Empirical Assessment and Modelling of RFI Impact on Aviation GPS/SBAS Receiver Performance

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BIOGRAPHY
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ABSTRACT
Radio frequency interference (RFI) on L-band affecting GNSS receivers might lead to unacceptable performance degradations when operating with GNSS only. Flights using GNSS based procedures and operated under Instrument Meteorological Conditions (IMC), are particularly concerned about such a threat. This paper focuses on the impact of RFI on GPS/SBAS receivers. Based on a recorded RFI event, the behavior of the receivers’ estimated protection level is analyzed. In order to understand the behavior of the HPL, the corresponding algorithm is analyzed in depth. It is shown, that RFI impacts only few HPL input parameters. The size of HPL is only dictated by the increased pseudorange noise as well as the number of tracked satellite signals. The latter is directly related to the receivers’ antenna pattern describing the expected Carrier to Noise Ratio (C/No). Hence, the vehicles attitude plays a relevant role, too. Different simulations are presented which describe the HPL behavior in a more general way.

METHOD FOR DETECTION OF POTENTIAL RFI
The method for RFI detection consists in installing mini quick access recorders (Figure 1) on board of two dozen helicopters operated by the Swiss Air Force and by Rega, the main Swiss Helicopter Emergency and Medical Service (Figure 2). Data is recorded from daily operations. By this way, large parts of Switzerland are randomly covered.

More than 60 parameters available on the helicopter’s ARINC 429 buses are constantly recorded. The data is retrieved from the onboard GPS/SBAS sensor and consist amongst others of the position and range domain including, carrier to noise ratio (C/No), receiver status, performance values etc. Additional data stems from the Attitude and Heading Reference System (AHRS) and the Flight Management System (FMS).

INTRODUCTION
In [1] a new method was presented on how the RFI situation can be assessed over a large region and during a long period. This was developed as part of the project called ‘Helicopter Recording Random Flights’ (HRRF) within the Swiss-wide Implementation Programme for SESAR-oriented objectives (CHIPS).

In the course of the project several potential RFI events were identified so far. In multiple cases the overall degradation of the GPS C/No reaches values down to -20dB and more, resulting in loss of signal tracking of one or more satellites. Even though a position can still be determined under these circumstances it has to be expected, that the receivers performance is degraded. The impact is determined by assessing the recorded on-board Horizontal Protection Level (HPL), the Horizontal Figure of Merit (HFOM), the number of satellites used for positioning and the Horizontal Dilution of Precision (HDOP).

Figure 1: Installed Avionica mini Quick Access Recorder.
Figure 2: EC635 of the Swiss Air Force (top) and EC145 of Rega (bottom). The GPS/SBAS antennas are mounted on the top of the fin in front of the strobe light (Courtesy VBS and Rega).

Based on measured carrier to noise ratio $C/No_{\text{meas}}$, GPS satellite azimuth and elevation angles as well as roll, pitch and yaw angles of the helicopters, the expected carrier to noise ratio $C/No_{\text{exp}}$ is derived depending on the incidence angle of the GPS signal at the antenna. Different filters are applied in order to eliminate unwanted signal effects like $C/No$ degradation for satellites in proximity of the radio horizon. This yields to an antenna pattern for the $C/No_{\text{exp}}$ which is depicted in Figure 3. It is clearly visible, that these values vary in a range of more than 15dB. This is mainly caused by the close environment of the receiver’s antenna, i.e. the helicopters fuselage etc.

Figure 3: GPS antenna pattern on top of a helicopter fin. The red arrow indicates the direction towards an arbitrary GPS satellite. The helicopter is aligned with the topocentric coordinate system.

For each epoch and for each satellite the $C/No_{\text{exp}}$ is subtracted from the measured carrier to noise ratio $C/No_{\text{meas}}$ which leads to a normalized carrier to noise ratio for each tracked satellite. Finally these differences are averaged. The resulting value is called average of normalized $C/No$. It is independent from effects caused by the helicopters attitude and fuselage disturbances. Further this value directly indicates by which amount in dB an RFI affects all carrier to noise values.

Figure 4 shows an event over a time period of 140 seconds. On the top of the figure all $C/No$ are degraded simultaneously followed by loss of signal tracking of three satellites. After about 30 seconds of severe RFI the signals begin to recover as well as the tracking of the three lost satellites is restored. The $C/No_{\text{exp}}$ is depicted on the bottom part of Figure 4 indicating the impact caused by the RFI, i.e. in this case down to -20dB.
EMPIRICAL ASSESSMENT OF RFI IMPACT ON GPS/SBAS RECEIVER PERFORMANCE

Further discussion is focusing on the performance assessment of GPS/SBAS receivers under influence of RFI. The main performance parameter being assessed is the protection level which is the contributor to the integrity. Emphasis is given to the horizontal position domain whereas the vertical position domain can be treated analogously. The protection level behavior is based on the RFI event shown in Figure 4.

Figure 5 shows the corresponding number of tracked satellites, the horizontal protection level (HPL), the horizontal figure of merit (HFOM) and the horizontal dilution of precision (HDOP) during the period of RFI.

Loss of satellite tracking occurs only when the signal degradation reaches at least -20dB compared to unaffected signals. Satellite tracking is resumed with diminishing RFI impact. The HPL remains constant at 0.0044 NM as long as all satellites are tracked. Only with loss of signal tracking, the HPL starts to increase up to a maximum value of 0.0069 NM. It appears that the RFI doesn’t influence the HPL during the initial phase of the event. The HFOM shows a similar behavior like the HPL. Obviously, the HFOM values are smaller than those of HPL. Finally, the HDOP values alter with the changing number of tracked satellites.

An alternative illustration for the HPL behavior is shown in Figure 6. The x-axis represents $C/No_{\text{sat}}$ whereas the y-axis is on the horizontal side. Each colored dot indicates one epoch. The color itself references to the number of tracked satellites at the corresponding epoch. The numbers related to the dots show the elapsed time in seconds since beginning of the RFI event. The represented period covers a time span of 50 seconds. The beginning of the RFI event is on the bottom right side. In a first phase, during the first 15 seconds, the dots shift towards left without altering the HPL. With loss of the first two satellite signal trackings the HPL starts to increase marginally. In a second phase, after roughly 30 seconds, the HPL scales up remarkably and comes back in a third phase. Finally, during the fourth phase, it returns in a horizontal shift back to the starting point. This behavior is represented in a simplified manner by the four gray arrows whereas the second and third phases might be tilted.

PROTECTION LEVEL ALGORITHM

For better understanding of the HPL behavior during an RFI event, it is necessary to take a look at the corresponding algorithm, which is described in [2].

The HPL for SBAS is calculated as follows:

$$HPL_{\text{SBAS}} = K_{H, \text{proc}} \cdot d_{\text{maj}},$$

(1)
The semimajor axis $d_{maj}$ is derived as follows:

$$d_{maj} = \sqrt{\frac{d_N^2 + d_E^2}{2} + \left(\frac{d_N^2 - d_E^2}{2}\right)^2 + d_{EN}^2} \quad (2)$$

with the variances of the position error $d_N$ and $d_E$ in north and east direction, respectively the covariance $d_{EN}$

$$d_N = \sqrt{\sum_{i=1}^{N} s_{N,i}^2 \sigma_i^2}$$

$$d_E = \sqrt{\sum_{i=1}^{N} s_{E,i}^2 \sigma_i^2}$$

$$d_{EN} = \sqrt{\sum_{i=1}^{N} s_{E,i} s_{N,i} \sigma_i^2} \quad (3)$$

$\sigma_i^2$ is the variance of the $i$th satellite pseudorange error. $N$ represents the number of satellites used for the position estimation. The variables $s_N$ and $s_E$ are the projections of $\sigma^2$ in east and north direction, i.e. $\sigma^2$ is converted from the range domain into the position domain. These variables are contained in the projection matrix $S$ which is derived from the least square adjustment for the position estimation

$$S = (G^T W G)^{-1} G^T W \quad (4)$$

where $G$ is the geometry matrix depending solely on the relative positions of the satellites with respect to the receiver antenna and $W$ the weighting matrix composed by the inverse of the variances $\sigma_i^2$.

The variance $\sigma_i^2$ is a sum of multiple zero mean, Gaussian distributed variances, i.e.

$$\sigma_i^2 = \sigma_{i,\text{iono}}^2 + \sigma_{i,\text{tropo}}^2 + \sigma_{i,\text{flt}}^2 + \sigma_{i,\text{air}}^2 \quad (5)$$

with

$$\sigma_{i,\text{iono}}^2 : \text{variance of ionospheric delay},$$

$$\sigma_{i,\text{tropo}}^2 : \text{variance of tropospheric errors},$$

$$\sigma_{i,\text{flt}}^2 : \text{variance of fast \& long term correction residuals},$$

$$\sigma_{i,\text{air}}^2 : \text{variance of airborne receiver errors}.$$

The variance of airborne receiver errors is further decomposed into:

$$\sigma_{i,\text{air}}^2 = \sigma_{i,\text{noise}}^2 + \sigma_{i,\text{mp}}^2 + \sigma_{i,\text{divg}}^2 \quad (6)$$

with

$$\sigma_{i,\text{noise}}^2 : \text{variance of noise error},$$

$$\sigma_{i,\text{mp}}^2 : \text{variance of multipath error},$$

$$\sigma_{i,\text{divg}}^2 : \text{variance of divergence error},$$

where

$$\sigma_{i,\text{divg}}^2 = 0.13 + 0.53 e^{-10 \Theta^2} \quad (7)$$

with $\Theta$ being the $i$th satellite position elevation.

Let’s assume that the exposure duration of a low to medium power RFI to a GPS/SBAS receiver on-board of a flying helicopter is below 60 seconds. The variation of most input parameters for the HPL is minimal during the exposure time and can therefore set to be constant. Following considerations are limited to the assumed exposure time:

- The $K$ factor is assumed to be constant during an RFI event as the probability of changing the procedure type during this period is negligible.

- The satellite geometry alteration is very small and therefore the variation of $G$ is negligible as long as tracked satellites remain the same. In case of satellite signal tracking loss the number of satellites $N$ decreases and alters the geometry matrix $G$ and consequently the HPL too.

- The variance of ionospheric delay can be assumed to be constant due to the fact, that it is derived from the transmitted SBAS messages. Severe ionospheric conditions like scintillations or large spatial or temporal ionospheric gradients are not included in the SBAS ionosphere model.
The variance of the tropospheric delay is derived through a model. The input parameters such as temperature, pressure, satellite elevation etc. alter minimally during short periods and hence the variance of the tropospheric delay too. This variance can therefore be assumed to be constant.

The variance of long term correction residuals can be assumed constant too due to the low temporal gradient. The fast term correction is basically caused by rapidly changing satellite clock errors and is independent from users’ position. Therefore this variation is independent from RFI and considered constant in order to avoid any non-RFI related influences on the HPL.

The variance of airborne receiver errors depends on multipath, divergence and receiver’s noise. According to equation (7), multipath depends on the satellite elevation, which changes only minimal during a short period. Hence, multipath is assumed to be constant. The divergence is mainly caused by the ionosphere and is independent from RFI and considered constant for further analysis. Finally the noise is dependent among others on RFI and alters the HPL.

To recap, a receiver affected by RFI influences the HPL only through the
1. number of tracked satellites \( N \), which in turn has an impact on the geometry matrix \( G \) and weight matrix \( W \).
2. noise error \( \sigma_{\text{noise}} \), which has an impact on the variance of pseudorange errors \( \sigma_i \) and consequently on weight matrix \( W \).

MODELLING OF RFI IMPACT ON HPL

Further discussion focuses on the number of tracked satellites \( N \) and its impact on HPL. In a first step, it is of interest to estimate the minimum required carrier to noise ratio \( C/No_{\min} \) that enables GPS satellite signal tracking. This value varies depending on different factors such as the type of RFI or the behavior of the receiver’s Automatic Gain Control (AGC). Based on assessments on different track losses recorded during RFI events, a range of values between 25dB-Hz and 30dB-Hz was observed. These values were reproduced under laboratory conditions with the use of GPS and RFI signal generators and applied to the same type of receiver as used on-board of the helicopters. Based on these observations a value of 28dB-Hz was chosen for \( C/No_{\min} \).

The difference between the \( C/No_{\min} \) and \( C/No_{\exp} \) corresponds to the maximum tolerable carrier to noise degradation without signal tracking loss

\[
\frac{C}{No_{\text{mar}}} = \frac{C}{No_{\min}} - \frac{C}{No_{\exp}} \quad (8)
\]

Note that the margin \( C/No_{\text{mar}} \) depends on GPS signal angle of incidence and varies for different helicopter types. Figure 8 depicts the \( C/No_{\exp} \) for the EC635 (top), respectively EC145 (bottom). Although the identical antenna type is used, the patterns vary remarkably, especially between the azimuths of 120° and 210° at lower elevations. The different antenna environment on both helicopters mainly causes this difference (see fin tip in Figure 2).

The antenna pattern describing the margin \( C/No_{\text{mar}} \) is derived with equation (8) and is depicted in Figure 9 for the EC635.

The circles within Figure 9 correspond to the satellite positions during the RFI event described in Figure 4. The red-bordered circles indicate the three satellites from which signal tracking was lost. This occurs at a \( C/No_{\text{an}} \) of -18 to -20dB-Hz, which perfectly coincides with the \( C/No_{\text{mar}} \) in Figure 9. However, if the helicopter’s attitude alters, then the satellite positions are changing as well. By consequence, different satellite signals would be lost.
resulting in a variable number of tracked satellites. In turn, the HPL is altered too. The finding is that the helicopter’s attitude influences the HPL. This finding can be considered comprehensible for large roll angles variation. Tough, the helicopter heading, while keeping the roll angle at 0°, influences the HPL too. Within Figure 9, a heading change would shift all satellite positions by the same amount to the right or to the left.

A simulation is carried out for the RFI where the helicopter heading is rotated 360° by 10° steps. Further the C/No_an is decreased gradually. First, the number of tracked satellites is estimated depending on the C/No_an and C/No_mar. Next, the HPL is derived for all helicopter headings. The required error variances for the HPL calculations are retrieved from EGNOS monitor stations operated by skyguide for the corresponding day. The variance of the receiver’s noise is kept constant despite an expected increase in course of the RFI event. The result is shown in Figure 10.

The number of tracked satellites at a C/No_an of -19dB-Hz varies between 8 and 11 while the HPL varies only between 0.0048NM and 0.0061NM. Despite the number of tracked satellites varies by three units, the impact on the HPL is relatively small. This can be explained by the generally large number of tracked satellites, which keeps the geometry matrix stable. At a C/No_an of -23.5dB-Hz the number of tracked satellites varies between 5 and 8, again within a range of three satellites. Now, the HPL varies over a larger range between 0.0051NM and ca. 0.008NM. By further decreasing the C/No_an the HPL begins to increase rapidly.

In a more general simulation, the satellite positions are altered too. 100'000 different situations are generated randomly. A constraint is to generate an initial situation with a constant number of tracked satellites (i.e. 12, 10 and 8) while keeping the orbit parameters reasonable to reflect the GPS constellation. This is achieved by deriving the satellite position probability density relative to Switzerland during a period of several years. The randomly generated satellite positions finally hold this satellite probability density.

The simulation results are shown in Figure 11 for initial situations with 12 (top), 10 (middle) and 8 satellites (bottom). The colors indicate the probability of occurrence within a bin of 0.05dB-Hz width and 0.0005NM height.

It results, that for an initial situation with 12 satellites the HPL remains constantly below 0.02NM for carrier to noise degradations down to -18dB-Hz. The HPL behavior is similar for the initial situation of only 8 satellites, but with the maximum HPL remaining below 0.04NM. In all cases, the HPL begins to increase rapidly for degradations below -18dB-Hz and stops at -26dB-Hz. Common to all initial situations is that a HPL of 0.1NM is rare and requires a carrier to noise degradation of more than -22dB-Hz.

Figure 10: Simulation of number of tracked satellites (bottom) and HPL (top) depending on helicopter’s heading and C/No_an.

Figure 11: Simulation of HPL depending on C/No_an for rotating helicopter heading, 100’000 satellite position situations and initial situations with 12 (top), 10 (middle) and 8 satellites (bottom).
Note, that the results of these simulations give an indication regarding the availability of the procedure under a degraded environment caused by RFI. However, there is no indication on the integrity due to the unknown Total System Error (TSE). Further, HPL degradation due to $\sigma_{\text{air}}$ isn’t taken into account at this stage.

CONCLUSIONS

This paper has assessed the impact of RFI on a GPS/SBAS receiver in terms of HPL degradation. This work is based on GPS and AHRS data recorded on-board of two dozen helicopters during several thousands of flight hours.

The HPL behavior for a GPS exposed to RFI is discussed by means of an example. It is observed, that the HPL alters only slightly despite degradations on all tracked satellites down to -18dB. The HPL mainly begins to increase when signal tracking of satellites are lost and is recovered when satellite tracking is resumed.

For better understanding of this behavior, the algorithm for the HPL calculation is analyzed. It is shown, that only the number of tracked satellites and the variance of noise error determines the HPL under RFI circumstances. Focusing on the number of tracked satellites it is further shown, that the GPS receiver antenna pattern has a direct impact on the size of HPL. Even more, it is shown through simulations, that the helicopter’s heading may remarkably vary the HPL value. More extensive simulations have shown, that even under strong RFI influence the HPL rarely reaches values of 0.1NM or more. On the other hand, position solutions are not possible at C/No degradations of more than 26dB. This finding varies depending on the receiver, antenna and helicopter type.

Further work will assess the variance of the pseudorange error due to noise when exposed to RFI in order to generate simulations that are more comprehensive.

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REFERENCES
