Collision Risk in Extended 500 ft RVSM Airspace with Geometric Altimetry

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***Abstract*—Aircraft in the en-route flight phase are assigned to flight levels, currently separated by 1,000 ft, and based on a barometric height. When switching to geometric altimetry (i.e., altitude determination based on Global Navigation Satellite System (GNSS) measurements), the accuracy increases without further degradation at higher altitude, as is the case for barometric altimetry. Therefore, it is investigated whether the vertical separation minima could be reduced to 500 ft while using geometric altimetry, which doubles the airspace capacity and allows aircraft to fly closer to their optimal altitude, resulting in fuel savings. This research outlines whether this RVSM-2 concept is feasible from a technical vertical collision risk perspective. The results show that the Target Level of Safety (TLS) could theoretically be met by a small margin. However, before RVSM-2 could possibly be implemented, other challenges must be overcome, such as issues related to the Airborne Collision Avoidance System (ACAS), jamming and spoofing of GNSS signals, and GNSS liability issues.**

***Keywords*—RVSM, 500ft vertical separation, collision risk, GNSS performance, geometric altimetry, ICAO CRM, TLS**

I. Introduction

Aircraft in the en-route flight phase are assigned to a Flight Level (FL) by Air Traffic Control (ATC). These FLs are currently defined using a barometric altimetry system, which relies on barometers onboard aircraft that convert atmospheric pressure to an altitude, according to the worldwide agreed definition of pressure altitude. In order to avoid mid-air collisions, aircraft are vertically separated, if not horizontally separated.

There is a minimum required distance between the assigned FLs. Currently, these vertical separation minima are set to 1,000 ft between FL290 and FL410, which is known as Reduced Vertical Separation Minima (RVSM). Above FL410, the separation minima are set to 2,000 ft, due to the fact that decreasing air pressure decreases barometric altimetry accuracy [1].

Within the scope of the Green-GEAR project, which investigates Green operations with Geometric altitude, Advanced separation and Route charging solutions [2], it is researched whether vertical separation minima can be further reduced to 500 ft from FL290 to FL600, when using geometric altimetry (i.e., using Global Navigation Satellite System (GNSS) measurements to determine altitude in a geodetic reference frame, such as the World Geodetic System 1984 (WGS 84)). The use of geometric altimetry appears promising, as altitude measurements made with a GNSS do not degrade with increasing altitude.

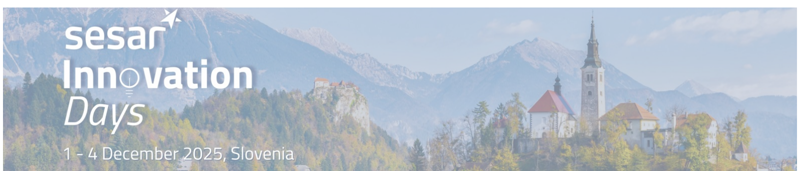
The further reduction of RVSM to 500 ft has several advantages. First, the airspace capacity increases by a factor of two, allowing more aircraft to fly in a block of airspace. Second, aircraft are allowed to fly closer to their optimum altitude, which could result in fuel savings. The choice for a reduction to 500 ft vertical separation is made since the implementation will be easier as the currently applied values of 1,000 ft and 2,000 ft are multiples of 500 ft. The concept of vertical separation minima of 500 ft while using geometric altimetry will be referred to as RVSM-2.

The separation of aircraft must be such that a deviation from the assigned FL does not cause a collision. Inaccuracies in altitude determination and physical disturbances introduce a collision risk. Under nominal circumstances, this risk is called the technical vertical collision risk, which is associated with the height-keeping performance of aircraft. In RVSM airspace, the safety objective for this risk is a Target Level of Safety (TLS) of $2.5 \cdot 10^{-9}$ fatal accidents per flight hour [1] [3]. The technical vertical collision risk is part of the total vertical collision risk, which also includes all the risk due to operational errors and in-flight contingencies, such as pilot/controller errors, height deviations due to emergency procedures, and turbulence[1] [1] [3].

The objective of this research is to assess the feasibility of introducing RVSM-2 in terms of the technical vertical collision risk. For this, several assumptions are made.

- The EUR RVSM airspace is considered, meaning that en-route traffic with assigned FLs is taken into account with a traffic mix similar to today. This implies that height-keeping errors are unchanged.
- For simplicity, a fixed routing airspace is assumed. While routing in the EUR RVSM airspace is generally not constrained to fixed routes, this assumption is considered conservative.
- Collision avoidance (safety nets) is excluded in the Collision Risk Assessment (CRA).

[1] Within the scope of Green-GEAR, wake-turbulence risk was also investigated. However, since this belongs to the total vertical collision risk, this is deemed out of the scope of this paper.



- Geometric altimetry is assumed to be introduced and to always be available in the RVSM-2 airspace. This implies that there is integrity, availability, and continuity of GNSS signals.

To assess whether the TLS can be met in an RVSM-2 context, the International Civil Aviation Organisation Collision Risk Model (ICAO CRM) is used, similar to RVSM [3] [4]. This model has to be adapted to the RVSM-2 environment, which is discussed in Section II. Here, a translation into requirements on the distribution and standard deviation of altimetry and flight technical errors is made. To see whether these requirements can be met, the performance of GNSS is discussed in Section III. Finally, Section IV discusses the feasibility of RVSM-2 and a conclusion is drawn in Section V.

II. Technical risk assessment for RVSM-2

The safety objective for the technical risk of RVSM-2 is a TLS in terms of a maximum accident probability per flight hour. In order to assess this safety objective, it is necessary to determine the collision risk in real-world operational practices.

A. *ICAO CRM*

The ICAO CRM comprises several key variables. The collision risk is described by (N_{az}) in fatal accidents per flight hour. Next, there is the probability of vertical overlap between two aircraft, $P_z(S_z)$, which is a function of the minimum vertical separation distance S_z. The probability of lateral overlap between two aircraft that are nominally flying along the same route segment is represented by $P_y(0)$. In addition, n_x describes the frequency with which aircraft enter into longitudinal overlap, per flight hour. Finally, K is a dimensionless geometric kinematic factor, taking into account, among others, relative speeds and aircraft height (λ_z). The variables are related through Equation 1 [3] [4].

$$N_{az} = P_z(S_z) \cdot P_y(0) \cdot n_x \cdot K \tag{1}$$

Since the implementation of RVSM-2 should not adversely affect the risk of en-route mid-air collisions, it must be ensured that the collision risk (i.e. N_{az}) does not exceed the TLS of RVSM. This is shown with the inequality in Equation 2, which is evaluated for RVSM-2 with $S_z = 500ft$.

$$N_{az} \leq 2.5 \cdot 10^{-9} \tag{2}$$

In order to assess the probability of vertical overlap, values have to be assigned to several variables in Equation 1, considering the current European situation. In the EUR region, $P_y(0)$ has a value of 0.51 if all aircraft use GNSS for horizontal navigation at all times. However, as GNSS accuracy increases, $P_y(0)$ also increases, since aircraft flying the same route, having 100% GNSS accuracy, have no lateral separation. Therefore, a value of $P_y(0) = 1$ is assumed, implying that aircraft have constant horizontal overlap.

In the last CRA (2023) of the EUR region, the product of n_x and K has a value of 0.026.[2] However, in the RVSM-2 airspace, aircraft are distributed over twice as many FLs. Assuming aircraft are spread evenly over the available FLs, the product would decrease by a factor of 2. Nonetheless, aircraft tend to have similar preferred FLs, meaning they would fly at the same FLs. Furthermore, similar to the introduction of RVSM, it is expected that en-route air traffic throughput increases significantly. Therefore, a value of 0.1 is estimated for the product of n_x and K. This leads to the inequality for $P_z(500)$ given in Equation 3.

$$P_z(500) \leq \frac{2.5 \cdot 10^{-9}}{1 \cdot 0.1} = 2.5 \cdot 10^{-8} \tag{3}$$

Note that the values chosen for $P_y(0)$ and the product of n_x and K are conservative. It has been verified that the sensitivity of the end results (i.e. the performance conditions on the navigation accuracy) with respect to these values is limited. Therefore, the adopted values are considered appropriate for the purpose of this study.

B. *Conditions on the Total Vertical Error*

The Total Vertical Error (TVE) is the difference between the actual and assigned altitude of an aircraft in flight. These altitudes refer to pressure altitudes in the context of barometric altimetry and to geodetic coordinates in the context of geometric altimetry. When considering nominal circumstances, there are two sources for the difference between actual and assigned altitude: flight technical and altimetry system errors, as will be considered in more detail in Section II-C.

Equation 3 lays a condition on the statistical properties of the TVE. To derive this condition, consider two aircraft flying nominally on the same route. Aircraft 1 is assigned to a fixed altitude. The altimetry system can be chosen such that this corresponds to altitude 0. Aircraft 2 is assigned to the fixed altitude S_z corresponding to the minimum vertical separation distance. The actual altitudes of aircraft 1 and 2 are denoted by z_1 and z_2 respectively and the averaged height of the aircraft is denoted by λ_z. Considering z_1 and z_2 as stochastic variables, the probability $P_z(S_z)$ of vertical overlap of the hulls of the aircraft as a function of the probability density of the TVE ($f^{\mathrm{TVE}}(z)$) is given by Equation 4, with all variables expressed in feet [3].

$$P_z(S_z) = \int_{-\lambda_z}^{\lambda_z} \int_{-\infty}^{\infty} f^{\mathrm{TVE}}(z_1) f^{\mathrm{TVE}}(S_z + z_1 - z_2)\, dz_1\, dz_2 \tag{4}$$

Equation 4 is often approximated using Equation 5 [3]. Here, $C(S_z)$ is the convolution integral as defined in Equation 4. Given an aircraft height of 50 ft, this leads to the expression in Equation 6.

$$P_z(S_z) \approx 2\lambda_z \cdot C(S_z) \tag{5}$$

[2] From private communication with the European Regional Monitoring Agency (EUR RMA).

$$C(500) \approx \frac{P_z(500)}{2\lambda_z} \leq 2.5 \cdot 10^{-10} \tag{6}$$

Equations 4 - 6 can be expressed in terms of the stochastic variables TVE_1, the TVE of aircraft 1, equal to z_1, and TVE_2, the TVE of aircraft 2, equal to $z_2 - S_z$. This is illustrated in Figure 1.

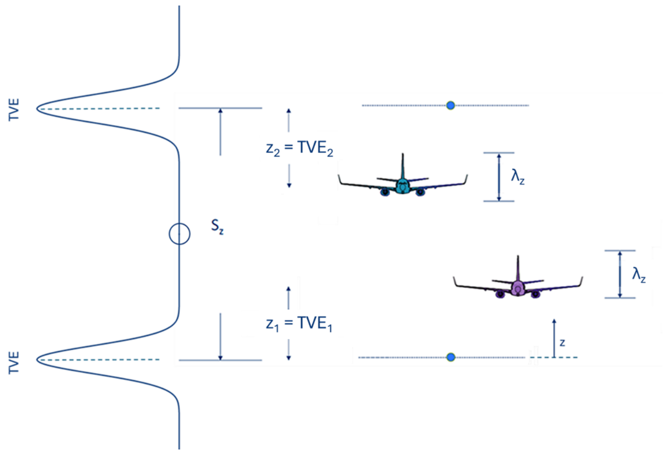


Figure 1. Visualisation of the TVE for two passing aircraft. The blue aircraft is flying out of the page and the purple aircraft is flying into the page.

Having outlined all relevant equations, conditions on the TVE can be determined. To do so, the following assumptions are made:

- The TVEs of aircraft are independent of each other. This might not hold in case of for example air turbulence, but then the correlation can be expected to be positive, such that this assumption is conservative.
- The TVE distribution is the same for each aircraft, independent of the circumstances. It might be that the distribution differs from the TVE distribution for one particular flight, for a particular aircraft type, for a particular part of the airspace, or for a particular period. However, from a mathematical modelling perspective, it is possible to construct the overall TVE distribution for the entire fleet, for the entire airspace, for a long period of time.
- The TVE distribution is symmetric around its zero mean. This assumption can be grounded on the evidence that there is no bias in GNNS altimetry (although this may not apply for the altimetry of certain aircraft types) and that there is no bias in the flight technical error (in accordance with the assumptions applied when introducing RVSM).

With these assumptions, the following approach is then adopted:

1) Assume a TVE distribution, being fixed or being parametrised by for example the standard deviation σ;
2) Express the probability density function in terms of the probability density function of the TVE distribution, applying the assumptions given above;
3) Verify that the function $C(S_z)$ is almost constant between $-\lambda_z$ and λ_z;
4) Calculate C(500) and check whether the inequality in Equation 6 is satisfied, or - if the TVE distribution is parametrised - for which values of the parameters the inequality is satisfied.

This approach is applied by assuming that the TVE has a Gaussian or a Laplace distribution. If the TVE is Gaussian with standard deviation σ_G, then $C(S_z)$ is also Gaussian; similarly if the TVE is Laplace-distributed with standard deviation σ_L, then $C(S_z)$ is also Laplace. When evaluating $C(S_z)$ at $S_z = 500ft$, it turns out that the inequality in Equation 6 is satisfied if $\sigma_G \leq 58ft$ in case of the Gaussian distribution and if $\sigma_L \leq 34ft$ in case of the Laplace distribution.

The condition on the standard deviation of a Laplace TVE is more stringent than the condition on the standard deviation of a Gaussian TVE since the tail of its distribution decays exponentially and thus slower than the tail of the Gaussian distribution.

With the conditions of the standard deviation of the TVE, conditions can be derived on flight technical and altimetry system errors, which is done in Section II-C.

C. *Conditions on the Altimetry System Error*

The Altimetry System Error (ASE) is the error associated to altimetry for example caused by inaccuracies of pressure measurements or GNNS signal receivers. Formally, it is defined as the difference between the actual altitude at which an aircraft is flying, and the altitude indicated by the altimeter display being used to control the aircraft.

The Flight Technical Error (FTE) is the error associated with the aircraft's altitude control, for example caused by turbulence. Formally, it is defined as the difference between the altitude indicated by the altimeter display being used to control the aircraft, and the assigned altitude.

The TVE is the sum of the FTE and the ASE, as illustrated below in Figure 2, adopted from [1]. The FTE and ASE are independent stochastic variables. Their probability densities ($f^{\text{ASE}}(a)$ and $f^{\text{FTE}}(a)$) are related to $f^{\text{TVE}}(z)$ through the convolution of Equation 7 [3].

$$f^{\text{TVE}}(z) = \int_{-\infty}^{\infty} f^{\text{ASE}}(a) f^{\text{FTE}}(z-a)\, da \tag{7}$$

As the TVE is the sum of the FTE and the ASE, conditions on the TVE distribution as derived in Section II-B can be expressed in terms of combinations of conditions on the FTE and ASE. When considering the feasibility of reducing vertical separation minima by introducing geometric altimetry, the main interest lies in conditions on the ASE.

The mathematically easiest way to proceed would then be to assume that both the ASE and FTE distributions are the same for all aircraft, are statistically independent and both have a Gaussian distribution with mean zero and have standard deviations σ_{ASE} and σ_{FTE} respectively. The TVE distribution is then also Gaussian, with mean zero and with a standard deviation σ given by Equation 8.

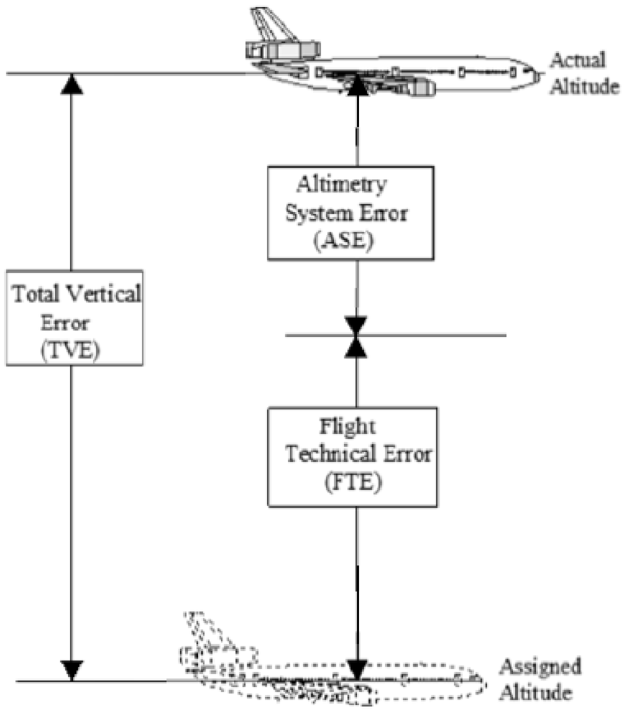


Figure 2. Decomposition of the TVE into the FTE and ASE [1].

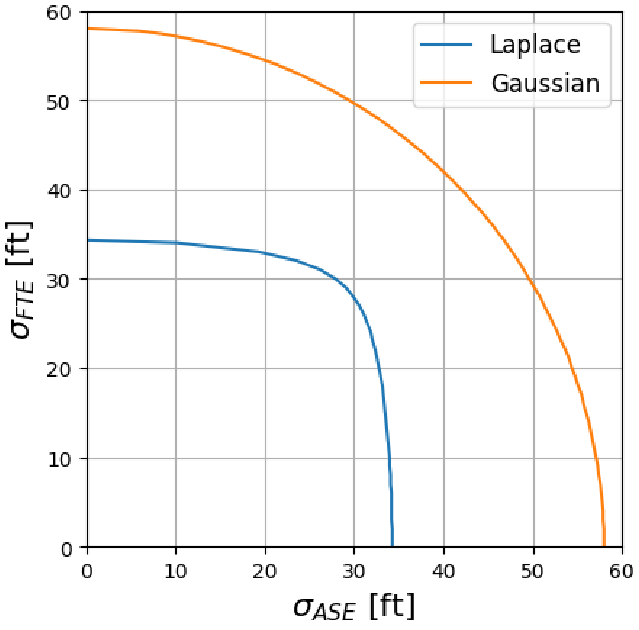


Figure 3. The maximal value of the standard deviation σ_{ASE} to meet the TLS of 500 ft vertical separation, given the standard deviation σ_{FTE} and given that the TVE is a sum of the ASE and FTE, both Laplace- or Gaussian-distributed, with zero mean.

$$\sigma = \sqrt{\sigma_{\mathrm{FTE}}^2 + \sigma_{\mathrm{ASE}}^2} \tag{8}$$

The condition $\sigma \leq 58ft$ as derived in Section II-B for this case would then lead to condition on the σ_{ASE}, if the value of the σ_{FTE} is known (and less than 58 ft, as otherwise the condition cannot be met anyway). However, this easy way to proceed is not in line with the currently applicable Minimum Aircraft System Performance Specification (MASPS) for RVSM approved aircraft as it allows that the FTE distribution has a distribution with an exponential decay, or with a possibly but not necessarily faster decay.

It is therefore alternatively assumed that both the ASE and FTE distributions are the same for all aircraft, are independent of each other and both have a Laplace distribution with mean zero and standard deviations σ_{ASE} and σ_{FTE} respectively. The function $C(S_z)$ can then be determined as a three-fold convolution of Laplace probability density functions. This convolution can be expressed as an integration in the complex plane of the characteristic functions, for which Cauchy's integral theorem can be applied [5]. This then leads to a condition on the values of σ_{ASE} and σ_{FTE} as indicated in Figure 3.

It can be seen in the figure that the curve in the σ_{ASE} - σ_{FTE} plane distinguishing whether the TLS is met or not, is more convex for Laplace distributions than for Gaussian ASE and FTE distributions. This reflects the fact that the tail of the convolution of two Laplace distributions is by approximation the tail of the one with the largest variation, while the tail of the convolution of two Gaussian distributions is determined using Equation 8, leading to a circle segment.

According to current estimations in the ICAO EUR region, the value of σ_{FTE} is 33 ft, lower than the value of 43 ft as prescribed by the MASPS for RVSM approved aircraft. The combination of this result and Figure 3 implies that the TLS is met if the σ_{ASE} is 20 ft or less. Whether this is feasible for GNNS is discussed in the Section III.

III. GNSS Performance

Now that the distribution and standard deviation of the FTE are established, the distribution and standard deviation of the ASE are analysed to determine whether the TLS of the technical vertical collision risk can be met. The ASE within the RVSM-2 concept corresponds to the accuracy of altitude estimates using GNSS. Therefore, it must be determined which parameter is used as a measure of GNSS accuracy, which is discussed in Section III-A.

A. *Accuracy measures in GNSS*

For the performance of GNSS, this research solely focuses on the accuracy. In this context, accuracy is defined as the difference between the altitude estimate of the GNSS receiver and the actual altitude at which the aircraft is flying. This difference originates from multiple sources, such as clock errors, ephemeris errors, atmospheric errors, and user equipment errors. The total error is known as the User Equivalent Range Error (UERE) [6].

The focus in assessing the feasibility of RVSM-2 lies in the vertical plane. Therefore, it is essential to relate the UERE to the Vertical Position Error (VPE). This is done using the Vertical Dilution of Precision (VDOP), a parameter that takes satellite geometry into account. The resulting relation is shown in Equation 9. Since the VDOP varies with the position of the satellites used to determine a position, the VPE varies with time and position [6].

$$\mathrm{VPE} = \mathrm{UERE} \cdot \mathrm{VDOP} \tag{9}$$

In the context of RVSM-2, the magnitude of the VPE is taken as a measure of the ASE.

B. GPS and Galileo performance

Currently, several GNSSs are operational. For this research, the performance of GPS, since it is already in use in aviation, and Galileo, because of its promising performance and the European focus of this study, are considered. The VPE depends on both the GNSS constellation and the operation mode (i.e., Single Frequency (SF) or Dual Frequency (DF)).

GPS and Galileo both publish VPE performance specifications, disregarding factors that are not under direct control of the GNSS, e.g. atmospheric effects, receiver noise, and antenna effects. These performance specifications should be seen as minimally expected performance metrics, but not as warranties or service level agreements. Both GPS and Galileo deny any responsibility for the performance of signals and services provided by the systems. Furthermore, since the open signals are free of charge, there is no contractual liability that could be evoked[3] [7] [8] [9].

The performance specification of GPS and Galileo are presented as a Minimum Performance Level (MPL). Here, a distinction is made between Average User Location (AUL) and Worst User Location (WUL). The concept of global WUL and AUL takes into account that various error sources are location-specific or dependent on the satellite geometry. The global average Signal In Space Error (SISE) (i.e., the error of the space segment) can be evaluated by computing the SISE at grid points evenly distributed over the satellite service area. The error is then computed as the RMS of the values at all the grid points in the Field of View (FOV) at each time step (typically five minutes). The maximum error then corresponds with the WUL, typically located at the edge of the FOV, and the average error corresponds with an AUL [10].

A common way to present VPE statistics is to indicate the 95% accuracy, corresponding to half the width of the interval in which 95% of the smallest errors are contained. Table I shows the MPL of GPS and the Galileo Open Service (OS) at AUL and WUL.

From Table I, it becomes clear that the specified performance of both GPS and Galileo is not sufficiently accurate to use in RVSM-2. However, the two GNSSs do provide the system's actual performance on a quarterly basis as well [11] [12] [13] [14]. Note that this performance is evaluated at ground stations, whereas in RVSM-2, the performance at cruise altitude is relevant. Here, there is limited multipath and less atmospheric noise, meaning that the accuracy could be higher in the RVSM-2 environment than presented in the quarterly reports.

TABLE I. GPS AND GALILEO OS SPECIFIED VPE (95%) AT AUL AND WUL [8] [9].

	AUL	**WUL**
GPS	13 m / 42.7 ft	33 m / 108.3 ft
Galileo	8 m / 26.2 ft	16 m / 52.5 ft

The 95% VPE and the corresponding 1σ value (assuming a Gaussian distribution) are shown in Table II for GPS and Galileo. The measurements for GPS are 'defined for position solution meeting the representative user conditions' [11] [12], and are made using a single receiver. The Galileo OS provides DF data based on real measurements, collected from a number of receivers. The SF data are not available. Constraints for these measurements are that the VDOP $\leq$ 6, the age of ephemeris does not exceed 4 hours and that recommendations regarding SIS health are followed. In addition, samples with local issues that are not due to the Galileo SIS are filtered out using outlier detection filters.

Table II shows that the achieved performance is significantly more accurate than the specified performance in Table I. Furthermore, it can be concluded that Galileo outperforms GPS, especially considering that the presented value of GPS is an average, whereas the value of Galileo is a maximum. Nonetheless, both GNSSs have a promising performance in an RVSM-2 context.

TABLE II. AVERAGE VPE (95%) OF GPS (SF) AND GALILEO (DF) FROM QUARTERLY PERFORMANCE REPORTS Q1 AND Q2 2024. THE VALUES FOR GPS ARE THE AVERAGE OF THE AVERAGE VPE PER DAY, WHEREAS THE VALUES OF GALILEO ARE SAID TO NOT HAVE EXCEEDED THESE VALUES ON A PER MONTH BASIS [11] [12] [13] [14].

	VPE (95%)	**VPE (1σ)**
GPS	3.98 m / 13.1 ft	2.03 m / 6.7 ft
Galileo	3.17 m / 10.4 ft	1.62 m / 5.3 ft

There are several ways to further improve the accuracy of GNSS measurements. One approach is multi-GNSS navigation, which combines satellites of multiple constellations to obtain a more accurate position estimate. This is achieved because there are more satellites in the field of view, therefore increasing the number of available signals and the VDOP [18]. The extent to which GNSS accuracy in aviation can be improved through the use of multi-GNSS is not yet known. However, it is expected to be operational in the near future. In March 2023, ICAO adopted new DF, multi-constellation standards, which will provide access to an expanded global infrastructure for international aviation [19].

A second way to improve GNSS accuracy is by using a Space-Based Augmentation System (SBAS). SBAS uses a network of reference stations to determine the GNSS error and

[3] Additionally, there is no reasonable basis for a contract claim against the U.S., as the government does not enter into any contractual agreements with either domestic or foreign parties for the use of the GPS system [8].

transmits corrections (and integrity information) to its users via geostationary satellites.

C. ASE distribution

Similar to the FTE, the distribution of the ASE has to be determined. The literature suggests that the majority of GNSS error distributions can be assumed to be a Gaussian distribution [9] [15] [16]. This Gaussian distribution describes most navigation system error distributions fairly well to the 95^{th} percentile. As stated in the Galileo OS documentation: "*The true characteristics of SISE and User Equipment Error (UEE) distributions are not necessarily Gaussian. However, both SISE and UEE can be considered sufficiently close to unbiased, uncorrelated Gaussian distributions, and hence SISE and UEE are expressed by means of their standard deviation*" [9]. Other research has shown that errors in position determination measurements do not necessarily follow a Gaussian distribution [17]. Furthermore, research shows that variations from the Gaussian distribution exist, especially in the tails of the GNSS error distribution [15]. However, it is hard to determine what the behaviour in the tail of the distribution is, since the events causing these errors are very rare. Therefore, the 'true' error distribution of the VPE is not fully known.

IV. Discussion

The objective of this research is to assess the feasibility of RVSM-2 from a technical vertical collision risk perspective. This is the case when a TLS of maximally $2.5 \cdot 10^{-9}$ fatal accidents per aircraft flight hour is met. This leads to the requirement $P_z(500) \leq 2.5 \cdot 10^{-8}$, which can be seen as a restriction on the TVE, and in particular on its tails. The TVE in turn is the sum of the FTE and the ASE. Consequently, the restriction on the TVE can be translated into conditions on the FTE and ASE, in terms of distribution type and σ values. This section discusses whether these conditions can be met and what additional challenges in the implementation of RVSM-2 are.

A. Distribution

In line with Section II-C, the FTE is assumed to decay as the tails of a Laplace distribution, or faster. However, the tail behaviour of the FTE in operational practise has not been analysed in detail. The current approach in RVSM CRA neglects the correspondence error and analyses the transponded altitudes with a granularity of 100 ft up to only ± 300 ft. Consequently, the actual decay of the FTE distribution remains uncertain.

During both the pre- and post-implementation phases of RVSM, the actual decay of the FTE distribution was not considered an issue since the contribution of the FTE to the TVE was smaller than that of the ASE. Moreover, the assumption of at least exponential decay was considered conservative, while remaining sufficient to meet the TLS. The FTE could decay faster than exponentially, but this has not yet been proven. Therefore, a Laplace distribution was assumed for the FTE.

As discussed in Section III, there is evidence that the VPEs of GNSSs are Gaussian-distributed if large deviations are ignored. Thus, it could be assumed that the GNSS ASE is Gaussian, but it seems that there are not yet data available to draw such a conclusion with sufficient statistical significance. Therefore, it is considered more appropriate to assume that the GNSS ASE distribution is Laplace. If the ASE distribution can be shown to be Gaussian, the conditions on the ASE could be relieved.

In line with Section II-C, the current MASPS prescribes a standard deviation of the FTE of 43 ft and that is not sufficient while the current measurements indicate a standard deviation of the FTE of 33 ft and that is just sufficient. An update of the requirements within the MASPS might be possible, but this would demand for a better analysis of the FTE in practice; one that is more accurate than the results presented in the RVSM post-implementation CRAs. Such a more accurate analysis seems possible, using ADS-B and more enhanced statistics, but it cannot be ruled out that it will show a worse performance. However, if it turns out that the FTE distribution in practice is as hoped for, or even better, it might still be an issue to specify the requirements for aircraft approval as compliance is then not easily shown. It is also possible not to refine these requirements within the MASPS, but then the evidence from the more accurate analysis should be allowed in the safety case of RVSM-2. That is up to aviation authorities to decide.

Based on a σ_{FTE} of maximally 33 ft and combining this with the actual performance of Galileo that shows that σ_{ASE} could be as small as 5.3 ft, the TLS of RVSM-2 could theoretically be met by a small margin. However, it must be ensured that the values presented are always valid.

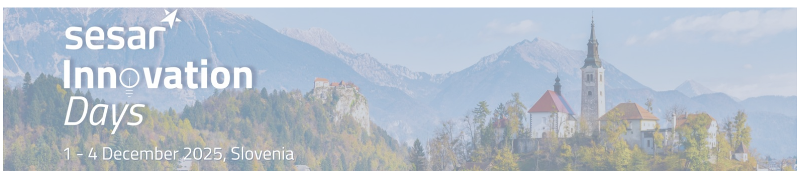
Several additional challenges must be addressed before RVSM-2 could potentially be implemented. These are discussed in the following sections.

B. Collision avoidance

In this CRA, collision avoidance is disregarded. This includes interventions such as the aircrew counteracting collisions due to Airborne Collision Avoidance System (ACAS) warnings or following ATC instructions.

In current operations, ACAS generates so-called Traffic Alerts (TA) and Resolution Advisories (RA), when there is a mode S- or mode C-equipped aircraft in the vicinity. TAs and RAs are issued for aircraft flying above FL200 at vertical separations less than 850 ft and 700 ft, respectively, provided that they fly within a certain horizontal distance [20]. This means that these will be issued with nominal passings in RVSM-2 airspace. For TAs, this could be considered as a major nuisance. However, in the case of RAs, safety could be severely compromised, as pilots are required to follow the issued advisories.

The adjustment of ACAS is a significant issue and resolving this issue is a prerequisite of the implementation of RVSM-2.



C. GNSS integrity

When transitioning from barometric to geometric altimetry, aviation becomes reliant on GNSSs. However, in recent years, flight crews have reported an increasing number of interference events [21]. These Radio Frequency Interference (RFI) events, also known as jamming and spoofing, impact flight planning, flight operations, and the workload of flight crews. This is already an issue in current operations and it will become a much bigger concern when aircraft fly using geometric altimetry.

In the RVSM-2 setting, the margins for 500 ft vertical separation are small. Even though aircraft could have alternatives for navigation, such as using inertial reference systems, or switching to barometric altimetry, a GNSS outage is a major safety threat. Therefore, increasing the robustness against jamming and spoofing is a prerequisite of the implementation of RVSM-2.

D. Liability of GNSS performance

The responsibility and accountability with regards to GNSS altimetry performance is rather complex as compared to barometric altimetry. For example, users of Galileo must accept that the provider “shall not be held responsible or liable for any damages resulting from the use of, misuse of, or the inability to use the Galileo Open Service” [9]. Perhaps it could be argued that integrity monitoring could account for this risk, but whether that is appropriate, considering the focus on the nominal case in this study, is also open for debate. Moreover, the statistical margins are that small, that even very rare atmospheric behaviour, due to sun or even star outbursts might need to be taken into these considerations. So, similar to the FTE, it is to the aviation authorities to decide what kind of evidence is required to show that GNSS performance is sufficiently reliable in order to introduce RVSM-2.

V. Conclusion

The objective of this research was to assess the feasibility of reducing the vertical separation minima to 500 ft between FL290 and FL600 with the use of GNSS altimetry, from a technical vertical collision risk perspective. The results show that the TLS could theoretically be met by a small margin. However, the error distributions are not well known, meaning that more detailed measurements on the behaviour of the FTE and the ASE are required to provide certainty.

Although it may be possible from a technical perspective to meet the TLS with current performance, there are several challenges that need to be overcome first. Regulatory and legislative aspects will likely pose a significant, possibly insurmountable challenge. Furthermore, there are operational issues that need to be resolved, such as ACAS RA conflicts and jamming and spoofing incidents. Future research shall have to demonstrate whether these challenges could be resolved to pave the way for a more efficient and higher capacity airspace.

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