Effect of the aeronautical L-DACS2 radio-frequency signals on the DME system performance

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Abstract—In this paper, we consider the Radio-Frequency Compatibility (RFC) of a candidate system for the future aeronautical communication infrastructure. This infrastructure is being developed within the International Civil Aviation Organization since 2004, to accommodate the air traffic load and improve the aerial security. The system presented in this paper is one of the two preselected proposals for the L-band Digital Aeronautical Communication System (L-DACS), which will be responsible for the continental communications. This proposed candidate is named L-DACS2 and is foreseen to use part of the L-band spectrum (960 to 1164 MHz) allocated to the Aeronautical Mobile Service reserved for communications relating to safety and regularity of flight. Despite its potentially large spectrum, the L-band is a challenging environment for aeronautical communications because of the channel propagation characteristics and the dense spectral occupation by a large number of aeronautical systems. On the other hand, the RFC characterizes the electromagnetic compatibility between two radio systems and determines if they can coexist in the same electromagnetic environment. For this reason, the RFC is one of the main issues for L-DACS deployment and if it is not satisfied, the flight safety could be endangered. Hence, we propose to study in this paper the impact of the L-DACS on the Distance Measuring Equipment (DME), which is a very important equipment that has been using this band for decades. According to recent studies performed in the frequency domain, that is assuming continuous transmission and air traffic domain variations, the achieved RFC level seems insufficient. The main objective of this work is to analyze the RFC between L-DACS2 and DME taking into account the time domain aspects of both systems. The idea is to verify and quantify the impact of the radio-frequency signals generated by a L-DACS2 interferer on the performance of a DME victim receiver. The study is performed for the co-site case (i.e. when both equipments are onboard of the same airplane), which is the most critical interference scenario due to the proximity of both systems. The results are obtained through computer simulations as well as laboratory measurements. They present the DME performance degradation for some values of the Signal to Interference Ratio, assuming a constant DME signal level and different L-DACS2 interference powers.

I. INTRODUCTION

According to the aeronautical authorities, the aerial traffic forecast will be in a continual increase after 2011. Hence, in the coming decades, more than twice the number of airplanes will be present in the aeronautical network. To accommodate this evolution, higher-data-rate communication will be fundamental to provide better safety, automatic communication and air traffic optimization. However, the current communication systems will be insufficient to accommodate this traffic increase and fulfill these new requirements.

In this context, the International Civil Aviation Organization launched in 2004 a joint Euro-American project to develop a Future Communication System suitable to this new aeronautical scenario and which will coexist with the existing communication systems. The Future Aeronautical Communication Infrastructure (FCI) will use complementary technologies across multiple frequency bands to ensure the voice and data communication. These technologies are the most promising to provide both safety-related and non-safety-related services.

The L-band Digital Aeronautical Communication System (L-DACS) is the part of the FCI dedicated to the continental safety related communications. This system is the evolution of the aeronautical communication system that nowadays employs the VHF aeronautical band (118 to 136 MHz). The L-DACS includes additional features such as air to air communication and high data rate communication. Many studies have been conducted to identify the most adapted technology to the new aeronautical requirements. Two candidates were preselected and one of them is the L-DACS2, which was proposed by the European Organization for the Safety Air Navigation (EUROCONTROL). Widely inspired from the Global System for Mobile Communications (GSM), which is the most popular standard for mobile telephone systems in the world, the L-DACS2 infrastructure lies over a well-know platform that provides high quality-of-service management.

In 2007, the International Telecommunication Union agreed to use the L-band allocated to the Aeronautical Mobile Service reserved for communications relating to safety and regularity of flight (960 to 1164 MHz) for the L-DACS. This band is currently allocated to the Aeronautical Mobile Service reserved for communications relating to safety and regularity of flight. As a result, in order to ensure the flight safety, further studies need to be performed to guarantee the electromagnetic compatibility (EMC) of L-DACS with on-board equipments in an aircraft. The EMC in both airborne and ground environments is an essential criterion without which the technology can never be deployed.

Hence, a main challenge for the L-DACS candidates is the Radio-frequency Compatibility (RFC) with all the legacy systems already using the L-band. One of them is the Distance Measuring Equipment (DME), which operates in the 960-1215 MHz frequency band. A recent work shows that, under the conventional EMC approach, i.e. assuming continuous L-DACS2 transmission and considering only frequency domain aspects, L-DACS2 could cause harmful interference on DME.

In this paper, we propose a deep analysis on the RFC of L-DACS2 and DME under realistic constraints. The idea is to study the time domain characteristics of both systems to evaluate the real impact of a L-DACS2 transmitter over a DME receiver. The results are presented in terms of the collision rate and its effect on the DME performance on the co-site scenario (same airplane), which is the most harmful case due to the systems proximity. Computer simulations and laboratory measurements were performed at Supélec with a commercial DME unit.

The RFC is the EMC between different radio systems, at their antenna ports.
This paper is organized as the following. First, in the Section II, we present L-DACS2 and DME systems and their time domain signals. After that, in the Section III, we explain our approach to represent the co-site interference situation. Then, in the Section IV, we implement this specific scenario using Matlab simulations and laboratory measurements. Finally, in the section V, we present and discuss the obtained results with respect to the L-DACS2 channel occupation rate and for different values of the signal to interference ratio.

II. L-DACS2 AND DME CHARACTERISTICS

The L-DACS2 [6] is a communication system which is expected to operate in the 960-975 MHz frequency band. It is widely inspired from the Global System for Mobile communications (GSM) system and is originated from two main standards: the All-purpose Multi-channel Aviation Communication System (AMACS) standard and the L-band Data Link (LDL) standard. The L-DACS2 employs a Gaussian Minimum Shift Keying (GMSK) modulation, its modulation index equals 0.5 and its $BT$ product equals 0.3 (where $T$ is the symbol duration ($T = 3.6923 \mu$s) and $B$ the 3 dB bandwidth). In addition, the system is based on the Time Division Duplex (TDD) technique. Each transmission cycle lasts one second and is based on messages exchanges between a Ground Station (GS) and a Mobile Station (MS) in its operational coverage. The information coming from the GS are transmitted via the Forward Link (FL) and those from the MS via the Reverse Link (RL). An L-DACS2 frame is divided into five sections, as shown in figure 1. The three sections LoG2, CoS1 and CoS2 are used only by the MS (respectively for connection, signalling and data messages) whereas the two remaining sections UP1 and UP2 are employed only by the GS. More specifically, each section of the frame is composed by smaller transmission units called basic slots. A one-second frame contains in total 150 basic slots and is based on an alternation between RL and FL messages.

The L-DACS2 communication is organized in five essential steps. First, the MS requests in LoG2 a connection to the serving GS. Second, the GS acknowledges this demand in the UP1 section of the next frame and allocates a slot to the MS for its signalling messages. In the third step, the MS indicates to the GS the section of the next frame and allocates a slot to the MS for its signalling messages. In the fourth step, the GS allocates a slot to the MS in the UP2 section and finally used by the MS to transmit its data to the GS in CoS2.

On the other hand, the DME is a radio navigation system which operates in the 960-1215 MHz frequency band and has been used for near a century. This system determines the slant distance between an airplane and a ground beacon through a succession of Gaussian pulse pairs. The frequency channel used by the airplane and the one employed by the ground beacon are separated by 63 MHz. According to its specifications [7], the DME transmitted signal consists of a maximum of 150 random pulse pairs per second. In each pair, the peaks of the two gaussian pulses are separated by at least $12 \mu s$ depending on the DME mode of operation. These signals are exchanged between an interrogator and a transponder to measure the distance between them.

The DME pulse pair expression is given by

$$x(t) = \exp(-\alpha t^2/2) + \exp(-\alpha(t - \delta t)^2/2),$$

where $t$ is the time in seconds, $\delta t$ is the interval between the two pulses of a gaussian pulse pair in seconds and $\alpha = 4.5 \times 10^{11} s^{-2}$ is such as the time difference between the two half amplitude points of a gaussian pulse equals $3.5 \mu s$. The figure 2 illustrates a DME gaussian pulse pair.

The DME communication starts on the interrogator that transmits a pulse pair stream to the transponder. Then, the transponder transmits back the received pair stream to the interrogator, with a certain delay. The airborne transceiver measures the time between transmission and reception, subtracts the delay, multiplies by the speed of light and divides by 2 to get its distance from the ground beacon.

III. SCENARIO REPRESENTATION

According to the International Telecommunication Union, both L-DACS2 and DME systems are foreseen to operate in the same frequency band. Thus, it is necessary to study the interference scenario between them when they use the same center frequency at the same time. This situation is called the co-channel mode. It is also important to evaluate the interference levels when both devices are located in the same airplane. This corresponds to the co-site scenario.

In this paper, we focus more particularly on the impact of a L-DACS2 interferer on a DME victim in the co-site case and co-channel mode. This scenario is the most critical situation for the RFC. First, the path loss is very low because of the proximity of both equipments. Second, the signals attenuation due to the transmitter and receiver spectral masks is minimal. Hence, the receiver is likely to suffer from the highest possible interference level from the transmitter.

To represent this scenario, we consider a DME interrogator and an L-DACS2 transmitter which are onboard of the same
The DME interrogator (called the victim) receives the summation of two signals: the useful signal coming from the DME transponder and the unwanted signal transmitted by the L-DACS2 equipment (called the interferer). The scenario is illustrated in Figure 3, and comprises three equipments: a DME interrogator (INT), a DME transponder (TRA) and a L-DACS2 transmitter (TX). The INT device comprises a receiver (the victim) and a transmitter (sending signals to TRA). The latter also comprises a receiver (getting signals from INT) and a transmitter (replying to these signals). To complete the scheme, two circulators are used to enable the switching functions of the two DME equipments. The interference process is emulated based on three main steps:

- In step 1, the DME interrogator INT generates a pulse pairs stream to the DME transponder TRA.
- In step 2, the DME transponder TRA transmits back the received stream to the DME interrogator INT.
- In step 3, the L-DACS2 TX interference is added to the DME transponder TRA transmission. The sum of both signals is then transmitted to the DME interrogator INT.

The DME system performance is related to the percentage of lost gaussian pulse pairs from step 1 to step 3. Because of the collision with the interfering L-DACS2 signal, some DME pairs sent by TRA in step 2 may not be received by INT in the step 3. As a result, the DME system performance degrades. When after a certain time delay (called the synchronization time), the interrogator receives in step 3 an insufficient percentage of the pair pulses compared to what has been transmitted in step 1, the synchronization between INT and TRA fails.

The longer the L-DACS2 signal is, the higher the DME performance degradation is. Our main contribution is to evaluate this degradation for different values of the L-DACS2 interfering signal, and with respect to the L-DACS2 channel occupation rate (related to the L-DACS2 signal duration).

IV. IMPLEMENTATION: SIMULATION AND MEASUREMENT

To emulate the scenario described above, we generate both L-DACS2 and DME signals for different transmission cases. Using these signals, we study the resulting interference based on two approaches: Matlab simulations and test bed measurements.

A. The transmission modes

Let us start by the L-DACS2 system. According to [6], two situations are possible within one L-DACS2 frame. Using the information given in the Section II, either the first or the second case occurs within one L-DACS2 frame. In the first case, the mobile station MS transmits a connection request (in the LoG2 section) whereas in the second case, the MS transmits its messages to the ground station to which it is already connected. A connected MS transmits fixed-duration signalization messages (in the CoS1 section) and variable-duration data messages (in the CoS2 section). These data messages contain between 1 and 10 basic slots, according to the L-DACS2 specifications. Table I depicts the time durations of the different possible MS signals within a L-DACS2 frame, where $N$ is the number of basic slots used for data message transmissions and $T$ the L-DACS2 symbol duration in seconds.

<table>
<thead>
<tr>
<th>MS Connection Status</th>
<th>Signal type</th>
<th>Duration ($\mu$s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not connected</td>
<td>Connection</td>
<td>$12 \times T$</td>
</tr>
<tr>
<td>Connected</td>
<td>Signalization</td>
<td>$301 \times T$</td>
</tr>
<tr>
<td>Connected</td>
<td>Signalization+data</td>
<td>$(301+1800 \times N) \times T$</td>
</tr>
</tbody>
</table>

We also study four situations for the DME interrogator: two different numbers of transmitted pairs per second, and two different time intervals between the two pulses in a transmitted pair. Based on the DME specifications [7], the DME interrogator transmits 150 pulse pairs per second in the search mode (when it is looking for a DME transponder in its coverage) and 30 pulse pairs per second in the track mode (once a connection is established with the DME transponder). The peaks of a single transmitted gaussian pulse pair are spaced by either 12 $\mu$s (X mode) or 36 $\mu$s (Y mode).

B. The simulation approach

We first implemented the scenario presented in the Section III through Matlab simulations. To study the DME performance degradation, we need to model the DME receiver. As such a model is not available so far in the literature, our idea is to assume that a DME pulse pair is lost (or not received) if it overlaps with the L-DACS2 signal. Under this assumption, the parameter to be studied is the collision rate between L-DACS2 and DME messages in the received signal of step 3.

We also assume that the DME transponder is perfect, which means that all the received pairs from the DME interrogator are retransmitted. Under these conditions, we can determine the maximum collision rate between L-DACS2 and DME signals for each type of L-DACS2 transmitted message and each transmitting mode of the DME transponder.

To get the collision rate, we generate the DME and L-DACS2 signals in a time window depending on the DME synchronization time [7]. Both signals are randomly created each second as follows. Each L-DACS2 signal is a rectangular time window whose width is the total signal duration, given by Table I. We recall that the L-DACS2 signal is either a LoG2 message or a CoS1 and CoS2 message, and respects the frame structure (see figure 1). The same process is applied for each DME gaussian pair, which means that the DME signal is represented by a succession of 30 (150, respectively) rectangular shapes of duration 15.5$\mu$s (29.5$\mu$s, respectively). In this case, the collision rate is defined by the proportion of DME pairs that overlap with the L-DACS2 signal.

C. The experimental approach

In addition to the simulations, we implemented our interference scenario through a laboratory test-bed at Supélec.

According to figure 3, the test-bed is composed by three devices. The interrogator is a commercial DME Bendix KN62A device and the transponder is a commercial DME Aeroflex IFR6000 Ramp test. In addition, the L-DACS2 transmitter is a vectorial generator Agilent E4438C ESG.
The DME signal at the interrogator is completely determined once a carrier is selected by the user. According to the tables specified in [8], this carrier (between 108 and 118 MHz) gives the transmission frequency channels of both interrogator and transponder transmitted signals as well as the separation between the two peaks of a single gaussian shape. The signals follow the equation 1 and the transmission frequencies are included in the 960-1215 MHz band.

On the other hand, to represent the interference, we need to create the interfering L-DACS2 signal. For this, we generated the L-DACS2 waveform in a computer using Matlab and taking into account the information given in the section II. We injected the obtained signal into the vectorial generator through a specific software, the commercial Agilent N7622A Signal Studio Toolkit. This tool imports the analog baseband L-DACS2 waveform (In-phase and Quadrature data files), controls the signal generator parameters such as the frequency carrier, the signal amplitude and its modulation, and adjusts the sample clock of the generator to avoid the distortions and discontinuities on the injected signal.

We created the baseband L-DACS2 signal similarly to the scheme detailed in [9] starting from a Non-Return-to-Zero (NRZ) binary data stream. This signal is GMSK modulated, which means that its expression follows equation 2:

\[ s(t) = A \exp(2j\pi f_c t + jh\pi \theta(t)), \]  
\[ A \] is the amplitude of the signal, \(f_c\) its frequency carrier, \(h\) its modulation index and \(\theta\) its instantaneous phase, given by equation 3:

\[ \theta(t) = \theta_0 + g(t) \ast i(t), \]  
\(\theta_0\) is the initial phase and \(\ast\) is the convolution between the input NRZ signal \(i(t)\) and the normalized modulating gaussian filter \(g(t)\) defined by equation 4:

\[ g(t) = \sqrt{\frac{2\pi}{\log(2)}} BT \exp \left(\frac{-2(\pi BT)^2}{\log(2)} t^2\right). \]

\(B\) is the bandwidth of the modulating gaussian filter, \(T\) is the symbol duration and \(g(t)\) is normalized so that \(\int_0^\infty g(t) dt = 1\). The corresponding block diagram is given in the figure 4 and consists of four main stages:

- First, the digital NRZ sequence is transformed to an analog binary signal through a Digital to Analog Converter (DAC). For this, the NRZ stream is oversampled.
- Second, the analog signal is convoluted with a gaussian filter, which \(BT\) product is the same as mentioned in the section II.
- Third, the filtered signal is integrated to obtain the phase of the modulated baseband signal.
- Finally, the In-phase (I) and Quadrature (Q) analog data streams are created by applying trigonometric transformations to the modulated phase.

The I and Q baseband stream are determined by equations 5 and 6, respectively:

\[ I(t) = A \cos(h\pi \theta(t)), \]  
\[ Q(t) = A \sin(h\pi \theta(t)). \]  

They are provided in figure 5 for an eight symbol input NRZ binary sequence. The baseband L-DACS2 stream is the complex signal which real and imaginary parts are I and Q, respectively. The power of this signal is consequently constant.

**V. RESULTS AND DISCUSSION**

We first present the simulation results. According to its specification [8], the DME interrogator should synchronize within two seconds. Using Monte Carlo approach, we generate both L-DACS2 and DME signals randomly each second and we compute the channel occupation rate every two seconds. We considered that the DME synchronization fails if the percentage of lost DME pairs at the interrogator is higher than 30%. Based on the assumption that a DME pulse is lost when it overlaps with the L-DACS2 signal, the simulation results do not depend on the L-DACS2 interference level. Figure 6 illustrates the probability of DME synchronization success with respect to the L-DACS2 channel occupation rate for the four DME transmission modes. It shows that when the channel occupation rate is higher than 15%, the synchronization may fail for the search mode. For the track mode, where the DME stream becomes shorter in time, the synchronization failure occurs when the L-DACS2 channel occupation rate is higher than 30%.

For the experimental results, we considered that when the DME interrogator is synchronized, its screen indicates, as shown in figure 7, its carrier (on the left) and its slant distance from the transponder (on the right). The DME synchronization succeeds if before the synchronization time expires, the distance is displayed. To perform the measurements, we selected the 108 MHz carrier for the DME interrogator. Hence, the transmission frequency of the interrogator and the transponder are 1041 MHz and 978 MHz, respectively. To study the L-DACS2 interference in the co-channel mode, the carrier of the L-DACS2 signal is equal to 978 MHz.

As the DME synchronization failure may depend on the L-DACS2 interference level, we carried out the study for different values of the Signal to Interference Ratio (SIR). We defined the SIR as the ratio of the useful peak power over the interference peak power. The useful power is transmitted by the DME transponder (in step 2) whereas the interference power is transmitted by the L-DACS2 generator (in step 3). For the measurements, we fixed the useful power and we took different values for the L-DACS2 interference power. We set the power...
of the transponder such as the useful received power at the interrogator equals -80 dBm (close to the DME equipment sensitivity). As the power of the L-DACS2 signal is constant during the analyzing time window, the SIR does not change once defined the L-DACS2 power in Signal Studio Toolkit. For each value of the SIR, we progressively increased the L-DACS2 channel occupation rate from 0% to 100% using the pulse function provided by the vectorial generator and we determined the rate above which the DME synchronization is lost. Figure 8 shows the observed DME synchronization success state with respect to the L-DACS2 channel occupation rate and for two values of the SIR. This state equals one in case of success and zero unless. It emphasizes that to keep successful the DME synchronization for at least a -80 dB SIR, the L-DACS2 channel occupation rate should be less than 60%.

These two figures emphasize that the DME synchronization is successful when the L-DACS2 channel occupation rate is less than 15%, even for the very bad values of the SIR. Actually, for low L-DACS2 channel occupation rates, both simulation and measurement results show that the collision rate between L-DACS2 and DME is statistically very low, which means that the interferer and the victim are functioning during distinct time intervals. In such a situation, the interference level decreases significantly.

For higher L-DACS2 channel occupation rates, the collision rate increases as shown by the simulations. However, when the SIR is sufficiently good (higher than -20 dB), the L-DACS2 would not cause harmful interference on the DME, when its channel occupation rate remains lower than 90%.

Now, taking into account the specifications of both systems, the maximal L-DACS2 channel occupation rate equals 6.7%. This corresponds to the longest L-DACS2 signal duration, where a connected mobile station uses the maximum allowed number of slots in the CoS2 section, i.e. ten slots each second (see table I). For all the other L-DACS2 transmission modes, the signal duration is lower and so is the channel occupation rate. Hence, in the aeronautical onboard environment presented herein, the DME would not suffer from any penalty from the L-DACS2 interference if the SIR is higher than -80 dB.

VI. CONCLUSION

In this paper, we studied the impact of an L-DACS2 transmitter on the DME system performance in the co-site scenario (same airplane) and the co-channel situation (simultaneous use of the same center frequency). For this, we created the L-DACS2 time domain signal. We proved by both simulations and measurements in our aeronautical test-bed that taking into account the time domain characteristics of both systems, the L-DACS2 interference would not cause harmful interference on the DME system with a SIR higher than at least -80 dB. A good RFC level between L-DACS2 and DME is achieved because during a given time slot, only one of them transmits or receives signals. Actually, this condition may be not permanently satisfied as a large number of systems are implemented within the same airplane. In this more complex environment, the use of more complicated interference mitigation techniques, such as common suppression buses (already deployed for several aeronautical systems) seems necessary to avoid the unwanted phenomena. Finally additional tests with other DME interrogators will be necessary to support these first results.

REFERENCES