Galileo E1 and E5a Performance

For Multi-Frequency, Multi-Constellation GBAS

Analysis of new Galileo signals at an experimental ground-based augmentation system (GBAS) compares noise and multipath in their performance to GPS L1 and L5. Raw noise and multipath level of the Galileo signals is shown to be smaller than those of GPS. Even after smoothing, Galileo signals perform somewhat better than GPS and are less sensitive to the smoothing time constant.

Mihaela-Simona Circiu, Michael Felux, *German Aerospace Center (DLR)*, and Sam Pullen, *Stanford University*

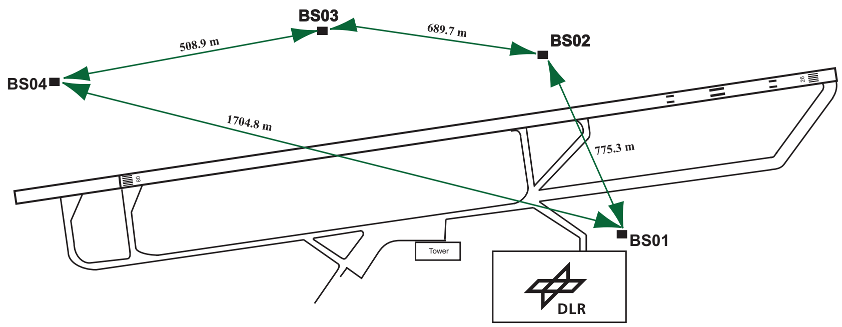
Several ground-based augmentation system (GBAS) stations have become operational in recent years and are used on a regular basis for approach guidance. These include airports at Sydney, Malaga, Frankfurt and Zurich. These stations are so-called GBAS Approach Service Type C (GAST C) stations and support approaches only under CAT-I weather conditions; that is, with a certain minimum visibility. Standards for stations supporting CAT-II/III operations (low visibility or automatic landing, called GAST D), are expected to be agreed upon by the International Civil Aviation Organization (ICAO) later this year. Stations could be commercially available as soon as 2018.

However, for both GAST C and D, the availability of the GBAS approach service can be significantly reduced under active ionospheric conditions. One potential solution is the use of two frequencies and multiple constellations in order to be able to correct for ionospheric impacts, detect and remove any compromised satellites, and improve the overall satellite geometry (and thus the availability) of the system.

A new multi-frequency and multi-constellation (MFMC) GBAS will have different potential error sources and failure modes that have to be considered and bounded. Thus, all performance and integrity assumptions of the existing single-frequency GBAS must be carefully reviewed before they can be applied to an MFMC system. A central element for ensuring the integrity of the estimated position solution is the calculation of protection levels. This is done by modeling all disturbances to the navigation signals in a conservative way and then estimating a bound on the resulting positioning errors that is valid at an allocated integrity risk probability.

One of the parameters that is different for the new signals and must be recharacterized is the residual uncertainty attributed to the corrections from the ground system (σ_{pr_gnd}). A method to assess the contribution of residual noise and multipath is by evaluating the B-values in GBAS, which give an estimate of the error contribution from a single reference receiver to a broadcast correction. Independent data samples over at least one day (for GPS) are collected and sorted by elevation angle. Then the mean and standard deviations for each elevation bin are determined.

Here, we evaluate the E1 and E5a signals broadcast by the operational Galileo satellites now in orbit. In the same manner as we did for GPS L5 in earlier research, we determine the σ_{pr_gnd} values for these Galileo signals. As for GPS L5, results show a lower level of noise and multipath in unsmoothed pseudorange measurements compared to GPS L1 C/A code.



▲ **FIGURE 1** DLR ground facility near Braunschweig Airport, also shown in opening photo at left.

Receiver	Latitude [°]	Longitude [°]	Height [m]
BS01	52°19' 2'' N	10°34' 2'' E	134.21
BS02	52°19' 6''N	10°33' 5'' E	137.53
BS03	52°19'20''N	10°33'16''E	133.25
BS04	52°19'17''N	10°32'36''E	131.51

▲ **TABLE 1** Ground receiver antenna coordinates.

DLR GBAS Facility

DLR has set up a GBAS prototype at the research airport in Braunschweig (ICAO identifier EDVE) near the DLR research facility there. This ground station has recently been updated and now consists of four GNSS receivers connected to choke ring antennas, which are mounted at heights between 2.5 meters and 7.5 meters above equipment shelters. All four receivers are capable of tracking GPS L5 (in addition to GPS L1 and L2 semi-codeless) and Galileo E1 and E5a signals. **FIGURE 1** gives an overview of the current ground station layout, and **TABLE 1** gives the coordinates of the antennas.

Smoothing Techniques

The GBAS system corrects for the combined effects of multiple sources of measurement errors that are highly correlated between reference receivers and users, such as satellite clock, ephemeris error, ionospheric delay error, and tropospheric delay error, through the differential corrections broadcast by the GBAS ground subsystem. However, uncorrelated errors such as multipath and receiver noise can make a significant contribution to the remaining differential error. Multipath errors are introduced by the satellite signal reaching the antenna via both the direct path from the satellites and from other paths due to reflection. These errors affect both the ground and the airborne receivers, but are different at each and do not cancel out when differential corrections are applied.

To reduce these errors, GBAS performs carrier smoothing. Smoothing makes use of the less noisy but ambiguous carrier-phase measurements to suppress the noise and multipath from the noisy but unambiguous code measurements.

The current GBAS architecture is based on single-frequency GPS L1 C/A code measurements only. Single-frequency carrier smoothing reduces noise and multipath, but ionospheric disturbances can cause significant differential errors when the ground station and the airborne user are affected by different conditions. With the new available satellites (GPS Block IIF and Galileo) broadcasting in an additional aeronautical band (L5 / E5), this second frequency could be used in GBAS to overcome many current limitations of the single-frequency system.

Dual-frequency techniques have been investigated in previous work. Two dual-frequency smoothing algorithms, Divergence Free (Dfree) and Ionosphere Free (Ifree), have been proposed to mitigate the effect of ionosphere gradients.

The Dfree output removes the temporal ionospheric gradient that affects the single-frequency filter but is still affected by the absolute difference in delay created by spatial gradients. The main advantage of Dfree is that the output noise is similar to that of single-frequency smoothing, since only one single-frequency code measurement is used as the code input (recall that carrier phase noise on both frequencies is small and can be neglected).

Ifree smoothing completely removes the (first-order) effects of ionospheric delay by using ionosphere-free combinations of code and phase measurements from two frequencies as inputs to the smoothing filter. Unlike the Dfree, the Ifree outputs contain the combination of errors from two code measurements. This increases the standard deviation of the differential pseudorange error and thus also of the position solution.

Noise and Multipath in New GNSS Signals

GBAS users compute nominal protection levels (H_0) under a fault-free assumption. These protection levels are conservative overbounds of the maximum position error after application of the differential corrections broadcast by the ground system, assuming that no faults or anomalies affect the position solution. In order to compute these error bounds, the total standard deviation of each differentially corrected pseudorange measurements has to be modeled. The standard deviation of the residual uncertainty (σ_n, for the nth satellite) consists of the root-sum-square of uncertainties introduced by atmospheric effects (ionosphere, troposphere) as well as of the contribution of the ground multipath and noise. In other words, these error components are combined to estimate σ_n^2 as described in the following equation:

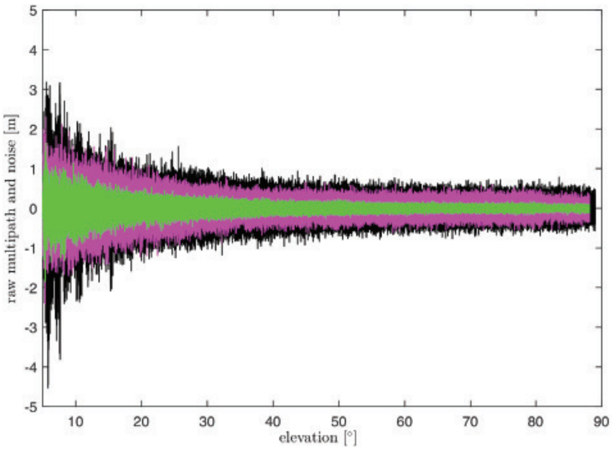
$$\sigma_n^2 = \sigma^2_{pr\_gnd} + \sigma^2_{pr\_air} + \sigma^2_{iono} + \sigma^2_{tropo} \quad (1)$$

The ground broadcasts a value for σ_{pr_gnd} (described later in the section) associated with the pseudorange correction for each satellite. These broadcast values are based on combinations of theoretical models and actual measurements collected from the ground receivers that represent actual system characteristics. Unlike the ground, σ_{pr_air} is computed based entirely on a standardized error model. This is mainly to avoid the evaluation of multipath for each receiver and each aircraft during equipment approval.

In addition to the characteristics of nearby signal reflectors, multipath errors are mainly dependent on signal modulation and other signal characteristics (for example, power, chip rate). In earlier research, we showed that the newly available L5 signals broadcast by the GPS Block IIF satellites show better performance in terms of lower noise and multipath. This mainly results from an increased transmitted power and a 10 times higher chip rate on L5 compared to the L1 C/A code signal.

In this work, we extend this evaluation to the new Galileo signals and investigate their impact on a future multi-frequency, multi-constellation GBAS. Characterization of these new signals is based on ground subsystem measurements, since no flight data with GPS L5 or Galileo measurements are available at the moment. We assume that the improvements observed by ground receivers are also applicable to airborne measurements. This assumption will be validated as soon as flight data are available.

The measurements used were collected from the DLR GBAS test bed over 10 days (note that Galileo satellite ground track repeatability is 10 sidereal days) between the December 14 and 23, 2013. In that period, four Galileo



▲ **FIGURE 2** Raw multipath function of elevation for GPS L1, Galileo E1 (BOC (1,1)) and Galileo E5a (BPSK(10)) signals.

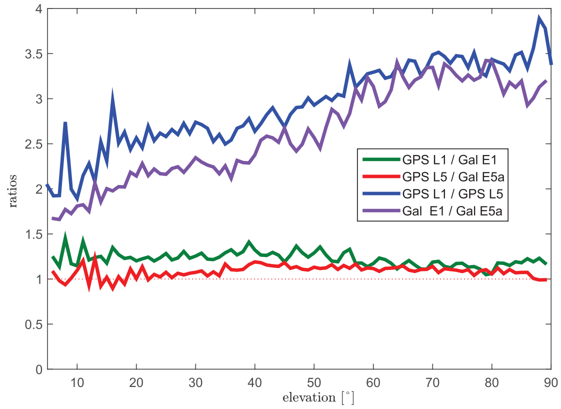
and four Block IIF GPS satellites were operational and broadcast signals on both aeronautical bands E1 / L1 and E5a / L5.

In **FIGURE 2**, the suppression of multipath and noise on the Galileo signals can be observed, where the code multipath and noise versus elevation for GPS L1 C/A BSPK(1), Galileo E1 (BOC (1,1)) and Galileo E5a (BPSK(10)) signals are shown. The code multipath and noise was estimated using the linear dual-frequency combination described in equation (2), where *MPi* represents the code multipath and noise on frequency i, ρ_i the code measurement, and ϕ_i,and ϕ_j represent the carrier-phase measurements on frequencies i and j, respectively. Carrier phase noises are small and can be neglected.

$$MP_i = \rho_i - \left(1 + \frac{2}{\alpha - 1}\right)\phi_i + \left(\frac{2}{\alpha - 1}\right)\phi_j \quad (2)$$

The multipath on the Galileo E1 (BOC(1,1)) signal (the magenta curve) is lower than the GPS L1 C/A (BPSK(1)) (black curve), especially for low elevation, where the advantage of the E1 BOC(1,1) is more pronounced. The lower values can be explained by the wider transmission bandwidth on E1 and the structure of the BOC signal. Galileo E5a (green data in Figure 2) again shows a better performance than Galileo E1. This was expected due to the higher chip rate and higher signal power. A comparison of the raw multipath and noise standard deviations for GPS L1, L5 and Galileo E1, E5a signals is presented in **FIGURE 3**.

The curves there show the ratios of the standard deviations for each elevation bin. The values for GPS L1 are almost 1.5 times larger than those for Galileo E1 BOC(1,1) (green curve) for elevations below 20°. For high elevations, the ratio approaches 1.0. This corresponds to the observations in the raw multipath plot (Figure 2). With the same signal modulation and the same chip rate, E5a and L5 have very similar results (red curve), and the ratio stays close to 1.0 for all elevations.



▲ **FIGURE 3** Ratios of the multipath and noise standard deviation function of elevation.

The blue and the purple curves in Figure 3 show the ratio of GPS L1 C/A (BPSK(1)) and GPS L5 (BPSK(10)), and Galileo E1 (BOC(1,1)) and Galileo E5a (BPSK(10)), respectively. The ratio of GPS L1 to GPS L5 (blue curve) increases with elevation from values around 2.5 for low elevations, reaching values above 3.5 for elevations higher than 60°. As Galileo E1 performs better, the ratio between Galileo E1 and Galileo E5a (purple curve) is smaller, from a value of 1.5 for elevations below 10 degrees to a value of 3.0 for high elevations.

Until now, we have presented the evaluation of raw code noise and multipath. However, in GBAS, carrier smoothing is performed to minimize the effect of code noise and multipath. The value that describes the noise introduced by the ground station is represented by a standard deviation called σ_{pr_gnd} and is computed based on the smoothed pseudoranges from the reference receivers. In the following section, we focus on the evaluation of σ_{pr_gnd} using different signals and different smoothing time constants. Note that, in this study, σ_{pr_gnd} contains only smoothed multipath and noise; no other contributions (for example, inflation due to signal deformation or geometry screening) are considered.

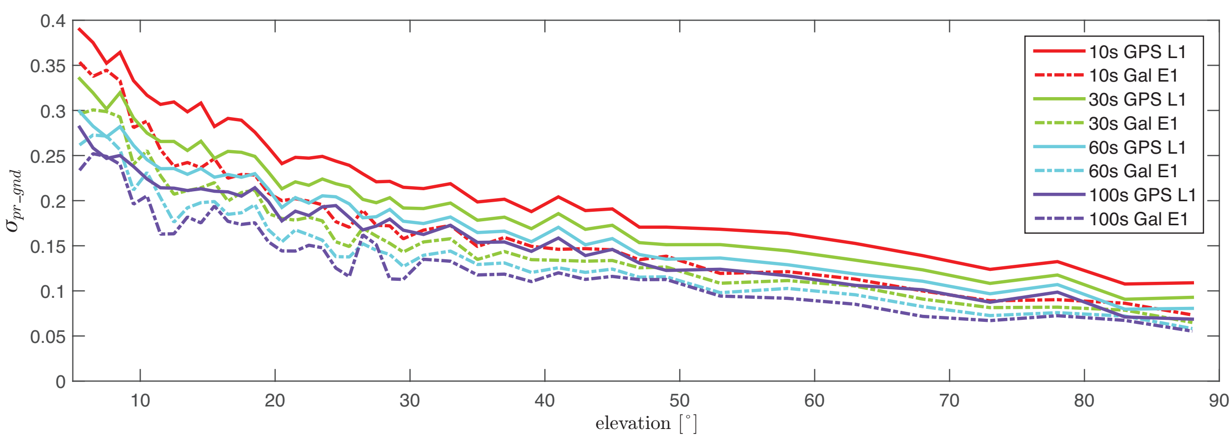
B-values and σ_{pr_gnd}

B-values represent estimates of the associated noise and multipath with the pseudorange corrections provided from each receiver for each satellite, as described in Eurocae ED-114A and RTCA DO-253C. They are used to detect faulty measurements in the ground system. For each satellite-receiver pair $B(i,j)$, they are computed as:

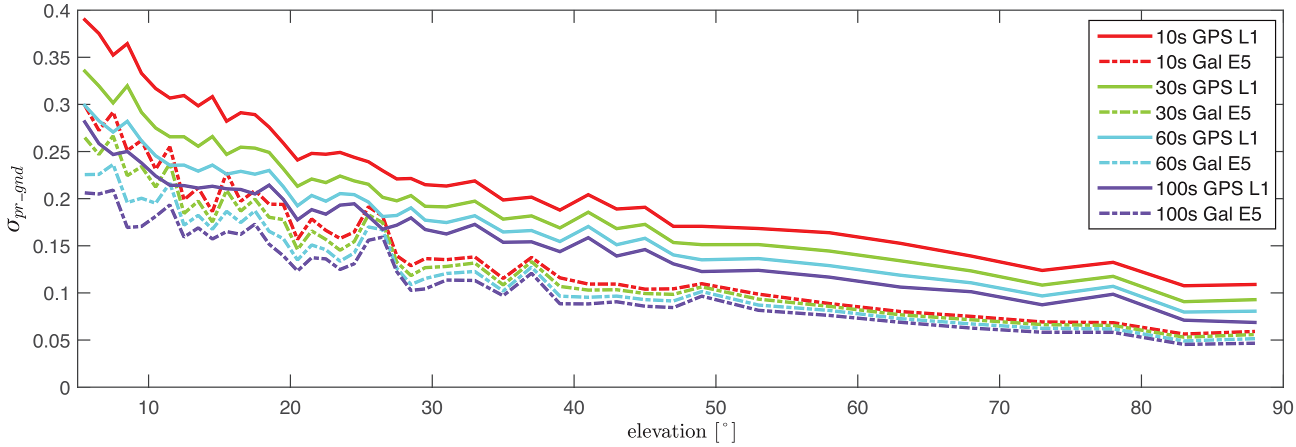
$$B(i,j) = PRC_{TX}(i) - \frac{1}{M(i) - 1} \sum_{k \neq j} PRC_{SCA}(i,k) \qquad (3)$$

where PRC_{TX} represents the candidate transmitted pseudorange correction for satellite i (computed as an average over all $M(i)$ receivers), and $PRC_{SCA(i,k)}$ represents the correction for satellite i from receiver k after smoothed clock adjustment, which is the process of removing the individual receiver clock bias from each reference receiver and all other common errors from the corrections. The summation computes the average correction over all $M(k)$ receivers except receiver j. This allows detection and exclusion of receiver j if it is faulty. If all B-values are below their thresholds, the candidate pseudorange correction PRC_{TX} is approved and transmitted. If not, a series of measurement exclusions and *PRC* and B-value recalculations takes place until all revised B-values are below threshold. Note that, under nominal conditions using only single-frequency measurements, the B-values are mainly affected by code multipath and noise.

Under the assumption that multipath errors are uncorrelated across reference receivers, nominal B-values can be used to assess the accuracy of the ground system.



▲ **FIGURE 4** $\sigma_{(pr\_gnd)}$ versus elevation for Galileo E1 (dotted lines) and GPS L1 (solid lines for different smoothing constants: red (10s), green (30s), cyan (60s), purple (100s).



▲ **FIGURE 5** $\sigma_{(pr\_gnd)}$ versus elevation for Galileo E5a (dotted lines) and GPS L1 (solid lines) for different smoothing constants: red (10s), green (30s), cyan (60s), purple (100s).

The standard deviation of the uncertainty associated with the contribution of the corrections (σ_{pr_gnd}) for each receiver *m* is related to the standard deviation of the B-values by:

$$\sigma^2_{pr\_gnd},m = \sigma^2_B \frac{(M-1)(N+1)}{N} \tag{4}$$

where *M* represents the number of the receivers and *N* represents the number of satellites used. The final sigma takes into account the contribution from all receivers and is computed as the root mean square of the standard deviation of the uncertainties associated with each receiver (Eq. 4).

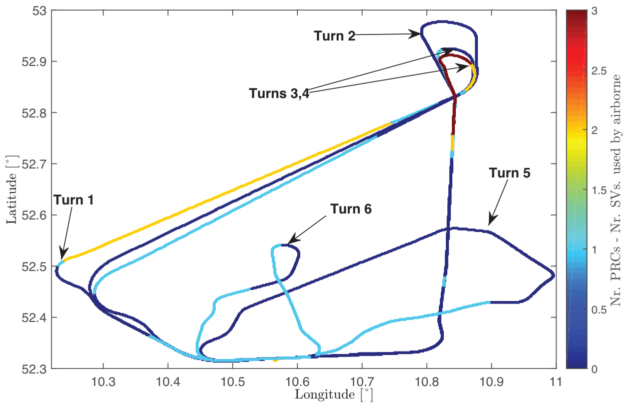
FIGURE 4 shows the evaluation of (σ_{pr_gnd}) for the Galileo E1, BOC(1,1) signal and the GPS L1 C/A signal for increasing smoothing time constants (10, 30, 60, and 100 seconds). Starting with a 10-second smoothing constant, Galileo E1 shows much better performance than GPS L1. The difference shrinks as the smoothing constant increases due to the effectiveness of smoothing in reducing noise and short-delay multipath. However, even with 100-second smoothing (the purple curves), Galileo E1 BOC(1,1) shows lower values of (σ_{pr_gnd}).

A similar comparison is presented in **FIGURE 5**, of the performance of GPS L1 and Galileo E5a. The Galileo E5a signal is significantly less affected by multipath, and the difference stays more pronounced than in the Galileo E1 – GPS L1, even with 100-second smoothing. It can be also observed that the Galileo signals have a lower sensitivity to the smoothing constant. The Galileo E1 signal shows an increase of sensitivity for low elevations (below 40°), while on E5a, a smoothing constant larger than 10 seconds has almost no impact on the residual error. Thus, a shorter smoothing constant on Galileo E5a generates approximately the same residual noise and multipath a 100-second smoothing constant on GPS L1.

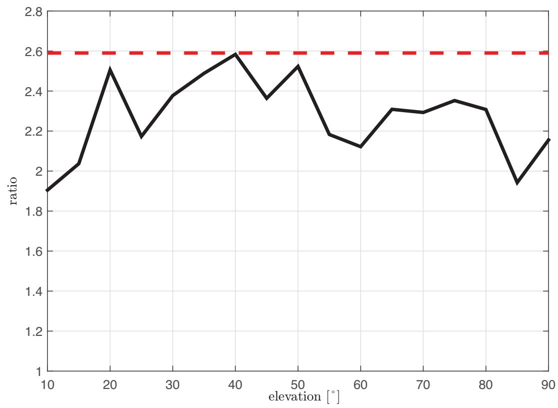
The values for (σ_{pr_gnd}) are, however, impacted by the number of satellites which are used to determine a correction. Since only a very limited number of satellites broadcasting L5 and Galileo signals are currently available, these results should be considered preliminary. The first evaluations strongly indicate that with the new signals, we get better ranging performance. Based on the performance advantage of the new signals, a decrease of the smoothing constant is one option for future application. This would reduce the time required (for smoothing to converge) before including a new satellite or re-including a satellite after it was lost.

In the current GAST-D implementation, based on GPS L1 only, guidance is developed based on a 30-second smoothing time constant. A second solution, one with 100 seconds of smoothing, is used for deriving the *Dv* and *Dl* parameters from the DSIGMA monitor and thus for protection level bounding (it is also used for guidance in GAST-C). During the flight, different flight maneuvers or the blockage by the airframe can lead to the loss of the satellite signal.

FIGURE 6 shows the ground track of a recent flight trial conducted by DLR in November 2014. The colors represent the difference between the number of satellites used by the ground subsystem (with available corrections) and the number of satellites used by the airborne subsystem in the GAST-D position solution. One of the purposes of the flight was to characterize the loss of satellite signals in turns. In turns with a steeper bank angle, up to 3 satellites are lost (Turns 1, 3, and 4), while on a wide turn with a small bank angle (Turn 2), no loss of satellite lock occurred. It is also possible for airframe to block satellite signals, leading to a different number of satellites between ground and airborne even without turns.



▲ **FIGURE 6** Ground track of a flight trial conducted by DLR. The colors represent difference between number of SVs used by the ground system and number of SVs used by the airborne.



▲ **FIGURE 7** Measured ratio $\sigma_{Ifree}/\sigma_{L1}$ function of elevation.

With this in mind, a shorter smoothing constant would allow the satellites lost to turns or to airframe blockage to be re-included more rapidly in the position solution. However, a new smoothing constant would have to be validated with a larger amount of data. Data from flights trials has to be evaluated as well to confirm that similar levels of performance are reresentative of the air multipath and noise.

In a future dual-frequency GBAS implementation, an important advantage of lower multipath and noise is to improve the Ifree position solution. In earlier research, we demonstrated that the error level of the Dfree solution is almost the same as for single-frequency, but an increase in error by a factor of 2.33 was computed for the Ifree standard deviation based on L1 C/A code and L2 semi-codeless measurements.

If the errors on L1 (E1) and L5 (E5a) code and carrier phase measurements are statistically independent the standard deviation of the σ_{Ifree} can be written as,

$$\sigma_{Ifree} = \sqrt{\left(1-\frac{1}{\alpha}\right)^2 \sigma_{L1}^2 + \frac{1}{\alpha^2}\sigma_{L5}^2} \tag{5}$$

where $\alpha = 1 - f_1^2/f_5^2$, and σ_{L1},σ_{L5} represent the standard deviations of the smoothed noise and multipath for L1 (E1) and L5 (E5a), respectively. Considering σ_{pr_gnd},L1(E1)) = σ_{pr_gnd},L5(E5a)) in equation (5), the noise and multipath error on Ifree (σ_{Ifree}) increases by a factor of 2.59.

FIGURE 7 shows the ratio $\sigma_{Ifree}/\sigma_{L1}$ using measured data. We observe that the measured ratio (the black curve) is below the theoretical ratio computed based on the assumption of statistically independent samples (the constant value of 2.59). This is explained by the fact that the multipath errors in the measurements are not independent but have some degree of statistical correlation. The standard deviations are computed based on the same data set used in the raw multipath and noise assessment using 100-second smoothed measurements sorted into elevation bins of 10° spacing.

Conclusion

We have shown how GBAS can benefit from the new signals provided by the latest generation of GPS and Galileo satellites. We have demonstrated improved performance in terms of lower noise and multipath in data collected in our GBAS test bed. When GBAS is extended to a multi-frequency and multi-constellation system, these improvements can be leveraged for improved availability and better robustness of GBAS against ionospheric and other disturbances.

Acknowledgment

Large portions of this work were conducted in the framework of the DLR internal project, GRETA.

Manufacturers

The ground facility consists of four **JAVAD GNSS** Delta receivers *(www.javad.com)*, all connected to **Leica** AR 25 *(www.leica-geosystems.com)* choke ring antennas.

MIHAELA-SIMONA CIRCIU is is a research associate at the German Aerospace Center (DLR). Her research focuses on multi-frequency multi-constellation Ground Based Augmentation System. She obtained a 2nd level Specialized Master in Navigation and Related Applications from Politecnico di Torino.

MICHAEL FELUX is is a research associate at the German Aerospace Center (DLR). He is coordinating research in the field of ground-based augmentation systems and pursuing a Ph.D. in Aerospace Engineering at the Technische Universität München.

SAM PULLEN is a senior research engineer at Stanford University, where he is the director of the Local Area Augmentation System (LAAS) research effort. He has supported the FAA and others in developing GNSS system concepts, requirements, integrity algorithms, and performance models sinceobtaining his Ph.D. from Stanford in Aeronautics and Astronautics.