GNSS Receiver Testing by Hardware Simulation in an Standardized Pulsed and CW Interference Environment

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BIOGRAPHY

Holmer Denks received his engineer diploma in electric engineering and communications at the University of Kiel, Germany, in 2002. There he was involved in investigation and simulation of communications systems. In 2002 he joined DLR. Since then he works in the field of satellite navigation. Currently he works on simulations of Galileo signals.

Achim Hornbostel received his engineer diploma and Ph.D. in electrical engineering from the University of Hannover in 1989 and 1995. He joined the German Aerospace Centre (DLR) in 1989, where he became member of staff at the Institute of Communications and Navigation in 2000 and is leading a research group on receivers and algorithms since 2005. He was involved in several projects for remote sensing, satellite communications and satellite navigation. His main activities are currently in signal propagation and receiver development. He is member of VDE/ITG and ION.

Vincent Chopard received his engineer diploma in aeronautical engineering from ENSICA (École nationale supérieure d'ingénieurs de constructions aéronautiques) in Toulouse in 2004. He was then involved in avionics system integration and validation. Since 2005 he has joined Thales and then he works on the algorithmic of satellite navigation.

INTRODUCTION

Future GNSS like Galileo and the modernized GPS will make the introduction of satellite navigation into new application areas possible, where conventional GPS cannot be used. These are in particular safety of life applications, e. g. landing approaches of higher categories in aviation. Highly specialized receivers will be developed for these applications, which must fulfill all requirements defined by the responsible authorities and certification bodies and must cope with the specific signal reception conditions in the application environments. These receivers need thoroughly testing under controlled and repeatable conditions.

In aviation environments various potential interference sources exist, which can degrade the performance of on-board receivers as well as the performance of ground based reference receivers which are part of a ground based augmentation system (GBAS). Therefore, besides functional receiver validation under nominal conditions also the behavior of the receiver under strong interference conditions, namely CW interferers, broadband noise as well as pulsed interference from Distance Measurement Equipment (DME) and the military Tactical Air Navigation (TACAN) must be tested. DME/TACAN is one of the main interference sources in the E5 Galileo band in aviation environments. Software and hardware simulations have shown already that DME interference can reduce the C/N_0 of a receiver by some dB even if pulse blanking is applied in the receiver [1], [2].

In the project "ANASTASIA", which is financed by the Sixth Framework Program of the EU, the development of a L1/E5 Galileo receiver for safety-of-life (SoL) applications has taken place. Now, at the end of the project this receiver is tested and validated with the help of hardware signal generators. For these tests the very powerful Multi-output Advanced Signal Test Environment for Receivers (MASTER) [3], [4], of the German Aerospace Center (DLR) is utilized. MASTER provides simulated Galileo and GPS signals at the nominal RF carrier frequencies and power levels, which are fed into the antenna port of the receiver under test. The combined output signal of the simulator contains the sum of the signals from all or some selected satellites in view for an arbitrary receiver position or track. It is possible to generate up to four different carriers at a time, e.g. GPS L1 and L2 as well as Galileo L1 and E5. All "true data", i.e. the positions of SVs and receivers, pseudo-ranges, errors and so on provided by the simulator, are logged and are therefore available for the analysis later on.

In this paper we will give an insight in the receiver tests undergone to prove the performance of the ANASTASIA receiver developed with the focus on interference. They have been performed following mainly the test procedures defined in the Galileo MOPS [4] by EUROCAE WG 62. Thus, these tests also give the first practical experiences with these Galileo MOPS test procedures. Different methods will be used for the DME interference generation: A test file containing a rough model derived from measurements over the Frankfurt hotspot which is provided in the Galileo MOPS by EUROCAE [5] as well as real data recorded during a measurement campaign also over the Frankfurt hotspot area [7]. In both cases the DME interference is first generated in baseband as a MATLAB file and than up-converted to RF with help of an AGILENT E8267D programmable signal generator. The test setup and preparations will be described in detail and test results will be presented. Especially a comparison between the degradation of the receiver due to the modeled and the measured DME interference will be done.

ANASTASIA PROJECT

ANASTASIA (Airborne New and Advanced Satellite techniques and Technologies in A System Integrated Approach) is an integrated project which funded by the European Community's Sixth Framework Programme (DG research); see www.anastasia-fp6.org. The core of ANASTASIA research is to provide on-board Communication, Navigation and Surveillance (CNS) solutions to cope with the expected increase in air traffic by 2020. We focus in this paper on ANASTASIA sub project (SP) 3 called Navigation and SP5 which deals with operational tests. Within SP3 a receiver mock-up has been designed for three Galileo bands (L1, E5a, E5b), which is compliant to the MOPS current standards. In SP5 the DME measurement campaign was carried out and the receiver is tested up to its limits regarding interferences, multi-paths and low level signals.

DME MEASUREMENT CAMPAIGN


Figure 1 Test aircraft

Within the project ANASTASIA a measurement campaign was carried out in March 2009 in order to obtain better and realistic data for the interference scenario in the E5 band for aviation. For this purpose flight trials were performed in different heights, i. e. at the flight levels (FL) 50, 150, 220 and 380, and data were recorded with a skyward looking Galileo navigation antenna (ANASTASIA antenna). The main area of interest in a geographical sense was around Frankfurt/Main, Germany where the European Hotspot in respect to DME/TACAN power is assumed to be.

Figure 1 shows the test aircraft. It is a Dassault Falcon 20E which is owned by DLR. This small jet is able to go to a maximum altitude of 42 000 ft (12800 m). Figure 2 shows the general setup for the measurements during the flight trials: The received signal is first fed into a low noise antenna preamplifier (LNA) and then is entering the RF-frontend, where filtering and additional amplification take place. The total RF-amplification is approximately 45 dB. As the main measurement equipment a vector power spectrum analyzer (Agilent E4443A (PSA)) is used. The PSA executes the down conversion as well as the digitalization with a bandwidth of up to 80 MHz. The control of the PSA is done via a PC. On that PC also the data is stored.

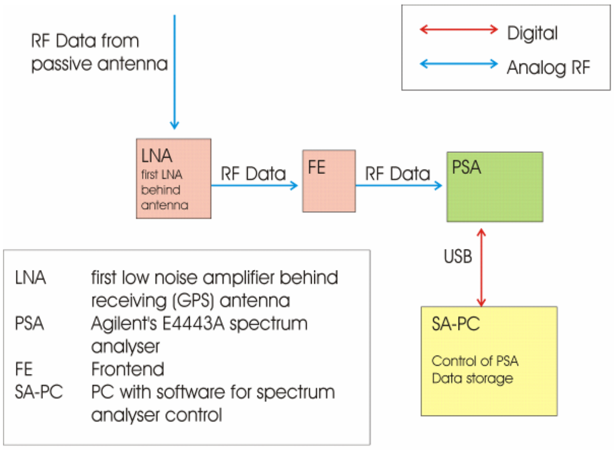

Figure 2 Test setup for data collection

ANASTASIA ANTENNA


Figure 3 Test Antenna mounted on top of the plain

The used antenna was a navigation antenna also developed within ANASTASIA which was mounted on top of the test aircraft as it is typical for navigation antennas. However, most of the interferers are radiating from the ground and, therefore, are not in the direct line-of-sight view of the antenna, but nevertheless reach the antenna by propagation along the aircraft body.

The ANASTASIA dual frequency antenna characteristics have been measured in the E5 band. The antenna has bee mounted for that purpose on a plate of approximately 26 cm radius. It was the same plate which was used later on for the test trials (compare Figure 3).

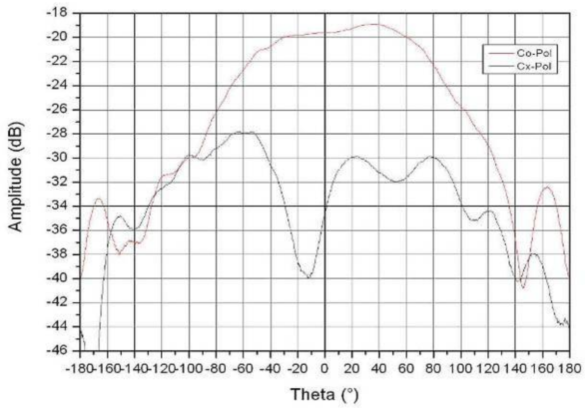

Figure 4 Antenna diagram at 1.149 GHz.

Figure 4 shows the antenna diagram measured at 1.149 GHz which was one of the borders in respect to the collected data. Figure 5 shows the gain over the frequency of the whole antenna. As can be seen the dependency of the frequency is quite small. The variation is about 2 dBm for 100 MHz.

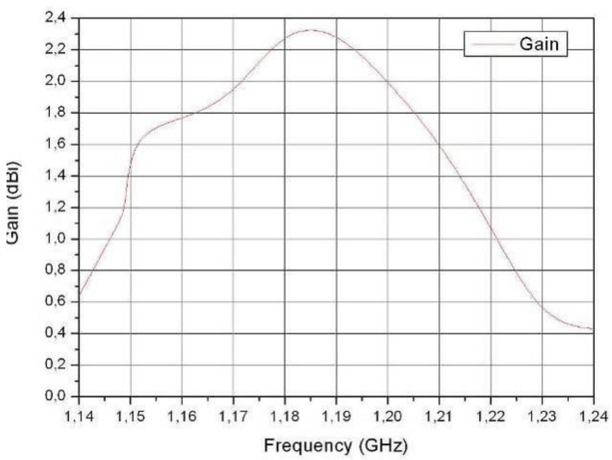

Figure 5 Gain of antenna

RECEIVER AND IMT

The test receiver which is shown in Figure 1 consists mainly of four parts: The RF Unit, the digital processing unit (DPU) and the receiver control. Not shown is the preamplifier. The receiver is capable to receive the Galileo navigation signals at three frequency bands: L1 (8MHz), E5a (20 MHz and E5b (14 MHz).

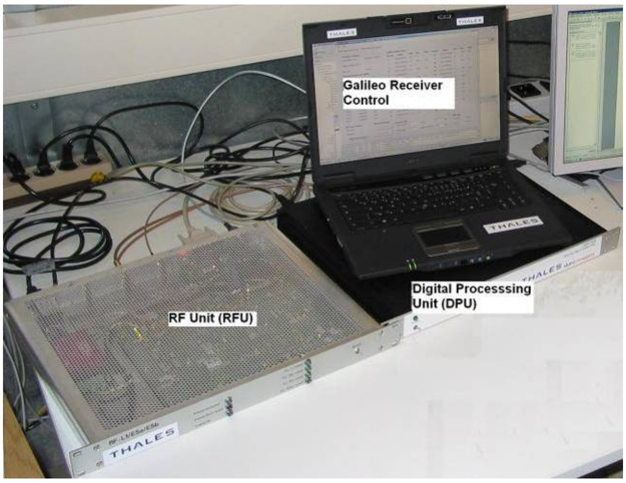

Figure 6 Test receiver

In [3] different interference mitigation techniques (IMT) based on pulse blanking which are implemented in this receiver were compared. The best performing technique was FDAF (Frequency domain adaptive filtering) which is used for this investigation. The principle of FDAF [8] is shown in Figure 7.

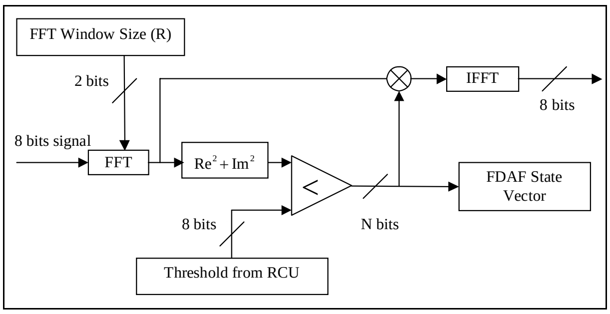

Figure 7: FDAF blanker principle

The threshold used by the FDAF algorithm has been chosen in a way that there is no useful signal energy lost in case of no interference. That means that the C/N_0 determined by the receiver in case of no interference is the same when using FDAF or not.

DME SCENARIO

The real data analyzed in the following have been recorded 2009/03/04 10:39:07 UTC between “TAUNUS” and “RUDUS”at flight level (FL) 380 which is typical for trans-atlantic flights. FL380 corresponds at that day and that position approximately to 11250 m over mean sea level. The plane was going straight; the bank angle was 0°. According to Eurocontrol at that time a peak in respect to traffic was nearly met.

Figure 8 Approximate position where the data has been taken

This dataset has been chosen because at this height the most DME stations are visible. In lower altitudes there are less DMEs visible but they have slightly more power. For more details about the test trials compare [7].

DME DATA FILES AND CALIBRATION

In these investigation two different interference scenarios has been used: The synthetical one from EUROCAE (compare [3]) and the measured one. A first overview of the interference scenario is given in Figure 9 which shows both scenarios in the frequency domain. In that figure the bandwidth of the used receiver is marked yellow. Note, the bandwidth of E5b is much smaller (14 MHz) than the bandwidth E5a (20 MHz).

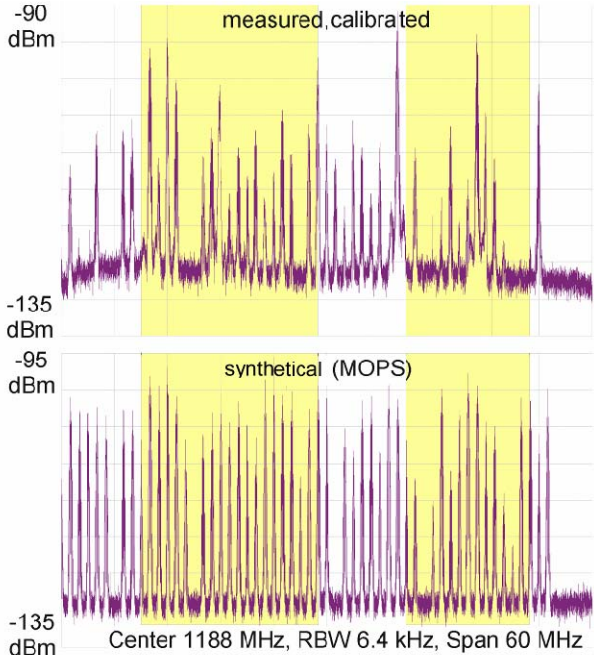

Figure 9 Spectrum of interference test signal

Figure 10 shows again for both scenarios a short part in time domain. In the upper part which presents the measured signal clearly the characteristically DME pulse pairs can be observed whereas in the bottom part, i.e. the modeled interference scenario, due to pulse collisions the individual pulses are not that clearly visible. The peak powers in both scenarios are similar.

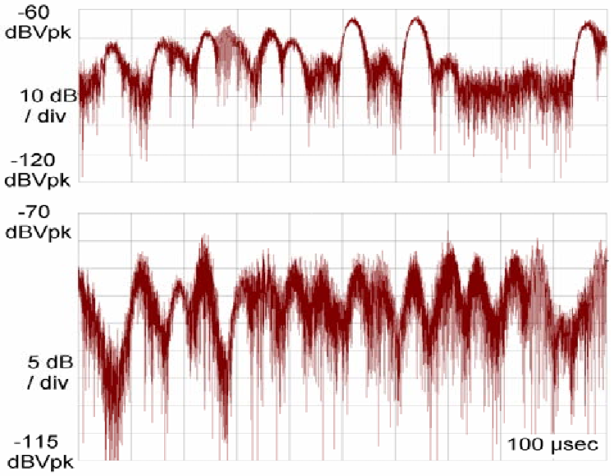

Figure 10 100 µsec of interference test signal in the time domain

Figures 9 and 10 show calibrated data, i.e. the raw data collected during the measurement campaign are corrected for the influence of the LNA and of the frond-end. The frequency dependent gain of the front-end was measured before each flight with help of a calibration signal that was fed into the input port of the antenna preamplifier at different power levels and swept versus frequency. An example of a resulting calibration curve which was applied to the raw data in the post processing is shown in Figure 11. The average gain of LNA and front-end is about 45 dB. The antenna pattern is not corrected for, because in the laboratory tests with MASTER the antenna is not simulated and the data as seen at the antenna output are directly fed to the receiver.

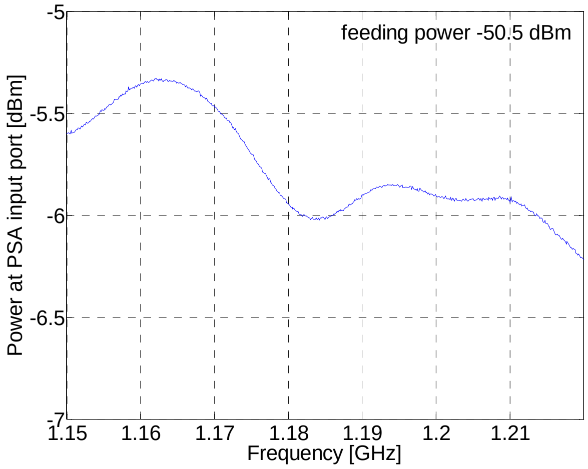

Figure 11 Calibration curve

A spectrogram depicts along the x-axis the power versus frequency like a simple plot of the spectrum but the power level being color coded. Along the y-axis time is plotted. For each time step one "slice" of the spectrogram is generated. The present (or last) time step is the bottom line, the first time step is the top line. Therefore it is possible to see from the spectrogram how a signal in respect to its power spectrum behaves with time. Especially pulses can be distinguished by dots or lines.

Figure 12 presents the spectrograms of both interference scenarios for 10 milliseconds. The upper one is the measured scenario the bottom one the modeled. Each horizontal line presents one DME/TACAN station. Again one can see that the modeled scenario is much more "symmetric" than the one from the real measured and calibrated data, i.e. that the stations are radiating with a more or less constant rate whereas in the measured scenario one can notice that the radiation rate is not constant. Note, the color coding is different for the two spectrograms for better visualization.

During the replay of the DME the power offset of the signal generator was adjusted with the help of a short CW pulse of known power as done before for the synthetic DMEs as well (compare [1]).

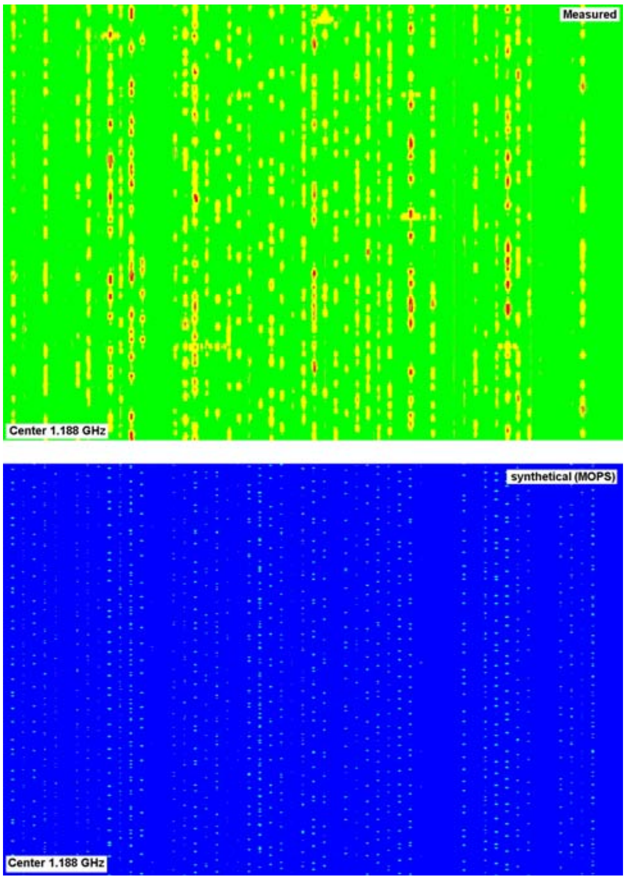

Figure 12 Spectrogram for 10 ms of data and 60 MHz bandwidth

SIMULATION SETUP

The general simulation setup consists of the MASTER system including the signal generator boxes connected to the receiver under test. Additionally a vector signal generator for the pulse generation and a simple CW generator for the CW interferer are used. A schematic overview of the system is given in Figure 13.
The core of MASTER consists of two modified GSS7790 multi-output full constellation simulators built by Spirent Communications Ltd. which provide besides GPS all Galileo (E1, E5, E6) satellite signals as digital baseband signals. MASTER is controlled by Spirent's SimGEN^{TM} SW running on a control PC. SimGEN^{TM} enables the user to define a simulation environment including parameters such as orbit parameters of the GNSS used, clock errors, iono- and tropospheric effects, antenna pattern, multipath and user trajectories. It is also used to define the satellite in view (SV) signal and its components as navigation data, pilot/data channel and modulation scheme according to the desired frequency band.

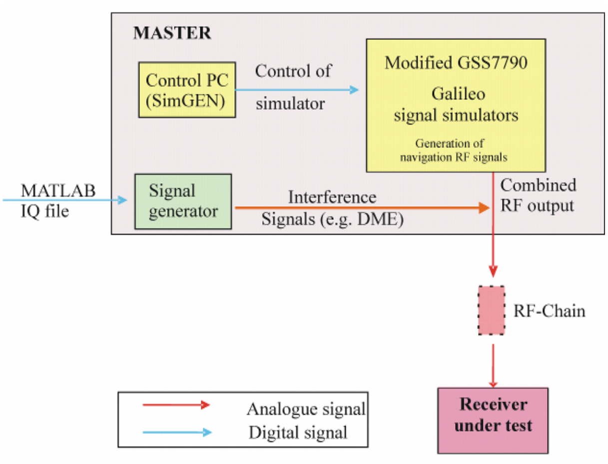

Figure 13: Schematic overview of test setup.

All signals are provided on a combined RF output of the simulator [4][5] at a nominal power level of about -130 dBm with a dynamic range of ±20 dB. The GNSS signal is then superposed with the interference signal which comes from the signal generator (an Agilent E8267D). The combined signal can be fed directly into the RF input port of a single antenna GNSS receiver or a further RF chain can be inserted between simulator output and receiver input (compare next section)

DETAILS ABOUT THE RF CHAIN

The purpose of the MOPS test is to validate the receiver itself without taking into account the pre-amplifier performances [9]. But since the noise, the interferences and the signal powers are specified at the output port of an active antenna an RF chain has to be implemented to provide the same RF level and noise floor as the active antenna. In the MOPS procedures a standard pre-amplifier with a worst-case noise figure of 4dB and a gain between 26.5 and 32.5 dB and cable losses of –3 to –13 dB are specified.

We need then to configure the RF test chain between the simulator and the receiver, in order to fit with the required performances of a standard chain. We use a first attenuator A1 between the Signal Simulator (S) and the test preamplifier (PA) in order to tune the equivalent temperature of the total chain. We use a second attenuator A2 after the test preamplifier (PA) to tune the gain of the overall RF test chain. This second attenuator has a negligible impact on the noise figure. In order to be able to simulate every test configuration, the test preamplifier used shall at least

- have a 38dB gain
- have a noise figure lower than 2dB and
- be wideband (L1, E5a and E5b)

The interference signals are generated by the programmable signal generator and integrated in the chain by a splitter just before the receiver input. The idea is to avoid any filtering of the interference signal by the test preamplifier. The basic test configuration with RF chain is shown in Figure 14.

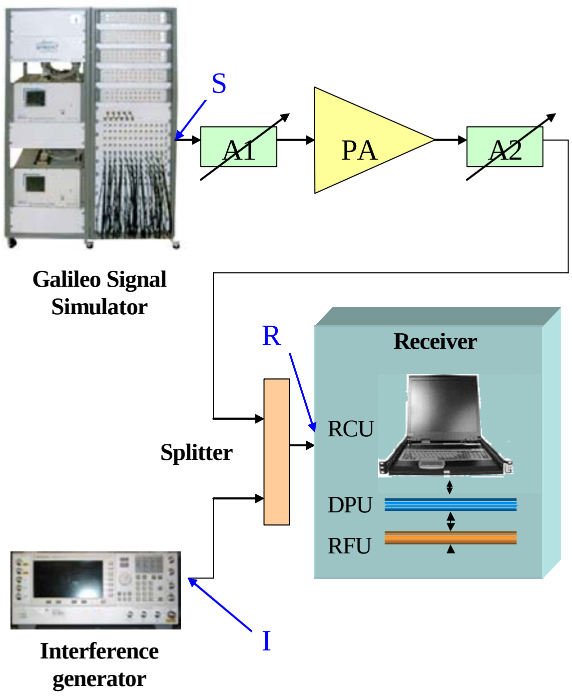

Figure 14: Setup with RF Chain

The setting of the attenuator A1 and A2 are determined as follows by using the equivalent noise temperature. The equivalent noise temperature required for the test is determined by its components:

- Intersystem interference (GNSS noise) I_{GNSS} = -187.0 dBm/Hz (= k_B * T_{GNSS} => T_{GNSS} = 14.5K)
- Sky noise: T_{sky} = 100K
- Noise figure F_{sPA} of standard pre-amplifier ($T_{sPA} = (F_{sPA} - 1)*T_0 = 438.4K$)
- Cable loss L_{cable} => $T_{cable} = (L_{cable} – 1) * T/ G_{sPA}$ where G_{sPA} is the gain of the standard pre-amplifier and T the physical temperature of the cable

The total noise temperature to be simulated is then $T_{req} = T_{GNSS} + T_{sky} + T_{sPA} + T_{cable}$

We assume a noise temperature of the simulator of T_{simu} = 50°C = 323K. The parameters of the RF-chain must be set in such way, that the simulated equivalent noise temperature is equal to the required total noise temperature Treq.:

- The attenuation A1 (to be set) leads to a noise temperature of TA1 = (A1-1)*T with T ~T0 = 290K.
- The true noise figure of the preamplifier used for the tests is 0.5dB. The equivalent noise temperature is then TPA = (FPA –1) * T0 / (1/A1).
- We assume here that the attenuation A2 and the splitter do not provide any more noise whereas in the real computation it is taken into account.

The total noise temperature of the RF chain is Tchain = Tsimu + TA1 + TPA which must be equal to Treq. From that TA1 resp. A1is determined. The total gain of the RF chain shall be G = GsPA-Lcable. The total gain of the RF chain is then G = GPA – A1 – A2 leading to A2 = A1 - G.

In practice, it is not easy to set the attenuation up to a decimal value. Therefore the attenuator values are rounded.

SIMULATION SCENARIOS

For this paper three different simulation scenarios have been set up using the two different interference scenarios as described above (Table 1).

	Scenario 1	Scenario 2	Scenario 3
RF Chain	No	Yes	No
SV power [dBm]	-118.4	-122.2*	-115.2**
Receiver dynamics	Dynamic	Dynamic	Static
Reference clock	Internal	Internal	External
Iono / Tropo	Standard	Off	Standard
Interf. scenario	Both	Both	Synthetical only

Table 1 Overview of used scenarios

* The power is 7 dB higher than given by the MOPS test procedure [9].
** Note, a 1:4 power splitter has been used here. In the scenarios 1 and 2 a 1: 2 power splitter has been used. The 1:4 power splitter adds another 3.2 dB attenuation which requires 3.2 dB more signal power

For the scenarios 1 and 2 the receiver movement is optimised in respect to maximal relative dynamic between receiver and most SV. In general it is an perpendicular ellipse placed under an orbital plan of the constellation but with non-constant accelerations and jerk. The non-constant velocity of the simulated aircraft which carries the receiver is in the order of 700 mph. Details can be found in [9].

In Figure 15 the influence of the RF chain on noise and signal level is shown. The upper part describes the situation without the RF chain as used in scenario 1 and the lower part describes the same with RF chain as used in scenario 2.

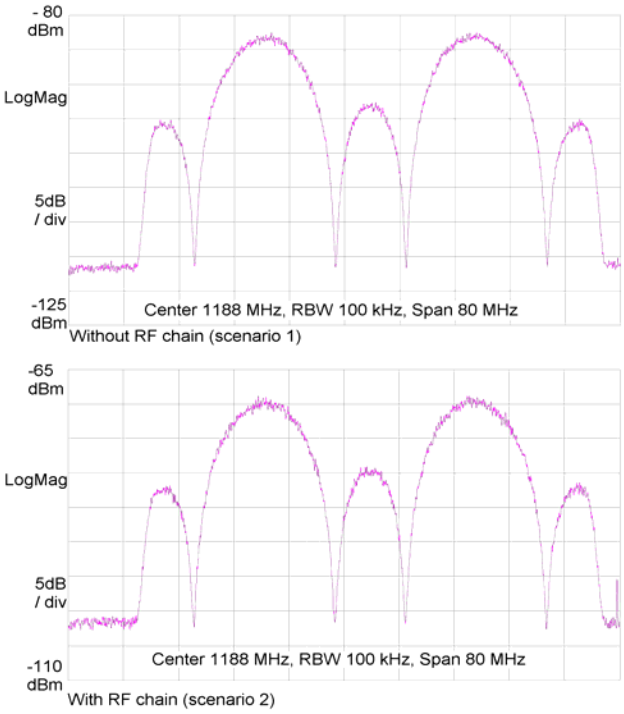

Figure 15: Galileo signal at receiver port (amplified by approx. 50 dB)

The values used for the RF chain in scenario 2 are A1 = 2.1 dB, A2 = 20.3 dB, G_{PA}= 38.7 dB. This results in an overall gain of the chain of 16.3 dB. Note besides the RF chain also the SV power differs in the two scenarios. As can be seen clearly in Figure 15 the peak power of the signal is about 12.5 dB = -122.2 dBm + 16.3 dB – (-118.4 dBm) higher in scenario 2 than in scenario 1.
But the noise level is also changed by the RF chain but in a different manner. This results to the same signal to noise ratio for the two scenarios.

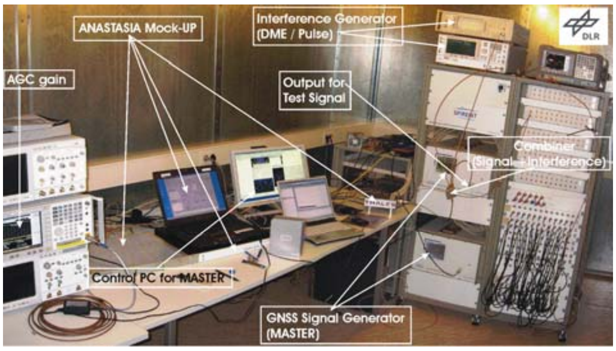

Figure 16: Test setup.

RESULTS

The following tables present the C/N_0 observed in the different test cases: Table 2 in case of scenario1 for the synthetical and measured interference, Table 4 gives the same for scenario 2. Table 5 is a short review of results presented already in [3] and Table 3 gives results for a modified scenario 1, i.e. with a different GNSS signal power The C/N_0 given in the following tables is a mean of the tracked 10 to 12 SV. Remember, in the interference free case it does not matter whether FDAF is used or not due to the chosen threshold within the FDAF algorithm compare section “RECEIVER AND IMT”).

	No DME	DME, no IMT	DME, FDAF	DME type
E5a	41.7	29.3	34.5	Measured
E5b	40.0	29.4	34.4	Measured
E5a	41.7	20.0*	34.5	Synthetical
E5b	40.0	22.9*	34.8	Synthetical

Table 2 C/N_0 without RF chain, power = -118.4 dBm (scenario 1) *Loss of all SV within 1 min

	No DME	DME, no IMT	DME, FDAF	DME type
E5a	44.8	32.4	37.7	Measured

Table 3 C/N_0 without RF chain (modified scenario 1, power = -115.2)

	No DME	DME, no IMT	DME, FDAF	DME type
E5a	41.2	36.5	40.0	Measured
E5b	40.5	36.9	39.3	Measured
E5a	41.1	30.8	39.2	Synthetical
E5b	40.5	31.6	39.0	Synthetical

Table 4 C/N_0 with RF chain, power = -122.2 dBm (scenario 2)

For comparison reasons results from [3] have been included (Table 5). The main difference here is the GNSS scenario (static scenario 3 instead of dynamic scenarios 1 and 2) where as the interference scenario is the same as used here for the synthetical DMEs. The results are similar when compared to the results of scenario 1 which also does not use the RF chain.

	No DME	DME, no IMT	DME, FDAF	DME type
E5a	41.7	18.3*	33.2	Synthetical
E5b	40.0	21.7	34.3	Synthetical

Table 5 without RF chain, power = -115.2 dBm (scenario 3) *Loss of all SV within 1 min

In Table 6 the average band power is given for the two receiver bands E5a and E5b and the two interference scenarios.

	Measured interference	Synthetical interference
E5a (20 MHz)	-78.2	-78.2
E5b (14 MHz)	-82.0	-80.5

Table 6 Band power of interference signal within the receiver bandwidth

Figure 17 and Figure 18 present the results in a graphical way. At the x-axis the three different cases are presented: no DME at all (reference), in the middle the DME present but the receiver not using any interference mitigation techniques and at the right side when the receiver uses FDAF in the presence of DME. The y-axes shows the corresponding C/N_0.

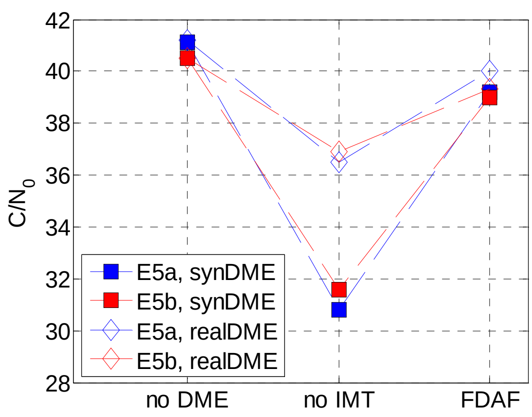

Figure 17: Comparison of influence of DME generation type (with RF chain, scenario 2)

The two interference scenarios are quite different in respect to the pulse repetition rate. This has an influence on the C/N_0 of the receiver: The synthetical interference forces the receiver down by another 5 dB (with RF chain) compared to the measured interference case whereas in case of no

RF chain the synthetical interference even causes an additional loss of 7 to 10 dB. However, when using FDAF the difference between the behaviour due to the two interference scenarios is minimal. The synthetical and the measured interference lead to the same C/N_0.

E5b is less strong degraded due to its lower bandwidth combined with less interference power (compare Table 6) in case off no IMT. Synthetic DME is much worse in case of no IMT but almost the same with FDAF (at least with RF chain.

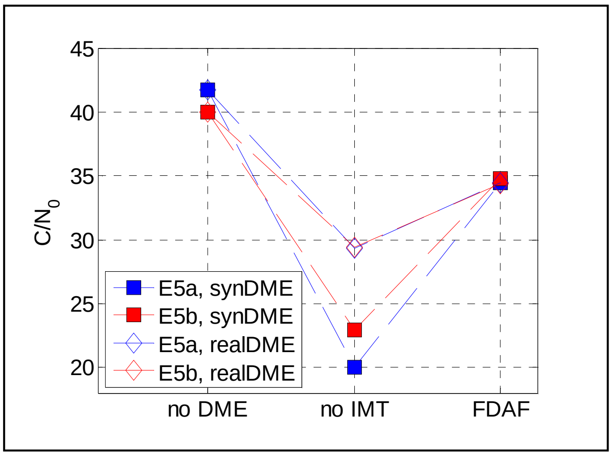

Figure 18: Comparison of influence of DME generation type (without RF chain, scenario 1)

Figure 19 shows that there seems to be no significant influence of the SV signal strength on the signal to noise degradation of the receiver when stressed by interference.

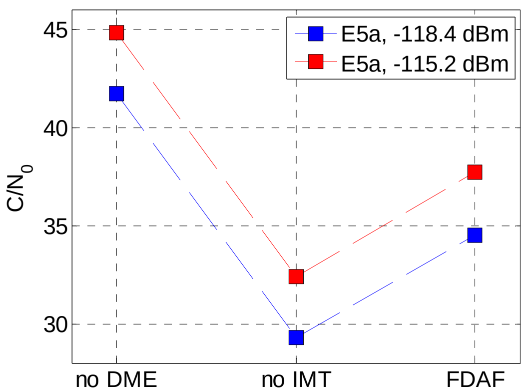

Figure 19: Influence of different power levels on degradation (scenario 1)

CONCLUSIONS

The influence of DME interference in the Galileo E5a and E5b band on the receiver performance has been investigated by hardware simulations with synthetic and measured DME data. The synthetic DME data were generated according to the procedure define in the Interim Galileo MOPS by Eurocae WG 62. The measured DME data were collected during a flight measurement campaign over the Fankfurt hotspot. For the snaphot of the collected DME data used in the analysis here, the C/N_0 degradation of the receiver without pulse blanking is higher with the synthetic data, and both with measured and synthetic DME data the C/N_0 degradation is more severe in the E5a band than in the E5b band. However, further data have to be analysed, before it can be decided whether these are general trends. When pulse blanking is applied, the C/N_0 degradation is reduced and the resulting C/N_0 is the same for synthetic and measured interference. In particular when a RF chain is inserted in the simulation set up, which emulates the signal and noise levels of at the output of an active Galileo receiver antenna, pulse blanking with FDAF is an effective mitigation technique and the C/N_0 reduction can be kept with in the range of 1 or 2 dB compared to several dB without mitigation.

ACKNOWLEDGEMENTS

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