Development and Performance Verification of Ground-Based Augmentation System through ILS inspection Procedure

ABSTRACT

There have been many researches to guarantee the required navigation performance of the CNS/ATM sub-systems(GBAS, SBAS, etc.) mainly in the accuracy or integrity aspect. However, it is also important the study about the interoperability and natural transition between the old and new nav-aids because of the very different features of them. Therefore, we focused on the verification of the performance of the new systems, especially GBAS, through the comparison with the conventional aircraft landing guidance system such as ILS. For the verification, we developed the GBAS system and conducted the ground tests, flight tests, and integrity monitoring tests. Additionally, in the analysis of the test data, we compared the GBAS navigation solutions with the data which are collected from the ILS inspection device - theodolite. From the analysis, we concluded that the developed GBAS system satisfied the Precision Approach Category I requirements in the aspect of accuracy, and had the consistency with the conventional aircraft precision approach guidance system.

INTRODUCTION

ICAO decided to use GNSS instead of the navigation aids that have been used up to the present. This system is based on GPS, GLONASS, Galieo and the augmentation systems to provide better performance. For the standardization of the system, ICAO provided the technical standards for GPS, GLONASS, SBAS and GBAS, and advised each country to develop and to utilize the system.

To prepare for future satellite navigation system, Civil Aviation Safety Authority(CASA) and KAC(Korea Airport Company) decided to develop GBAS in 1997. The first GBAS prototype was developed according to the research program of three years. Afterwards, it has been conducted the research and development program; the performance evaluation and modification of the prototype.

This paper provides the H/W and S/W configuration of the GBAS system and various analyses about the performance through the flight tests and integrity monitoring tests.

SYSTEM CONFIGURATION

This section describes the configuration of the GBAS ground system and the airborne system used in performance evaluation of the ground system.

GBAS Ground System

The ground system includes a GNSS receiver, a VHF data link device for the communication with the airborne system and a PC. The PC controls the H/Ws, processes the GNSS measurements and displays the statuses of the entire ground system. Figure 1 describes this configuration, and Figure 2 is the screenshot of the ground system S/W operating.

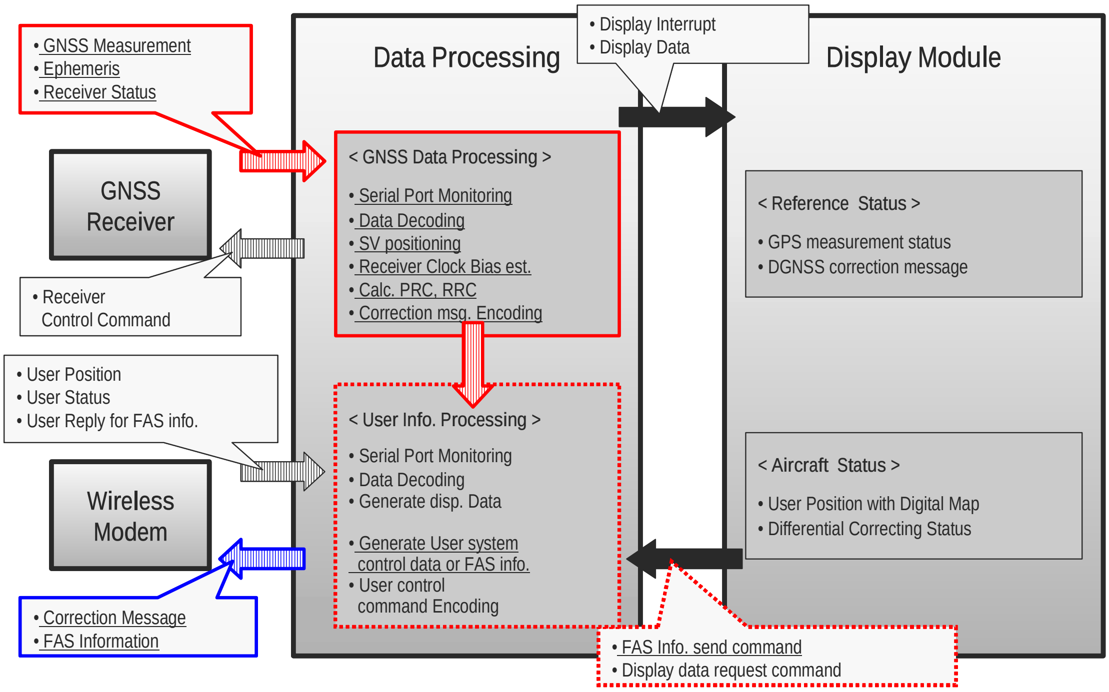

Figure 1. Configuration of Ground System

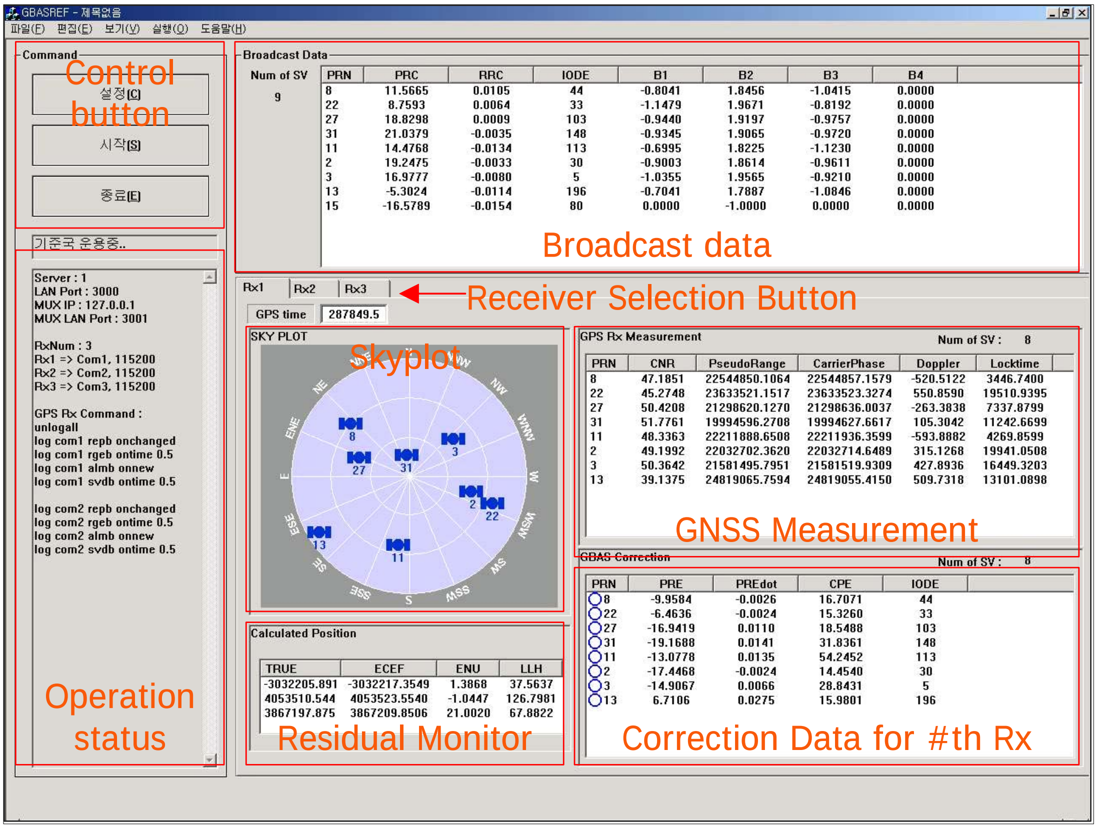

Figure 2. Screenshot of Ground System S/W

This is similar to general DGNSS reference station, meets the international standards of ICAO. This system uses the GBAS standard data transmission protocol, SARPs suggested by ICAO. Compared with the basic DGNSS correction transmission protocol (RTCM), SARPs can provide higher resolution correction data, more precise statistical confidence level of the correction, and more tightened integrity monitoring parameter. Four message types are defined currently.

Airborne System

Like the ground system, airborne system also includes a GNSS receiver, a VHF data link device and a PC. PC controls the H/Ws, processes the GNSS measurements, and shows cockpit display. Figure 3 describes the configuration of the airborne system.

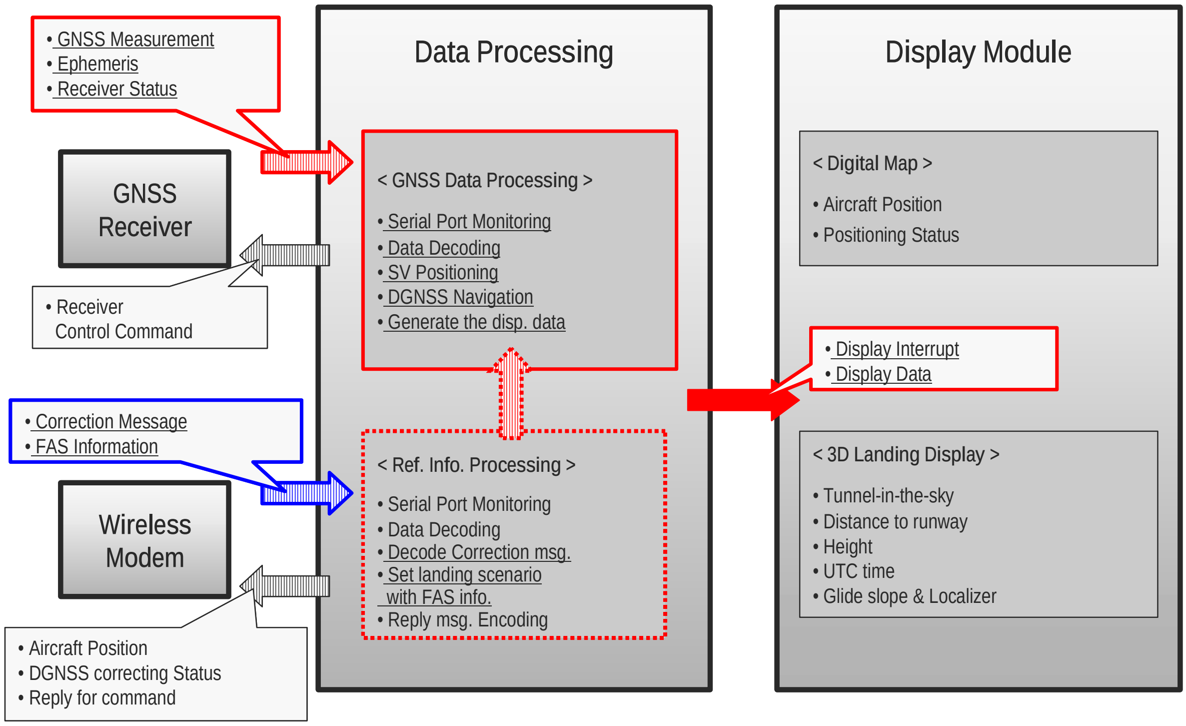

Figure 3. Configuration of Airborne System

Airborne system S/W consists of two parts; the navigation module and cockpit display module. The navigation module determines the various nav-solutions including the position, velocity, and attitude of the aircraft from the GNSS measurements and correction data. The solutions are transmitted to the cockpit display module via ethernet. The cockpit display module transforms the nav-solutions into geometrical and spatial information via tunnel-in-the-sky over the background to which the virtual reality is applied. Figure 4 and 5 are the screenshots of the each S/W module in airborne system.

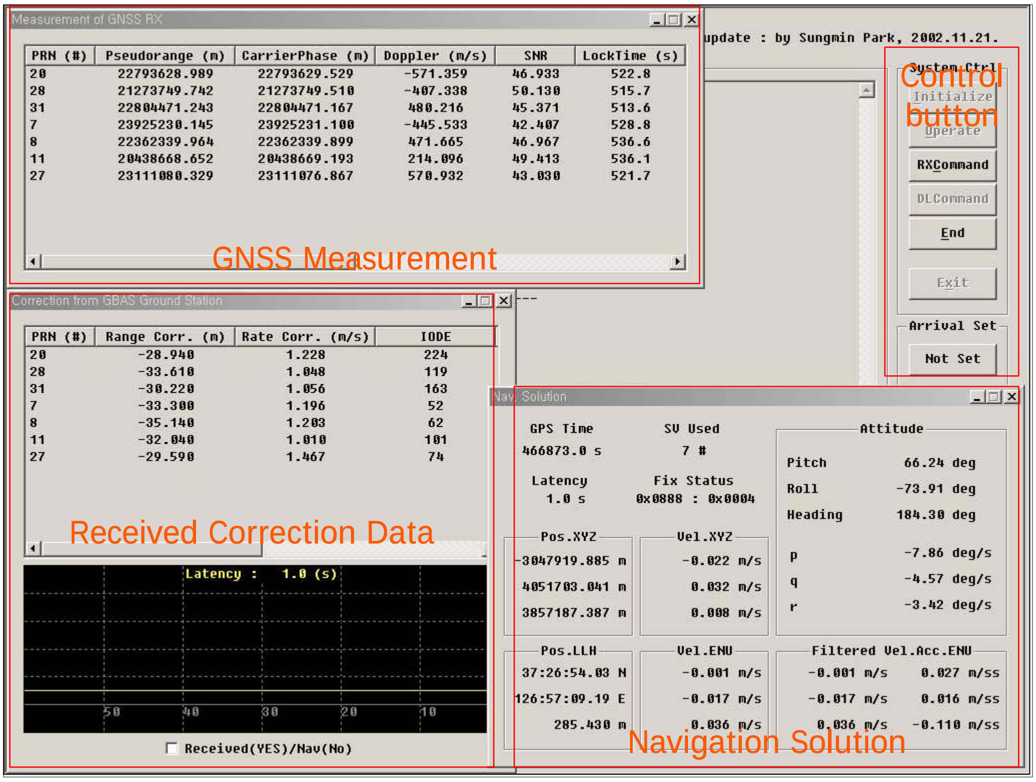

Figure 4. Screenshot of Airborne System : Navigation

Figure 5. Screenshot of Airborne System : Cockpit

PERFORMANCE ASSESSMENT

We implemented the ground and airborne system. From 2000 to 2002, we conducted ground and flight tests for the performance assessment of accuracy, and integrity monitoring tests for that of integrity. This chapter includes the each test process and the analysis results of them.

Ground Test

Before flight tests, we conducted three types of ground tests at Ulsan airport; static zerobaseline and non-zerobaseline test for 24 hours respectively, and dynamic test using a mini-van.

The results of static tests are shown in Table 1. Both horizontal and vertical positioning errors of the non-zerobaseline test are bigger than those of the zero-baseline test because of non-common error sources.

Table 1. Static Test (meter, 2DRMS, 95%)

Test	horizontal	vertical	Remarks
zerobaseline	0.219	0.323	24 hours
non-zerobaseline	1.149	1.602	24 hours

We installed the airborne system in a mini-van and drove road around runway for ten times. Figure 6 shows the differences between the real-time navigation solution and the true trajectory of the vehicle. The way to determine the true trajectory will be mentioned afterwards. Table 2 summarizes the statistical values resulted from the accuracy analysis using the positioning errors in Figure 6.

Table 2. Dynamic Test (meter, 2DRMS, 95%)

Test	Horizontal	Vertical
Dynamic Test	1.225	1.686

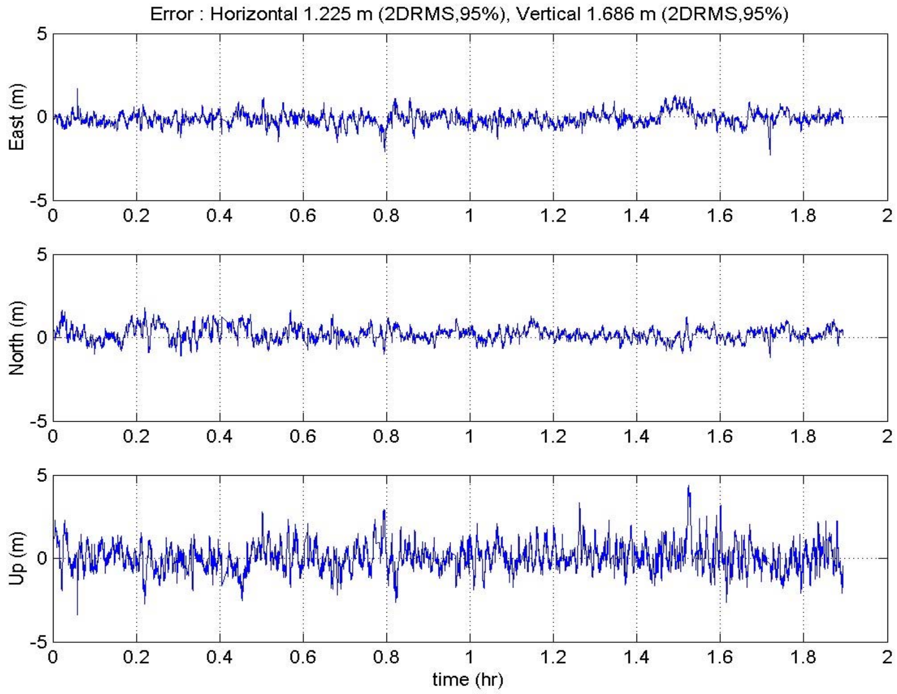

Figure 6. Hor/Vertical Errors vs. Time (Dynamic Test)

These results of the ground tests show the potential that the developed GBAS system may satisfy the Precision Approach Category I requirements.

Flight Test

Flight tests were performed at the Ulsan airport with the inspection aircraft (Challenger 601/3R) owned by the CASA (Figure 7).

Figure 7. Inspection Aircraft : Challenger 601/3R

Flight Scenario : The GBAS coverage volume presented by FAA consists of two sub-volumes. One is the approach coverage volume. The other is the VHF data broadcast coverage volume. The volumes may be sketched roughly like a cylinder as presented in Figure 8. We designed a flight scenario for the approach coverage volume: 1) approaching to the origin of the Ulsan airport with level flight at the altitude of 10,000ft, 2) bypassing the origin and flying out along the line of positive 35°direction, 23 nm radius and the altitude of 1,300ft. 4) After the flight test for approach coverage volume, the aircraft repeats the precision approach procedure.

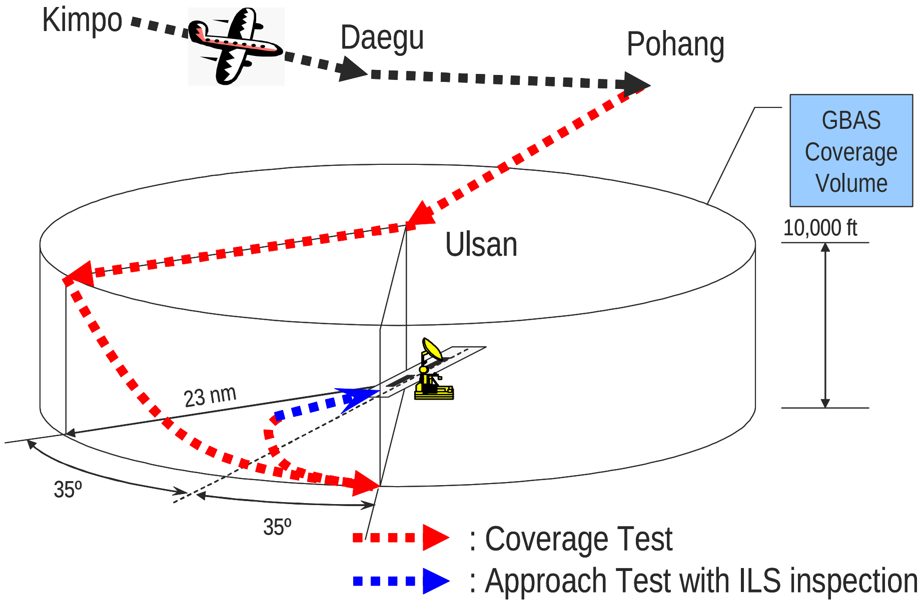

Figure 8. Flight Scenario

Accuracy Analysis : To obtain the true trajectory of the vehicle, we adopted Ashtech Z-12 receiver, which shared the GNSS antenna with GBAS airborne system. If the data collected by the Ashtech receiver are post-processed, we can get the vehicle's trajectory that has the accuracy of cm-level. It is sufficient to analyze the GBAS accuracy performance of meter-level.

We considered only the epochs at which the aircraft are within the GBAS coverage volume and the real-time positions were computed without failure of data link caused by the local terrain.

However, in case of the flight test, the aircraft is maneuvering from right above the ground to more than altitude 10,000ft. It resulted in the varying accuracy level according to the height of the aircraft because the correlation of the GNSS error sources, especially tropospheric delay is gradually lowered in proportion to the difference between the GNSS antenna of ground and airborne system.

Out of the documents that describe the GBAS, RTCA/DO-245 suggests the horizontal and vertical accuracy level, that is, NSE (Navigation Sensor Error) with 95% error limit value as a function of the distance and height from the touchdown point. Table 3,4 show the horizontal and vertical NSE limits for the each precision approaches.

Table 3. Horizontal NSE Limit[5]

Type	95% Horizontal NSE Limit (meter)	Distance (D, meter)
CAT-I	≤ 16.0	291 〈 H ≤ 873
	≤ 0.00176*D + 14.46	873 〈 H ≤ 7212
	≤ 27.2	H 〉 7212
CAT-II/IIIa	≤ 6.9	0 〈 H ≤ 291
	≤ 0.000835*H + 6.66	291 〈 H ≤ 7212
	≤ 12.7	H 〉 7212

Table 4. Vertical NSE Limit[5]

Type	95% Vertical NSE Limit (meter)	Height (H, feet)
CAT-I	≤ 4.0	100 〈 H ≤ 200
	≤ 0.0117*H + 1.66	200 〈 H ≤ 1290
	≤ 16.7	H 〉 1290
CAT-II/IIIa	≤ 2.0	50 〈 H ≤ 100
	≤ 0.0117*H + 0.83	100 〈 H ≤ 1290
	≤ 15.9	H 〉 1290

For the 20 tests of precision approaches, Figure 9 shows the horizontal trajectories determined from the GBAS navigation solutions, and Figure 10 shows the vertical trajectories. These trajectories are compared with the carrier DGNSS trajectories determined from the Ashtech Receiver.

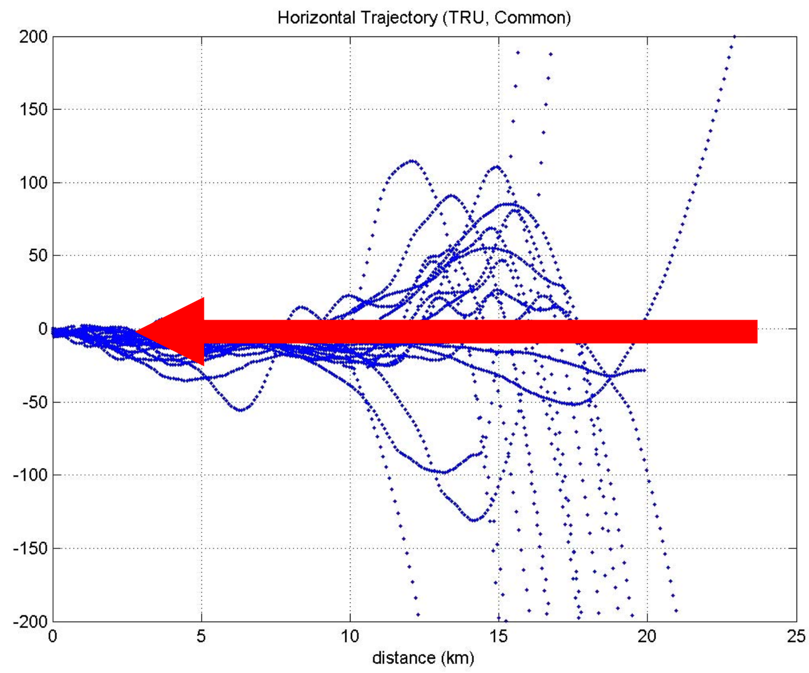

Figure 9. Horizontal Landing Trajectory

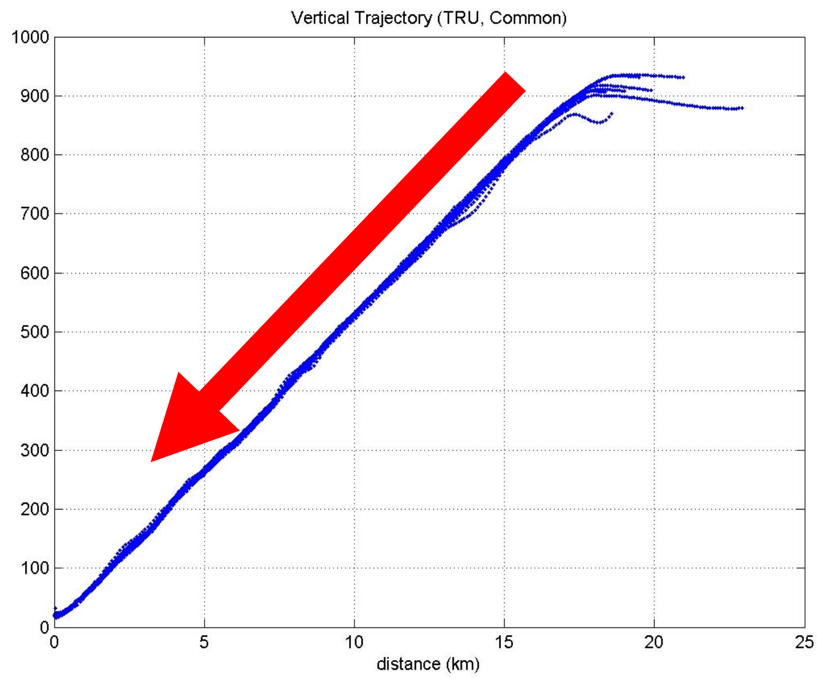

Figure 10. Vertical Landing Trajectory

Considering the suggested requirements, we can find that the vertical error limit is more threatening to the GNSS-based sensors than horizontal one. Generally, the GNSS positioning error is less accurate in vertical direction because of the satellite constellation. Here, it is presented only the vertical NSE values of the developed GBAS system. In Figure 11, the first shows the error samples of the GBAS navigation solutions, and the second means the 95% values of the samples.

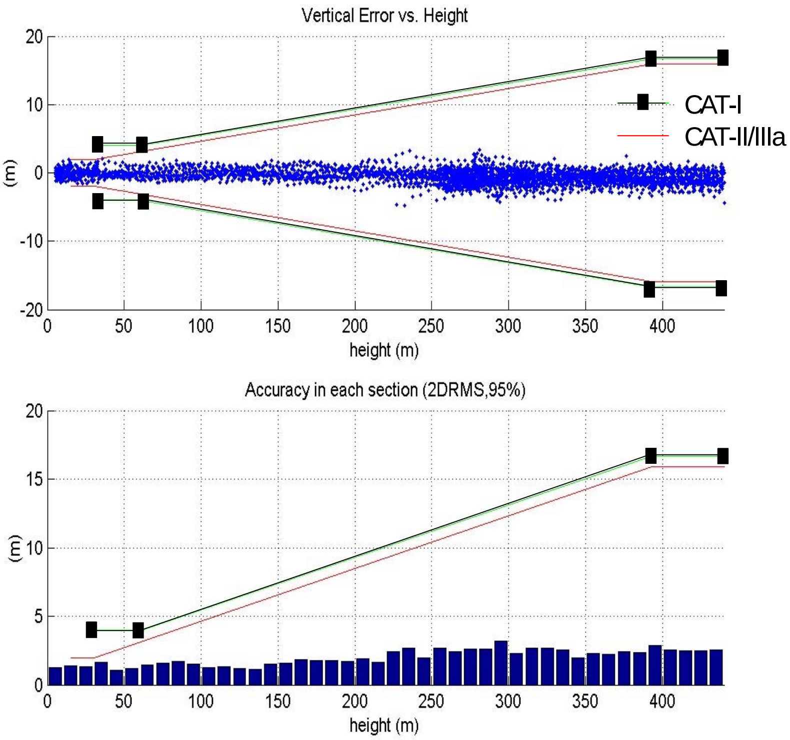

Figure 11. Vertical Error vs. Height (Flight Test)

This figure shows that the GBAS system can meet sufficiently the Category I precision approach requirement in the accuracy aspect out of the parameters of RNP (Required Navigation Performance). It will be proved the actual performance of the system through more flight tests that were scheduled.

Integrity Monitoring Test

GBAS Integrity Monitoring Functions : Figure 12 shows the GBAS integrity monitoring procedure. 3 GNSS antennas and receivers have been installed and each antenna and receiver receives the GNSS signal to process measurements. While the measurements are being processed, QM (Quality Monitoring) functions work. Then, the system generates broadcast data with the measurements that have been processed in each receiver and passed MRCC (Multiple Receiver

Consistency Check). At last, VDB broadcasts the correction messages to the airborne subsystem.

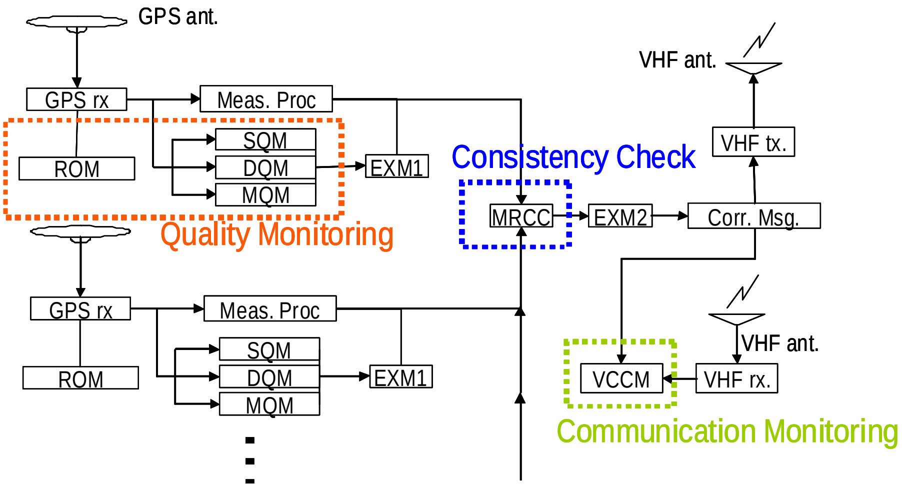

Figure 12. GBAS Integrity Monitoring Procedure

The system has six monitoring functions. ROM (Receiver Operation Monitoring) monitors the receiver operation status. QM function has three parts-SQM (Signal Quality Monitoring), DQM (Data Quality Monitoring), and MQM (Measurement Quality Monitoring). SQM assess power and code structure of received signal to confirm that they are within specifications. DQM checks the navigation messages to confirm that the calculated satellite positions are valid. MQM monitors the pseudorange and carrier phase measurements to detect excessive acceleration, such as step or other rapid changes of them. And MRCC checks the consistency of the measurements from each reference receivers to detect failures of receivers. VCCM (VHF Communication Channel Monitoring) monitors the broadcasting status. This integrity monitoring system shall cease broadcast of a failed ranging source measurement block within 3 seconds of the onset of the failure.

Quality Monitoring Test : To test QM functions, we constructed a test bed as shown Figure 13. For the nominal and failure test, GNSS simulator (STR 4500) was used in generating simulated GNSS signal. The GNSS simulator system is GSS STR4500 of Spirent Communication LTD. The specifications of GNSS simulator is described in Table 5. The system consists of two part-RF signal generator and computer controller. A simulator control software in the computer controls the RF signal part (Figure 14) and shows position, attitude, GNSS satellite information and simulated measurements. For failure test, some faults are injected into the simulation scenario-by-scenario generation system-GSS STR4760 of Spirent Communications LTD. With this test, we could conclude that the QM functions works as we expected.

Table 5. Specification of GNSS Simulator

Sub-systems	Spec.
RF Signal Generator	L1 1575.42 MHz 12 Channels GPS C/A with data at 50bps Level -130dBm nominal
Controller	CPU 433MHz OS : Microsoft Windows98 TM USB port RAM : 64Mb

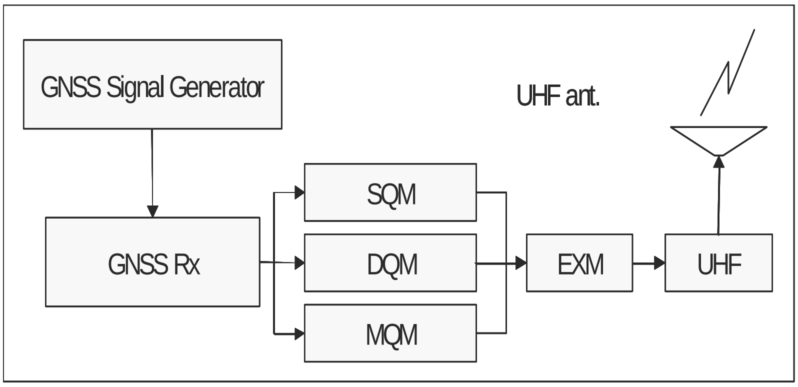

Figure 13. Quality Monitoring Test Bed

Figure 14. GNSS Simulator : RF Signal Part

MRCC Test : To test MRCC function, we used 3 GNSS antennas and receivers. In this test, we didn't use GNSS simulator but real GNSS signal. To simulate a faulted situation, we intentionally injected biases into pseudoranges of a receiver. Figure 15 shows PRCs(PseudoRange Corrections) from three receivers and the averaged PRC. In this test, biases were injected into Rx 1, so the PRC of Rx 1 is far from those of other receivers. To detect the fault, we calculated B-values which are receiver failure check indexes and the fault detection threshold of them. In Figure 16, we can decide that the B-value of Rx 1(B1) is over the threshold and Rx 1 has some faults. Then, we can exclude the faulted measurement, and generate correct averaged PRCs for broadcasting(Figure 17).

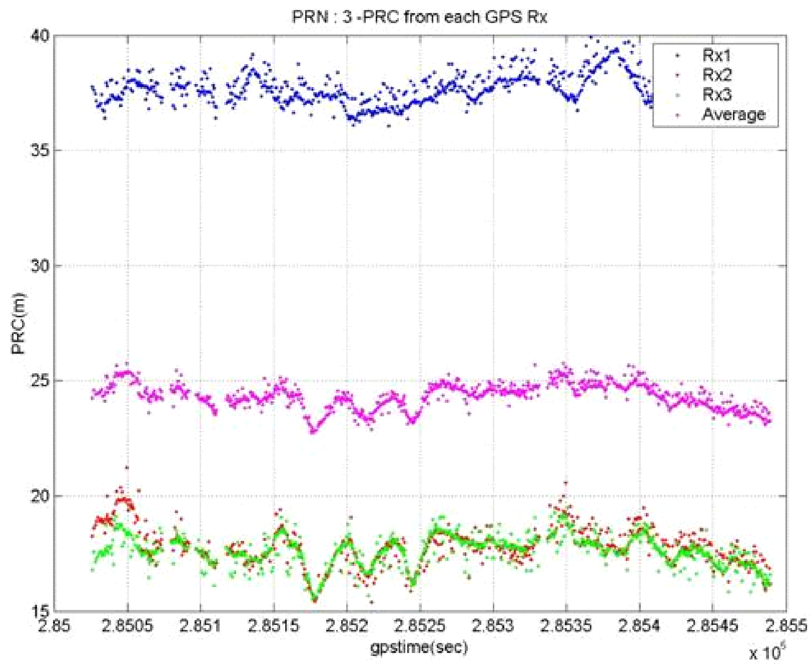

Figure 15. PRCs from each Receiver and Averaged PRC

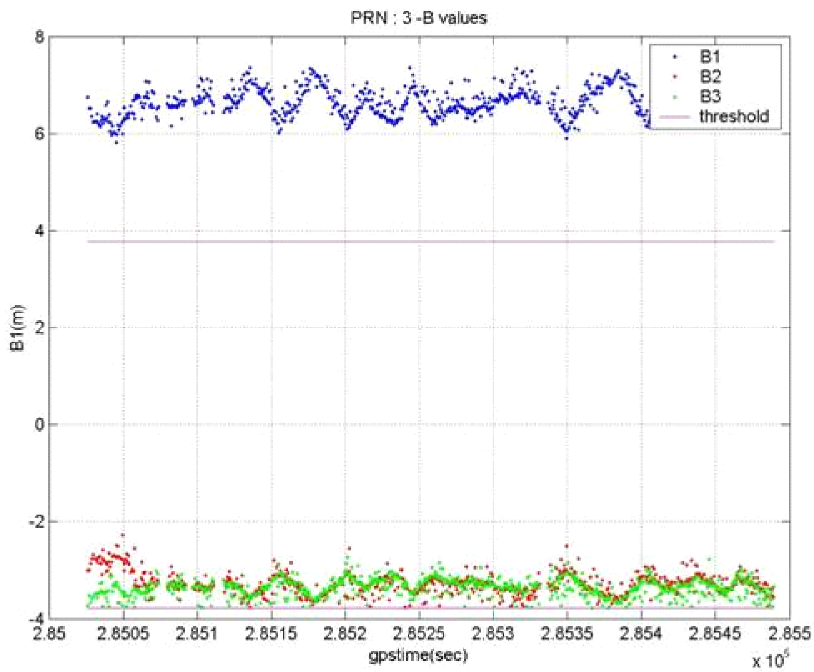

Figure 16. B-values for each Receiver

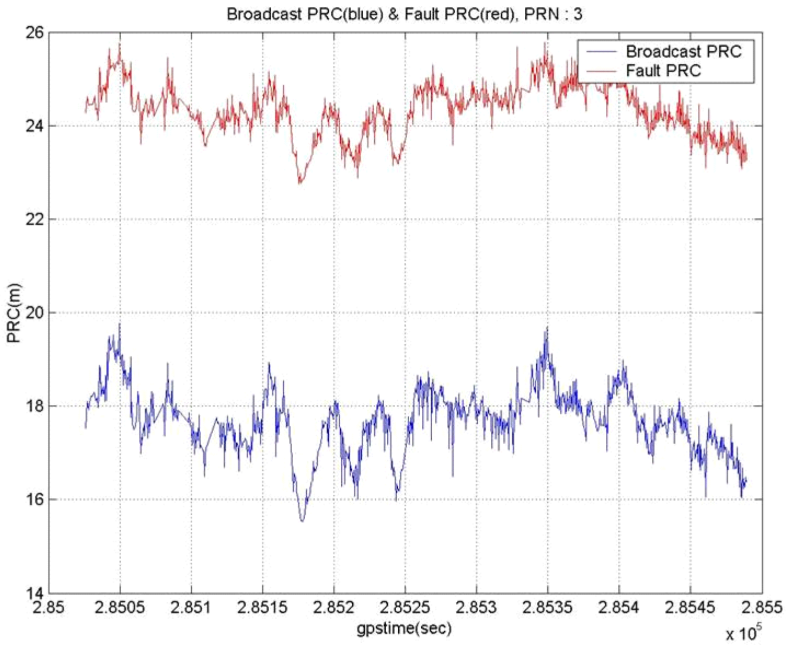

Figure 17. Exclusion of Faulted Measurement

COMPARISON WITH THEODOLITE

Until now, we have dug into the GBAS system by comparing with the true system, Ashtech Z-12 receiver. However, the true system is also based on the GNSS. Therefore, we have to follow a different way to verify the consistency between the developed GBAS and conventional nav-aids. The GBAS is devised to replace the systems that serve as a guide for precision approach of aircraft, such as ILS, MLS, etc. Therefore, we can verify the previously analyzed GBAS performance by comparing with those systems.

Theodolite is a measuring or surveying device by reading the elevation and azimuth angle of the target object from a reference, also used in the inspection of ILS. The theodolite measurements are transmitted to the inspection aircraft via wireless modem. So, the inspection system determine the status of ILS system by comparing them with received ILS signals. Our objective is to compare the theodolite measurement with our GBAS navigation solution, and confirm the consistency between them.

Figure 18 shows that, with a theodolite, a inspector measures the true trajectory - described by GP (Glide Path) and LLZ (Localizer) angle - of the aircraft that now tries to land on the runway.

Figure 18. Theodolite

The most different feature of the GNSS against the conventional systems is the coordinate system. GNSS is based on the WGS-84 ellipsoid. But the others are based on the locally defined ellipsoid (ex. Bessel ellipsoid) or other coordinate system such as TM (Transverse Mercator) projected coordinates. The differences are not dealt successfully with only a few simple transformations between them.

According to the documents related to the GBAS or GNSS, the FAS (Final Approach Segment) parameter will be defined with the WGS-84 ellipsoid and its coordinate system. Therefore, it is necessary to transform the conventional coordinate values of the reference points in each airport after the minute investigations, or re-survey them totally.

We compared the recorded theodolite data with the GP and LLZ angles into which the GBAS navigation solutions are transformed (Figure 19). In calculation of the GP and LLZ angle from the GBAS nav-solution, we considered the distortion of the reference plane (WGS-84 ellipsoid or Mean Sea Level), and solve the inherent problem to a sufficient extent. Therefore, there is no serious problem caused by the reference plane. The results are presented in Figure 20 (GP) and 21 (LLZ).

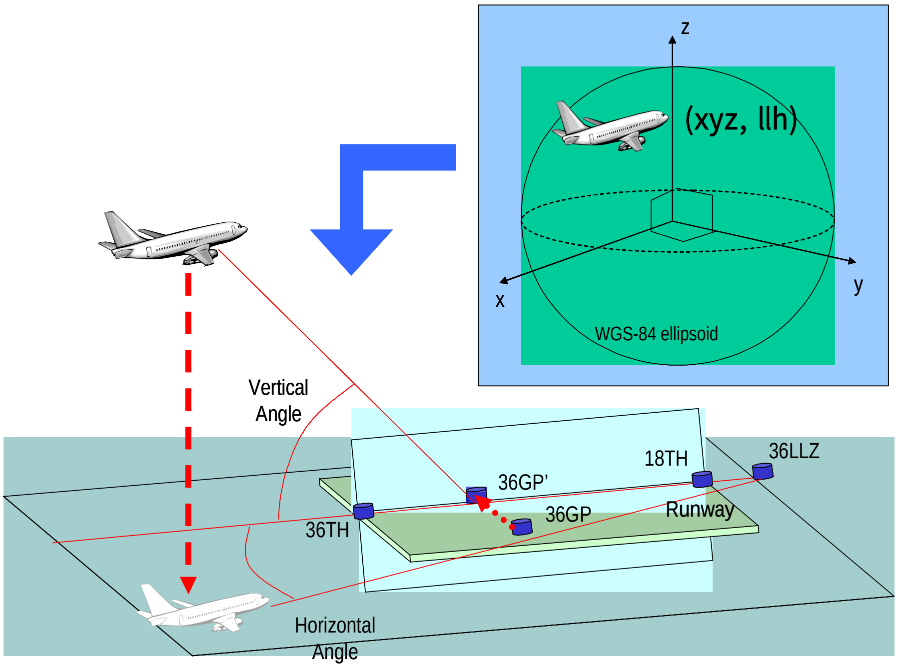

Figure 19. Coordinate Transform

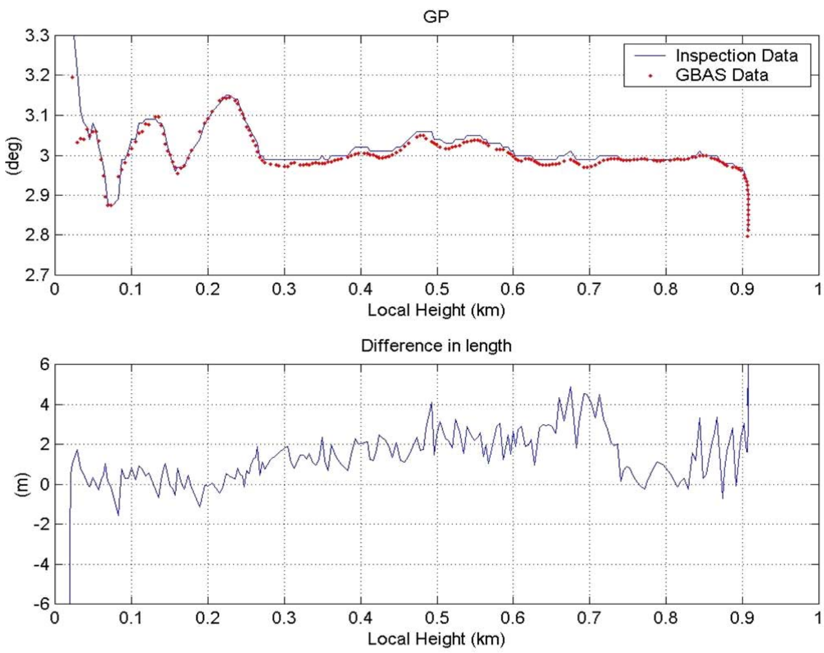

Figure 20. Comparison of Glide Path Angle

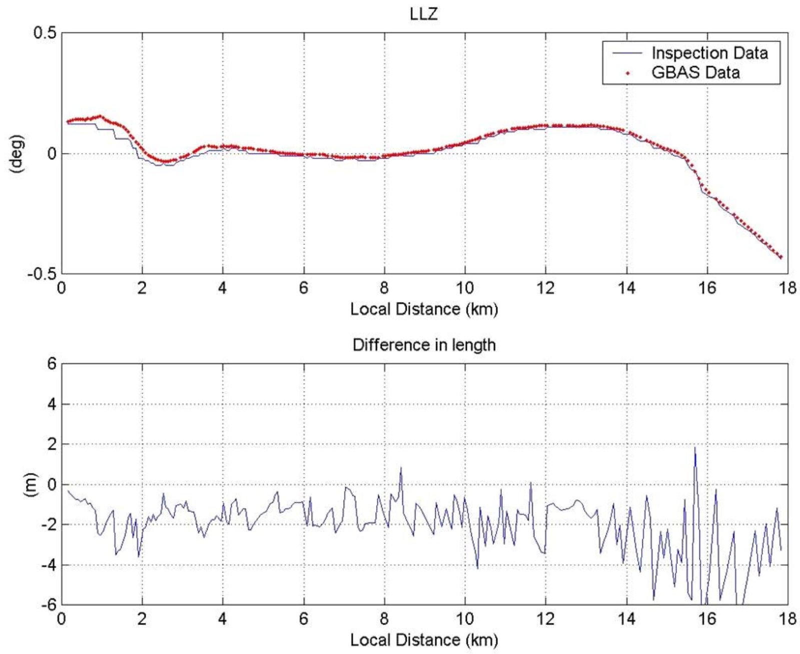

Figure 21. Comparison of Localizer Angle

In each figure, the first shows the GP and LLZ angle profile in angular unit. The blue line is the theodolite data and the red dot is the GP angle calculated from the GBAS navigation solutions. The second plot shows the differences in length unit.

Even though we can see the consistency between the GBAS navigation solutions and the theodolite deviation angles, there are some regions where the difference values are over the 4 meters. These are caused by the limitations of the theodolite used in flight inspections as follows.

1) Theodolite-operational error caused by the inspector, generally 0.02 deg.
2) Lever arm between ILS antenna and GNSS antenna installed on the aircraft. It is varying according to the attitude of aircraft.
3) 0.01 deg resolution of the theodolite measurement.

Through the simple calculations, we can see the accuracy level of the theodolite graphically in Figure 22. The error of the angular measurement may be amplified according to the distance from the reference point. The maximum error is over the 1 meter in the region where the distance is about 3 km. Therefore, the theodolite data may not be composed into the true trajectory of the aircraft, but used as a reference to verify the consistency between the GBAS and the conventional landing guidance system such as ILS.

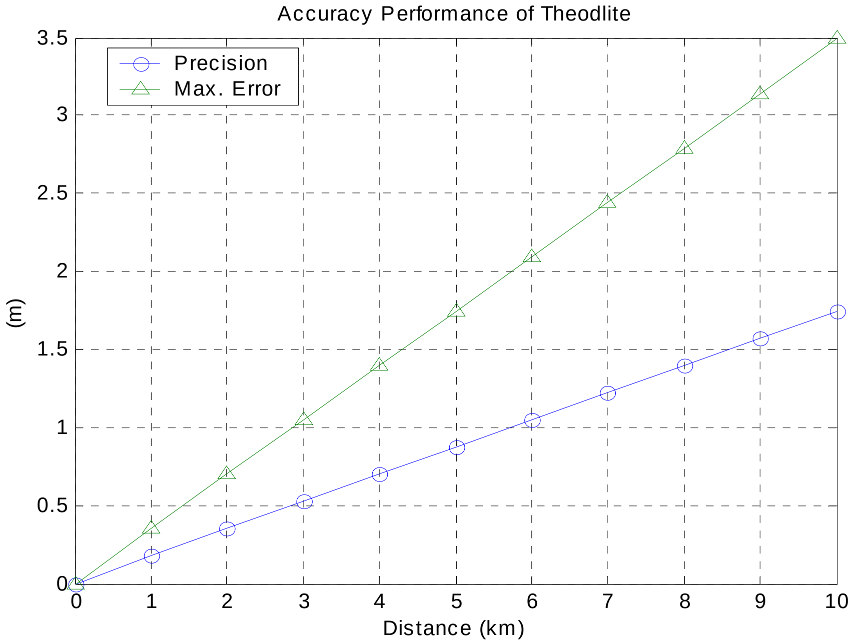

Figure 22. Accuracy Performance of Theodolite

The differences of GBAS nav-solutions from the theodolite data are less than 0.04 deg excluding the region where the measurements are not confidential (around the GP antenna), and the error values in the length unit are still below the requirements of Category I. Although there are the above-mentioned limitations, we can find that the GBAS system is consistent with the conventional systems.

CONCLUSIONS

This paper included the introduction to the GBAS system developed in Korea, and its performance evaluation process. The GBAS system satisfies the Standards and Recommended practices suggested by ICAO. Moreover, the performance meets the Category I requirement.

We conducted the ground tests and the flight tests in parallel with the ILS inspections including GBAS coverage volume tests and precision approach tests. In the process of accuracy performance evaluation, we adopt the post-processed carrier DGNSS positions as a true trajectory of aircraft. Because the way can not detect any bias included in GNSS, we try to compare the GBAS navigation solutions with the ILS inspection device, theodolite. So, we found the consistency between them. This means that the new landing guidance system is consistent with the conventional one such as ILS. However, there are some unavoidable limitations of the device and error sources added in its operation. More systematic test and analysis will be scheduled for the next flight.

For integrity monitoring, monitoring functions have been included in the system. For the test of this system, a GNSS simulator that can generate simulated GNSS signal and inject arbitrary faults into the signal was used. And the simulation scenarios for nominal and failure tests were generated. Several tests were performed so that the integrity monitoring functions implemented in the system are confirmed that they works as we expected. For evaluation of the system, more tests should be performed for long time and for many different cases.

We will continue to develop and to modify the GBAS system to meet the Category II and III requirements. We hope that this research activity on GNSS in Korea will contribute to the development of global civil aviation technology.

ACKNOWLEDGEMENTS

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