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RESEARCH ARTICLE

Audio degradation of climax mode transmission in air traffic control

H. Vignoli Muniz and E. Parente Ribeiro

Department of Electrical Engineering, Federal University of Parana, Curitiba, PR, Brazil
Corresponding author: H. Vignoli Muniz; Email: hildovig@hotmail.com

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Abstract
Airspace control plays an important role in the safety and fluidity of air traffic. A fundamental service for this purpose is audio communication through frequencies in the VHF bands. This paper describes the evaluation of the audio degradation of voice transmissions from control centre to the aircraft. The effects of more than one station broadcasting on the same frequency with carrier offset (climax mode) are analysed using perceptual evaluation of speech quality (PESQ) perceptual model. Comparative studies are performed to verify the degree of degradation of different audio transport systems and climax situation.

Nomenclature

ACC	area control centre
AM	amplitude modulation
ATN-BR	aeronautical telecommunications network of Brazilian airspace control system
CW	Curitiba
E1 2Mbps	TDM link (32 channels of 64Kbps)
FIR	flight information region
GS	ground station
ICAO	International civil aviation organization
IP	internet protocol
IPS	internet protocol suite
ITU-T	Telecommunication standardization sector
MOS	mean opinion score
MPLS	multiprotocol label switching
PESQ	perceptual evaluation of speech quality
RDC	contracted deterministic network
RS	Rio grande do sul
SESQ	single-ended evaluation of speech quality
TDM	time-division multiplexing
VHF	very high frequency
WAN	Wide area network

1. Introduction
Analog VHF communication is still widely used in airspace control communication in several countries. The Brazilian Airspace Control assumes gigantic proportions and its 22m square kilometers are divided in flight information regions (FIR). There are five of these large regions: Brasília FIR, Curitiba FIR, Recife FIR, Atlantic FIR and Amazon FIR. Redundancy in communication with aircraft is required,

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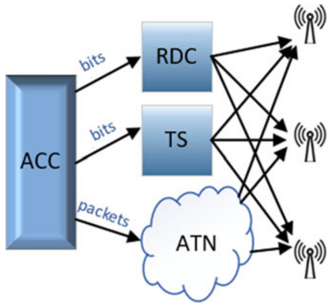

Figure 1. *Audio Transmission by ACC-CW to aircraft through different channeling networks in FIR-CW.*

among other reasons, for safety. This motivates that voice signals be transmitted by more than one transport medium between area control centre (ACC) and ground station (GS) and be transmitted by more than one ground station to the aircraft. When two stations transmit on the same frequency channel, a standardised carrier offset is applied to minimise interference from nearby stations transmitting on the same channel. This mode of communication is called climax [1].

Several regions in Brazilian airspace have climax situations. It is theoretically predicted and observed in practice, by pilots' testimonies, that climax affects the quality of delivered audio, especially in the controller-to-pilot direction. In the pilot-to-controller direction, there is equipment in the ACC that selects the best signal received from the stations for reproduction to the controller.

Previous works have investigated degradation due to climax. Using simulations with signal degradation equivalent to climax (addition of white and impulsive noise, audio phase shift, interfering tones and data loss) speech quality was assessed for different conditions [2]. Another study, using real audio recordings transmitted to aircraft, found good correlation between subjective MOS (mean opinion score) evaluation and the objective perceptual PESQ (perceptual evaluation of speech quality) method [3]. Some climax situations were identified with significant degradation when compared to situations without climax, but there were no systematic analysis of degradation with respect to the number of stations or comparisons between different audio transport networks.

The current study aims to investigate degradation in the aeronautical mobile service on transmissions to the aircraft with climax in regions under the responsibility of ACC-CW. The audio communications were in the range of 118–137MHz (VHF – very high frequency), using amplitude modulation (AM), in half-duplex through remote stations responsible for exchanging messages with the aircraft. These stations can be quite far from the ACC, as they are responsible for providing coverage over an area of approximately 1.8m km^2, which corresponds to the flight region of Curitiba (FIR-CW). Audio transport between stations and the control centre is performed digitally over a deterministic wired or satellite network, or a statistical network (packet switching).

Degradation due to each of the transport networks will also be examined. Figure 1 illustrates how the audio signal from the ACC is sent to the VHF stations by one of the selected transport medium and then transmitted to the aircraft. The contracted deterministic network (RDC) and satellite network (Telesat) are deterministic networks that transport the audio bit stream. The aeronautical telecommunications network of Brazilian airspace control system (ATN-BR) is a packet network that internally has statistical and deterministic switching transport.

2. Background

Climax or multicarrier systems are used in situations where redundancy is needed to provide greater communication reliability, operational safety, and system stability. It allows the controller to use more than one station as a means of communication for mobile aeronautical services. Climax consists of two or more stations transmitting the same audio signal on the same frequency channel. In Fig. 2, the coverage

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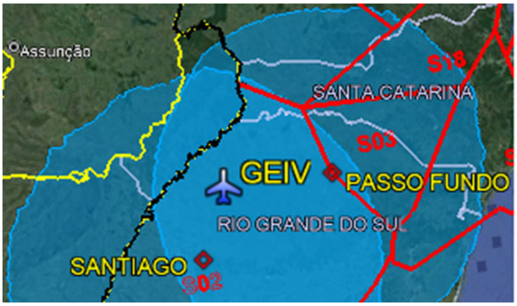

Figure 2. *Example of a two-station climax in FIR-CW, Passo Fundo/RS and Santiago/RS, at Level 200 (20,000 feet).*

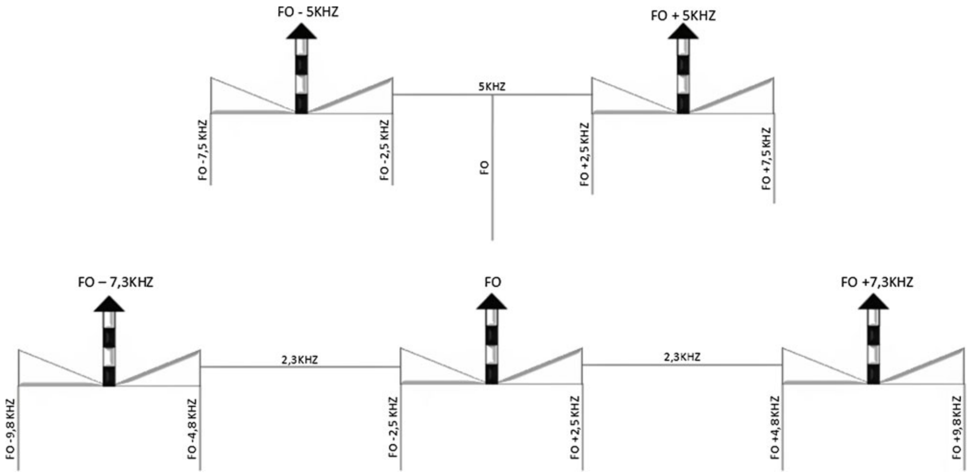

Figure 3. *Standard offset with respect to central frequency (F0) for two (top) and three carriers (bottom).*

areas (blue) of the station antennas (represented by diamonds) from Passo Fundo/RS and Santiago/RS can be seen. The intersection between them is in light blue, represents the region where communication occurs in climax. There is a standardised small frequency shift for each of the transmitting stations involved, to avoid greater degradation when the plane is in these intersections.

For carrier offset systems on channels spaced by 25, 50, and 100kHz, the minimum separation requirements are as follows (ICAO ANNEX 10 VOLUME III, 2007, p. 257):

- Two-carrier system: carriers are separated by plus or minus 5kHz from the centre frequency, requiring a frequency stability of plus or minus 2kHz (15.3 parts per million at 130MHz), as shown in Fig. 3 (top).
- Three-carrier system: carriers are separated by plus or minus 7.3 and 0kHz from the centre frequency, requiring a frequency stability of plus or minus 0.65kHz (5 parts per million at 130MHz), as shown in Fig. 3 (bottom).

The International Civil Aviation Organisation (ICAO) has been producing documentation related to the concept of the Aeronautical Telecommunications Network (ATN) for the future of aeronautical communications for some time now. This type of network uses digital data links for voice communication and provides other air traffic services [4]. ICAO has adopted a criterion for the possible use of the ATN network as a strategy for integrating air traffic communications, as the use of an ATN/IPS

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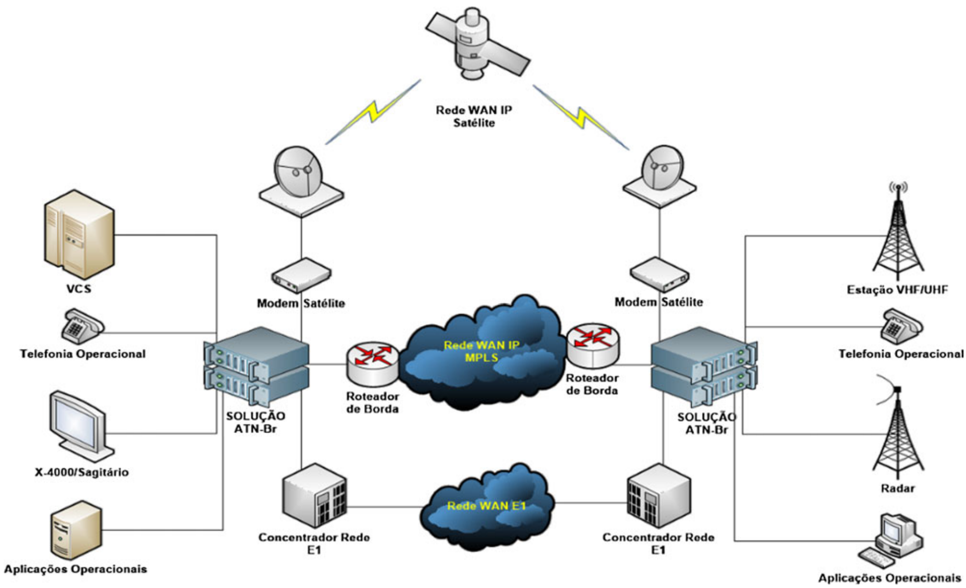

Figure 4. *ATN-BR – WAN Networks and associated services and applications [7].*

(Internet Protocol Suite) network allows for the reliable and continuous interoperability necessary for these end-to-end IP communications [5]. The ATN-BR network uses conventional network elements and software-defined elements, capable of converging different applications and services. The network assumes that all connected equipment is already digital. Therefore, there was a stage of modernisation of various equipment that migrated from analog to IP (Internet Protocol) [6]. Its architecture takes into account each application, category or prioritisation, controlling the flow of data differently for each one. According to the global trend of using IP technology in Air Traffic Control, the adopted project solution is based on EUROCAE recommendations. Considering the Brazilian geographic aspect, a possible instability of telecommunications services offered by telecommunications operators and the need for communication reliability, the decision was made to establish three large WAN networks for the ATN-BR network – E1/TDM, IP/MPLS, IP/VSAT, as shown in Fig. 4 [7]. The ATN-BR infrastructure is responsible for integrating these different means of communication into continuous point-to-point and point-to-multipoint transmissions between military organisations that use or provide these services for airspace control.

In the ATN-BR network, switching between long-distance networks can be automatic with configurable route criteria and priorities to ensure the required availability for each type of service and operational application, enabling management and optimisation of available communication resources. This network classifies different traffic classes that will be constantly monitored so that actions can be taken in case of inoperability and degradation [8–10]. A major differential of ATN-BR is the intelligent management of available long-distance channels, using technology capable of managing preferred paths and lowest cost for each location where the network is implemented, by verifying failure or obtaining a certain degradation value, making it possible to provide greater reliability in maintaining services provided for airspace control.

2.1. PESQ

Recommendation P.800 [11] describes a subjective way of measuring speech quality by averaging opinions of independent persons to obtain a MOS. The evaluators provide a rating from 5 (excellent) to 1 (unacceptable). Such analysis is used as a reference but has high associated costs, as it requires a large group of persons for evaluation. Objective models use computational calculation and are based on

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mathematical models to estimate audio quality, but sometimes they fail to capture the subjective perception of speech satisfactorily. PESQ, a perceptual method defined in ITU-T P.862 [12], uses knowledge of the human auditory system, taking into account the perception of speech. It is an intrusive objective method (uses the original signal in its analysis) to predict speech quality. The result can be converted to MOS scale for comparison. Such a method is consolidated and has been used, at times, to attempt validation of different study models [13] or to verify the quality of different services and applications together with single-ended evaluation of speech quality (SESQ) in packet networks and different codecs [14]. The choice for PESQ was due to it being a practical, fast, widely used and recognised method for measuring audio quality. As demonstrated by Frigotto and Pohl [3], the correlation values between this objective method and subjective when random phrases were used in the aeronautical mobile service were over 92%. It should be noted that PESQ achieved better performance than SESQ in almost all investigated conditions.

3. Methodology

The methodology consisted of transmitting various pre-recorded speeches from the control centre to the pilot and recording the received signal on the aircraft. Figure 5 shows the signal path. Audio is sent from audio console at the ACC, through the cross-connect frame (CCF) and the selected transport network to the GS. It is then transmitted by VHF radio and subsequently captured by the aircraft. Depending on aircraft position, it will receive the signal from one, two or three ground stations.

A subset of original audios from Frigotto and Pohl [3] was used. The original audios were recorded in a studio with the conditions recommended by ITU-T P.800, such as low reverberation and environmental noise. Both male and female speakers recorded random sentences in English and in Portuguese. They also recorded common air traffic control sentences. The procedure defined in this standard for recording short, random phrases in a controlled environment was followed. The signals received and recorded on the aircraft were exported by PROTOOLS software using 16-bit resolution and 44.1kHz sampling rate. To verify the quality with PESQ, the received audios had their sampling rate converted to 16kHz. In our study, the audios were randomly selected and the type of sentence whether technical jargon or common phrase does not influence the PESQ objective metric as opposed to a subjective MOS evaluation. The following steps were followed to investigate audio degradation:

1. Coordination was carried out with the control centre, pilots and aircraft to take advantage of flights for audio transmission between control and the aircraft. With certainty of a flight from a particular aircraft and the possibility of mission sharing, the entire route of the aircraft was planned from its origin to destination. According to a predetermined table, the sectors and frequency channeling in the route are determined and an appropriate audio transmission order was standardised. Through coordination with the control centre, all the aircraft in a particular sector were instructed to tune in only to the main frequency and the study aircraft to tuned in to the secondary frequency.
2. The audios were transmitted via the secondary frequency through the Telesat channeling, and after that the same audios were then sent via the ATN-BR Network on this same frequency. The channeling change was made directly on the audio console at the control centre transparently to the pilot. Then, two more sets of audios were sent through the deterministic network channeling and the ATN-BR network, on the main frequency. Thus, the audios were sent by three different means of transportation from the control centre to remote stations that transmit on VHF to aircraft.
3. The quality of each received audio was computed by the PESQ method, with the comparison of the original audio, obtaining scores on the same MOS scale (0–5). It is worth noting that to know in which climax situation the aircraft was, its coordinates (latitude, longitude and altitude) were recorded at the time of audio transmission and later verified through the irradiation diagram of the stations in the specific sector to determine its climax condition.

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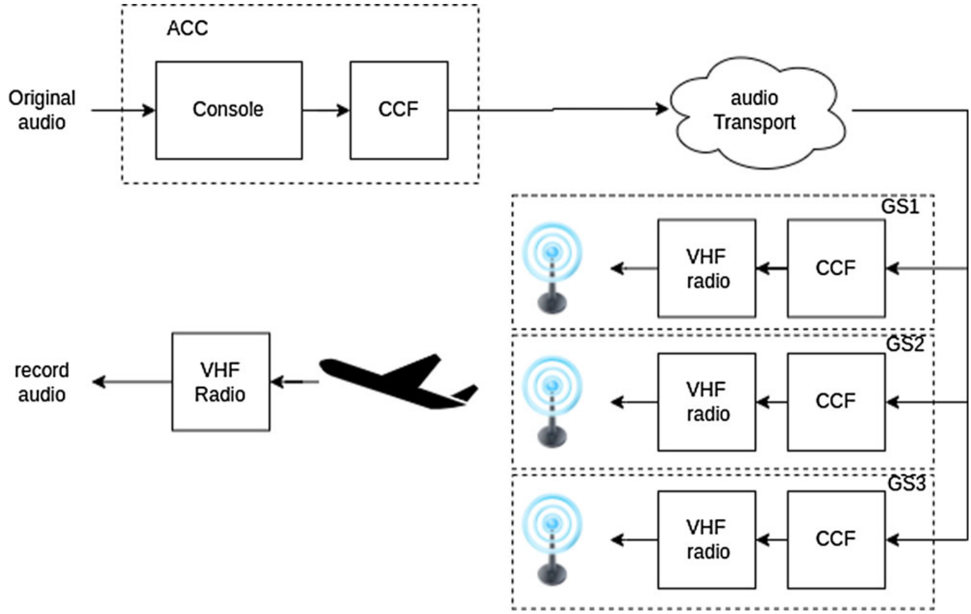

Figure 5. *Audio signal path from ACC to pilot cabin via one, two or three ground stations according to flight area.*

The data used for this project were collected from six different flights using two aircraft (CARAVAN and GEIV) with different flight levels, days, sectors, altitudes, antenna distances and weather conditions. From these flights, 287 audios were captured after discarding unwanted interference, such as simultaneous communications from other aircraft on the same channel.

4. Results

As an initial verification, Fig. 6 illustrates the PESQ scores obtained from the 287 test audios. There were 133 audios recorded in regions without climax (blue circle) and 154 audios recorded in climax conditions (green cross) either with two or three stations transmitting on the same frequency. Their average scores are plotted as blue and green lines. There is a great dispersion of values that range between 1.01 and 3.38. The average of PESQ values in transmissions without climax, 2.66, was higher than in transmissions with climax, 2.03. This indicates that PESQ scores were able to capture audio degradation due to climax under diverse flight conditions.

In order to verify the separation between the means, the 95% confidence interval was calculated. Figure 7 shows the means of PESQ scores for each number of antennas (stations) used and their respective confidence intervals. This suggests that the quality of communication as measured by PESQ reduces in transmissions with climaxes with two and three antennas. But the different conditions where the audios were recorded will be further investigated.

The average scores with 95% confidence interval for each of the three transmission media that were carrying the audios are shown in Fig. 8. For one station transmitting, the confidence intervals overlap. Therefore, it cannot be affirmed which transport medium is the most suitable. However, for two and three stations transmitting, it can be noticed that the RDC medium produced higher scores than Telesat and ATN, with no overlap of the confidence interval. It is worth noting that there was no situation in which the aircraft was in a climax of three stations when transmitting through Telesat so that it could be compared.

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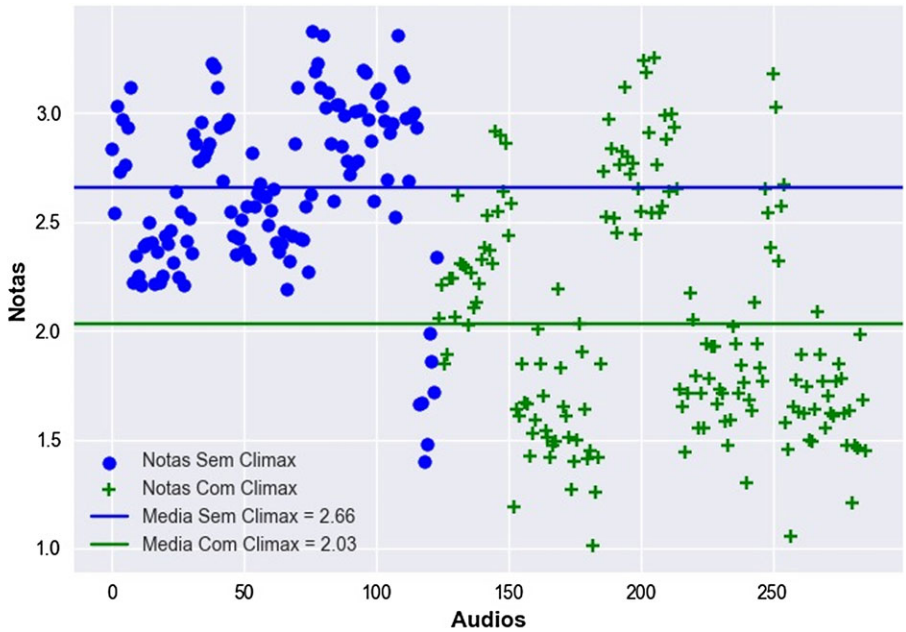

Figure 6. *All transmissions (climax and non climax).*

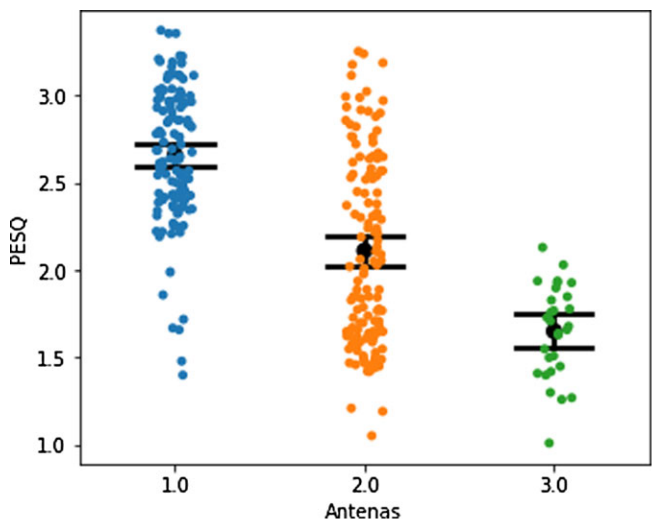

Figure 7. *Mean PESQ with 95% confidence interval for 1, 2 and 3 antennas.*

Another way to analyse the channel media in climax transmission is through the score histograms, shown in Fig. 9 A lower quantity of transmissions can be observed with three stations (green), but they are concentrated in lower values (between 1.0 and 2.1). A greater number of transmissions were obtained with two stations (orange), which are spread out with values scattered. Transmissions with only one station (without climax) also show some dispersion, but they are further to the right with higher PESQ scores.

The observed values show a lot of dispersion because they were obtained in quite distinct contexts: different altitudes, aircraft, terrain, distance from the transmitting antenna to the aircraft and even

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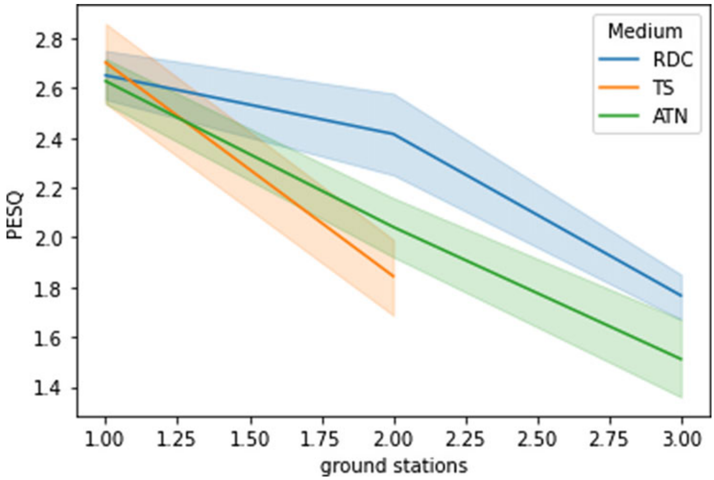

Figure 8. *Mean PESQ with 95% confidence interval for each transport type versus number of antennas.*

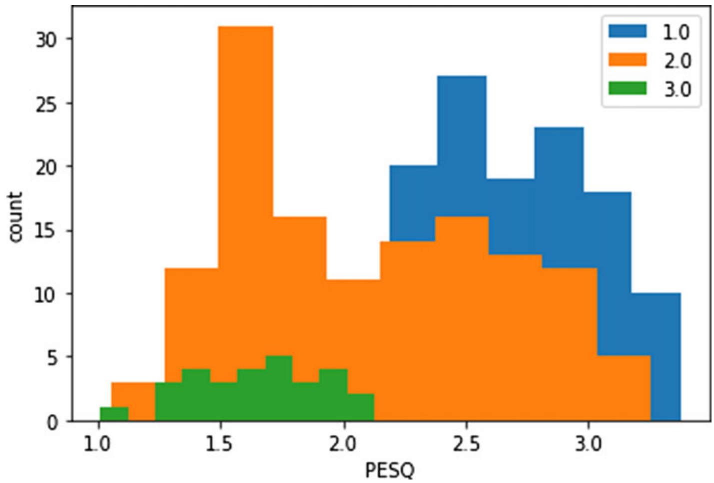

Figure 9. *PESQ histogram for 1, 2 and 3 antennas.*

weather conditions. Thus, an accurate statistical analysis with a non uniform sampling may be impaired. Therefore, we sought to isolate some variables to better understand the degradation factors. When looking at PESQ scores for each flight, there was less dispersion of scores due to more homogeneous weather con ditions, aircraft and flight levels. By analysing the cases by sectors of FIR-CW in each flight, even more homogeneous conditions were observed, but there is only a small number of audios, for each degradation situation, for a consistent analysis.

Another important condition is related to the type of aircraft. Figure 10 shows the average PESQ scores obtained with the two aircraft used in the tests. It can be observed that the scores obtained with the GEIV aircraft were lower than those obtained with the Caravan aircraft.

This can be explained because the recording of the audio received by the pilot was done differently in the two aircraft. The audio was recorded directly from the line output in the Caravan aircraft. In the GEIV the audio was captured from the cabin with a microphone, which can cause greater degradation. The flight altitudes of these aircraft may also influence. The GEIV tends to use higher altitudes, with greater distance to the antennas and possibly greater signal fading.

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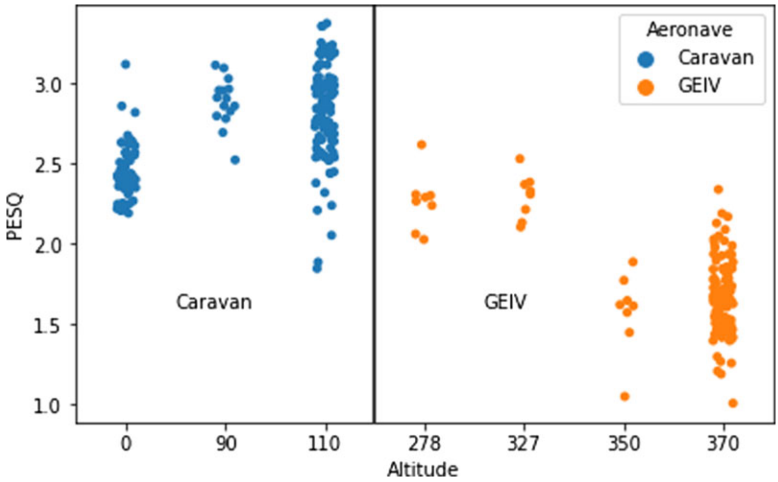

Figure 10. *PESQ average versus altitude for each aircraft.*

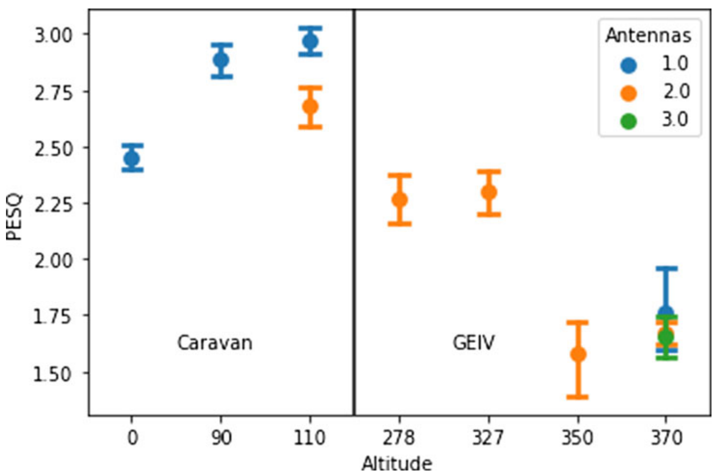

Figure 11. *PESQ average with confidence interval versus altitude for 1, 2 and 3 antennas.*

Figure 11 shows the PESQ averages with confidence intervals as a function of altitude and climax situation, with one, two and three antennas. Firstly, the behaviour without climax, with one antenna in blue, is observed. Level 0 indicates that the aircraft is on the ground. The obtained PESQ average was lower, possibly due to obstacles, buildings and terrain around the runway. Level 90 and 110 have similar scores, within the confidence interval margin. Level 370 has a lower PESQ average, mainly due to the difference in the way the audio is captured from the two aircraft. Measurements with transmissions by three antennas were obtained with GEIV at level 370. At this altitude, the scores were very low. The confidence intervals for one, two and three antennas overlap, and it is not possible to draw a statistically significant conclusion about the climax degradation. However, at altitude 110, PESQ scores were only from Caravan aircraft where audio was recorded directly from console and PESQ values are higher. There were 48 audios with one antenna and 49 audios in climax with two antennas. The confidence intervals do not overlap and are well separated, supporting that audio quality degradation in climax mode with two antennas can be detected with PESQ objective metric. Figure 12 shows a scatter plot to indicate the number of test audios analysed for each altitude and the dispersion os PESQ values.

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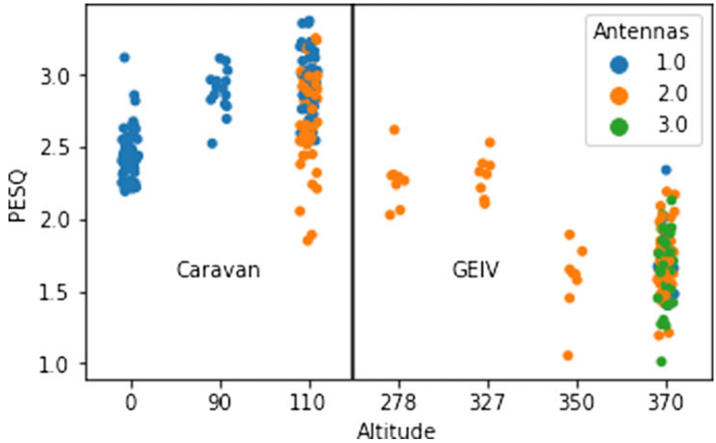

Figure 12. *PESQ values versus altitude for 1, 2 and 3 antennas.*

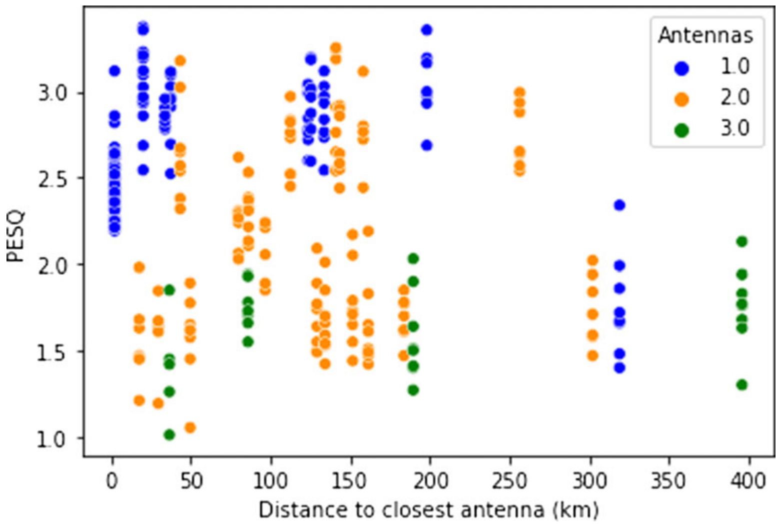

Figure 13. *PESQ values versus horizontal distance to closest antenna.*

The influence of the distance between the aircraft and the ground station can been analysed in Fig. 13. A scatter plot of the PESQ scores as a function of the horizontal distance to the closets antenna, regardless of transmission mode (climax or non climax) does not evidence significant correlation, in this observed range, up to 400km. For longer distances, the fading might introduce noticeable degradation in terms of PESQ. Also, all the testes conducted with one, two and three antennas were performed with different distances without any significant bias to a particular distance range.

It is possible to verify the degradation of audio due to the transport medium, as shown in Fig. 14, grouping the data by flight level. When the aircraft was on the ground (level 0), the transport via the contracted deterministic network (RDC) had a higher mean than transport via the ATN network, with separate confidence intervals. However, at other levels, the confidence intervals overlapped.

5. Conclusion

Speech quality analysis was performed in various flight conditions using the objective perceptual PESQ method. A total of 287 speech transmissions were used with two types of aircraft during six flights,

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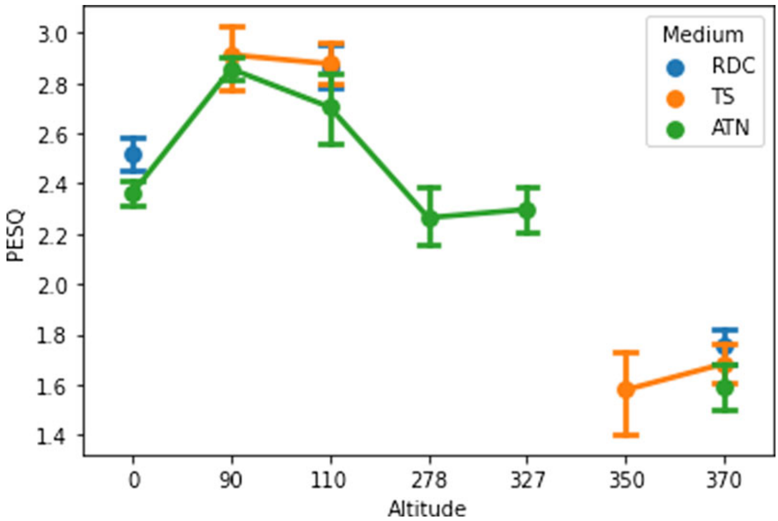

Figure 14. *PESQ average versus altitude for each transport medium.*

at altitudes ranging from 0 to 37,000 feet. Forty-six percent of the transmissions were through a single ground station, while 54% were through two or three stations in a climax situation. It was possible to verify that transmissions without climax obtained an average PESQ higher than transmissions with climax. It was also possible to verify degradation due to the number of transmitting stations, which showed a reduction in quality perceptual score. Due to the lack of homogeneity in test conditions, some variables were analysed in isolation. When only Caravan aircraft with direct audio connection was considered, at altitude 11,000 feet, there were 48 audios with one antenna with average PESQ 3.0 and 49 audios in climax with two antennas with average PESQ 2.7. The confidence intervals do not overlap and are well separated, supporting the fact that PESQ can capture audio quality degradation of transmissions in climax mode.

Regarding scores by flight, there was less dispersion of scores due to more homogeneous weather conditions, aircraft and flight levels. By analysing the cases by sectors of FIR-CW in each flight, even more homogeneous conditions were observed, although with fewer tests for analysis. Lower degradation was observed when the audio was transported through the deterministic network of the contracted company. For audios transported by the statistical network (ATN), some degradation situations were observed. However, the ATN network can use quality of service configurations, select multiple paths or other traffic engineering approaches to obtain equal or superior quality compared to other transports. It can also bring greater flexibility in management and operation, which can be analysed once it is fully delivered for operation.

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