Improved Ionospheric Monitoring for Future Dual-Frequency GBAS

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ABSTRACT

As of today, all Ground Based Augmentation Systems operate using only the navigation signals from GPS (and Glonass for a number of stations in Russia) in the L1 band. Ionospheric activity, especially in equatorial and polar regions, limits the availability of the service in those regions. Therefore, an extension to dual-frequency and multi-constellation (DFMC) techniques is currently being developed. In previous work we presented an initial concept for ionospheric monitoring and preliminary evaluations using the L1/L2 frequency combination of GPS. In this paper we present an analysis of the monitoring threshold depending on the number of satellites and constellations used. Furthermore, we discuss the potential issue of multiple satellites being affected by a gradient simultaneously which causes the monitoring to become quite sensitive in the original monitoring concept. Next, we consider the impact of ground and airborne noise and multipath on the monitoring performance using latest results of the effort of developing the respective models. Finally, we show the performance of the monitor in real-world operations using flight test data from flight trials with our Airbus A320 and our experimental dual-frequency multi-constellation GBAS ground station with the currently available Galileo satellites broadcasting signals on E1 and E5a and the GPS Block IIF satellites that broadcast signals on L1 and L5.

Keywords: GBAS, DFMC, Dual-Frequency, Ionosphere

1. INTRODUCTION

The Ground Based Augmentation System (GBAS) provides differential corrections and assures integrity of the navigation solution for aircraft flying precision approaches based on the use of Global Navigation Satellite Systems (GNSS). Operational GBAS ground stations today provide corrections for the L1 signals of GPS only (apart from several stations in Russia that also augment Glonass signals). By its principle GBAS generates corrections that are valid only at the location of the GBAS. A decorrelation of the ionospheric error typically occurs. In extreme cases, this decorrelation can become significant already over very short baselines such that a GBAS user operating at distances of just few kilometers from the GBAS station already sees a significantly different ionospheric delay. Such a situation would lead to potentially harmful position errors and have to be monitored and avoided. In the single-frequency single-constellation GBAS this is ensured by developing an ionospheric threat space for the specific region where the GBAS is installed. This is done over a long period of monitoring using a network of stations to properly characterize the effects that occurred in that area and includes the determination of the largest decorrelation of the ionospheric delay over distance. All currently operational stations are located in mid-latitude regions with rather benign ionospheric conditions. In polar and equatorial regions ionospheric disturbances in the form of amplitude and phase scintillations and plasma bubbles are frequent and may show significantly steeper gradients than in mid-latitudes. This significantly limits the area of operation for GBAS. It is expected that high availability of the service in areas with active ionospheric conditions requires the use of dual-frequency and multi-constellation techniques. Significant effort is currently ongoing in development of such future GBAS service types to overcome existing limitations and enable global use of GNSS as primary means of navigation for aircraft in all phases of flight. While forming an ionosphere-free combination of the dual-frequency measurements is one option, a preferable way of processing the data would be to continue using single-frequency positioning and exploit the second frequency for monitoring purposes only. The reason is that in the iono-free combination also the noise and multipath of both frequencies is combined, leading to a degraded nominal performance of the navigation solution (Gerbeth 2016).

One main benefit from a new service type is, of course, the expectation to mitigate the effect of ionospheric disturbances. Therefore, an appropriate concept for positioning has to be developed, together with the appropriate integrity concept to ensure safety of the service for the users.

As part of this effort, a transmission scheme for GBAS corrections and integrity parameters for two frequencies and two constellations was developed. One of the main design drivers was to maintain backwards compatibility and use the existing VHF Data Broadcast (VDB) with its limited capacity (Stanisak et al. 2015). Based on this concept we developed a method to mitigate the threat of ionospheric gradients for single-frequency positioning and using the second frequency only for monitoring purposes (Felux. 2017). Due to the nature of the differential corrections it is not possible to directly estimate and compare the ionospheric delay at the ground station and the airborne receiver. The developed monitoring concepts therefore compares the difference of pseudo-ionospheric delay estimates from the corrections and actual ionospheric delay estimates after a mean-removal step to identify potential differences between the ground station and an airborne user. Depending on the number of available satellites and signals and the expected residual noise and multipath, the monitoring technique can become challenging.

2. REVIEW OF MONITORING CONCEPT

In this section the monitoring concept that was initially presented in (Felux 2015) and extended in (Felux 2017) is revisited for convenience. After a recapitulation of the principal idea, further considerations on the necessity to detect simultaneously affected satellites are presented.

2.1 Limitations by VDB Link

By the principle of how GBAS is operating, a ground station transmits corrections, integrity parameters and approach reference coordinates to arriving aircraft via a VHF data broadcast (VDB). The capacity of the VDB link is, however, quite limited. Currently, augmentation of all GPS satellites visible at the reference station is possible. However, with the intent to use also signals from more than one constellation and on two different frequencies, the available space in the VDB message becomes an issue. Further considerations also have to be put to the fact that some large airports may need two VDB transmitters at two different locations in order to ensure sufficient coverage on all approaches and runways. This further limits the space available in the VDB message assuming that the two transmitters are broadcasting in an alternating scheme. It may thus become necessary to even reduce the update rate of the GBAS corrections and integrity parameters in order to ensure that all desired values can be transmitted for dual-frequency and dual-constellation GBAS. In the SESAR project a VDB message transmission scheme was developed that fulfills all these criteria and ensures that the system is backwards compatible to existing single-frequency and single-constellation users (Stanisak et al. 2015). It is used as baseline assumption for the development of future GBAS.

One significant limitation in this concept is that the available message space does not allow transmitting estimates of the ionospheric delay as seen by the ground station. This would enable a simple and fast ionospheric monitoring on board of an aircraft by comparing the ionospheric delay at the ground station with an ionospheric delay estimate at the airborne receiver. In order to still benefit from the availability of the second frequency a different monitoring scheme was developed.

2.2 General concept

The ionospheric monitor that was developed in (Felux 2015) and (Felux 2017) proposes a method to compare a quantity derived from the transmitted pseudorange and range-rate corrections to another quantity derived from ionospheric delay estimates in the airborne receiver. This section only gives a brief summary of the work. For more details the interested reader is referred to the cited papers. A delay common to all satellites (mostly to adjust for receiver clock biases but also affecting a common ionospheric delay to all satellites) is removed in the process of generating the GBAS corrections in the ground station. However, it is still possible to derive a ‘pseudo-iono delay’ $\tilde{I}_{PRC,i}$ from the pseudorange corrections $PRC_{f,i}$ and range rate corrections $RRC_{f,i}$ on frequency f for satellite i. This can be described by

$$\tilde{I}_{PRC,i} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2} \cdot [(PRC_{L5,i} + \Delta t \cdot RRC_{L5,i}) - (PRC_{L1,i} + \Delta t \cdot RRC_{L1,i})] \tag{1}$$

where Δt is the time difference between the current time of the measurements and the generation time of the corrections. In order to account for clock differences the average over all N available measurements on the airborne receiver is removed. The final pseudo iono delay measure $I_{PRC,i}$ for the estimates from the ground is then

$$I_{PRC,i} = \tilde{I}_{PRC,i} - \frac{1}{N}\sum_{i=1}^{N} \tilde{I}_{PRC,i} \tag{2}$$

This will be an indicator of how much the iono delay differs between the satellites in view. On the airborne side, the receiver can calculate the actual ionospheric delay $\tilde{I}_{air,i}$ per satellite from the smoothed dual-frequency pseudorange measurements $\hat{\rho}_{f,i}$.

$$\tilde{I}_{air,i} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2}(\hat{\rho}_{L5,i} - \hat{\rho}_{L1,i}) \tag{3}$$

In order to make these estimates comparable to the delay differences calculated from the GBAS corrections, the mean is removed from the airborne ionospheric delay estimates in order to obtain

$$I_{air,i} = \tilde{I}_{air,i} - \frac{1}{N}\sum_{i=1}^{N} \tilde{I}_{air,i} \tag{4}$$

This $I_{air,i}$ in comparison to the $I_{PRC,i}$ should now be similar. If they differ by more than a certain threshold, the presence of an ionospheric gradient can be assumed. The monitoring condition for each satellite can then be described by

$$\left| I_{air,i} + I_{PRC,i} \right| \leq \frac{E_{v,iono}}{\left| s_{vert,i} \right|} - k \cdot \sigma_{monitor,i} \tag{5}$$

where $E_{v,iono} = 8.4\text{m}$ is a maximum tolerable vertical position error due to an ionospheric gradient (further discussed in Section 3.3), $\left| s_{vert,i} \right|$ is the projection factor onto the approach plane in the position solution and

$$\sigma_{monitor,i} = \frac{f_{L5}^2}{f_{L1}^2 - f_{L5}^2} \sqrt{\sigma_{gnd,L1}^2 + \sigma_{gnd,L5}^2 + \sigma_{air,L1}^2 + \sigma_{air,L5}^2} \tag{6}$$

describes the residual noise and multipath in the corrections (the σ_{gnd}) and the airborne pseudorange measurements after smoothing (the σ_{air}) for each frequency. The k-factor results from the allocated integrity risk for the monitor and is calculated as

$$k = -\Phi^{-1}(0.5 \cdot p_{md}) = -\sqrt{2} erf^{-1}(p_{md} - 1) \tag{7}$$

with the standard Normal distribution Φ, the Error function erf and p_{md} the allocated missed-detection probability. The required integrity risk is 10^{-9} for CAT-II/III operations, resulting in a k-factor of 6.1. This factor is assuming no credit for the (typically rather low) prior probability of a gradient actually occurring in a way that it could be threatening for a GBAS user without being detected. In recent work (Yoon 2019), a data-driven prior probability of 10^{-3} was assumed for the occurrence of an extreme ionospheric gradient. Assuming that prior probability, the missed detection probability would increase from 10^{-9} to 10^{-6} and relaxing the inflation factor from 6.1 to just 4.9 according to Equation (7).

3. DISCUSSION OF THE MONITORING PROPERTIES

The previous section revisited the ionospheric monitor, the reason for its development and the general concept. In this section the influences of the different factors shall be discussed more in detail.

3.1 Considerations on multiple satellites simultaneously affected without detection by other monitors

The concept as described only works for one satellite affected at a time. However, this assumption may be overly optimistic. Therefore, a monitoring concept considering also the possibility that more than one satellite is affected was developed and presented in (Felux 2017). The monitoring as presented in that paper, however, does not take any credit for the low prior probability of such a case actually happening. With a prior probability of 10^{-3} for a worst case gradient occurring, the probability of that gradient affecting two satellites simultaneously is even lower. We conservatively assume that the prior probability of two satellites being simultaneously affected without any other monitor already triggering an alert (e.g. the code-carrier divergence monitor or the measurement quality monitor) to be 10^{-6}. By the same argument, assuming three simultaneously affected satellites would only have a prior probability of 10^{-9} and thus be on the same order as the integrity requirement. It is therefore considered sufficient for the monitor to consider only the single affected satellite case and the two-affected satellites case with the appropriate assumptions for the prior probability. For two affected satellites i and k, and the prior probability of 10^{-6} the monitoring condition would then be

$$I_{test,i} + I_{test,k} \leq \frac{E_{v,iono}}{\left|s_{vert,i} + s_{vert,k}\right|} - 3.3 \cdot \sqrt{\sigma^2_{monitor,i} + \sigma^2_{monitor,k}} \tag{8}$$

3.2 Effect of noise and multipath and latest developments in the model development for Galileo

As it is apparent from Equation (6), the residual errors included in the corrections (in form of σ_{air}) and in the smoothed airborne pseudorange measurements (σ_{gnd}) per frequency and constellation are a necessary input for the monitor to perform its duty. The σ_{gnd} depend on the installation of the GBAS ground station and are transmitted in the GBAS message. For the evaluations in this paper shown in Section 3, we use the model developed in (Gerbeth 2016) assuming multipath-limiting antennas (MLA), as they are used in operational GBAS ground stations.

The σ_{air} are model-based standardized parameters. Currently, the airborne uncertainty is standardized only for GPS L1 (and Glonass). However, an effort to characterize and standardize the appropriate values also for Galileo E1, Galileo E5a and GPS L5 is currently underway in the frame of the DUFMAN project funded by the European commission. For the evaluations in this paper we use the models that were experimentally derived for the installation on DLR's Airbus A320 test aircraft and presented in (Felux 2019). The standard deviations are modelled to be constant over all satellite elevations. The values used are summarized in Table 1. Note that this installation on DLR's test aircraft does not use an antenna that is compliant with current dual-frequency antenna standards (RTCA 2018), but shows worse performance.

Table 1 Summarized values used for σ_{air} for each constellation and frequency

Signal	σ_{air}
GPS L1	0.7m
GPS L5	0.4m
Galileo E1	0.85m
Galileo E5a	0.3m

Initial results from flight tests within the DUFMAN project with a compliant antenna and a representative installation show significantly better performance (Circiu 2019). For the results in this paper, however, we decided to stay with the results that were determined for our test aircraft. This ensures the results are representative for the gathered data and on the other hand the results shown here can be considered to be very conservative as smaller σ_{air} would significantly facilitate the monitoring.

3.2 Largest acceptable vertical position error caused by an ionospheric disturbance

The $E_v$parameter used in the monitoring describes the largest vertical position error an aircraft can handle and still land safely. The details of the derivation are described in (Felux 2017) and go back to the touchdown requirements specified in the Certification Specifications for all-weather operations (EASA 2003) which states that

$$200\text{ ft} \leq NTDP - \frac{NSE_{vert,ff,95\%} + E_{v,iono}}{\tan(GPA)} - FTE_{ff,95\%} \tag{9}$$

where NTDP is the nominal touchdown point on the runway (1290ft behind the threshold) $FTE_{vert,ff,95\%}$ the flight technical error at its 95th percentile ($\sigma_{FTE} = 180ft$) and GPA the glide path angle of the approach transmitted in the GBAS message (typically 3°). The value of $NSE_{vert,ff,95\%}$ is the current estimated navigation performance at the 95th percentile of its distribution and is characterized by the zero-mean standard deviation

$$\sigma_{NSE} = \sqrt{\sigma^2_{gnd} + \sigma^2_{air} + \sigma^2_{iono} + \sigma^2_{tropo}} \tag{10}$$

It can therefore be considered as a function of the current estimated navigation performance, which is calculated anyways as the protection level. Alternatively, the protection level must be smaller or equal to 10m for the final approach. Therefore, a maximum value for $\sigma_{NSE} = 1.72\text{m}$ can be safely assumed, otherwise the system would be unavailable for use.

4. EVALUATIONS IN FLIGHT TESTS

In this section we're showing actual results from a flight test that took place on the 22nd of November 2017 with our research aircraft Airbus A320 in the area of Braunschweig in northern Germany. At that time between 8 and 10 satellites of the combined Galileo and GPS constellations (for GPS only the Block IIF satellites with the L5 payload were considered) were visible.

In a first assessment only the single-affected satellite case is studied. In order to get an idea about the satellite geometry the skyplot as seen during the flight is shown in
Figure **1**. The resulting vertical projection factors s_vert as they are used in Equations (5) and (8) in the determination of the monitoring threshold are shown in Figure 2.

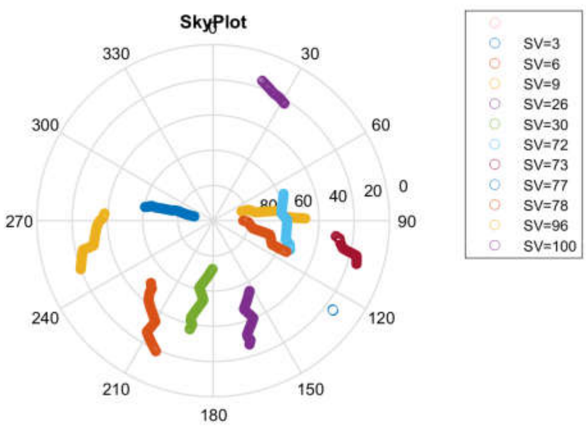

Figure 1
Skyplot during test flight (only Galileo and GPS Block IIF satellites)

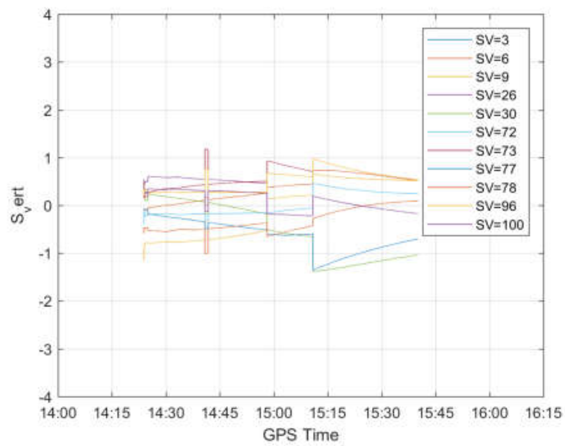

Figure 2
Vertical projection factors for each satellite during the flight

In the following, we selected the thresholds for satellites that illustrate some of the above mentioned properties.

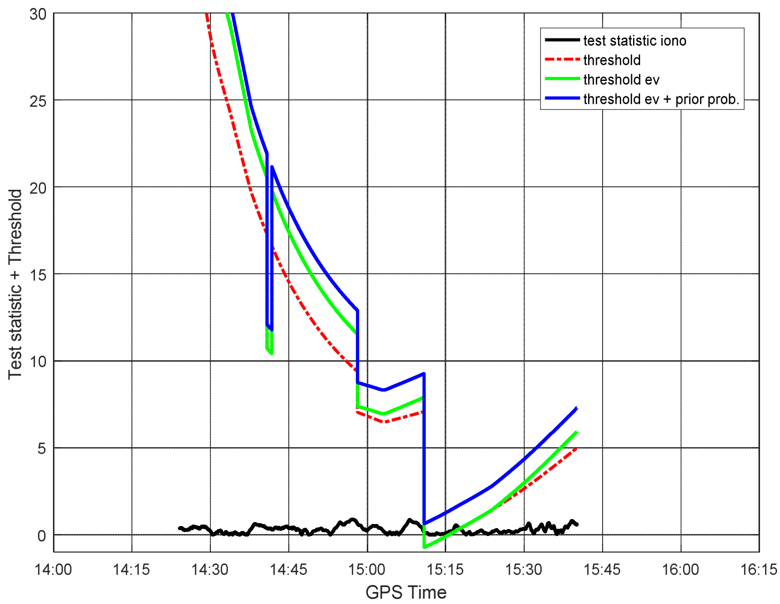

Figure 3 Test statistic of the iono monitor (black). Monitoring thresholds for PRN77 for a constant E_v of 8.4m (red), an E_v depending on the current protection level (green) and additionally taking credit for the prior probability of an ionospheric disturbance.

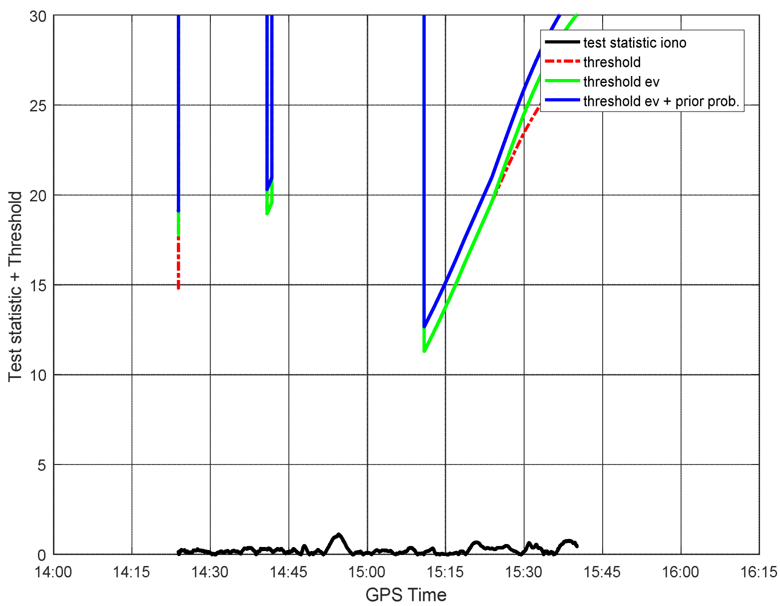

Figure 4 Test statistic of the iono monitor (black). Monitoring thresholds for PRN72 for a constant E_v of 8.4m (red), an E_v depending on the current protection level (green) and additionally taking credit for the prior probability of an ionospheric disturbance.

Figure 3 shows the results for PRN 77. It is a satellite that becomes increasingly important as it is the highest elevation satellite at the time and therefore the monitoring threshold becomes quite low. Shortly after 15:10 it becomes the satellite with the largest s_vert and therefore the lowest monitoring threshold. It can be seen that for the cases where no credit is taken for the prior probability of an iono front occurring and the worst navigation performance is assumed, the monitoring threshold becomes negative making the monitoring impossible as the test statistic is by definition always positive.. However, with the more realistic assumptions the monitoring condition with the actual navigation performance and taking credit for the prior probability of iono increases the threshold above the test statistic so that no false alert would be triggered in this case.

Figure 4 on the other hand, shows a satellite with a very high monitoring threshold. PRN 72 is a medium elevation satellite almost at the same location in the skyplot as PRN 9 with s_vert values that stay rather close to zero. Therefore, the contribution of the satellite to the vertical position estimate is very limited so that even large errors would not lead to significant errors. Therefore, the monitoring condition for this satellite can be easily fulfilled.

The situation becomes more complex when assuming all the combinations of two simultaneously affected satellites. Figure 5 shows the results for the worst-case combination of two affected satellites at each epoch. Shown in red is the monitoring threshold for the two-affected case without taking credit for any prior probability. It should be mentioned that for the combination of two satellites the threshold sometimes becomes negative and therefore makes the monitoring again impossible. However, further consideration has to be put on the physical possibility of an ionospheric disturbance affecting two satellites at completely different azimuth and elevation angles. An ionospheric phenomenon, such as a plasma bubble or a large scale ionospheric gradient typically would not impact the lowest and highest elevation satellites (that typically have the largest s_vert values) at the same time. Therefore, the plot shows an example for two affected satellites with a realistic combination of affected satellites. It can also be seen, that without taking credit for the low prior probability of two simultaneously and not detected satellites the threshold tends to be small and therefore prone to false alerts.

However, when assuming a prior probability of 10^{-6} (as previously discussed in Section 3.1) of such an event happening then the monitoring condition is substantially relaxed as shown by the blue curve in Figure 5The threshold now is increased for the largest part of the flight to values that are uncritical for the monitoring and do not pose a significant risk of creating false alarms.

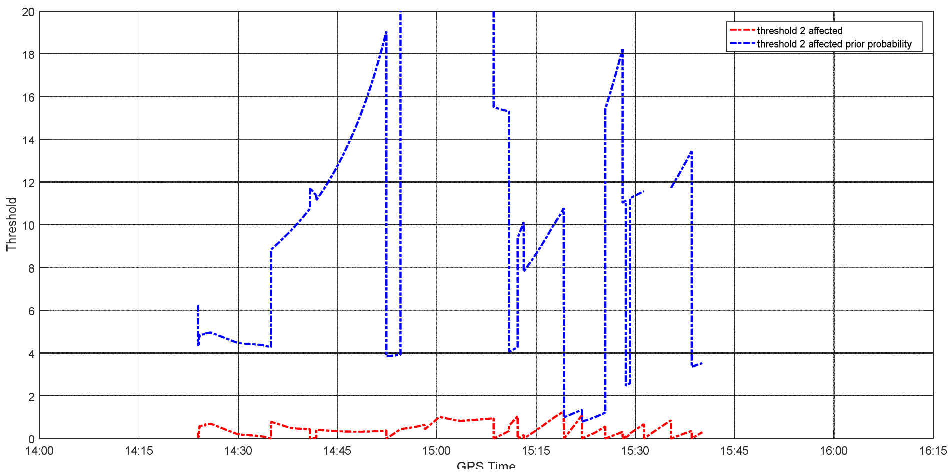

Figure 5 Monitoring condition for two satellites with (blue) and without (red) taking credit for the probability of two simultaneously affected satellites without detection.

5. CONCLUSIONS

In this paper we presented further studies of an ionospheric monitor for dual-frequency GBAS using single-frequency positioning and the second frequency for monitoring purposes. A monitoring technique was discussed and the impact of the different contributors was evaluated.

The paper showed evaluations of a flight test with under calm ionospheric conditions. It showed the benefit of taking into account the current estimated navigation performance. A better navigation performance allows for a larger ionospheric error and therefore relaxes the monitoring condition. Furthermore, it was shown that considering the prior probability of an ionospheric disturbance occurring and affecting a GBAS user has a significant impact on the expectable performance. While it is possible that monitoring becomes impossible in weak geometries, taking credit for the prior probability relaxes the monitoring condition and reduces the potential false alarm rate. It is, however, subject to further investigations if such weak geometries could actually occur in real-world operations or would lead to protection levels or s-factors that would render the service unavailable by other monitors. It is expected that with increasing number of satellites available the weight of each single satellite decreases in the position solution leading to smaller s_verts that with the satellites available during the flight.

In addition to the single-affected satellite case, also the case of two affected satellites may have to be considered. The monitoring condition becomes even more challenging in this case, however, the probability of having two affected satellites without detection is becoming very low. Therefore, taking credit for this low prior probability relaxes again the monitoring condition. Further considerations have to be put into the question which combinations of two affected satellites would have to be considered.

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