Concept for a Dual Frequency Dual Constellation GBAS

Michael Felux, Mihaela-Simona Circiu, Boubeker Belabbas, Michael Meurer *German Aerospace Center – DLR*
Mirko Stanisak *Technische Universität Braunschweig*
Carl Milner, Yiping Jiang, Alize Guilbert *ENAC*
Andreas Lipp, *Eurocontrol*

ABSTRACT

This paper proposes one possible concept for a dual frequency dual constellation GBAS architecture. It is based on a single frequency L5/E5a mode as primary processing scheme for best standard performance, a switch to an ionosphere free combination in case of ionospheric disturbances and supporting also classical GBAS approach service types (GAST) C and D for single frequency GPS-based CAT I and CAT II/III modes. The concept is supported by a proposal of how to transmit the required corrections in the existing capacity limited VDB broadcast and is backwards compatible to legacy GBAS. A discussion about the benefits and remaining issues of the proposed architecture concludes the paper.

INTRODUCTION

The Ground Based Augmentation System (GBAS) is a landing system for aircraft. It is built around a differential architecture for Global Navigation Satellite Systems (GNSS) and provides integrity information and thus enables safe, precise and reliable guidance for aircraft on the approach and in the near future also during landing and roll-out.

Currently, an ever growing number of GBAS installations is in operation throughout the world including the airports of Frankfurt, Zurich, Houston, Newark and Sydney. All current stations offer only the GBAS approach service type (GAST) C which supports CAT I approaches, i.e. approaches with a minimum decision height of 200 ft. Current research and development effort is focused on providing a GBAS service to support also CAT II and III approaches (GAST D). In all those service types corrections are provided for single frequency measurements only. However, relying on only one frequency, unmitigated ionospheric disturbances can cause significant differential positioning errors. Thus, either very conservative error bounding or a significant amount of sensitive monitoring is required which might influence the availability especially in equatorial and auroral regions significantly [1,2].

With the growing Galileo and Beidou constellations and an improving GLONASS constellation, together with the introduction of a second usable frequency for aviation in the L5 band on all new GPS satellites multiple GNSS with at least two frequencies are potentially available for navigation. The use of a second frequency allows the calculation of an ionospheric free (Ifree) position solution and might be able to mitigate most of the ionospheric threat.

However, the large number of possible new signals to be included in GBAS corrections provides a significant amount of possible combinations of frequencies, constellations and smoothing time constants, and thus in the end many possible processing modes. Each mode comes with different advantages and disadvantages. Therefore a difficult trade-off has to be made when deciding on supported modes and corrections to be transmitted.

This paper proposes one possible scheme how such an architecture could look like. It is, however, not to be seen as an agreed draft for processing from SESAR, but should rather serve as basis for illustrating some of the most important constraints and the associated difficulties and trade-offs necessary in the definition phase of multi frequency multi constellation GBAS services.

CONSTRAINTS ON A DUAL FREQUENCY DUAL CONSTELLATION GBAS ARCHITECTURE

When defining a new GBAS architecture a large number of navigational and practical constraints have to be met.

A significant constraint results from the requirement to be backward compatible to existing GAST C/D systems. There will be a significant amount of users equipped with GAST C/D avionics until a new GBAS service type will be defined, standardized and implemented. By January 2015 Boeing sold more than 1100 aircraft equipped with a legacy GBAS Landing System (GLS) and as of June 2015 Airbus reported that 30 of their customers also selected the GLS option [8, 9]. A new service therefore requires provision of GPS L1 corrections and integrity parameters for GAST C and GAST D through the current VDB broadcast as specified today without impacting existing GLS users.

Any additional corrections and parameters have to be accommodated in the very limited remaining capacity of the VDB. This is a very tough requirement since it might require sending corrections at a lower update rate than the currently used 2 Hz. This has an impact on integrity and could cause difficulties to meet the stringent time to alarm requirements.

Furthermore, a new architecture should not be too complex and include too many different processing modes. Many modes would mean a long and expensive development and certification process for the manufacturers and thus complex and expensive user equipment. Additionally, for each mode compliance with the appropriate requirements has to be demonstrated. Furthermore, all mode changes have to be investigated which would result in an enormous validation effort.

Another important issue is the international acceptability of a proposed scheme. The developed concept should support different constellations and combinations of them. It would not make sense to limit the usability to specific systems. This might lead to problems (e.g. in case of mandates to use a certain constellation) and would probably not find support in a standardization process at ICAO level.

Finally, of course all existing requirements have to be met also by the new processing modes while providing significant advantage over the legacy systems. This is also somewhat of a challenge since several assumptions, such as the failure rate of a satellite for example, are derived from experience with the systems. Introducing new GNSS constellations, such information might not yet be available and relevant failure modes might not yet be known.

The details of a chosen architecture will still require a significant amount of further investigations, however at least the aforementioned requirements have to be fulfilled in any cases.

POSSIBILITES FOR SIGNAL USE IN DIFFERENT SCENARIOS

The more constellations and frequencies are potentially available the larger the number of possible combinations of navigation data. This section discusses the most important modes which will then be evaluated in the following sections.

The first and most obvious set of modes are the legacy GAST C and GAST D modes supporting CAT I and CAT II/III approaches, respectively.

As extension it is also possible to include signals from a second constellation on the same frequency, e.g. the Galileo E1 signals. The processing of the signals (e.g. 100 seconds / 30 seconds smoothing) and integrity monitoring (inflating sigmas for ionospheric threat mitigation) would be accomplished in the same way as with current systems if ground and airborne GBAS equipment can use the same second constellation. These modes would benefit from an improved geometry associated with typically much smaller protection levels and thus improved availability of the GBAS landing system. This is especially beneficial at airports with significant required masking angles for the ground station due to suboptimal sites for the reference antennas. It could potentially also bring benefits during increased ionospheric activity which often only affects a part of the sky. Even when monitors exclude individual satellites a good geometry could in many cases still be available. As the single and dual constellation cases are similar in processing and integrity monitoring (not so much in performance though), we regard them as only one mode for the rest of the paper.

In a similar way as in the other modes, positioning could be based on the signals from L5 / E5a instead of L1. It is possible to either offer a CAT I or a CAT II/III service based on the single frequency L5/E5a signals (again, either from one or two constellations with the same advantages of improved performance for the dual constellation case). The CAT I mode would have to provide inflated sigmas such that the ground stations completely protects a user from the ionospheric threat. For this service type we use the designator GAST E in this paper.

Furthermore, a CAT II/II mode is possible which we call GAST F SF (single frequency) in this paper. Integrity could be provided in a similar way as in current systems with uninflated sigmas. However, the ionospheric threat mitigation needs to be handled in a different way. In this work we propose to base positioning on L5/E5a only but include the information on L1/E1 for ionospheric monitoring purposes. This makes GAST F SF not a true single frequency mode anymore and might be not optimal. However we regard the possibility to lose L1/E1 signals while having L5/E5a signals available as rather small and less significant than the gain resulting from better noise and multipath performance. In case of a loss of L1/E1 CAT II/III capability would be lost and a switch to GAST E would have to occur.

With the ionosphere being the main reason for the significant monitoring required in GBAS, a natural candidate for a new service type is of course a dual frequency solution which allows forming an ionospheric free (IFree) combination such that the ionospheric delay is eliminated almost completely. This mode shall be called GAST F DF (dual frequency). Again, it is possible to base processing on measurements from a single constellation or from two constellations. Of course also in this service type, the larger number of satellites available in the dual constellation scenario improves navigation performance by a decrease in protection levels.

The scenarios under consideration in this paper are thus four single frequency positioning modes (GAST C, D, E and F SF) and one dual frequency mode (GAST F DF). All of them can be used either with a single GNSS constellation or in a dual constellation processing mode. The single constellation case is relevant in case of either a constellation outage or if the ground station provides corrections for constellations "A" and "B", whereas the airborne equipment supports constellation "B" and "C". In this case only the common constellation "B" could be used for navigation.

PERFORMANCE MEASURES

In order to assess the performance of the different service types mentioned in the previous section a metric is necessary. Of course it is desirable that the new processing modes should support operations without visibility limitations (i.e. CAT III conditions) including automatic landings. In order to support automatic landings it is assumed that the same methodology for airworthiness assessment as in GAST D is followed, namely the demonstration of a safe landing in the touchdown box

with a very high probability. The detailed requirements are defined in [6] and [7]. While GAST D, F SF and F DF are going to meet these performance requirements it is not entirely clear how the performance in terms of availability for each mode will look like. The availability is impacted by epochs where the protection levels exceed the alert limits, but also by triggering of low-level monitors, such as the airborne code-carrier divergence monitor or the ionospheric gradient monitor in the GBAS ground system. The vertical protection level VPL for the H0 case according to [11] in GAST C and D is defined as

$$VPL_{Apr,H0} = K_{ffmd}\sqrt{\sum_{i=1}^{N} s_{Apr,vert,i}^2 \cdot \sigma_i^2} + D_v \quad (1)$$

where K_{ffmd} is the fault-free missed detection multiplier, according to the desired level of integrity, N is the number of satellites used for positioning, the s-values are the projection factors for each satellite from the pseudorange into the position domain, the σ_i are the standard deviations of overbounding distributions of the expected residual pseudorange error for each satellite i and D_v is the vertical difference in a position solution based on 100s and another position solution based on 30s smoothed pseudoranges in case of GAST D and 0 in case of GAST C. From Equation (1) it is becomes obvious that the protection level is mainly influenced by the satellite geometry (defining the s-values) and the expected residual errors on the corrected pseudorange measurements (represented by σ_i). The latter ones are defined as

$$\sigma_i^2 = \sigma_{iono}^2 + \sigma_{tropo}^2 + \sigma_{pr,air}^2 + \sigma_{pr,gnd}^2 \quad (2)$$

with contributions from residual ionospheric and tropospheric errors, as well as errors from the measurements of the airborne receiver (mainly noise and airframe multipath), and a small contribution coming from the corrections from the ground system. The ionospheric uncertainty would only be relevant in case of single frequency processing, whereas the tropospheric uncertainty is not frequency dependent and thus persists for all processing schemes. However, both uncertainties become smaller as the aircraft approaches the destination airport and the GBAS station. The receiver noise and multipath from the ground station are of course independent of aircraft positions and thus remain unchanged in one service type. The $\sigma_{pr,gnd}$ are derived from at least 24 hours of measurements from the ground station and represent very well the actual performance of the station [12]. The airborne noise and multipath, however, are bounded by the $\sigma_{pr,air}$ parameter, which is given in an elevation dependent model. This model has to be conservative in order to cover all aircraft installations with sufficient confidence. The airborne noise and multipath is much larger than the contribution from the ground system since no multipath limiting antennas and highly protected antenna sites are available on the airframe. Furthermore, the measurement errors increase especially during the last phase of the approach and

during roll-out because signal reflections from the ground impact the receiver.

First results about the airborne performance of the new signals are presented in [3]. However, the work presented here is based on the observed performance of $\sigma_{pr,gnd}$. The measurements used to derive these models were taken from DLR's GBAS test bed located in Braunschweig in northern Germany. The test bed uses Leica AR-25 choke ring antennas and Javad Delta 3 receivers. The reference locations and especially the antennas do not fulfil the requirements for actual GBAS stations. However, the results give a good indication as to what can be expected from the new signals and the different processing schemes. As the noise and multipath performance drive the protection levels they have a very close relationship to the availability of the system and are thus used within this work as metric to assess GBAS performance.

PRELIMINARY PERFORMANCE ASSESSMENTS OF THE DIFFERENT MODES

In GAST C only GPS L1 measurements are used. The position is calculated using a smoothing time constant of 100s. In GAST D also only GPS L1 measurements are used, however with a smoothing time constant of just 30 s. The reduction in smoothing time brings a significant increase in the residual noise and multipath in the pseudoranges used for navigation. This increase between the two smoothing time constants is clearly visible in Figure 1(the black and the blue curve) which shows an evaluation of the DLR GBAS test bed from a 40 day period. In a dual constellation case a combined GPS/Galileo GAST C/D–like scenario is also possible. In that case Galileo E1 signals would be used in the same way as GPS L1 signals with the same monitoring and error bounding strategy. The respective curves for Galileo are also depicted in Figure 1. Again a significant decrease in noise and multipath can be seen between the 30 s and 100 s smoothed pseudoranges. In general the Galileo performance seems to be somewhat better than the performance of GPS.
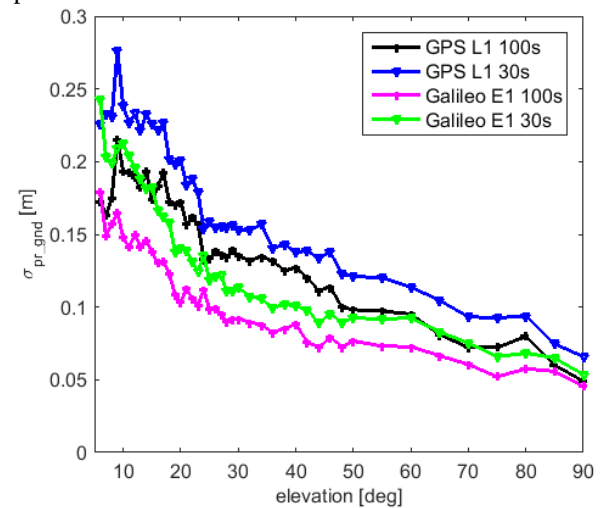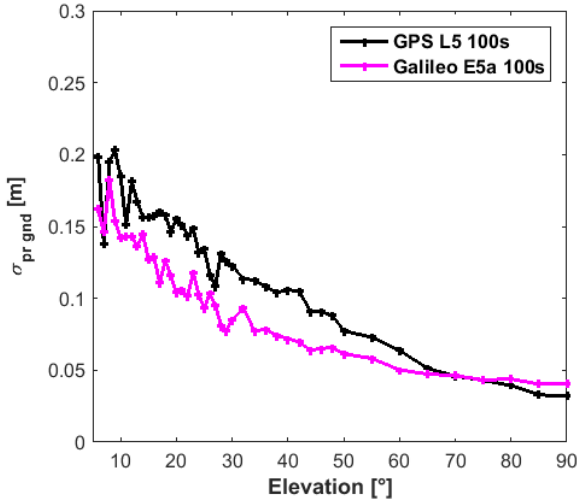

Figure 1 Sigma pr_ground from GBAS test bed in Braunschweig for GPS L1 and Galileo E1 with a 100 s and 30 s smoothing time constant.

Another feasible processing scheme is the use of L5/E5a measurements only. Figure 2 shows the same evaluations for the signals from GPS L5 and Galileo E5a with a smoothing time constant of 100 s. As will be explained in the next section it is unlikely to have corrections also available for a 30 s smoothing time constant due to limited capacity of the VDB datalink.

Figure 2 Sigma pr_ground from GBAS test bed in Braunschweig for GPS L5 and Galileo E5a with a 100s smoothing time constant.

As in the L1/E1 case the Galileo signals mostly have slightly lower values than GPS. Overall the L5/E5a signals perform somewhat better than the L1/E1 signals after 100 s smoothing but the difference in these measurements is moderate. Looking at data from flight trials, however, the difference between the signals on the two frequencies is much more pronounced as shown in [3, 10]. Especially when it comes to bounding the errors on the airborne side by models this advantage can bring a substantial benefit with $\sigma_{pr,air}$ having the largest contribution to the protection levels near the airport.

The previous figures were showing the curves for single frequency processing. As previously described, it is also possible to form an Ifree combination ρ_{Ifree} using pseudorange measurements from two frequencies ρ_{L1} and ρ_{L5} since the ionospheric delay is frequency-dependent. This can be written as

$$\rho_{Ifree} = \frac{f_{L1}^2 \cdot \rho_{L1} + f_{L5}^2 \cdot \rho_{L5}}{f_{L1}^2 - f_{L5}^2} \qquad (3)$$

where f_{L1} and f_{L5} denote the carrier frequencies of the navigation signals. In the same way it is possible to combine the pseudorange corrections for L1 and L5 with the same smoothing time constant in order to obtain an Ifree correction. This property makes all the ionospheric monitoring in the ground and airborne systems unnecessary, however at the cost of significantly increased uncertainty in the position solution. The noise increase results from the combination of the noise and residual errors on the L1/E1 and on the L5/E5a measurements. A plot for GPS only measurements

showing this property is depicted in Figure 3. It shows a comparison of the Ifree performance based on 100 s smoothing in comparison to the 30 s smoothed L1 curve. The comparison of the two different smoothing times is useful in this case since CAT II/III capability in GAST D is provided based on 30 s smoothed measurements.

The ratios between the blue and red curve in Figure 3 represent the expected increase in noise from GAST D to an Ifree service. For low elevations the observed ratio is about 1.8 while it decreases to a value of about 1.3 for high elevations.
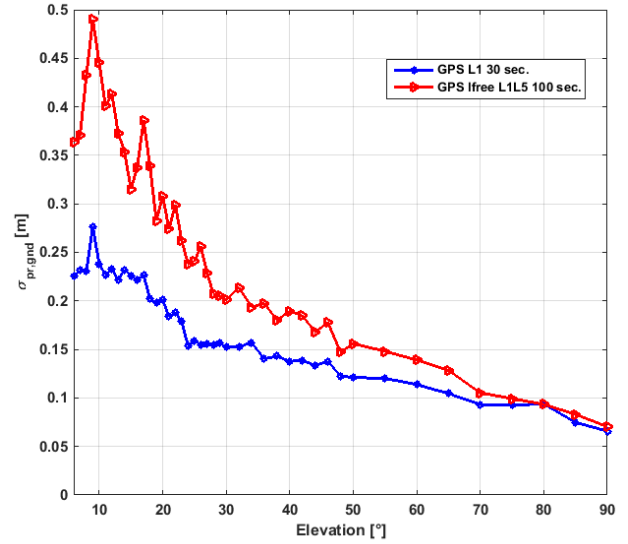
Figure 3 Sigma pr_ground from GBAS test bed in Braunschweig for an Ifree combination (red) in comparison with the L1 signals from GPS only.

In summary these evaluations have shown that the best nominal performance can be expected from single frequency L5/E5a measurements. Slightly worse are the currently used L1 measurements. Through the combination of two noisy code measurements the Ifree dual frequency solution has by far the largest residual uncertainty and thus the worst nominal performance of the schemes discussed. An exact quantification of the noise increase remains to be done for a quantitative performance assessment of all the schemes.

FEASIBILITIES AND CHALLENGES OF THE DIFFERENT PROCESSING SCHEMES

Multi-Constellation / Multi-Frequency GBAS services will require additional messages to be broadcast using the VHF Data Broadcast (VDB). These messages have to meet two important constraints in order to allow seamless operations.

On the one hand backwards compatibility has to be ensured. On the other hand, the VDB capacity is quite limited. This is especially true for future GBAS ground facilities at complex airports where multiple VDB transmit antennas will be necessary in order to provide sufficient VDB coverage for all runways. Such an example is depicted in Figure 4.

Slot		
Slot A **Altern.**	MT2 51 B	MT4 (3 FAS) 133 B
Slot B **Ant. 1**	MT1 (N=18) 215 B	
Slot C **Ant. 1**	MT11 (N=18) 140 B	MT4 (FAS) 51 B
Slot D **Ant. 1**	MT1 (N=10) 127 B	MT11 (N=10) 84 B
Slot E **Ant. 2**	MT1 (N=18) 215 B	
Slot F **Ant. 2**	MT11 (N=18) 140 B	MT4 (FAS) 51 B
Slot G **Ant. 2**	MT1 (N=10) 127 B	MT11 (N=10) 84 B
Slot H		

Figure 4 VDB message scheme for a dual-antenna setup. Only the white spaces are available for additional information for a second frequency and constellation.

Here, a possible distribution of VDB messages for a dual-antenna GAST-C / GAST-D setup supporting two constellations is shown. Seven (out of eight) slots per frame are already almost completely allotted to legacy VDB messages and are not available for future multi constellation and multi frequency VDB messages. Thus, only one complete slot (slot H in Figure 4) will be available for additional messages.

In order to meet all CAT-III requirements in such a constrained environment, special care has to be taken with respect to the VDB format definition for MC/MF GBAS services. Within SESAR 15.3.7, first proposals for implementing such services are available. No final decision has been taken yet.

The current VDB proposals thus introduce new concepts like splitting messages including the corrections from a second frequency over multiple consecutive frames by reducing the minimum update rates of the corrections. According to these schemes which are described in detail in [5] it would be possible to transmit legacy corrections for GAST C/D, additionally 30s and 100s smoothed corrections and integrity parameters from a second constellation for L1/E1. The available VDB capacity for corrections for a second frequency, however, is limited. Depending on the exact scheme chosen it might not always be possible to send the additional corrections at the same update rate of 2 Hz but maybe at just 1 Hz or even 0.5 Hz.

Such a decrease in update rate has several implications. It obviously becomes very difficult reaching the required 2 seconds time to alarm requirement for automatic landings in case of update rates as low as 0.5 Hz. For that case an additional high-rate message which contains integrity flags to invalidate corrections if necessary has to be sent at every message transmission (i.e. at a rate of 2 Hz). Furthermore, the range rate corrections gain much more importance as the extrapolation time based on the RRCs increases significantly. This situation is depicted in Figure

5 and could lead to larger errors which have to be bounded accordingly.
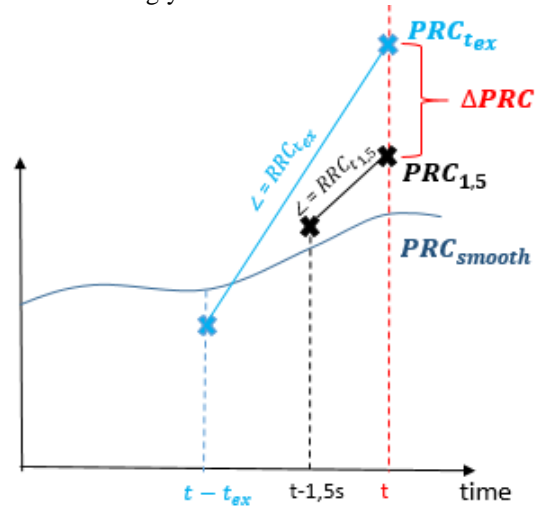
Figure 5 PRC and RRC over time

A study including theoretical calculations and actual measurements on this effect showed, however, that with a rather small inflation of the expected standard deviations such a scheme could be feasible [13]. An increase in the parameters would lead to increased protection levels which is of course not desirable. Again, a quantitative assessment of the increase in the uncertainty versus the decrease in the expected nominal noise and multipath performance has to be performed in order to determine a quantitative result on the expectable total performance. As it might be possible to live with an only slightly decreased update rate it is likely that the performance of L5/E5a is still going to yield some benefit of the L1/E1 performance.

In summary, it is possible with the corrections mentioned above to support the following service types:
- Legacy GAST C/D service
- Extended GAST C/D service, including corrections and integrity parameters for a second constellation
- GAST E service, i.e. an L5/E5a CAT I mode based on GAST C positioning and integrity concepts
- GAST F SF service, i.e. an L5/E5a only positioning service with lower measurement noise but possibly with slightly increased integrity parameters due to the potentially lower update rate of the corrections. Ionospheric threat mitigation, however, requires a second frequency
- GAST F DF service, i.e. a dual-frequency service type (single or dual constellation) by combining the single frequency corrections and measurements to an ionospheric free solution

The GAST F DF service type in this scenario has one implication about the smoothing time for the correction for the second frequency: If these corrections should be used to form ionospheric free combinations, the same smoothing time constant as for the corresponding corrections on L1/E1 has to be applied. That means that either 100 s or 30 s are the only candidates for an L5/E5a

smoothing time constant. Due to the larger impact of noise and multipath due to the use of two noisy code measurements the longer smoothing time of 100 s is the much more likely candidate to be chosen.

PROPOSAL OF A DFDC GBAS ARCHITECTURE

Considering the expectable performance of the discussed processing techniques, along with the constraints on backwards compatibility and VDB capacity one proposal for a dual frequency dual constellation GBAS architecture is drawn in Figure 6 and can be described by the following processing modes:

- Use GAST F SF (i.e. single frequency L5/E5a, dual constellation) whenever possible as primary navigation mode
- In case of an ionospheric event switch to GAST F DF for an ionospheric free solution (single or dual constellation, dual frequency)
- In case L5/E5a a is unavailable (e.g. if the airborne receiver is a single frequency L1 receiver or in case of RFI on L5) use GAST D (or extended GAST D with a second constellation) if possible
- In case the GAST F DF performance is not sufficient (i.e. protection levels are too large) revert to GAST E if L5/E5a is available or to GAST C (possibly extended GAST C with dual constellation) otherwise and lose CAT II/III capability but retain at least CAT I capability.
- In case GAST D is unavailable the same actions should be taken as defined today (either identify and exclude problem or revert to GAST C)
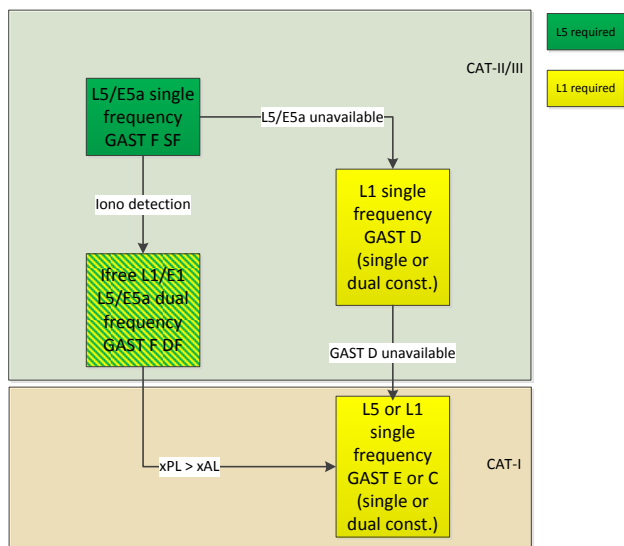
Figure 6 Processing scheme for a dual frequency dual constellation GBAS

DISCUSSION AND CONCLUSIONS

In this paper we investigated the expectable performance of different single and dual frequency and dual constellation GBAS processing modes. Based on the observations and taking into account several constraints mainly coming from VDB capacity we suggested an architecture of a DFDC GBAS which is supported by a proposal of how to transmit the necessary corrections and integrity parameters. As previously mentioned, this draft scheme is not to be seen as an agreed draft solution within SESAR as there are many tradeoffs between this and other different architecture candidates still to be made. Some of the downsides of this proposal include:

Iono detection: There has so far been no method agreed on which would ensure timely and reliable detection of ionospheric disturbances in case of a single frequency L5/E5a processing. As every future L5/E5a capable receiver is assumed to have L1/E1 included an onboard ionospheric estimate and a comparison to the received corrections is one strategy currently under investigation. This would mean, however, that GAST E is not a true single frequency mode if the monitoring for ionospheric disturbances is based on a dual frequency method. Thus, there is no stand-alone L5/E5a CAT II/III mode as backup, e.g. in case of L1 RFI. A downgrade to CAT I would in such a case be the consequence.

New extensive validation: Each new mode requires extensive validation activity and appropriate performance and error models. Using existing positioning with new integrity monitoring and an ionospheric free mode would only have one additional mode to be validated while this proposal requires the effort for two new modes. Furthermore, any switching between modes requires extensive validation and might lead to go-arounds. Thus the number of modes should be kept as low as possible.

Iono-free performance: As shown above, the performance decreases significantly with respect to all single-frequency modes if a dual frequency combination is formed. It still remains to be seen if the GAST F performance will be sufficient to support CAT II/III approaches while maintaining a sufficiently high availability.

These and several more implications are all taken into account and investigated further within SESAR in order to define an optimized architecture which is feasible under all given constraints and at the same time provides most benefits to its users.

ACKNOWLEDGMENTS

DISCLAIMER

The contents presented in this document are for informative purposes only. The authors' institutions grant permission to ION for the purposes of the conference only.

The opinions expressed herein reflect the authors' view only. This document is provided "as is", without warranty of any kind, either express or implied, including, without limitation, warranties of merchantability, fitness for a particular purpose and non-infringement. The SJU does not, in particular, make any warranties or representations as to the accuracy or completeness of this document.

Under no circumstances shall the SESAR Joint Undertaking be liable for any loss, damage, liability or expense incurred or suffered that is claimed to have resulted from the use of any of the information included herein including, without limitation, any fault, error, omission, interruption or delay with respect thereto. The use of this document is at the [recipients of the document] sole risk.

Any reproduction or use of this document other than the ones defined above requires the prior written approval of the SJU.

REFERENCES

[1] M. Yoon, D. Kim, J. Lee, S. Pullen "Multi-dimensional Verification Methodology of Ionospheric Gradient Observations during Plasma Bubble Events in the Brazilian Region" Proc. of the ION PNT 2015, Honolulu, HI, USA

[2] T. Fujiwara, T. Tsujii "GBAS Availability Assessment and Modelling of Ionospheric Scintillation Effects" Proc. of the ION PNT 2015, Honolulu, HI, USA

[3] M.-S. Circiu, M. Felux, B. Belabbas, M. Meurer, J. Lee, S. Pullen "Evaluation of GPS L5, Galileo E1 and Galileo E5a Performance in Flight Trials for Multi Frequency Multi Constellation GBAS" Proc. of the ION GNSS+ 2015, Tampa, FL, USA

[4] M.-S. Circiu, M. Felux, S. Thölert, F. Antreich, M. Vergara, M. Sgammini, C. Enneking, S. Pullen "Evaluation of GPS L5 and Galileo E1 and E5a Performance for Future Multi Frequency and Multi Constellation GBAS" Proc. of the ION ITM 2015, Dana Point, CA, USA

[5] M. Stanisak, A. Lipp, T. Feuerle "Possible VDB Formatting for Multi-Constellation / Multi-Frequency GBAS, Proc. of the ION GNSS+ 2015, Tampa, FL, USA

[6] EASA 2003, Certification Specifications for All Weather Operations, (CS-AWO)

[7] FAA 1999, CRITERIA FOR APPROVAL OF CATEGORY III WEATHER MINIMA FOR TAKEOFF, LANDING, AND ROLLOUT, AC 120-28D

[8] Boeing presentation at the 16th International GBAS Working Group, June 2015, Atlantic City, USA

[9] Airbus presentation at the 16th International GBAS Working Group, June 2015, Atlantic City, USA

[10] DLR presentation at the 16th International GBAS Working Group, June 2015, Atlantic City, USA

[11] RTCA DO-253C (2008), Minimum operational performance standards for GPS local area augmentation system airborne equipment

[12] Eurocae ED-114A (2013), Minimum Operational Performance Standards Specification for Global Navigation Satellite Ground Based Augmentation System Ground Equipment to Support Category I Operations

[13] C. Milner, A. Guilbert, C. Macabiau „Evolution of Corrections Processing for the MC/MF Ground Based Augmentation System (GBAS)", Proc. of the ION ITM 2015