Evaluation of Multi-DME Positioning Performance in Japan through Flight Experiments

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ABSTRACT

An alternate positioning method for aircraft using Multi-DME in case of GNSS signal loss is being developed and discussed in the international standardization organizations. DME provides a continuous slant range using a DME ground station and airborne equipment. Aircraft position can be determined using two ranges of DME instead of GNSS, which is called DME/DME and has been used so far. Multi-DME positioning uses multiple ground stations and improves positioning performance in comparison to DME/DME. Multi-DME can assure the integrity of the positioning for RNP routes because anomalies of the positioning can be detected by RAIM technologies.

The applicability of the Multi-DME to Japan should be clarified because the land is mainly composed of mountainous areas. Therefore, flight experiments were conducted around Tokyo International Airport (NRT) and Sendai Airport (SDJ) using the experimental aircraft and DME/Pulse Analyzer (EDS300), which can obtain 10 DME distances simultaneously. The experimental results show that the Multi-DME performance is degraded due to the mountainous area at SDJ though sufficient performance was obtained around NRT which is located on the Kanto Plane. This paper reports the details of the evaluation results.

INTRODUCTION

GNSS is mainly used for aircraft navigation, but the GNSS signal power received near the ground surface is extremely low since GNSS signals are sent from an altitude of approximately 20,000 km. So, there are many cases that the GNSS system cannot be used due to interferences [1]. In addition, there have been many cases that the system cannot be used for long periods of time due to intentional jamming. Recently, spoofing has also been reported[2]. Therefore, one of the challenges for ICAO (International Civil Aviation Organization) is to build a GNSS backup in order to maintain safe and efficient aircraft operations even if GNSS systems become unavailable. This backup system is called APNT (Alternate Positioning, Navigation and Timing) and being studied to be built by reutilizations of DME (Distance Measuring System) which are used in conventional navigation and RNAV routes by DME/DME[3][4]. The multi-DME positioning[5][6][7] that utilizes the DME currently in operation is being discussed by the committee of EUROCAE and RTCA as one of backup systems, and standardization is underway. Issues in introducing multi-DME into Japan should be clarified using flight experiments.

Since Japan is conposed of mountainous areas, there are concerns that the performance of multi-DME deteriorates due to the mountains. Therefore, multi-DME performances have been evaluated through flight experiments at two airports. One is Narita International Airport which is located on the Kanto Plateau and offers good conditions for multi-DME positioning. Another airport is Sendai International Airport which is located in the mountainous area and offers bad conditions for multi-DME positioning. This paper reports the details of the evaluation results.

MULTI-DME POSITIONING

DME is a distance measuring system for aircraft, which is shown in Figure 1. The DME system on board sends an interrogation pulses from the aircraft and receives the reply pulses from the ground DME station and calculates the distance using the time interval. Positioning by DME has been used so far, but it utilizes only two DME ground stations. Furthermore, it does not have the ability to detect anomalies in positioning. So, two DME positioning is used within the radar coverage in Japan.

Figure 2 shows the multi-DME positioning method. Multi-DME method can detect anomalies from the differences between the calculated positions and the distances used in the position calculation since the multi-DME can be generated several sets of DMEs.

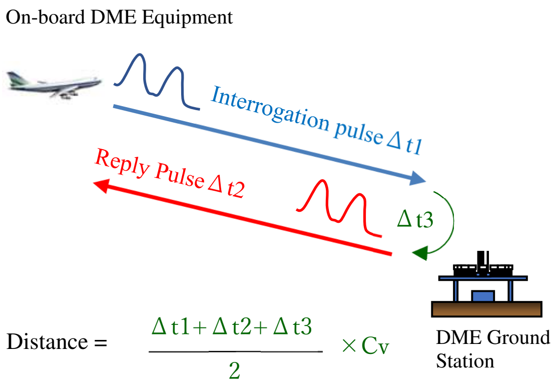

Figure 1 Distance Measuring Equipment

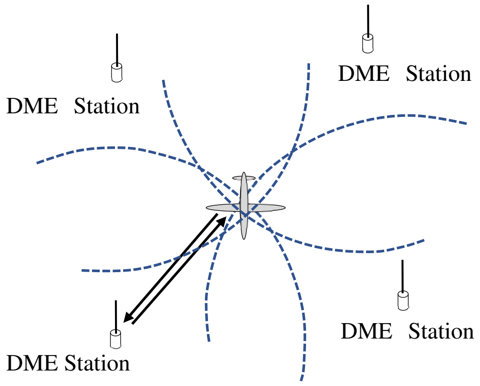

Figure 2 Multi-DME positioning

This section shows how to determine the position of an aircraft by distances from multiple ground DME stations. Since the number of equations is larger than that of variables (x, y, z) given by the unknown position of the aircraft, the solution is determined by the least squares method. In addition, since the simultaneous equations are nonlinear, the iteration by Newton Raphson Method is applied to calculate the positions.

In the case that the number of terrestrial DME stations used for positioning is N and the position of the terrestrial DME station $\boldsymbol{X_n} = (x_n, y_n, z_n)^T (n = 1,2,\cdots,N)$, $\boldsymbol{R_n}$ which is given by $\boldsymbol{i}$-th position $\boldsymbol{X_i} = (x_i, y_i, z_i)^T$ in the iteration is given by

$$\boldsymbol{R_n} = \begin{pmatrix} r_1 \\ \vdots \\ r_n \\ \vdots \\ r_N \end{pmatrix} = \begin{pmatrix} \sqrt{(x_1 - x_i)^2 + (y_1 - y_i)^2 + (z_1 - z_i)^2} \\ \vdots \\ \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} \\ \vdots \\ \sqrt{(x_N - x_i)^2 + (y_N - y_i)^2 + (z_N - z_i)^2} \end{pmatrix} \qquad (1)$$

Differences between $\boldsymbol{R_m}$ given by ranging data and $\boldsymbol{R_n}$ are

$$\boldsymbol{D_r} = \begin{pmatrix} D_{r1} \\ \vdots \\ D_{rn} \\ \vdots \\ D_{rN} \end{pmatrix} = \boldsymbol{R_m} - \boldsymbol{R_n} \qquad (2)$$

Amount of correction $\boldsymbol{D_x}$ in the Newton-Raphson method can be calculated by

$$\boldsymbol{D_x} = (\boldsymbol{A^T A})^{-1} \boldsymbol{A^T D_r} \qquad (3)$$

$$\boldsymbol{A}=\frac{\partial R_n}{\partial X_i}=\begin{pmatrix}\frac{\partial r_1}{\partial x_i} & \frac{\partial r_1}{\partial y_i} & \frac{\partial r_1}{\partial z_i}\\ \vdots & \vdots & \vdots\\ \frac{\partial r_n}{\partial x_i} & \frac{\partial r_n}{\partial y_i} & \frac{\partial r_n}{\partial z_i}\\ \vdots & \vdots & \vdots\\ \frac{\partial r_N}{\partial x_i} & \frac{\partial r_N}{\partial y_i} & \frac{\partial r_N}{\partial z_i}\end{pmatrix}=\begin{pmatrix}\frac{x_i-x_1}{r_1} & \frac{y_i-y_1}{r_1} & \frac{z_i-z_1}{r_1}\\ \vdots & \vdots & \vdots\\ \frac{x_i-x_n}{r_n} & \frac{y_i-y_n}{r_n} & \frac{z_i-z_n}{r_n}\\ \vdots & \vdots & \vdots\\ \frac{x_i-x_N}{r_N} & \frac{y_i-y_N}{r_N} & \frac{z_i-z_N}{r_N}\end{pmatrix} \quad (4)$$

The solution is updated by equation (5). The iteration is conducted until $\boldsymbol{D_x}$ becomes enough small.

$$\boldsymbol{X_{i+1}}=\boldsymbol{X_i}+\boldsymbol{D_x} \qquad (5)$$

Here, barometric altitude can be utilized even if GNSS is not available. It is shown that the utilization of the barometric altitude provides high accuracy positioning of Multi-DME[6]. So it was utilized in this study. The position solution becomes $x_i$and y_i in 2-dimension, since the barometric altitude determines z_i.

If the barometric altitude is utilized, the position is solved in the condition N≧2 since z_i is given by the barometric altitude. If N=2, the equation (3) becomes

$$\boldsymbol{D_x}=\boldsymbol{A^{-1}}\boldsymbol{D_r} \qquad (6)$$

When, the position is solved using many DME stations, it is possible to detect an anomaly in the distances that provides the position and exclude it from the position calculation. Multipath is a threat and causes large error of DME[8]. FDE (Fault Detection and Exclusion) makes it possible to suppress the degradation of position accuracy due to the anomaly. When an anomaly occurs in the distance measurements, the difference between the distance determined by the position solution and the actual distance measurement value becomes large. The statistic value D is given by the difference between the numerical solution $\boldsymbol{\widehat{R}_n}$ obtained by the Newton Raphson method and the actual measured distance $\boldsymbol{R_m}$ as

$$D^2=\left(\boldsymbol{R_m}-\boldsymbol{\widehat{R}_n}\right)^{\boldsymbol{T}}\cdot\left(\boldsymbol{R_m}-\boldsymbol{\widehat{R}_n}\right) \qquad (7)$$

If this statistic D exceeds a certain threshold, it can be judged that an anomaly contains in the distances. When positions are calculated by two DME stations using barometric altitude, statistic D becomes always zero, so anomalies cannot be detected.

EQUIPMENT FOR FLIGHT EXPERIMENT

Accuracy and applicability of the multi-DME positioning was evaluated using DME/Pulse Analyzer (EDS-300, manufactured by Rohde & Schwarz)[9], which is a measuring instrument that can measure distances from 10 DME stations simultaneously. The aircraft used in the flight experiment was a Beechcraft B300 shown in Figure 3, which is owned by the Electronic Navigation Research Institute. Figure 4 shows the measurement system and equipment. The DME/Pulse Analyzer and GNSS receiver were mounted on a rack installed in the aircraft. This text can be used optionally to introduce your conclusions.

Figure 3 Experimental aircraft

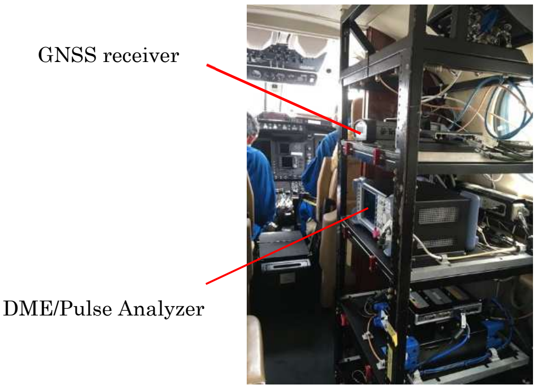

Figure 4 Equipments on board

The measurement system diagram is shown in Figure 5. The distances obtained by the DME/Pulse Analyzer were recorded by a PC via the network. The software shown in Figure 6 was fabricated in the measurement. The multi-DME distances up to 10 DME can be obtained simultaneously. The position provided by GNSS receiver was assumed as the true position which was required to calculate the distance and position errors. The DME antenna of the aircraft is installed at the bottom of the aircraft, and was used to transmit interrogation pulses from the DME/Pulse Analyzer and receive reply pulses from the ground station.

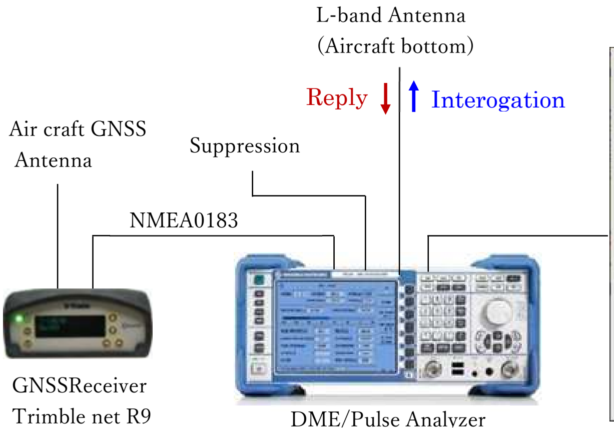

Figure 5. Equipment setup

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51 2022-02-17 13:48:15.603018
slot1  0,1,1,   P D  R,27450,1197.0,-50.203,-nan,11.971,0.286,70.0,track,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot2  0,2,2,   P D  R,27455,1015.0,-66.426,-nan,11.711,1.475,84.0,track,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot3  0,1,3,   P    ,27410,1162.0,-88.191,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot4  0,2,4,   P    ,27415,1164.0,-89.578,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot5  0,1,5,   P    ,27421,1211.0,-87.500,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot6  0,2,6,   P    ,27426,1042.0,-77.405,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot7  0,1,7,   P    ,27431,1194.0,-90.878,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot8  0,2,8,   P    ,27436,1167.0,-86.839,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot9  0,1,9,   P    ,27440,1170.0,-79.644,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
slot10 0,2,10,  P    ,27445,1204.0,-90.334,-nan,-nan,-nan,-nan,search,00¥xb0 00.00000000' N,00¥xb0 00.00000000' E,NO GPS
```

```
Measurement Mode was Changed to Multi-DME =READY.

Slot1:110XON  Slot2:54XON  Slot3:75XON  Slot4:77XON  Slot5:124XON  Slot6:81YON  Slot7:107XON  Slot8:80XON  Slot9:83XON  Slot10:117XON
```

Measurement Mode
● Multi-DME
○ One DME ranging
○ One DME ranging + Pulse View

Data Acquisition Times/sec [Hz]: 2

One DME ranging Setting
Channel: 110 X ○ ON ● OFF

Pulse View Setting
Acquisition Interval[sec]: 99999
Wait time adjust[msec]: 0 bf DME_get, 0 bf pulse_get

Command to EDS-300
Reply: EDS300 SW 01.62z

Mult-DME Channel Setting
SLOT1 CH No.[X,Y]: 110 X ● ON ○ OFF
SLOT2 CH No.[X,Y]: 54 X ● ON ○ OFF
SLOT3 CH No.[X,Y]: 75 X ● ON ○ OFF
SLOT4 CH No.[X,Y]: 77 X ● ON ○ OFF
SLOT5 CH No.[X,Y]: 124 X ● ON ○ OFF
SLOT6 CH No.[X,Y]: 81 Y ● ON ○ OFF
SLOT7 CH No.[X,Y]: 107 X ● ON ○ OFF
SLOT8 CH No.[X,Y]: 80 X ● ON ○ OFF
SLOT9 CH No.[X,Y]: 83 X ● ON ○ OFF
SLOT10 CH No.[X,Y]: 117 X ● ON ○ OFF

Figure 6 DME/Pulse Analyzer operation software

VALIDATION BY FLIGHT EXPERIMENT

Narita International Airport

Narita International Airport is located on a plain, so there are few mountains which block the line of sight between the DME ground stations and the aircraft. Additionally, there are many DMEs around this airport because of the high traffic. The condition is rather good for multi-DME positioning. A flight experiment was conducted to evaluate the performance of multi-DME at the SID/STAR around this airport. Figure 7 shows the flight path of the measurement. This route is SWAMPN, which is one of the standard arrival routes at Narita Airport and connects the enroute to the approach route. This route is RNAV1 and the autonomous abnormality monitoring is not currently required. However, we conducted an evaluation under the assumption that the autonomous integrity monitoring is necessary on this route considering overlaying RNP1 on RNAV1. Four DME stations were selected to evaluate the performance of the multi-DME positioning which are NRE, CVT, SHT and HUC, though there are many DME stations around Narita International Airport. Here, CVT, HUC, and SHT are TACAN, which are aeronautical navigation facilities that can be used by commercial aircraft and provide ranging information as well as DME.

Figure 7 Evaluation route and DME around Narita International Airport

Figure 8 shows the positioning error using four stations calculated by the difference from the true position (GNSS). The position error using two distances from NRE and HUC is also shown as a reference. The horizontal axis is time [seconds], and the horizontal axis in Figure 8 corresponds to the red line part of the flight path in Figure 7. Figure 8 shows that there is no improvement in accuracy with four stations compared to two. One reason for this is thought to be bad geometry of the stations. Though it is preferable that the ground stations are located scattered in wide angles, the positioning on the SWAMP N uses the distances with narrow angles because this air route is over the ocean. Furthermore, there may be errors in the distance measurements used in the positioning calculations. It can also be seen that in the case of four stations, an extremely large positioning error occurs around 37430 seconds. This time becomes point C on the route shown in Figure 7. Here, although this system can obtain distance measurement data of up to 10 DME ground stations simultaneously, there was a lot of data loss. So calculations were conducted using the data that could be obtained at the target four stations at the same time. The cause of this are being investigated currently.

Figure 9 shows the statistic D calculated using 4-station positioning and 3-station positioning with an arbitrary station excluded to analyze whether this positioning anomaly can be detected or not. It can be seen that the statistic D of four stations positioning become extremely large at the time when the positioning anomaly occurs, so it can be seen that the positioning anomaly can be detected by the statistic D. In addition, Figure 9 shows that the statistic D become smaller in the case of three stations excluding CVT stations.

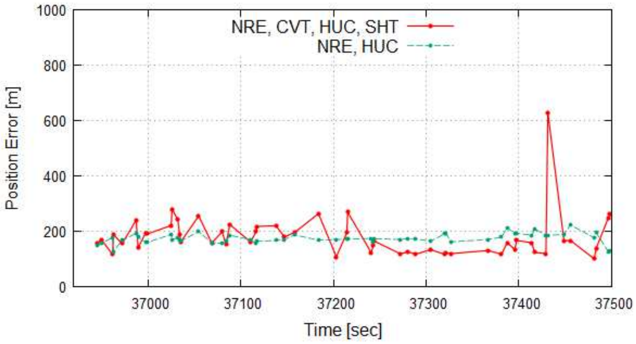

Figure 8 Position error

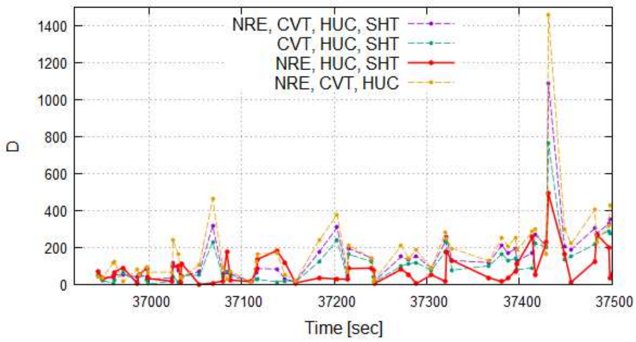

Figure 9 statics D

Figure 10 shows the position error of three stations excluding one arbitrary station. This figure shows that the position error becomes smaller when the positioning excludes CVT which increase statistic D as shown in Figure 9. These results show that the position anomaly was caused by the ranging error of the CVT station, and it was found that the position anomaly could be reduced by the exclusion.

Figure 11 shows the distance errors of each DME ground station which is used for position calculation. This figure shows that a large error are observed at CVT station at the time of about 37430 seconds when a large positioning anomaly occurred by the positioning by the four stations. This ranging error is considered to be the cause of the anomaly in the positioning by four stations. However, this study clarifies that this distance measurement anomaly can be detected and excluded using the statistic D. It is necessary to set a threshold to determine and detect an anomaly. When the statistic D exceeds the threshold, anomaly is detected.

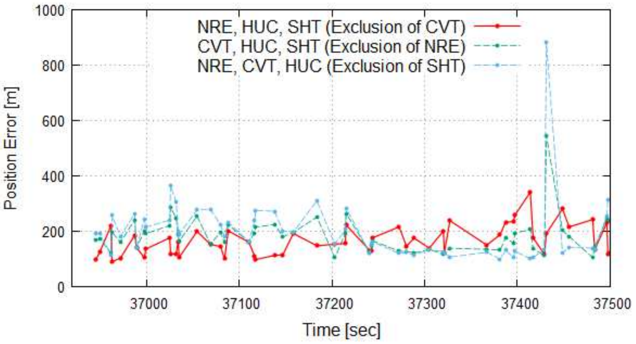

Figure 10 position error excluding arbitrary station

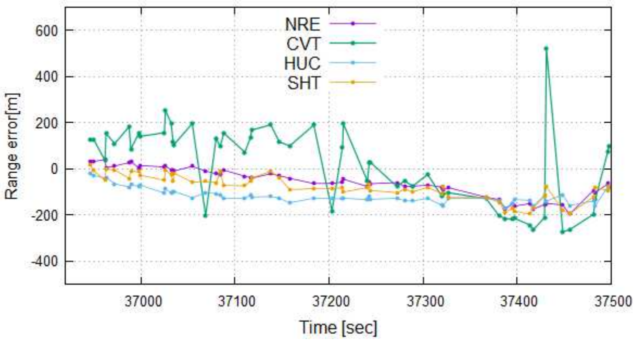

Figure 11 Distance error of each station

Sendai International Airport

The evaluation of Multi-DME performance was also conducted at Sendai International airport which is located in a mountainous area. Figure 12 shows the air route for departure of the Sendai airport. The accuracy of the multi-DME positioning was evaluated on this route. Figure 12 also shows the ground DME stations around the airport. This departure route starts from the airport. DME station named SDE and ISD are located close to the runway of the Sendai airport. Since these two stations are located in almost the same position, the geometry cannot be improved. However, when an anomaly occurs at SDE station, ISD can be available instead of SDE. YTE, HPE, IXE, and FKE are located around the air route.

The evaluation results of the distance error of each DME are shown in Figure 13. Figure 13 shows the errors from the time of departure (35300sec) to the time of leaving the route (36500sec). Here, no data means that the distance data couldn't be obtained due to loss of tracking. Figure 13 shows that SDE and ISD at the airport can be tracked from the time of departure. The distance measurement between the aircraft and IXE started after 35400sec, since IXE is located at the coast and there is no obstruction from the topography. After that, the distance measurement of HPE started immediately since there is no obstructions by terrains. Although YTE is close to the airport and air-route, distance measurement was only possible for two short periods, indicating that it is almost impossible to be used on this departure route. The cause is shielding by intervening mountainous areas. It was found that FKE could not be tracked for a while after departure, but started tracking at 36,000 sec, about halfway through the route. As shown in Figure 13, the distance error of IXE is larger than 200m. It seems to be larger than normal because DME errors are usually 100m at most. There may be some problem with the measurement system. The causes are being investigated currently.

Fig.12 Evaluation route and DME around Sendai International Airport

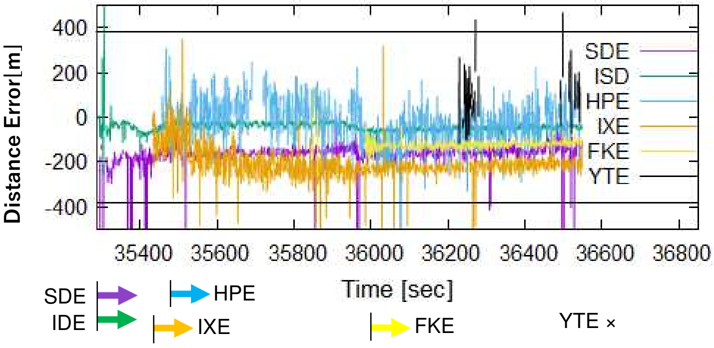

Fig.13 DME error

Figure 14 shows the multi-DME positioning errors. SDE, ISD, HPE, and IXE were used in the position calculation up to 36,000sec. After that, the distance measurement of FKE started and was added in the position calculation. The result shows the error becomes small after the distance measurement of FKE was added.

Figure 14 shows the extremely large fluctuations and errors were occurred until FKE was received. The reason is that SDE, ISD, HPE, and IXE are arranged in a straight line, and the air-route is also in that straight line. That means that the positional relation is extremely bad. Generally, it is desirable for DME ground stations to exist surrounding the aircraft and flight route, but this route does not have such a situation. This will be difficult issue when the multi-DME positioning is deployed in the island country which has the coast land and mountainous area such as Japan. The distance measurement of DME located on the mountainous area at low altitude becomes impossible. Moreover, the DME stations cannot be installed on the sea. As a result, the large positioning errors are caused at low altitude due to bad geometry. It is necessary to arrange DME ground stations in Japan[10] which are suitable for multi-DME for RNP operation.

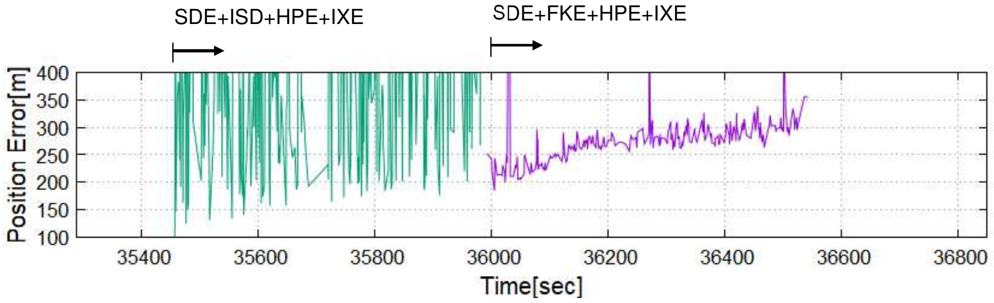

Figure14 Positioning error by multi-DME

CONCLUSIONS

This paper shows the applicability of multi-DME positioning to Japan, which is being discussed in the standardization organizations. As a result, multi-DME performance deteriorated around the airport located in mountainous area, though good applicability was showin around the airport located in plain areas. The problem in Japan is that the DME ground stations are installed in the coastal area and the aircraft fly along the cost line. The utilization of multi-DME in conjunction with other sensors such as IRU is required to satisfy the RNP requirement.

The DME errors obtained by these flight experiment seems to be larger than normal because DME errors are 100m at most. Especially, the errors around Sendai Airport are larger. Moreover, although this system can obtain distance measurement data of up to 10 DME ground stations simultaneously, there was a lot of data loss. So calculations were conducted using the data that could be obtained at the target multiple stations at the same time.There may be some problem with the measurement system, so the causes are being investigated currently.

ACKNOWLEDGMENTS

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