Regional Integrity Analysis using modernized GPS, Galileo and SBAS

*Sang Sul Han[1], Dae Sik Shin[2], Jong Chul Cho[3], Chansik Park[4], Hyang-Sik Jun[5], Gi-Wook Nam[6], Sang Jeong Lee[7]

[1]Agency for Defense Development (E-mail: ieedall@add.re.kr)
[2] Department of Electronics Engineering, Chungnam Nat'l Univ.(E-mail: shin6050@cslab.cnu.ac.kr)
[3] Department of Electronics Engineering, Chungnam Nat'l Univ.(E-mail: nix4102@cslab.cnu.ac.kr)
[4] School of Electrical and Computer Engineering, Chungbuk Nat'l Univ.(E-mail: chansp@chungbuk.ac.kr)
[5] Korea Aerospace Research Institute (E-mail: hsjun@kari.re.kr)
[6] Korea Aerospace Research Institute (E-mail: gwnam@kari.re.kr)
[7] School of Electrical and Computer Engineering, Chungnam Nat'l Univ.(E-mail: eesjl@cnu.ac.kr)

Abstract

ICAO defines performance requirements of navigation system such as accuracy, integrity, continuity and availability. The integrity is most significant performance requirement in aviation where safety of life is crucial. Many researches on this topic anticipate that GPS with SBAS or Galileo can meet APV requirements and GPS with GBAS or Galileo with GBAS will meet CAT II and III requirements. These performance expectations are based on global analysis. In this paper regional integrity analysis in Korea using various combinations of modernized GPS, Galileo and SBAS is given. The simulation results show that CAT I requirement can be met using modernized GPS and Galileo alone, however, CAT II and III are not met even augmenting SBAS because of VPL. A more efficient augmentation such as GBAS which can reduce VPL dramatically is required to meet CAT II and III in Korean region.

Keywords: Integrity, HPL, VPL, GPS modernization, Galileo, SBAS

1. Introduction

Not only accuracy but also integrity, continuity, and availability are significant performance measure of navigation system in aviation area, therefore, ICAO (International Civil Aviation Organization) defines RNP (Required Navigation Performance). In near future, GNSS (Global Navigation Satellite System) guarantees better performance owe to GPS modernization and Galileo. Many researches on the integrity monitoring have been performed. RAIM (Receiver Autonomous Integrity Monitoring) is easy to implement and gives reasonable performance but it still hard to apply to aviation where safety of life is most crucial. In GIC (Ground Integrity Channel), base stations at known place are monitoring the satellite signals and transmission media to generate the integrity information to broadcast to nearby users. PL (Protection Level) and IR (Integrity Risk) are most popular concepts in GIC. PL is used in WAAS (Wide Area Augmentation System) and LAAS (Local Area Augmentation System). Users compute PL and compare it with predefined AL (Alarm Limit) to evaluate integrity monitoring using its own measurements and received integrity information from base stations. IR is proposed and used in Galileo where integrity risk instead of PL is directly computed. It will satisfy 99.5% availability while current PL in WAAS provides 95% availability [1]. In Galileo, multi regional integrity monitoring system named ERIS (External Regional Integrity System) is also considered which strengthen the integrity in regional base [2].

The results of many researches anticipate the requirement of APV (Approach Operations with Vertical Guidance) can be easy met using modernized GPS and Galileo. Nevertheless, it is expected that GNSS alone cannot satisfy the ICAO requirements. Therefore augmentation is needed for a precise guidance and navigation system near the airport. The requirements of CAT (Category) I, II and III can be met by GPS and GBAS (Ground Based Augmentation System) or Galileo and GBAS. These expectations are based on the global analysis and do not concerns the combined use of the modernized GPS and Galileo. The primary objective of this research is to evaluate the regional performance of various combinations of modernized GPS, Galileo, and SBAS. The GSSF-SVS (Galileo System Simulation Facility – Service Volume Simulator) from VEGA Informations-Technologien GmbH is used as simulation tool. This program supports PL with GIC and RAIM but not IR yet.

In the next chapter, integrity monitoring concept and UERE (User Equivalent Range Error) budget are described. In the chapter 4, this paper shows simulation results for integrity performance in Korea. Finally, conclusion of this research is proposed in the last chapter.

2. Required Navigation Performance

ICAO regulates performance requirements of the navigation system in aviation. These requirements depend on flight altitude, visible range, and decision altitude for flight phase. ICAO presents each requirement for accuracy, integrity, continuity, and availability and requests navigation system to satisfy these requirements. Relationship between these requirements is represented well in figure 1. And table 1 shows each performance requirement for flight phase[7].

First of all, navigation system should satisfy the accuracy performance which has most obvious requirement. Thereafter integrity performance can be considered. And thereafter continuity and availability performances can be considered also. In this paper, integrity performance only is considered for simplicity of analysis.

Figure 1. Relationship between performance requirements

Table 1. Performance requirement for flight phases

Operation	Accuracy (95%)	Integrity		
		Integrity (1-Risk)	Alert Limit	Time-to-Alert
Oceanic	12.4nmi	$1\text{-}10^{-7}$/hr	12.4nmi	2min
En-route	2.0nmi	$1\text{-}10^{-7}$/hr	2.0nmi	1min
Terminal	0.4nmi	$1\text{-}10^{-7}$/hr	1.0nmi	30s
NPA	220m	$1\text{-}10^{-7}$/hr	0.3nmi	10s
APV I	220m(H) 20m(V)	$1\text{-}2\times10^{-7}$/approach	0.3nmi(H) 50m(V)	10s
APV II	16m(H) 8m(V)	$1\text{-}2\times10^{-7}$/approach	40m(H) 20m(V)	6s
Cat. I	16m(H) 4.0-6.0m(V)	$1\text{-}2\times10^{-7}$/approach	40m(H) 10-15m(V)	6s
Cat. II	6.9m(H) 2.0m(V)	$1\text{-}10^{-9}$/15s	17.3m(H) 5.3m(V)	1s
Cat. III	6.2m(H) 2.0m(V)	$1\text{-}10^{-9}$/15s	15.5m(H) 5.3m(V)	1s

3. Integrity Monitoring Methods in GNSS

3.1 GIC Protection Level

In DGPS (Differential GPS), the ground stations at known position receive satellite signals and compare the measurements with computed range to generate PRC (Pseudorange Correction). The PRC is broadcasted to neighborhood users to compensate spatially common errors. Meanwhile the correctness of generated PRC is checked by examining the statistics of PRC. GIC means ground based integrity monitoring system using DGPS broadcasting channel. Therefore, GIC techniques are designed and implemented in DGPS such as LAAS and WAAS.

At first, WAAS was designed to meet CAT-I requirement of ICAO in whole North America. CAT-I is the highest requirement that an aircraft can precisely approach in an airport. Because of integrity, WAAS provides APV not CAT-I. Integrity monitoring system of WAAS calculates horizontal and vertical protection levels to satisfy given integrity risk. In this case, integrity risk requirement is allocated by fixed rate and calculated protection levels are compared with predefined alert limit requirement.

Protection level is calculated by equation (1) [3].

$$HPL_{GIC} = F_{RF}^{-1}(1-P_{hmd})\sqrt{\frac{d_{11}+d_{22}}{2}+\sqrt{\left(\frac{d_{11}-d_{22}}{2}\right)^2+d_{12}^2}}$$
$$VPL_{GIC} = F_{CEF}^{-1}\left(\frac{P_{vmd}}{2}\right)\sqrt{d_{33}} \quad (1)$$

P_{vmd} and P_{hmd} are the vertical and horizontal miss detection probabilities of navigation system, respectively. F_{CDF} is the complementary error function and F_{RF} is the Rayleigh function. These two functions are defined by equation (2) and (3).

$$F_{CEF}(t) = \frac{1}{\sqrt{2\pi}}\int_t^{\infty} e^{-y^2/2}dy \quad (2)$$

$$F_{RF}(t) = \int_t^{\infty} ye^{-y^2/2}dy = 1-e^{-t^2/2} \quad (3)$$

In equation (1), d_{ij} are the diagonal terms of matrix D which is defined by inverse of matrix (G^TG) and matrix G is defined by dot product of weighting matrix Ω in equation (4) and matrix G_M which represents LOS (Line of Sight) vector , i.e., geometrical allocation of satellites.

$$\Omega = \begin{bmatrix} \sigma_1 & & \\ & \ddots & \\ & & \sigma_N \end{bmatrix} \quad (4)$$

Integrity performance is evaluated by comparing results of protection levels and alert limits.

2.2 RAIM Protection Level

In this paper, parity space method among many RAIM techniques is applied to detect and isolate a failure of satellite. In this method, protection levels are calculated by equation (5) [3].

$$HPL_{RAIM} = \underset{k=1,\ldots n}{Max}\left[\frac{d_T + F_{CEF}^{-1}(P_{md})}{|p_{1k}|}\sqrt{b_{11}^2+b_{22}^2}\right]$$
$$VPL_{RAIM} = \underset{k=1,\ldots n}{Max}\left[\frac{d_T + F_{CEF}^{-1}(P_{md})}{|p_{1k}|}|b_{33}|\right] \quad (5)$$

P_{fa} is the false alarm probability and integer n is the number of measurements. And d_t is defined as threshold value. The relationship between protection level and alert limit is described as figure 2[6].

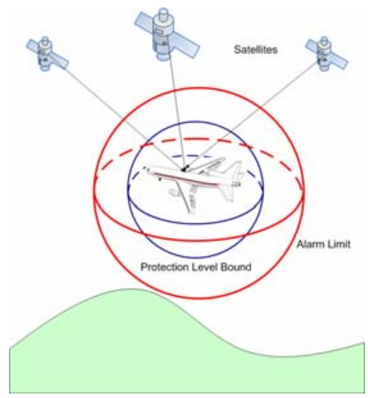

Figure 2. Relationship between PL and AL

2.3 Integrity Risk

In Galileo, instead of PL, integrity risk is directly computed using following equations. It will satisfy 99.5% availability while current PL in WAAS provides 95% availability. The integrity risk is calculated as the weighted sum of the combination of all faulty and fault-free modes of all satellites. To ensure compliance to the specified integrity risk the total integrity risk is directly calculated at the vertical and horizontal alert limit. In this method, integrity risk is calculated by equation (6) [8].

$$P_{HMI}(VAL,HAL) =$$

$$1-erf\left(\frac{VAL}{\sqrt{2}\cdot\sigma_{u,V,FF}}\right)+e^{-\frac{HAL^2}{2\xi_{FF}^2}} \quad (6)$$

$$+\sum_{j=1}^{N}\left(P_{fail,sat_j}\cdot\frac{1}{2}\left(1-erf\left(\frac{VAL+\mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right)+\frac{1}{2}\left(1-erf\left(\frac{VAL-\mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right)\right)$$

$$+\sum_{j=1}^{N}\left(P_{fail,sat_j}\cdot\left(1-\chi^2_{2,\delta_{u,H}}cdf\left(\frac{HAL^2}{\xi_{FM}^2}\right)\right)\right)$$

Fault-Free modes Vertical and Horizontal integrity risks are calculated by equation (7) and (8).

$$P_{IntRisk,V,FF} = 1-erf\left(\frac{VAL}{\sqrt{2}\cdot\sigma_{u,V,FF}}\right) \quad (7)$$

$$P_{IntRisk,H,FF} = e^{-\frac{HAL^2}{2\xi_{FF}^2}} \quad (8)$$

Faulty modes Vertical and Horizontal integrity risks are calculated by equation (9) and (10).

$$P_{IntRisk,V,FM} = \frac{1}{2}\left(1-erf\left(\frac{VAL+\mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right)+\frac{1}{2}\left(1-erf\left(\frac{VAL-\mu_{u,V}}{\sqrt{2}\cdot\sigma_{u,V,FM}}\right)\right) \quad (9)$$

$$P_{IntRisk,V,FM} = 1-\chi^2_{2,\delta_{u,H}}cdf\left(\frac{HAL^2}{\xi_{FM}^2}\right) \quad (10)$$

2.4 UERE Budget

In GNSS measurements, errors form many sources are included. Navigation system should consider space errors and user errors in order to calculate protection level. Space errors include clock error and orbital error and user errors include ionospheric delay, tropospheric delay, receiver noise, and multipath effect etc. Budget of these errors are enumerated in table 1[5].

Table 2. Error budget of GPS L1 signal

Segment Source	Error Source	1σ Error(m)
Space/Control	Broadcast clock	1.1
	L1 C/A group delay	0.3
	Broadcast ephemeris	0.8
User	Ionospheric delay	7.0
	Tropospheric delay	0.2
	Receiver noise	0.1
	Multipath	0.2
System UERE	Total	7.1
Total + 10% Margin(m)		7.8

Table 3. Error budget of GPS L1/L5, Galileo E5a-L1 and SBAS

	GPS L1/L5	Galileo E5a-L1	SBAS
Total + 10% Margin(m)	1.80	1.33	1.0

In table 3, error budgets of GPS L1-L5 and Galileo E5a-L1 are given. These dual frequency service is intended to SoL(Safety of Life) service. The error budget of SBAS is given for WAAS[4].

4. Regional Integrity Analysis

To evaluate the regional performance of various combinations of modernized GPS, Galileo, and SBAS in Korea, integrity performance of GPS, Galileo, and SBAS navigation systems are analyzed in this paper. The GSSF from VEGA is used as a simulation tool. GPS L1 and L5 signal and Galileo E5a-L1 signal with SoL service are considered. And SBAS in a geo-stationary satellite over Korea is considered also. Figure 3 shows constellation of GPS, Galileo, and geo-stationary satellite used in this paper. The simulation is done for the region of 120 ~ 134 deg. longitude and 28~46 deg. latitude. Total simulation times are 24 hours. The values in figure 4~7 are the maximum VPL computed at a candidate location for 24 hours.

Figure 3. GPS, Galileo, and SBAS constellation

The figure 4-7 are map plots of vertical protection levels for navigation systems; GPS L1/L5, Galileo E5a-L1, GPS L1/L5 + Galileo, SBAS / GPS L1/L5 + Galileo. Figure 4 shows that the maximum VPL using GPS L1/L5 is larger than 60 which is hard to apply APV-I. Figure 5 show a large improvement by using Galileo E5a-L1. It should be note that the performance of Galileo is superior than GPS in the dual frequency service. Figure 6 and 7 show gradual improvement by combining GPS, Galileo and SBAS. The CAT-I can be met with this combination but CAT-II, III is still hard to meet.

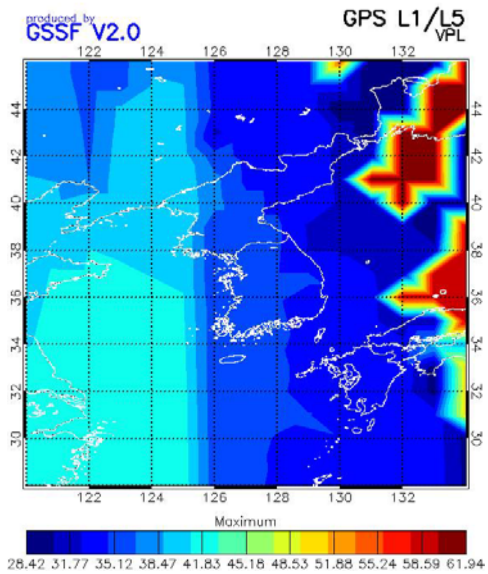

Figure 4. VPL for GPS L1/L5

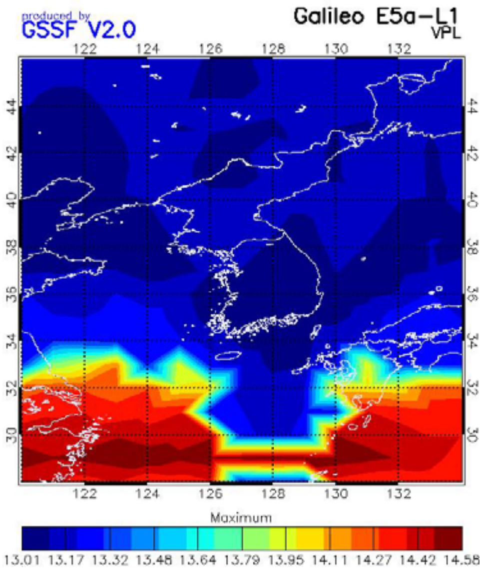

Figure 5. VPL for Galileo E5a-L1

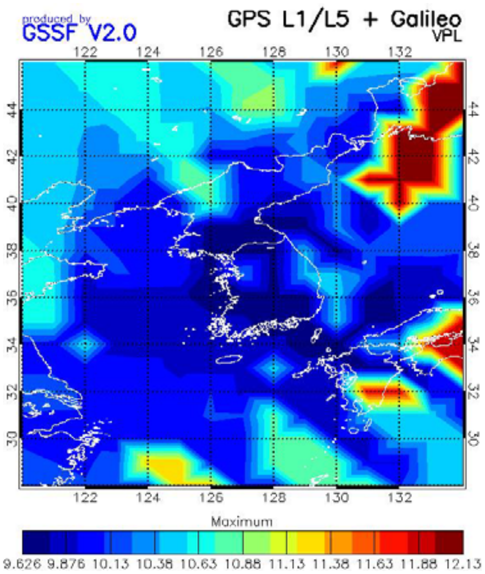

Figure 6. VPL for GPS L1/L5 + Galileo

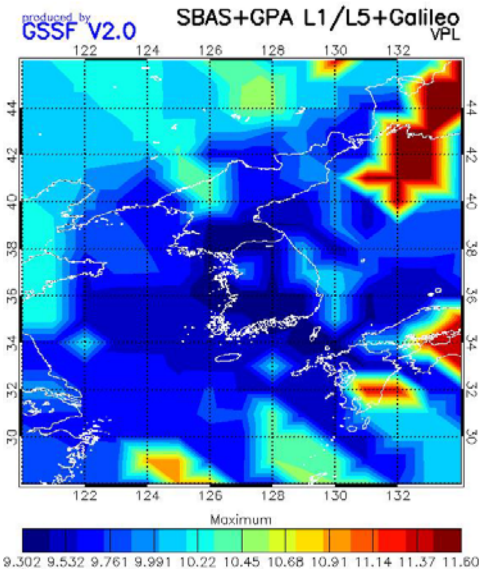

Figure 7. VPL for SBAS / GPS L1/L5 + Galileo

Protection levels of various simulation scenarios are summarized in table 4. In the paper, HPL is far less than VPL because of satellite constellation. In table 5, simulation results with SBAS are given. Table shows the more satellites, the better performance. However, still CAT II, III is not met even with dual frequency GPS/Galileo and SBAS. It is expected that GBAS is probable candidate to meet CAT II and III. Figure 8 and 9 summarize the GIC simulation results.

Table 4. Simulation results of GPS and Galileo

	Protection Level	
	GIC	RAIM
GPS L1	HPL 65.5m VPL 129.3m	HPL 99.3m VPL 146.8m
GPS L1/L5	HPL 19m VPL 35.12m	HPL 29.6m VPL 43.8m
Galileo E5a-L1	HPL 7.5m VPL 13.2m	HPL 20.2m VPL 27.5m
GPS L1 + Galileo	HPL 7.2m VPL 12.5m	HPL 15.3m VPL 23.5m
GPS L1/L5 +Galileo	HPL 6.1m VPL 9.8m	HPL 8.3m VPL 13.2m

Table 5. Simulation results of GPS, Galileo and SBAS

	Protection Level	
	GIC	RAIM
SBAS/GPS L1 + Galileo	HPL 6.8m VPL 12.0m	HPL 12.3m VPL 20.5m
SBAS/GPS L1/L5 +Galileo	HPL 5.6m VPL 9.4m	HPL 7.4m VPL 11.5m

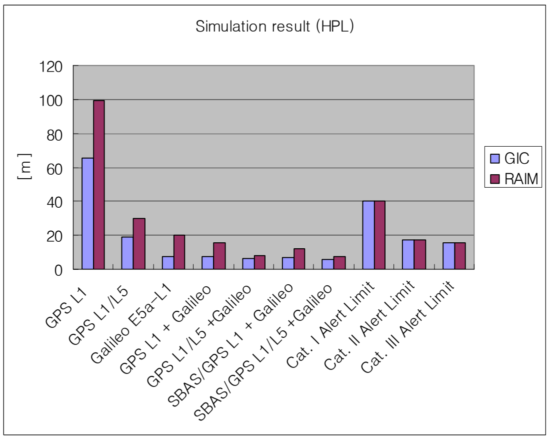

Figure 8. Simulation Result of HPL

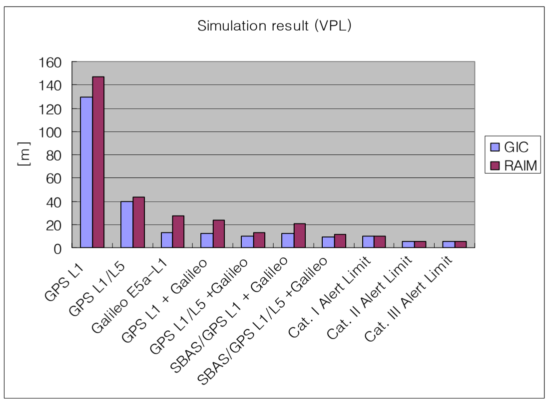

Figure 9. Simulation Result of VPL

5. Conclusions

In this paper regional integrity analysis in Korea using various combinations of modernized GPS, Galileo and SBAS is given. Single frequency and dual frequency GPS, Galileo and combined GPS/Galileo/SBAS constellation are examined to estimate the integrity monitoring level in Korea. The simulation results show that CAT I requirement can be met using modernized GPS and Galileo alone, however, CAT II and III are not met even augmenting SBAS because of VPL. A more efficient augmentation such as GBAS which can reduce VPL dramatically is required to meet CAT II and III in Korean region. Currently, the impact of ERIS and GBAS is investigated and the implementation issues are researched.

References

1. Oehler, V. et. Al, "The Galileo Integrity Concept and Performance", *ION GNSS 17th International Technical Meeting of the Satellite Division,* Long Beach, CA, 21-24 Sept. 2004, pp. 604~615.
2. Helmut Blomenhofer, "GNSS/Galileo Global and Regional Integrity Performance Analysis", *Proceedings of ION-GNSS-2004*, Long Beach, CA., Sept. 21-24, 2004.
3. Frank Zimmerman, *Galileo System Simulation Facility – Models and Algorithms (SVS Only),* VEGA Informations - Technologien Gmbh.
4. RTCA, *Minimum Operational Performance Standard for Global Positioning System/Wide Area Augmentation System Airborne Equipment,* RTCA/DO-229B, November 28, 2001.
5. Jan, Shau Shiun, "Analysis of a Three-Frequency GPS/WAAS Receiver to Land an Airplane," *Proceedings of ION GPS 2002*, Portland, OR, September 24-27, 2002.
6. Jiyun Lee, "GPS-Based aircraft landing systems with enhanced performance: beyond accuracy," *Ph.D. Dissertation,* Stanford University, March 2005.
7. Ochieng, WY, "GPS Integrity and Potential Impact on Aviation Safety", *CAA 2003.*
8. Oehler, V. et. Al, "User Integrity Risk Calculation at the Alert Limit without Fixed Allocations", *Proceedings of the ION GNSS 17th International Technical Meeting of the Satellite Division*, Long Beach, CA, 21-24 September 2004.