

Satellite Selection in the Operational GBAS Context

Daniel Gerbeth, Maria Caamano, Mihaela-Simona Circiu, Michael Felux,
German Aerospace Center (DLR)

BIOGRAPHIES

Daniel Gerbeth received a Bachelor and Master's degree in Electrical Engineering and Information Technology from Karlsruhe Institute of Technology, Germany in 2014. During Master studies he specialized in aerospace technology and navigation. After working in the field of sensor fusion and navigation aiding at Fraunhofer IOSB he joined German Aerospace Center (DLR) in May 2015 and is involved in the research on GBAS since then.

Maria Caamano received a Master's degree in Telecommunications Engineering from the University of Oviedo, Spain, in March 2015. During Master studies, she specialized in the field of signal theory and communications. The same year she joined the German Aerospace Center where she is working on the impact of ionospheric irregularities in the single-frequency single-constellation GBAS.

Mihaela-Simona Circiu studied Computer Engineering at Technical University Gheorghe Asachi, Romania. She obtained a 2nd level Specialized Master in Navigation and Related Application from Politecnico di Torino, Italy in 2012. Since 2013 she has been working as a research associate at the Institute of Communications and Navigation at the German Aerospace Center. Her main focus is multi-frequency multi-constellation Ground Based Augmentation System.

Michael Felux received a diploma in Technical Mathematics from the Technical University of Munich in 2009. The same year he joined the German Aerospace Center where he has been working on the development of the GBAS GAST C testbed at the research airport in Braunschweig and its upgrade to GAST D. He was involved in flight testing and ground validation of the station and the approach procedures. Since 2015 he is coordinating DLRs research on GBAS-based navigation.

ABSTRACT

When incorporating multiple constellations into future Ground Based Augmentation Systems (GBAS) a problem with limited VDB (VHF Data Broadcast) capacity might arise. Apart from that, the number of airborne receiver tracking channels could be insufficient to use all satellites in view as well. One way to overcome these issues is to perform any kind of satellite selection to limit the number of used satellites with least possible influence on performance.

While the general process of how to select most useful satellites efficiently has been largely covered lately, this paper focuses on the incorporation of such algorithms into GBAS. It investigates different factors that constrain the approach of simply selecting 'the best set in every epoch independently' and shows how to overcome some limitations. These constraints include limitations in satellite visibility, loss of satellites during approach (i.e. in curves) and convergence times in the airborne processing until satellites are of use. Various protection level simulations are performed to show the influence of the named factors on the nominal performance.

Additionally, this paper describes methods how airborne users can perform stand-alone selection in a most efficient way and later transition into GBAS, which requires using the satellites actually provided with corrections from the ground. Taking into account all these contextual influences on top of the selection process, results show satellite selection is still applicable in GBAS ground stations.

I. INTRODUCTION

The Ground Based Augmentation System (GBAS) provides precision approach guidance for CAT I approaches. In the near future, the development and standardization of a CAT II/III capable system will be completed. Both of these systems are based on GPS single frequency L1 signals only. One of the main constraining factors in the definition of a new multi-frequency multi-constellation (MFMC) concept is the limited capacity of the VDB (VHF data broadcast) link which is used to provide corrections and integrity parameters to landing aircraft.

Current GPS L1 corrections and integrity parameters still have to be broadcast in order to allow single-frequency GAST-C/D approaches even in a MFMC GBAS station. One possibility to overcome this problem is to reduce the update rate for the corrections of further frequencies and constellations. To fulfill the time to alert requirements, additional integrity messages have to be broadcast with a higher update rate and the integrity concept would have to be revised in order to ensure that with the lower correction update rate all requirements can still be met.

This paper is based on an alternative approach, broadcasting only additional corrections and integrity parameters for a thoroughly selected subset of all visible satellites. This allows maintaining the current update rate while still benefiting from the better geometrical diversity of multiple constellations as well as a second frequency.

Satellite selection in general was a topic of several papers in the past, providing different algorithms to perform the task. The common goal is in general to find a subset of all satellites currently in view which provides the best (whereby *best* depends on the application) navigation performance under given side conditions. Simple and computationally efficient approaches using only satellite elevation and azimuth were presented by Zhang [1], Song [2] and Park [3]. Also the widespread approach of selecting the highest satellites, assuming the best signal quality with highest elevation, falls into this category. Another group of algorithms tries to maximize polyhedron volumes or matrix determinants [4–6] as they correlate well with the geometrical dilution of precision (GDOP) of a set. Both of these strategies suffer from the missing possibility to take into account any satellite weighting (e.g. due to signal quality) and focus on 3D positioning, making them less suitable in our context. Phatak presented a method in [7] which allows efficient exchange of single satellites in a set which we utilize in our approach as well. Beyond that, approaches applying genetic algorithms [8] or artificial neural networks [9] were presented earlier.

Aside from the incorporated algorithm itself, herein we specifically focus on the influence of operational constraints on the use of satellite selection in GBAS. These constraints come from different factors, mainly satellite visibility (above the elevation limit) and filter convergence times. When a GBAS ground station makes a selection of satellites to broadcast corrections for, these factors should be considered instead of just selecting the satellites that lead to the best performance at a given epoch right at the ground stations location. While the topic of satellite selection in general has been largely covered very recently, [10–13], this work is not limited to a specific selection algorithm but valid for any kind of selection.

We will primarily address three main aspects in this paper:

- Optimizing the selection on ground for the whole GBAS service volume and considering convergence times
- Considering satellite-out cases in the selection process to avoid single performance-crucial satellites
- Strategies for airborne receivers not capable of tracking all satellites in view or with limited processing power

II. METHODS

General Assumptions

First of all we want to make some general statements in terms of the simulations and studied aspects in this paper. One important fact to mention again is that the studies we are going to present are not specific to a single selection method. Instead the results and implications apply to any kind of satellite selection in GBAS. As used algorithm in this work we utilize our previously presented optimization method [11] with slight modifications in line with Walter et al. [10]. Using an exhaustive search instead could change some of the results slightly, but as previous studies in [11] showed the heuristic algorithm to differ by well below 1% on average, we decided on a heuristic approach for the reason of inapplicable computation times otherwise.

The general idea of the heuristic selection is to use a measure based on all satellites currently in view which allows to judge the probability of a satellite to be part of a best-n set. This measure to perform the initial selection is given as

$$s_{measure,i} = \frac{(s_{3,i} + \tan(\theta_{GPA}) \cdot s_{1,i})^2}{p_{i,i}} \quad (1)$$

with

$$\mathbf{S} = (\mathbf{G}^T \cdot \mathbf{W} \cdot \mathbf{G})^{-1} \mathbf{G}^T \cdot \mathbf{W} \quad (2)$$

and

$$\mathbf{P} = \mathbf{W} - \mathbf{W} \cdot \mathbf{G} \cdot \mathbf{S} \quad (3)$$

where \mathbf{G} is the satellite geometry matrix in ENU (East North Up coordinates) and \mathbf{W} is the weighting matrix [14]. Lowercase variables ($s_{i,j}$) refer to the element in row i and column j of the respective matrix (uppercase). The angle θ_{GPA} describes the glide slope inclination of the current approach path, typically about 3 degrees.

Using this measure, an initial set of satellites is selected and then iteratively optimized in a ‘greedy exchange’ way. A detailed overview of the optimization can be found in [11].

To judge and compare the performance in the following studies, we mostly utilize vertical protection levels (VPLs), overbounds of the remaining differential position errors, as they give a good indication of the nominal performance to expect. The focus is on the vertical domain here, because the vertical protection is both harder to fulfill and more critical during final approach and landing. Details on the computation of the protection levels can be found in RTCA DO-253C [14]. As the absolute value of the achieved protection levels is also not of major interest in this studies, but instead the relative changes due to different modifications on the selection, we will not go into details here and refer to the standards of our previous works instead [11, 15].

Service Volume and Convergence Time Considerations

Satellite visibility within the service volume

When performing any satellite selection in GBAS in the ground station, it has to be taken into account that very low elevation satellites are not necessarily usable for airborne users. Depending on the distance to the ground station and the altitude of the aircraft, a satellite might be still (or already) below the elevation mask and therefore unusable. Broadcasting corrections for these satellites might be of no use for at least part of the users and therefore degrade the average performance. It is consequently desirable to take the influence of satellite visibility into account when performing the selection on the ground.

We will compare two different methods how this can be achieved. The first, simple approach is to raise the elevation limit for satellites taken into account during selection. By raising the elevation limit by about 1 degree, it can be made sure that the selected satellites are visible (above the elevation limit) to all users within the service volume of 43 km. This assumes the airborne users to be not more than 3000 m above the ground reference, as height difference is one of the two influencing factors on the local satellite elevation. When a larger radius than 43 km is supposed to be served, then this limit on the ground has to be adjusted accordingly, as the curvature of the Earth accounts for the second influencing factor. While this approach is easy to implement and makes sure no corrections are sent that are ‘needless’ for some users, it also comes with an expected loss of performance. From a geometric point of view, low elevation satellites provide a large contribution to the achieved performance. Removing the lowest 1 or more degrees of elevation over all azimuths can therefore influence the protection levels significantly in some situations.

To overcome this, the second approach is more complex. The idea is to sample the service volume at relevant locations (Marked in red in Figure 1) and perform independent selections. These locations we use are defined by intersections between edges where satellite visibility regions start/end (gray) and additionally the edge of the service volume (black). Afterwards, the performance of the different sets is computed throughout the service volume and the best of these sets finally broadcast. This procedure is by far more complex and requires a significantly higher processing power, but also is more flexible and offers tuning opportunities. One option for example is to optimize the selection only for the (known) approach routes, ignoring areas where no arriving flights are passing normally. This can offer quite some potential as can be seen from the approaches towards Frankfurt Airport in Figure 2. The major part of the GBAS service volume is actually never used. Whether a satellite is visible in these regions or not is consequently not relevant, easing the constraints on what satellites to broadcast corrections for. Nevertheless, in this paper we limit the simulations to optimizations for the whole service volume, sampled at equally space locations. Otherwise the results are heavily dependent on the actual approach routes at each airport.

Handling of rising and setting satellites

The setting of satellites below the elevation limit is related to the satellite visibility regions. When a satellite is newly included into a selection it might take the airborne processing some time to actually use it, depending i.e. on the number of receiver channels. To tackle this problem, we introduce a minimum time the satellite needs to stay above this limit to be included in the selected set. The minimum time is based on the convergence time of the airborne filters. Any satellites setting within a time smaller than the actual filter convergence time would not grant any use for airborne users. Therefore minimum remaining usability times of at least 2τ can be considered reasonable (where τ is the airborne convergence time).

Satellites that set within a shorter time span are not included into the selection. This does not affect satellites already present in the currently broadcast set. These stay within the selection as long as they are above the elevation limit or until replaced by another satellite for performance reasons (i.e. smaller protection level).

Limiting the exchange rate of satellites over time

A last aspect which has to be considered in terms of optimizing the selection on the ground is the rate at which satellites in the selected set are exchanged. This relates to the filter convergence in the airborne processing again as with the setting satellites. Here we assume an airborne user without capability of tracking all satellites in view. Any change in the set of received corrections

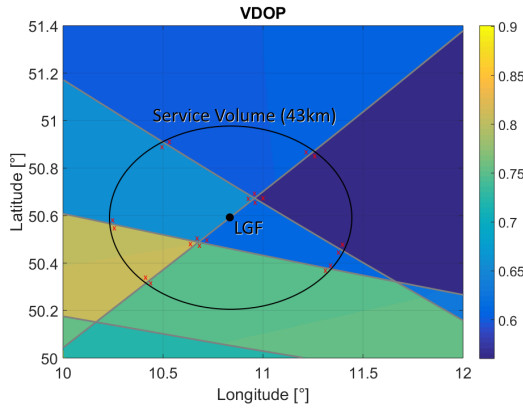


Figure 1: Example for satellite visibility across GBAS service volume.

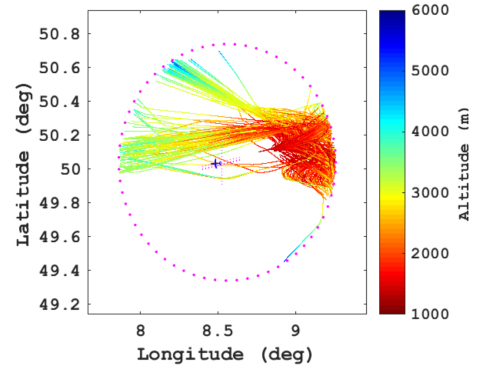


Figure 2: Example plot of one day of approaches towards Frankfurt Airport as given in [16].

(i.e. the ground selection) would require the airborne user to replace the satellite. When the newly used satellite was not tracked or incorporated in the GBAS processing before, it requires some time until it is usable. Until then the aircraft would be limited to the remaining satellites. In the rare case of multiple satellites exchanged within a short time, the airborne user could experience a significantly degraded performance with the previous satellites no longer (no corrections) and the new satellites not yet (not converged) usable.

An option to overcome this issue is to limit the number of exchanged satellites to one per time-step and additionally introduce a timeout τ between changes. This timeout should base on the airborne convergence time. After an exchange the ground selection should wait for at least τ seconds before the next satellite is exchanged. This could mean sometimes, that the selection is not optimal anymore, when there would be an improving exchange but the timeout would not have been passed yet. Only in case an airborne user can track and use all satellites in view, a change in the set of received corrections could be incorporated without any delay.

Consideration of Satellite-Out Cases

In this section we want to study the influence of satellite outages on the selection. The question is especially: can we make our selection more robust against sudden satellites drops by giving up some nominal performance? These outages are not so rare, when considering curves during the approach. Bank angles up to 30 degrees make these outages especially immanent to low elevation satellites, when the wings or fuselage cut the line of sight.

This probability of lost satellites during an approach is incorporated into the selection process by replacing the common VPL as measurement to judge the quality of a set. Instead, an adjusted ‘protection level’ is computed by combining the protection level of possible out cases weighted by their probability of occurrence. The adjusted protection level for judging the sets is given as

$$VPL_{adjusted} = p_0 \cdot VPL_{full} + p_1 \cdot VPL_1 + p_2 \cdot VPL_2 + \dots + p_1 \cdot p_2 \cdot VPL_{1,2} + \dots \quad (4)$$

with p_i as the outage probability of satellite i and VPL_i the protection level with satellite i removed. We assume p_0 as the probability of no satellite outage, i.e. complementary probability to all out-cases considered.

The probability of a satellite outage we use follows a piecewise linear function over elevation el given by:

$$p(el) = \begin{cases} 0.20, & 0 < el < 20 \\ 0.20 \cdot (40 - el)/20, & 20 \leq el < 40 \\ 0, & 40 \leq el \leq 90 \end{cases} \quad (5)$$

Thus we assume a constant maximum outage probability of 20% up to 20 degrees of elevation. Afterwards, from 20 to 40 degrees of satellite elevation the probability drops linear towards zero. This can be seen as a conservative overbound of expected loss probability during curvy approaches and was modeled after DLR flight trial data. The general selection procedure as we described it before stays the same. A starting set is selected based on the $s_{measure}$ and then gradually optimized by single exchanges. Instead of common VPL the $VPL_{adjusted}$ is minimized.

Airborne Selection Strategies

In this part we have to distinguish different scenarios. One is dedicated to stand-alone positioning, i.e. before transitioning into the GBAS service. This is also relevant in the case of for example unmanned aerial systems (UAS) with limited battery life and strong

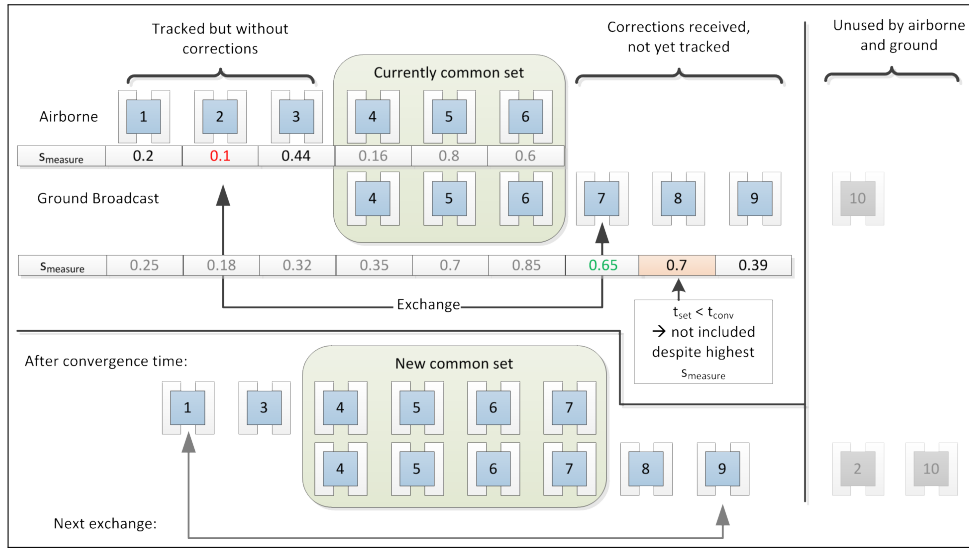


Figure 3: Sketch of the airborne satellite exchange scheme for transition into GBAS. In the example PRN 2 is exchanged with PRN 7. PRN 8 is ignored due to imminent set below the elevation mask. Instead of using the $s_{measure}$ for determining the exchanges, an exhaustive (brute force) search could be performed for optimal results.

demand on (power) efficient positioning. The second topic regards the actual transition from a not differentially corrected position (using e.g. SBAS or ARAIM) to the use of GBAS.

Stand-Alone Users in Continuous Operation

In terms of continuous operation of stand-alone users an approach was presented quite recently from Swaszek et al. in [12]. Similarly in [11] we already used the previously selected set as one of our starting sets for the optimization problems in continuous operation. If necessary this can be even further simplified by performing a search for the best subset only in case of trigger events. This reduces the required computations drastically while having a minor impact on the achieved performance.

We can identify three simple trigger events which allow efficient scheduling of new satellite selections during continuous operation:

- Rise of a new satellite
- Setting of a satellite
- Time since the last set search/optimization

All of them are quite obvious, as the slowly evolving satellite geometry changes mostly when new satellites become usable or previous ones drop out. An additional timed trigger, e.g. every 5-10 minutes, allows ‘coasting’ through periods without set or rise events. This could also be triggered whenever processing power is ‘free’ in performance critical UAS applications, enabling a flexible, still optimal performance.

Transition to GBAS

In terms of a user approaching a GBAS station to perform a landing, it is necessary to align the tracked and used (in the GBAS processing) satellites with the ones provided with corrections from the ground. If the airborne receiver is capable of tracking all satellites in view (of the supported constellations) this is trivial. The GBAS processing can just utilize the measurements from all corrected satellites then.

Otherwise, there needs to be a procedure to exchange satellites currently tracked with the satellites provided with corrections from the ground station. The algorithm we propose for this is fairly straightforward. To limit the drop in performance due to a sudden exchange of many satellites (which can happen in a multi-constellation scenario) they should be exchanged one by one. The timeout between the exchanges can be equal to the filter convergence times, i.e. 30 or 100 seconds in the current GBAS.

Exchanges should be performed in a way that the least influential satellite in the tracked set is exchanged with the most beneficial from the satellites with broadcast corrections. One simple measure that allows judging the influence on the performance without any brute force iterations is the one given in Eq. 1. From the currently tracked satellites that are not in the broadcast, the satellite with the smallest $s_{measure}$ (i.e. a small contribution to the performance) would be replaced first.

The replacement would be the satellite with the highest $s_{measure}$ of the remaining satellites. In this case the measure would be calculated for the all-in-view solution, using almanac data to compute azimuth and elevation of the satellites where necessary. One restriction has to be made here: satellites about to set below the horizon should be excluded from the procedure. Three cases can be distinguished based on the time until a satellite sets below the elevation mask:

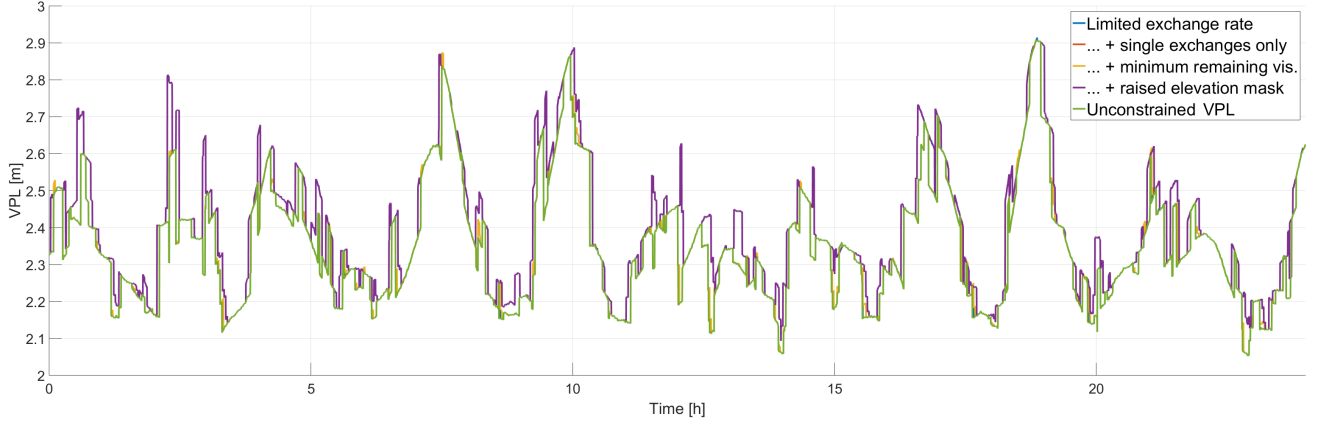


Figure 4: Influence of different constraints on achieved nominal protection levels over one day.

- $t_{set} \lesssim t_{convergence}$: The satellite sets before the airborne filters are even converged and is therefore ignored.
- $t_{convergence} < t_{set} < t_{landing}$: The satellite sets during the expected time until landing. It is therefore treated with lower priority.
- $t_{set} > t_{landing}$: The satellite stays visible during approach and landing. These satellites are exchanged first.

The remaining time that satellites stay above the elevation mask, t_{set} , can be estimated using the ephemeris or almanac data. Filter convergence $t_{convergence}$ is known from the performed processing. For $t_{landing}$, estimations have to be made either based on the actual current approach route or, if not available, distance and speed(-profile) until touchdown. An illustration of the exchange scheme is given in Figure 3.

III. RESULTS AND DISCUSSION

As mentioned earlier already, the protection levels we use here as comparative measure, are computed according to RTCA DO-253C [14]. As assumptions for σ_{air} and σ_{ground} we use models developed at DLR and previously published in an open access article [15].

Some additional general simulation parameters are collected in the following list:

- Current GPS (30 sat.) and nominal future Galileo (27 sat.) almanacs for satellite orbits
- Aircraft velocity 70 m/s, except for the final simulation where a speed profile is used
- σ_{air} and σ_{ground} as in [15], 100 s models for both GPS L1 and Galileo E1
- GBAS ground station broadcasts corrections for 12 satellites from dual constellation
- Airborne receiver tracks 12 satellites
- Locations at low (0°), medium (55°) and high latitudes (75°) and 10° longitude
- We only compare heuristic selections: the baseline ‘best sets’ are always also heuristically found and not by exhaustive search
- We only consider H0 protections levels, not ephemeris or H1 PL (see [14] for details)

In case of additional assumptions, these are mentioned in the according sections.

Service Volume and Convergence Time Considerations

We start with presenting results for service volume and convergence time considerations. Figure 4 shows resulting protection levels over a full day of simulation in medium latitudes, assuming 5 km distance to the GBAS reference point. Starting with an unconstrained optimization (green line), i.e. the best set is selected in each time step independently, different constraints are added. To get a better view of the time-behavior we show one exemplary hour of the plot magnified in Figure 5. Figure 6 completes the picture with according histograms.

The first constraint we take a look at is limiting the exchange rate to match with the airborne filter convergence times (blue line). As we assume 100 s processing modes here, an exchange can only occur every 100 s. In general this has a minor influence, as sets change rather slowly over time in general. When considering 30 s processing modes the influence becomes basically negligible.

Secondly, we limit each of the set modifications to a single satellite and ignore satellites that are setting below the elevation mask within the convergence time of 100 s. During the simulated day it occurred about 100 times that more than one satellite was exchanged in comparison to the set from the time step before. In these cases the selection comes out of track and needs some time to ‘converge’ back to the optimum. This can be seen in a nice example around 10.1 hours into the simulation where actually 3

satellites change in the best set. Nevertheless, the error made here stays minor with about 5 cm or 2%. In total the errors are mostly negligible and last about 5 minutes at most. The exclusion of setting satellites affects the selection only in two occasions on millimeter level. In general it can be said that satellites in the right azimuth region make their way into the best set earlier than within the last minutes of visibility which renders this restriction unproblematic.

As a last constraint we limit the selection to satellites whose elevation is high enough to be usable all over the service volume (violet line). We went with this simple approach of assuring the satellite set performance all over the area here, as the more complex optimization using satellite visibility regions showed no major benefit without specific areas within the terminal area to optimize for. This can be also seen in a comparative histogram in Figure 7. Especially from Figure 4 it gets clear that the raised limit has the biggest influence on the VPL, causing some significant spikes occasionally. A statistical overview on the 24 hours is given as histogram in Figure 6. We show the relative increase of the protection levels compared to the unconstrained VPL. While the increase in case of the exchange constraints stays well below 10%, it reaches up to 20% when introducing a raised elevation mask. Nevertheless, the influence on the performance barely implies any consequences on the availability. The spikes mostly happen, when the VPL is comparably low and the overall worst VPL of the day is basically unchanged regardless of the constraints.

In Figure 7 we tie in with the previous histograms and show the variability over latitudes. From knowledge of the satellite orbits it is to expect that especially the raised elevation mask has a growing influence when more low elevation satellites are present. This matches with the results in the three histograms: we see the distribution spreading out when going further towards the pole. Errors increase up to 34% in case of a station at 75° North. However, even in high latitudes with unfavorable satellite geometries, the general performance shows to be still suitable for GBAS applications.

In the middle histogram we plot additionally (red) the results when using the second described approach of using satellite visibility regions to optimize the ground selection. While this shows some benefit in special cases with only a limited area of the service volume actually used by approach routes, the performance when no such side conditions are given is comparable to the straightforward rise of the elevations mask.

Consideration of Satellite-Out Cases

In the second part of this subsection we will study the VPL performance implications when considering satellite-out cases during the selection process. We limit the shown plots to a location in medium latitudes here, as the results showed to be fairly similar for all locations. Figures 8 and 9 show the achieved protection levels for a part of the simulated time as well as the according histogram when no outages occur. In terms of the adjusted selection this can be seen as ‘worst case’, as there is no gain possible. Consequently the achieved protection levels are mostly larger compared to the common selection. The average VPL over the day increases by about 5% in this case, with a maximum increase of 25%.

This expected negative influence starts to get compensated by the more robust sets when we start taking out satellites. Between one and two affected satellites the mean performance evens out and for three satellites we have a slightly better average performance as seen in Figures 10 and 11. In this case we take out 3 random satellites (according to the probabilities from Eq. 5) in every simulated epoch. Even more relevant than the average performance is that spikes, as they start to occur in the commonly selected

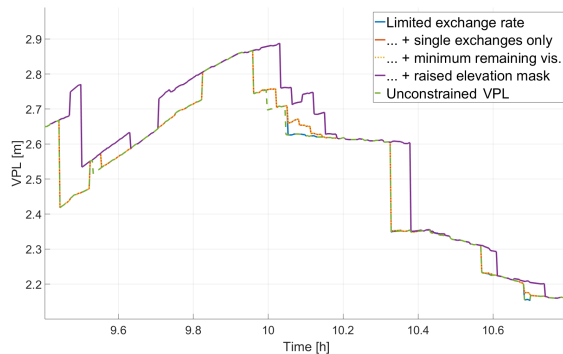


Figure 5: Zoom of Figure 4 to make time behavior visible.

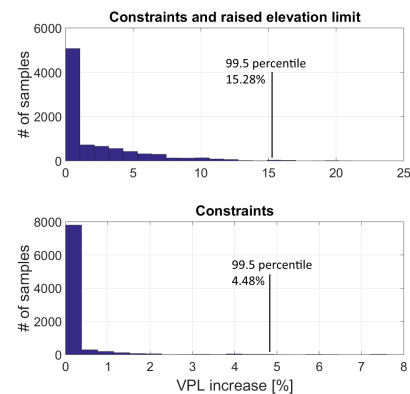


Figure 6: Histogram of VPL increases due to selection constraints. Bottom histogram includes the exchange constraints, the top one additionally a raised elevation mask.

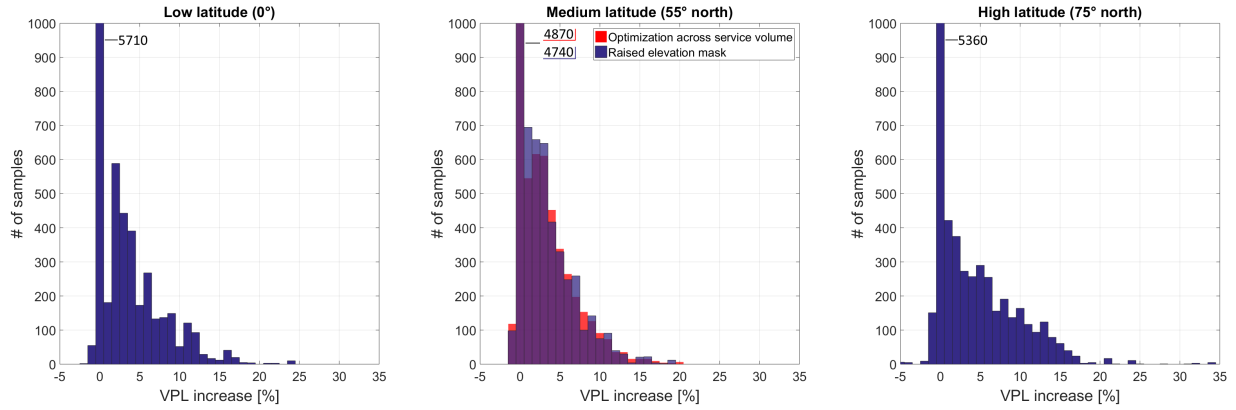


Figure 7: Influence of the constraints in the selection on the average VPL performance for different latitudes. Center histogram compares simple raised elevation mask with ‘exhaustive’ optimization over service volume.

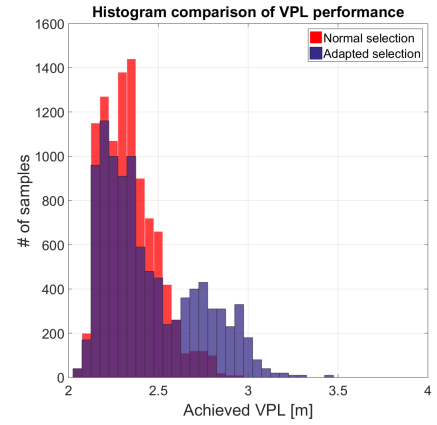
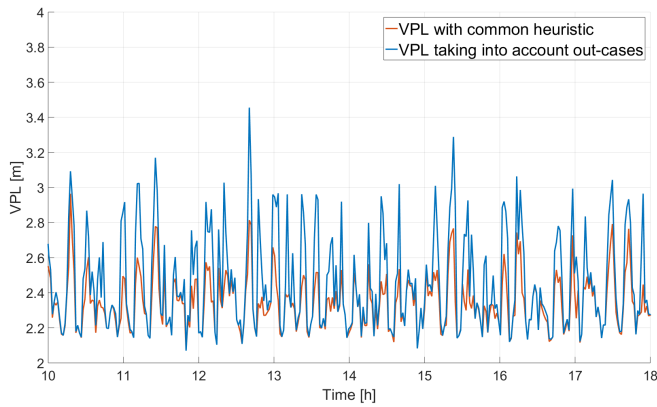


Figure 8: VPL over time, comparing common heuristic and optimization for satellite out cases. In this simulation no outages are present.

Figure 9: Histogram for to the full simulated day in Figure 8.

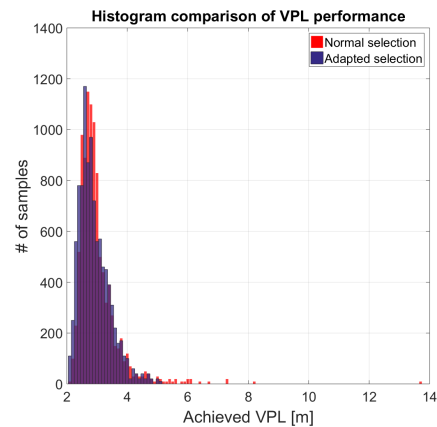
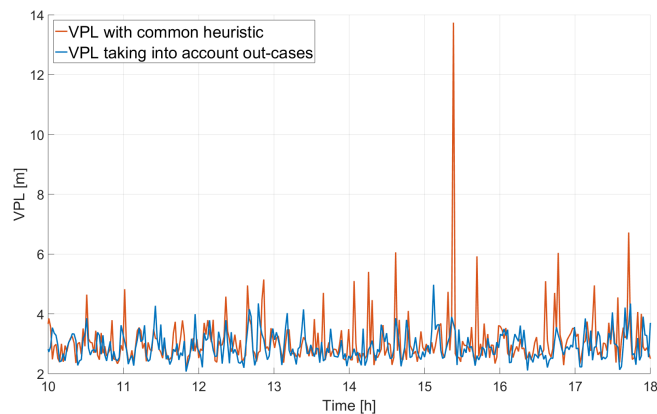


Figure 10: VPL over time, comparing common heuristic and optimization for satellite out cases. In this simulation 3 random outages are present.

Figure 11: Histogram for to the full simulated day in Figure 10.

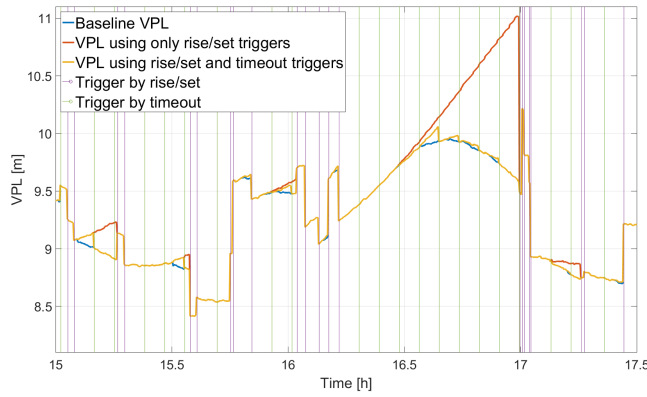


Figure 12: Snapshot of period with most significant divergence within 24 hours simulations time. Baseline VPL (SBAS in this case) is optimized at each epoch. In the other cases the selected sets are kept except for trigger events

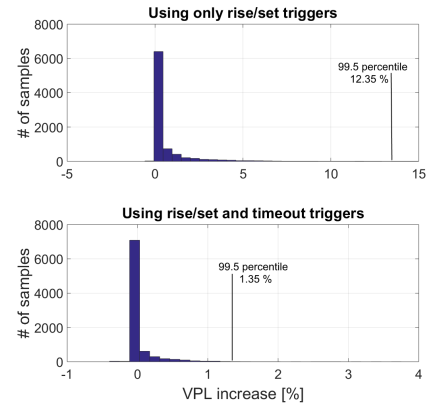


Figure 13: Histogram of relative SBAS VPL increases within 24 hours of simulation. Top plot uses only satellites sets and rises. Bottom includes trigger after fixed timeout.

sets, are less likely and less pronounced with the modified selection strategy. Giving up some nominal performance can help even in some of the simulated cases to keep the system available while a commonly selected set of 12 satellites would be rendered unusable by the 3 lost satellites. Even though that might be unlikely, it is definitely not impossible to lose 3 out of 12 selected satellites thinking of 180° turns within the terminal area as seen from the typical approach routes of Frankfurt in Figure 2. Taking this into account – maybe even with an azimuth dependent outage probability based on the approaches – could therefore help increasing the availability, considering the average performance leaves some margin.

Airborne Selection Strategies

After the ground related results in the last two subsections, we turn towards the airborne side now. As in GBAS the airborne side would not perform any selection on it's own but rely on the provided corrections (and therefore selection) from the ground, we perform simulations for an SBAS scenario here. In Figure 12 we show a part of a 24 hours simulation of stand-alone airborne selection (12 satellites from dual constellation). For the baseline VPL (blue) the selection is performed in every epoch to get the best performance with highest computational effort. In red we see the achieved VPL when we limit the number of set searches drastically by only performing them when a satellite sets or rises (violet lines). While the red curve follows the baseline quite well for major parts of the day, between hour 16 and 17 in a longer segment without triggers, the VPL starts to drift away significantly. When we add a simple timed trigger now (green lines), in this case every 5 minutes, we can see the VPL (yellow) following the baseline very well. A simple trade-off is present here between the wait interval until a new set is searched and the achieved performance. Nevertheless, with a very rare trigger as in the example, we already achieve very good results. Looking at the histograms in Figure 13 we see that the VPL increases by less than 1% most of the times for the latter case. For most applications, especially thinking of computationally limited UAS applications, this would probably be enough while reducing the computational cost significantly.

In terms of the proposed satellite exchange scheme we do not show explicit results in this part, but utilize the algorithm in the conclusive simulation described in the following.

Bringing the Pieces Together

In a final plot we want to bring all the previous bits and pieces together and show the VPL performance during 1000 simulated landings towards an airport in medium latitudes. All simulations start at a distance of 43 km from the ground reference station, i.e. at the edge of the service volume. Start times of the simulations are equally spaced within 10 days to get diversity in terms of satellite geometry. The aircraft starts with 12 tracked satellites optimized for stand-alone positioning. Therefore an alignment might be necessary in the first minutes of the approach.

The ground station incorporates all the previous constraints: limited exchange rate and exchange timeout, raised elevation mask for optimization across the service volume and consideration of out-cases. Figure 14 shows the achieved protection levels as a cloud of plots (blue) as well as the achieved mean at each distance (yellow). Additionally the minimum, maximum and mean values of the same approaches, not taking into account any of the constraints are given for comparison (black lines).

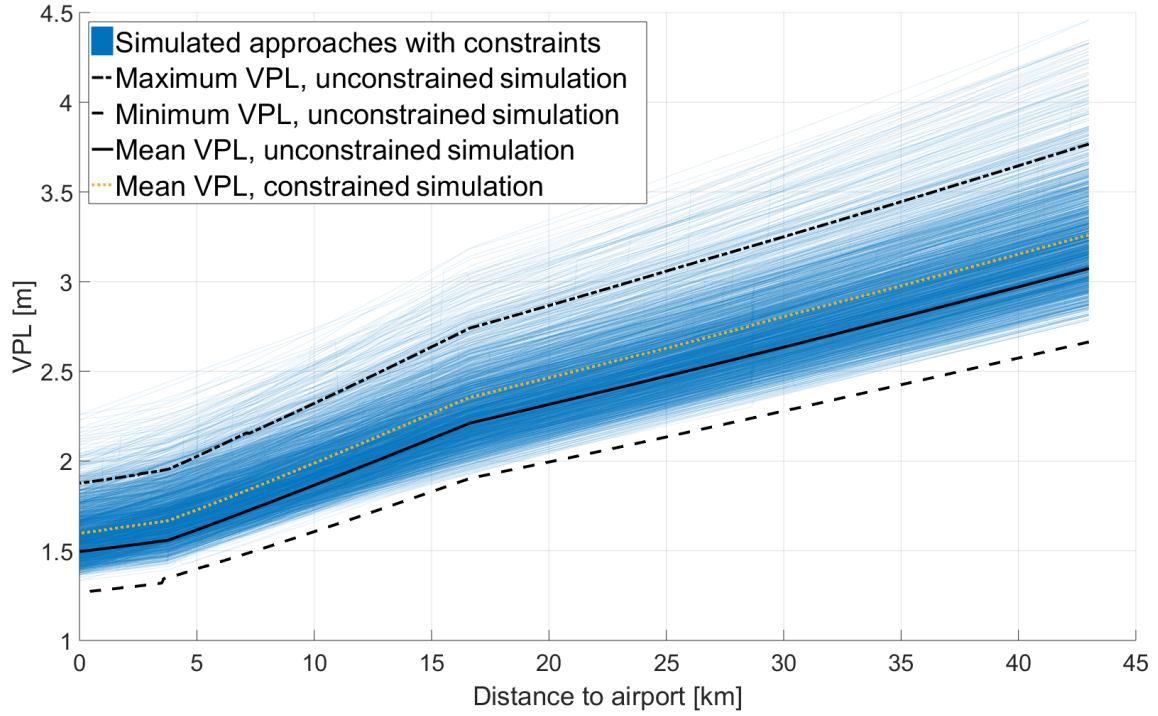


Figure 14: Stacked VPLs from 1000 simulated approaches combining all the previous constraints. As comparison we show minimum, maximum and mean VPL along the approach for the unconstrained case.

We can find again in the plots the impact on the performance that could be expected from the previous simulations. The average VPL increase by about 6-8% along the approach, both following the same shape (introduced by speed and height profile, see [15]), as expected. In terms of the maximum VPLs we see some rare outliers which exceed the unconstrained maximum by about 18-21%. Also this is understandable, as we saw some significant outliers already in Figure 6 when introducing the raised elevation limit. Some geometries are especially susceptible to a loss of low elevation satellites, for example when the only low satellite in a wider azimuth range is missing. However, the VPLs during all the approaches in the simulation stay well below the vertical alert limit which is 10 m close to the airport and increases towards the edge of the service volume.

IV. CONCLUSIONS AND FUTURE WORK

In this paper we studied various operational constraints and presented possible modifications of satellite selection in GBAS. First we investigated the implications of different satellite visibilities and filter convergence times on the ground station selection. We could show that taking these constraints into account has visible but not significant influence on the expected performance for airborne users.

We showed in a general example that it is possible to trade off nominal performance versus more tolerance against satellites outages, mostly due to banking of the plane. In a real application this can be further adapted to each specific airports. As the most common approach routes are known, it is possible to design an azimuth-elevation dependent map of the probability of losing track of a satellite. This allows optimizing performance and will be part of further studies.

Furthermore we showed how simple triggers can be used to reduce the computational demand on airborne users significantly while retaining most of the performance and even allowing a flexible trade-off. Additionally we proposed a straightforward scheme for satellite exchanges when transitioning from stand-alone GNSS navigation into GBAS.

Finally we combined all previous studies and showed the effect on the performance during approaches when all of the constraints are taken into account. The results show that even when considering many constraints and limitations, satellite selection in a multi-constellation GBAS stays applicable.

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