Flight Experiment of GBAS in Japan

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BIOGRAPHIES

Shinji Saitoh received his M. Eng. in Electronic Engineering from the University of Electro-Communications (UEC) in 1998. He joined Electronic Navigation Research Institute (ENRI), Ministry of Transport (MOT) in 1998. Currently, he is researching in the area of GPS and GBAS at ENRI, independent administrative institution (IAI).

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Naoki Fujii is the manager of new landing system section, ENRI, IAI. He received M. Sc. from Kobe University in 1979. He was charged with development of siting criteria of ILS, MLS and aircraft address monitoring system. He is currently working in field of development of GBAS.

ABSTRACT

Electronic Navigation Research Institute (ENRI) in Japan have been developing and evaluating Ground Based Augmentation System (GBAS) includes VHF Data Broadcast (VDB) system. We conducted flight experiments of the GBAS at Sendai airport. We installed temporarily an experimental GBAS ground station and executed the experiments in two types of procedure. One is level flights including orbit and arc flight patterns for checking the performance of the stacked array antenna for null effects, and the other is approach flights from 1,500 feet altitude for testing the total performance of GBAS system.

The VDB system with horizontal polarization generally has a null problem. Therefore we made a stacked array antenna known for a solution of the null problem and installed it at Sendai airport. The ground station consisted of four sets of reference GPS antenna, GPS receiver and personal computer (PC), and a Work Station (WS) to generate GBAS augmentation messages. The experiments were carried out with Beechcraft B99 Airliner loaded a GBAS VDB receiver, a GPS receiver and a PC for computing its real-time differential GPS (DGPS) position and recording GBAS data.

In the experiments, we also executed post-processed kinematic carrier-phase differential positioning to get reference positions. The results of flight to check the null problem showed deep nulls were reduced by the stacked array antenna and no message errors were detected in GBAS service area. In the approach flights, we carried out real-time DGPS positioning using GBAS augmentation information (GBAS-DGPS) and computed difference between real-time GBAS-DGPS position fixes and post-processed kinematic position fixes for evaluating positioning error of GBAS. Final result shows total positioning accuracy of our experimental system is nearly equal to CAT-III. This paper introduces our GBAS equipments and the flight test results about it.

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INTRODUCTION

ENRI have been conducting studies, researches, development of procedures and prototype systems, test and evaluation on navigation systems so as to provide Civil Aviation Bureau of the Ministry of Land, Infrastructure and Transport, Japan (JCAB) with technical materials for their planning and implementation of navigation systems.

We had developed and evaluated a Navigation Augmentation Broadcast System (NABS) with C-band. But the C-band system had a problem of shadowing and multipath by a body of the aircraft.

Now, ENRI have been developing and evaluating GBAS VDB system. We has built up the pre-prototype model for testing system concept and carried out flight trial for GBAS total system. We have already developed VDB system and executed flight test, and shown that the VDB system with horizontal polarization has a null problem and the message errors occur near null points in GBAS service area [1]. One of solutions for the problem is adapting stacked array antenna. Therefore we made a stacked array antenna and installed it at Sendai airport in north-east region of Japan , in January 2001.

We conducted flight experiments of the GBAS VDB system with new VDB stacked antenna in 23 to 26 January and 23 July to 3 August 2001 at Sendai airport. In the experiments, we installed temporarily an experimental GBAS ground station. The ground station has four sets of reference GPS antenna, GPS receiver and PC, and a WS to generate GBAS augmentation information. The experiments were carried out with our experimental aircraft Beechcraft B99 Airliner, shown in Figure 1. The B99 Airliner loaded a GBAS VDB receiver, a GPS receiver and a PC as a GBAS airborne station. A VHF antenna for receiving GBAS-VDB and a GPS receiving antenna were mounted on a roof of the aircraft.

Figure 1: ENRI's experimental Aircraft Beechcraft B99 Airliner
A VHF antenna for receiving GBAS-VDB is mounted on fore part of a roof. A GPS receiving antenna is mounted on rear of the VHF antenna.

In the experiments, we executed two types of flight procedure. One is a level flight including orbit and arc flight patterns for checking the performance of the stacked array antenna for null effects, and the other is an approach flight from 1,500 feet altitude for testing the total accuracy performance of the GBAS system.

This paper describes overview of our experimental GBAS-VDB system and results of flight experiments for testing total performance of its system.

OVERVIEW OF ENRI'S EXPERIMENTAL SYSTEM

Figure 2 shows the configuration of the GBAS for the flight experiment. It is a temporary system for experiment and consists of GBAS ground station included reference station and monitor station, and GBAS airborne station. Its detail is described below. In addition, stacked array VDB antenna is introduced.

Ground Subsystem

Figure 3 shows the photograph of the experimental GBAS VDB system ground station main site. It was installed in the Iwanuma branch of our institute next to Sendai airport. It has five PCs for converting from binary GPS receiver message of various type

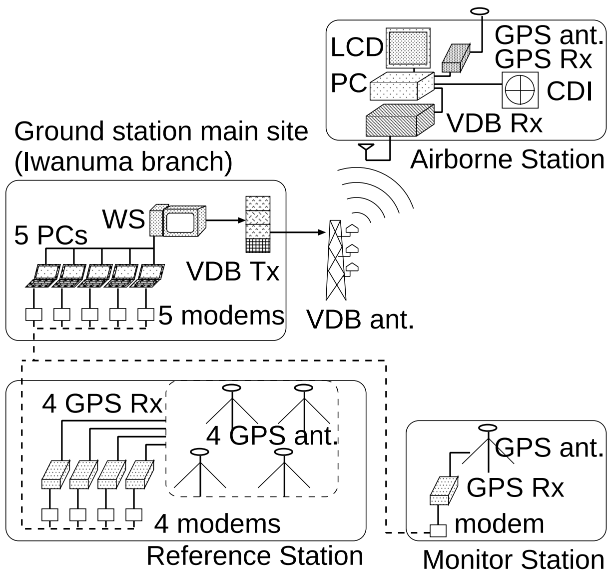

Figure 2: Configuration of Experimental GBAS subsystem

Figure 3: Experimental GBAS ground station main site
From right: VDB transmitter, WS and PCs

with many manufactures to NMEA message, five modems connecting with reference station and monitor station and VDB transmitter connected to a new VDB transmit array antenna, shown in Figure 7. The reference station has four sets of GPS receiver (NovAtel MiLLen. STD.) , GPS receiving antenna (NovAtel GPS600), and modem. The monitor station also has a GPS receiver, GPS antenna and modem. A elevation mask of all GPS receivers were set to 5 degrees through the experiments.

The WS generate the GBAS augmentation messages from pseudoranges, carrier-phase measurements and ephemeris data obtained by four GPS receivers at reference station. Moreover the WS checked the computed position of monitor station using GPS data from monitor station. The messages made by the WS were broadcasted by the VDB system. In the experiments, the system broadcasted GBAS type 1 messages at the rate of 2 Hz, and type 2, 4 and 5 messages at the rate of 0.1 Hz.

Figure 4 shows photographs of four GPS antennas for GBAS reference station. All antennas were NovAtel GPS600 antennas and settled in Sendai airport at green area in front of Iwanuma branch of ENRI, along A runway and A-1 taxi way. The height of each GPS antennas were different, 1.7m to 4.0m, for reducing multipath effect from ground, and separation of each antennas were about 80m, formed a square. These dispositions are shown in Figure 5.

Trimble 4000SSi and 5700 GPS receivers were installed at ground station for calculating reference position by post-processed kinematic carrier-phase differential position fixes. A GPS antenna for these receivers was mounted on top of VDB antenna tower.

The summary of GBAS reference station in the

Figure 4: Reference GPS antennas
Each height of antenna was 1.7m (upper left), 2.0m (upper right), 3.0m (lower left), 4.0m (lower right).

Figure 5: Configuration of GBAS sites in Sendai airport

Table 1: Summary of GBAS reference station

GBAS reference station	
number of GPS antennas	4 (GPS600L1/L2)
disposition	square
height	1.7m, 2.0m, 3.0m, 4.0m
separation	about 80m
GPS receiver	NovAtel MiLLen. STD.
Elevation mask angle	5 degrees
kinematic reference station	
GPS receiver	Trimble 4000SSi Trimble 5700
antenna position	top of VDB tower

experiments was shown in Table 1.

The monitor station was installed away about 1km from the reference station and it has a NovAtel MiLLen. STD. GPS receiver, NovAtel GPS600 GPS antenna and modem connected to the ground station main site.

Figure 6 shows the σ_{pr_gnd} value in pseudorange measurements of GBAS site in Sendai airport. The

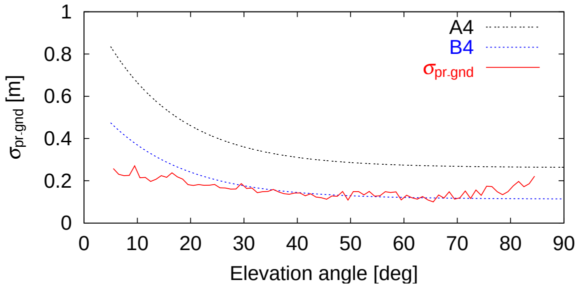

Figure 6: σ_{pr_gnd} of Sendai airport GBAS site and GBAS designator values

black dashed curve is A4 (accuracy designator is 'A' with four ground receivers), the blue dashed curve is B4 (accuracy designator is 'B' with four ground receivers) and the red solid curve is the σ_{pr_gnd} value obtained at GBAS site in Sendai airport. We used B4 value for computing GBAS position fixes and protection level in the experiments.

Stacked array VDB antenna

The new VDB stacked array antenna, shown in Figure 7, consists of triple omni-directional antennas (similar to VOR side-band Alford-loop antenna). Each height of loop antennas is 15.5 meters (top), 10.5 meters (middle) and 5.5 meters (bottom). And phase delays were $\pi/2$ radians (middle) and π radians (bottom) from phase of top antenna. The transmitting power was 15 watts through the flight experiments, but its capability of maximum transmitting power was 50 watts, because of reducing the interference on television sets. The transmitting frequency was 108.5 MHz and modulation was D8PSK. Table 2 shows summary of the new VDB stacked array antenna.

Table 2: Characteristics of VDB system with stacked array antenna

frequency	108.5 MHz
transmit power	15W (max 50W)
transmitting antenna	Alford-loop (similar to VOR side-band ant.) , 3 stacked array
height from ground	5.5m , 10.5m , 15.5m
power splitter ratio	1 : 1 : 1
phase delay [deg]	180 : 90 : 0
polarization	horizontal

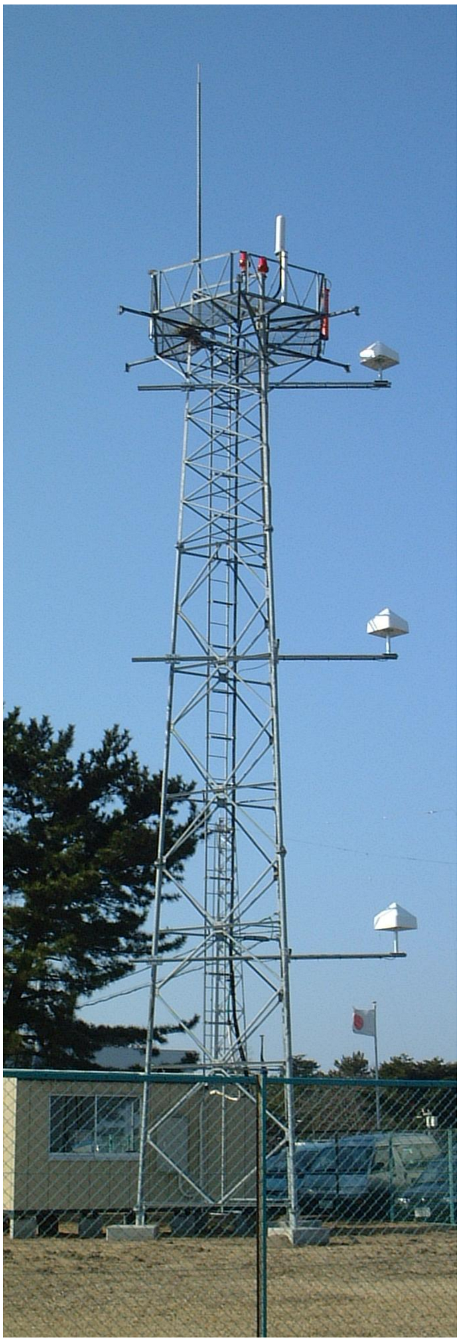

Figure 7: New VDB stacked array antenna
Height of segment was 15.5m (top), 10.5m (middle), 5.5m (bottom) each.
Another GPS antenna for kinematic reference was mounted on top of this tower, height of 17.2m.

Airborne Subsystem

Figure 8 shows airborne station of our experimental GBAS VDB system. The airborne station consists of a GBAS-VDB receiver, NovAtel MiLLen. STD. GPS receiver and PC for processing and recording the GBAS and GPS data. The PC computes the aircraft position using pseudoranges from GPS receiver and

Figure 8: Experimental GBAS airborne subsystem
top: LCD display
middle: PC for GBAS processing
bottom: GBAS-VDB receiver

GBAS pseudorange corrections from VDB receiver. The positioning rate was 4Hz. Trimble receivers (4000SSi and 5700) for computing carrier-phase DGPS reference position were also installed onboard. Table 3 summarizes equipments loaded onboard in the aircraft.

Table 3: Equipment loaded onboard in B99

equipment	
GBAS-VDB receiver	
Personal Computer	for GBAS processing
GPS receiver	
GBAS station	NovAtel MiLLen.STD.
kinematic reference	Trimble 4000SSi
	Trimble 5700

FLIGHT EXPERIMENTS

We conducted GBAS flight experiments in January and July 2001. We executed two types of flight procedure in the experiments. One is a level flight including orbit and arc flight patterns for checking the performance of the stacked array antenna for null effects, and the other is approach flights from 1,500 feet altitude for testing the total performance of the GBAS system. We executed real-time DGPS positioning using GBAS augmentation messages through the approach flights.

Flight Experiment for VDB Stacked Array Antenna

First, we conducted level flight of 8,000 feet altitude. This flight includes two round trips from Sendai airport to 55 nautical miles (NM) away to the direction of 110° clockwise from magnetic north. Figure 9 shows results of this experiment.

A single VDB antenna with horizontal polarization has null problem and caused message errors near null points. Figure 10 shows result of previous experiment with single Alford-loop VDB antenna on level flight of 8,500 feet altitude in June 1999.

Figure 9 and Figure 10 show the receiving power level,

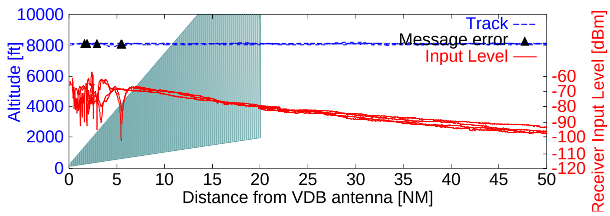

Figure 9: Results of level flight with 3 stacked array antenna in January 2001
The cadet blue area indicates the SARPs requirement coverage of GBAS-VDB

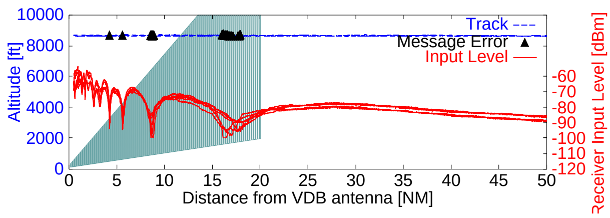

Figure 10: Results of level flight in previous experiment with Single Alford-loop antenna in June 1999

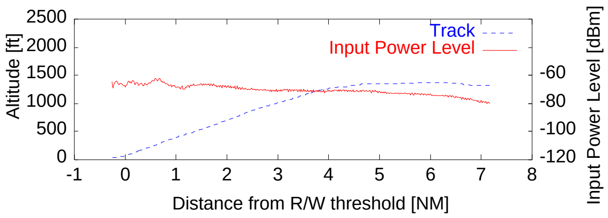

Figure 11: Results of approach flight with 3 stacked array antenna in January 2001

the altitude of aircraft, the positions of message error occurred, and SARPs requirement coverage of GBAS-VDB. The red solid curve is the receiving power level, the blue dashed line is the altitude of aircraft, the black triangle is the position of error occurred and the cadet blue area is SARPs requirement coverage. The horizontal axis indicates distance from VDB antenna, the left vertical axis displays the altitude of aircraft and the right vertical axis displays the receiving power level.

Figure 9 displays that there are no nulls and no message errors occurred in SARPs requirement coverage, while the null appears due to single Alford-loop antenna shown in Figure 10. Figure 9 shows the lowest null caused in inbound flight with elevation angle about 12.5° at the 6 NM distance from VDB antenna.

We conducted approach flight from 1,500 feet altitude for testing new VDB antenna performance at approach phase of flight. Figure 11 shows an example. The red solid curve is the receiving power level and blue dashed curve is altitude track of aircraft. The horizontal axis displays distance from the runway threshold and the left vertical axis displays the altitude of aircraft and the right vertical axis displays the receiving power level. The receiving power has enough level to satisfy the SARPs requirement and no errors were detected at the SARPs requirement coverage.

Reference Position

In the experiments, we used post-processed kinematic carrier-phase differential position fixes as reference positions of aircraft. Through flight in January 2001, we found bias errors in vertical direction and found that post-processed kinematics carrier-phase differential positioning jumped often, perhaps due to cycle slip, when the attitude of aircraft changed. Then we executed touch-and-go flight in July 2001, and we selected available data by altitude of aircraft trajectory on runway, when a separation, between altitude of aircraft trajectory and runway surface including height of GPS antenna on aircraft, was within about a foot.

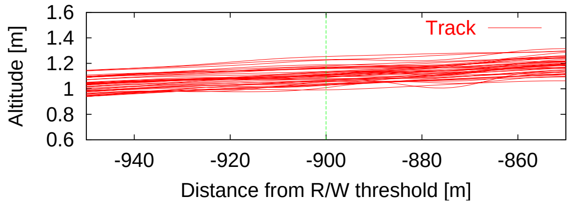

Figure 12: Post-processed kinematic positions on the runway
mean=1.106 [m], σ=0.061 [m], MAX−MIN=0.262 [m], 42 samples at 900 meters distance from runway threshold.

Figure 12 shows post-processed kinematic positions, when aircraft was on the runway. The red solid line is track of aircraft. The horizontal axis is distance from the runway threshold and the vertical axis is altitude from the runway threshold. At the 900 meters distance point from runway threshold, we estimate the positioning accuracy of post-processed kinematic was 6 centimeters (at 1 σ) in the experiments.

Flight Experiment of Real-time GBAS-DGPS positioning

We conducted approach flight for measuring GBAS positioning accuracy in January and July 2001.

Figure 13 and Figure 14 show tracks of twenty-seven times approach flights (touch-and-go flights) to B27 runway in July 2001. The horizontal axes of both figure

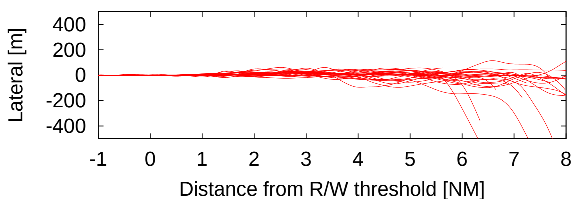

Figure 13: Horizontal Aircraft track

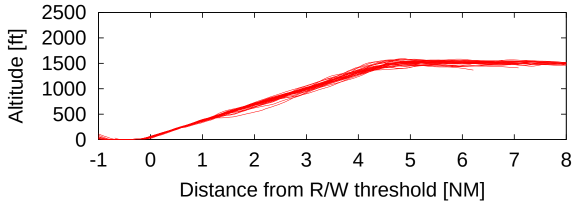

Figure 14: Vertical Aircraft track

show distance from the runway threshold. The vertical axis of the Figure 13 shows lateral shift from extended runway center-line, while the vertical axis of the Figure 14 shows aircraft altitude. These data were selected by aforementioned method.

Figure 15 shows vertical error, track of aircraft and B27 runway surface level. The horizontal axis shows horizontal distance from the runway threshold and the vertical axis shows vertical errors in meters and aircraft altitude in meters. The red solid line displays vertical errors of GBAS-DGPS, the blue dashed curve displays altitude of aircraft track and the black solid curve displays altitude of runway surface including height of GPS antenna on aircraft. We selected kinematics positioning data as references, when a separation of blue and black curve was within about a foot at touchdown point.

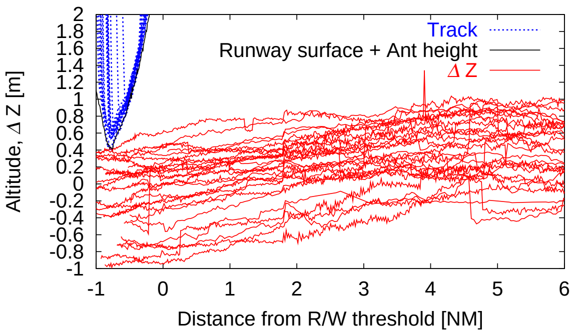

Figure 15: Vertical error and aircraft track

The vertical error by real-time processing data, shown in Figure 15, has a trend in accordance with distance from runway threshold. Then we checked GBAS parameters, and we found the tropospheric correction parameters ΔN_R, in type2 message, was wrong. Figure 16 shows results of re-calculated GBAS-DGPS. The axes are same in Figure 15 and the red solid line shows vertical errors. No trend would be found in this figure.

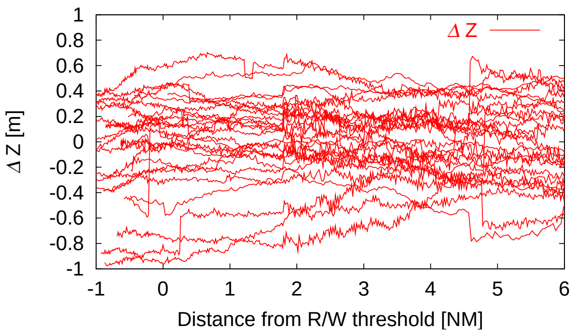

Figure 16: Corrected vertical error of re-calculated GBAS-DGPS

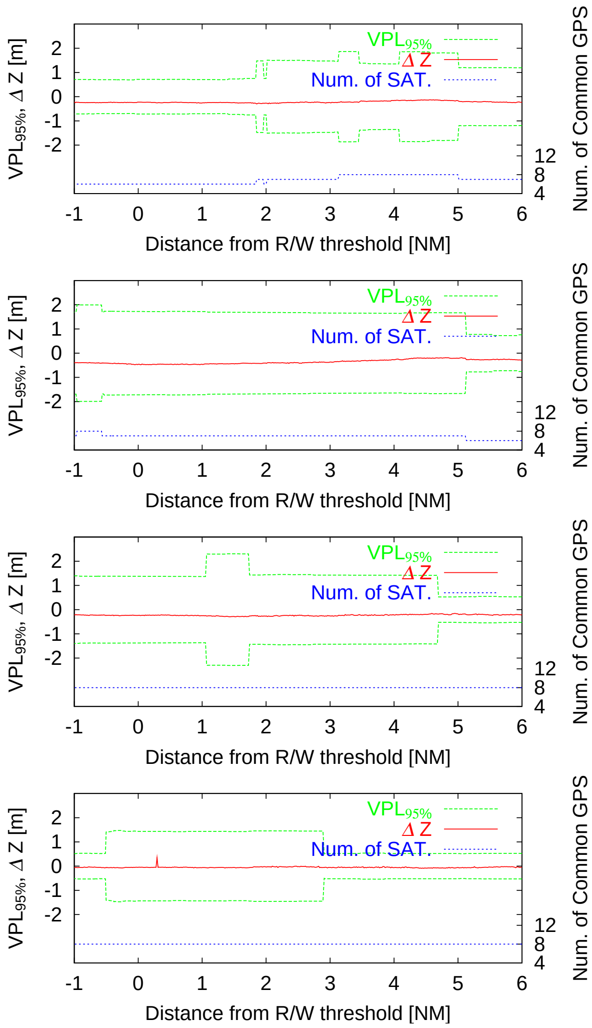

Figure 17: Examples of vertical error and $VPL_{95\%}$ 1st to 4th approaches in July 31 2001

Figure 17 and Figure 18 show examples of vertical error and $VPL_{95\%}$. The $VPL_{95\%}$ value indicates 95% probability value of VPL and to be compared with $VAL_{95\%}$. We bring in this value because we didn't have enough samples for statistics analyzing. A definition of $VPL_{95\%}$ is below.

$$VPL_{95\%} = \frac{2}{K_{ffmd}} VPL_{H0}$$

The K_{ffmd} is 5.847 (four references) for our experiments. The horizontal axes are distance from the runway threshold, the left vertical axes are $VPL_{95\%}$ and ΔZ (vertical error) in meters and right vertical axes are number of common GPS satellite. The green dashed line is $VPL_{95\%}$, the red solid line is vertical error and the blue dashed line is number of satellite using GBAS positioning.

Through the experiments, we found the vertical errors were always within $VPL_{95\%}$. When the number of common satellite was changed, the vertical error

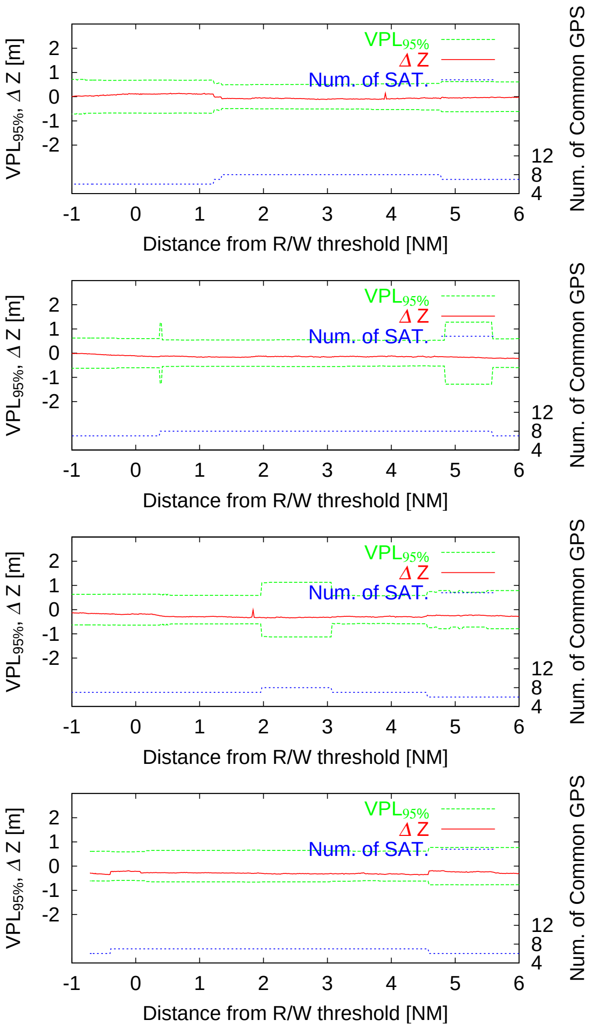

Figure 18: Examples of vertical error and $VPL_{95\%}$ 5th to 8th approaches in July 31 2001

experiences a step bias shift, shown in the 5th and the 8th approaches in Figure 18. But this shift was small, less than few ten centimeters. Also the lateral errors were within $LPL_{95\%}$, not shown in this paper.

Table 4 shows results of GBAS-DGPS errors with

Table 4: Results of GBAS-DGPS Positioning Errors (B27 R/W T&G, July 2001)

	ΔX	ΔY	ΔZ
mean value μ [m]	-0.207	0.012	0.009
std. deviation σ [m]	0.137	0.161	0.341
2σ [m]	0.273	0.323	0.682
$\lvert\mu\rvert + 2\sigma$ [m]	0.480	0.335	0.691
maximum value [m]	-0.485	0.737	-0.977
RNP95% [m]	—	16.000	4.000
AL95% [m]	—	13.682	3.421
number of samples	11623	11623	11623
approaches	27	27	27

Table 5: Positioning errors at monitor station

	ΔX	ΔY	ΔZ
μ [m]	-0.004	0.046	0.097
σ [m]	0.100	0.123	0.280
$\lvert\mu\rvert + 2\sigma$ [m]	0.204	0.292	0.657

regard to carrier-phase differential position fixes as reference of the approach flights. ΔX indicates error of along runway, ΔY indicates error of across runway (lateral) and ΔZ indicates error of vertical (altitude). The value of RNP95% is required navigation system error (95%) defined in SARPs [2] and AL95% value is modified alert-limit value with 95% probability value to be compared with 2σ error of experimental observations, computed with K_{ffmd} multiplier defined in SARPs [2].

We also analyzed data of the monitor station. The results of the analysis show $|\mu| + 2\sigma = 0.657$ [m] in the vertical errors, shown in Table 5. This result was better than at the airborne station , $|\mu| + 2\sigma = 0.691$ [m] shown in Table 4. Its value was appropriate with considerations of moving of aircraft and accuracy of kinematic positioning.

Table 6 shows specifications of NSE 95%. The results of the FAA flight test reported in the ION meeting [4] show the vertical errors ($|\mu| + 2\sigma$) was 1.6 to 2.3 meters at 100 feet above touchdown (CAT-II). Their system positioning accuracy was nearly CAT-II accuracy and LAAS CAT-III. Table 7 shows vertical and lateral navigation system error (NSE) at variant distance from the runway threshold in the approach of twenty-seven times touch-and-go flights to B27 runway with our experimental system. A distance of 900 meters correspond to CAT-I decision height, 300 meters correspond to CAT-II and 0 meters correspond to CAT-III.

Table 6: Specifications of NSE 95%

	specification according to GNSS draft SARPs [3]	specification according to LAAS MASPS
CAT I	200 feet decision height	
Lateral	≤ 16.0 m	≤ 16.0 m
Vertical	$\leq 4.0 \sim 6.0$ m	≤ 4.0 m
CAT II	100 feet decision height	
Lateral	≤ 6.5 m	≤ 6.9 m
Vertical	≤ 1.7 m	≤ 2.0 m
CAT III	50 feet decision height	
Lateral	≤ 3.9 m	≤ 6.2 m
Vertical	≤ 0.8 m	≤ 2.0 m

Table 7: NSE results, variant distance from R/W threshold

Distance of 300m corresponds to 100ft height above touchdown and distance of 900m corresponds to 200ft in case of gride path angle is 3°.

distance from R/W threshold	0m	300m	900m
	CAT-III	CAT-II	CAT-I
vertical			
μ [m]	0.001	0.002	0.002
σ [m]	0.389	0.397	0.359
$\lvert\mu\rvert + 2\sigma$ [m]	0.778	0.795	0.721
lateral			
μ [m]	−0.040	−0.038	−0.026
σ [m]	0.175	0.166	0.166
$\lvert\mu\rvert + 2\sigma$ [m]	0.390	0.371	0.358
number of samples	27	27	27

The results of 95% probability vertical error ($|\mu| + 2\sigma$) was 0.80 meters at 300 meters distance from threshold and 0.79 meters above threshold, and CAT-II specification of vertical NSE is 1.7 meters and CAT-III is 0.8 meters. Comparing these values, our experimental system has enough accuracy using CAT-II and it has nearly CAT-III accuracy.

CONCLUSIONS

This paper presents the information of current GBAS developing and evaluating status in Japan.

We clarified following two matters in this paper.

- Using the stacked array VDB antenna is one of the best solutions for the null problem according to level flight experiments.
- Positioning accuracy of our experimental GBAS-VDB system satisfies GBAS NSE specifications for the CAT-II and the system accuracy is nearly equal to CAT-III.

We will upgrade of reference GPS antennas and check for integrity of our GBAS equipment by more experiments.

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REFERENCES

[1] S. Saitoh, S. Fukushima, N. Fujii; *Results of GBAS flight test* (described in Japanese language), Proceedings of the 32nd ENRI lecture meeting, June, *2000.*

[2] ICAO, SARPs, Annex 10, Nov., *2001.* (publishing schedule)

[3] Report of ICAO GNSSP WG/B, Appendix E, Wellington New Zealand, Mar., *1998.*

[4] John Warburton, Cliff Mackin, Ruben Velez; *Flight Test Results of the FAA Local Area Augmentation System Test Prototype*, Proceedings of the ION 53rd Annual Meeting , *1997.*