Extension of communication aeronautical services coverage over the ocean via antenna optimisation

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***Abstract*—Aeronautical communications are based on ground transmitting/receiving antennas, with a given range, delimited by transmission powers, among other aspects. For routes in transcontinental flights over large oceanic paths, coverage problems may exist, given the large distances that the aircraft may be from ground stations, creating communication problems. The use of multi-frequency systems and directional antennas can contribute to minimize this problem, by extending coverage from the ground station, since it is not possible to act on the aircraft one. For given flight routes, radiation patterns for ground stations can be optimised with directional antennas, from which actual commercial antennas can be deployed. To address this problem, high directive antennas Yagi Uda Antennas radiation patterns were analysed in order to extend the voice communication coverage over the ocean and a suggestion of the location of the ground station, in Azores. Ones conclude that an 18 elements' Yagi antenna, with a maximum forward gain of 16.35 dBi, can extend, in the direction of maximum propagation, about 6.99% comparing with the current omnidirectional array with 2.5 dBi of gain. In terms of coverage area, some part of the Azores' FIR can be covered using only 18 elements' Yagi antennas, covering approximately 46.05% of the FIR, which corresponds in an improvement of 2.96% comparing with the current coverage area**

Aeronautical Voice Communication; VHF Propagation; Coverage Extension; Radiation Patterns; Yagi Antennas; Multi-frequency Systems

I. INTRODUCTION

Before radio was available for aeronautical communications and for pilots to warn the control tower that they were about to land, pilots dipped a wing and that signal was often misinterpreted. It is stated in [1] that the modern system of air traffic control (ATC) was born at the Cleveland Airport in Ohio where it was constructed a control tower on top of an old hangar and equipped that facility with radio transmitting and receiving equipment. The communication transmitters were 15 W radios that permitted voice communication with pilots over approximately 24 km.

International Civil Aviation Organization (ICAO), formed in April 1947, soon recognized that a more structured approach to aeronautical communications was required. In parallel to the formation of ICAO and due to its growing influence, the VHF 118 MHz – 132 MHz band was designated for aeronautical communications by the World Radio Conference (WRC) in Atlantic City in 1947 with the advent of the Aeronautical Mobile (Route) Service (AM(R)S). The AM(R)S, by definition, is 'a service reserved for communication relating to the safety and regularity of flight, primarily along national or international civil air routes'.

Firstly, AM(R)S system used Double Side Band in Amplitude Modulation (DSB-AM), mainly due to its simplicity and resilience in the environment, with 200 kHz channel spacing accommodating 70 channels over the whole band. Then, in 1950, to double the capacity to 140 channels, the channel spacing changed for 100 kHz. At the same time, an extension of the band was allocated for AM(R)S to 118–136 MHz increasing the number of channels to 180.

Ten years later, this methodology was extended further with 50 kHz channel spacing, now easily achievable, and this, doubled the capacity again to 360 channels at the rate of 50 kHz. Finally, in 1972, 25 kHz channel spacing was introduced with theoretical 720 channels. However, that was not enough to curb demand. Therefore, in 1979, WRC extended the AM(R)S allocation in the VHF band even more to 117.975–137.000 MHz, which is where it is today, with a theoretical 760 channels at the rate of 25 kHz achievable.

In domestic airspace, flight information is typically transmitted and received using Very High Frequency (VHF) and Ultra-High Frequency (UHF) voice radio whereas their propagation is limited by the radio horizon. Places not covered by neither VHF nor UHF must be covered by High frequency (HF) radio and/or by satellite voice systems (SATVOICE).

NAV Portugal is responsible for the supervision of every flight on both Santa Maria and Lisbon Flight Information Regions (FIRs) and Santa Maria is one of the largest FIRs located in the Atlantic Ocean. In the Ocean Control Centre in Santa Maria, there is a modern communications centre that ensures effective long-distance coverage, using an HF system, since this is an Oceanic Flight Information Region.

At first, communication was only in high frequency (HF) bands or even in medium frequencies, prone to static and atmospheric noise, but not for long time. Air-ground communications relied upon very high frequencies (VHF) due to its high-quality capability of transmitting voice in very high ranges, limited by the elevation of the ground station, the altitude of the aircraft and the ground topology between the two. For high-flying aircrafts, the range can go up to 300 NM.

So this work is precisely motivated by extending coverage, in VHF, beyond the horizon where a model for optimised antenna radiation patterns will be developed by multi-frequency systems, in Azores.

II. BASIC CONCEPTS

A. *VHF Aeronautical Mobile Communication*

A satisfactory fact about VHF is that it is a line of sight system, which for an aircraft flying at sufficient height gives sufficient signal from the ground and to the ground controller. Communication between the pilot and the controller on the ground normally is via VHF analogue voice radio, where one channel is assigned to an ATC. If the aircraft is getting closer to that sector, the pilot shall tune the radio to the channel assigned to the sector.

When a message needs to be transmitted, by the pilot or the controller, they must listen first to the channel to see if it is busy and, if so, wait for a quiet period in the traffic on that channel. Normally the waiting period is relatively short because, for most channels, the transmissions are short and traffic is light. For highly congested channels, the wait can be 30 seconds or more. With judgement and experience, the pilot/controller will press the push-to-talk (PTT) switch and state his/her message, as fast and succinct as possible, to minimize channel occupancy. Then, the sender will listen to the channel until he/she receives acknowledge that the message was sent successfully. In case of failure, it means that two transmitters were activated at the same time and both failed to communicate or the receiver failed to listen the message. Therefore, a new message should be sent.

For audio communication, conventional amplitude modulation (AM) is used with channel spacing of 25 kHz (760 channels) or in 8.33 kHz spacing (theoretically 2280 channels) although the latest is not going to be considered. Worth noting that even though frequency modulation gives higher speech quality, it is not typically used since covers a 300-kHz bandwidth and that speech quality is not required.

Double sideband with amplitude modulation (DSB-AM) is very easy to work with, power-efficient and compatible with other equipment. Also, permits stations with stronger signals to overtake weaker stations, or suffering interference, and does not suffer from the capture effect found in frequency modulation (FM) (which only the stronger of two signals at, or near, the same frequency will be demodulated). In case of both pilot and the control tower are transmitting at the same time, other aircraft will hear a mixture of both transmissions, instead of just one of them.

B. *Propagation Models*

In generic mobile systems, a coverage area is typically split into rural, sub-urban or urban areas. In aeronautical equivalent these terms are en-route coverage, terminal manoeuvring area (TMA) coverage and local airport coverage. In addition, the airspace can be divided in upper and lower ones. The separation between the two happens at flight level (FL) 245 (approximately an altitude of 7450 m). Far away from the TMA, aircrafts usually flight at FL300 or higher. Because the purpose of this work is to evaluate and extend the coverage for long distances, it will always be assumed that the aircraft is en-route and that is close to the TMA the aircraft will be flying at FL245.

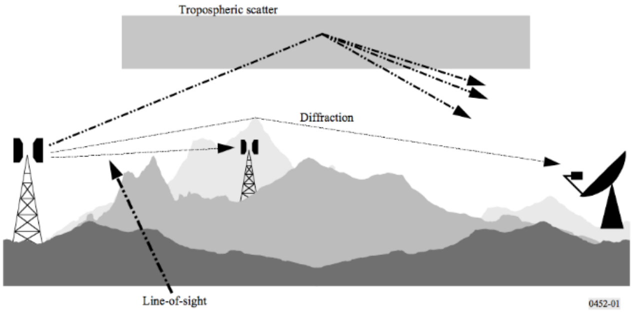

Figure 1: Main Propagation Mechanisms for VHF communication.

Figure 1 presents the main propagation mechanisms for both short and long distances. Losses in the pathway is something that is unavoidable. If the distance between the aircraft and the VHF ground station does not go beyond the radio horizon, ones expect the radio wave to propagate in LOS. Of course, that in case of having some considerable obstacles in the path, the strength of the signal can lose a part of its strength and that extra attenuation shall be taken into account.

Beyond the horizon, diffraction can be used to establish communication at short distances. However, as the propagating distance increases, the path loss increases rapidly and beyond a certain distance, scattering due to tropospheric irregularities are much more important than diffraction. This is due to the signal fading of scattering being relatively slow as the distance increases compared to high signal fading due to diffraction.

Ducting, the trapping of signals in waveguide-like duct formed by atmospheric layers of different refractive index, can propagate in VHF signals with very little loss over long distances. Unfortunately, ducting is rare and relatively unpredictable, and it is difficult to calculate the magnitude, length, and frequency characteristic of a duct in advance.

C. *Antennas for Aeronautical Communication*

The radiation pattern of a vertical dipole is omnidirectional when in free space radiating the same amount of power in any radiation power in all positions perpendicular to the antenna, with the signal strength dropping to zero on the antenna axis. [2] gives the vertical normalised gain of a linear dipole:

$$F(\theta) = \frac{\left(\cos\left(\frac{\pi L}{\lambda_{[\mathrm{m}]}}\right)\cos\theta\right) - \left(\cos\left(\frac{\pi L}{\lambda_{[\mathrm{m}]}}\right)\right)}{\sin\theta} \qquad (1)$$

where:

- L: length of the dipole;
- θ: angle between the vertical plane and the beam direction.

A half-wave dipole has a maximum gain of 2.15 dBi, in the plane perpendicular to the antenna axis. Adding wire connecting the two ends on a half-wave dipole, can give a fourfold increase in feed impedance, turning it less prone to impedance variations. As for the radiation pattern and gain, they are very similar to the latter.

Other type of antennas that are used in aeronautical purposes are the quarter-wave vertical antenna and 5/8λ vertical antennas:

A quarter-wave vertical antenna consists in a quarter wave above a ground plane antenna. One thing that is very important when installing VHF stations is the height since antennas need to be raised enough to be above nearby obstructions. Also, it is omnidirectional pin the horizontal plane and consists of a single end-fed element. Most of the energy is concentrated on the horizontal lobe where it is considered the relative gain of an isotropic source as 1 in all directions.

A 5/8 λ Vertical antenna is used when an omnidirectional is needed all-round and not just horizontally. Nevertheless, the gain continues to be greater in the horizontal orientation. Relative to a dipole, the peak gain is close to 4dBd.

However sometimes the gain of only one antennas it is not enough and for that reason, it is needed to increase the number of antennas thus arrays of dipoles or folded dipoles are often used as ground station antennas. A collinear antenna array is a set of dipoles mounted parallel and collinear to each other and they radiate vertically polarized radio waves. Stacking multiple dipoles in a vertical collinear array, increases the radiation power in horizontal directions and, for ground-to-air communications, reduce the power radiated down toward the earth where is wasted. Doubling dipoles would mean theoretically doubling the gain (3 dB) however, that does not happen due to spread radiation imperfections and losses. A collinear is suited for long distance communications in a central position and it is ideal for mounting at the top of a structure or top of a tower or pole. [3] gives the radiation pattern of an array:

$$G_{array}(\theta, \phi) = G_{antenna} \times F_{aa}(\theta, \phi) \tag{2}$$

where:

- $G_{antenna}$: gain of the array antenna element;
- F_{aa}: Antenna array factor.

F_{aa} depends on the excitation distributed among the various antennas and the distance between elements and is given by [3]:

$$F_{aa}(\theta, \phi) = \sum_{n=1}^{N_{ant}} e^{j(n-1)\gamma_{del}} \tag{3}$$

$$\gamma_{del}(\theta, \phi) = k d_{ant[\mathrm{m}]} \cos\theta + \delta_{[\mathrm{rad}]} \tag{4}$$

where:

- N_{ant}: number of elements in the array;
- γ_{del}: phase delay;
- k: wave number;
- d_{ant}: distance between the dipoles;
- δ: electric phase difference between the N^{th} antenna and the reference one.

Thought, in cases where the traffic is more concentrated in one section than the others, directional antennas can be more useful than omnidirectional ones:

The Yagi antenna is a higher directive antenna because of its design that consists in a reflector, a driven element and directors. Starting firstly by the driven element, which is normally a half dipole or a folded dipole, the Yagi's element is fed with power. Behind the driven element, there is a reflector that will improve the performance of the antenna, by reducing the level of radiation or pick-up from behind the antenna (backwards direction) and, because of that, adding typically 4 or 5 dB of gain in the forward direction. More gain will come from the directors, which are placed in front of the driven element, in the direction of the maximum radiation. Each director will add around 1 dB of gain in forward direction thus as number of directors increases that gain per director is reduced. In addition, for high gain levels, the antenna becomes very long and the gain is limited to around 20 dBi.

The panel antenna consists in a single simple half-wave dipole mounted at a pre-determined distance from an integral reflecting plane, or for more complicated arrays of 4 (or more) narrow or broad-band, linearly or circularly polarized elementary radiators.

D. State of the Art

In [16] is stated that the belief that VHF services could be used to provide reliable communication beyond the horizon started in 1960, in an extended range VHF symposium hosted by International Aerodio Ltd. After that, many installations have been put in operation worldwide. However, only recently, and because of the increasing of the traffic in oceanic airspace, VHF extending communication systems became a clear choice. As said before, this happens such as tropospheric scattering, atmospheric refraction and diffraction in a few ways. Whatever the means, the signal is likely to be significantly attenuated. So, all over-the-horizon coverage systems involve the boosting of transmitted power and the reception of weak signals. This requires the use of some or all the following:

- High Power Amplifiers on Transmitters.
- Low-Noise Pre-Amplifiers on Receivers.
- High Gain - and consequently directional - Antennas.

Clearly such systems can exacerbate the difficulties associated with interference between radios, so this must all be carefully considered in the system design.

According to [4], a Northrop Grumman subsidiary, Park Air Systems has already implemented some 20 over-the-horizon VHF systems around the world, including in Greenland, Iceland, Singapore and China. Over-the-horizon VHF communications systems are preconfigured and transportable. They are built and tested at Park Air's facility in Peterborough, UK, before being sent for installation and commissioning.

The one implemented in China exceeded the expectations and its location is at the southern coastal city of Sanya, that provides long-range air traffic communication over the South China Sea and it was an agreement between the aviation administration of China and neighbouring Vietnam to establish a joint area of responsibility (AOR) over the South China Sea. Typically, air traffic using southern routes is transiting from Bangkok, Kuala Lumpur and Singapore to destinations such as Hong Kong and Japan.

With the Park Air's solution, there is no need to change the airborne radios meeting International Civil Aviation Organization (ICAO) standards and uses a ground transmitter of 250 W carrier power to achieve the desired field strength for aircraft at long range.

At the Sanya's installation, the transmitter is connected to a pair of directional antennas aligned to project a powerful beam in the required direction. Each antenna is composed by a six elements' stacked Yagi array with four dipoles radiators mounted on a horizontal support per element, mounted on a tower/platform with power level of some 750 W. The resulting horizontal beam width is some 90º, and the vertical beam width is approximately 60º. This beam is broad enough to provide coverage for all aircraft flying within the area of responsibility, but is concentrated enough to afford sufficient forward gain to reach aircraft out to the maximum range and altitude.

Another case where the VHF was extended was in Dutch Caribbean Air Navigation Service Provider (DC-ANSP) to deliver ground-to-air communication system for deployment in Curacao. Curacao is one of the busiest airports in the Caribbean region with high flight traffic between North and South America. As said in [5], Northrop Grumman Park Air Systems initially conducted a site survey, followed by a detailed assessment of the predicted coverage that would be achieved. The latest high power 200 W T6 VHF radios have been delivered as part of the system. The installation of the radios, to be located on the hilltop site Seru Gracia on the island of Curacao, will provide ground-to-air communications for pilots throughout the Curacao Flight Information Region, one of the busiest in the Caribbean region due to the high volume of flights between North and South America. The set of extended range communication solutions includes transmitters with a power of up to 300 W, mast-head amplifiers and high-gain antenna arrays.

Other successful example of VHF coverage extension is shown in the ICAO's report [7], i.e., the enhancement of VHF coverage over Indian airspace in the Oceanic region. The Air control centre coverage of Mumbai and Trivandrum airport over Arabian Sea has been enhanced by putting Remote Controlled Air to Ground Communication (RCAG) at Agatti (an island in Arabian Sea) controlled from Mumbai and Trivandrum airport. To ensure further improvement, Airports Authority of India (AAI) deployed high power VHF Transmitter with directional antenna at Chennai and Port Blair and High power VHF Transmitters at Kolkata and Vishakhapatnam, in order to improve the coverage in the Bay of Bengal.

III. IMPLEMENTATION

A. Propagation Models

Oceanic Azores' FIR is an incredibly vast area of 5.138.160, 886 km^2 and it covers a wide area of the North Atlantic. The purpose of this study is to extend communication aeronautical services coverage over the ocean via antenna optimization.

In the interest of the studying the coverage for that vast area, the ground stations are set fixed into their possible locations with their well-known radiation patterns, noise figures, sensitivities and height. On the other hand, the coordinates of the aircraft change from point to point among a defined geographic volume, i.e., the develop model assumes the aircraft as a point target in a horizontal plane parallel to the Earth leaving out of account the yaw, pitch and roll angles.

Regarding the coverage analysis, it can be divided it in two situations: line-of-sight propagation coverage analysis and the over-the-horizon ones. The chosen mechanism will be the one with lower path loss.

It is worth stating that LOS coverage analysis should consider the terrain profile and the first order Fresnel ellipsoid model to determine if an aircraft and a GS are in view or if their radio-path is obstructed by the terrain.

It is also worth noting, that at VHF and UHF bands, seawater refraction index is about (-1) and therefore the sea surface is a good reflector for these radio waves. In some conditions, detected signals in the receiver are summation of direct and reflected.

The received power can be now obtained by [8]:

$$P_{r[\mathrm{dBm}]} = -77.21 + E_{r\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right]} + G_{r[\mathrm{dBi}]} - 20\log f_{[\mathrm{MHz}]} \quad (5)$$

where:

- E_r: Electric Field Strength in the receiving antenna.

The received power can also be expressed by [8]:

$$P_{r[\mathrm{dBm}]} = P_{EIRP[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} - L_{p[\mathrm{dB}]} \quad (6)$$

$$P_{r[\mathrm{dBm}]}{=}P\_t[\mathrm{dBm}] + G\_t[\mathrm{dBi}] + G\_r[\mathrm{dBi}] - L\_(p[\mathrm{dB}]) \quad (7)$$

where:

- P_{EIRP}: Equivalent isotropically radiated power;
- P_t: Power fed to the transmitting antenna;
- L_p: Total path loss between the transmitting and the receiving antennas.

Because of the power sensitivity of both airborne and ground station antennas, and due to the significantly decrease of the strength of the signal beyond the horizon, the only possible way to improve the received power is by increasing the gain of the ground station antenna or the transmitting power of the ground station antenna. Moreover, the reason for it is that both the transmitting power and the gain of the aircraft cannot be changed since it is not practical and the frequency is limited to the air band. However, most of the time, it is useless to increase the transmitting power of the GS, because even though the signal is strong enough for the controller to communicate with the pilot, the pilot may not be capable of communicating with the controller. Vice-versa can also happen, when the aircraft is close to the GS antenna.

For the communication to happen correctly, the net link margin must be above a defined value. The net link margin provides a measure of the power surplus in the link, between the operating point and the point where the link can no longer be maintained:

$$\Delta P_{r[\mathrm{dB}]} = P_{r[\mathrm{dBm}]} - P_{r,min[\mathrm{dBm}]} \tag{8}$$

$$P_{r,\mathrm{min}[\mathrm{dBm}]} = -77.21 + E_{r,min\left[\frac{\mathrm{dB\mu V}}{\mathrm{m}}\right]} + G_{r,min[\mathrm{dBi}]} - 20\log f_{[\mathrm{MHz}]} \tag{9}$$

where:

- ΔP_r: Received Power above the threshold/sensitivity;
- $P_{r,min}$: Sensitivity/Threshold - Lowest power level at which the receiver can detect an RF signal;
- $E_{r,min}$: Lowest field strength such as to provide on a high percentage of occasions an audio output signal with a wanted/unwanted ratio of 15 dB, with a 50 per cent amplitude modulated (A3E) radio signal. ICAO recommends these values to be [9]:
  - Airborne: $E_{r,\mathrm{min}} \approx 29.54$ dBμV/m;
  - Ground Station: $E_{r,\mathrm{min}} \approx 26.06$ dBμV/m;
- $G_{r,min}$: Receiver's lowest gain power.

B. Radiation Pattern

A simple method for the estimation of three-dimensional radiation patterns from the horizontal and vertical cuts is presented in (10), which leads to lower errors compared to some common methods.

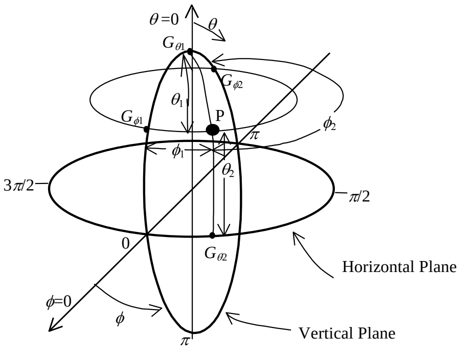

Figure 2: Definitions for application of the interpolation method of the 3-D radiation pattern (extracted from [10]).

According to [10], the interpolation method is based on the assumption that both horizontal and vertical radiation patterns of the antenna are available, $G_H(\phi)$ and $G_V(\theta)$. With help of the it, it is possible to observe that $G_H(\phi)$ has a known range of 2π, with $\phi \in [0, 2\pi[$, as well as $G_V(\theta)$, with $\theta \in [0, \pi[$ for $\phi = 0, \pi$.

Calculating the directional gain of the ground station antenna, $G_{GS}(\theta,\phi)$, in any direction $P(\theta,\phi)$, can then be viewed as an interpolation problem, i.e., one wants to obtain the value of a function in a general point, from the knowledge of its value in specific points whose interval contains the general one.

Because one is dealing with two coordinates θ and ϕ, this can be solved as a 2-D problem and, to help visualise the problem, it is helpful to map the surface of the sphere (Figure 2) onto a planar surface (Figure 3), defined by the two coordinates:

- The north and south poles of the sphere, $\theta = 0$ and $\theta = \pi$, correspond respectively to the upper and lower horizontal lines, in which the directional gain is know from the vertical cut, $G_{\theta 1} = G_V(\theta = 0)$ and $G_{\theta 1} = G_V(\theta = \pi)$ (the same notation is used, since the point of interest never uses both values in the interpolation, and either one or the other is used);
- the central horizontal line corresponds to the equator, $\theta = \pi/2$, on which the horizontal cut of the radiation pattern is defined and known, $G_{\theta 2} = G_H(\phi)$;
- the left and right vertical lines correspond to different representations of the same meridian, $\phi = 0$ or $\phi = 2\pi$, which is associated to the half of vertical cut in the (usually defined as) forward direction of the antenna, $G_{\phi 1} = G_V(\theta, \phi = 0)$;
- the central vertical line corresponds to the meridian $\phi = \pi$, which is associated to the half of vertical cut in the (usually defined as) backward direction of the antenna, $G_{\phi 2} = G_V(\theta, \phi = \pi)$.

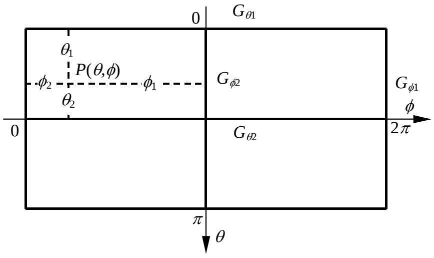

Figure 3: Mapping of the sphere's surface onto a planar surface (extracted from [10]).

Therefore, a final formulation for the interpolated directional gain in any direction $P(\theta,\phi)$ can be obtained by:

$$G_{GS} = \frac{[\phi_1 G_{\phi 2} + \phi_2 G_{\phi 1}]\frac{\theta_1\theta_2}{(\theta_1+\theta_2)^2} + [\theta_1 G_{\theta 2} + \theta_2 G_{\theta 1}]\frac{\phi_1\phi_2}{(\phi_1+\phi_2)^2}}{[\phi_1 + \phi_2]\frac{\theta_1\theta_2}{(\theta_1+\theta_2)^2} + [\theta_1 + \theta_2]\frac{\phi_1\phi_2}{(\phi_1+\phi_2)^2}} \tag{10}$$

As for the aircraft, [9] recommends that the transponder antenna system installed on an aircraft should have a radiation pattern nominally equivalent to that of a quarter-wave monopole on a ground plane. However, in reality, because of reflection, refraction and dispersion effects caused by the structure of the aircraft the radiation pattern can variate for different positions or even from aircraft to aircraft. Therefore, the estimated gain is never truly accurate.

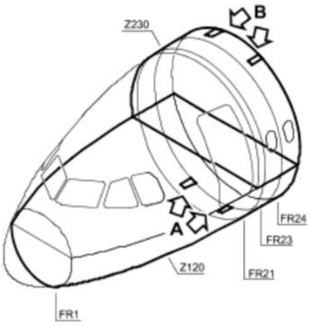

Figure 4: Aircraft’s fuselage transversal cut showing transponder antennas locations (extracted from [11]).

As in Figure 4, there is four antennas in a typical commercial aviation aircraft: two on the bottom (pointed as A) and the other two on top of the fuselage (pointed as B). To provide omnidirectional coverage for lower and upper airspace the antennas commonly are set in the front of the fuselage and normally the antennas are either planar or wire monopoles 42 encapsulated on a blade shaped dielectric to provide protection and minimise aerodynamic drag [11] . For this work, the antenna is assumed as a wire monopole.

C. Simulator Implementation

In order to analyse the coverage area in the Azores’ Islands for different type of antennas, a simulator was created with the models above described. This simulator estimates the gains of the GS antenna dependent of the position of the aircraft as well as the gain of the aircraft’s antenna, the path loss between the transmitting and receiving antennas and subsequently the received power on the transmitter.

In of the received power being above the threshold/sensitivity then the communication for that distance and on that location of the aircraft is saved as received.

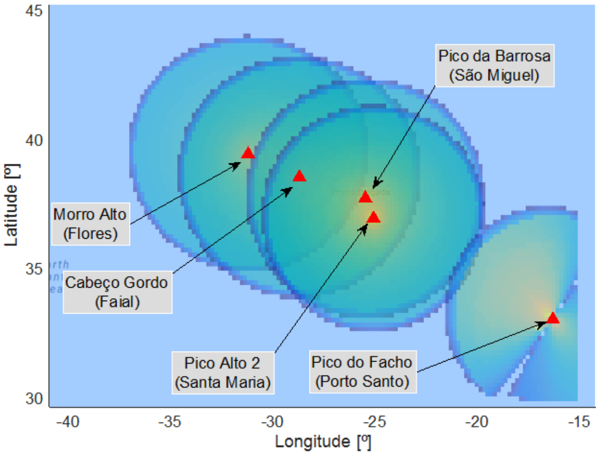

Figure 5: Estimated coverage of Azores' FIR given by the simulator.

At the end, the simulator pictures the covered area in the Azores’ FIR map as it shown in Figure 5 and respective current GS locations in Azores. Note that with the exception of the antenna in Porto Santo that is a 2-array Yagi 3-elements antenna with a forward gain of 9 dBd, all the others are omnidirectional arrays with a forward gain of 0 dBd in S. Miguel’s and in Santa Maria’s GS antennas and of -1.1 dBd in Flores and Faial.

Afterwards, the estimated coverage area was calculated covering about 44.73% of the Azores’ FIR.

IV. RESULTS ANALYSIS

Until the radio-horizon, these antennas already implemented are enough and even though collinear omnidirectional antennas have higher gains, comparing with the ones implemented, it is not enough to propagate the signal beyond the horizon and for that reason, and high gain directive antennas must be study. Skymasts Manufacturer presents three relevant types of Yagi antennas with greater gains. These are the 6 elements’ Yagi antenna [12], with a maximum gain of G_{max}=10.65 dBi, the 12 elements’ Yagi [13] with a maximum gain of G_{max}=14.15 dBi and an 18 elements’ Yagi [14] with G_{max}=16.35 dBi. More elements represent a higher forward gain, more side lobes and smaller Half Power Beam Width (HPBW). Therefore, even though for greater distances the Yagi 18 elements’ antenna is expected to propagate further, when the aircraft flies close to the GS, some coverage problems may exists.

The first step, to understand whether these antennas are adequate for this work or not, is to estimate the improvement of the coverage area compared with the one obtained by the ones already implemented.

Figure 6 defines the trajectory of the aircraft that it is going to be studied in Figure 7. Note that it is defined as negative distances when the aircraft is on the left side of the GS and positive when it is right, i.e., the aircraft flies north. Figure 7 represents the coverage for each type of antenna located at the same geographic coordinates as the one implemented in Morro Alto, Flores (h_{GS}=859 m) with the aircraft at a FL245 (the minimum height possible in the upper space) which, of course, for higher FL the coverage will improve. Fact that must be taken into consideration is whether there is enough power for the pilot to receive the signal from the GS properly.

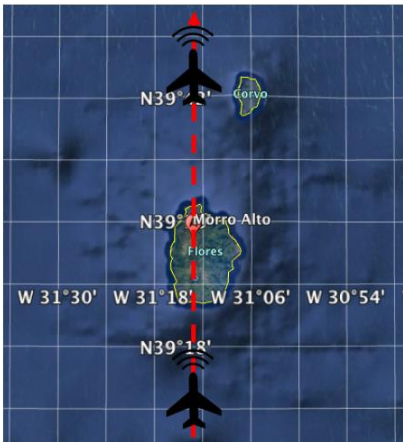

Figure 6: Path representation to analyse the coverage length in Morro Alto, Flores.

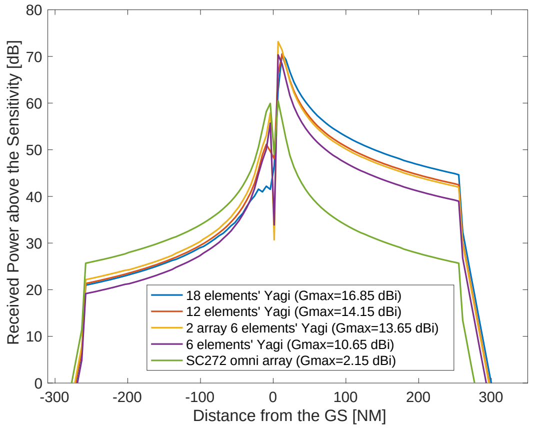

Figure 7: Coverage for each antennas' type in Nautical Miles when the aircraft is flying South->North (FL245).

Figure 7 assures that there is no poor communication when the aircraft comes close to the GS, so, there will be no need to retune the frequency in these situations even for the higher directive antennas.

The non-symmetrical behaviour in Figure 7, it was already expected since the front-back ratio of the Yagi antennas is considerable. It is also relevant to study how the link behaves with the distance when the aircraft is flying from West to East.

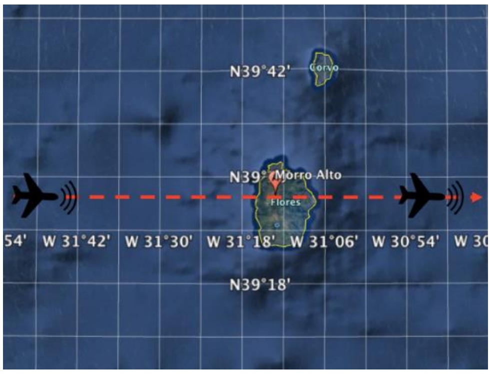

Figure 8: Aircraft's route flying from West to East.

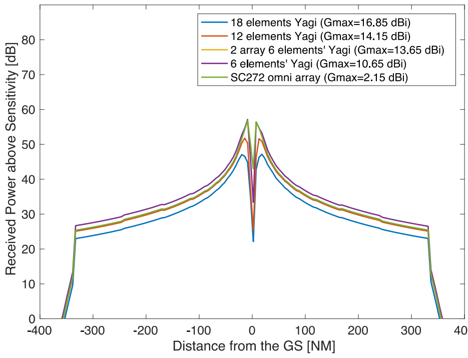

Figure 9: Coverage for each antennas' type in Nautical Miles when the aircraft is flying West->East (FL245).

Figure 8 shows the communication between the pilot and the GS in Morro Alto, Flores, when the aircraft flies from west to east. There are no significant obstacles obstructing the link between the receiving and transmitting antennas therefore the coverage distance, represented in Figure *9*, is a bit longer than the one in Figure 7. Of course, since the radiation pattern is symmetrical, unlike the one presented in Figure 7, it is expected for the received power to be also symmetrical. Little differences can come due to obstructions of the link.

Studied the coverage close to the GS, where the aircrafts fly at lower heights, ones must study now the realistic coverage above the horizon where they fly much higher.

Table 1: Comparison between the maximum distance for each antenna's type for FL245 and FL400.

Antennas	**G_{max} [dBi]**	**d [NM]**	
		FL245	**FL400**
SC272 omni array	2.15	278	329
6 elements' Yagi	10.65	293	348
Two Array Yagi 6	13.65	296	349
12 elements' Yagi	14.15	298	
18 elements' Yagi	16.85	299	352

For this work, tests were made for FL400 concluding that, using a Yagi 18 elements' antenna at the GS, can cover 352 NM (Table 1). Worth noting that the aircrafts can fly even above that height.

Most of the traffic flows above the TMA and, for that reason, it is the most concerning area to be covered. For this thesis, it was considered the antenna with greater gains – Yagi 18 elements' antenna – however, and since the difference of maximum extension distances between the Yagi 18 elements' and the 6 elements' one differs only by 4 NM, which is not really significant, the 6 elements' Yagi could be also considered, since it has the advantage of being a smaller antenna.

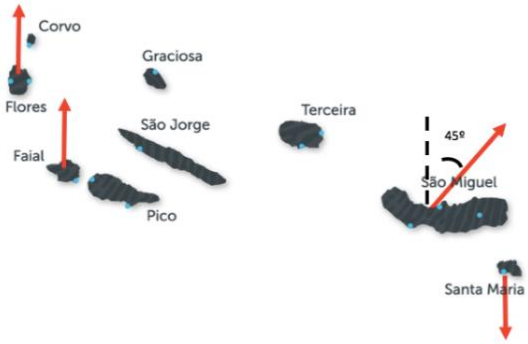

Figure 10: Direction of maximum propagation of the 18 elements' Yagi antennas in the GSs (adapted from [15]).

In a way of covering more area, and since the Santa Maria GS and the one in São Miguel are close to each other, the antenna in Santa Maria was pointed to the south in order to cover a larger area, as it is illustrated in Figure 10. To extend the coverage area even more, since the Faial GS covers a great part of the same area as the one by the GS in S. Miguel, it was evaluated whether the covered would be increased in case of rotating the antenna horizontally to East. Concluding, the best way was to rotate horizontally 45º to east the antenna set in São Miguel, and the coverage expand.

Santa Maria is located above S. Miguel, and it would not benefit to point the Santa Maria's GS also in the North direction. Also, the Yagi in Porto Santo covers the East part and all the other GSs cover west. Therefore, Santa Maria's GS if pointed south can increase the coverage area above the TMA.

When close or beyond the radio horizon, the vertical/polar angle θ_{GS} is close to 90°. Therefore, there are no need to tilt the antenna vertically, since the concern of this thesis is to cover areas beyond the horizon.

To reduce interference, common areas covered by different GSs cannot have the operating frequencies. Therefore, Faial's GS antenna needs to have an operating frequency band different from the one in Flores as well as the one in S. Miguel. Santa Maria's GS antenna and the S. Miguel's cannot have the same working frequency band. So, in order to reduce interference, in a 3-frequency system, Faial's and Santa Maria's GS antennas can operate with the same frequency band and Faial's and S. Miguel's need to be different from the other two.

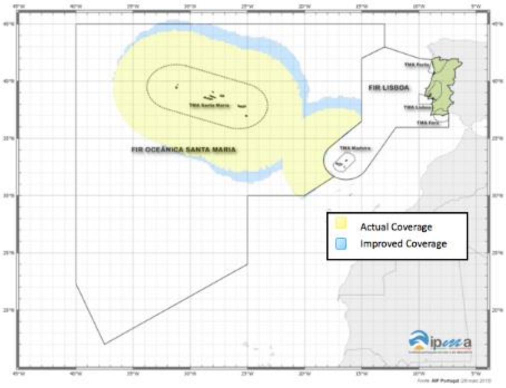

Figure 11: Comparison between the improved and the actual coverages.

Table 2: Comparison between the current and the improved coverage area.

Current Estimated Total Coverage Area [NM^2]	669 250	Improvement of 2.96 %
Improved Estimated Total Coverage Area [NM^2]	689 05	
Area Extension [NM^2]	19 800	
Maximum distance extension [NM]	21.6	Improvement of 7.77%

To conclude, with this new solution, and as it is deployed in Figure 11 and in Table 2, the total coverage area in Azores' oceanic FIR is about 46.05%, which, comparing with the one already implemented, has an expansion of +2.96%.

NAV Portugal only uses three working frequencies for the communication between the aircraft and the GS. However, a study of the coverage for a 4-frequency system can also be interesting to do (Figure 12).

Figure 12: 18 elements' Yagi antennas directions of maximum propagation for the 4-frequency system (adapted from [15]).

Getting another 18 elements' Yagi in Flores and in Faial, both pointed out to southwest SW (halfway between south and east) will increase the coverage in that direction when compared with the one in Figure 12.

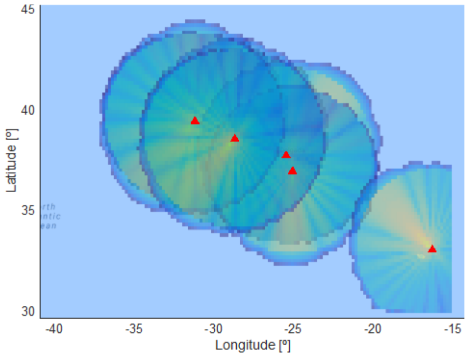

Figure 13: Coverage in case of having 4-frequency system.

Finally, the total covered area of all seven antennas (five antennas covering the area portrayed in Figure 10 and the two new antennas) is illustrated in Figure 13.

Table 3: Total coverage improvement for 4-frequency system.

Current Estimated Total Coverage Area [NM^2]	669 250	**Improvement of 4.89%**
Improved Estimated Total Coverage Area [NM^2]	701 979	
Area Extension [NM^2]	32 728	

As presented in Table 3, and comparing with the solution with five GSs, there is an increase of area of 1.88% and with the current one, of 4.89%. To reduce interference, the new antenna added to Morro Alto, Flores can work at the same frequency as the one in S. Miguel since these two ground station don't have overlapping covered areas and the forth frequency band links to the new antenna in Cabeço Gordo, Faial

Since 2% is not a significant improvement, and since setting new antennas translate in adding more ground controllers, this solution does not represent a priority.

V. CONCLUSIONS

In domestic airspace, flight information is typically transmitted and received using VHF and UHF voice radio whereas their propagation is limited by the radio horizon. Places not covered by either VHF or UHF must be covered by HF radio and/or by SATVOICE something that is very expensive.

A typical omnidirectional antenna, in high altitudes, normally are enough to cover the aircrafts until close to the radio horizon. However, near the radio-horizon, the curvature of the Earth turns itself into an obstacle and the received power decreases drastically and the received power does not received enough power for the communication to be successful. Therefore, in order to extend the signal beyond that, ones could increase the transmitting power or the gains of the GS antenna as well as the aircrafts'. However, it is not practical to change all the antennas in all the airborne and, in addition, most of the time, it is useless to increase the transmitting power of the GS, because even though the signal is strong enough for the controller to communicate with the pilot, the pilot may not be capable of communicating with the controller. Vice-versa can also happen, when the aircraft is close to the antenna. So, only the radiation pattern of the GS antenna can be practical to change. For that reason, a model considering the propagation models, antennas' radiation patterns and their locations, using directional antennas and multi-frequency systems is proposed and implemented in a simulator, conceding an estimation of the coverage area. Following, one recaps the main concepts for the realization of this work.

In order to determinate whether the signal is received above the threshold power of the receiving antenna, it is needed to estimate the path loss caused by either the decay throughout a path or obstacles. For long distances, the main propagation mechanisms in VHF are the free space path loss model until the radio horizon and the diffraction through Earth's Curvature and Tropospheric Scattering beyond that. However, close to the GS there must be a special attention to the profile of the terrain, which can cause some additional attenuation on the signal. The Fresnel's Ellipsoid Model, Digital Elevation Model, Effective Earth's Radius Model, Knife-Edge and Deygout Methods evaluate that extra attenuation.

NAV Portugal only have omnidirectional antennas limited to the radio horizon, in the Azores' Islands, thus directional antennas shall be analysed. Yagi Antennas are very widely used as a high-gain antenna in VHF whose maximum gain increase if the number of driven elements increase. Therefore, 6 elements, 12 elements and 18 elements' Yagi received powers variation had been analysed when the path length increases. In case of being above the threshold, the signal is received properly. As expected, the 18 elements' Yagi covers larger distances and it is the one that it is proposed for this work.

Another aspect that should be paid attention is whether there is any interference for longer distances. NAV Portugal's advice was to consider only three operating frequencies. Therefore, it is proposed for the Faial's GS antenna to have an operating frequency band different from the one in Flores as well as the one in S. Miguel. Santa Maria's GS antenna and the S. Miguel's cannot have the same working frequency band. Thus, in order to reduce interference, Faial's and Santa Maria's GS antennas can operate with the same frequency band and Faial's and S. Miguel's need to be different from the other two and to each other.

In addition, there was not the need to change the location of the antennas, since they are located in high mountainous areas with almost none obstructions.

Close to the Azores' TMA, the aircrafts are obliged to fly at FL245 thereupon that is considered the worst-case scenario. Of course, when far from the TMA, aircrafts fly at FL300 or even higher which means more coverage for farther distances. Hence, one analysed the FL245 and FL400 cases and 18 elements' Yagi extends in the direction of maximum propagation about 6.99% comparing with the SC272 omnidirectional array with 2.5 dBi of gain set in Flores.

The majority of the traffic flows in the upper part of the FIR; thus, ones must prioritise that area. For that reason, replacing the all the antennas with 18 elements' Yagis ones, pointing North was the first experiment. Of course, since the GS in Santa Maria is near and above the one in S. Miguel, it is more beneficial for it to be pointed south, expanding the area also above Santa Maria. Also, by observation, if S. Miguel was rotated 45º east, the total coverage area also increases since a big part of the coverage above S. Miguel is also covered by the ones in Santa Maria e Faial's. Covering of 46.05% of the FIR, there is an improvement of 2.96% comparing with the actual coverage area.

In case of using 4-frequency systems, it is then possible to improve the coverage area below the TMA, adding one antenna in Morro Alto, Flores, and other in Cabeço Gordo, Faial, pointing southwest increasing 1.88% of the covered area when comparing with the 3-frequency system and of 4.89% of the total coverage.

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