Feasibility of the Frequency Planning for LDACS Air-to-Air Communications in the L-band

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***Abstract*—The 960-1215 MHz frequency range in the L-band is allocated worldwide on a primary basis to the aeronautical radio navigation service (ARNS). At the World Radio Conference 2007, the frequency range 960-1164 MHz within the L-band was additionally allocated to the aeronautical mobile (route) service (AM(R)S) on a co-primary basis to allow future communication systems to share large parts of the L-band with the existing radio navigation services. The L-band digital aeronautical communications system (LDACS) will operate its air-ground (A/G) and air-to-air (A2A) data links under AM(R)S allocation in the L-band ensuring spectrum sharing without mutual harmful interference. In this paper, we propose a frequency planning methodology for the LDACS A2A data link yielding no harmful interference towards the legacy systems operating in the L-band. We also assess the feasibility of the LDACS A2A frequency planning in the north-east coast of North America, the North Atlantic Corridor, and western Europe. Our results indicate that LDACS A2A can operate in the 960-1164 MHz frequency range without affecting the proper operation of the legacy systems. Whilst the available spectrum is maximized in oceanic airspace and reduced in continental airspace, LDACS A2A can employ numerous frequency channels in most locations. The lower part of the L-band presents the most promising results, as LDACS A2A can operate there in any considered location. In fact, the lowest frequencies can be used anywhere in the considered region, which might allow LDACS A2A to have a globally available frequency channel for its operation.**

***Index Terms*—LDACS, A2A, Frequency Planning, Cell Planning, DME, TACAN, L-band**

I. INTRODUCTION

Air traffic management (ATM) is being modernized worldwide, e.g., under the SESAR [1] framework in Europe and NextGen [2] in the USA, to sustain air traffic growth by providing new services and operational concepts. Some of these services require the availability of an air-to-air (A2A) data link capable of exchanging data directly between aircraft. As discussed in [3], currently available A2A data links are already reaching saturation and are not expected to be capable of supporting the new data intensive applications and concepts. These are to be supported by the extension towards A2A communications of the L-band digital aeronautical communications system (LDACS). Whilst the LDACS air-ground (A/G) component has already been developed [4], demonstrated in flight trials [5], and is currently undergoing the standardization process within the International Civil Aviation Organization (ICAO) [6], the LDACS A2A data link is currently being developed within the German national project IntAirNet co-funded under the German aviation research program LuFo ("Luftfahrtforschungsprogramm").

LDACS shall operate in the 960-1164 MHz frequency band under co-primary aeronautical mobile (route) service (AM(R)S) allocation. Since this part of the L-band is allocated on a primary basis to the aeronautical radio navigation service (ARNS), LDACS is only allowed to operate in this frequency band if the existing ARNS systems are not harmfully interfered. Given that some of these systems occupy most of the 960-1164 MHz frequency range, a careful frequency planning must be conducted for LDACS in order to find the frequency channels that LDACS can use in each region without affecting the proper operation of the ARNS systems. The feasibility of the frequency planning for LDACS A/G has been assessed in [7]. Based on the results, the 964-1010 MHz and 1110-1156 MHz frequency bands have been proposed for allocation to the LDACS A/G reverse and forward links, respectively.

In this paper, we propose a frequency planning methodology for LDACS A2A, that can also be applied to the LDACS A/G reverse link, and that yields no interference towards the ARNS systems operating in the L-band. We apply the proposed methodology to assess the feasibility of the frequency planning for LDACS A2A in the L-band under the constraint of avoiding harmful interference to legacy L-band systems. This work contributes to the development of LDACS A2A by analyzing the possible frequency bands where LDACS A2A might operate in the region of interest. After assessing how different operating parameters influence the spectrum availability of LDACS A2A, we derive recommendations for its design.

The paper is structured as follows. In Section II, we describe the LDACS communications system, including the A/G and A2A components, as well as the legacy systems operating in the L-band that have to be taken into account in the LDACS A2A frequency planning. We discuss the methodology for the frequency planning in Section III, including the mathematical model, the compatibility criteria, and the databases employed in our analysis. The results of the frequency planning are shown in Section IV and the conclusions are drawn in Section V.

II. LDACS A/G AND A2A

LDACS is a cellular point-to-multipoint communications system, where each ground station (GS) serves airborne stations (ASs) located within a certain volume of space called cell [4]. Once the AS is connected to a GS, it gains access to the aeronautical telecommunication network (ATN) and becomes capable of communicating with other ATN users, such as air traffic control centers or other ATM entities.

LDACS is limited to regions where the GSs can be deployed. Consequently, it will not be possible to give direct support to aircraft operating in oceanic, remote, and polar (ORP) regions in its current state. This is to be solved by the LDACS extension towards A2A communications, hereinafter denoted as LDACS A2A, which shall extend the coverage of LDACS towards ORP regions by using intermediate ASs as relays. In other words, LDACS A2A will allow ASs to communicate directly with each other and, if needed, to relay messages towards and from the GSs. This way, even ASs operating in regions without ground infrastructure will have access to the ATN network by using both LDACS A2A and LDACS A/G components of LDACS. In fact, one of the main objectives in the design of LDACS A2A is to extend the LDACS coverage to the aircraft flying in the North Atlantic Corridor between North America and Europe.

Altogether, LDACS A2A could be seen as a communications, navigation, and surveillance (CNS) system. In addition to extending the LDACS A/G coverage, there are many other applications for LDACS A2A. First, LDACS A2A can be used for any application requiring direct communications between aircraft. For example, aircraft could use LDACS A2A to disseminate events and useful information, such as weather reports, among other aircraft, as well as to back up the flight recorder content on other aircraft, which would help reacting to aircraft incidents and clarifying them swiftly. Second, aircraft could navigate using LDACS A2A. For example, an AS could estimate its position by using pseudo-range multi-lateration from LDACS A2A transmissions from other aircraft with a good position estimation, e.g., derived from a Global Navigation Satellite System (GNSS) or from the LDACS A/G system. Third, LDACS A2A can be used for surveillance in an ADS-B (Automatic Dependent Surveillance - Broadcast) fashion. Each AS can broadcast useful information, such as identification, position, and velocity vectors. This information is picked up by neighbouring aircraft to be aware of its presence and act accordingly. This would allow aircraft to maintain a minimum separation with other aircraft and to coordinate trajectories with them.

LDACS A2A will operate in the 960-1164 MHz aeronautical frequency band following the World Radiocommunication Conference allocation for AM(R)S [8]. In order to communicate with other aircraft, an LDACS A2A station will require, at least, one frequency channel. Ideally, this channel would be available worldwide. Additional frequency channels might be used dynamically to achieve the data throughput required by the aforementioned applications. However, the 960-1164 MHz frequency band is already being employed by ARNS systems, including the distance measuring equipment (DME) and the tactical air navigation system (TACAN), both providing the slant range between an interrogating airborne station, i.e., the interrogator, and a responding ground station, i.e., the transponder. These systems employ frequency channels spaced 1 MHz apart and spanning most of the aeronautical L-band. Thus, LDACS A2A might have to share a part of the spectrum with DME and TACAN. This is already done by LDACS A/G, which operates its reverse link in the 964-1010 MHz frequency band and its forward link in the 1110-1156 MHz frequency band. LDACS A/G can still operate in the shared spectrum given that each DME/TACAN transponder only employs a pair of frequency channels to communicate with the interrogators in its coverage range. Thus, the frequency channels not used in a certain region might be employed, in principle, by the LDACS A/G stations deployed in that region. More specifically, LDACS A/G stations operating in a certain region will be able to use certain frequencies if minimum frequency and distance conditions with the DME/TACAN operations are guaranteed. The subset of frequency channels that can be used in each region, or location, is obtained by applying frequency planning ensuring no harmful interference towards the other systems. Given that LDACS A2A will, most likely, have to share spectrum with DME and TACAN systems, a similar frequency planning as the one conducted for LDACS A/G will have to be applied in order to guarantee the interference-free operation of all systems.

Although DME and TACAN are considered to be the main users of the aeronautical L-band, additional communications, navigation, and surveillance systems operate in this band and must be taken into account in the LDACS A2A frequency planning. Several surveillance systems operate at the 1030 MHz and 1090 MHz frequencies, including the secondary surveillance radar (SSR), the traffic alert and collision avoidance system (TCAS), and the ADS-B service. In addition, although it is not used broadly, the universal access transceiver (UAT) system operates at 978 MHz. Another user of the L-band is the JTIDS/MIDS military communications system, which uses pseudo-random frequency hopping to quickly switch among 51 frequency channels distributed in three sub-bands between 969 MHz and 1206 MHz [9]. In addition, in order to protect the radionavigation satellite service (RNSS) operating in the upper part of the L-band, the ITU Resolution 417 restricts the maximum equivalent isotropic radiated power (EIRP) that an AM(R)S system can employ in the 960-1164 MHz frequency band [10].

In this work, we first define and conduct a frequency planning yielding the frequency channels that can be used by LDACS A2A without affecting the operation of DME and TACAN. Then, we show and analyze the results of the frequency planning for different candidate LDACS A2A frequency bands, taking into account the other systems operating in the L-band and the ITU Resolution 417.

III. FREQUENCY PLANNING

The objective of the frequency planning for LDACS is to find a frequency, or a set of frequencies, that can be used by the LDACS stations in each region without any interference with the DME/TACAN operation. As different contributions have shown that LDACS can cope with DME/TACAN interference if suitable interference mitigation schemes are employed [11], our frequency planning only focuses on finding the frequencies that yield no interference from the LDACS stations towards DME/TACAN. To simplify the notation, we only refer to DME hereinafter, although we equally consider TACAN.

The frequency planning conducted in this work is based on the cell planning strategy defined for LDACS A/G in [7]. In contrast to the work conducted in [7], where mainly the LDACS transmissions from LDACS ground stations were taken into account, we consider the transmissions from LDACS airborne stations, i.e. from the aircraft. Therefore, our strategy can be applied to the frequency and cell planning of LDACS A2A and of the LDACS A/G reverse link.

A. Compatibility Criteria

Our strategy is based on the fact that DME and LDACS can operate simultaneously and in the same region if the desired-to-undesired signal power ratio, hereinafter denoted as D/U ratio, is maintained in any case above a certain D/U compatibility threshold. If we consider the interference from LDACS towards DME, then our frequency planning has to guarantee that the D/U ratio (in this case, DME-to-LDACS signal power ratio) at any DME receiver will always stay above the D/U compatibility threshold. This threshold can be obtained by conducting compatibility measurements between DME and LDACS, and generally varies with the frequency separation between the DME and LDACS transmissions. Let us denote the measured D/U threshold for compatibility between LDACS and DME as $D/U_{th,T}(\Delta f_T)$ for DME transponders, and as $D/U_{th,I}(\Delta f_I)$ for DME interrogators.

B. Signal Propagation Model

Let us first consider a wireless radio transmission at a frequency f between two stations separated by a distance d. The signal transmitted by one station is received by the other station with a signal power denoted by P_{rx}, which can be obtained as

$$P_{rx}[\text{dBW}] = EIRP[\text{dBW}] - L_p(d,f)[\text{dB}] + G_{rx}[\text{dBi}] - L_{rx}[\text{dB}], \quad (1)$$

where the EIRP is obtained as

$$EIRP[\text{dBW}] = P_{tx}[\text{dBW}] + G_{tx}[\text{dBi}] - L_{tx}[\text{dB}], \quad (2)$$

and $L_p(d,f)$ represents the path losses for a distance d and a signal frequency f. G_{tx} and G_{rx} denote the gains of the transmitting and receiving antennas, respectively, and L_{tx} and L_{rx} represent the losses between the radio and the antenna of the transmitter and of the receiver, respectively. Assuming free-space signal propagation and radio line-of-sight (LOS) between transmitter and receiver, we can estimate the path losses as

$$L_{p,los}[\text{dB}] = 20\log_{10}(d[\text{km}]) + 20\log_{10}(f[\text{MHz}]) + 32.45\ \text{dB}. \quad (3)$$

However, given the earth curvature, long-range communications are generally blocked by the earth from a certain distance known as radio horizon. The radio horizon $r_h(h_{tx}, h_{rx})$ depends on the altitude of the transmitter, i.e., h_{tx}, and of the receiver, i.e., h_{rx}, and can be estimated as

$$r_h[\text{km}] = 130.4\left(\sqrt{h_{tx}[\text{km}]} + \sqrt{h_{rx}[\text{km}]}\right), \quad (4)$$

assuming a earth radius of 6378.137 km and scaling it by a factor of 4/3 to account for the signal refraction in the atmosphere. From the radio horizon, a signal attenuation of 1.6 dB per nautical mile (NMi), i.e., $a = 1.6$ dB/NMi, can be expected in the L-band. Therefore, we can obtain the path losses $L_p(d, f, h_{tx}, h_{rx})$ more generally as

$$L_p[\text{dB}] = \begin{cases} L_{p,los}(d,f) & \text{if } d \le r_h \\ L_{p,los}(r_h,f) + a\cdot(d-r_h) & \text{if } d > r_h \end{cases}. \quad (5)$$

Considering now the interference from LDACS towards DME, we can obtain the D/U ratio of a DME communication interfered by an LDACS transmission as

$$D/U\ [\text{dB}] = D\ [\text{dBW}] - U\ [\text{dBW}], \quad (6)$$

where D and U can be obtained using (1) for DME and LDACS parameters, respectively. The D/U ratio is obtained slightly differently for the DME transponders and the DME interrogators.

C. Location of DME Transponders and Interrogators

In order to conduct the frequency planning, the geographical location of the DME transponders is required, as well as some parameters of the DME transponders, such as the employed frequency channels, EIRP, and coverage region. This information is publicly available for some regions of the world. For example, the ICAO updates regularly the so-called COM3-Table, which contains this information for a part of Europe.

In contrast with the DME transponders, the DME interrogators are installed in the aircraft and can move arbitrarily. Therefore, their position cannot be predicted in advance but a worst-case position must be considered in the frequency planning. Following our approach based on the D/U ratio, the worst-case location of the DME interrogator will be the position where it is affected by the lowest D/U ratio.

D. Obtaining the D/U Ratio for DME Transponders

In this case, we consider that a DME transponder at an altitude h_T is receiving a transmission from a DME interrogator at a frequency f_T. In addition, it receives simultaneously an LDACS transmission at a frequency f_L from an LDACS station at an altitude h_L. The distance d_L between the DME transponder and the LDACS station can be obtained easily, as the positions of both stations are known. The position of the

LDACS station and its transmit frequency are input parameters for the frequency planning.

Using (6), we can obtain the D/U ratio for DME transponders using a DME signal power of $D = -96$ dBm. This is the minimum signal power at which long-range DME transponders must still be able to reply to an interrogation [7]. The power of the LDACS signal is obtained as

$$U_T[\text{dBm}] = EIRP_L[\text{dBm}] - L_p[\text{dB}] + G_T[\text{dBi}] - L_T[\text{dB}], \quad (7)$$

where $EIRP_L$ represents the EIRP of the LDACS station, L_p the path losses, G_T is the DME antenna gain at the direction of arrival of the LDACS transmission, and L_T represents the losses between the antenna and the radio of the receiving DME station. Whilst L_p is obtained using (5), we assume a maximum antenna gain $G_T = 9.1$ dBi [7] and no losses, i.e., $L_T = 0$ dB, which are conservative assumptions in favor of the DME system.

The LDACS station can operate without affecting the operation of the DME transponder if

$$D/U_T = -96 - U_T[\text{dBm}] \geq D/U_{th,T}(\Delta f_T) + \zeta \quad (8)$$

is fulfilled, where $\Delta f_T = f_T - f_L$, and ζ is a safety margin considered for the frequency planning. We use $\zeta = 10$ dB in our analysis.

E. Obtaining the D/U Ratio for DME Interrogators

In this case, we consider a DME interrogator receiving a transmission at a frequency f_I from a DME transponder. The DME interrogator is located within the coverage range of the DME transponder, at an altitude h_I and a distance d_I to the transponder. The LDACS station transmits at a frequency f_L and flies at an altitude h_L. The distance between the LDACS station and the DME interrogator is denoted by d_L.

The D/U ratio can be obtained as

$$\begin{aligned} D/U_I &= (EIRP_T - L_p(d_I, f_I) + G_I - L_I) \\ &\quad - (EIRP_L - L_p(d_L, f_L) + G_I - L_I) \quad (9) \\ &= EIRP_T - EIRP_L - (L_p(d_I, f_I) - L_p(d_L, f_L)), \end{aligned}$$

where we assume that the DME interrogator has the same antenna gain and receiver losses for both signals. If the interrogator is also within the LOS of the LDACS station, the D/U ratio simplifies to

$$D/U_I = EIRP_T - EIRP_L - 20\log_{10}\left(\frac{f_I}{f_L}\right) - 20\log_{10}\left(\frac{d_I}{d_L}\right). \quad (10)$$

We have to guarantee that no DME interrogator within a certain DME cell is affected by the LDACS operation at a certain frequency and location. Thus, we obtain the minimum D/U ratio that a DME interrogator can experience anywhere in the cell, and compare it with the minimum D/U ratio required for compatibility. This could be done by obtaining the D/U ratio for each position in the cell. However, it can be simplified by distinguishing two cases depending on the location of the LDACS station. First, when the LDACS station is outside the DME cell, the minimum D/U ratio is found when the DME interrogator is on the DME cell border closest to the LDACS station. The exact location on the border can be found by obtaining the D/U ratio for different altitudes h_I between the minimum altitude $h_{I,min}$ and the maximum altitude h_{DME} considered. We use $h_{I,min} = 1000$ feet in our analysis. The maximum altitude h_{DME} is given by the maximum coverage altitude of each DME cell. Second, when the LDACS station is inside the DME cell, the minimum aircraft separation becomes the deciding factor. The minimum D/U ratio is observed in the close vicinity of the LDACS station at the position maximizing d_I/d_L but still guaranteeing the minimum horizontal and vertical separation, i.e., Δd_h and Δd_v, respectively. Although the minimum separation between aircraft depends on the airspace regulations, we use $\Delta d_h = 2.5$ NMi and $\Delta d_v = 1000$ feet in our frequency planning as a simplification. Note that higher separations leading to less stringent interference conditions, i.e., higher minimum D/U ratio, are expected in general.

The LDACS station can operate without affecting the operation of any DME interrogator operating in the DME cell if

$$min(D/U_I) \geq D/U_{th,I}(\Delta f_I) + \zeta \quad (11)$$

is fulfilled, where $min(D/U_I)$ is the minimum D/U ratio for any location within the DME cell, and $\Delta f_I = f_I - f_L$.

F. DME-Compatible LDACS A2A Frequency Planning

The operation of LDACS A2A at a certain location, i.e., coordinates and altitude, and using certain transmission parameters, i.e., EIRP and transmit frequency, is considered to be compatible with DME if (8) and (11) are satisfied for all DME transponders and interrogators. In order to evaluate this condition, we first load the information of the DME transponders, including their location, i.e., coordinates and altitude, coverage range R_{DME}, coverage altitude h_{DME}, EIRP, and frequency channels. Then, we iterate over each transponder and evaluate (8) and (11). If both conditions are fulfilled for all DME transponders and, consequently, for all DME interrogators, the LDACS position and transmission parameters are compatible with DME. We then iterate over all the positions and transmission parameters of the LDACS station that we want to evaluate.

G. DME/TACAN Database and D/U Thresholds for Compatibility

The DME/TACAN information used for our frequency planning is extracted from different sources. For Europe, we use the so-called COM3 table officially published by ICAO, which contains the information of the pan-European DME and TACAN transponders, including their coordinates, EIRPs, frequency channels, and coverage ranges and altitudes. For North America, however, we have not found a publicly available official DME/TACAN database. In order to conduct this frequency planning, the FAA provided us with a list of DME transponders deployed in North America, including their coordinates, EIRPs, frequency channels, and coverage ranges and altitudes. For Canada, we consider the DME transponders listed in [12]. Given that only the coordinates and frequency

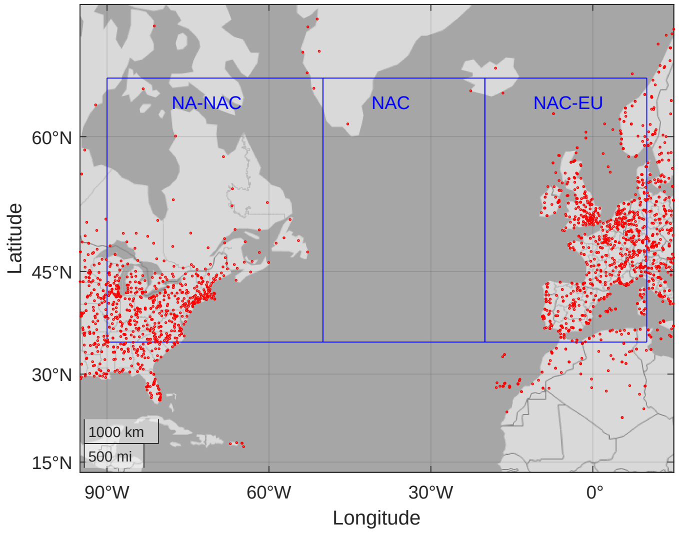
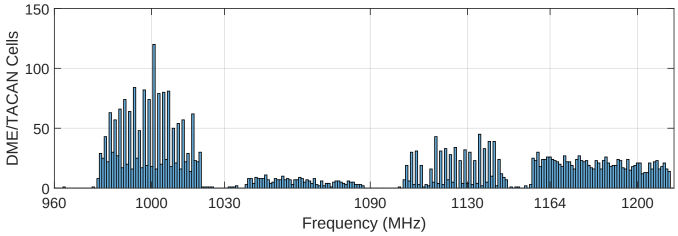
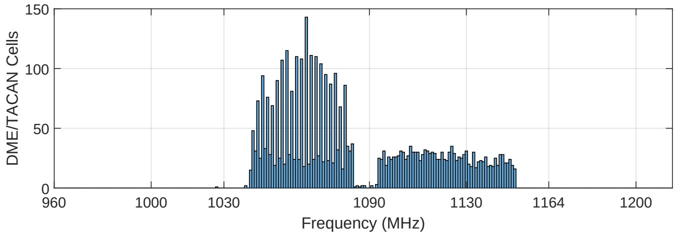


Fig. 1: DME/TACAN transponders (red dots) and region of interest (labelled blue rectangles) considered for the LDACS A2A frequency planning.



(a) Transmit frequencies of DME/TACAN transponders.



(b) Transmit frequencies of DME/TACAN interrogators.

Fig. 2: Number of considered DME/TACAN transponders using each frequency for transmissions (Fig. 2a) and receptions from interrogators (Fig. 2b).

channels are provided in [12], we assume that the DME transponders cover a range of 130 NMi up to an interrogator altitude of 60 000 feet with an EIRP of 100W. We additionally found in [13] a list of the DME and TACAN transponders deployed in Greenland, including their coordinates, frequency channels, and coverage ranges and altitudes. As no EIRP was provided, we consider 100W EIRP as a conservative assumption in favor of DME/TACAN. In addition, we assume $h_T = 10$ m for all DME/TACAN stations. Note that, as only a part of the DME/TACAN information has been extracted from an official database, this frequency planning should not be considered as final but as a best effort to assess the feasibility of a frequency planning for LDACS A2A.

We show in Fig. 1 the position of the DME and TACAN transponders considered in our frequency planning, as well as the three segments comprising the region of interest for our LDACS A2A frequency planning. Note that the DME and TACAN transponders located outside the region of interest are also taken into account in the frequency planning. Fig. 2 depicts the number of DME/TACAN transponders using a certain frequency for transmissions (Fig. 2a) and for receptions from DME/TACAN interrogators (Fig. 2b). As expected, most of the aeronautical L-band is used by DME/TACAN stations. In practice, only the lowest frequencies, i.e., between 960 and 978 MHz, and the frequencies around 1030 MHz and 1090 MHz, allocated to surveillance systems, are not widely used by DME/TACAN.

The minimum D/U signal power ratio required by DME/TACAN to operate correctly despite the LDACS A/G operation was estimated in several preliminary measurements conducted in the laboratory and presented in [14]. Given that no compatibility measurements between LDACS A2A and DME/TACAN are still available, and that the LDACS A2A transmissions are expected to be very similar to the transmissions in the LDACS A/G reverse link, we use the obtained measurement results as basis for our analysis. In addition to the LDACS A/G transmissions, these measurements also considered the background interference generated by other DME/TACAN and JTIDS/MIDS stations. Unfortunately, the evaluation of the measurement data showed that the background interference (without LDACS) used in the measurements had been unrealistically overdimensioned and could, in fact, disrupt the DME/TACAN operation even without LDACS. In addition, some limitations in the measurement setup prevented the analysis from yielding conclusive results for the low signal power domain. Consequently, the estimated minimum D/U ratios were considered to be too conservative in favor of DME/TACAN and new measurements, with a refined compatibility criteria, a realistic background interference and more sensitive measurement equipment, were regarded as necessary. Given that less stringent D/U thresholds are expected from the future compatibility measurements between LDACS and DME, we employ the preliminary minimum D/U signal power ratios to assess the feasibility of the LDACS A2A frequency planning even under unrealistically strict conditions.

Table I contains the preliminary minimum D/U ratio $D/U_{I,th}$ required by the DME/TACAN interrogators to operate correctly. These values are based on the compatibility tests conducted between the reverse link of LDACS A/G and the receiving DME/TACAN interrogators. Note that the D/U threshold depends on the frequency separation Δf between the LDACS and DME/TACAN signals. In addition, one can see that the D/U threshold decreases very slowly for $\Delta f \geq 2$ MHz, which is partly caused by the low sensitivity of the employed measurement setup during the tests. For frequency separations higher or equal than Δf_{stop}, it is assumed that the LDACS transmissions do not affect the DME/TACAN operation, regardless of the D/U signal power ratio. Unfortunately, Δf_{stop} could not be measured in the conducted compatibility tests because of the limiting measurement setup. Therefore, we assume $\Delta f_{stop} = 20$ MHz in our frequency planning.

Given that the maximum frequency of the LDACS A/G reverse link is 1010 MHz, and we can see in Fig. 2b that the minimum receive frequency of the DME/TACAN transponders is much higher, i.e., above 1030 MHz, no compatibility measurements were conducted between the LDACS A/G reverse link and the DME/TACAN transponders as receivers. Consequently, we employ for our frequency planning the results of the compatibility measurements between the LDACS A/G forward link and the receiving DME/TACAN transponders. The preliminary minimum D/U ratio $D/U_{T,th}$ required by the receiving DME/TACAN transponders to operate correctly can be seen in Table II.

Considering that the employed minimum D/U signal power ratios are derived from the compatibility measurements between LDACS A/G and DME/TACAN, and that the conducted measurements have been regarded as unrealistically challenging for DME/TACAN, our frequency planning should not be regarded as final but as a first analysis of the feasibility of the LDACS A2A frequency planning. Nevertheless, the frequency planning methodology proposed in this paper can be applied to conduct the final LDACS A2A frequency planning when conclusive D/U thresholds and an official DME/TACAN database are available.

H. Compatibility with other systems operating in the L-band

Unfortunately, no compatibility criteria have been defined yet between LDACS and the systems operating at 1030 MHz and 1090 MHz, such as SSR. However, it can be assumed that a minimum frequency separation between those frequencies and the LDACS A2A frequencies should suffice to guarantee the compatibility. In fact, we can see that the frequency bands allocated to LDACS A/G are separated by, at least, 20 MHz to the 1030 MHz and 1090 MHz frequencies. If the same criteria is applied to LDACS A2A, we can expect LDACS A2A not to be allowed to operate between 1010 MHz and 1050 MHz, and between 1070 MHz and 1110 MHz. A similar approach could be expected for UAT, which operates at 978 MHz. In this case, however, the UAT operating frequency falls within the LDACS reverse link frequency band and no minimum frequency separation can be inferred from it.

Although the impact of LDACS A/G on JTIDS/MIDS has been assessed in [9], no compatibility criteria between LDACS A/G and JTIDS/MIDS have been defined so far. In addition, we have not found any information regarding either the location of fixed JTIDS/MIDS stations, or the national restrictions limiting the use of certain frequency channels. Consequently, we do not take JTIDS/MIDS into account in our frequency planning.

In addition, the ITU Resolution 417 safeguards the operation of the RNSS receivers by restricting the maximum EIRP that an AM(R)S system can use at certain frequencies. Given that the ITU Resolution 417 does not specify the maximum EIRP for pulsed transmissions, as the ones expected for LDACS A2A, we consider the maximum EIRP shown in Fig. 3 for non-pulsed transmissions as a worst-case assumption. Thus, for an EIRP of 41 dBm, the highest frequency that LDACS A2A would be allowed to use is 1128.1 MHz in the worst case. In order to have a more complete view of the spectrum availability for LDACS A2A, we first conduct the frequency planning without considering the ITU Resolution 417, and then take it into account in the discussion of the results and in the definition of the candidate frequency bands for LDACS A2A.

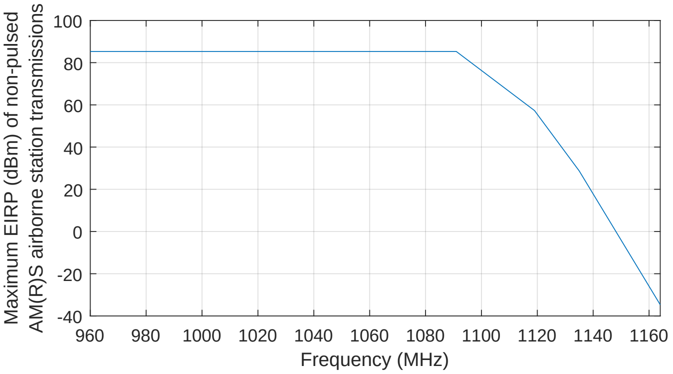


Fig. 3: Maximum EIRP of AMR(S) non-pulsed transmissions in the 960-1164 MHz frequency band according to the ITU Resolution 417 [10].

IV. RESULTS

We focus our analysis on the North Atlantic Corridor and its connecting American and European territories, i.e., northeast coast of North America and western Europe. We consider a region of interest limited by a longitude between 90°W and 10°E, and a latitude between 35°N and 65°N. We divide this region into the three segments shown in Fig. 1: *NA-NAC* for longitudes between 90°W and 50°W, *NAC* for longitudes between 50°W and 20°W, and *NAC-EU* for longitudes between 20°W and 10°E.

In order to conduct the frequency planning, we define the set of positions where the aircraft carrying the LDACS A2A radio can be located. We divide the region of interest into a latitude-longitude grid with 0.1° steps. For each location, we consider different LDACS airborne station altitudes $h_L = (1, 3, 6, 9, 12, 15, 18)$ km. As the frequencies to be used by LDACS A2A have not been decided yet, we initially assume that it might operate anywhere in the aeronautical L-band between 960 and 1164 MHz. In addition, we consider a 0.5 MHz frequency grid as the one considered for LDACS A/G. Thus, the candidate frequency channels for the LDACS A2A frequency planning are centered at $f_L = (960, 960.5, 961, ..., 1163.5, 1164)$ MHz. We initially assume an LDACS A2A EIRP of 41 dBm, i.e., $EIRP_L = 41$ dBm, which is the expected value given in the LDACS specification [4] for the LDACS airborne station.

We conduct the frequency planning described in Section III for the entire region of interest and show the results for each

TABLE I: Considered D/U threshold for receiving DME/TACAN interrogators [14].

$\|\Delta f\|$ [MHz]	0	0.5	1	2	3	4	5	10	$\geq 14 < \Delta f_{stop}$
$D/U_{I,th}$ [dB]	15	1	-20	-45	-49	-47	-45	-50	-52

TABLE II: Considered D/U threshold for receiving DME/TACAN transponders [14].

$\|\Delta f\|$ [MHz]	0	0.5	1	1.5	2	2.5	3	4	5	6	$\geq 7 < \Delta f_{stop}$
$D/U_{T,th}$ [dB]	13	16	6	-2	-5	-9	-14	-30	-41	-52	-57

one of the three segments separately. We first analyse the percentage of locations where each candidate frequency channel can be used at the different altitudes of the LDACS A2A transmitter. Fig. 4 shows the obtained results for the *NAC-EU* segment defined in Fig. 1. One can see that some frequencies, approximately between 1040 MHz and 1156 MHz, can only be used in some locations at certain aircraft altitudes. In general, less frequencies are available for high-flying LDACS A2A stations, which can be explained by their higher radio LOS (see (4)). As expected from Fig. 2, the frequencies around 1030 MHz and 1090 MHz yield practically no interference towards DME/TACAN. However, these frequencies are allocated to surveillance systems and a separate compatibility analysis should be conducted to assess whether LDACS A2A can operate around those frequencies. Likewise, we can see a small group of frequencies in the higher part of the L-band, i.e., around 1154 MHz, where LDACS A2A could operate in most regions without affecting DME/TACAN. However, this operation might not be feasible because of the ITU Resolution 417. The most interesting frequency band where LDACS A2A could operate in the *NAC-EU* region is the lower L-band, i.e., between 960 MHz and 1040 MHz, for multiple reasons. First, these frequencies are usable in more locations compared to higher frequencies. Second, the altitude of the LDACS A2A station does not affect significantly the number of locations where a frequency can be used. Third, it would be in line with the LDACS A/G allocation for the airborne station transmissions, i.e., 964-1010 MHz. Fourth, the 33 frequency channels between 960 MHz and 976 MHz can be used in more than 95% of the considered locations and, most importantly, the 15 frequency channels between 960 MHz and 967 MHz can be used anywhere in the *NAC-EU* region. These results are crucial for LDACS A2A, as they show that there is a subset of frequencies that do not require any further coordination with DME/TACAN, at least in the *NAC-EU* region and under the parameters of our analysis.

Fig. 5 shows the results of the frequency planning for the *NA-NAC* region (see Fig. 1). Comparing Fig. 4 and Fig. 5, we see that the results for both regions are generally quite similar. However, we observe that most frequencies, with the exception of the frequencies above 1137 MHz, are usable in more locations in the *NA-NAC* region than in the *NAC-EU* region. Again, the most promising frequency band for LDACS A2A is the lower part of the L-band between 960 MHz and 1040 MHz. In fact, the 37 frequency channels between 960 and 978 MHz can be used in more than 95% of the *NA-NAC* region. Moreover, the three frequency channels between 960 MHz and 961 MHz can be used anywhere.

Fig. 6 shows the results of our frequency planning for the

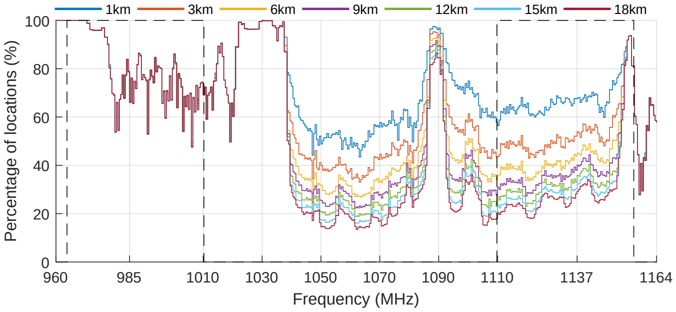


Fig. 4: Percentage of locations in the *NAC-EU* region where each frequency can be used by LDACS A2A without interfering the DME/TACAN operation. The different lines show the results for different LDACS A2A altitudes h_L. The black dashed line defines the LDACS A/G frequency bands.

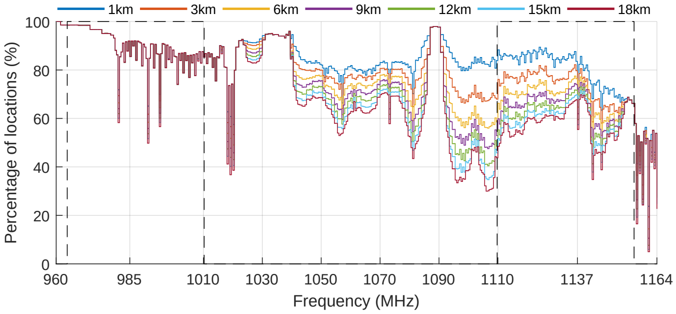


Fig. 5: Percentage of locations in the *NA-NAC* region where each frequency can be used by LDACS A2A without interfering the DME/TACAN operation. The different lines show the results for different LDACS A2A altitudes h_L. The black dashed line defines the LDACS A/G frequency bands.

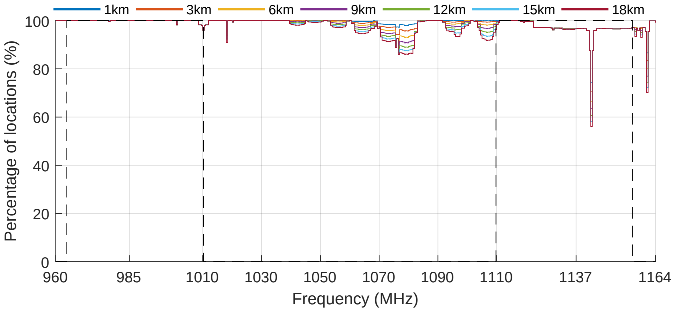


Fig. 6: Percentage of locations in the *NAC* region where each frequency can be used by LDACS A2A without interfering the DME/TACAN operation. The different lines show the results for different LDACS A2A altitudes h_L. The black dashed line defines the LDACS A/G frequency bands.

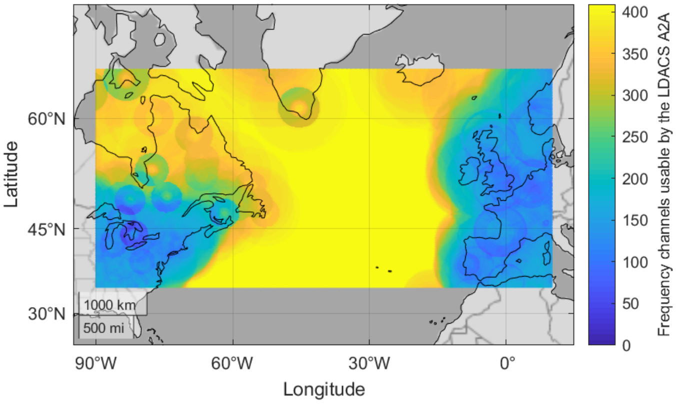


Fig. 7: Number of frequency channels between 960 MHz and 1164 MHz, in steps of 0.5 MHz, that LDACS A2A can use without interfering the operation of DME/TACAN.

North Atlantic Corridor, i.e., the *NAC* region (see Fig. 1). As expected because of the absence of DME/TACAN stations operating in the ocean, most frequencies can be used anywhere in the *NAC* region without affecting the operation of DME/TACAN. In fact, practically all frequency channels up to 1040 MHz are usable throughout the *NAC* region, and only a few frequencies are restricted in some locations close to the mainland.

Interestingly, the reverse link of LDACS A/G starts from a frequency of 964 MHz. However, we see in the results shown in Fig. 4-6, that the lower frequencies, i.e., 960-964 MHz, could be of great interest for the operation of LDACS A2A. These frequencies present the lowest impact towards DME/TACAN and they could be used almost everywhere within the entire region of interest. In fact, an LDACS A2A operation in a globally usable frequency channel might be possible at these frequencies. However, an LDACS A2A operation at the lowest frequencies might require to develop additional compatibility criteria between LDACS A2A and the mobile communication systems operating below 960 MHz. In addition, the importance of the lower part of the L-band for LDACS A2A stresses the need for specific compatibility criteria between LDACS A2A and UAT operating at 978 MHz.

In order to have a more complete view of the results of the LDACS A2A frequency planning for the entire region of interest, we now depict in Fig. 7 the number of frequency channels, between 960 MHz and 1164 MHz in steps of 0.5 MHz, that can be used by LDACS A2A without affecting the operation of DME/TACAN. For each location, we only consider the frequency channels that can be used at all considered altitudes, i.e., in the worst case. We can see in Fig. 7 the significant difference in the number of available frequency channels between the mainland regions and the North Atlantic Corridor, where most frequency channels can be used. Thus, the total spectrum available for the LDACS A2A stations would reach a maximum in the North Atlantic Corridor and decrease gradually as the airborne stations approach the mainland. Additionally, we see that LDACS A2A will be able to use numerous frequency channels in the transition between the oceanic and the continental airspace. This is an important result as LDACS A2A is expected to extend the LDACS A/G coverage towards oceanic, remote, and polar regions, and therefore a high throughput might be required in the transition regions for the LDACS A2A stations to act as gateways for the LDACS ground stations. In the continental airspace, we see that LDACS A2A can still use a significant amount of frequency channels.

Logically, LDACS A2A will also have to be compatible with the other systems operating in the L-band. As discussed in Section III, we assume that a frequency separation of 20 MHz between the LDACS A2A transmissions and the 1030 MHz and 1090 MHz frequencies is enough to guarantee the compatibility between LDACS A2A and the surveillance systems operating at those frequencies. In addition, we take into account the ITU Resolution 417 and assume that LDACS A2A might not be allowed to operate at a frequency above 1128.1 MHz if an EIRP of 41 dBm is used. These constraints are fulfilled if LDACS A2A operates in three discontiguous frequency bands: 960-1010 MHz, 1050-1070 MHz, and 1110-1128 MHz. Fig. 8 shows the number of frequency channels that LDACS A2A can use without affecting the operation of DME/TACAN if we restrict the LDACS A2A transmissions to these three frequency bands. Similarly to Fig. 7, we see that the number of available frequency channels is maximum in the oceanic airspace and reduces gradually as the airborne stations approach the mainland. The airborne stations flying in continental airspace will still be able to use a significant amount of frequency channels, especially in Europe. In the *NA-NAC* region, however, we find some locations where the number of frequency channels available for LDACS A2A is significantly lower than in other mainland regions. Fortunately, LDACS A2A can still employ at least 5 frequency channels in any considered location and altitude.

Considering now that LDACS A2A might only be able to operate in the frequency bands already allocated to LDACS A/G, we show in Fig. 9 the number of frequency channels available for LDACS A2A in the 964-1010 MHz and 1110-

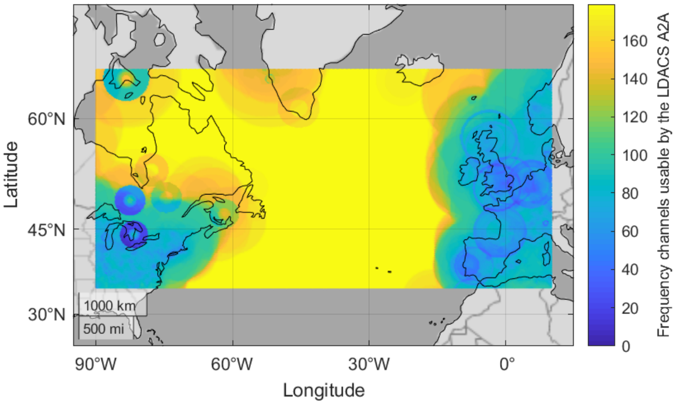


Fig. 8: Number of frequency channels that LDACS A2A can use without interfering the operation of DME/TACAN. In order to protect the operations at 1030 MHz and 1090 MHz and to fulfill the ITU Resolution 417 for non-pulsed AM(R) airborne station transmissions with an EIRP of 41 dBm, we only consider the frequency channels within three discontiguous frequency bands: 960-1010 MHz, 1050-1070 MHz, and 1110-1128 MHz.

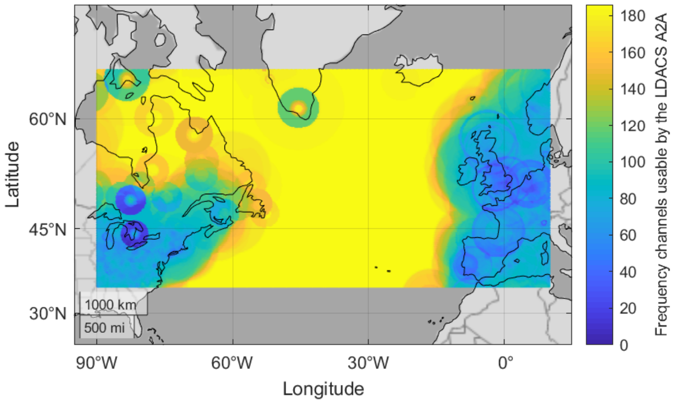


Fig. 9: Number of frequency channels in the LDACS A/G frequency bands, i.e, 964-1010 MHz and 1110-1156 MHz, that LDACS A2A can use without interfering the operation of DME/TACAN.

1156 MHZ frequency bands. We still observe that LDACS A2A will be able to operate using numerous frequency channels in any considered region. Even in the most challenging locations, LDACS A2A can still operate using, at least, 2 frequency channels. These results are very important for LDACS A2A as they indicate that, even under the many worst-case assumptions made throughout our analysis, LDACS A2A can still find frequencies to operate in any considered location and altitude. In reality, a higher number of usable frequency channels are expected, especially in the most challenging regions.

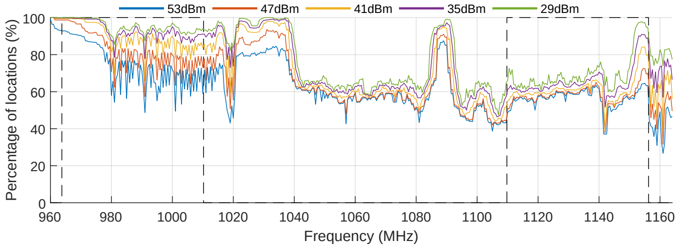


Fig. 10: Percentage of locations within the entire region of interest (including *NA-NAC*, *NAC*, and *NAC-EU* regions) where each frequency can be used by LDACS A2A without interfering the DME/TACAN operation. The different lines show the results for different LDACS A2A EIRPs. The black dashed line defines the LDACS A/G frequency bands.

Let us now assess how a different LDACS A2A EIRP affects the frequency planning. Fig. 10 shows the percentage of locations in the entire region of interest (including the *NA-NAC*, *NAC*, and *NAC-EU* regions) where LDACS A2A can use the frequency channels in the 960-1164 MHz frequency band at different EIRPs without affecting the operation of DME/TACAN. As expected, decreasing the EIRP increases the percentage of locations where a frequency channel can be used. In addition, we see that the frequencies below 1040 MHz generally profit more from the decrease in the EIRP than the higher frequencies. It is also important to notice that a decrease in the EIRP increases the number of frequency channels that can be used anywhere in the region of interest. This is very important for LDACS A2A as it indicates that the EIRP could be reduced in the most challenging locations to enable the LDACS A2A operation at certain frequencies of interest. Thus, we recommend LDACS A2A to be able to adjust its transmit power dynamically. This would allow LDACS A2A to profit from a higher EIRP, e.g., in order to increase its data throughput or communications range, in the less challenging regions, but to also be able to reduce the EIRP in order to use enough frequency channels in the most challenging regions.

Fig. 11 shows the minimum number of frequency channels available in a percentage of the locations for different LDACS A2A EIRPs and for different frequency bands. We can see in Fig. 11a the results for the 960-1010 MHz, 1050-1070 MHz, and 1110-f_{max} MHz frequency bands, where f_{max} is the highest frequency fulfilling the ITU Resolution 417 for each EIRP (see Fig. 3). One can clearly see that a lower EIRP yields more candidate frequency channels and, in any case, more usable frequency channels. Moreover, we see that the minimum number of frequency channels available in any location is 5 for the expected LDACS A2A EIRP of 41 dBm. It increases up to 7 and 42 for an EIRP of 35 dBm and 29 dBm, respectively, and decreases down to 3 and 0 for an EIRP of 47 dBm and 53 dBm, respectively. These results indicate that the EIRP could be reduced in order to find more frequency channels where LDACS A2A could operate in the most challenging regions. In addition, the results in Fig. 11a show that LDACS A2A will still be able to operate even if its EIRP has to be increased up to 47 dBm, but that it will no longer be able to operate in some regions if a much higher

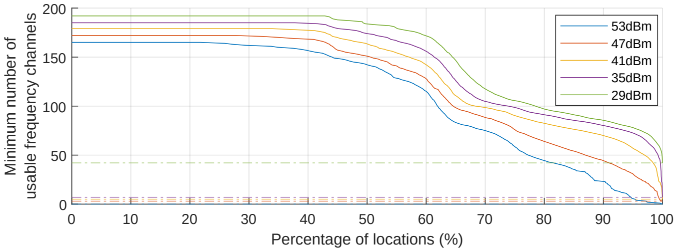
EIRP of 53 dBm is used.

Let us now limit the frequency planning to the LDACS A/G frequency bands. The minimum number of usable frequency channels for a percentage of the locations is shown in Fig. 11b for both LDACS A/G frequency bands combined, i.e., 964-1010 MHz and 1110-1156 MHz. Comparing Fig. 11a and Fig. 11b, we see that the results for both frequency alocations are quite similar. However, an LDACS A2A operation with an EIRP of 47 dBm, which is feasible for the frequency bands considered in Fig. 11a, might not be supported in all locations if only the LDACS A/G frequency bands are considered. Importantly, LDACS A2A would still be able to use, at least, 2 frequency channels within the LDACS A/G frequency bands in any considered location if the expected EIRP of 41 dBm is employed. The number of usable channels can still be effectively increased by decreasing the EIRP below 41 dBm. The results for the 964-1010 MHz reverse link band and for the 1110-1156 MHz forward link band are shown separately in Fig. 11c and Fig. 11d, respectively. One can see that the 964-1010 MHz frequency band suffices for LDACS A2A to be able to operate at any considered location with the expected EIRP of 41 dBm. Moreover, many frequency channels are usable in most of the considered locations, e.g. at least 60 frequency channels in 90% of the locations. We also see that the EIRP could be reduced to effectively increase the number of channels usable in the most challenging regions. Note that these results are also very important for the LDACS A/G reverse link, as they indicate that it will be able to operate anywhere in the region of interest even without having to reduce its expected EIRP of 41 dBm. LDACS A2A could still operate in many locations if only the 1110-1156 MHz frequency band is employed. However, this band would not suffice for LDACS A2A to operate anywhere in the considered region. These results highlight the importance of the lower part of the aeronautical L-band for the operation of LDACS A2A, especially in the continental regions as shown in Fig. 4 and Fig. 5.

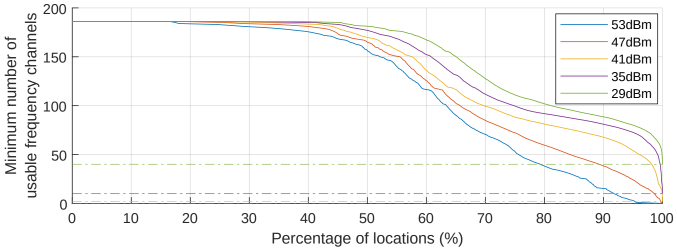
V. CONCLUSION

In this paper, we propose a frequency planning methodology for LDACS A2A yielding no harmful interference towards the operation of DME and TACAN. This methodology can also be applied to the frequency planning of the LDACS A/G reverse link. Using a very conservative compatibility criteria, we apply the proposed methodology to assess the feasibility of the LDACS A2A frequency planning in the 960-1164 MHz aeronautical L-band. We restrict our frequency planning to the north-east coast of North America, the North Atlantic Corridor, and western Europe.

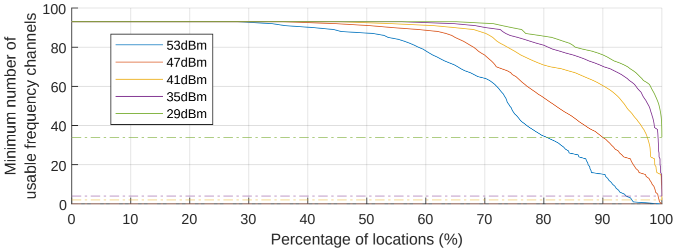
The obtained results show that LDACS A2A will be able to operate in numerous frequency channels within the 960-1164 MHz frequency band without affecting the proper operation of DME and TACAN. In the North Atlantic Corridor, as soon as the LDACS A2A station is sufficiently separated from the mainland, the entire aeronautical L-band can be employed



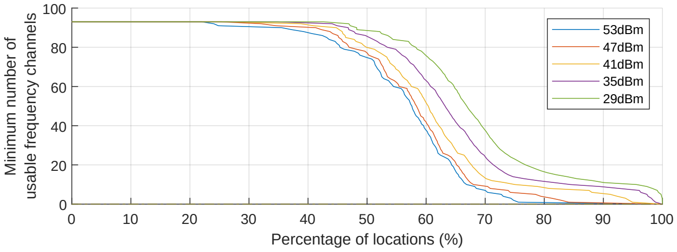
(a) Considering the frequency bands 960-1010 MHz, 1050-1070 MHz, and 1110-f_{max} MHz, where f_{max} is the maximum frequency channel allowed by the ITU Resolution 417 for each considered EIRP.



(b) Considering the LDACS A/G frequency bands: 964-1010 MHz and 1110-1156 MHz.



(c) Considering the LDACS A/G reverse link frequency band: 964-1010 MHz.



(d) Considering the LDACS A/G forward link frequency band: 1110-1156 MHz.

Fig. 11: Minimum number of usable frequency channels for a percentage of the locations and for different LDACS A2A EIRPs. Note the horizontal lines indicating the minimum number of frequency channels usable in any considered location for the different EIRPs.

without disturbing the DME/TACAN operation. In the continental airspace, the number of usable frequency channels decreases but still remains high in most locations, especially in Europe. Although some small regions in North America present challenging compatibility conditions, our results show that LDACS A2A can operate anywhere in the region of interest, as multiple frequency channels are always usable. Even considering the compatibility with the systems operating at 1030 MHz and 1090 MHz, as well as the ITU Resolution 417 safeguarding the RNSS receivers, LDACS A2A can still operate anywhere in the region of interest and numerous frequency channels can be used in most locations. Moreover, we see that LDACS A2A could benefit from adapting its EIRP dynamically. It could reduce the EIRP in the most challenging regions to be able to use more frequency channels, and increase it in the less challenging regions to, for example, increase its data throughput or communications range. In any case, the results clearly show that the lower part of the L-band, i.e., 960-1040 MHz, is the most promising frequency band for LDACS A2A operation, especially in the continental airspace. Thus, LDACS A2A could successfully operate in the LDACS A/G reverse link band, i.e., 964-1010 MHz. In addition, the frequencies 960-964 MHz yield practically no interference towards DME/TACAN, and LDACS A2A would greatly benefit from operating there as well. In fact, some of these frequencies can be used anywhere in the considered region of interest, which might allow LDACS A2A to have a globally available frequency channel for its operation.

ACKNOWLEDGMENT

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