A case study for potential implications on the reception of Galileo E6 by amateur radio interference on German highways considering various transmitter-receiver-signal combinations

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BIOGRAPHY

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ABSTRACT

With multi-frequency GNSS services more and more moving to the center of attention in safety critical applications of navigation and timing, interference – whether intentional or not – poses as a problem to be addressed. Especially in the case where the user needs high accuracy in addition to high reliability, the tolerable amount of interference shrinks to a minimum. With the dawn Galileo's High Accuracy Service, a freely available PPP service broadcast by the MEO constellation itself, we focus on the use case of autonomous driving in this study. We derived a method to display potential implications of interference on the E6B signal reception on German highways based on the characteristics of the interference signal & transmitter, user receiver and distance between them. Considering this, the delta in C/N_0 (signal-to-noise ratio) is computed and may be understood as a "worst case" impediment. The topography is neglected in this study. With the procedure established, we parametrize three different receiver categories representative for various market sectors as well as two types signals, which are reckoned among the most popular within the amateur radio community on the E6 band. The final product of the study comprises a heatmap for each scenario, identifying the impact of a certain transmitter location on the closest user receiver. We show that, for specific receiver-signal combinations, coexistence is possible regarding the ($1dB$-IPC) $1dB$ interference protection criterion [1] to a large extent, yet there are still areas affected by severe interference.

I. INTRODUCTION

Modern GNSS offer various services over multiple frequency bands and allow the user receiver to determine its position with high precision and accuracy. Especially with regard to safety critical applications in land-based navigation, such as autonomous driving, precise, accurate and reliable GNSS poses as the key technology for absolute navigation as well as a welcome solution for independent and continuous on-board sensor calibration during operation. Highest quality positioning is enabled by obtaining an unobstructed GNSS signal, among other aspects, to perform ranging and decode navigation bits properly. Interference – whether intentional or not – upholds the potential to deny the user device exactly that.

Considering Galileo's own "High Accuracy Service" [2], a PPP service to be broadcast in the near future on E6B by the MEO standard constellation itself, and one of its most prominent use cases, i.e. autonomous driving, we take a closer look at potential interference on this upcoming enhancement of the European GNSS. Since autonomous driving most probably will not be deployed everywhere at once and at the same time, we assume a gradual rollout of the technology starting on highways only (which is already happening to some extent). Therefore, the areas of impact in this investigation were chosen to be the highways in Germany. Assuming, when it comes to accurate absolute navigation, the vehicle navigation unit relies on the PPP correction data broadcast on E6B to a certain extent, flawless signal reception must be guaranteed on the autonomous driving enabled corridors. If we draw the comparison to aviation, any RF transmission within safety critical frequencies around an airport by third parties is strictly prohibited. Yet on the other hand, a GNSS receiver used in aviation must be robust to specific threats. This suggests that receiver hardening, or rather receiver signal processing and interference handling, must be taken into account. Additionally, the E6 band is already considerably populated, due to an active amateur radio community worldwide, where Germany is no exception. This gives us a potentially highly challenging environment for the Galileo E6B reception and underlines the necessity to address this issue.

II. BASE STUDY CRITERION

Let's start with some basic assumptions to define the framework. Note, that all computations are carried out in dB. Fixing the value for implementation losses inside the receiver to a reasonable 2 dB value, we compute the power spectral density N_0 (which we assume to be white) in the absence of interference:

$$N_0 = T + k_b + L_{Rx} = -202.24\ dBW/Hz. \tag{1}$$

- T ... Temperature in dBK (293 K = 24.36 dBK)
- k_b ... Boltzmann-Constant -228.6 $dBWs/K$
- L_{Rx} ... Receiver implementation loss (2.0 dB)

The desired HAS signal on E6B shall be received from a satellite at high elevation, for which we define a C/N_0 of 45 dB as a high to mid-range noise level for a satellite used for ranging in a precise positioning technique. Additionally, applying the ground noise level from (1), we compute the received power C from said satellite at the receiver, again in the absence of interference, in (2):

$$C = N_0 - C/N_0 = -157.24\ dBW \tag{2}$$

Similarly, we compute the received power from the source of interference I_{in} by applying (3). In general, we define the interference transmitter as an isotropic antenna, we fix the polarization loss L of the receiving antenna to 3 dB and the receiver antenna gain at five degree elevation G_{Rx} to -3 dB. The interference signal is assumed to arrive at five degree elevation at the GNSS antenna, since this is the lowest elevation to be declared operational services for according to the Galileo Open Service ICD. We do assume a free propagation of the interference signal to the receiver and neglect any contribution from the topography (no blocking by hills, no ground wave).

$$I_{in} = EIRP - L - 20log\frac{4\pi d}{\lambda} + G_{Rx} \tag{3}$$

- I_{in} ... Received power from interference
- $EIRP$ ... Equivalent isotropically radiated power
- L ... Polarization loss (= 3.0 dB)
- d ... Distance to receiver
- λ ... Interference wavelength ($= c/f$)
- G_{Rx} ... Receiver antenna gain 5° elevation (= -3.0 dB)

I_{in} respective the $EIRP$ and λ will be treated in more detail in the next section. The actual effect of the interference on the receiver's C/N_0 for that particular satellite may now be computed using (4) by inserting N_0, C and I_{in} from the previous equations.

$$(C/N_0)_{effective} = \frac{C}{N_0 + \frac{I_{in}}{QR_c}} \tag{4}$$

- R_c ... Chip rate ($R_{\text{c,E6-B/C}} = 5.115$ MHz)
- Q ... Q-factor

The chip-rate R_c is taken from the Galileo ICD [3] and again, Q will be subject of the next chapter. Finally, the base criterion for this study boils down to one measure $\Delta(C/N_0)$, given by (5):

$$\Delta(C/N_0) = C/N_0 - (C/N_0)_{effective} \tag{5}$$

In other words, the measure we investigate is the difference in signal-to-noise ratio $\Delta(C/N_0)$ of the desired signal of one particular satellite with and without the presence of interference, with C/N_0 being the case of no interference and $(C/N_0)_{effective}$ representing impeded signal reception. Of course, one might argue that this does not reflect reality entirely. Polarization loss and antenna gain have to be considered together, as they influence each other. Furthermore, different antenna and receiver setups are operating on different noise floors with different noise characteristics and their respective polarization losses and antenna gains. Our approach to use the same value for G_{Rx}, L and L_{Rx} for all receiver types still holds though, as this would also affect the received power from the satellite calculated in (2), and therefore, in a first approximation, would shift C/N_0 and $(C/N_0)_{effective}$ for the same amount and cancel out.

As stated in the introduction, our case of interest is an autonomous vehicle operated on German highway as shown in Figure 1. If we take a closer look at Equation (3), the impact of the interfering transmitter not only depends on the hardware characteristics of transmitter and receiver, but also on the signal propagation from one to the other, expressed by the distance of them being apart. Parameter d accounts for that, and in our investigation we did not take into account any local topographic properties or occlusion, but only the pure 2D geometric distance. This is another "worst case" consideration, since the shape of the landscape also may block a significant amount of electromagnetic waves broadcast from the ground.

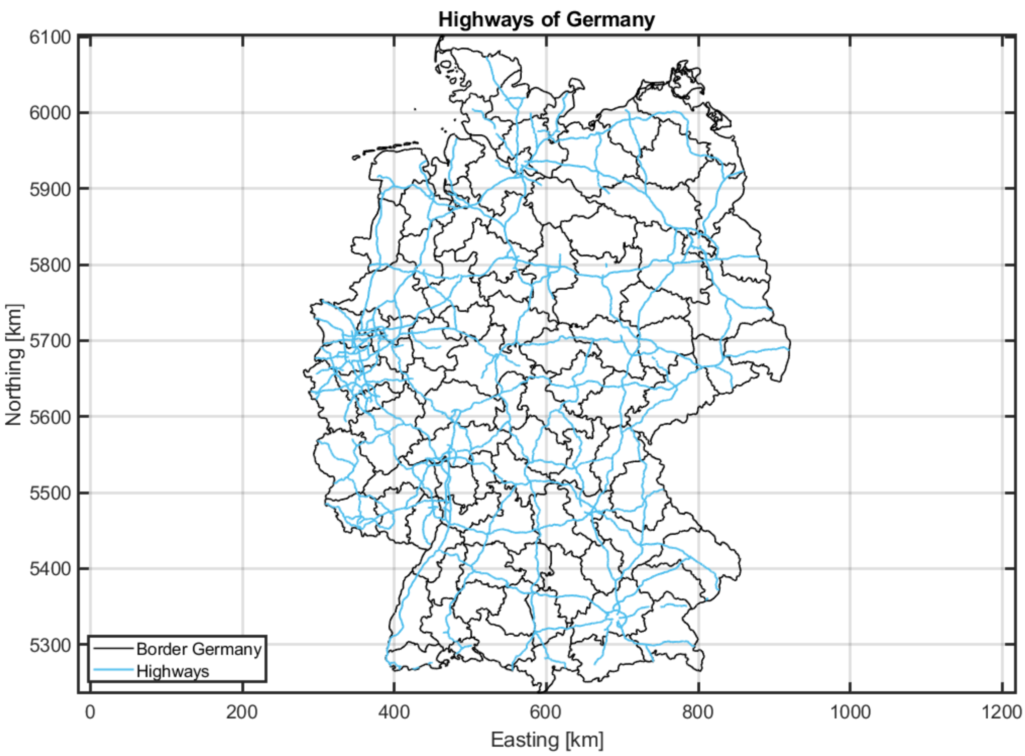

Figure 1: Highway map of Germany

Moreover, we state that there is only one amateur radio transmitter operating at any given time, since we do not want to treat complex multi-source scenarios at this point. Our objective is not only to determine whether the coexistence between amateur radio transmissions and Galileo E6B is possible, but also where and how. Given the highway map, the GNSS receiver is constrained to be located on one of the roads. d being in the numerator of the log function in (3) implies, that the closer both receiver and amateur radio transmitter are located the bigger the potential implication on the E6B reception. This means for each transmitter location investigated, we only need to consider the closest possible receiver location in order to determine the maximum impact of the broadcast station. Now, given specific receiver and transmitter characteristics, which will be derived in the next chapters, the algorithm takes following form:

- Step 1: Define a 250 m spaced meshed grid over Germany
- Step 2: Place radio transmitter on current grid point
- Step 3: Compute distance to the closest point located on a highway
- Step 4: Compute $\Delta(C/N_0)$
- Step 5: Store $\Delta(C/N_0)$ at the location of the current grid point
- Step 6: Move to next grid point and resume from Step 2 until the end of the grid

This procedure yields the maximum impact of a transmitter location on the reception at the highway for a certain signal and receiver configuration, displayed at the potential transmitter position.

III. INTERFERENCE & RECEIVER CHARACTERIZATION METHOD

To categorize transmitter and receiver, we use one parameter each. For the transmitter, we make use of the Effective Isotropic Radiated Power $EIRP$ of (3), where the maximum signal power is virtually transmitted in every direction so that it reflects a worst case consideration to the amateur radio signal. It is computed as:

$$EIRP = P_T - L_C + G_a \tag{6}$$

- P_T ... Output power of the transmitter
- L_C ... Cable loss
- G_a ... Antenna gain

Meanwhile first transmitter patterns and calibration results became public [4], which in fact show that typical amateur radio transmission antennas may very well be highly directional. The case computed in this study can therefore be understood as the transmitting antenna being directed orthogonal to the closest highway at zero degree elevation. In other words, we represent with $EIRP$ in the calculations a worst-case consideration in which the directivity of the antennas is always aimed in every direction of the calculation point.

As far as the receiver is concerned, we use the Q-factor [5] to express the robustness against interference:

$$Q_{approx} = \frac{1}{R_c \int_{-BW/2}^{BW/2} S_I\,(f) S_S\,(f)\,df} \tag{7}$$

- $S_I(f)$ ... PSD of interference
- $S_S(f)$ ... PSD of desired GNSS signal
- $Q = 0dB$ ... with infinite bandwidth and a CW at center frequency
- $Q > 0dB$ ... offset to the center frequency or even out-of-band with a limited receiver bandwidth
- R_c ... chip rate ($R_{c,\text{E6-B/C}} = 5.115$ MHz)

The robustness of a GNSS receiver to a particular type of interference can be indicated by the robustness factor Q. The Q-factor is derived from the spectral separation coefficient (SSC) of how the power spectral density (PSD) of the interference and the GNSS signal are related to each other. Additionally, the Q-factor is normalized with the chip rate of the GNSS signal. This normalization is cancelled later in (4). Furthermore, the filter effect of a receiver is also taken into account, which in the simplest case is calculated with a brick-wall filter and its bandwidth BW, as indicated in (7). If the Q-factor is given in decibels, the relative effect of the effective signal-to-noise ratio can be directly predicted when comparing different receivers. When a receiver is hardened against interference, the Q-factor increases with successful interference suppression. Due to the dependence of the spectral overlays on each other, the central frequency of the interference relative to the GNSS signal is crucial. The more distant the interference is from the GNSS center frequency, the less influence the interference has on the receiver for BPSK modulations such as Galileo E6-B/C. In other words, the Q-factor increases with higher distance to the center frequency. Figure 2 illustrates with the yellow background color, where narrow-band amateur radio signals ($BW \leqslant 150$ kHz) can occur. There, the central frequency is 1291 MHz as in our examples from Table 1. All of the energy of the interfering signal is concentrated in a few spectral lines. The spectrum of the code replica of Galileo E6-B/C $S_{\text{S,E6-B/C}}(f)$ within a GNSS receiver (tracking unit) is equivalent to the filtering effect against non-GNSS signals. The worst-case narrow-band interference occurs on the second side lobe with a center frequency of approximately 1291.5 MHz, where the normalized PSD value is -84.9 dBW/Hz. In the central frequency of E6, it would be -67.1 dBW/Hz, resulting in a difference of 17.8 dB. Thus, the worst-case narrow-band interference experiences an attenuation of about 17.8 dB. Thus, the Q-factor increases by 17.8 dB, when the same interference is shifted from the central frequency to the second side lobe.

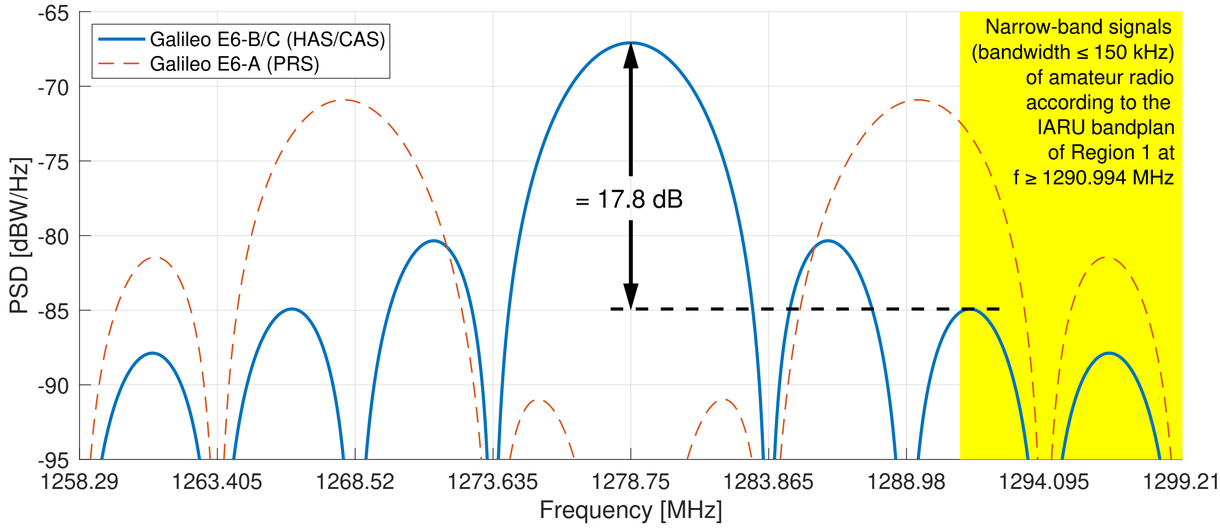

Figure 2: Normalized power spectral density of the Galileo E6 signals and the indication of the frequency range for narrow-band amateur radio signals according to the IARU bandplan Region 1

Finally, it should be mentioned that this natural mitigation effect by correlation can only be effective if the instantaneous dynamic range is available in the entire signal chain. This is not necessarily common in conventional implementation of GNSS receivers. To reduce the computational and implementation effort, the resolution of the amplitude is intentionally limited to a low number of bits of one to four bits. A resolution of six bits would be quite necessary to achieve this natural mitigation effect of 17.8 dB. It is assumed that two bits alone are reserved for the GNSS noise floor.

IV. SIGNAL AND RECEIVER CONFIGURATIONS

In order to keep the complexity as low as possible, but still demonstrate the effects of unhardened and hardened receivers, two different amateur radio signals and three receiver configurations were used for the simulation. We consider two different signals

Signal	Generic Name	$EIRP$	Center Frequency	Bandwidth
FM (Voice)	Low Power Signal	13.50 dBW	1291.00 MHz	up to 20 kHz
FSK (Data)	High Power Signal	18.26 dBW	1291.00 MHz	150 kHz

Table 1: Amateur radio signals

for our scenarios (see Table 1) to which we will later on refer with a respective generic name. The parameters are taken from the German test campaign [6] and slightly modified to cover the signal group 1 to 3. This group of signals are narrow-band signals with a maximum bandwidth of 150 kHz. Group 4 are broadband signals for analog and digital amateur television (ATV). ATV signals are not considered, since previous studies showed that there is no coexistence possible [6].

Signal 1 **(low power signal)** is a frequency-modulation (FM) signal with a voice message. The occupied bandwidth is limited to 20 kHz and the $EIRP$ is set to 13.50 dBW.

Signal 2 **(high power signal)** is a frequency-shift keying (FSK) signal with a fixed sequence of typical data traffic. The speed of the data traffic is 128 kHz, so that the maximum occupied bandwidth of 150 kHz can be ensured. The $EIRP$ is set to 18.26 dBW.

For both signals, the center frequency is set to 1291 MHz, because it reflects a worst-case situation. The center frequency for a transmitting station is normally between 1296 to 1299.975 MHz according to the IARU bandplan for the ITU-Region 1 [7].

Receiver type	Q-factor [dB]
Galileo ICD	15
Geodetic	50
Automotive (mass market)	50

Table 2: Three different GNSS receivers and their Q-factors

To differentiate how strongly the receiver is affected by the respective signals due to its signal processing, used bandwidth and spectrum overlap, we assign corresponding Q-factors to them in Table 2.

Receiver 1 **(Galileo ICD)** is a GNSS receiver, which is implemented according to the requirements of the Galileo Open Service Signal-In-Space Interface Control Document (Galileo OS SIS ICD) [3]. The receiver bandwidth is assumed here to be infinite or as specified by the ICD for E6 without any constraints. This means that no hardening measures such as filtering of interference are applied. From the previous explanation (see also Figure 2), we know that the natural robustness of GNSS signals is dependent on the center frequency of the interference. At our frequency of 1291 MHz, we know that this attenuation and thus also the Q-factor would be 17.8 dB. We are therefore very tolerant (worst case consideration), if we only assume a Q-factor of 15 dB for the simulations. The already discussed prerequisite of instantaneous signal dynamics of the receiver in the front end and the digital signal processing with at least six bits for the quantization should be mentioned again here.

Receiver 2 **(Geodetic)** is one of the high-end geodetic receiver. This geodetic receiver was also used in the German measurement study [6] and showed that a Q-factor of 50 dB is achieved in every test case following the IARU band plan. It should be noted that the input filter has a bandwidth of only 30 MHz with a frequency offset of 4 MHz. These parameters do not seem to affect on a geodetic application with E6-B/C.

Receiver 3 **(Automotive)** is a GNSS receiver with requirements as needed for autonomous driving. For an automotive application that requires a mass-market segment, we assume a receiver with a limitation of the bandwidth. This makes the receiver more cost-effective anyway and, in addition, the robustness increases considerably given our assumptions for amateur radio signals from Table 1. The main lobe of the E6-B/C signals requires a bandwidth of 10.23 MHz. Even with a bandwidth of 20 MHz, an additional filter performance of 25 dB should be achievable. Together with the natural robustness as assumed in “Receiver 1 (Galileo ICD)”, we achieve at least a Q-factor of 50 dB. This value is equivalent to “Receiver 2 (Geodetic)”.

V. HEATMAPS

Now let’s get to the results. This section depicts the heatmaps of the corresponding scenarios. We start with Figure 3 and Figure 4, showing the implications on the Galileo ICD Receiver for the low power as well as the high power amateur radio (AR) signal. Both signal respective transmitter - receiver configurations suggest that there is no coexistence possible (with respect to the $1dB$-IPC), since the lowest signal depreciation within the German borders for this receiver type for both signals ranges within 1 and 3 dB. However, it needs to be pointed out again that the actual topography was not considered. The actual signal depreciation for said transmitter-receiver configuration is supposed to be less than computed here.

At first glance, especially from the pan-view perspective, Figure 5 suggests that there is only very little influence on the E6B reception for the Geodetic/Automotive Receiver in the case of our specified Low Power AR Signal. Within the better part of Germany, every potential transmitter location for this signal type causes less than 1 dB of interference on highways. Pointing the magnifying glass on a dense highway net close to the western border of Germany, however, Figure 6 reveals that a transmitter located within approximately 4 km to a highway would yet again exceed the 1 dB threshold. Yet this suggests though, that in this specific case only a narrow band around the highways would be in need of regulatory protection, given the 1 dB IPC is deemed mandatory. Alternatively, the transmission power of the amateur radio signal could be reduced to minimize the radius.

For our last combination, the High Power AR Signal and Geodetic/Automotive Receiver, Figure 7 already shows in the pan-view some orange areas along the German Highway net. Still, most potential transmitter locations are well below the target interference. Putting the spotlight to the same dense highway area as before, Figure 8 shows a similar plot, but wider area of effect next to the roads as compared to Figure 6. The potential distance perpendicular to the highway in need of protection measures approximately 6 km. As said in the beginning though, local and regional topographical circumstances as well as AR transmitter antenna specifics would need to be taken into account, in order to tune the actual area in need of protection on site.

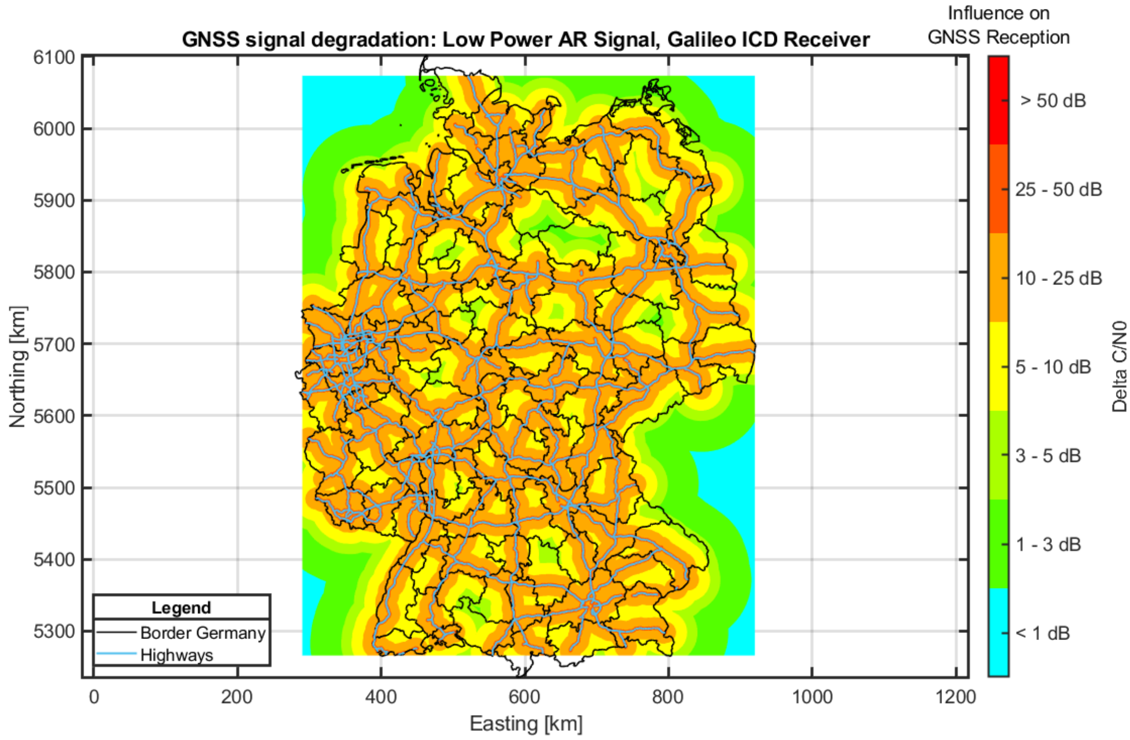

Figure 3: GNSS Signal Degradation by Amateur Radio Transmission of a Low Power Signal for a Galileo ICD Receiver

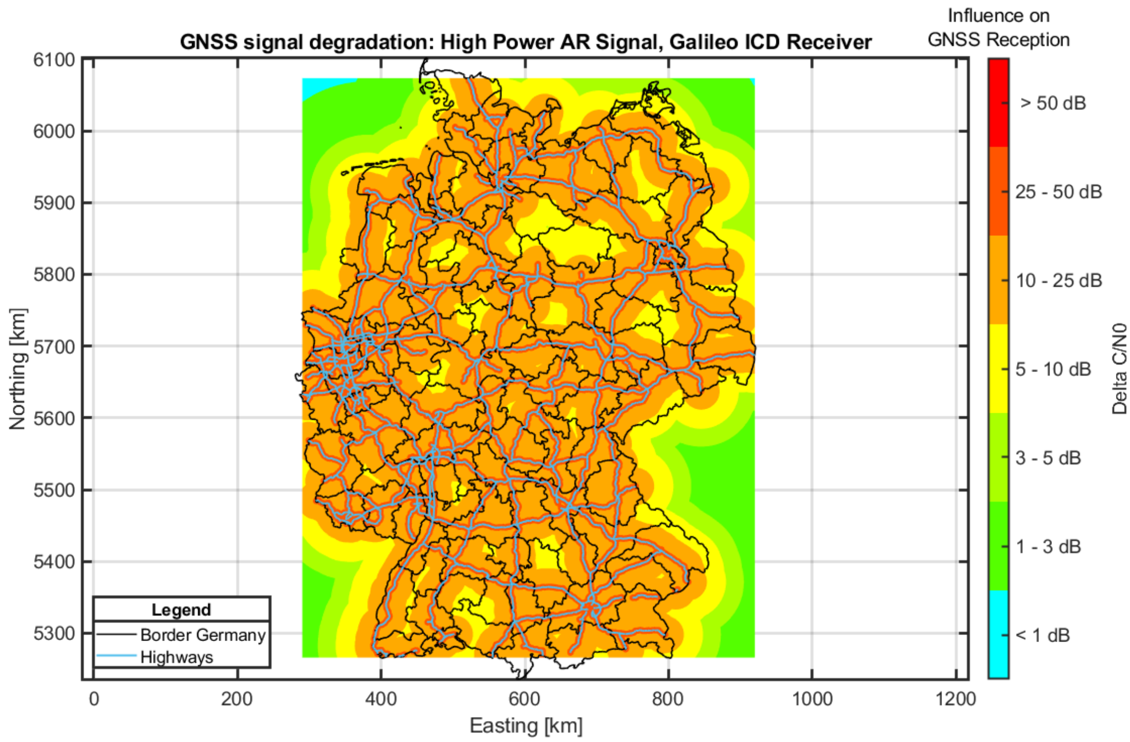

Figure 4: GNSS Signal Degradation by Amateur Radio Transmission of a High Power Signal for a Galileo ICD Receiver

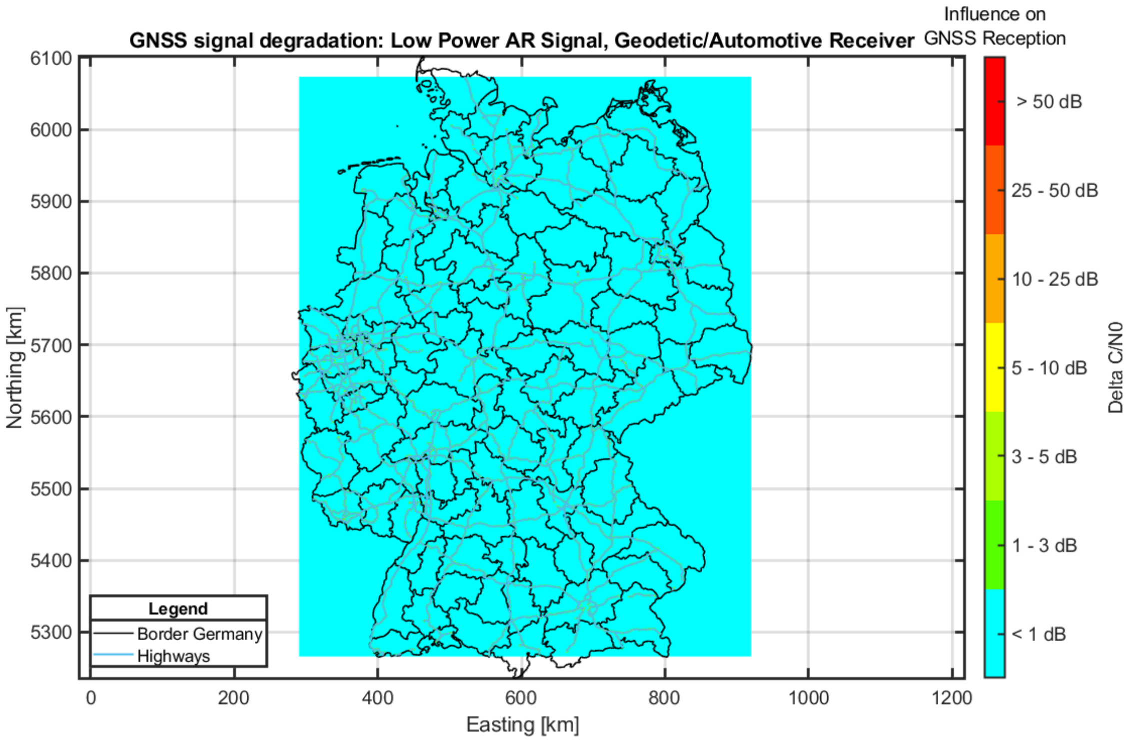

Figure 5: GNSS Signal Degradation by Amateur Radio Transmission of a Low Power Signal for a Geodetic/Automotive Receiver

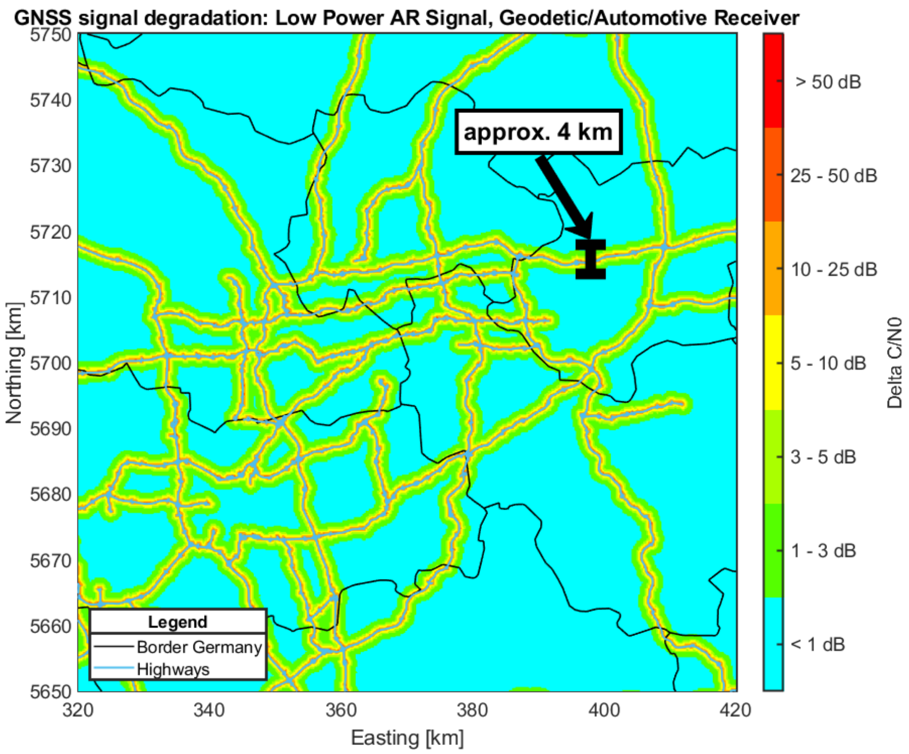

Figure 6: Spotlight on dense Road net, Low Power Signal - Geodetic/Automotive Receiver

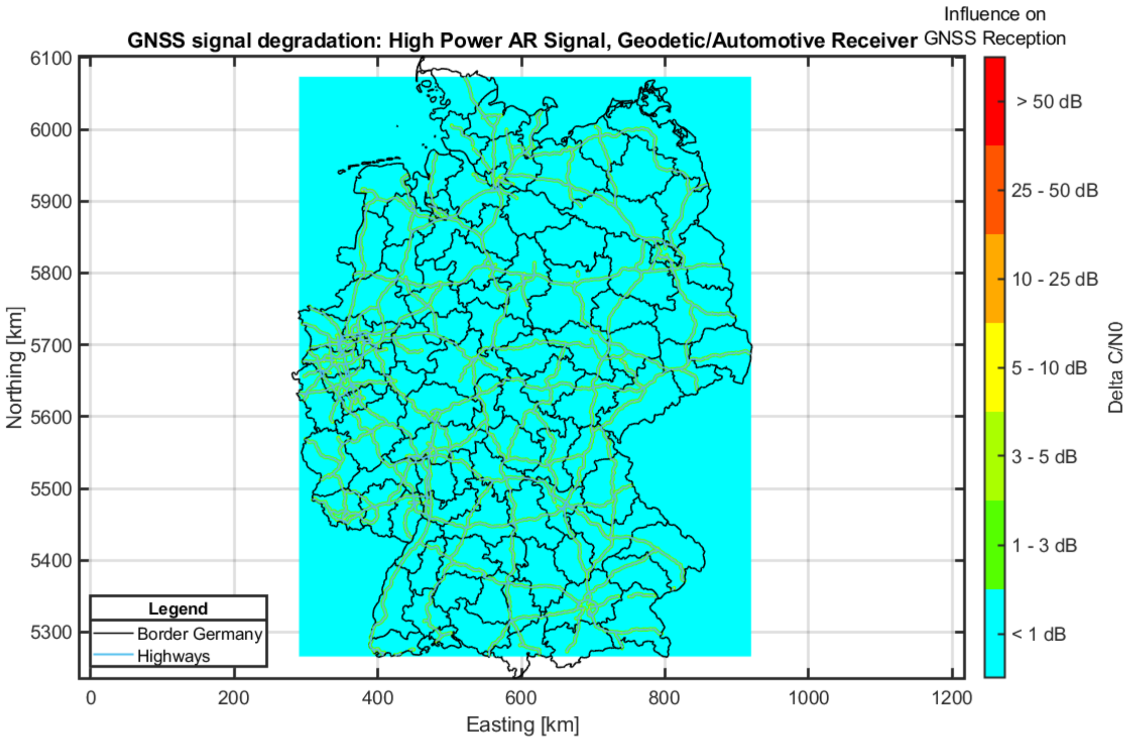

Figure 7: GNSS Signal Degradation by Amateur Radio Transmission of a High Power Signal for a Geodetic/Automotive Receiver

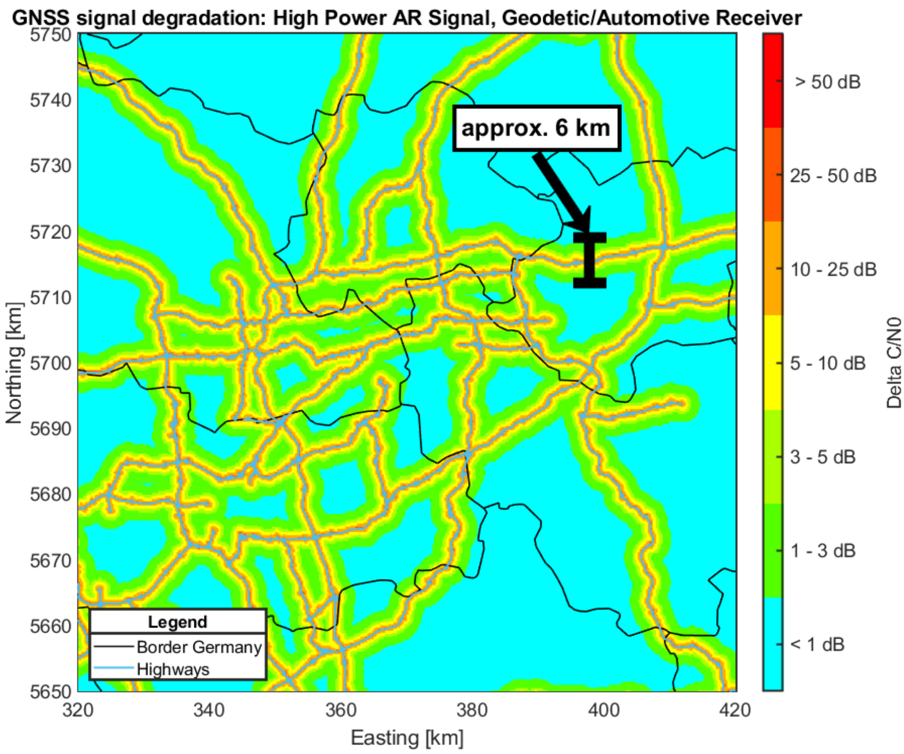

Figure 8: Spotlight on dense Road net, High Power Signal - Geodetic/Automotive Receiver

VI. CONCLUSION

The paper considers radio amateur interference to the Galileo E6 band and knowingly, we have considered only one GNSS application (driving on a highway). Our intention with this paper is, that anyone can get an easy access to the complexity of the interference and potential coexistence topic between Galileo E6 and amateur radio signals. The complexity comes definitely up, when the real situation needs to be reflected in all details and for all GNSS applications.

The heat map figures show, that there is no coexistence possible in a classical consideration of GNSS with the ***Galileo ICD*** receiver and the given scenarios. But, the receiver types ***Geodetic*** and ***Automotive*** allow a coexistence under certain restrictions. Under the classical consideration of GNSS, we understand the treatment of interference as done as in the protected RNSS/ARNS bands E1/L1 and E5/L5, which always aim the spectral pureness for the GNSS noise floor. There are a few exceptions such as in the E5/L5 band, where coexistence with pulsed signals has been worked out in the past to allow DME, TACAN and other radar systems to operate in the same band. In our work, the $1dB$ interference protection criterion was applied to identify harmful interference for GNSS, as well as a worst-case consideration at the cost of amateur radio.

Given the scope and significance of this overall topic, it cannot be stressed enough that we do neither suggest nor advertise any regulatory efforts, which are currently assessed by the respective agencies (such as ITU or CEPT) and the national authorities behind them. This study is driven by the pure interest in the subject itself, where, in our opinion, spectral freedom for the involved parties is the ideal scenario, when searching for solutions. It should be the main directive to grant this freedom whenever possible. Whenever overlap is unavoidable, a bilateral approach is most promising in our eyes. On the one hand in such a case, amateur radio signal transmission power thresholds should be reconsidered, on the other hand GNSS receivers need to be equipped with at least a minimum of robustness, in order to cope with real world conditions (which would result in an increase of the Q-factor). We understand though, that this is difficult, especially since an increased robustness in the receiver comes with a price, literally. Increasing the robustness of the receiver in the actual meaning of hardening affects cost, form factor, energy consumption and development resources. These are all attributes to which especially the mass market sector is very sensitive. Our results stem from the facts that we gathered under the assumptions made in this study, and our proposed solutions reflect a scientific approach to a problem solution.

ACKNOWLEDGEMENTS

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