennas. The individual GPS signals are radiated from the radiation antennas separately. This is the key point of the present approach. The antennas should be deployed appropriately.

When a specific GPS signal is received in the target space, the delay of the signal is caused by (1) the distance between the satellite and the antenna of the receiver on the ground surface, (2) the length of optical fiber or coaxial cable connecting the surface receiver to the reradiation antenna and (3) the distance between the reradiation antenna and the receiver antenna in the target space. (1) can be measured by the surface receiver, and (2) is known. Hence, (3) is obtained, if (1) and (2) are subtracted from the measurement by the receiver in the target space. So, the position of the target receiver antenna may be determined by applying the usual procedure.

If another receiver is placed in the target space and used as a reference, the single difference between the receivers cancels (1) and (2), since (1) and (2) are common in both measurements. And the single difference is equal to that of (3). This corresponds to a situation that the satellite locates at the position of the reradiation antenna.

In the present paper, the above mentioned reradiation approach is investigated theoretically. A method of experiment and experimental results are also discussed. In spaces similar to those mentioned above, there exist problems such as near-far and multi-reflection problems. The effects and solutions are proposed through experiments by wired transmission, those in a radio dark room and those in an actual environment. The phase distance is much more effective than the pseudo range.

2. THEORY OF UNDERGROUND GPS

GPS signals don't attain underground space. Hence, they must be generated by any means. For this kind of purpose, pseudolites are used usually (Rizos (2001)). A new method based on reradiation of GPS signals is discussed below.

As shown in Figures 1 and 2, GPS signals are received on the ground surface. They are demodulated and divided into individual satellite signals, and the individual signals are then modulated separately. They are lead to antennas in the underground space through optical fibers or coaxial cables.

The method is summarized as follows:

1. A surface GPS receiver receives GPS signals.
2. GPS signals are demodulated and divided into individual satellite signals, and are re-modulated separately.
3. The individual signals are transferred to re-radiation antennas placed in an underground space, for an example, on the ceiling.
4. The individual signals are re-radiated by the re-radiation antennas.
5. The range measured by an underground GPS receiver is the sum of
   (a) the range between the satellite and the surface GPS receiver,
   (b) the length of the cable connecting the surface receiver and the re-radiation antenna
   and
   (c) the distance between the re-radiation antenna and the underground GPS receiver.
6. (a) can be measured by the surface GPS receiver, and (b) is equal to the length of the cable.

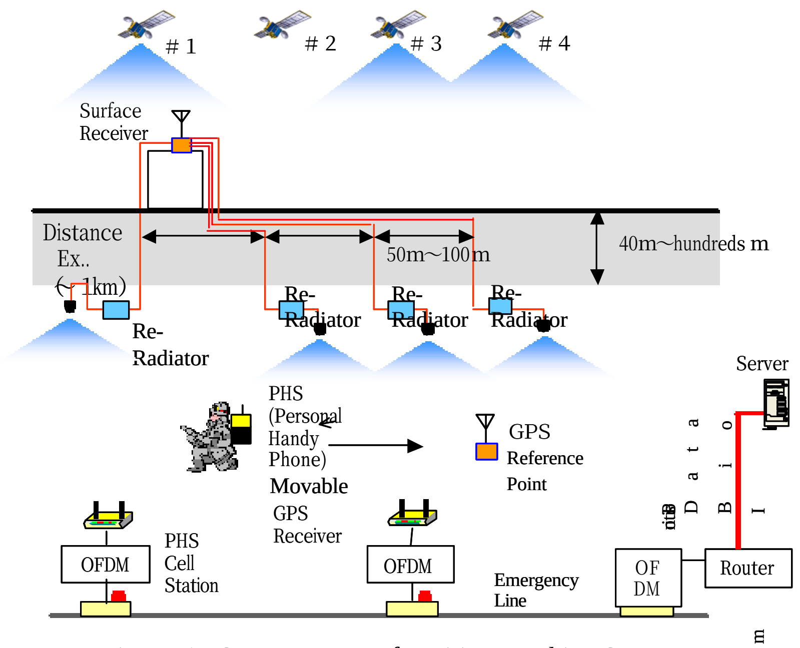


Figure 1 System Image of Position Tracking System by a Portable Telephone with a GPS Receiver in Under Grounds and in Buildings

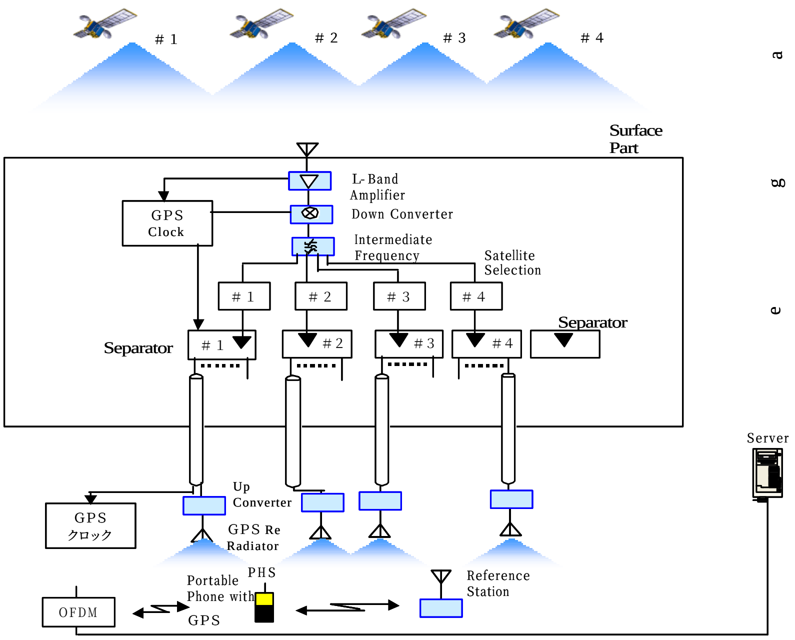


Figure 2 Details of Principle

7. The range between the re-radiation antenna and the underground GPS receiver antenna is given by subtracting (a) and (b) from the range measured by the underground GPS receiver. 8. The positions of the re-radiation antennas are known. So, the position of the underground GPS receiver may be calculated.
9. If a reference receiver is introduced and a relative measurement is applied, the single difference between the rover and reference receivers cancels (a) and (b) in item 5.
10. In this situation, the satellites may be considered, as if they exist at the point of the re-radiation antennas.

In the following, the above-mentioned method is explained in details by using mathematical formulas. The following notations are used:

N : the number of satellites,
superscript i : referring to a satellite,
subscript a : referring to a receiver,
P_a^i : pseudo or phase range between the satellite i and the receiver a,
r_a^i : geometrical distance between the satellite i and the receiver a,
d^i : noise due to the satellite i,
d_a : noise due to the receiver a,
d_a^i : noise due to the transmission path connecting the satellite i and the receiver a,
l : wave length of the carrier waves,
N_a^i : initial phase ambiguity of the range between the satellite i and the receiver a.

An observation equation on the observable P_a^i can now be written as

$$P_a^i = r_a^i + d^i + d_a + d_a^i + e_a^i + lN_a^i, \quad i = 0,1,\cdots,N-1;\ a = 0,1 \tag{1}$$

where e_a^i is the miscellaneous random noise which can't identify the source. In case of pseudo ranges, the initial phase ambiguity N_a^i may be ignored.

The SSSD (satellite-satellite single difference) of Equation (1) gives

$$(\nabla P)_1^{ij} = (\nabla r)_1^{ij} + (\nabla d)^{ij} + (\nabla d)_1^{ij} + (\nabla e)_1^{ij} + l(\nabla N)_1^{ij}, \quad i = 0,1,\cdots,N-2;\ j = N-1 \tag{2}$$

where $(\nabla \bullet)^{ij}$ refers to the SSSD:

$$(\nabla \bullet)^{ij} = (\bullet)^i - (\bullet)^j \tag{3}$$

The noise d_a due to the receiver a is eliminated by the SSSD.

The RRSD (receiver-receiver single difference) of Equation (1) gives

$$(\Delta P)_{01}^i = (\Delta r)_{01}^i + (\Delta d)_{01} + (\Delta d)_{01}^i + (\Delta e)_{01}^i + l(\Delta N)_{01}^i, \quad i = 0,1\cdots N-1 \tag{4}$$

where $(\Delta \bullet)_{ab}$ refers to the RRSD:

$$(\Delta \bullet)_{ab} = (\bullet)_{ab} - (\bullet)_{ab} \tag{5}$$

The noise d^i due to the satellite i is eliminated by the RRSD. When the rover and base receiver are close, $(\nabla d)_1^{ij}$ may be ignored.

The SRDD (satellite and receiver double difference) of Equation (1) gives

$$(\nabla\Delta P)_{01}^{ij} = (\nabla\Delta r)_{01}^{ij} + (\nabla\Delta d)_{01}^{ij} + (\nabla\Delta e)_{01}^{ij} + l(\nabla\Delta N)_{01}^{ij}, \quad i = 0,1\cdots,N-2;\ j = N-1 \tag{6}$$

where $(\nabla\Delta \bullet)_{ab}^{ij}$ refers to the SRDD:

$$\begin{aligned}(\nabla\Delta\bullet)_{ab}^{ij} &= (\nabla\bullet)_a^{ij} - (\nabla\bullet)_b^{ij} \\ &= (\Delta\bullet)_{ab}^i - (\Delta\bullet)_{ab}^j \\ &= (\bullet)_a^i - (\bullet)_a^j - (\bullet)_b^i + (\bullet)_b^j\end{aligned} \tag{7}$$

The noise d^i due to the satellite i and the noise d_a due to the receiver a are eliminated by the SRDD. When the rover and base receiver are close, $(\nabla d)_{01}^{ij}$ may be ignored.

On the other hand, let

r_S^i : distance between the satellite i and the surface receiver S,
$\overline{r}_{R_i}^S$: length of the cable connecting the surface receiver S and the reradiator R_i,
$\hat{r}_0^{R_i}$: distance between the reradiator R_i and the base receiver 0,
$\hat{r}_1^{R_i}$: distance between the reradiator R_i and the rover receiver 1.

The distance r_a^i can be written as

$$r_a^i = r_S^i + \overline{r}_{R_i}^S + \hat{r}_a^{R_i}, \quad i = 0,1,\cdots,N-1;\ a = 0,1 \tag{8}$$

Hence, SSSD $(\nabla r)_a^{ij}$, RRSD $(\Delta r)_{ab}^i$ and SRDD $(\nabla\Delta r)_{ab}^{ij}$ are

$$(\nabla r)_1^{ij} = (\nabla r)_S^{ij} + (\nabla\overline{r})_{R_iR_j}^S + (\nabla\hat{r})_1^{R_iR_j}, \quad i = 0,1,\cdots,N-2;\ j = N-1 \tag{9}$$

$$(\Delta r)_{01}^i = (\Delta\hat{r})_{01}^{R_i}, \quad i = 0,1,\cdots,N-1 \tag{10}$$

$$(\nabla\Delta r)_{01}^{ij} = (\nabla\Delta\hat{r})_{01}^{R_iR_j}, \quad i = 0,1,\cdots,N-2;\ j = N-1 \tag{11}$$

From the observation Equations (2), (4), (6) and (9), (10), (11), $(\nabla\hat{r})_1^{R_iR_j}$, $(\Delta\hat{r})_{01}^{R_i}$ and $(\nabla\Delta\hat{r})_{01}^{R_iR_j}$ can be calculated. Namely, if errors are neglected

$$(\nabla\hat{r})_1^{R_iR_j} \approx (\nabla P)_1^{ij} - (\nabla r)_S^{ij} - (\nabla r)_{R_iR_j}^S - l(\nabla N)_1^{ij}, \quad i = 0,1,\cdots,N-2;\ j = N-1 \tag{12}$$

$$(\Delta\hat{r})_{01}^{R_i} \approx (\Delta P)_{01}^i - l(\Delta N)_{01}^i, \quad i = 0,1\cdots N-1 \tag{13}$$

$$(\nabla\Delta\hat{r})_{01}^{R_iR_j} \approx (\nabla\Delta P)_{01}^{ij} - l(\nabla\Delta N)_{01}^{ij}, \quad i = 0,1\cdots,N-2;\ j = N-1 \tag{14}$$

where $(\nabla r)_S^{ij}$ and $(\nabla r)_{R_iR_j}^S$ can be obtained from the observables at the surface receiver and the length of the cables connecting the surface receiver and the reradiators respectively.

Let the coordinate of the reradiator R_i and that of the receiver a be $(x^{R_i}, y^{R_i}, z^{R_i})$ and (x_a, y_a, z_a) respectively. Since $\hat{r}_a^{R_i}$ can be written as

$$\hat{r}_a^{R_i} = \sqrt{(x^{R_i} - x_a)^2 + (y^{R_i} - y_a)^2 + (z^{R_i} - z_a)^2} \qquad (15)$$

$(\nabla \hat{r})_1^{R_i R_j}$, $(\Delta \hat{r})_{01}^{R_i}$ and $(\nabla \hat{r})_{01}^{R_i R_j}$ are given as

$$(\nabla \hat{r})_1^{R_i R_j} = \sqrt{(x^{R_i} - x_1)^2 + (y^{R_i} - y_1)^2 + (z^{R_i} - z_1)^2} - \sqrt{(x^{R_j} - x_1)^2 + (y^{R_j} - y_1)^2 + (z^{R_j} - z_1)^2} \qquad (16)$$

$$(\Delta \hat{r})_{01}^{R_i} = \sqrt{(x^{R_i} - x_0)^2 + (y^{R_i} - y_0)^2 + (z^{R_i} - z_0)^2} - \sqrt{(x^{R_i} - x_1)^2 + (y^{R_i} - y_1)^2 + (z^{R_i} - z_1)^2} \qquad (17)$$

$$\begin{aligned}(\nabla \hat{r})_{01}^{R_i R_j} = & \sqrt{(x^{R_i} - x_0)^2 + (y^{R_i} - y_0)^2 + (z^{R_i} - z_0)^2} \\ & - \sqrt{(x^{R_j} - x_0)^2 + (y^{R_j} - y_0)^2 + (z^{R_j} - z_0)^2} \\ & - \sqrt{(x^{R_i} - x_1)^2 + (y^{R_i} - y_1)^2 + (z^{R_i} - z_1)^2} \\ & + \sqrt{(x^{R_j} - x_1)^2 + (y^{R_j} - y_1)^2 + (z^{R_j} - z_1)^2} \qquad (18)\end{aligned}$$

If either of Equations (12) and (16), Equations (13) and (17) and Equations (14) and (18) are used, the coordinates (x_1, y_1, z_1) of the rover antenna may be obtained.

In the above discussions, the method to determine the initial phase ambiguity N_a^i is not given. The simplest way is to determine N_a^i by using known coordinates such as the starting point and to use it in the following positioning calculation.

An idea to solve this problem is shown in Appendix A.

The above discussions mention the problem and the solution from the theoretical viewpoint. From a practical viewpoint, the following items are the unique problems in a confined space:

(1) Near / Far Problem
(2) Multi-Reflection
(3) Antenna Interference

The solutions to individual items may be given as

(1) Device for reradiation:
  (1-a) Adoption of pulsing of GPS signals [2,3]
    Signal of a different channel is radiated on a different time.
  (1-b) Change of radiation pattern
    The power downward is weaker than that sideward.
  (1-c) Increase of dynamic range of a receiver
(2) The phase range gives much better results than the pseudo range.
(3) The interferences between the radiation antennas decay rapidly as the distances between them increase. So, these interference may not give any practical problems. However, if the radiation antennas are placed close, the interferences become very remarkable. CDMA (Code Division Multiple Access) seems to be robust to these interferences. The interferences between the receiver antennas may not give serious problems.

3. EXPERIMENTAL METHOD

3.1 GPS SIGNAL GENERATORS AND RECEIVERS

Figure 3 shows GPS signal generators and GPS receivers. The signal generators are synchronized by the GPS time signals. Two receivers are used. One of them is the base receiver and the other is the rover receiver. So, the measurement of the double difference is possible. The receivers outputs are not only pseudo ranges but also phase distances, and the double difference measurement of the phase distances is also possible.

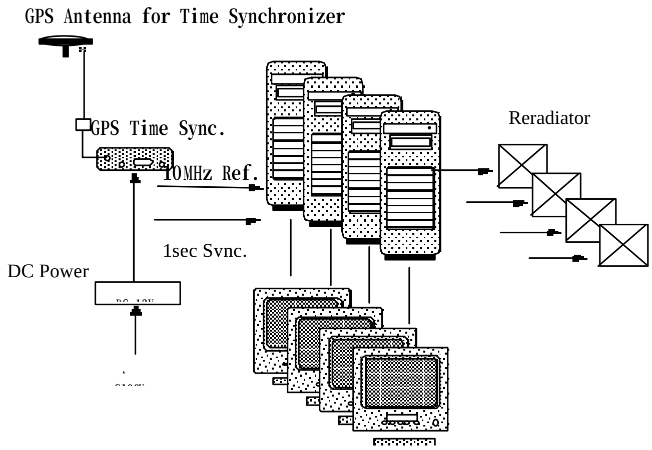


Figure 3a GPS signal generators

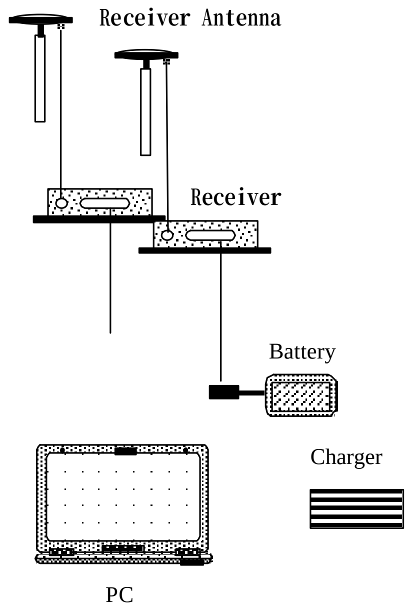


Figure 3b GPS receivers

3.2 PSEUDO RANGE MEASUREMENTS IN WIRED TRANSMISSION

Before experimenting in wireless transmission, basic properties are confirmed in wired transmission as shown in Figure 4. The length of the coaxial cables corresponds to the transmission distance in the wireless case and is changed to simulate the change of the transmission distance in the wireless case. However, the transmission speeds are different in both cases. The speed in the coaxial cable used in the present experiment is 67% of the speed in vacuum.

Through this experiment, the following items are investigated:

(1) Separation of signals.

(2) Relationship between the coaxial cable lengths and the double difference of pseudo ranges.

(3) Resolution of the double difference.

In Figure 4, the signal generators 1 and 2 corresponds to the satellites 1 and 2. The lengths of the coaxial cables 5, 10 and 15m, and four cables were prepared for each length. So, the double difference can change from –20 to +20m with separation of 5m.

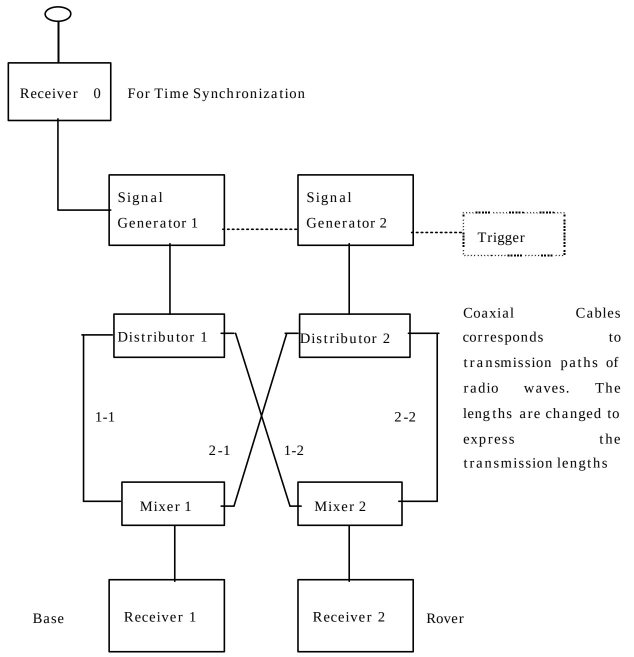


Fig. 4 Experiment by wire

3.3 EXPERIMENTS IN A RADIO DARK ROOM

In order to verify the positioning principle and to obtain the precision of the measurement, experiments were conducted in a radio dark room as shown in Figure 5.

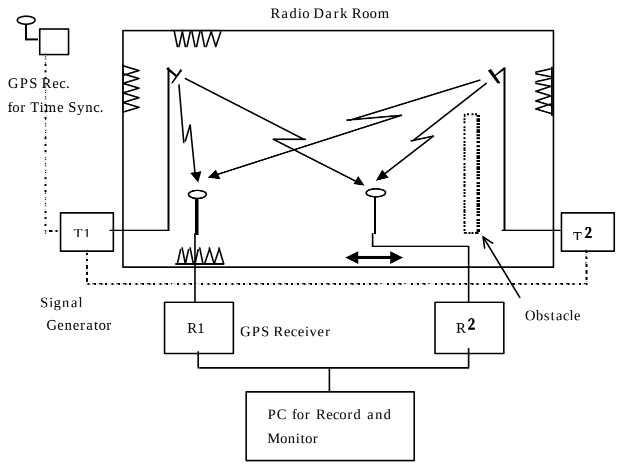


Fig. 5 Experiment in a radio dark room

Specifically, distances between radiation antennas and receiver antennas were measured, and the SRDD (satellite and receiver double difference) was calculated from the measured data. On the other hand, the theoretical SRDD was obtained geometrically from the coordinates of the radiators and the receivers. By comparing the both SRDDs, the measurement accuracy was obtained. In a radio dark room, more reliable measurements are feasible, since the multi-path effects are small there.

By comparing the coordinates of the rover antenna calculated from the measured SRDD with the real coordinates, the accuracy of the coordinates level were also obtained.

3.4 EXPERIMENTS IN AN ACTUAL ENVIRON-MENTS

In a real environment, reflections from ceilings, walls and various obstacles have influences on positioning: the so-called multi reflection. To verify the possibility of a positioning based on GPS technology in these environments, experiments illustrated in Figure 6 were conducted.

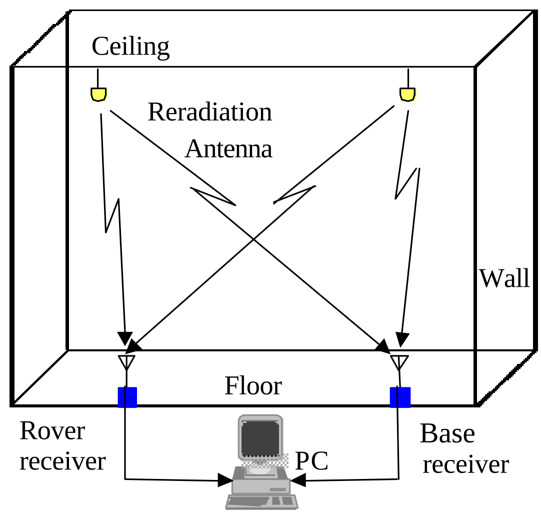


Fig. 6 Experiment in an actual environment

4. EXPERIMENTAL RESULTS

4.1 EXPERIMENTS IN WIRED TRANSMISSION

The experimental results are shown in Figure 7. The precision of the measurement is not satisfactory, but the linearity is confirmed. This assures the possibility of the positioning based on GPS technology in a confined space such as the underground.

4.2 EXPERIMENTS IN A RADIO DARK ROOM

The precision of the pseudo range is not satisfactory for the present purpose. On the other hand, that by phase distance is very high. The accuracy is better than 5cm. The

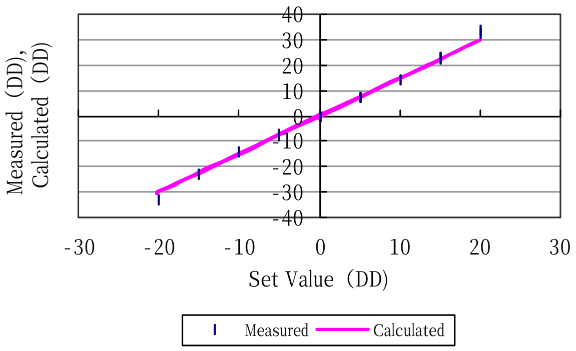


Fig. 7 Relationship between the double difference of pseudo ranges and that of coaxial cable lengths.

high stability and quick response are also verified. In the following experiments, the distance between the radiation antennas are 6m, the height is 2.5m. The height of the receiver antennas is 0.1m. The epoch is 1sec.

(1) Stability test

To investigate the stability, the rover antenna was fixed, and the data were collected for 15 min. The origin of the coordinates is taken on the floor at the center between the radiation antennas. The direction connecting the radiation antenna 1 to the radiation antenna 2 is taken positive. The positions of the receiver antennas are taken at $(-1.0m, 0.1m)$ and $(+1.0m, 0.1m)$. As shown in Figure 8, no drifts are observed both in pseudo and phase distances. The variations are several meters in pseudo range data and several millimeters in phase distance. The stability of the phase range data is satisfactory.

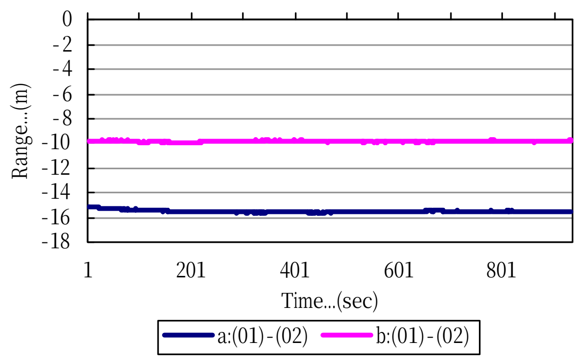


Figure 8a SSSD (Satellite-Satellite Single Difference) of pseudo range (Stability test)

(2) Precision test

To investigate the positioning precision, precison tests were conducted. In the first example, receiver antenna b (base antenna) was fixed at $x = 2.5m$, and antenna a (rover antenna) was moved from $x = -2.5m$ to $x = 2.5m$ with the increment of $0.5m$. The results are shown in Figure 9. The pseudo range data don't reflect the movement of the rover antenna correctly, since the movement of the rover antenna is too small. However, the movement is acquired explicitly. In Figures 9c and 9d, the

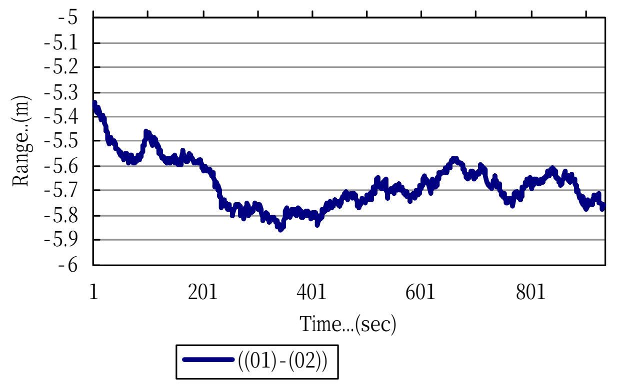


Figure 8b SRDD (Satellite-Receiver Double Difference) of pseudo range (Stability test)

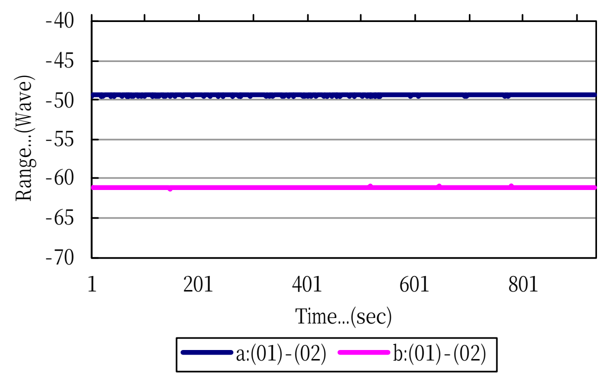


Figure 8c SSSD of phase range (Stability test)

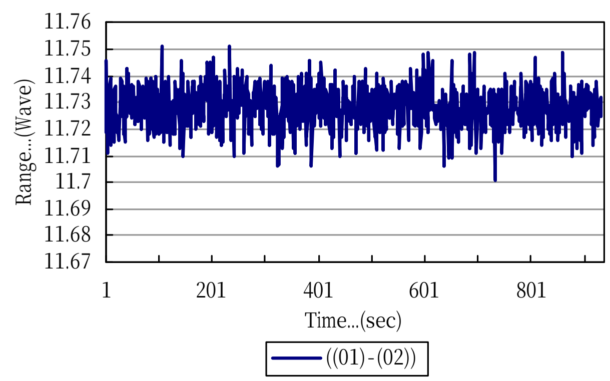


Figure 8d SRDD of phase range (Stability test)

lock is lost at 2150sec, and a slip is observed. The correction is shown in Figures 9e and 9f.

In another example, antenna a (base antenna) is fixed at $x = +1.0m$. Antenna b (rover antenna) is placed at $x = -1.0, -0.75, -0.5, -0.4, -0.3, -0.2, -0.15, -0.1, -0.05, 0, +0.05, +0.1, +0.15, +0.2, +0.3, +0.4, +0.5, +0.75, +1.0, +0.5, 0, -0.5, -1.0m$. The results of the phase range are shown in Figure 4.2.3. By using the phase range, the rover antenna movement of $5cm$ is acquired clearly. Namely, If the phase range is used, the positioning accuracy better than $5cm$ may be possible.

The measured results of the phase range are compared with the calculated and real results in the Figure 10. A comparison of measured SRDD with calculated SRDD of phase range (Precision test) is shown in Figure 10c. In Figure 10d, the coordinates calculated from measured SRDD of the phase data are compared with the real coordinates. The same results are also shown in Table 1.The

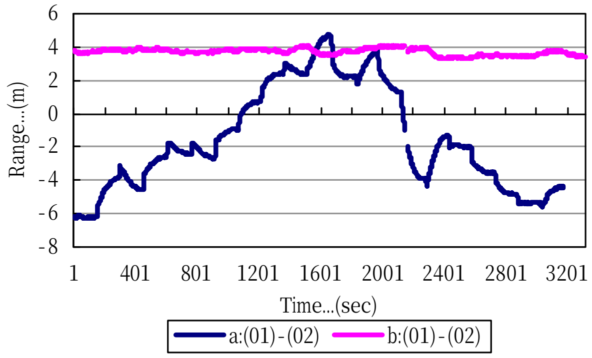


Figure 9a SSSD of pseudo range (Precision test)

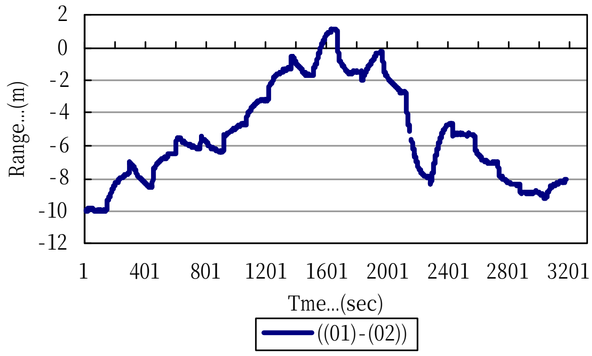


Figure 9b SRDD of pseudo range (Precision test)

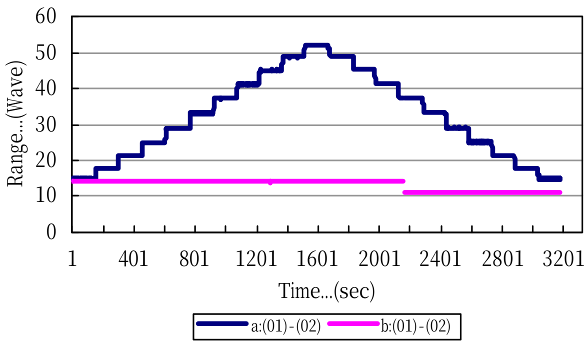


Figure 9c SSSD of phase range (Precision test)

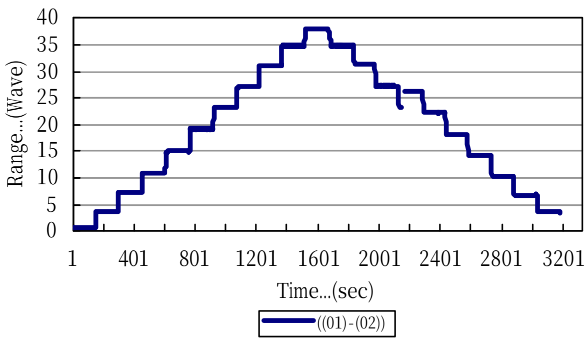


Figure 9d SRDD of phase range (Precision test)

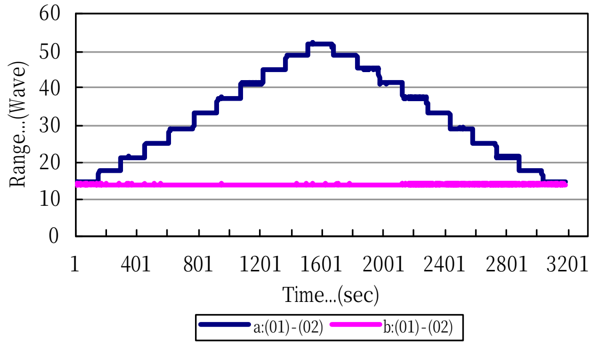


Figure 9e SSSD of phase range with slip corrected (Precision test)

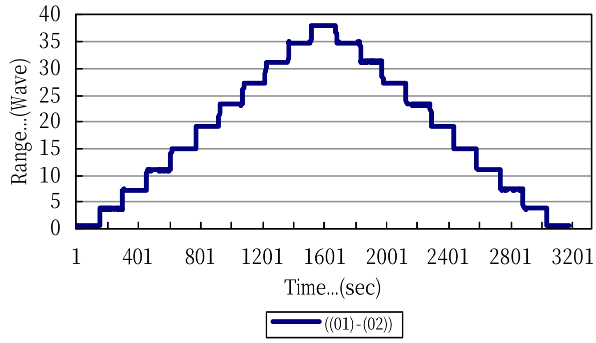


Figure 9f SRDD of phase range with slip corrected (Precision test)

difference between the measured and calculated SRDDs are in the level of $\pm 2cm$. The difference between the measured and real coordinates are also in the level of $\pm 2cm$.

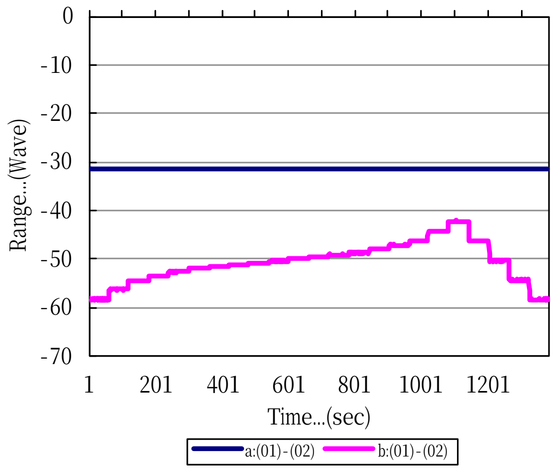


Figure 10a SSSD of phase range (Precision test)

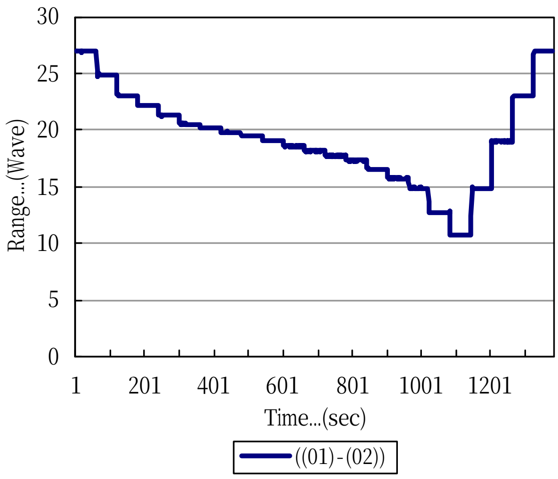
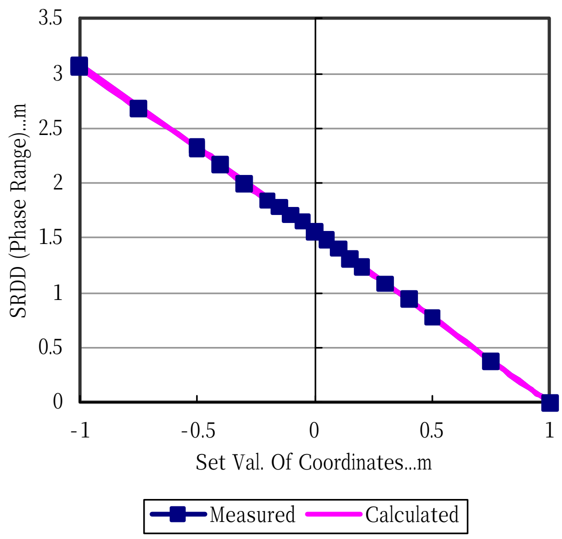


Figure 10b SRDD of phase range (Precision test)

Figure 10c Comparison of measured SRDD with



calculated SRDD of phase range (Precision test)

Table 1 Comparison of measured coordinates with real ones
(Precision test)

File Name	Real Coordinates (m)	Measured DD (wave)		Measured DD (m)	Calculated DD (m)	Measured Coordinates (m)
		Original Data	Corrected* Data			
1206_2_1	-1	26.9	16.1	3.059	3.08	-0.99
1206_2_2	-0.75	24.9	14.1	2.679	2.7	-0.73
1206_2_3	-0.5	23.1	12.3	2.337	2.32	-0.51
1206_2_4	-0.4	22.2	11.4	2.166	2.16	-0.4
1206_2_5	-0.3	21.3	10.5	1.995	2.01	-0.29
1206_2_6	-0.2	20.5	9.7	1.843	1.85	-0.19
1206_2_7	-0.15	20.2	9.4	1.786	1.77	-0.16
1206_2_8	-0.1	19.8	9	1.71	1.7	-0.11
1206_2_9	-0.05	19.5	8.7	1.653	1.62	-0.07
1206_2_10	0	19	8.2	1.558	1.54	-0.01
1206_2_11	0.05	18.6	7.8	1.482	1.46	0.04
1206_2_12	0.1	18.2	7.4	1.406	1.38	0.09
1206_2_13	0.15	17.7	6.9	1.311	1.31	0.15
1206_2_14	0.2	17.3	6.5	1.235	1.23	0.2
1206_2_15	0.3	16.5	5.7	1.083	1.07	0.29
1206_2_16	0.4	15.8	5	0.95	0.92	0.38
1206_2_17	0.5	14.9	4.1	0.779	0.76	0.49
1206_2_18	0.75	12.8	2	0.38	0.38	0.75
1206_2_19	1	10.8	0	0	0	1
1206_2_20	0.5	14.9	4.1	0.779	0.76	0.49
1206_2_21	0	19	8.2	1.558	1.54	-0.01
1206_2_22	-0.5	23	12.2	2.318	2.32	-0.5
1206_2_23	-1	27	16.2	3.078	3.08	-1

* The corrected Data are obtained by making the value zero when the rover and base antennas are at the same position.

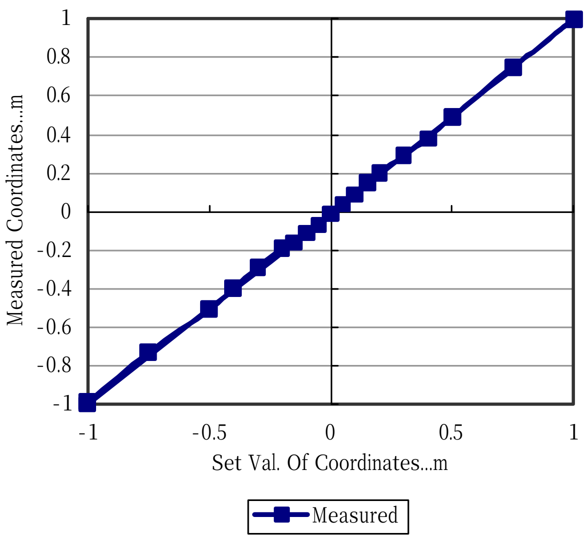


Figure 10d Comparison of measured coordinates with real ones (Precision test)

4.3 EXPERIMENTS IN AN ACTUAL ENVIRONMENTS

To investigate the possibility of a positioning based on GPS technology, experiments were conducted in a passage beside the radio dark room in the same building. The results are shown in Figures 11.

Antenna b (base antenna) was fixed at $x = 2.5m$, and antenna a (rover antenna) was moved from $x = -2.5m$ to $x = 1.5m$ with the increment of $0.5m$. The lock is lost at 340sec, and a slip is observed. However, the lock is recovered instantly. In Figures 11e and 11f, the slip is corrected. The results similar to the ones obtained in the radio dark room are obtained. The phase range is robust to the multi reflection, and very effective.

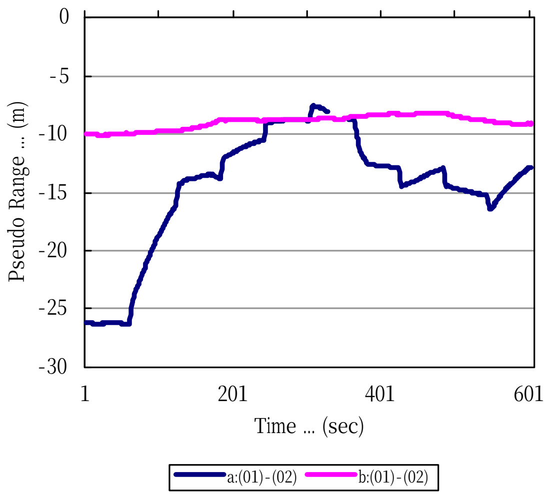


Figure 11a SSSD of pseudo range (Experiments in an actual environment)

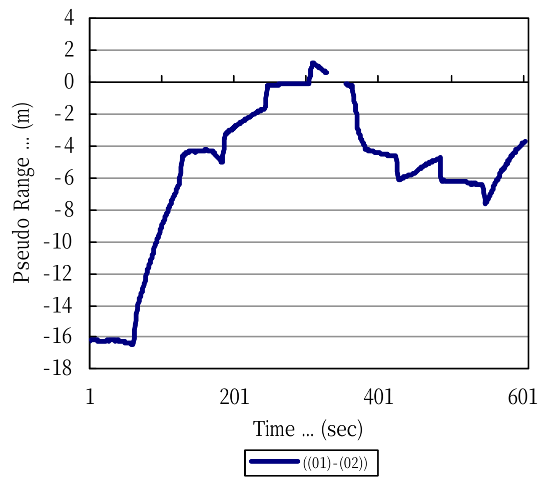


Figure 11b SRDD of pseudo range (Experiments in an actual environment)

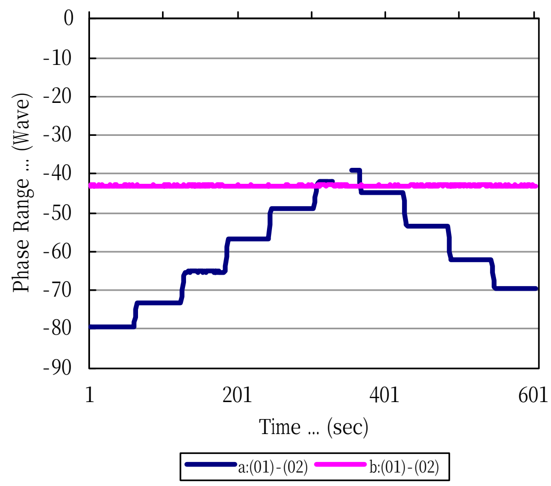


Figure 11c SSSD of phase range (Experiments in an actual environment)

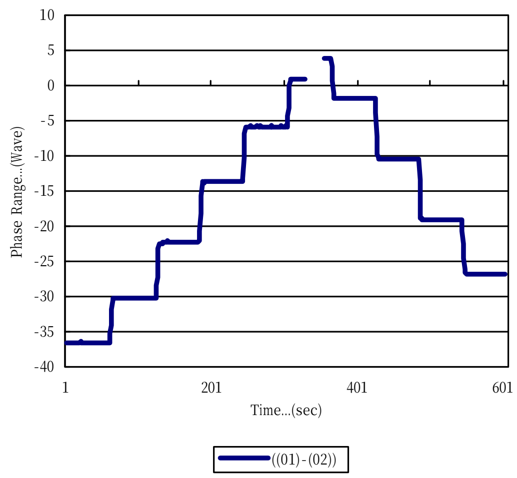


Figure 11d SRDD of phase range (Experiments in an actual environment)

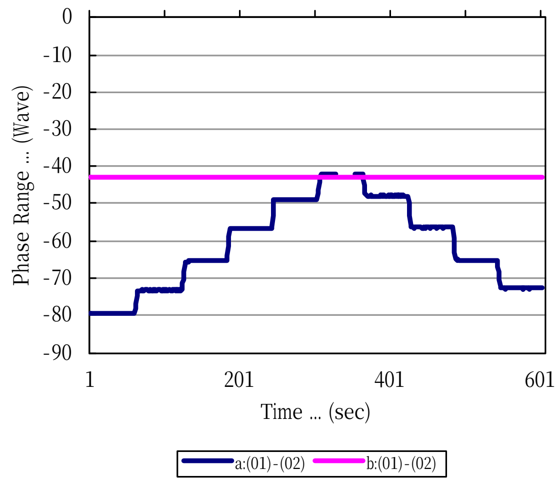


Figure 11e SSSD of phase range after correction (Experiments in an actual environment)

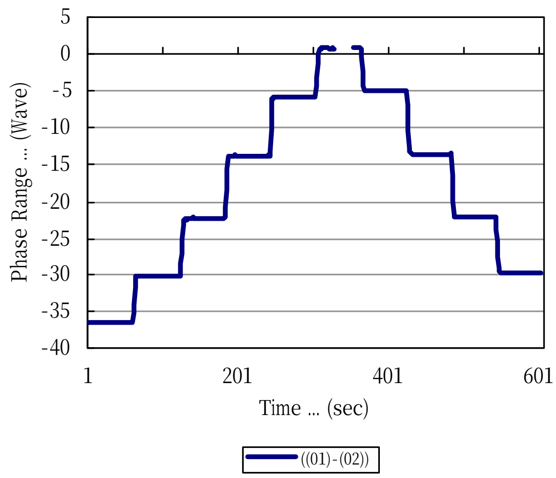


Figure 11f SRDD of phase range after correction (Experiments in an actual environment)

5. CONCLUSIONS

A possibility of positioning based on GPS technology with an accuracy of centimeter order in a space where GPS signal can't be received was shown. The present method uses conventional GPS receivers, and the GPS signals are generated by reradiation of the GPS signals. The conclusions obtained are shown below.

5.1 VERIFICATION OF THEORY BY EXPERIMENTS

(1) In case of the underground GPS, the distance between a radiation antenna and a receiver antenna is very close. Even in the situation, a possibility of the positioning algorithm of the underground GPS was verified by experiments by a wired transmission.
(2) The high stability, high precision and quick response were confirmed by experiments in a radio dark room. The precision of the pseudo range is about $5m$, but that of the phase range is $\pm 2cm$ that is same as RTK (Real Time Kinematics) on the ground surface.
(3) The rover antenna was moved quickly by a electrically driven carriage, and the response was confirmed. The response may be same as that of a conventional RTK.
(4) Experiments were also conducted in an actual space where reflection from ceilings, walls, floors and obstacles exist, and the possibility of the underground GPS was assured. The phase range is found to be very robust to the multi-path reflections.

5.2 PROBLEMS TO BE SOLVED FOR PRCTICAL APPLICATION

(1) Two GPS signal generators and the two GPS receivers were used in the present experiments, and a one dimensional positioning was conducted. For the verification of the principle and the confirmation of the precision, the present experiments may be sufficient. However, for the practical application, three dimensional positioning experiments using four GPS signal generators should be done.
(2) For the practical application, downsizing of the receiver antenna must be realized for downsizing of the receiver. The proximity of the radiation and receiver antennas may be advantageous for the purpose.
(3) In the present experiments, the maximum distance between the radiation antennas was 6m. For the practical application, this should be more than 20m. In the situation, Near/Far problem may be the key point [2, 3]. The radiation pattern of the radiation antenna may be one of the cost effective solutions.
(4) The phase range may be more suited in positioning in multi path reflection environments than the pseudo range. However, if the phase range is used, the initial phase ambiguity must be solved by any means. An idea is shown in Appendix A.
(5) For a practical application, a combination with INS (Inertial Navigation System) and map mapping may realize a robust system.

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APPENDIX A AN IDEA TO SOLVE THE INITIAL PHASE AMBIGUITY

In the following, an specific example is used to explain the idea.

1. A method using two radiation antennas

The two radiation antennas are placed at $x = -3m$ and $x = +3m$. The height is $z = 2.5m$. The base receiver antenna is set at $x = -3m$, and the rover antenna moves between $x = -3m$ and $x = +3m$. The height is $z = 0.1m$. The fraction of the SRDD (Satellite-Receiver Double Difference) calculated geometrically is shown in Figure A.1. As shown in the figure, there exist complex number of candidates for the rover antenna position. Hence, the rover antenna position can't be determined definitely for a given SRDD in this case.

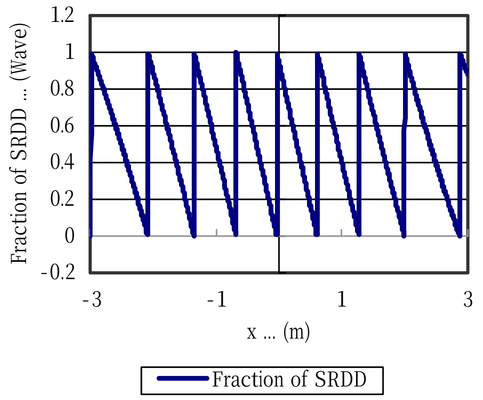

Figure A.1 Fraction of calculated SRDD using two radiation antennas

2. A method using three radiation antennas

The three radiation antennas are placed at $x = -3m$, $x = 0m$ and $x = +3m$. The height is $z = 2.5m$. The base receiver antenna is set at $x = -3m$, and the rover antenna moves between $x = -3m$ and $x = +3m$. The height is $z = 0.1m$. In this case, two independent SRDDs can be obtained. The SRDD calculated by using the radiation antennas placed at $x = -3m$ and $x = 0m$ and

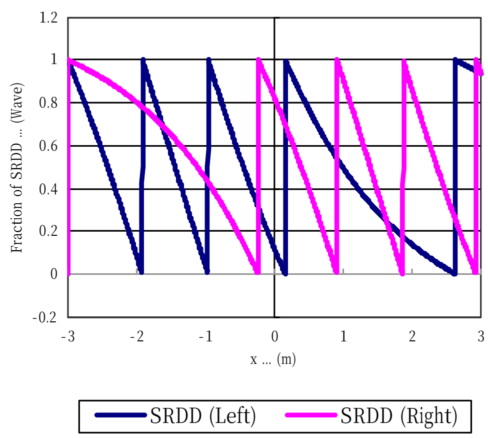

Figure A.2 Fraction of calculated SRDD using three radiation antennas

that calculated by using the radiation antennas placed at $x = 0m$ and $x = +3m$ are shown in Figure A2. As shown in the figure, there exist only one position candidate for a pair of SRDDs. Hence, the rover antenna position can be determined definitely for a given pair of SRDDs in this case.