GNSS Inter-Constellation Phasing: Validation of the Worst-Case Assumption

Markus Rippl, *German Aerospace Center (DLR)*

BIOGRAPHY

Markus Rippl is a research fellow with the Institute of Communications and Navigation (IKN) at the German Aerospace Center (DLR). His field of work is the integrity of GNSS-based navigation using receiver-side algorithms. He received his Diploma in Electrical Engineering and Information Technology from Technische Universität München (TUM) in 2007.

ABSTRACT

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) uses satellite range measurements from multiple GNSS constellations to determine navigation integrity. Providing robustness against multiple simultaneous satellite faults, ARAIM needs a much higher number of available measurements than a classical RAIM [1]. Studies [2, 3, 18] expect that the performance of ARAIM based integrity will be sufficient to allow for LPV-200 based operations only if two complete constellations are present.

Performance simulations using GPS and Galileo constellations use an arbitrarily selected definition of the relative positioning of orbital planes of these two constellations. In reality however, the orbital plane phasing between Galileo and GPS is a determined parameter varying very slowly due to orbit perturbation. Because the RAAN (Right Ascension of the Ascending Node) parameter of all orbits drifts slowly and this drift rate depends on the orbital altitude of the spaces vehicle, Galileo and GPS have different RAAN drift rates. As a result, identical RAAN phasing between the two constellations reappears at a period of 11 years, and a potential worst case would persist for significant time, i.e. several years. Identification of such a worst case constellation phasing is thus important to avoid too optimistic performance estimates in simulations. Most previous performance studies assume that the worst case constellation phasing exists when three of the GPS planes have identical RAAN parameters to the Galileo planes as this setup fosters weak geometries where satellites from GPS and Galileo appear to be close together. This worst case assumption has been confirmed in DOP-based studies such as [4] for navigation accuracy, but not yet for ARAIM performance.

Because ARAIM based navigation is much more susceptible to small and weak geometries it is necessary to review the validity of the worst case assumption with respect to ARAIM. Moreover, past work on inter-constellation phasing effects has only compared the "full alignment" scenario with the "most separated" scenario where Galileo planes are distributed exactly in the middle between the GPS planes. This paper analyses ARAIM performance for a more detailed range of RAAN phasing scenarios, and determines the worst case for ARAIM based navigation integrity.

Furthermore we demonstrate the projected performance for the Galileo mission under the assumption that the recently launched Galileo SVs already define the inter-constellation phasing. By extrapolation of available orbit data to a full Galileo constellation the ARAIM performance at Galileo FOC and during the first years of operation is predicted.

The results obtained from the simulations demonstrate that the constellation phasing does impact the ARAIM performance, but the magnitude of this change is small. The minor characteristic of this effect is also confirmed for a combined constellations based on current GPS configuration and Galileo at FOC. The individual impact on the ARAIM VPLs for specific users however is rather large and can be observed in both directions, i.e. the change from a "best case" to a "worst case" constellation phasing has a positive impact for the performance of some users, and a negative impact for other users.

INTRODUCTION

With launching the first two Galileo satellites in October 2011 a first orbital plane of the new constellation has been established. A second orbital plane was added after another pair of IOV satellites had been launched in Oct. 2012. All following launches will be adjusted to establish the corresponding satellites in these two existing orbital planes and a third one, all planes having an angular spacing of 120 degrees. With this important step towards

Final Operational Capability (FOC), a specific parameter that is important to the performance of a combined constellation of GPS and Galileo satellites has been fixed: The relative phase angle between each Galileo and each GPS orbital plane.

Although each individual GNSS constellation will be maintained in its nominal shape and configuration by the ground segment, they both rotate very slowly with respect to an inertial reference frame due to natural orbit perturbation. The magnitude of this rotational motion depends on the orbit altitudes and is in the order of a few to tens of of degrees per year for MEO orbits used in current GNSS constellations. While GPS SVs orbit the earth at an altitude of 20,188 km in average [5], the Galileo SVs use a different altitude of 23,616 km [6]. The result is that natural orbit perturbations affect the two constellations differently, and the relative phase angle between two orbital planes of one Galileo plane and one GPS plane will change at a rate of approximately 5.14 degrees per year [4].

Problem definition

The angular spacing of the six orbital planes in GPS is nominally 60 degrees between any of the adjacent planes. For Galileo with three existing planes, the spacing is 120 degrees. One specific Galileo plane can therefore be arranged up to 30 degrees away from the closest GPS plane. In the following simulations, two simplifications are made:

1) It is assumed that a relative phase angle of more than 30 degrees and less than 60 degrees leads to approximately the same performance level as the corresponding setup with a phase angle between zero and 30 degrees, i.e. the performance level depends on the phase angle in a symmetrical way. This assumption is made to simplify the analysis in terms of computational load and data size.
2) Furthermore it is assumed that different orbital planes on the same RAAN position behave identically; i.e. any scenario with an additional offset of $n \cdot 120°$ for the Galileo RAAN phasing leads to approximately the same positioning and integrity performance. In fact the Galileo orbital planes have an additional offset of the mean anomalies between slots on different planes, so this assumption is again a simplification.

Taking into account the slow RAAN drift of each constellation, the resulting possible scenarios lie in between two extrema where either three GPS planes coincide with the Galileo planes (Figure 1), or their relative phase angle measures 30 degrees (Figure 2). In previous work [4] it is assumed that a worst case exists for positioning accuracy if the planes overlap.

Intuitively the reason for this behavior seems to be founded in inferior geometric diversity due to the orbits of Galileo and GPS satellites being almost identical. In fact the analyses published in [4, 7] have demonstrated that alignment of Galileo planes with three GPS planes leads to positioning accuracy that is worse both for horizontal and for vertical navigation, although the magnitude of this effect is small.

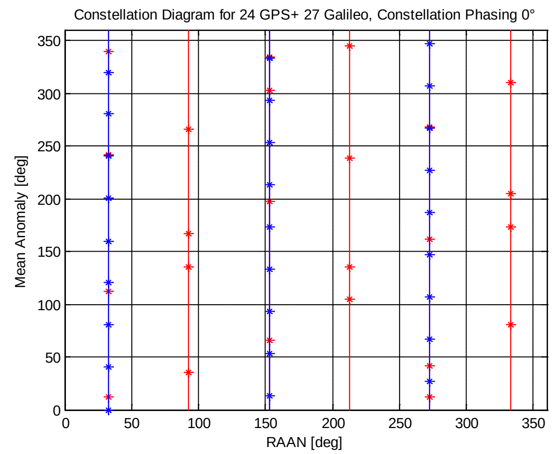

Figure 1: Constellation Diagram for nominal GPS and nominal Galileo constellations, with an inter-constellation phasing angle of zero degrees. Three GPS (red) orbital planes coincide with the Galileo planes (blue).

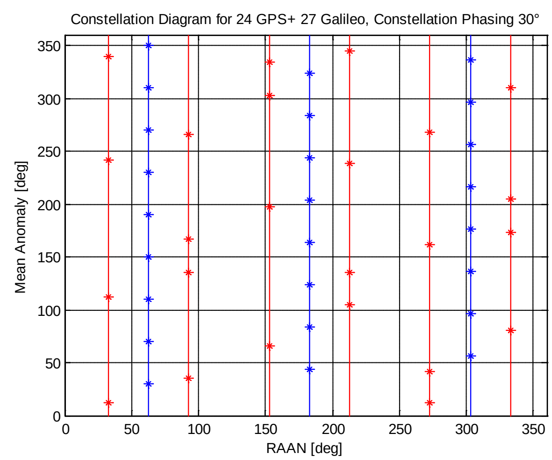

Figure 2: Constellation Diagram for nominal GPS and nominal Galileo constellations, with an inter-constellation phasing angle of 30 degrees. The RAAN distance between any GPS and Galileo planes is maximized.

A very promising application that can fully exploit the system properties of two modernized GNSS constellations is positioning with enhanced navigation integrity, in particular using Receiver Autonomous Integrity

Monitoring (RAIM). The set of algorithms being under investigation allow for vertical guidance under LPV-200 requirements are collectively referred to as ARAIM, or Advanced Receiver Autonomous Integrity Monitoring. The most promising candidate to allow for future ARAIM applications is the MHSS (Multiple Hypothesis Solution Separation) algorithm [8, 9, 10] which has recently been consolidated in a joint US/EU effort in the ARAIM Ad-Hoc working subgroup of the EU/US WG-C [11, 12]. Its main function is the provision of an error bound for the position error which is referred to as the Protection Level (PL). In general the vertical component for this error bound has the most stringent requirements and thus in the remainder of this work the Vertical Protection Level (VPL) is the only integrity error bound under analysis. A fundamental difference of MHSS-ARAIM with respect to classical RAIM approaches such as [1] is that it implicitly integrates a set of sufficiently probable fault modes into the computation of the error bounds. For every fault mode a solution separation is computed which is the difference between the position estimate containing all measurements and a solution based on a subset of measurements. As a consequence the protection levels that are determined by this algorithm are more susceptible to small geometries than when using all-in-view based RAIM. Especially when a rather high prior probability for satellite faults is assumed the reduction of geometry size within the fault hypotheses can be two, or even more satellites.

MHSS based ARAIM determine the VPL for a specific epoch from the maximum of all partial VPLs. Each partial VPL_j corresponds to one fault mode (i.e. a unique combination of excluded and included measurements) and consists of a solution separation and additional error contributions that model the noise and bias of nominal measurements. Those contributions are projected into the axis of interest, in this case the vertical axis.

$$\mathrm{VPL} = \max_{all\ j} VPL_j$$

$$= \max_{all\ j} \left[D_j + K_{MD,j}\sigma_{v,j} + \sum_{i=1}^{N} \left|S_j\right|_{3,i} b_{max} \right] \qquad (1)$$

The solution separation D_j is an estimate of the position estimate difference between a solution taking all measurements into account and a solution based on a subset of measurements. The noise term $K_{MD,j}\sigma_{v,j}$ is based on a Gaussian overbound of the nominal error noise projected into the vertical domain, and the bias term $\sum_{i=1}^{N} \left|S_j\right|_{3,i} b_{max}$ is a projection of the sum of assumed worst-case nominal measurement biases into the vertical axis. The influence of the subset geometries in all considered fault modes can be directly seen.

It is therefore interesting to evaluate

- whether ARAIM is more sensitive to inter-constellation phasing than an all-in-view based PVT solution,
- how much degradation due to constellation phasing can be expected in average as well as for selected users or regions, and
- whether the present constellation phasing constitutes a worst case, or when such a worst case would come into effect.

The remaining paper is organized as follows. The subsequent section is an accurate definition of the used ARAIM algorithm, the performance metric that is of interest and the methodology of analysis with respect to determining that metric. A section describing the simulation scenarios follows, together with the presentation of results corresponding to "nominal constellation" simulations. Additional simulations examine whether constellation fault threats remove any of the measured impact. A last simulation section deals with the simulation of projected constellations as they can be expected from today's situation. A concluding section summarizes the study.

METHODOLOGY

The primary objective of the present work is to estimate whether ARAIM, in its current implementation as an MHSS-based RAIM algorithm, is influenced more from GNSS constellation drift than non-MHSS based PVT&RAIM algorithms are. The fact that MHSS uses a set of reduced geometries within the computation of VPLs supports the presumption that this is the case.

The ARAIM algorithm version described in [12] is used throughout this work. It is an MHSS based ARAIM algorithm that constitutes its search tree directly from assumptions on the satellite fault rate P_{sat}. The consequence is that the fault rate directly drives the number of fault hypotheses and as such, the search depth of the algorithm or the number of excluded satellites. An a-priori state probability derived from satellite fault probabilities can be allocated to each of the fault hypotheses. In this work the satellite fault probabilities are assumed to be identical among the satellites, i.e. a common fault rate of 10^{-5} per SV per approach is assumed. For geometry sizes up to 28 SVs in view this choice results in the ARAIM algorithm taking into account at most 1 faulted satellite at a time.

Besides faults that affect single satellites ARAIM also considers threats that pertain to a complete constellation. These fault modes are referred to as wide (constellation) faults and their origin can be manifold: Miscalculation of parameters of the ephemerides in the ground segment may affect a large number of satellites or all of them, and one particular fault mode that has been of high interest is the Earth Orientation Parameter (EOP) fault. While the magnitude of the risk for these faults can only be roughly estimated at this time, it is common sense that their existence needs to be considered in the threat model for ARAIM. Depending on the prior risk for a constellation fault, it might be allocated to a partition of the integrity budget without the corresponding fault mode being investigated as an MHSS hypothesis. If the fault probability is sufficiently high however, a fault hypotheses need to be considered where all the satellites from one constellation are excluded. These correspond to partial solutions based on single constellations for a two-constellation scenario, and the resulting partial VPLs have proven to be a main performance driver for the common VPL. It appears to be possible that this effect significantly reduces the possible impact of constellation phasing on the ARAIM performance [Personal Communication with Dr. J. Blanch, Stanford University, 2013]. To examine this assumption, the simulations have been executed both with a constellation fault prior of 10^{-6} (large enough to force constellation fault modes being present in the hypothesis search tree) and without constellation fault probability. While previously stated that constellation faults are relevant threats to ARAIM, it is however expected that those might be mitigated by ground and onboard monitoring to an extent where the remaining risk is small enough not to create fault hypotheses [13, 14, 15]. The consequence is that both scenarios might apply to reality in the future and thus this study is extended correspondingly.

A later extension of the ARAIM algorithm [9] describes the optimal allocation of the available integrity budget across all partial solutions so as to equalize the resulting partial VPLs. The approach can be described as shifting integrity budget towards partial solutions corresponding to the highest partial VPLs, until all partial VPLs are sufficiently equalized. In result the maximum VPL is reduced. With respect to the analysis of the constellation phasing effect it may be assumed that this optimization step leads to a certain equalizing effect also for VPL changes that may be introduced by a constellation phase shift. Simulation results where optimization has been enabled have therefore been compared to results without optimization in a section of the results presentation, confirming that a minimal effect can be seen (not demonstrated in this paper).

The desired quality metric in this study is the ARAIM performance with respect to common requirements such as the LPV-200 requirement [16]. LPV-200 is the least stringent requirement set that defines performance criteria for vertical guidance and consists of a set of individual metrics that are compared to their corresponding thresholds [17]:

- The probability of a vertical errors with a magnitude greater than 35m (Vertical Alert Limit or VAL) shall be limited to 10^{-7} (VPL requirement)
- The probability of vertical errors under system failure conditions that are larger than 15m shall be limited to 10^{-5} (EMT requirement)
- The fault-free vertical error shall not exceed 10m with a probability higher than 10^{-7}
- The fault-free vertical accuracy of the position solution shall be below 4m 95% of the time (Accuracy requirement)
- Continuity of the service shall be assured at a probability of $1 - 4 \cdot 10^{-6}$ in any 150s interval

For the definition of the quality metric used here it is necessary to recognize which of the ARAIM-specific computations have a direct dependency on the fault hypotheses. The Fault-Free Vertical Accuracy requirement and the Fault-Free 10m requirement both apply to the case that none of the measurements have non-nominal conditions, and thus are directly linked to the all-in-view geometry. It can be assumed that the constellation phasing impact on these metrics is identical to that demonstrated for all-in-view positioning in [4]. The EMT requirement refers to a monitor limiting the fault probability of those faults that cause a vertical position error greater than 15m, and as such includes the computation of a solution separation. The VPL equation (1) also includes both the respective all-in-view geometry and a subset of the reduced geometries. If an effect different to that seen with PVT can be observed with ARAIM, it is therefore visible from the change of the VPL values.

The availability of ARAIM based integrity can be determined from verifying if all the requirements stated above are met. In the present study, the figure of interest is the variation of this ARAIM availability caused by constellation phasing. Availability with respect to the VPL error bound is given when the VPL magnitude is below the alert limit of 35m. However this is usually the case for any user assuming two full constellations and the satellite fault rates mentioned before. A potential effect on ARAIM performance could possibly be masked by this threshold test, so a more direct measure of the influence is therefore the VPL results itself.

To allow for meaningful interpretation of the VPL data derived from bulk user simulations it is convenient to measure a quantile value of each of the VPL distributions corresponding to a specific user location. This summarizing operation of the data fulfills two functions: Firstly, the complexity of the data is reduced by removing the time dependency. Secondly it may be assumed that two individual VPL values stemming from the same user at the same time, but with different constellation phase angles are decorrelated because the corresponding geometries are rather distinct. By determining a statistical property over the distribution of VPLs for a specific user during the whole simulation interval, this decorrelation is partly removed. The simulated phase angle parameter influences the position of all Galileo satellites in terms of their longitude. A secondary step to level out the data is hence to average the data over all users with the same latitude in addition to the temporal summary. However as the results from previous simulation studies show that a certain correlation among user VPLs at equal latitudes exist, this second step is not strictly necessary.

A good statistical property of a distribution of VPL results corresponding to a single location is a quantile such as the 95%, 99.5% or 99.9% value. It marks the worst case for this user and is compliant with the method of measuring the coverage for a selected region [18]. While the LPV-200 requirement of 35m for the worst case VPL is met without problems for the current simulation setup, it must be noted that the general performance level of ARAIM in a real application may change due to various parameters such as URA, nominal biases, or satellite fault probabilities. Therefore this analysis does not take into account the availability of the VPL requirement with respect to the 35m limit. Instead a fixed quantile of the user VPLs is analyzed.

Horizontal metrics have been mostly unstudied in previous performance analyses [18]. On the one hand, the horizontal error bound HPL is usually lower than VPL due to user geometries which are mostly favorable for horizontal navigation. On the other hand, the horizontal requirements for integrity are much less stringent in aviation applications. It can therefore be assumed that whenever the vertical requirements are met for a specific user, the horizontal requirements are met as well. This simplification is of course only agreeable as long as a prediction of the true performance is desired. In operational use, the avionics receiver has to ensure both the vertical and the horizontal requirements are met all the time.

In conclusion the following means of measuring the impact of constellation phasing are applicable:

- Comparison of a high quantile of the VPL distributions for each user

- Where observed, an impact on the LPV-200 availability at a specific location (i.e. variation of the percentage of users that experience a 99.5% VPL availability of 35m or less). This metric however is not meaningful in the sense that too many parameters can change the actual ARAIM performance in a later real scenario and thus a small degradation of VPL performance might become relevant.

- Comparison of the VPL distributions summarized both over time and over longitudes (latitude dependent mean or high quantile VPLs)

Instead of comparing the absolute VPL values, it is convenient to determine the relative variation of VPL. With the preliminary definition of the "worst case" as a zero-degree phase angle scenario and the "best case" as the 30-degree offset scenario, we can derive a parameter describing a differential VPL:

$$dVPL = VPL_0 - VPL_{30} \tag{2}$$

With this definition it can now be described how specific dVPL values need be interpreted with respect to the hypothesis being tested:

- Positive dVPL values support the hypothesis that constellation phasing has an impact on ARAIM performance and that the zero-degree scenario (aligned planes) performs worse than the maximum-offset scenario (30°)

- Negative dVPL values suggest that the offset scenario performs worse than the in-phase scenario. These values still support the hypothesis that an impact can be demonstrated, but conflict with the general findings of [4].

- Small values of dVPL suggest that there is only little impact on ARAIM performance.

In addition the following auxiliary parameters help verify the results applying to positioning accuracy:

- Dilution of Precision (DOP), in particular Vertical DOP (VDOP) and the DOP change due to phasing. The DOP change can be measured both as a change of the average DOP for a specific user or of a high DOP quantile.

- Geometry size and geometry size change, both as an average or a high quantile value.

SIMULATION USING NOMINAL CONSTELLATION DATA

In the first set of simulation results the impact of constellation phasing on a nominal scenario is investigated. This scenario is set up using the nominal constellation description of 24 GPS satellites [5], and 27 Galileo satellites [6]. As a baseline, the Galileo planes are fully aligned with three GPS planes, resulting in a so-defined worst case phasing scenario. The inter-constellation phase angle, i.e. an offset of each RAAN parameter in the Galileo constellation, is then set to 30 degrees to obtain a scenario defined as the best case.. The simulations cover a worldwide user grid with a spacing of two degrees both in latitude and longitude and the duration is ten days at a time interval of 10 minutes.

The assumptions on the SIS performance have been chosen identically to the simulations in [12, 11], i.e. a URA value of 0.75m for GPS and 0.957m for Galileo has been chosen. The nominal biases are bounded at 0.75m (GPS) and 1.0m (Galileo). The prior probability of satellite fault is set to 10^{-5} per satellite and per approach, and the constellation fault prior is set to zero for the results presented in this section.

Confirmation of PVT-related results

The simulation scenarios in [4] have been reconstructed from the assumptions defined in the reference and the Vertical Dilution of Precision (VDOP) for the user grid has been analyzed. Figure 3 shows the 95% VDOP for each location during a simulation run of 10 days. The best locations in terms of availability of good geometries for vertical navigation can be found at latitudes of around 55 degrees and around the equator.

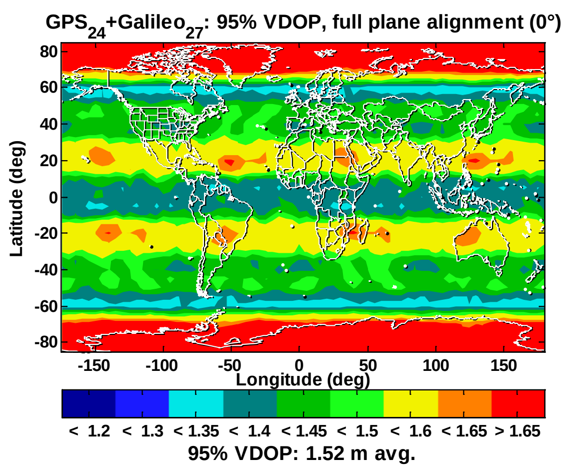

Figure 3: 95% VDOP for the "Worst Case" scenario.

The data in Figure 4 shows the same scenario, but with the Galileo constellation shifted by 30 degrees. According to our previous definition, this is assumed to be the best case, and in fact a small improvement of the VDOP can be seen. However the effect can only be observed at very small magnitudes. The averaged 95% VDOP, taken over all users and normalized about the area corresponding to each grid point in the simulation, is only 0.02 smaller than with the worst case.

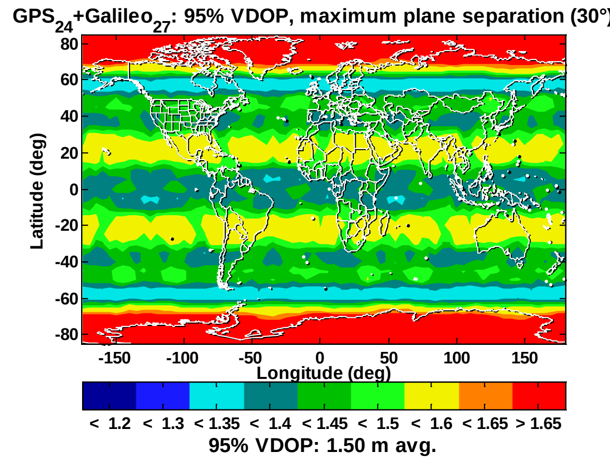

Figure 4: 95% VDOP for the "Best Case" scenario. The average VDOP for all users is only 0.02 smaller than for the worst case.

The lower bound on the geometry size is another metric that supports the results shown before. In Figure 5 and Figure 6 the 5th percentile of the geometry size for all users is shown. The difference can best be seen in mid-latitudes, where the areas with dark blue color are smaller for the best case, and instead the cyan areas are larger. Users in these areas would benefit from a at least 13 satellites in view at 95% of the time when constellations are maximally separated.

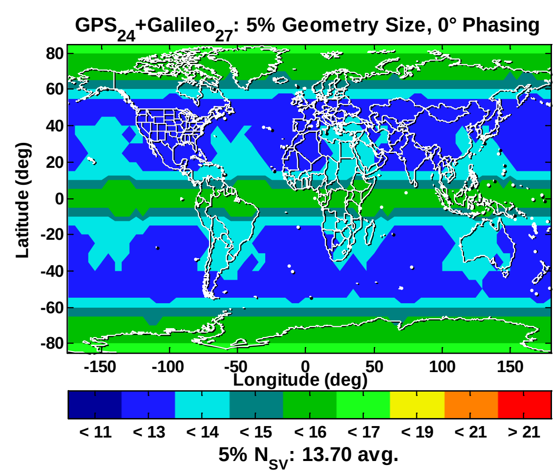

Figure 5: 5% Geometry size for the "Worst Case" scenario.

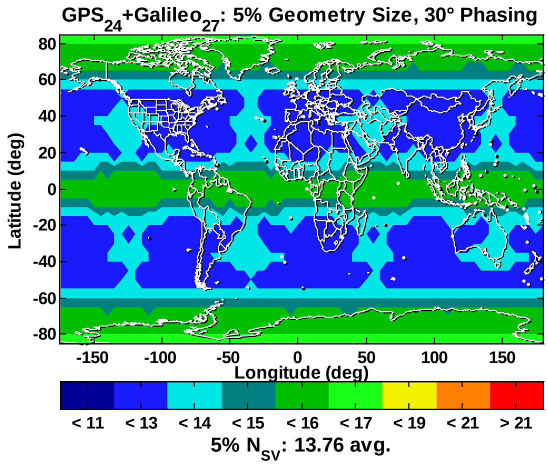

Figure 6: 5% Geometry size for the "Best Case" scenario.

Impact on ARAIM

The next part of data evaluation covers ARAIM-specific metrics. For each constellation phase setup, one VPL result for every simulated user at every simulated time steps is predicted. The character of scenario parameterization (i.e., RAAN offset variation) changes the longitudinal positions of a part of the satellites significantly, Two VPL data points belonging to the same simulated user are then based on two completely different geometries for the same user at the same time but with different constellation phasing; hence a meaningful interpretation of such pairs of data is difficult.

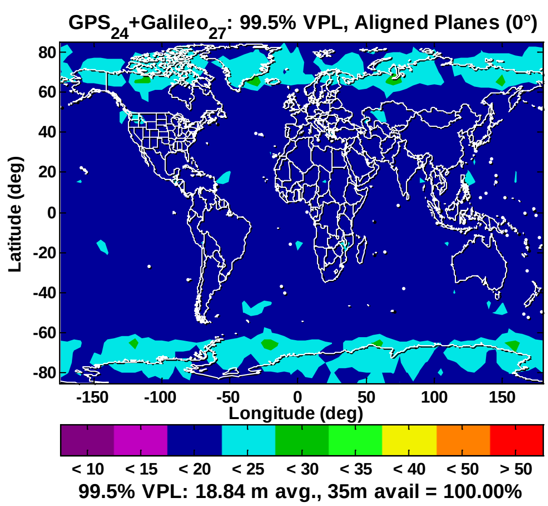

Figure 7: 99.5% VPL for the "Worst Case" scenario, Nominal GPS and Galileo constellations, no constellation faults.

Figure 7 and Figure 8 show the upper bound (99.5th percentile) for the ARAIM VPL in a scenario with aligned phases and one scenario with separated phases. By reducing the set of VPLs to a quantile, user locations become more comparable between two phase angle scenarios.

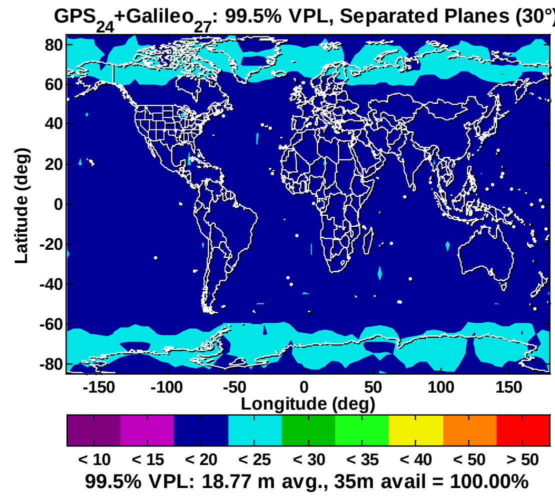

Figure 8: 99.5% VPL for the "Best Case" scenario, Nominal GPS and Galileo constellations, no constellation faults. The average 99.5% VPL for all users is only 7cm smaller than in the worst case.

The variation in terms of VPL performance can indeed be observed but is very small. Furthermore it can be noted that already for a nominal constellation of 24+27 SV and using the present assumptions both scenarios result in a performance level that has sufficient margin towards the requirement of 35m.

Differential analysis of VPL quantiles

A direct comparison of VPL values between different constellation phasing parameters is possible when the differences in VPL are transformed into statistical features. As discussed any tuple of VPLs from the same user at the same time does not result in a meaningful differential value because the underlying geometries are generally different. It is more meaningful to compare two worst case VPL bounds such as the 99.5th percentile, irrespective of their temporal connection. The values under investigation here are therefore determined by

$$dVPL_{99.5}(x) = Q_{99.5}(VPL_0(x,t)\ \forall\, t) - Q_{99.5}(VPL_{30}(x,t)\ \forall\ t) \qquad (3)$$

where $VPL_0(x,t)$ denotes the VPL as a function of location and time, at a constellation phasing of zero degrees and $VPL_{30}(x,t)$ for 30 degrees. The quantile function $Q_{99.5}$ returns the 99.5th percentile of its argument, taken over all t.

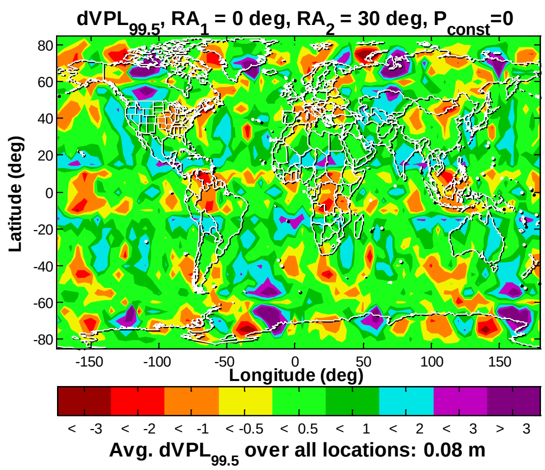

Figure 9: dVPL-99.5%. This plot represents the change of VPL at the 99.5%-worst case for every user due to constellation phasing. Although the range value is large, the averaged change in 99.5%-VPL is in the centimeter range.

Figure 9 is a graphical representation of this change. It depicts the change in the almost-worst case VPL for every user due to constellation phasing and with otherwise identical assumptions. For a lot of users, the change of the worst case geometry only results in a VPL difference below the magnitude of 0.5m (light green areas). Other users experience either a VPL performance decrease of up to 3 meters, or a performance decrease of up to 3 meters. Only selected areas experience a change with even larger magnitude (dark red/dark purple). In contrast to the rather broad range of values the averaged dVPL taken over all user locations is very small.

DISCUSSION

The results with nominal constellation sizes and setups showed that surprisingly, not much difference can be observed in both PVT and ARAIM performance when the orbital planes of two constellations are rotated with respect to each other. Complete alignment of two orbital planes causes that a larger number of satellites rotate in the same plane in inertial space and correspondingly, other locations at MEO altitudes remain uncovered. Still the resulting performance remains largely unmodified. The difference can best be observed when a snapshot of satellite positions at t_{oa} is plotted as in Figure 10 and Figure 11. The affiliation of individual satellites with orbital planes is illustrated graphically by plotting the instantaneous ground projections of these orbits in red for GPS, and in blue for Galileo.

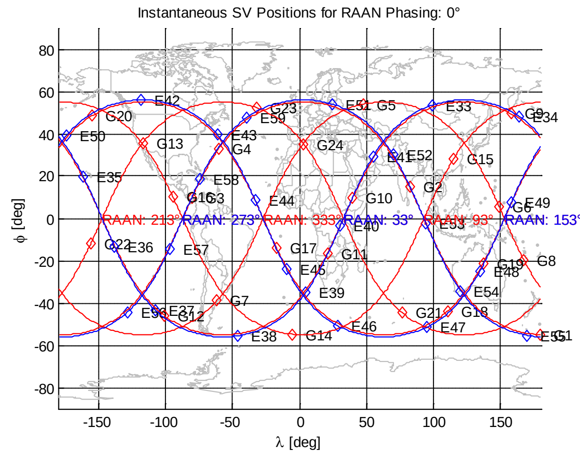

Figure 10: Instantaneous SV positions and instantaneous ground projections of the six GPS planes and 3 Galileo planes, when the RAAN phasing is set to 0°.

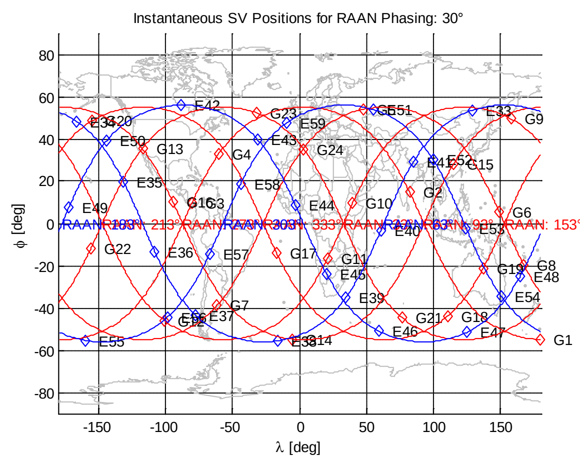

Figure 11: Instantaneous SV positions and instantaneous ground projections of the six GPS planes and 3 Galileo planes, when the RAAN phasing is set to 30°. The instantaneous distribution of satellites appears to be more homogenous.

However the simulation results do not allow the identification of such a worst-case effect very clearly. An explanation for this averaging behavior can be derived from a representation of the orbital constellation where the actual ground plots of all satellites in two constellations have been superseded. The ground plots of GPS satellites repeat after one day with only a small longitude offset due to the difference of sidereal days to earth days (Figure 12). However individual satellites have individual ground tracks irrespective of their orbital plane. This is explained by the earth rotation which continuously adds a longitudinal offset to the satellite's position in the ECEF frame as it is circling on its orbit. This offset can be altered by changing the mean anomaly of a satellite on its orbit.

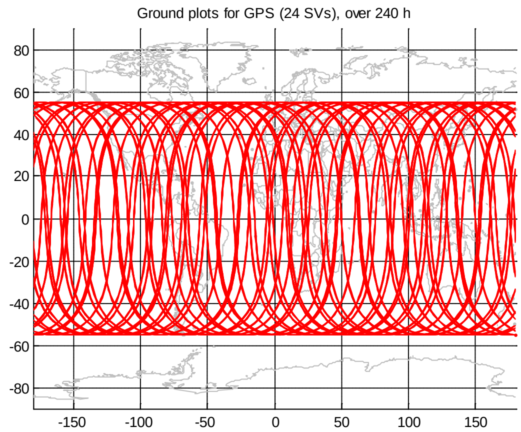

Figure 12: Ground plots of a GPS constellation during a 10 days interval. Individual ground tracks repeat with a small longitudinal offset after one day (lines appearing as thick red are in fact ten thin red lines). The ground tracks of satellites on the same orbital plane however are different, i.e. 24 different ground tracks exist.

The ground plots of Galileo satellites have a different characteristic however. The walker constellation only repeats after 10 days. Consequentially a more distributed pattern of ground tracks can be observed, even at shorter time periods such as 48h (Figure 13).

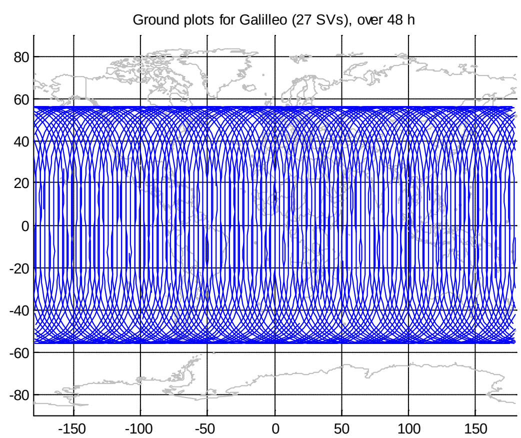

Figure 13: Ground plots of a Galileo constellation during a 48h interval. Individual ground tracks do not repeat within this interval. A very well-distributed coverage of all areas between the maximum latitudes is the result. The interval was chosen in spite of 10 days as to leave individual ground tracks distinguishable.

Figure 14 is a summary of the ground plots of both constellations over a time period of only 12 hours with a constellation phasing of 30 degrees (best case). Figure 15 shows the same interval with the worst case phasing (0 degrees). Even over this relatively short time interval the distributions are virtually identical. This is a possible explanation why constellation phasing has such a small impact on navigation and integrity performance.

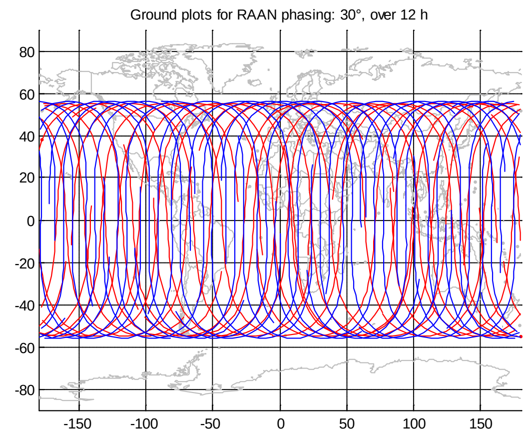

Figure 14: "Best Case" ground plots of a combined Galileo+GPS constellation during a 12 hour interval.

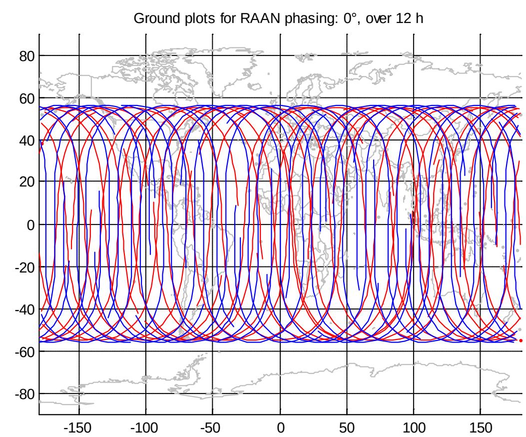

Figure 15: "Worst Case" ground plots of a combined Galileo+GPS constellation during a 12 hour interval.

CONSEQUENCE OF CONSTELLATION FAULT HYPOTHESES

The previous simulations have assumed that no constellation fault threat needs to be considered by the ARAIM algorithm, i.e. either a ground system or auxiliary onboard monitors remove the risk of unidentified constellation faults to an extent where the remaining risk can be accommodated in the available integrity budget directly. In Figure 16 the same scenario as in Figure 9 is shown, but constellation fault modes have been integrated into the ARAIM hypotheses tree. The prior risk of one constellation fault is 10^{-6}, and as such the ARAIM VPL is a maximum VPL of all geometries where either one satellite or a whole constellation was excluded. As a consequence these significantly smaller constellations including either only GPS or only Galileo satellites limit the ARAIM performance most of the time. Since the two constellations are only rotated between one and the other scenario, only a small remaining impact on the difference of the worst-case VPL can be observed.

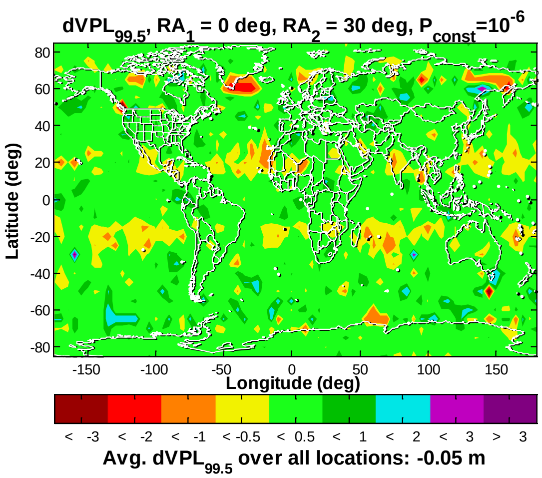

Figure 16: dVPL-99.5% with constellation fault priors set at 10^{-6}.

It can be observed that the value range for the parameter under investigation is significantly narrowed. The mean value of all VPL variations (dVPL) is again very small. This data confirms the hypothesis on the reduced impact of constellation phasing when a high constellation fault probability is present.

VERIFICATION OF LINEARITY ASSUMPTION

Up to now only scenarios with a zero-degree phasing and a thirty-degree phasing have been examined. Although the difference of VPL performance between those two is small, it cannot be obviated that a different relative phase angle between these two extreme values might lead to a completely different performance level, thus establishing a worst case outside the scenarios investigated. In order to exclude this possibility the simulations from the first scenario have been repeated also with RAAN phase angles between 0 and 30 degrees at a spacing of 5 degrees. To examine this larger set of data appropriately, another layer of statistical summarization is introduced. The previous results have demonstrated that the individual user locations and their corresponding ARAIM performance levels exhibit some degree of correlation between users with the same latitude. The cause for this effect lies in the combined longitudinal movement of the satellites with respect to earth, resulting both from orbital motion and earth rotation. In order to exploit this correlation all users with the same latitude are now summarized. Figure 17 indicates these results by taking the maximum $dVPL_{99.5}$ of every latitude (solid lines) and the average $dVPL_{99.5}$ (dotted lines). It can be observed that all the phase angles have approximately the same influence on the dVPL per latitude. From this result it can be assumed that no significant worst or best case exists outside the previously examined two scenarios.

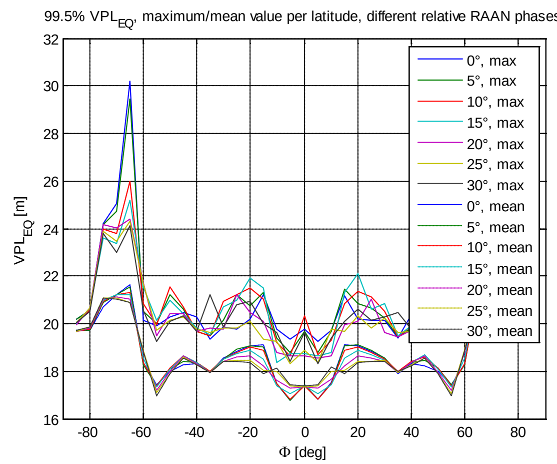

Figure 17: dVPL-99.5% by latitude for scenarios ranging from 0 to 30 degrees RAAN offset.

PERFORMANCE OF GPS+GALILEO AT FOC

The second part of simulation scenarios considers a hypothetical constellation setup where the latest actual orbital data has been used as a basis. On the one hand GPS has been operating far above its assured constellation size for years now. On the other hand the launch of the first four Galileo satellites has now fixed the inter-constellation phasing between these two systems. Taking these facts into account is the rationale for this part of the analysis.

It can be foreseen that the effect of constellation phasing will be even smaller with larger constellation sizes. The present results confirm this assumption.

Figure 18 is a snapshot of the current constellation as of Oct. 2012 after the launch of a second pair of Galileo satellites. Surprisingly the constellation RAAN parameters appear to be aligned with three existing GPS planes which corresponds to the situation previously denoted as the "worst case".

By extraction of the existing RAAN parameters from Galileo TLE data, a nominal 27 SV Galileo constellation at the same phasing can be added to the latest GPS almanacs. A best case scenario is obtained by shifting the three Galileo planes by 30 degrees. With the annual drift rate of each of the constellations, this configuration would become effective approximately in 2018.

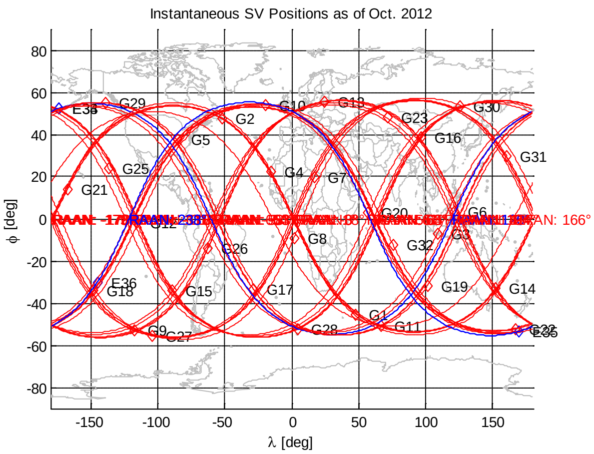

Figure 18: Instantaneous SV positions and instantaneous ground projections of currently available SVs (31 GPS and 4 Galileo)

The results in Figure 19 look similar to those based on nominal constellations. Areas with a very high variation have however decreased w.r.t. the nominal scenario. The average impact of constellation phasing is also small when a current GPS constellation is the baseline (0.13m), and the distribution of users with positive and with negative consequences is similar. The results confirm the assumption that a higher number of satellites furthermore reduces the impact of constellation phasing.

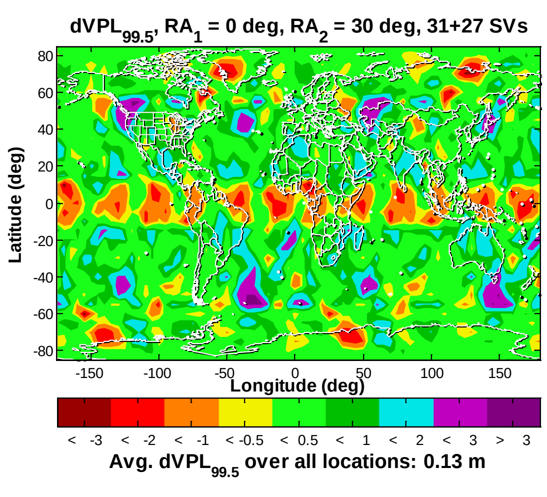

Figure 19: dVPL-99.5% of the current GPS constellation combined with the projected full Galileo constellation.

CONCLUSIONS

The objective of this work was to verify if and how much the RAAN difference between GPS and Galileo orbital planes will affect future ARAIM users. In reality, this parameter changes at a slow rate, i.e. best cases and worst cases with respect to constellation phasing would alternate at a cycle time of around 11 years. To obtain clarification on the impact, nominal constellations of GPS and Galileo have been simulated at different relative phase angles of the orbital planes. A grid of users performing MHSS-based ARAIM navigation was simulated, and the VPL results of these users have been recorded and analyzed statistically.

The extensive simulations have shown that although it can be demonstrated that the constellation phasing does impact the ARAIM performance, the magnitude of this change is small. A second set of simulations using current GPS almanac data and extrapolating the TLE data from present Galileo IOV satellites to a 27-SV Galileo constellation confirm that the impact is equally marginal for the constellations we can expect after Galileo is at FOC. A data set derived from simulations where constellation fault hypotheses have been added to MHSS further demonstrate that the constellation fault modes remove some impact caused by constellation phasing. This is explained by the fact that the constellation fault hypotheses, if assumed with sufficient risk, drive the overall VPL performance of MHSS ARAIM.

The relative rotation of one constellation with respect to the other one introduces considerable changes in individual user geometries. Hence, the individual impact on the ARAIM VPLs for specific users is rather large and can be observed in both directions, i.e. the change from a "best case" to a "worst case" constellation phasing does impact some users performance levels in a positive way as well as in a negative way. Due to the averaging nature of the orbital ground tracks however, the overall impact of those changes levels out to almost zero.

The summarized result of this work is therefor that the impact of inter-constellation phasing is minor with respect to global ARAIM performance, but rather large for specific users. Consequently, it is justifiable to assume any phase offset between the orbital planes of GPS and Galileo for simulative estimation of performance. However different studies with a mismatch in the phase angle may not be comparable below the level of global performance due to large discrepancies in regional performance.

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