

### Assessment and Design of Multilateration Telecommunication Systems installed in NAV Portugal, EPE

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### Dissertation submitted for obtaining the degree of Master in Electrical and Computer Engineering

Jury

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Sep. 2011

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To the Ones I love

# Acknowledgements

My first acknowledgement is to Prof. Luís Correia, the supervisor not only of the thesis but also of the personal development during the past 8 months of work. From whom I acquired an exceptional working method and support during this thesis development. I am also thankful for the hours spent answering my questions, which are certainly worth a lot of money.

To the engineers from NAV Portugal, namely Eng. Carlos Alves, Eng. Luís Pissarro and Eng. André Maia, whose contribution for the work is indisputable. Unfortunately stories are told that people from external companies do not support you enough, but this was certainly not the case. I am thankful for the numerous exchanged emails to clarify my doubts, the regular meetings to give feedback from the work and the help developing the final document.

To the "Basement" colleagues, Diogo, Pedro, Ricardo, Tiago. Mainly due to the intellectual discussions that stimulate the interest in each other thesis. Among ourselves we tried to use each others as the first source to solve problems, at any hour or day. For them I wish the best success in their working careers.

To all my friends, because life is not only just about work. Time spent partying with you is certainly the best way to forget about the troubles in my life. To, Rita, Catarina, Inês, Margarida, Joana, Rui, Zé, Jaime, João, José, Tiago, Miguel, Fernando, Diogo, Madalena, Jorge, Teresa, Cristina, for all the support.

Last but not the least, I am thankful to my parents, grandparents, brothers and Filipa who no matter what are always present in the good and the bad times. I am sorry for the lack of available time in the last few months but I will certainly make it up.

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## Abstract

Air space surveillance systems are continuously in progress to increase the space capacity and safety. Multilateration is a proven technology to accurately identify aircraft. A latency model is developed to study the influence of delay in multilateration system, using different communication links. A coverage simulator is also developed as a tool for the study and design of new systems to be implemented. Finally, additional requirements of this system are analysed for a better understanding of it. In the latency model, it is shown that the influence of the delays is not important, and any kind of link can be used to provide communication from the different sensors to the central processor. The capacity of the links depends on the layers used for the communications, but for 250 airplanes the required capacity is around 276 kbps. Finally, a minimum number of 4 sensors are enough to run the location algorithm, but it does not meet the requirements for the tracking probability, a number in the range {5, ..., 10} being necessary to do so.

### Keywords

Surveillance, Multilateration, Requirements, Delay, Coverage.

### Resumo

Os sistemas de vigilância aérea estão continuamente em desenvolvimento com o objectivo de melhorar quer a capacidade de gestão do espaço aéreo quer a segurança da operação. Recentemente, apesar de conceptualmente ser já antiga, a Multilateração foi introduzida em sistemas de vigilância para a navegação aérea, considerando as suas potencialidades e os baixos custos associados. Um modelo de atraso é desenvolvido para estudar o efeito dos atrasos nos requisitos do sistema e a influência dos diferentes tipos de canais de comunicação. Um simulador de cobertura foi desenvolvido como ferramenta auxiliar para estudo e desenho de novos sistemas de multilateração que se pretendam futuramente instalar. Finalmente, mais requisitos deste recente sistema são analisados para melhor compreensão do funcionamento do seu próprio funcionamento. A influência dos atrasos no sistema não é significativa e pode ser utilizado qualquer tipo de meio de transmissão. A capacidade necessária em cada canal depende dos cabeçalhos usados, sendo que para 250 aviões será próxima de 276 kbps. Finalmente, o número mínimo de 4 sensores para executar o algoritmo de localização, contudo não é suficiente para responder aos requisitos seguimento, sendo necessário um número na gama de {5, ..., 10} para os respeitar.

#### Palavras-chave

Vigilância, Multilateração, Requisitos, Atraso, Cobertura.

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# List of Acronyms

ADS	Automatic Dependent Surveillance	
ADS-B	Automatic Dependent Surveillance Broadcast	
AGL	Above Ground Level	
ANSP	Air Navigation Service Provider	
CP	Central Processor	
CPS	Central Processing System	
CRTT	Communication Round Trip Time	
DF	Downlink Format	
eLCMS	embedded Local Control Monitoring System	
FDM	Frequency Division Multiplexing	
FL	Flight Level	
GEO	Geosynchronous Orbit	
GPS	Global positioning System	
GUI	Graphical Unit Interface	
IGMP v2	Internet Group Management Protocol version 2	
IP	Internet Protocol	
ITU-R	International Telecommunication Union - Radiocommunication	
ITU-T	International Telecommunication Union – Telecommunication	
LAM	Local Area Multilateration	
LAN	Local Area Network	
LEO	Low Earth Orbit	
LoS	Line Of Sight	
MAX	Maximum	
MDT	Maintenance Display Terminal	
MEO	Medium Earth Orbit	
MLAT	Multilateration	
MMF	Multi Mode Fibre	
MSL	Mean Sea Level	
NAV Portugal, EPE	Navegação Aérea de Portugal	
PSR	Primary Surveillance Radar	
RefTran	Reference Transmitter	
RF	Radio Frequency	
RU	Remote Unit	

SMF	Single Mode Fibre
SSR	Secondary Surveillance Radar
TDOA	Time Difference of Arrival
ТМА	Terminal Manoeuvring Area
ТОА	Time of Arrival
ТР	Target Processor
TWR	Tower
UDP	User Datagram Protocol
UL	Uplink
VPN	Virtual private network
WAM	Wide Area Multilateration

# List of Symbols

α <sub>dec</sub>	Declination angle
α <sub>desc</sub>	Descent angle
$\alpha_{mag}$	Route magnetic angle
$\alpha_{real}$	Route real angle
$\Delta_{interval}$	Update interval of the MLAT system
$\Delta t$	Time interval
$\Delta t_{System}$	Time difference for the system delay
$\Delta  au_{air}$	Difference in the air propagation delay
θ	Angle between two points
$\theta_{az}$	Angle of the azimuth
λ	Longitude
$\lambda_{ADS-air}$	Messages arrival rate of ADS-B messages sent when airborne
$\lambda_{ADS-mv}$	Messages arrival rate of ADS-B messages sent when moving
$\lambda_{ADS-sta}$	Messages arrival rate of ADS-B messages sent when stationary
$\lambda_{SL}$	Arrival rate of Mode S long messages
$\lambda_{SS}$	Arrival rate of Mode S short messages
ε <sub>path</sub>	Path inclination
$\sigma_{CRTT}$	Standard deviation of the CRTT
$\sigma_{fixed}$	System standard deviation
$\tau_{air}$	Air propagation time
$ au_{DL}$	Downlink propagation time
τ <sub>link</sub>	Link propagation time
$ au_{UL}$	Uplink propagation time
φ	Latitude
$\psi_{obs}$	Angle between the sensor and an obstacle
A <sub>dist</sub>	District area
A <sub>total</sub>	Total covered area
B <sub>modal</sub>	Modal bandwidth
С	Speed of light in the vacuum
CRTT	Communication round trip time
$d_1$	Ground distance between the sensor and reflection point
$d_2$	Ground distance between the airplane and reflection point

$d_{air-max}$	Maximum distance to the airplane
$dN_1$	Refractivity lapse rate
$d_{obs}$	Distance to the obstacle
$D_{path}$	Path length
$d_{RH}$	Radio horizon distance
f	Transmission frequency
G <sub>t</sub>	Transmission gain
G <sub>r</sub>	Receiving gain
h <sub>air</sub>	Airplane altitude
h <sub>ef</sub>	Effective height
h <sub>final</sub>	Airport MSL height
h <sub>initial</sub>	Initial MSL height of the approach
$h_L$	Lowest antenna height
h <sub>obs</sub>	Height of the obstacle
$h_r$	Height of the receiver
h <sub>RU</sub>	MLAT sensor height
$h_t$	Height of the transmitter
Κ	Climate parameter
L	Link length
L <sub>c</sub>	Connector losses
L <sub>d</sub>	Attenuation coefficient for distance
L <sub>fad</sub>	Maximum fading attenuation
L <sub>max</sub>	Maximum length
$L_p$	Path loss
L <sub>s</sub>	Splice losses
N <sub>air</sub>	Number of airplanes
N <sub>az</sub>	Number of azimuths
N <sub>c</sub>	Number of connectors
N <sub>points</sub>	Number of test points
N <sub>s</sub>	Number of splices
N <sub>sensor</sub>	Number of sensors
N <sub>smp</sub>	Number of elevation samples per azimuth
N <sub>veh</sub>	Number of vehicles
$p_{CT}$	Probability of continuous tracking
p <sub>nrec</sub>	Not receiving probability of a MLAT sensor
$P_r$	Received power
p <sub>rec</sub>	Receiving probability of a MLAT sensor
P <sub>t</sub>	Transmitted power.
$p_{TDOA}$	Probability of executing the TDOA algorithm

$P_w$	Probability of exceeding the fading margin
R <sub>b</sub>	Binary transmission rate
R <sub>Earth</sub>	Earth effective radius
r <sup>air</sup>	Ratio of targets airborne
r <sup>mv</sup>	Ratio of targets moving
r <sup>sta</sup>	Ratio of targets stationary
$\overrightarrow{r_{air}}$	Position vector of the airplane
$\overrightarrow{r_{RU}}$	Position vector of the sensor
Т	Time of the message sent from the airplane
T <sub>ADS</sub>	Generated traffic for ADS-B messages
t <sub>extra</sub>	Extra delay
t <sub>fixed</sub>	Fixed delay
$t_{hop}$	Delay of one hop in a communication link
t <sub>isl</sub>	Inter-satellite delay
$t_{link}$	Total link delay
$T_S$	Traffic for Mode S messages
t <sub>sync</sub>	Synchronisation time
t <sub>t</sub>	Transmission time
t <sub>VPN</sub>	Maximum delay for a VPN system
$t_{ heta}$	Random jitter delay
V <sub>msg</sub>	Message size
V <sub>SL</sub>	Mode S long messages size
V <sub>SS</sub>	Mode S short messages size

# List of Software

Google Earth Matlab r2007b Microsoft Excel 2007 Microsoft Word 2007 Microsoft Power Point 2007 Microsoft Visio 2007 Microsoft Visual Studio 2010 Paint Geographical Information system Matlab development environment Calculation and chart tool software Text editor software Presentation software Flowchart tools software C# development environment Image editing software

# **Chapter 1**

### Introduction

This chapter gives a brief overview of the work. It includes the context in which the thesis was developed and the main motivations. At the end of the chapter, the work structure for the thesis is presented.

#### 1.1 Overview

Since the Wright brothers built the first airplane in the XIX century, the number of flying airplanes has been permanently increasing. A study conducted by Massachusetts Institute of Technology states that in 2006 almost 28 million airplanes flew, and that a growth of 4 to 5% is still expected in the next 10 years [MIT11]. In June 2011, Portugal had 25 991 flights [ANA11], which does not contemplate every flights that travelled through the Portuguese airspace. These values give a brief overview of the increase in flights since the XIX century.

Travelling by airplane is considered safer than by car, because there are very strict requirements in terms of safety. One of them is the surveillance technology required to monitor every target in the airspace. These surveillance systems must guarantee that a large number of airplanes travel simultaneously in the air safely.

NAV Portugal is responsible for providing air traffic services in the Portuguese airspace in accordance with the international and national recommendations and standards. There is a lot of equipment required for the provision of the airspace surveillance, such as radars, radios or communication stations in many locations [NAV10], which involve a considerable investment, not only for the deployment as well as for the maintenance. Like any other company, every Air Navigation Service Provider (ANSP) need to upgrade their system's to provide the surveillance service with the higher level of safety to all aircraft in our airspace. All this must be performed in an efficient way, and with limited funds, so every new system implementation and upgrades must be carefully studied and analysed by a cost benefit analysis.

With the performances of new telecommunication systems, the airspace surveillance technology could also improve the capacity to meet these safety requirements. There are three principles for surveillance defined by Eurocontrol [Euro05]:

- An independent non-cooperative surveillance system to track all targets. This is provided by
  Primary Surveillance Radar (PSR) system, which is the oldest surveillance system. This system is
  not the most efficient one, but it is still recommended to be kept, because it is the only way of
  detecting a target if the electronic equipment fails.
- An independent cooperative surveillance system to track cooperative targets, which means that even though it is required that the target sends a message, the localisation is calculated in the ground station. There are two systems to comply with this principle. The secondary surveillance radar (SSR) was the first system to be used in this category, but more recently a new system named Multilateration (MLAT) appeared and can replace the SSR.
- A Dependent cooperative surveillance, which means that the localisation information is supplied by the flying target, instead of being calculated from the ground. The system that supports this principle is automatic dependent surveillance (ADS), which allows the ground station to receive a message with the airplanes location measured by their equipment.

The focus of this thesis is in the independent cooperative surveillance category, more specifically in the latest innovation which is MLAT.

The historical surveillance technique for this principal is the SSR, which has been used since the 1980s, although continuously being improved. But since the late 1990s that MLAT research has been increasing, mainly due to the United Kingdom and France, which have pilot systems in their airports [Euro08]. According to Figure 1-1, in the long term, the three different surveillance categories will focus on PSR, ADS and MLAT, with a progressive decrease in the use of the SSR. Beside the surveillance systems to be used in the future, Figure 1-1 also shows that the telecommunication systems to distribute the data and the surveillance data processing will continue to be used independently of the surveillance techniques used.



Figure 1-1 - Future evolution in surveillance systems (extracted from [Euro08]).

The difference between SSR and MLAT is large, and the technical differences are shown in Chapter 2. The fact is that MLAT can replace the SSR in the independent cooperative surveillance system category, because it improves the efficiency, accuracy, infrastructure costs and safety. Another main advantage of the MLAT system is the possibility to monitor the airplanes on the grounds at an airport.

Concerning MLAT and SSR costs, a study was performed by ERA [ERA10] (ERA is a surveillance system's manufacturer). The results provided by the study are shown in Figure 1-2. In terms of costs, there is a large difference in the acquisition and maintenance price, which will decrease a lot the expenses for the ANSPs. It shows that in terms of costs, the MLAT solution is better, being one of the reasons that it will be used in the long term.

Beside the costs, there are two main characteristics that also give preference to MLAT, the accuracy of the system for close traffic and safety. According to Figure 1-3, the gain in accuracy is clear between the SSR (RADAR) and MLAT (WAMLAT). There is also an increase in safety because the MLAT system by itself is redundant, and even if some parts of the system fail it will continue to work, unlike SSR that if the radar itself needs to be maintained or fails, the system will stop working.

Another part of the surveillance systems, which is analysed in this thesis, are the communication links used in air surveillance, which are very important and will have to be used always. In Figure 1-1

beside the surveillance techniques, it is also shown that the processing and distributing equipment will have always to be kept. Their role is the backbone of surveillance. Information must be distributed usually to more than one place, and that is accomplished by many telecommunication links spread through the network. In the MLAT case the telecommunication links will actually be more used than before, because the information gathering to provide an airplane location is not concentrated in one site, but in more than five, whose information will have to be forwarded to the same processing place.







Figure 1-3 - Radar vs. MLAT Accuracy (extracted from [SmCa06]).

In 2011, many MLAT systems have already been developed and many more are planned. Figure 1-4 contains the countries that have already started to deploy MLAT systems. This map is not up to date, because Portugal and maybe some more countries have already started adopting MLAT as a surveillance system, and are not considered in it. Although SSR is a well-established system, the replacement by MLAT will happen in the near future; there are still many areas to cover within countries that have not started deploying systems, namely in Africa and South America.

NAV Portugal has already an operational MLAT system in the Lisbon airport, which is used in this thesis to give more detail to the architecture and even to collect data to improve the analysis. Besides the already implemented system, there are four other systems, each one of them in a different environment.

The next system to become operational will be in Azores, to cover the central group of islands. This system is currently in the test phase and is expected to become operational this year. There are two other projects running; Lisbon Approach Area MLAT project, that is currently on the procurement phase and another project for Madeira and the North region of Portugal also currently on the procurement phase.



Figure 1-4 - MLAT implementation worldwide (extracted from [ERA10]).

The main goal of this thesis is to assess the current communication links used in the MLAT systems owned by NAV Portugal, to help developing the new system that will be implemented in the North region of Portugal, and to assess the Virtual Private Network connections' tolerable delay in the Lisbon system. To achieve these goals, two simulators were developed, one to analyse the delay in the communication links and the other to design the coverage in a MLAT system. This last simulator, besides the individual coverage calculations, also allows overlapping different antennas' coverage, which is useful for technologies that require coverage overlapping, such as MLAT. Finally, the surveillance requirements were crossed with the MLAT system, to check if the 4 sensors per location are enough to comply with them.

Although there are many papers concerning different parts of MLAT there are few that analyse entire systems. This thesis innovation has two parts, in the telecommunication links assessment and in the system design. The first part considers the analysis of already implemented systems and the overall magnitude of the delay impact in each type of link to support a MLAT system. The other contribution is concerning the system design, which analyses some requirements that even though being considered by manufacturers, their implication has not yet been published.

Also, the coverage simulator has the potential to be used as a tool for developing systems which need coverage overlapping. There are many coverage simulators in the market, including the one used by NAV Portugal, which some results are used in this thesis. But there are a few drawbacks because sometimes, it is not possible to get the intermediate values such has the land profile, the specific coordinates of the coverage analysis, the overlapping of different coverage maps and finally the paid

price.

#### 1.2 Motivation and Contents

*"The secret is the soul of business"*: this translated Portuguese saying is quite accurate in the technological business, because technology manufacturers, usually, are not willing to provide very specific details of their products.

Every ANSP buy the MLAT systems from a manufacturer and, even though manufactures have the responsibility that the system meets the requirements, it is also important that the ANSP gets some knowhow of the implemented systems. It is important for working with the system and to judge critically the implementations proposals of the manufacturers.

The present work is focused in assessing the MLAT telecommunication systems installed by NAV Portugal and also to provide a preliminary study for a system to be implemented in the North region of Portugal. In order to assess the telecommunication links, only two aspects were to be analysed, the required capacity for the links, and their maximum tolerable delay to comply with the MLAT system. The other main subject of the thesis is to study the coverage requirements of one system, and then to make a proposal of a possible system configuration to be implemented. A study of the localisation requirements is completed, and a complete proposal for a new system is presented.

This thesis is composed of 5 chapters, including the present one, and 6 annexes. It is organised in the following way:

- In Chapter 2, one presents an introduction to the existing surveillance systems, including the technical principals of MLAT. The most common telecommunication links possible to use in a MLAT system are also described, and finally a state of the art in MLAT.
- In Chapter 3, the MLAT architecture and the three developed models for the latency, coverage analysis and to calculate the maximum latency in a communication link are presented. A description of both developed simulators based in the latency and coverage model is also presented. Finally, the MLAT requirements and their implication in the overall system are shown.
- In Chapter 4, the results are presented. It includes both results of the simulators, meaning the
  expected delays of the current systems and the coverage studies performed for the North region
  of Portugal and the results of the maximum tolerable delay for the communication links in a
  system to be implemented. Other results are presented that are important to understand this
  system, such as the required telecommunication system capacity and how to meet the regulator
  recommendations.

The final chapter of the thesis briefly summarizes every conclusion drawn from the work, but also gives a more global analysis of the problem under study. Finally some recommendations for future work are given in order to continue developing the MLAT understanding.

# **Chapter 2**

## **Basic Concepts**

This chapter provides an overview of the current status of the air space surveillance systems, giving more detail to the multilateration systems. A brief description of the telecommunication links more commonly used in multilateration systems is presented, and the state of the art in this technology is addressed as well.

#### 2.1 Air Space Surveillance

Ever since the first airplanes that air surveillance became indispensable for civil or military traffic, and that many methods to supervise the air space in which MLAT is included are available. For military purposes, the most important feature is that the airplane may not want to be detected, so the detection must be made entirely from the ground independently of aircraft equipment carriage, but for civil use one must take advantage of the plane electronics to have more information. Figure 2-1 contains the available surveillance methods, each one of them considered limited by Line of Sight (LoS).



Figure 2-1 - Surveillance environment (adapted from [Euro08]).

The first surveillance method to appear was the radar, in this case the Primary Surveillance Radar (PSR). By being the first, it is also the most limited because it detects all flying objects but cannot distinguish among them. The radar transmitter sends a direct energy ray and the small proportion reflected on the object is detected by the radar receiver. The azimuth of the radar antenna gives the airplane's position angle while, by knowing the time taken for the pulse to hit the target and return, the distance of the target is calculated. In order to detect objects in the entire area, it is required for the radar to rotate with a certain frequency. There are three main disadvantages in using PSR: firstly, in terms of energy, it has a high consumption due to the radar rotation and the energy beam; secondly, there is no possibility of exchanging information; and finally, the radar's received signal may be easily lost, because the path distance twice the distance between the airplane and the radar [Euro08]. Although there are many disadvantages, in case of electronic failure in the plane, this is the only usable method [Euro08].

In fact, for civil purposes, it is rarely necessary to use the primary radar, because there is no need for the airplane not being able to communicate with a ground facility. With the Secondary Surveillance Radar (SSR) a new window was opened, because now airplanes were able to send information from their navigation equipment to a receiver, giving their altitude and identification, which were not possible with the primary radar. To do so, a transponder was included in the airplane to receive and transmit information, working in the same frequency as the SSR. It operates based on queries and the target replies with a coded signal. FDM (Frequency Division Multiplexing) is used to separate the interrogations, ground station to airplane (1 030 MHz) from the replies airplane to ground station (1 090 MHz) [Euro08]. The transmitted reply messages, which are also used in MLAT systems, are

Modes A and C (Mode A/C) [Nav08]. With SSR, the distance between the radar and the airplane is calculated by the time difference between the interrogation and reply message. Adding this information to the altitude reports the airplane 3D position is known. This position is updated on every radar sweep, having a period in [4, 12] s, depending on the radar [Era10].

As shown in Figure 2-2, the information contained in Mode A/C messages is quite limited, having only 12 bits for that purpose, even though being a 15 bits message. The 12 bits information is different between both Modes: for Mode A, the flight identification, also known as Squawk Ident, is transmitted, while in Mode C, the flight altitude, given by the airplane instruments, is transmitted. The problem of both Modes is that they are replies to a broadcast interrogation, meaning that to refresh an airplane's position, an interrogation broadcast message has to be sent and the airplane has to reply.



Figure 2-2 - Mode A/C message (extracted from [Euro08]).

SSR Mode S (Select) is an improvement of the simple SSR system with Modes A and C, because with this Mode it is possible to make selective interrogations. Airplanes are now identified by a unique 24 bit address, which is included in the reply and interrogation message. Two Mode S messages were developed, a long one with 112 bits, Downlink Format (DF) 20 and DF 21, and a small one with 56 bits, DF 04 and DF 05. Both Modes transmit the information from Modes A or C, but with some more fields beside the ones used in the conventional SSR. There are also equivalent DFs for squitter messages that are sent on a regular basis, without the request of the ground station. The messages structure is shown in Figure 2-3 and Figure 2-4.

S	hc	ort	M	ode S	Replies (DF04 / DF05)	
5	3	5	6	13	24	
04 05	FS	DR	UМ	AC / ID	AP	
Lo	<u>on</u>	g	Mc	de S I	Replies (DF20 / DF21)	
5	3	5	6	13	56	24
20 21	FS	DR	UM	AC / ID	MB	AP

Figure 2-3 - Mode S messages (extracted from [Euro08]).

The fields from each DF messages are described by:

- Format number (FN): Contains the code for each DF.
- Flight status (FS): Informs if the airplane is airborne or not.
- Altitude Code (AC): Flight altitude, is sent in Mode DF04 and DF20 that corresponds to the Mode C message.

- Identification (ID): Airplane identification is sent in Mode DF05 and DF21, corresponding to the Mode A message that is not a unique code.
- Address/parity (AP): Unique address of the airplane or error detection code.
- Message B (MB): Real time data.
- Address announced (AA): Unique address of the airplane.
- Parity information (PI): Error detection code.
- Message E (ME): Can transmit different information like: call sign and airplane category; airborne position; surface position or airborne velocity.

Acquisition	(Short)	Squitter	(DF 11)	)
-------------	---------	----------	---------	---

5	3	24	24	
11	CA	AA	PI	

Contains 24 bit aircraft address

#### Extended (Long) Squitter (DF 17)

5	3	24	56	24
17	СА	AA	ME	PI

Figure 2-4 - Mode S squitter messages (extracted from [Euro08]).

Both surveillance techniques, PSR and SSR, are only used for air-ground communications, but with the final surveillance method, Automatic Dependent Surveillance (ADS), the airplane can control its own positioning and navigate without ground support. The ADS system relies on the own airplane onboard navigation systems, such as altitude, position or projected flight path, to report the information to the ground station or to other airplanes. There are two Modes for ADS, ADS-Contract and ADS-Broadcast (ADS-B). ADS-C is used to provide information obtained by the own on-board sensors to a ground station on regular bases defined upon the setting of a contract, and if the airplane is not within the range of the station, it uses a satellite data link. This type of ADS is not supported by any MLAT system because it has a different frequency [Nav08].

ADS-B is the only ADS system supported by MLAT. It is a surveillance application that transmits, on a regular basis, parameters such as position, track, and ground speed, through a broadcast data link, which can be received by any airplane with this system or ground station within range. This type of system revolutionised surveillance, because an airplane, when airborne and without a ground station within range, can show every ADS-B messages received, from nearby airplanes, in the pilot display that helps navigation. The reports are sent within a certain time interval depending on the flight status, see Table 2-1, and the message structure is DF17, shown in Figure 2-4, and DF18 that has exactly the same structure as DF17. The difference between DF18 and DF17 is that DF18 is used for transmitters that cannot respond to interrogations, like a Reference Transmitter or a ground vehicle incorporated with a device that transmits its position, velocity and identification.

The MLAT system is another surveillance system that must be compatible with every of the systems described, except the primary radar that does not involve any exchange of information. It is necessary

to consider the frequency and size of every message for the design of a system.

Name	Overview	Average interval
Airborne position	Position of aircraft; transmitted while airborne	0.5s
Surface position	Position and velocity of aircraft; transmitted on ground	0.5s (5s stationary)
Aircraft identification and type	Aircraft identification (callsign) and category	5s (10s stationary)
Airborne velocity	Velocity of aircraft; transmitted while airborne	0.5s
Target State and Status	Mode A, NIC, NAC, SIL in DO260A	1s

Table 2-1 – Squitter messages frequency (extracted from [Euro08]).

#### 2.2 Multilateration

#### 2.2.1 System Architecture

The airplane's location is not only necessary to know when airborne, but also when it is on the ground, so recently a new system was developed to provide surveillance of Mode A/C, Mode S and ADS-B near the airport, MLAT [Euro08]. From now on, all airplanes are required to keep the transponders operational even if they are stationary.

The MLAT working principle is based on separated sensors that receive the signal sent from an airplane, and by crossing information, they are capable of detecting the airplane's position, which is basically the same function as the SSR. Knowing the coordinates of at least three different sensors, and the signal time difference of arrival, the solution of gives the airplane's location.

There are two sub types of MLAT, the Local Area Multilateration (LAM) and Wide Area Multilateration (WAM). The former is for airplanes and vehicles surveillance in the airports area, and obviously is not enough to replace SSR, because of the difference in surveillance domain. On the other hand, the latter is the option that can replace the SSR, because it is wide area, meaning that the sensors are widely spread to provide coverage of an area the same size, or wider than the SSR coverage in order to replace it.

MLAT is defined by the method used to calculate the Time Difference of Arrival (TDOA) and by the method used to synchronise the sensors; depending on the chosen method, there are implications in the system architecture. For the TDOA method, there are two possibilities, cross correlation systems and Time of Arrival system (TOA): the former can be used with any signal and the TDOA is calculated through the cross-correlation between the signals, while in the latter, the time of arrival is measured in waveforms signals, such as the SSR transponder signals. TOA systems are widely used in multilateration, unlike cross correlation ones, so only this one is described in what follows, Figure 2-5

presenting its architecture.



Figure 2-5 – MLAT TOA architecture (extracted from [Nev05]).

The elements involved in this technique are:

- Transponder: each airplane is incorporated with two transponders, one active and one backup, that is responsible for transmitting the messages from the airplane to the ground.
- Antennas: they are spread through an area, depending on the desired coverage, receiving the Radio Frequency (RF) signal sent from the plane.
- Down converter: it converts the RF signal to baseband.
- Digitisation: it converts the signal into a digital representation.
- TOA Measurement: it timestamps the message with the receiving time.
- TOA Correlation: it calculates the time differences among the different signals received.
- TDOA Algorithm: it calculates the airplane position with the time differences.
- Tracker: it continuously plots the airplane position and may reject data to improve accuracy.

The MLAT Central Processor (CP) is considered to include the blocks TOA correlation, TDOA algorithm and tracker, while the sensor includes the down converter, digitisation and TOA measurement. A telecommunication link is required to connect each sensor to the CP.

The other fundamental characteristic in the architecture is the method of synchronisation used. Since all sensors have to precisely timestamp the message received, to calculate the TDOA, they all need to be synchronised, two possibilities being available: common and distributed clock systems.

In common clock systems, the digitisation is done in the CP, so there is no need to synchronise the sensors. The problem with this topology is that the delay until the signal is received in the central station must be accurately known to calculate the TDOA; on the other hand, the receiver can be very simple and all the complexity is transferred to the central station. It should be taken into consideration that the CP is better placed in the middle, to reduce the communication link distances and have similar delay. The links to use with this type of synchronisation must be very fast and with a small jitter delay, which may only be accomplished by using microwave links and optical fibres [Nev05].



Figure 2-6 - Common clock system architecture (extracted from [Nev05]).

Finally, in the distributed clock system, receivers are more complex, because they need to handle the digitisation and timestamp before forwarding the message to the CP, but on the other hand there is much more flexibility for the communication link, because they support a much higher delay. The main disadvantage is that it is required to use a synchronisation technique for the sensors clock, which can be: transponder synchronised system; standalone Global Navigation Satellite System (GNSS) synchronised system; and common view GNSS synchronised system. Independently from the synchronisation technique, the architecture is always the same, as in Figure 2-7. The function of the synchronisation technique is to assure that all local clocks have the same time base.



Figure 2-7 - Distributed clock system architecture (extracted from [Nev05]).

According to the chosen system architecture, there are different requirements to the communication links between the sensors and the CP. In the case of a common clock system, the links must all have the minimum latency possible, so one should use fibre or microwave links, while with distributed clock systems, there are no latency requirements, because the timestamp has already occurred. Even though latency is not critical, it must be assured that the latency between the fastest and slowest links does not exceed a certain value, due to the MLAT processor constrains [Nev05].

#### 2.2.2 Time Difference of Arrival

A MLAT system works on the principle of TDOA, the principles involved being based on Figure 2-8. The number of sensors required differs if the goal is to calculate the Two Dimensions (2-D) or Three Dimensions (3-D) position: in the former, three or more sensors are necessary, against the four or more for the latter. Both solutions may be used, because even if the system is not able to calculate the airplane's altitude, it may use the information sent from the airplane to have it. Defining  $(x_i, y_i, z_i)$  as the position of receiver *i*, (x, y, z) as the airplane position, *t* as the time the signal sent from the airplane,  $t_i$  the time when the signal is received by receiver *i*, and *c* the speed of light in vacuum, the following equation can be obtained for each sensor:



Figure 2-8 - TDOA principle (extracted from [Euro08]).

The MLAT processor then has to solve the equations system for one specific sensor (sensor 1). The solution is given by the intersection among N-1 hyperboloids, where N is the number of sensors involved in the TDOA method. The hyperboloids equations are shown in (2.2) and the graphical solution in Figure 2-9:

$$\sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} - \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} = c_{[m/s]} \cdot (t_{i[s]} - t_{1[s]}), i \in \{2, 3, 4\}$$
(2.2)

Figure 2-9 - MLAT result (extracted from [Nev05]).
The solution of this system gives the airplane's position, but there is an error associated to the process, due to the error in the time-stamping, because sensors are not exactly synchronised. This error would increase if there was no time-stamping, because the accuracy of detecting the difference in propagation times in each link is smaller than the synchronisation accuracy. The more sensors involved in the process, the higher the system accuracy is [Euro08]. According to [Nev05], with a specific distribution of sensors, it is possible to achieve the SSR accuracy with only five sensors.

# 2.3 Telecommunications Systems Supporting Multilateration

### 2.3.1 Introduction

The telecommunication system to use depends on the requirements of the service for which it is supporting. In the case of MLAT it is shown if a certain feature of the telecommunication system is important or not. The characteristics to be evaluated are:

- Capacity: It is the most important feature of the majority of the systems, but concerning MLAT, it is
  one of the least important, because the exchanged messages are not very large and the required
  capacity is not very high. Even so, the maximum traffic of messages should be calculated to know
  the minimum capacity of the telecommunication link.
- Latency: It is the total time of the message to get from the airplane to the CP. It contains a system delay component, a delay in the telecommunication link, and the delay over air. It must be assured that the latency in the system does not exceed a certain value, and that the difference between the fastest and slowest sensors is lower than a certain time.
- Fading: It is a problem present in radio link communication channels. Although it does not happen in optical fibres, if one considers microwave links, it is necessary to take it into consideration.
- Distance: It is important to know the maximum distances achievable with each kind of link, because in the case of WAM link lengths may be quite large.

The goal of studying the communication links is to know which are the limitations or advantages in the possible systems to study. One considers optical fibres, microwave links, satellite links, and Virtual Private Networks (VPN).

## 2.3.2 Optical Fibre

The telecommunications system most used nowadays are optical fibres, because it is the type of communication link with the highest bit rates and less errors. The bit rate depends on the fibre and laser used, but the rates are much above the one that is required by a MLAT system. The communication channel, depends mostly on the fibre modes, it being either Single Mode Fibre (SMF) or Multi Mode Fibre (MMF).

Initially, MMF was used, since by having a larger core it is easier to inject the signal, hence, working

with worse lasers. MMFs support data rates from 10 Mbps up to 10 Gbps, with standards in development to support up to 100 Gbps [FOLS08]. The limitation in a fibre is given by the losses or the modal dispersion. The standards currently defined for MMF from ISO/IEC 11802 specifications are OM1 to OM4, and the values for the maximum attenuation and minimum modal bandwidth are given by the Table 2-2 [FIA10] and [FIA08].

Maximum Attenuation		Min b [N	imum m andwid ⁄IHz × k	iodal th m]	Maximum distance @ 100Mbs [km] maxir		maxin	Attenuation for the num distance [dB]			
Category	ory [ab/km]		LE	LED Laser		LED		Laser	LED		Laser
	850 nm	1300 nm	850 nm	1300 nm	850 nm	850 nm	1300 nm	850 nm	850 nm	1300 nm	850 nm
OM1	3.5	1.5	200	500	N/A	2	5	N/A	7	7.5	N/A
OM2	3.5	1.5	500	500	N/A	5	5	N/A	17.5	7.5	N/A
OM3	3.5	1.5	1500	500	2000	15	5	20	52.5	7.5	70
OM4	3	1	3500	500	4700	35	5	47	105	5	141

Table 2-2 – OM standards.

The minimal modal bandwidth imposes a maximum distance for a given transmission rate, which is shown in the previous table, based on:

(2.3)

$$L_{\max [km]} = \frac{B_{modal[MHz \times km]}}{R_{b[Mbps]}}$$

where:

- $L_{\text{max}}$ : Maximum fibre length.
- $B_{modal}$ : Modal bandwidth.
- $R_b$ : Transmission rate.

In the case of SMF, the core is smaller, having less dispersion than in the MMF. The limitation in this fibre is also from the fibre losses, but not from the modal dispersion, because there is only one mode propagating, so the other limitation is the chromatic dispersion. ISO/IEC 11801 specifies OS1 and ISO/IEC 24702 specify OS2, which have defined the maximum values for attenuation, shown in Table 2-3.

Table 2-3 - OS Standards (adapted from [FIA08]).

Wavelength [nm]	Maximum attenuation [dB/km]		
	OS1	OS2	
1310	1.0	0.4	
1385	Not specified	0.4	
1550	1.0	0.4	

Recent SMFs have chromatic dispersion compensation, so the limitation is only given by the fibre attenuation, which is imposed by the laser power, receiver sensitivity, and system margin.

Beside the fibre losses there are extra attenuations to be considered, the connector losses and splice losses that are used to connect different fibre sections to achieve higher lengths. Each element losses depend on the manufacturer, but there are maximum values recommended by the International Telecommunication Union - Telecommunication (ITU-T) shown in Table 2-4, the total losses being:

 $L_{p_{[dB]}} = L_{d[dB/km]} \cdot d_{[km]} + N_c \cdot L_{c[dB]} + N_s \cdot L_{s[dB]}$ (2.4) where:

- $L_p$ : Total path losses.
- $L_d$ : Attenuation coefficient with distance.
- *d*: Link length.
- $N_c$ : Number of connectors.
- $L_c$ : Connector losses.
- $N_s$ : Number of splices.
- *L<sub>s</sub>*: Splice losses.

#### Table 2-4 - Optical elements recommended loss (adapted from [ITUT09])

Attenuation coefficient	Typical link value [dB]
Splice	Maximum 0.5
Connector for SMF	Maximum 0.5
Connector for MMF	Maximum 1.0

The total latency for an optical fibre is given by [FOIA08]:

 $t_{link[s]} = t_{t[s]} + \tau_{link[s]} + t_{\theta[s]} + t_{fixed[s]}$ 

#### where:

- $t_{link}$ : Total link delay.
- $t_t$ : Transmission time.
- $\tau_{link}$ : Propagation delay.
- $t_{\theta}$ : Random jitter delay
- $t_{fixed}$ : Fixed delay.

Propagation delay is a characteristic that is of no concern, because the propagation speed can be roughly approximated by the speed of light divided by the optical index of the glass ( $n \sim 1,5$ ), which is fast enough for any system one may consider. Transmission time depends on the fibre transmission rate and the message volume ( $V_{msg}$ ), being given by:

$$t_{t[s]} = \frac{V_{msg[b]}}{R_{b[bps]}}$$
(2.6)

The major disadvantage of the fibre is the civil construction to install the cables, especially with a

(2.5)

point-to-point topology, which involves digging to protect the cables. Concerning capacity, distance and delay limitations, there are not any with this type of telecommunication link.

## 2.3.3 Microwave links

Another solution is the microwave links, being very much used when the distances are large, because unlike optical fibres, construction costs are minimal and high rates can also be achieved. The range of radio frequencies available in Portugal for microwave links is approximately from the 400 MHz to 30 GHz [Anac10].

The first step in the design of this type of links is to assure that there is LoS between both antennas, which depends on the antenna's height and elevation profile in between them. By considering Earth's effective radius, the radio horizon distance is given by [Rdg09]:

$$d_{\rm [km]} = 3.569 \sqrt{h_{t[m]}} + 3.569 \sqrt{h_{r[m]}}$$
(2.7)

where:

- $h_t$ : Height of the transmitter.
- $h_r$ : Height of the receiver.

In this thesis, there are two different cases to study, short distances around 2 km and long distances up to around 200 km, due to the differences between a WAM and LAM. For the former, path loss can be approximated by Free Space model, the received power being given by [Corr09]:

$$P_{r[dBm]} = P_{t[dBm]} + G_{t[dBi]} + G_{r[dBi]} - 20 \log \left(\frac{4\pi d_{[m]} f_{[Hz]}}{c_{[m/s]}}\right)$$
(2.8)

where:

- $P_r$ : Power received by the receiver.
- $P_t$ : Transmitted power.
- $G_t$ : Transmission gain.
- $G_r$ : Receiver gain.
- *f*: transmitting frequency.
- *d*: Distance between the antennas.

If a LAM system is considered, the path loss is estimated by the Flat Earth model, under the assumptions that  $d >> h_r$ ,  $h_t$  [Corr09]:

$$P_{r[dBm]} = -120 + P_{t[dBm]} + G_{t[dBi]} + G_{r[dBi]} + 20\log(h_{t[m]}) + 20\log(h_{r[m]}) - 40\log(d_{[km]})$$
(2.9)

The model for the multipath fading is given by [ITU09]:

$$P_{w[\%]} = K L_{[km]}^3 \left( 1 + \left| \varepsilon_p \right| \right)^{-1,2} \times 10^{0.033 f_{[GHz]} - 0.001 h_{L[m]} - \frac{L_{fad_{[dB]}}}{10}}$$
(2.10)

$$|\varepsilon_{\rm p}| = \frac{|h_{r[{\rm m}]} - h_{t[{\rm m}]}|}{L_{\rm [km]}}$$
(2.11)

$$K = 10^{-4.2 - 0.0029 dN_1} \tag{2.12}$$

where:

- $P_w$ : Probability of exceeding the attenuation value.
- *K*: Climate parameter.
- $\epsilon_p$ : Path inclination.
- *L<sub>fad</sub>*: Maximum fading attenuation.
- $h_L$ : Lowest height between the receiver and transmitter.
- $dN_1$ : Refractivity lapse rate in the first 65 m not exceeded for 1% of the year ( $dN_1 = -200$  in Portugal) [ITU03].

The final characteristic of a microwave link that influences its capacity is the bandwidth, which is also related to its cost, because when using a beam the frequency must be acquired from the regulator and the price is related to the bandwidth. There are many types of modulations that can be used, but binary modulations are not considered, taking M-PSK and M-QAM; obviously, when M increases the required signal to noise ratio also increases. The bit error probability is given by [Lei08]:

$$P_{b_{[M-PSK]}} = \frac{2}{\log_2 M} Q\left(\sqrt{2\log_2 M} \sin\frac{\pi}{M} \sqrt{\frac{E_b}{N_0}}\right)$$
(2.13)

$$P_{b_{[M-QAM]}} = \frac{4}{\log_2 M} \left( 1 - \frac{1}{\sqrt{M}} \right) Q\left( \sqrt{\frac{3\log_2 M}{(M-1)}} \sqrt{\frac{E_b}{N_0}} \right)$$
(2.14)

In order to achieve a certain bit error probability with a chosen modulation, by using (2.13) or (2.14), the required signal to noise ratio is calculated, which affects the link budget. The bandwidth of both modulations is the same, being a compromise between the nominal and optimum bandwidths with the goal of maximising spectral efficiency.

Table 2-5 - Spectral efficiency and bandwidth (extracted from [Lei08])

		Nominal	Optimum	
Modulations M-PSK and M-QAM	Bandwidth [Hz]	$B_{nom} = \frac{2R_b}{\log_2 M}$	$B_{min} = \frac{R_b}{\log_2 M}$	
	Spectral efficiency	$\rho_{nom} = \frac{R_b}{B_{nom}} = \frac{\log_2 M}{2}$	$\rho_{opt} = \frac{R_b}{B_{nom}} = \frac{\log_2 M}{4}$	

Every attribute depends on the used equipment, except the attenuation that depends on the environment. Beside propagation loss, one has to consider the absorption by the atmospheric gases for frequencies higher than 10 GHz [ITU09]. The total delay in a microwave link is the same as in the optical fibre, but in this case the propagation speed is considered to be equal to the speed of light.

These days, there is no problem to develop a microwave link to have enough capacity to support a

MLAT system. Concerning the distances involved in a WAM system, the microwave link is also enough, because even without LoS or with a too long path, repeaters may be used.

## 2.3.4 Satellite Link and Virtual Private Network

In case it is difficult to implement a proprietary solution, it is possible to rent one from any service provider with a network in the area. Abstracting from the system description itself, when a communication link is rented there are advantages and disadvantages. The advantages are that there is no need to design the communication link, not to maintain it, and investment capital is saved by not constructing the system. On the other hand, there are two main disadvantages: the service is contracted and needs to be paid for the leased time and bandwidth, as long as the system is working; the latency must be negotiated with the service provider in order to guarantee the required values. These links are usually satellite systems and VPNs.

There are three types of circular satellite orbits: Geosynchronous orbit (GEO), Medium Earth Orbit (MEO) and Low Earth Orbit (LEO), which the respectively altitudes are 35 786 km, [8 000, 20 000] km and [500, 2 000] km [ISAT11]. The communication frequencies for fixed satellite communications in Portugal are from 3.8 to 30 GHz [Anac10]. The major problem concerning a satellite link is the delay, so it must be taken into consideration, especially in a system with strict delay requirements, which is given by [Emm00].

$$t_{link[s]} = t_{t[s]} + \tau_{UL[s]} + \tau_{DL[s]} + t_{isl[s]} + t_{\theta[s]} + t_{fixed[s]}$$
(2.15)

where

- t<sub>UL</sub> and t<sub>DL</sub>: Uplink/downlink propagation delay depending on the orbit altitude of the satellite. For small distances, considering that the transmission angle is 90° to the surface plane, the distance is given only by the altitude.
- *t*<sub>*isl*</sub>: Inter-satellite link delay, which is not usually considered, because no matter the altitude of the satellite, for the distances in this case both communication ends are in the same satellite footprint.

Considering a GEO satellite, up- and downlink times approximately 238 ms, which is much more than any terrestrial link. In terms of using or not the satellite for a MLAT system, the maximum delay for the link must be carefully negotiated and compared with the maximum delay associated with the system. On the other hand, it is much easier to use a satellite link in a remote place, rather than any other terrestrial system.

The final telecommunication link to analyse is the VPNs. A VPN may have a complex implementation for the service provider in terms of security and routing, but is transparent for the user. It consists of using a public communication network to transport the information; obviously the path length and delay are not always the same, and although mainly optical fibres are used, it is not sure that there is not any other type of link in between.

Both VPNs and satellites work the same way from the surveillance agency viewpoint. Delays and price are negotiable. Knowing the MLAT system's requirements, mainly the delay and capacity, the ANSP

will have to guarantee them. The main difference between them is the price and the capacity available in both types of links. If there is the possibility of using a VPN, it should certainly be used, because of the smaller price and delay for the same capacity.

## 2.4 State of the art

Nowadays, MLAT is a surveillance technique that is being worldwide used, but still studies are being conducted to get more knowledge concerning this technique. This section intends to show the research that has been done in the past and what is being done now, in manly four areas: sensors synchronisation, algorithm for the TDOA, accuracy of the system, and sensors location.

The basis for the MLAT is the TDOA algorithm, which has been improving since the late 1980s when Smith and Abel in [SmAb87] proposed the spherical interpolated method. Many other methods have been proposed since, such as Chain and Ho in [ChHo94] or Savage et. al. in [SaCr06]. Still, the research in better and more efficient localisation algorithms is being performed with numerous articles. Every manufacturer has its own TDOA algorithm, which may differ a lot from each other and also influence the accuracy of the system.

There are studies, such as [BoZh10], which try to maximise the coverage for a given accuracy using genetic algorithms, but the main disadvantage is that in a real system, the localisation also depends on the construction site. To synchronise the sensors, if required, there are many ways of achieving it as discussed in Section 2.2.1. The two approaches more used are by using reference transmitters or satellite, the latter being recommended to use with more dispersed sensors [Chao09].

[Nev05] is a complete report to analyse the advantages and disadvantages of MLAT, and how to achieve a service equivalent to the SSR. They state that with five sensors the same accuracy as the SSR is achieved, among other information such as:

- The best signals to use in MLAT, which are the signals explained in this thesis.
- Possible synchronisation methods and their classification in terms of accuracy.
- Accuracy for specific sensor's geometrical configurations.
- Best way to choose the receivers.

With the development of the mathematical concepts behind MLAT, the improvement of the MLAT system itself has been mainly driven by MLAT manufacturers, the European Organisation for the Safety of Air Navigation (Eurocontrol), and the European Organisation for Civil Aviation Equipment (Eurocae). Most of the research available concerns test pilots performed in many different countries, and the advantages of adopting MLAT instead of the SSR. In October 2009, Eurocontrol published a press release, in [Euro09], after a workshop with an international group of experts stating, "*Wide Area Multilateration – A surveillance technique that is ready for use*".

There are four manufactures with implementation experience, Era, Roke Manor, Indra Systems, and

Sensis Corporation. All of these companies have experience developing any MLAT system for any region or airport (WAM or LAM). The main disadvantage is that when developing a new system, the ANSP may not be prepared to evaluate the planning in a critical way. On the other hand, all the responsibility to achieve the requirements is on the manufacturer's side, which has to be guaranteed.

# **Chapter 3**

# Models and Simulators

This chapter provides the description of the latency and coverage simulator and the associated models. Other models to assess a MLAT system are also described despite not being used in the simulators.

# 3.1 NAV Portugal Multilateration Systems

## 3.1.1 System Architecture

In Section 2.2, a general description of the MLAT algorithm and the sensors synchronisation has been presented. In a real MLAT system, there are many more components to provide basic functionalities that are not referenced in the theoretical analysis. This chapter intends to describe the top level architecture for the MLAT system installed in the Lisbon airport.

Figure 3-1 contains the current system installed in the Lisbon airport. There are four main components of the system, the transponders to equip the aircrafts or ground vehicles, the Remote Units (RUs) or sensors, the reference transmitters, and the Central Processing System (CPS), that contains the CP. All the components in the system are redundant, because in a critical system the hardware must be redundant in order to avoid single failures.

The first main component of the system is the transponder incorporated in the airplane or ground vehicle. This transponder is the communication equipment of the airplane that receives and transmits the surveillance messages, which for this system are Mode A/C, Mode S and ADS-B. In the case of the airplane, the transponder contains two antennas, one at the top and the other at the bottom. When airborne it uses both antennas alternately, while when on the ground the default transponder is the one on the top. The justification for using both antennas when airborne is mainly because sometimes, when changing routes, the bottom antenna can lose LoS for the receivers, so with both it is guarantee that at least one of them is at LoS.

RUs work as sensors in a MLAT system. Each RU can be configured as a receiver or transceiver: when acting as a receiver, it receives, decodes and timestamps Mode A/C, Mode S and ADS-B replies, while as a transceiver, it can also transmit 1030MHz interrogations. In addition, it has two more important capabilities, GPS interface and communication interface. The GPS interface is optional, but when used, the RU is able to receive time information signals and use them for time synchronisation. The communication interface connects the RU to the CP, via and communication system. In this specific case, only optical fibres are used [Sns09b].

The third main component is the Reference Transmitters (reftrans), which are responsible for the time synchronisation of the sensors. Instead of using GPS synchronisation, reftrans transmit DF 18 squitter messages at a rate of approximately one per second. DF 18 messages have exactly the same structure of DF 17 in Figure 2-4, but it is also used for a ground vehicle. It is through these messages that synchronisation is achieved.

Finally, there is the CPS, which is an Ethernet-based Local Area Network (LAN) with communication and data processing equipment. Data is collected from the different sensors and distributed threeways, so that the target position is calculated and displayed. Two data streams are forward to the primary and secondary operational system, while the third stream is used for a test system.



Figure 3-1 - System Architecture Lisbon (extracted from [Sns09c]).

Even though there are two operational systems, they are equivalent, since both simultaneously process replies; the only difference between them, if no failure is reported, is that only the primary system provides output reports. When detected any failure in the primary system, the secondary assumes the role of primary. As shown in Figure 3-1, the main components of the CPS are:

- Target Processor (TP), processes the sensor replies, which means calculating the three dimensional position based on the TDOA algorithm.
- Maintenance Display Terminal (MDT) provides display, such as, target positions, statistics, data recording and system archival. Sensors in normal operating mode are controlled through this component. There are two MDTs, one local and another for remote access.
- Cisco Smart Switch multiplexes data from every sensor to the correspondent TP.
- HP Switch is used for internal communication between the TPs and MDTs. Internet Group Management Protocol has been enabled in these switches for correct handling of multicast data.

There is one last component of the system outside the CPS, which is the eLCMS (embedded Local Control Monitoring System) that provides fault diagnostics and local control over the RUs.

To avoid failures in the operative system, the test system was also implemented to evaluate the impact of any changes or to test any possible improvement before executing it on the operational systems. The test system shares the Cisco Smart Switch with the primary target processor, but besides that, has an independent system with its own TP, HP Switch and MDT. Any RU can be controlled by the test MDT, but then it stays offline for the operational system's MDT so that any change does not impact the on operational system.

## 3.1.2 Support Communication System

Sensors are spread through the terrain, and to connect each one of them to the CP, a telecommunication link is required for each of them. In the Lisbon LAM it was chosen to use a point-to-point topology with two optical fibres per sensor, each one for a communication link, uplink and downlink. There were two options available for the fibres, SMF and MMF. Table 3-1 contains the description of both types of fibres, but in the Lisbon system only SMFs were used. Instead of optical fibres, any other communication link could have been chosen. The latency specifications are that the latency between the fastest and slowest link does not exceed 500 ms.

The information exchanged in the fibre lines between the RUs and the TP is typically Internet Protocol (IP) with a connection-less scheme; besides the message itself, it is added the IP header, User Datagram Protocol (UDP) header, Internet Group Management Protocol version 2 (IGMP v2) header and finally the Ethernet frame header, the specific values of the overheads being shown in Table 3-2 [Nav11]. It must be noticed that other headers can be used by different manufacturers.

As explained in Chapter 2, squitter messages have a minimum rate in messages per second that also depends on the airplane or vehicle positions. For the specific system implemented in Lisbon, the different messages rate corresponding to the different formats available are given by Table 3-3 [Nav11]. The types of messages inherited from SSR, Mode A/C and Mode S, do not have a fixed

sending frequency, but if this system is a real substitution of the SSR, it means that it has to achieve at least the highest frequency of the previous system. Taking into consideration that the SSR could only make an interrogation on each rotation period for each airplane, and having a rotation period of 4 s the frequency of this SSR is considered 0.25 messages per second.

Specification/Standard	SMF Description	MMF Description	
Output	Ethernet over Fibre	Ethernet over Fibre	
Fibre Cable [µm]	9	50/62.5	
Max Distance [km]	10	2	
Max Data Rate [Mbps]	100	100	

Table 3-1 - SMF/MMF Specifications and Standards (adapted from [Sns09b])

Table 3-2 – Overheads in MLAT messages

Header	Overhead [Bytes]
Ethernet Frame	14
IP	20
UDP	8
IGMP v2	8
Total Overhead	50

Table 3-3 - Exchanged messages rates and sizes [NAV11]

Surveillance System	Downlink Format	Transmitted Information	Size [B]	Size with overhead [B]	Frequency [msg/s]
	DF17	Position or velocity updates	14	64	Moving: 4 Stationary: 0.2
ADS-B	DF17	Airplane identification and callsign	14	64	0.2
	DF18	Position or velocity updates for a vehicle or RefTrans	14	64	Moving: 4 Stationary: 0.2
	DF11	Airplane address	7	57	Airborne: 1
	DF4/DF5	Airplane identification or altitude code	7	57	0.25
Mode S	DF20/ DF21	Airplane identification or altitude code plus real-time data reports	14	64	0.25

Before the model implementation, and to analyse values given by the manufacturer, it is necessary to calculate some parameters that are directly related to the communication system, such as the rate and volume of the exchanged messages. These variables depend on the number of airplanes at range, the traffic generated, and size of the exchanged messages. The system must guarantee at least 250 airplanes or vehicles simultaneously [NAV08] and the different message sizes and frequencies that they are sent are shown in Table 3-3. The following equations are defined to calculate the expected traffic:

$$\overline{T_{S}}_{[bps]} = N_{air} \times (V_{SL[b/msg]} \times \overline{\lambda_{SL}}_{[msg/s]} + V_{SS[b/msg]} \times \overline{\lambda_{SS}}_{[msg/s]})$$
(3.1)

$$\overline{T_{ADS}}_{[bps]} = (N_{air} + N_{veh}) \times V_{SL[b/msg]} \times (r_{\%}^{air} \times \overline{\lambda_{ADS-air}}_{[msg/s]} + r_{\%}^{mv} \times \overline{\lambda_{ADS-mv}}_{[msg/s]} + r_{\%}^{sta}$$

$$\times \overline{\lambda_{ADS-sta}}_{[msg/s]})$$
(3.2)

where:

- $\overline{T_s}$ : Average traffic for Mode S messages transmitting Mode A/C information.
- $\overline{T_{ADS}}$ : Average traffic for ADS-B.
- *N<sub>air</sub>*: Number of airplanes at range.
- *N<sub>veh</sub>*: Number of vehicles.
- $\overline{\lambda_{SL}}$ : Average message arrival rate per airplane for long Mode S.
- $\overline{\lambda_{SS}}$ : Average message arrival rate per airplane for short Mode S.
- $\overline{\lambda_{ADS-air}}$ : Average message arrival rate per airborne target for ADS-B.
- $\overline{\lambda_{ADS-mv}}$ : Average message arrival rate per moving target for ADS-B.
- $\overline{\lambda_{ADS-sta}}$ : Average message arrival rate per stationary target for ADS-B.
- $r_{\frac{v}{2}}^{air}$ : Ratio of targets airborne.
- $r_{\%}^{mv}$ : Ratio of targets moving.
- $r_{\%}^{sta}$  : Ratio of targets stationary.
- *V<sub>SS</sub>*: Size of short Mode S messages.
- *V<sub>SL</sub>*: Size of long Mode S messages equivalent to ADS-B.

The capacity estimation also depends on the area each sensor covers and theirs receiving probability. To study the coverage of each sensor, it is necessary to analyse the intersection between the sensor's coverage areas with the MLAT area. Concerning the receiving probability, it obviously reduces the traffic expected in the link, but also decreases the probability of the success of the TDOA algorithm, because to have a successful localisation in the CP, 4 sensors must receive the message.

### 3.1.3 Localisation Requirements

There are always standard requirements in a surveillance system, especially in the airplane probability of detection. The requirements for this system in terms of probability of detection are defined by Eurocae [NAV11]:

- Track Initiation: it is defined as the time from when an airplane enters the operational coverage area to the output of the first position from the MLAT system.
- Continuous tracking: it is defined as the time between two consecutives position updates.

From the Eurocae recommendations, the track initiation shall be less or equal to 5 times the defined update interval with the probability of 99%, and the continuous tracking less or equal to the update interval with the probability of 97%. For the continuous tracking, only one successful MLAT position is required, but for the track initiation two or three consecutive ones are required. The update interval for the WAM system is 5 s [NAV11].

The localisation probability depends only on the sensor's receiving probability, the number of messages sent, and the number of sensors at LoS of the target. To calculate the probability of executing successfully the TDOA algorithm, it is used:

$$p_{TDOA} = 1 - (\sum_{0}^{3} p_i)$$
(3.3)

$$p_i = C_i^{N_{sensor}} \times p_{nrec}^{(N_{sensor}-i)} \times (1 - p_{nrec})^i$$
(3.4)

where:

- $p_{TDOA}$ : Probability of having enough sensors to execute the TDOA algorithm.
- *p<sub>i</sub>*: Probability of the CP receive i messages.
- *N<sub>sensor</sub>*: Number of sensors covering the area.
- $p_{nrec}$ : Probability of a sensor not receiving a message sent from an airplane.

Having the probability of executing the TDOA with one message sent, it is possible to verify the localisation requirements. Starting with the continuous tracking, it must be assured that an airplane position is refreshed every 5 s. This probability depends on the number of messages sent within the update interval and the probability of executing the TDOA algorithm. The continuous tracking probability is given by:

$$p_{CT} = 1 - (1 - p_{TDOA})^{INT(\lambda_{air[msg/s]} \times \Delta_{interval[s]})}$$
(3.5)

where:

- $p_{CT}$ : Probability of continuous tracking.
- $\lambda_{air}$ : Rate of messages sent by an airplane airborne.
- $\Delta_{interval}$ : Update time interval, in this case its 5 seconds.

Finally, it is necessary to define the track initiation probability. Knowing the number of messages sent from an airplane in 5 update intervals, the probability of successfully initiating a tracking is the probability of having a sequence of two or three TDOA positions. The parameter that determines the number of consecutive messages required to initiate the tracking depends on the system's configuration, but the referred values are the most common cases [NAV11].

It is a simple matter of probabilities, but the solution is not trivial. To obtain this probability, a Markov chain is used, and for the specific situation of requiring three messages, the Markov chain diagram is given by Figure 3-2. The states identified by S0, S1, S2 and S3 represent the number of consecutive position calculation and p is the probability of executing the TDOA algorithm.



Figure 3-2 - Markov chain for track initiation problem.

The solution of the  $n^{th}$  iteration of a generic Markov chain is given by:

$$\vec{u}^{(n)} = \vec{u}^{(0)} \times M^n \tag{3.6}$$

where:

- $\vec{u}^{(0)}$ : Vector with the initial state.
- $\vec{u}^{(n)}$ : Probability vector of each state in the  $n^{th}$  iteration.
- *M<sup>n</sup>*: Transition matrix of the Markov chain power to the number of iterations.

The transition matrix depends on the Markov chain of the specific problem, and so the solution for a sequence of two or three is different. The transition matrix for a sequence of three,  $M_3$ , and the matrix for a sequence of two,  $M_2$ , are:

$$\boldsymbol{M}_{3} = \begin{bmatrix} 1 - p & p & 0 & 0 \\ 1 - p & 0 & p & 0 \\ 1 - p & 0 & 0 & p \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
(3.7)
$$\boldsymbol{M}_{2} = \begin{bmatrix} 1 - p & p & 0 \\ 1 - p & 0 & p \\ 0 & 0 & 1 \end{bmatrix}$$
(3.8)

Considering that the initial state is S0 and solving (3.6), the vector  $\vec{u}^{(n)}$  contains the probability of being in each state. The interesting result for this analysis is the probability of being in S3, for 3 consecutive messages, or S2 for two consecutive messages.

This Section allows concluding about the number of sensors required for any MLAT system, and to assess if the requirement of 4 sensors is enough to meet them.

## 3.2 Latency Model

As previously discussed, the latency in a MLAT system may be critical, and therefore it must be analysed, mainly to study the influence of having mixed links in the system. A model is developed to analyse the global delay involved in a MLAT system, which depends on the communication links used and the airplane position. Two different scenarios are analysed, LAM and WAM systems. The model separates between two components, the air interface and the link.

Firstly, the propagation delay in the air interface  $(\tau_{air})$ , which is the time elapsed between the airplane and the sensor calculated by (3.10). Secondly, the delay in the communication channel  $(t_{link})$ , which depends on the type of communication link used. In the case of being an optical fibre or a radio link (2.5) is used, while if it is a satellite link one uses (2.15). There is a particularity, more common in the radio links, which is the existence of more than one hop until the final destination is reached. This implies that the total link delay is given by the sum of each hop delay, where *i* is the hop number: The synchronisation delay ( $t_{sync}$ ) is related to the maximum difference between the reception of the MLAT signals. The processor needs to collect the different data from the different sensors, so the first signal to arrive to the CP will have to wait until the last one arrives. The synchronisation delay for a given sensor is calculated from (3.11), while the final synchronisation delay for the entire system is given by the maximum synchronisation time of each of the individual sensors. The limitation in this system, as discussed before, is given by the time of synchronisation that should be no higher than 500 ms. Figure 3-3 shows the schematic for the latency model.

$$\tau_{air_{i[s]}} = \frac{|\vec{r}_{air} - \vec{r}_{RUi}|_{[m]}}{c_{[m/s]}}$$
(3.10)

$$t_{sync_{i[s]}} = max \left\{ (\tau_{air_{n[s]}} + t_{link_{n[s]}}) - (\tau_{air_{i[s]}} + t_{link_{i[s]}}) \right\}, \qquad n \in [1, N_{sensor}]$$
(3.11)

#### where:

- $\vec{r}_{air}$ : Position of the airplane.
- $\vec{r}_{RUi}$ : Position of the airplane and sensor, respectively.







The synchronisation time and the channel delay calculations have been explained, but the air propagation time has only been referenced as a distance between two position vectors divided by the speed of the signal. If the problem consisted in a simple plane with coordinates (x,y,z), it would be calculated by a Pythagoras theorem, but in a real situation there are two differences. Firstly, Earth is a sphere, and secondly, the positions are given in angles (geographical coordinates). The problem is shown in Figure 3-4, and it is separated into two different steps: calculating the ground distance between the airplane and the sensor (d), and then solve the length of the direct ray.



Figure 3-4 - Air propagation distance.

The shortest path between two points, A and B, on a sphere is called the orthodrome. Given the coordinates of each point the ground distance are known [Kui99]:

$$\theta_{[rad]} = acos(\cos\phi_{B[rad]}\cos(\lambda_{A[rad]} - \lambda_{B[rad]})\cos\phi_{A[rad]} + sin\phi_{B[rad]}sin\phi_{A[rad]})_{[rad]}$$
(3.12)

$$d_{[NM]} = R_{Earth_{[NM]}} \times \theta_{[rad]}$$
(3.13)

where:

- $\phi_A$ : Latitude of the point A.
- $\lambda_A$ : Longitude of the point A.
- $\phi_B$ : Latitude of the point B.
- $\lambda_B$ : Longitude of the point B.
- *R<sub>Earth</sub>*: Earth effective radius in nautical miles.
- $\theta$ : Angle between point A and B.

In order to calculate the length of the direct ray, three hypotheses have been tested: flat Earth (Figure 3-5), spherical Earth, and a simplification of the spherical Earth. The flat Earth model is the simplest, and it is only valid for short distances in which the Earth curvature is negligible [Fig02]. Earth radius should be taken into account for large distances, namely beyond the radio-horizon [Corr09].





Direct 
$$ray_{[NM]} = \sqrt{(h_{RU[NM]} - h_{air[NM]})^2 + d_{[NM]}^2}$$
 (3.14)

where:

- $h_{RU}$ : Sensor's height.
- *h<sub>air</sub>*: Airplane's altitude.
- *Direct ray*: Distance separating the airplane from the sensor.

The second hypothesis is the most accurate one, because it uses a theoretical model to account for Earth radius. This model shows different results from the flat one, especially for large distances. The schematic for the Earth model is also represented by Figure 3-4 and it solves the problem by approximating the sphere to a flat model but with a correction of the sensor's and airplane's height, called effective height. The height correction is related to the distance from the reflection point. The equations necessary to correct the heights of the sensor and airplane are (3.15), (3.16), (3.17), (3.18) and must be solved in that order [Fig02]. After that, (3.14) is used with both heights corrected.

It must be taken into consideration that this calculation is performed for each airplane position as many times as the number of sensors in the network. Solving a third degree equation when multiple points are being analysed may result in a high simulation delay.

$$d_{1[NM]}^{3} - \frac{3}{2} d_{[NM]} d_{1[NM]}^{2} + (\frac{1}{2} d_{[NM]}^{2} - R_{Earth[NM]} (h_{RU[NM]} + h_{air[NM]}) d_{1[NM]} + h_{RU[NM]} R_{Earth[NM]} d_{[NM]}) = 0$$
(3.15)

 $d_{\rm [NM]} = d_{1 \rm [NM]} + d_{2 \rm [NM]}$ 

$$h_{ef-RU[NM]} = h_{RU[NM]} - \frac{d_{1[NM]}^2}{2R_{Earth[NM]}}$$
(3.17)

(3.16)

$$h_{ef-air[\text{NM}]} = h_{air[\text{NM}]} - \frac{d_{2[\text{NM}]}^2}{2R_{Earth[\text{NM}]}}$$
(3.18)

#### where:

- $h_{ef-RU}$ : Equivalent sensor's height in the flat Earth model.
- $h_{ef-air}$ : Equivalent airplane's height in the flat Earth model.
- $d_1$ : Ground distance between the sensor and the reflection point.
- *d*<sub>2</sub>: Ground distance between the airplane and the reflection point.

The third and last model is only valid for the WAM system, the simplification coming from the fact that the altitude of the airplane is many times larger than the sensor's height, even considering sensors in high hills. This fact implies that the point of specular reflection is in the nearby region of the sensor, resulting in a very small  $d_1$  compared with  $d_2$ . Using this simplification, (3.19), the effective heights of the airplane and sensor is given by (3.20) and (3.21).

$$d_{[NM]} \cong d_{2[NM]} \tag{3.19}$$

$$h_{ef-RU[NM]} = h_{RU[NM]} \tag{3.20}$$

$$h_{ef-air[\text{NM}]} = h_{air[\text{NM}]} - \frac{d_{[\text{NM}]}^2}{2R_{Earth[\text{NM}]}}$$
(3.21)

Considering the three possible ways to calculate the length of the direct ray, the relative error of the models comparing to the spherical Earth model is less than 0.08 % for the flat Earth, and less than 0.002% for the spherical Earth simplification, assuming:

• 
$$h_{RU} \in [5, 2000] \text{ m}$$

•  $h_{air} \in [9500, 29500]$ ft

• *d* ∈ [0, 200] NM

It is reasonable to assume that any model can be used for a MLAT system, but the spherical Earth model is not used because of the elapsed time solving the third degree equation. For the LAM analysis, the flat Earth model is used, and for the WAM analysis, the spherical Earth simplified one is used. The latter allows prevention of the increase in the coverage radius that is possible in other MLAT systems.

This model is used to predict the difference between the times of arrival to the CP originated by the messages sent from every sensor. It should be noticed that two effects are not being considered: the deviation of the MLAT system processing time, and the extra delay by using more than one link. This last effect can be for either using two different types of links or having more than one hop, and in both cases there is a time elapsed for receiving the message and forwarding it to the next link.

This section gives the basic equations and foundation for the implementation of the latency simulator, which calculates the expected delay for airplanes located in a given position.

## 3.3 Maximum Latency Model

NAV's Lisbon WAM system, which is already being implemented, will have all of the sensors outside the airport, except one, with VPN links to connect them to the CP. It is essential to have an estimation of the maximum tolerable delay that these links must support, in order to negotiate with the service provider. The prediction of this latency is quite similar to the latency model, but in this case it considers that the fastest sensor is one of the sensors located in the airport.

The latency between different RUs depends on the position of the airplane, but the maximum value of the difference is given by the distance between both sensors, plus the difference in the link delay. Figure 3-6 contains a schematic analysis to model the maximum distance between two sensors and an airplane. In this case, it considers that one sensor is located in the airport and the other is any WAM sensor. In Figure 3-6,  $d_b$  is defined as the shortest path between the airplane and the WAM sensor,  $d_a$  the same distance but to the airport sensor, and  $d_{\Delta}$  the distance between both sensors. It is easily seen that the alternative path to the sensor WAM ( $d_a + d_{\Delta}$ ) is always larger than  $d_b$ . By analysing the worst case in Figure 3-6, the conclusion is that the maximum difference between  $d_a$  and  $d_b$  is  $d_{\Delta}$ .

The equation describing the solution for the maximum delay in a VPN is:

$$t_{VPN\,i[s]} = t_{synch[s]} - \Delta t_{system[s]} - \Delta \tau_{air\,i[s]} + t_{link\,f[s]} - t_{extra[s]}$$
(3.22)

where:

- t<sub>VPN i</sub>: Maximum delay for the rented VPN system for sensor i.
- t<sub>synch</sub>: Maximum synchronisation time allowed by the system.

- $\Delta t_{system}$ : Time difference based in the standard deviation of the MLAT system processing time.
- $\Delta \tau_{air i}$ : Difference in propagation time between the slowest and the fastest sensor.
- $t_{links f}$ : Link delay of the fastest sensor.
- t<sub>extra</sub>: Extra delay in the VPN because the signal arrives to the NAV Portugal building and not the CP which has an extra 2 721 m of length [NAV11].



Figure 3-6 - Maximum distance (adapted from [Sns09c]).

Every value in (3.22) is easy to calculate, except  $\Delta t_{system}$  and  $t_{extra}$  that do not have a theoretical approach. First, the system processing time includes the time the sensor takes to receive the message, the time stamping, the time forwarding the message to the communication link, and the receiving time in the CP, and these values can only be calculated from real measures. It is necessary to test the system and analyse the delays to estimate this time. A test option is implemented to measure this delay, which sends messages from the CP to the sensor, and then the sensor processes the message and returns it to the CP. The system measures the time elapsed in this process, Communication Round Trip Time (CRTT), and its standard deviation:

$$CRTT_{i[s]} = 2t_{link\ i[s]} + t_{fixed\ i[s]}$$
(3.23)

$$\overline{t_{fixed}}_{[s]} = \frac{\sum_{1}^{n_{max}} t_{fixed i[s]}}{N_{sensor}}$$
(3.24)

$$\overline{\sigma_{fixed}}_{[s]} = \sqrt{\left(\sum_{1}^{N_{sensor}} \sigma^2_{CRTT \, i}\right) \frac{1}{N_{sensor}}}$$
(3.25)

where:

- *CRTT<sub>i</sub>*: CRTT for sensor *i*.
- *t<sub>fixed i</sub>*: System processing time, for sensor *i*.
- $\overline{t_{fixed}}$ : Average system processing time.
- $\sigma_{CRTT i}$ : Standard deviation of the CRTT of sensor *i*.

 $\overline{\sigma_{fixed}}$ : Average system standard deviation.

Considering that the system processing time is given by a Gaussian distribution, one has to consider this delay variation with a certain confidence interval to calculate the maximum delay in the VPN links.

Finally, there is the extra delay that is also a problem in the latency model. If a link has more than one hop, there is an extra processing time due to the time elapsed forwarding the message from a link hop to the next one. This extra delay may also depend on the type of links, since delays differ if it is radiofibre or radio-radio. There are two ways to consider this value: either there are measured values in real links to estimate, or the same processing time of the sensors can be taken. The latter is obviously the worst case possible, because there is no process in the message to extract information or time stamping when forwarding from one link to another.

With this model, it is possible to predict the maximum allowed latency, but there are random times involved and their standard deviation should be considered. Having the values for the delay, they can be compared with the telecommunications offer.

#### 3.4 **Flight Routes**

One has to know exactly where the airplanes are, in order to simulate their possible positions. This section is used in the latency simulator, to calculate the different airplane positions.

In the airspace, if airplanes were to use always the shortest path between two points, their route would be defined by the orthodrome, described in the Section 3.2, but this means that the route angle would always change, which does not lead to an easy navigation. Therefore airplane routes are defined by a loxodrome, i.e., the path that take us from one point to another always following the same angle, allowing a much easier navigation. Airspace routes have many checkpoints and the angles are always changing, but they are the same in between two contiguous checkpoints, each route being defined by a specific name and Flight Level (FL).

Figure 3-7 is presented as an example of the airspace in the area of Lisbon, including the coverage radius of 30 NM from the airport. These are also examples of test positions that can be defined in the simulator, although it must be taken into consideration that the angle that defines the loxodrome is different from the one shown in the map. This happens because the magnetic North is different from the actual North, the magnetic North being the angle that the navigation equipment measures and the actual North the theoretical angle used in models. Figure 3-7, and every navigation map, contains always the magnetic angle and not the actual angle, the relation between them being given by:

$$\alpha_{real[\circ]} = \alpha_{mag[\circ]} - \alpha_{dec[\circ]}$$
(3.26)

where:

 $\alpha_{real}$ : Real route angle.

- $\alpha_{mag}$ : Magnetic route angle.
- $\alpha_{dec}$ : Declination angle given in relation to West.



Figure 3-7 - Airplane routes in the Lisbon region [NAV10]

The loxodrome angle that connects two points, A and B, and the path length ( $d_{path}$ ), are given by [Kui99]:

$$\alpha_{real[rad]} = \operatorname{arccot}\left(\frac{\sum \phi_B - \sum \phi_A}{\lambda_{B[rad]} - \lambda_{A[rad]}}\right)_{[rad]}$$
(3.27)

$$\Sigma \phi_i = \ln\left(\tan\left(\frac{\pi}{4} + \frac{\phi_{i[\text{rad}]}}{2}\right)\right) \tag{3.28}$$

$$d_{path[NM]} = R_{Earth[NM]} \times \left| \phi_{B[rad]} - \phi_{A[rad]} \right| \times \left| sec\alpha_{real[rad]} \right|$$
(3.29)

where:

•  $\sum \phi_i$ : Vertical spacing of the parallel *i*.

Through these equations, it is possible to estimate the declination of any map, by calculating the real angle between two points, (3.27), and with the real angle given by the maps. Using both angles in (3.26), the declination is retrieved. The longitude defined with West coordinates is negative, and it must be taken into account that there always two solutions when using trigonometric functions. There is also a specific case, which is when an airplane is travelling always in the same parallel, occurring for  $\alpha_{real}$  equal to 90° or 270°. Using (3.29) the distance of the path would be zero, because  $\phi_{B}$  [rad] –  $\phi_{A}$ [rad] = 0; instead (3.30) is used [Alx04]:

$$d_{path[NM]} = R_{Earth[NM]} \times \frac{\lambda_{B[rad]} - \lambda_{A[rad]}}{\sec \phi_{[rad]}}$$
(3.30)

The value  $\sec \phi$  is the stretching factor, depending on the parallel latitude. If the airplane were to travel

the equator, then this equation would be the equivalent to (3.30) with an angle of 0° or 180° [Alx04].

From the previous equations, one can also be concluded that a path can be defined from either a starting position and an angle or two different positions. Two test possibilities are considered: a section defined by two points, and a route defined by a starting point and a route angle. The difference between them is that a section is always the path between both specified points at a certain altitude, and the route calculates the intersection from the starting point with the desirable coverage radius. With these two types of testing positions, it is possible to define every path of an airplane, being limited to the coverage radius or not. It is complex to define a circle with latitude and longitude and intersect it with a route; an easier approach is to travel through the route until the distance between the point and the centre of the coverage area is approximately equal to the radius.

The last type of testing position is a particular case, approach to the runway, which is obviously very used, but has different characteristics from the section or route. Details of the approach are described in [NAV10], but it was decided [NAV11] that the approach should be defined by the runway orientation angle, starting point of the approach, initial altitude, and descent angle in percentage. Figure 3-8 shows part of the approach definition for a runway in the Lisbon airport, containing the required parameters (except the runway angle, which is included in [NAV10]). The approach distance and the altitude are given by:

$$d_{path[ft]} = \frac{h_{initial[ft]} - h_{final[ft]}}{\tan(\alpha_{desc[rad]})}$$
(3.31)

$$h_{i[ft]} = h_{initial[ft]} - d_{i[ft]} \times \tan(\alpha_{desc[rad]})$$
(3.32)

where:

- *h*<sub>initial</sub>: Initial Mean Sea Level (MSL) approach altitude.
- *h<sub>final</sub>*: Airport MSL height.
- $\alpha_{desc}$ : Descent angle.
- $h_i$ : Height in a specific point of the approach.
- $D_i$ : Relative distance from the starting point.

Unlike single points, every other test types have a certain number of points in the path they define, so one must also include the number of test points for each path. The coordinates of the path separated by a given interval are:

$$d_{interval[NM]} = \frac{d_{path[NM]}}{N_{points} - 1}$$
(3.33)

$$\phi_{i[\text{rad}]} = \phi_{initial[\text{rad}]} + \frac{d_{interval[\text{NM}]}}{R_{Earth[\text{NM}]} \times |sec(\alpha_{real[\text{rad}]})|} \times (i-1)$$
(3.34)

$$\lambda_{i[rad]} = \lambda_{initial[rad]} - \frac{\left(\sum \phi_{i[rad]} - \sum \phi_{initial[rad]}\right)}{\cot(\alpha_{real[rad]})}$$
(3.35)

where:

- *d<sub>interval</sub>*: Distance between fixed intervals.
- $N_{points}$ : Number of points to test in the path.

• *i*: Test position, if i = 0 is the initial point and if  $i = N_{points} - 1$  is referring to the final point.



It should be noticed that the latitudes and longitudes may be positive or negative depending on the airplane position: latitude is positive if the airplane is in the North hemisphere, and longitude is positive when related to the East.

In summary, this Section contributes to the definition of the types of airplane positions that can be used in the simulator, i.e., single points, sections, routes, and approaches.

## 3.5 Coverage model

In a MLAT system, every sensor has its own coverage map, being essential to know them, in order to predict the required number of sensors in the whole system.

The first part of the coverage analysis is to get the land profile for each azimuth, which can be achieved through Google servers, which are the basis for services like Google Maps or Google Earth. An example of a land profile analysis retrieved from Google Earth is shown in Figure 3-9. Land elevation values are given by the ground distance from the initial point, and if small distances are considered this graph would be the only thing required to make the calculations; but, as explained in latency model, flat Earth can only be applied for small distances. To calculate the coverage map, the spherical Earth model is used, which assumes that the height of the ground sensor, airplane and land obstacles are much smaller than the Earth radius.



Figure 3-9 - Google Earth elevation profile.

Firstly, one needs to calculate the specular reflection point, which in this particular case is not directly related to the point in which there is the reflection, but to the radio horizon distance [Fig02].

$$d_{RH[km]} = \sqrt{h_{[km]} \times 2R_{Earth[km]}}$$
(3.36)  
where:

•  $d_{RH}$ : Radio horizon distance of the specified position.

• *h*: Height in the specified position.

In Figure 3-10, the specific problem is described: every obstacle has a height correction, depending on the distance from the tangent to the Earth surface, which is located at a distance of  $d_{RH-RU}$  from the sensor. Land elevations in the same reference plane are given by:

$$h_{ef\ obs[km]} = h_{obs[km]} - \frac{\left| d_{RH-RU[km]} - d_{obs[km]} \right|^2}{2R_{Earth[km]}}$$
(3.37)

where:

- $d_{obs}$ : Distance from the sensor to the obstacle.
- $d_{RH-RU}$ : Radio horizon distance for the sensor, using (3.36).
- *h*<sub>obs</sub>: Height of the obstacle.

Equation (3.37) considers that  $d'_i \cong d_i$ , meaning that any distance in the new reference plane is approximately the same as in the Earth surface. From all elevations in the same reference plane, dotted line in Figure 3-10, the coverage line is calculated.

For each obstacle, there is a coverage line with an angle,  $\psi_{obs\,i}$ , the goal being to determine the final coverage line angle,  $\psi$ , that is given by the highest  $\psi_{obs\,i}$ . Each angle depends on the distance from the sensor and the obstacle's height. Sensor's height does not need to be considered, because its equivalent height in the reference plane is always zero. The coverage angle  $\psi_{obs\,i}$  is given by:



Figure 3-10 - Coverage diagram model.

Figure 3-10 illustrates two different airplane positions: position 1 and position i. The former is the case in which there is no obstruction, hence, the coverage distance is given by the sum of the radio horizons of the sensor plus the one of the airplane. For the latter, the coverage distance is given by the intersection of the airplane with the coverage line, i.e.:

$$d_{air[km]} = \frac{h_{ef \ air[km]}}{tan\psi} \tag{3.39}$$

The effective height of the airplane is calculated in the same way as used for obstacles, (3.37), but it also depends on the distance between airplane and sensor. Replacing (3.37) in (3.39) and simplifying:

$$\frac{d_{air[km]}^2}{2R_{Earth[km]}} + d_{air[km]} \times \left(tan\psi - \frac{d_{RH-RU[km]}}{R_{Earth[km]}}\right) + \frac{d_{RH-RU[km]}^2}{2R_{Earth[km]}} - h_{air[km]} = 0$$
(3.40)

The solution of (3.40) gives the cover distance for a given airplane's height and azimuth. All these steps enable the calculation of coverage for a given azimuth, but the coverage of a sensor needs to be radial, meaning that this calculation needs to be performed for many azimuths in [0°, 360°].

The sensors are limited to a maximum range and can even be limited by configuration, so this parameter may be different for each sensor. After analyzing two reference suppliers of MLAT sensors, Comsoft [Com11] and ERA [ERA10], the first has a maximum coverage of 250NM while the other has 200NM. From the market availability, the maximum possible range of the sensors is considered to be around 200 NM. The parameter of the range must also be considered in the coverage analysis and the maximum coverage cannot exceed this limitation of the equipment. After calculating  $d_{air}$ , it must be compared with the maximum allowed distance between the airplane and the sensor.

To calculate the maximum range for a given FL, two equations must be used, (3.37) and (3.41).

$$d_{air-\max[km]} = \sqrt{d_{range[km]}^2 - h_{ef air[km]}^2}$$
(3.41)

where:

- *d<sub>range</sub>*: Maximum range of the sensor.
- *d<sub>air-max</sub>*: Maximum covering distance on the ground for the specific flight level.

The intersection of the flight level with the coverage line results in a second degree equation, (3.40), but for the maximum distance the solution is given by a fourth degree one. Due to this fact, and also considering that these calculations are done only once for each sensor, an iterative process is used. With the coverage distance and the maximum distance, for each azimuth, the final coverage is given by the minimum of  $(d_{air-max}, d_{air})$ .

All the procedures to analyse the coverage of a given sensor have been shown, but for a MLAT system our interest is for many sensors, so a way of classifying each sensor is required. Two comparisons have been developed for the individual coverage in the required area: qualitative and quantitative. Maps are divided into the covered districts and the Terminal Manoeuvring Area (TMA), the latter region being included because it requires a special attention due to particular requirements.

Starting by the qualitative analysis, it is useful to know which area inside the district is really covered, as well as a notion of the quantity covered. Table 3-4 contains the legend to be used when classifying each of the districts, four main categories being considered: total, almost total (total -), half and nothing (0). The category Total-NE and Half S are only shown as example and it must be noticed that any other combination of geographical directions are valid in conjugation with the word Total- or Half.

The main usage of this classification is known which sectors within the district are covered, reference coordinates being added to the classification.

Legend	Approximate covered area	Description
Total		Total coverage of the area
Total - NE	$\bigcirc$	Almost total coverage except the North East area (other possibilities; N; S; W; E; NE; NW, SE; SW)
Half S		South half covered of the area (other possibilities; N; S; W; E; NE; NW, SE; SW)
0		Nothing is covered

Table 3-4 - Qualitative analysis legend.

For the quantitative classification, the area of the districts and an approximated percentage of covered area are considered. From [IGP10], the area of each district can be retrieved, and the approximate total covered area can be estimated by (3.42). The total covered area is also referred as utility of the sensor.

$$A_{total[\%]} = \frac{\sum_{i=0}^{N_{dist}} (A_{i[\%]} \times A_{dist \ i[km^{2}]})}{A_{total[km^{2}]}}$$
(3.42)

where:

- *A<sub>total</sub>*: Percentage of the total sensor's covered area or utility.
- $A_{dist i}$ : Area of the correspondent district.
- $A_i$ : Percentage of the area covered in the correspondent district.

This Section explains the basics for the coverage simulator implementation, and for the study of a MLAT system global coverage. The implementation of the coverage simulator is described in Section 3.7.

## 3.6 Latency Simulator

## 3.6.1 Simulator Structure and Parameters

The goal of this Section is to describe the implementation of the latency model in a simulator, which estimates the synchronisation time of the sensors for some possible airplane positions. As explained before, there is a big difference between LAM and WAM.

The simulator allows assessing the communication links delay in a MLAT system. It was developed

considering the systems already implemented, but it was developed to be as compatible as possible to any other MLAT system. In order to accomplish this, it supports the most used types of communication links in MLAT, and the possibility of the existence of more than one type of link for each sensor.

#### The simulator is described in

Figure 3-11, and it has been implemented using MatlabR2007b [MatL11]. First the system and the airplane test positions are described, and then the latency model from Section 3.2 is applied. Afterwards, there is a result analysis to determine the synchronisation time and also which messages arrive within the maximum time allowed. Finally, the output is generated with the results of the system analysis for each position that was tested. Although there are differences between LAM and WAM, the general structure of the simulator is the same, differing only in some specific algorithms.



Figure 3-11- Simulator general structure.

The simulator requires two input files that are selected using the Graphical User Interface (GUI) and a few parameters also introduced in the GUI:

- (System description file).xlsx: it contains the description of the MLAT system with every sensor and the communication links.
- (Test positions file).xlsx: it contains the positions of the airplanes to be tested (Section 3.4).

Both files differ if the simulation is for a LAM or WAM system, and a more details can be found in Annex A, which contains the user manual of the simulator. In the GUI, although default values are defined, it is possible to change the following parameters:

- Maximum synchronisation time.
- Coverage radius.
- Declination in the area to analyse.

Coverage radius and declination are only used in the WAM analysis, and the radius is defined taking the coordinates defined by the CPS of the system description file.

The output is written in an Excel file (\*.xlsx) containing, for each test position, the results of the latency model, its name being the concatenation of "Output\_" with the name of the test positions file.

## 3.6.2 LAM and WAM Simulator

The LAM flowchart is required to understand its algorithm. Although this is just the implementation of the latency model, more computations are required, Figure B.1.

The LAM simulator starts by reading the first input file that contains every sensor on the network, and the links each one has. With this information, the link delay  $(t_{link})$  of each sensor is calculated, which depends on the communication link, explained in the Section 3.2.

The second step is to read and analyse the second input file, which contains the test positions. For each point, the simulator reads the coverage, also included in the second input file, and calculates the propagation delay from the position to each of the covering sensors ( $\tau_{air}$ ); this propagation delay is then summed to the link delay previously calculated. Only the fastest five sensors are considered to calculate the synchronisation; more sensors could be used, but to meet the requirements only five are considered critical. This synchronisation time is the difference between the fastest and slowest of the five sensors.

The output format of the LAM analysis is different from the WAM one, because the latter has much more information to display, which is not considered to show the delay of each position to each sensor, unlike LAM. The output file states, for each position, the synchronisation time, the fastest and the fifth fastest (slowest) sensor, and the total delay for each sensor that covers that position.

The other type of analysis performed by the simulator is the WAM system. The WAM flowchart is presented in Figure B.2, and also describes the steps of the simulator.

Besides the format difference between both input files, the first part that involves reading the description file and test positions is the same as in the LAM algorithm. The main difference comes when the types of path are identified. For the single point test position, the analysis is similar, but for sections, approach, and routes, there are a few calculations to perform before having the final test points to test.

For the section, as explained in Section 3.4, the simulator calculates all points in it based on the total number of points to test. The approach is identified by a starting position and an angle, the landing position is calculated, and with these two coordinates a section is defined; the same function used in the section calculation to get the intermediate points is used. Besides the intermediate points, the flight altitude for each point also needs to be computed. Finally, for the route, it intersects the coverage area by an iterative process, and there are two situations to define the two points for the route:

- Initial point inside the coverage area: it only calculates one intersection with the coverage area, and the other point to define the section is the starting position.
- Initial point outside the coverage area: the two points used to define the section are intersections with the coverage area.

Discovering the two points that define the route, the simulator's procedure is similar to the section test, computing the intermediate points by using the section method. When there is no more analysis to perform, the simulator writes an excel output file discriminating every test positions types, the intermediate positions, and the delay analysis. An extra output in a WAM analysis is the list of sensors that are able to forward the message to the CP within the synchronisation time.

This Section roughly describes the simulator. In terms of how to use the simulator, there is a more detailed explanation in Annex A.

# 3.7 Coverage Simulator

## 3.7.1 Simulator Structure and Parameters

There is much software available to perform coverage analysis, but none of it is free, and usually it does not allow a more detailed analysis, considering the elevation profile and coverage angle. A specific software was also developed to allow a higher flexibility in the data output, being possible to export the analysis to Google Earth, where more than one coverage map can be analysed and overlapped with other sensors coverage. This simulator was developed using Microsoft Visual Studio [MVS11].

As explained in Section 3.5, the coverage analysis contains two major areas: the elevation profile and the coverage analysis. Figure 3-12 shows the general structure of the coverage simulator.



Figure 3-12 - Coverage simulator general structure.

The first part of the simulator, the elevation profile, starts by requiring the configurations of the sensor, so that it may request the elevation profile from Google servers. This step is the main limitation of the simulator, because land profile elevation is limited to 25 000 points per day. After the elevation profile request, a more detailed analysis can be done, because it is possible to navigate between azimuths and analyse each one of them individual. For each azimuth, the land profile is shown and two more functionalities were implemented, the height correction that is shown simultaneously with the land profile, and also the coverage line for that azimuth that is shown simultaneously with the corrected height graph.

The last part of the simulator is the complete coverage analysis, which also requires some configurations, the most important one being the flight level. The final result is shown in the simulator, and a Google Earth file with the final result is also created.

The output files are be very important mainly to compensate the limitations of the Google Server in terms of points allowed per day. There are no input files, but to complete the elevation profile and coverage analysis, some parameters are required. For the elevation profile, one must define:

- Simulation name.
- Sensor's latitude and longitude.
- Sensor's height.
- Sample points, which contain the number of points to require the elevation per azimuth.

- Range to cover, which contains the range to get the elevation profile.
- Number of azimuths, which contains the number of azimuths to get the elevation profile in the defined range.

To complete the coverage analysis, three more parameters are required:

- Flight level of the airplane.
- Maximum range of the sensor.
- Colour to display the output in Google Earth.

Besides the configuration parameters, there are three types of output files. The first output file is to save the data collected from Google servers, and elevation profile parameters, the second is to generate the final coverage map in Google Earth, and the third is an auxiliary file that can save any graph from the application to an image file.

The first output file allows saving the land profile of a certain sensor, only later making the coverage analysis for one or more flight levels. With this functionality, it is possible to minimise servers' limitations, because data can be collected in different days or with different IP addresses, and only after having all data, one can study the global coverage. The format of this output file is \*.txt whose name is the concatenation of "Output\_" with the simulation name. The file contains all parameters: simulation name, latitude, longitude, sensor height, number of azimuths and for each azimuth contains the number of points, the azimuth degree, and each of the points. Each point contains the elevation, the coordinates, and the distance from the sensor's location.

The second output file is a Google Earth one with the final coverage map. The format \*.kml is a type of xml file that Google uses to represent markers, lines or polygons [Go11a]. Knowing the covered distance for each azimuth, they are translated into latitude and longitude, and after having all azimuths, the \*.kml polygon is created. The colour of the polygon is a parameter defined in the configuration, and the file name is the name of the simulation.

The final output file is to retrieve simulator images, instead of using a print screen solution. It may be saved with most of the common image file types, and the name is defined by the user. This file is not very important for the simulator results, and it is only used to retrieve a more specific analysis for a certain azimuth.

This Section summarises the possible outputs of the simulator, which are used to analyse the results. A brief summary of the structure and functionalities of the coverage simulator is also made.

## 3.7.2 Elevation Profile

With the definition of the elevation profile parameters defined in Section 3.7.1, it is possible to complete the request of the elevation profile, which is the beginning of the coverage analysis study.

Google developed two request possibilities to get elevation profiles: one is by giving a single point and the other by giving a path with the desired number of points in between. Both possibilities can be used, but the simplest one, used in the simulator, is the latter. The requests to Google are based on

URL requests, and there is a library that basically builds the HTTP messages and receives the response obtained from Google [Go11c].

It has already been explained that this service has a few limitation [Go11b]: 2 500 requests per day, 512 elevation points per request, and 25 000 points per day. The limitation of 2 500 requests per day means that even if the possibility of requesting individually each point had been considered, it could not be used, because 2 500 points would be the maximum to request. The simulator does not control the number of points that were actually requested, even though it informs the user if the request was successful or not. It must be taken into account that the number of requested points is given by:

$$N_{points} = N_{az} \times N_{smp} \tag{3.43}$$

where:

- *N<sub>points</sub>*: Total number of points requested to Google in the simulation.
- $N_{az}$ : Number of azimuths to get the elevation profile.
- *N<sub>smp</sub>*: Number of elevation samples per azimuth.

Another way of improving efficiency, concerning Google limitations, is to make the coverage analysis just for a limited range. For instance, if a sensor has a sector covering the ocean, this area may be excluded from the analysis and one only performs an 180° analysis.

The finalisation of the elevation profile requests consist of defining the paths for which the request is going to be made. The azimuths to analyse are given by (3.44), and the coordinates of the path from a sensor location to another following the azimuth previously defined, (3.34) and (3.35). These equations also need to define the distance for which the elevation profile must be retrieved, and for this matter a range of 80 NM is considered. At first, some results were taken for 100 NM, but considering that every point defining the coverage line is within 80 NM, the distance was reduced, improving the accuracy of the elevation profile. This range to ask for the elevation profile is different from the coverage range, because the obstacles very far away from the sensor will not influence the coverage angle.

$$\theta_{az\,i} = \theta_{initial} + \frac{\Delta\theta}{N_{az}} \times i \tag{3.44}$$

where:

- $\theta_{az i}$ : Angle of the respective azimuth.
- $\theta_{initial}$ : Minimum of the range defined by the user.
- $\Delta \theta$ : Amplitude of the range defined by the user.
- *i*: Actual azimuth  $\in [0, N_{az} 1]$ .

After data are collected, their export is done, saving the first output file. The procedure to get the complete elevation profile has been described, but the data analysis is still missing. The elevation profile of the first azimuth is displayed, but it is possible to travel through every other azimuth. These graphs do not require any more calculations, besides the values retrieved from Google. The result of a

land profile example is shown in Figure C.4.

The second step of the elevation profile is to correct the heights using (3.37), an example of the height correction for the same example used in Figure C.4 being shown in Figure C.5. The effective land height is displayed together with the land profile elevation. From (3.37), it is concluded that the higher the distance from the obstacle to the sensor's radio horizon, the larger the height correction. This specific sensor is located at approximately 800 m MSL from the ground, which, from (3.36), gives a radio horizon of 101 km. Beyond the radio horizon, the increase in the height correction is not linear but squared.

## 3.7.3 Coverage

There are basically two types of coverage that are distinguished in the simulator: coverage profile and global coverage. The former calculates individually the coverage line for each azimuth, and plots it in the simulator, while the latter calculates the global coverage and plots the coverage map.

The coverage profile flowchart is shown in Figure 3-13. An azimuth land profile must be selected to calculate a coverage line, and then land profile heights are corrected. With the corrected heights, the simulator calculates every coverage line for each of the elevation points retrieved from Google servers, always registering the maximum angle, (3.38). Finally, after computing every coverage line, the simulator plots the result.



Figure 3-13 - Coverage line flowchart.

Figure C.6 contains the coverage line calculated for the sensor's azimuth used in the example of Section 3.7.2. It is displayed over the effective height profile, and the influence of the obstacles in the

nearby region of the sensor is clear. It should be noticed that the units of the x-axis are in [km], while the y-axis are in [m], which is why the coverage line slope looks higher than its real value.

The last coverage analysis to compute is the global coverage, i.e., a coverage profile analysis for every azimuth. Figure 3-14 contains the flowchart for the total coverage calculation. The simulator starts by calculating the sensors range limitation from Section 3.5, which is calculated once, because it only depends on the sensor and flight level. After calculating the maximum distance for the specified airplane's height and sensor's range, the coverage line for every azimuth is calculated, and then it calculates the intersection with the airplane from (3.40). As explained in Section 3.7, the maximum distance of the airplane.



Figure 3-14 - Total coverage flowchart.

To finalise the global coverage, a plot is shown, Figure C.7, which gives the coverage distance for each azimuth, and a \*.kml file is created to show the results onto Google Earth. To create the Google Earth file for each azimuth angle and distance, a set of coordinates must be calculated to define a path between the sensor's location and the maximum covered distance. To calculate the new set of coordinates for each azimuth, (3.34) and (3.35) are used. The creation of the \*.kml file is described in the input parameters and output files of this Section. Examples of this last file are shown in Annex C.

The coverage simulator is a useful tool to use in the study of any MLAT system to be developed, and it is used in this thesis for a specific study.

## 3.7.4 Simulator Assessment

The values of the simulator must be compared with a real coverage simulator available, in order to assess it. In this thesis, some coverage maps are shown and they can be used to compare with the simulator results.

Choosing the WAM Fanhões sensor, the comparison between both simulators is shown in Figure 3-15. Both analyses calculate the LoS coverage.

The parameters used in the coverage simulator were 36 azimuths and 500 elevation points per azimuth. With 36 azimuths, it is expected that the accuracy decreases comparing with NAV's software, but this simulator is always limited to a few number of azimuths, due to the Google server limitation on elevation requests. Besides the clear difference in accuracy, due to the previously mentioned limitations, there is a reduction in the length of each azimuth. For instance, the south of Algarve is considered to be covered in NAV's software, where as in the coverage simulator it is not completely covered.

Even though having these two limitations, and assuming that the software not developed in this thesis is precise, the coverage shape is very similar. Having a shorter range means that this simulator is more restrictive than the other, otherwise the implications would be worse. With a higher coverage range the validity of the results near the cell edges would be arguable.



a) Fanhões with NAV's software



b) Fanhões with coverage simulator

Figure 3-15 - Coverage simulator assessment.

Another test for the simulator concerns the sensor range limiting coverage. In order to test the range limitation to 200 NM, which is the value considered for the study, the same sensor was used, but the FL was increased to FL300, so that the coverage exceeds the sensor's maximum range, Figure 3-16. For this specific case, the radio horizon of the airplane plus sensor is 220.4 NM, but the range limits that distance to 199.8 NM.


Figure 3-16 - Coverage for FL300 and maximum range 200 NM.

This Section validated the developed coverage simulator, so that it may be used as a tool to design MLAT systems. More information concerning the use of the simulator can be found in Annex C, where the user's manual.

# **Chapter 4**

## **Results and Data Analysis**

In this chapter, the simulation results for the analysis of the current multilateration systems, the complete preliminary study for a new multilateration system, and tolerable delay for the VPN links in Lisbon are analysed. Other small analysis to the multilateration systems are analysed, such as the communication link capacity and the impact of the regulator requirements in the systems.

## 4.1 NAV Portugal Implemented Systems

Currently, there is one operational MLAT system, one being finalised and another in procurement phase. Although there are studies being conducted for other MLAT systems, only the three described have the study finalised.

The first MLAT system is located in the Lisbon airport: it consists of a system on the airport grounds (LAM), and is already in operational use. There is a project (in procurement phase) to expand this system to cover a 30 NM radius from the Airport (WAM) that foreseen to be concluded during the next year [NAV11]. Although there are differences between a LAM and WAM, concerning this thesis, both types are described by the sensors location, the communication link description of each sensor, and the individual coverage analysis. The final system to be analysed is located in the Azores.

The Lisbon LAM system is composed of the CPS, fourteen RUs and two reftrans. In Figure 4-1, the sensors are identified by 1 to 14 and the blue squares represent the reftrans, x1 and x2.



Figure 4-1 - Lisbon LAM system sensors location first phase (extracted from [Sns09c]).

The individual and global coverage of the sensors is shown in Annex D, Figure D.1 to Figure D.4. The coverage maps are used when analysing the effects of the delay in the system, and also to give a perspective of the study that needs to be conducted prior to the decision concerning the sensors location.

Table 4-1 describes, in a more detailed way, the RUs geographical coordinates, above ground level (AGL), communication link used, their length and capacity. Column ID in Table 4-1 is the name identification of the corresponding component, which is used in what follows. All RUs, except RU7 that is co-located with the CPS, use a fibre link with lengths smaller than 6 km and with a capacity of 100Mbps. Reftrans, which are co-located with sensors RU1 and RU7, do not have a specified communication link, because the synchronisation is via radio link, the only requirements being that every RU have LoS for at least one reftran.

ID	Latitude [DD°MM'SS.SS"]	Longitude [DD°MM'SS.SS"]	Communication Link	Link Capacity [Mbps]	Elevation AGL [m]	Optical cable length [km]
CPS	38°46'45.66"N	9° 8'22.56"W	None Required	N/A	N/A	N/A
Reftran X1	38°46'51.30"N	9° 7'55.74"W	None Required	N/A	33.0	N/A
Reftran X2	38°46'45.66"N	9° 8'22.56"W	None Required	N/A	8.0	N/A
RU1	38°46'51.30"N	9° 7'55.74"W	fibre	100	33.0	1.78
RU2	38°47'21.06"N	9° 7'49.26"W	fibre	100	13.0	3.14
RU3	38°47'51.90"N	9° 7'50.34"W	fibre	100	3.0	5.16
RU4	38°47'57.18"N	9° 7'35.28"W	fibre	100	3.0	4.60
RU5	38°46'51.78"N	9° 7'45.06"W	fibre	100	15.0	2.33
RU6	38°46'41.94"N	9° 7'53.52"W	fibre	100	20.0	1.32
RU7	38°46'45.66"N	9° 8'22.56"W	fibre	100	8.0	0.00
RU8	38°46'10.80"N	9° 7'48.18"W	fibre	100	19.0	4.15
RU9	38°46'06.18"N	9° 7'47.40"W	fibre	100	18.0	4.37
RU10	38°46'00.48"N	9° 8'00.24"W	fibre	100	8.0	4.71
RU11	38°45'50.10"N	9° 8'20.04"W	fibre	100	28.0	3.47
RU12	38°45'45.90"N	9° 8'44.04"W	fibre	100	3.5	2.58
RU13	38°46'09.78"N	9° 8'37.92"W	fibre	100	15.0	1.45
RU14	38°47'09.06"N	9° 8'17.46"W	fibre	100	3.0	0.93

Table 4-1 – Lisbon LAM sensors description (calculated from [Sns09c]).

The Lisbon WAM system is not isolated from the LAM one, and both systems sensors will work together. It will use six extra sensors added to the LAM ones, and is going to be implemented to supply surveillance up to a 30 NM radius from the airport and for a minimum altitude of 1000 ft. The CPS is common to both systems, and no reftrans are required because the synchronisation is done by GNSS, hence, the GPS interface available in the sensors is used.

One sensor from the airport, RU11/TAR, is used to describe the system, since it is one with the best coverage outside the airport [NAV11]. Figure 4-2 shows the geographical location of the 7 sensors. The coverage maps for each sensor are different from the LAM usage, because coverage requirements are not at the ground level but for an altitude of 1000 ft. Even though requirements are 1000 ft, the coverage analysis included in Annex D, Figure D.5 to Figure D.11, is shown for commons FLs (FL defines the altitude in hundreds of feet): FL100, FL200 and FL300.

As shown in Table 4-2, the TAR sensor is the same as RU11 of LAM, and all other sensors (except Montejunto) will use a VPN that will be rented to a telecommunications operator. The maximum latency tolerable for the VPN links has not been yet defined, being one component of this thesis' results. There are two differences between this WAM and the previous LAM: firstly, the sensors' altitude is given by the MSL, which is a measured used in avionic to give the height relative to the average sea level; secondly, being a wider system, there are no links that go straight to the CP, so there is usually a mix of communication links. In this specific case, every sensor located outside the airport will forward the messages by their specific link to the NAV Portugal building, and only from there the messages will be forward to the CP. To connect the building to the CP, an extra optical fibre with a length of 2.721 km is used.



Figure 4-2 - Lisbon WAM sensors location (using Google Earth).

RUID	Latitude [DD°MM'SS.SS"]	Longitude [DD°MM'SS.SS"]	Elevation MSL [m]	Communication Type	Communication link Capacity [Mbps]	Communication link length [km]	extra optical fibre length [km]
Arrabida	38°29'34"N	8°57'44"W	356	VPN	0.2	N/A	2.72
Caparica	38°38'32"N	9°13'17"W	95	VPN	0.2	N/A	2.72
Espichel	38°25'27"N	9°11'09"W	183	VPN	0.2	N/A	2.72
Fanhões	38°53'16"N	9°09'46"W	340	VPN	0.2	N/A	2.72
Montargil	39°04'38"N	8°11'15"W	235	VPN	0.2	N/A	2.72
MonteJunto	39°10'23"N	9°02'52"W	670	Microwave link	6.0	47.72	2.72
TAR (RU 11) airport	38°45'50"N	9°08'20"W	135	Fibre	100.0	3.47	N/A

Table 4-2 - WAM sensors description (calculated from [NAV11])

Concerning the located in the Azores, all communications use microwave links, and connect every sensor to the CPS located in the airport of Horta, more specifically in the airport control Tower (TWR). Figure 4-3 contains the sensors location in Google Earth and the microwave links represented as red lines. TWR Horta, represented by an airplane in Figure 4-3, is the CPS for this system. There are only two sensors directly connected to the CP, GS\_01 and GS\_02, the rest being connected to GS\_00 by one or more microwave links, and from there they are connected to the CP using a repeater, triangle in Figure 4-3 [ERA11]. A more detailed description of each sensor's location, link capacity and length, number of hops per link is shown in Table 4-3.

The ground sensors have three possible configurations that can be used simultaneously: receiver, transmitter and reftran. All sensors represented in Table 4-3 have receiving capabilities, but only GS\_00, GS\_04, GS\_05 and GS\_07 can work as transmitters. The synchronisation of the sensors in this system is similar to the one used in Lisbon's LAM, the sensors that incorporate the reftran functionality being GS\_00, GS\_05 and GS\_09.



Figure 4-3- Azores WAM sensors (using Google Earth).

ID	Equipment type	Latitude	Longitude	Elevation MSL [m]	Communication link	Communication link capacity [Mbps]	Communication link length [km]	Number of hops
GS_00	RU	38°34'33.20"N	28°42'47.50"W	1,052	Microwave link	0.256	17.26	2
GS_01	RU	38°31'11.73"N	28°37'24.60"W	140	Microwave link	0.256	7.86	1
GS_02	RU	38°27'58.86"N	28°30'40.90"W	122	Microwave link	0.256	18.60	1
GS_03	RU	38°31'52.25"N	28°26'27.31"W	351	Microwave link	0.256	41.46	3
GS_04	RU	38°27'45.33"N	28°15'49.14"W	862	Microwave link	0.256	110.06	5
GS_05	RU	38°42'33.16"N	28°12'04.46"W	483	Microwave link	0.256	64.06	3
GS_06	RU	38°36'01.02"N	27°55'56.32"W	845	Microwave link	0.256	86.54	5
GS_07	RU	38°32'58.13"N	27°46'06.17"W	193	Microwave link	0.256	184.66	5
GS_08	RU	39°02'09.60"N	28°01'45.10"W	382	Microwave link	0.256	103.26	4
GS_09	RU	38°43'48.50"N	27°19'09.30"W	1,028	Microwave link	0.256	140.76	4
GS_10	RU	38°36'02.96"N	27°59'18.15"W	178	Microwave link	0.256	81.56	4
Repeater	repeater	38°31'15.71"N	28°37'37.25"W	106	N/A	N/A	N/A	N/A
TWR-Horta	CPS	38°31'16.26"N	28°42'49.26"W	65	N/A	N/A	N/A	N/A

Table 4-3- Azores WAM sensors description (calculated from [ERA11] and [NAV11]).

The only system already in place and working is the Lisbon LAM but the other projects presented in this Section are already defined. The systems that are analysed and the required information to understand them has been described.

## 4.2 Communication Links Required Capacity

As explained in Chapter 3, the assessment of the capacity required for the communication links depends on various factors, and there are two different situations: the required capacity and the expected one. The requirement of this system is that it must simultaneously support 250 airplanes in the air. All the capacity calculations are obtained from (3.1) and (3.2) and overheads in Table 3-2.

Concerning the maximum capacity, the first row of Table 4-4 contains the total traffic produced by 250 airplanes airborne, which is 712.1 kbps. A slight correction to be made on this value is that the overhead from the IGMP V2 header is often not used; by removing this header the maximum traffic is 620.9 kbps. In reality, if the airplanes are required to keep their transponder on, even while on the

ground, the probability of having 250 airplanes airborne is even lower. Even so, for a critical surveillance system this last requirement must be always guaranteed.

The calculation of the expected traffic in each communication link has been done for some possible system configurations, meaning the different ratios of stationary, moving or airborne airplanes. A useful characteristic of the requirements is that a moving airplane sends the same messages as a moving vehicle, so the ratio of moving airplanes ( $r_{\%}^{mv}$ ) contains both vehicles and airplanes. Four cases for the positions distribution were considered, all of them with a total of 250 targets, Table 4-4.

r‰ <sup>sta</sup> [%]	$r_{\%}^{mv}$ [%]	$r_{\%}^{air}$ [%]	Traffic without overhead [kbps]	Traffic with overhead [kbps]
0	0	100	142.1	712.1
50	25	25	78.4	383.4
70	15	15	Not calculated	274.7
80	10	10	Not calculated	220.4

Table 4-4 - Results for different airplane positions.

This table illustrates the impact of the overhead in the messages, which itself is responsible by around 77 % of the exchanged volume, and also the influence of the number of airborne airplanes. In a real situation, the possibility of having simultaneously 250 airplanes in the air is not realistic, and the most realistic situation is closer to the 70/15/15 configuration. This difference means that the real expected traffic is much smaller than the required capacity, and considering the difference from the 70/15/15 configuration to every airplane airborne, the capacity decreases around 61%.

Due to some factors, such as multipath, overlap of different signals (garbling) and interfering signals (jamming), the receiving probability is reduced and as a consequence so does the required capacity. Garbling is a problem that occurs from the different signals overlapping, being similar to multipath, because both cause a distortion of the signal at reception, but garbling increases with the number of airplanes, unlike multipath that only depends on the environment. Even if distorted, the receiving signals may be used for identification, but they do not produce an accurate solution for the TDOA algorithm, so they may be discarded, which obviously reduces the traffic in the communication link, but leads also to a decrease in the detection probability [Nev05]. Interference is also an existing problem to consider, having the same effect of signals corruption, thus, the messages are also discarded.

There is one last factor that could have implications in the reduction of the capacity required for the communication links, i.e., coverage. If a sensor only covers a part of the surveillance area, it would be also reasonable that instead of the 250 airplanes it would only cover a part of it. This occurs for a LAM system, where the coverage maps in Annex D show that there is no sensor covering the entire airport. On the other hand, the WAM systems coverage is much different. Even though requirements demand a 1000 ft coverage, in a real situation airplanes fly above 9 500 ft, and most of them in the highest routes around 29 500 ft. The coverage maps for the Lisbon WAM, Annex D, show that the coverage area is much larger than the 30 NM radius from the airport, which means that no reduction in the traffic

is expected due to less coverage area.

The configurations of the sensor may introduce an increase or decrease in the coverage area, which may decrease the number of airplanes covered, hence create a reduction of the expected traffic. These sensors configurations can be achieved by changing the antenna or the receiver's sensitivity. If a sensor is configured for the maximum range capability, this last factor may introduce an opposite effect on the required capacity. Having the sensor with a much larger coverage radius, and if the maximum of 250 airplanes is only for the MLAT coverage area, there is the possibility of having more than 250 airplanes at range. Considering that most of the airplanes fly in the highest routes [NAV11] and analysing the coverage maps, it stands out that almost the entire country is covered by each of them. This could cause problems, because any sensor would receive messages from such a large area, achieving 250 airplanes, or even more.

Considering for example a receiving probability around 40 %, applied to the value calculated of 620.9 kbps the required link capacity would be 248.16 kbps To prevent the unexpected effects of having the system working at the maximum capacity, it is usual to consider a usage factor, usually expressed as  $\rho$ , between 0 and 1, giving a margin for the capacity; if the usage factor is 1, then, when the system is at the maximum capacity, the link is totally used. With a usage factor of 90%, the required capacity would be 275.7 kbps, but considering this factor the system would be more robust to critical situations. The disadvantage of not considering a usage factor smaller than 1 is that in the case of having 250 airplanes in the air, the average traffic generated is equal to the links capacity, but the probability of successfully forward the message to the CP would be much lower, because the instant traffic may be higher than the capacity of the link.

This Section analyses the results to define the desired capacity for a MLAT link. It depends mainly on the system's equipment and the final calculated value of 275.7 kbps was using reference values from the Lisbon WAM system. For every other systems, it must be assessed if the number of targets and the receiving probability is the same and if not the calculations must be repeated.

### 4.3 Localisation Requirements Analysis

A reduction in the receiving probability decreases the required capacity, but it also has a negative impact in the network, because it affects the overall probability of executing the TDOA probability. Localisation requirements are presented in Section 3.1.2, and the effect of the receiving probability in these requirements must be analysed.

Figure 4-4 shows the probability of a message being received by 4 or more sensors, using (3.3), in a network of 20 sensors, considering the number of sensors at  $LoS \in [4,20]$ . Different values for the error probability were also considered, including the value considered in Section 4.2, which is an error probability of 60 %.

As expected, by increasing the error probability the execution of the TDOA is less likely to occur. With

an error probability of 60 %, which is equivalent to a receiving probability of 40 %, the probability of receiving successfully a message with 5 sensors is approximately 10 %. By increasing the number of sensors, the success probability increases.



These results are not final, because requirements do not define the probability of execution of the TDOA localisation with one message, but rather with more than one. Track initiation and continuous tracking, beside the probability of executing the TDOA algorithm, depend also on the frequency of sent messages. Using Table 3-3, the frequency of messages sent by an airborne airplane is 5.7 msg/s.

Concerning the continuous tracking, it means that in an update interval, 5 s, the airborne airplane must be localised with a 97 % probability. In one update interval, the airplane sends on average 28 messages. From (3.5) and considering different receiving probabilities, the results for the continuous tracking probability are shown in Figure 4-5. In a location covered by 4 sensors, the only way to meet this requirement is if the sensors have an error probability smaller than 40 %. For a 50 %, 60 % and 70% error probability, the required number of sensors to meet the requirements are respectively, 5, 6 and 7 sensors at LoS.

Finally, track initiation must be assessed. This requirement demands that the tracking initiation of the airplane must be accomplished in 25 seconds with a probability of 99 %. [NAV11]. Only two situations are considered concerning the number of consecutive messages to initiate the track, two or three. This is because they correspond to the most common used by air traffic system controllers. Using the transition matrices, (3.7) and (3.8), in (3.6) considering that the initial state is having 0 messages, the probabilities of initial tracking can be calculated. The analysis was made for a different number of sensors at LoS, and the probabilities of executing the TDOA collected from Figure 4-4. Figure 4-6 contains the results for 2 consecutive messages, while Figure 4-7 shows for 3 messages.

As expected, the probability of initial tracking is higher when only two messages are required instead of three. On the other hand, when configuring the system for two consecutive messages more display errors may happen. There is always a difference in one sensor from one analysis to another, except when the error probability is 70 %. In this last case, there is an increase in two sensors to meet the

requirement compared to the two messages result.



Figure 4-7 - Track initiation probability with 3 consecutive messages.

The required number of sensors to meet the requirements depends on both analysis, and also on the number of messages to initiate the tracking. Table 4-5 contains the summary of the impact of each requirement. The limitations are imposed by the track initiation and not by the continuous tracking.

Considering 60 % for the error probability, implies that the number of sensors necessary to cover each location is 6 or 7, depending on the number of messages to initiate the tracking. If the receiving probability is higher, the number of required sensors is smaller. This conclusion is only valid for the TMA, for en-route airplanes the requirements are less restrictive while in an airport they are more.

Error	Continuous	Track initiation (> 99%)				
probability	tracking (> 97%)	2 messages	3 messages			
40%	4	5	6			
50%	5	6	7			
60%	6	7	8			
70%	7	8	10			

Table 4-5 - Overall MLAT requirements in terms of airplane detection.

These conclusions have considered only 4 values for the error probability, and that the TDOA requires 4 sensors to localise an airplane, which is the minimum number of sensors to have a 3D localisation. If a system uses 2D localisation, the number of required sensors to localise an airplane is 3 instead of 4. In this last case, the probabilities are higher and the number of required sensors smaller. With this analysis the conclusion is that when implementing a MLAT system, one must take into consideration that the minimum number of sensors to run the TDOA algorithm is not enough.

## 4.4 Sensors Processing Time

Up to now, the major concern has been the time difference between the fastest and slowest sensors, and not the processing time. The processing time has been assumed has constant, so it would take the same exact time independent of the sensor, but this is not true in a real system. It is possible to gather information to estimate the sensors processing time in the Lisbon LAM. Resulting from the measurements, Table 4-6 shows for each sensor the values for  $CRTT_i$  and  $\sigma_{CRTT i}$ , which are used to get the fixed processing time of the equipment.

Analysing the measures, the first thing to notice is that the length of the fibre is not related to CRTT, e.g., the delay of RU3 is smaller than RU14, while RU3 fibre length is more than 5 times larger. This means that the order of messages arrival is not possible to determine only considering the channel delay. The reason for this is because the average CRTT is much more than 100 times larger than the channel delay, which is different for each sensor. Having a large CRTT also means that its standard deviation is large and for the distances in the links of the Lisbon LAM, the value itself is much larger

than the channel delay. If the links are VPN or satellite, the delays are much larger than CRTT, and then this conclusion is not valid.

RU3 has a standard deviation much higher than the rest of the others, which does not have a reasonable explanation, since all have the same type of link, approximately the same order of distances and exactly the same equipment. One considers that the RU3 standard deviation has been an exceptional case, not being considered to calculate the average fixed time and its standard deviation.

The column *Total Channel Delay* is obtained by the same equations used in the simulator to calculate the link delay, while the mean fixed time for each sensor, calculated by (3.24), is presented in the column *Mean fixed time*. The mean fixed time for each sensor is very close to CRTT, having also a standard deviation higher than the calculated link delay, which means that the estimation of the synchronisation time between optical and microwave links, having only a difference of a few kilometres, is not accurate. On the other hand, the fixed time being the highest delay means that the maximum synchronisation time is much smaller than the 500 ms limitation.

RU ID	Optical link length [km]	Communication round trip mean [ms]	Communication round trip standard deviation [ms]	Total Channel delay [ms]	Mean fixed time[ms]
RU 1	1.784	9.868	0.354	0.015	9.839
RU 2	3.135	9.919	0.326	0.021	9.876
RU 3	5.164	10.003	1.402	0.031	9.940
RU 4	4.604	9.983	0.343	0.029	9.926
RU 5	2.325	9.957	0.357	0.017	9.923
RU 6	1.322	9.967	0.346	0.012	9.943
RU 7	0.000	9.964	0.350	0.006	9.953
RU 8	4.145	10.139	0.367	0.026	10.086
RU 9	4.367	10.164	0.358	0.027	10.109
RU 10	4.707	10.106	0.376	0.029	10.048
RU 11	3.469	10.086	0.327	0.023	10.040
RU 12	2.575	10.093	0.371	0.018	10.056
RU 13	1.453	10.090	0.363	0.013	10.064
RU 14	0.926	10.106	0.369	0.010	10.086

Table 4-6 - Channel delay results and real data measured.

The value for the average fixed time,  $\overline{t_{fixed}}$ , using (3.25) is 9.992 ms and the value for the average standard deviation time,  $\overline{\sigma_{fixed}}$ , using (3.26) is 0.355 ms. These values define the processing time, and from now on, it must be taken into consideration that the processing time is not a deterministic value but rather defined by statistical distribution.

## 4.5 Lisbon Sensors Maximum Latency

The WAM system in Lisbon will have five sensors, communicating via VPN. As discussed in Chapter 2, the VPN connections require a maximum delay to guarantee that the system works in terms of delay. This Section calculates the maximum latency required for each of the VPN links.

In VPN connections, sometimes it is not possible to reach the CP directly and this is the case of the future VPN connections for the WAM sensors. Table 4-7 contains the extra delay to be considered for the VPN links due to the channel delay of the 2.721 km fibre connecting the NAV Portugal building to the CP, the channel delay of the sensor in the airport to the CP and the synchronisation time considered. It must be noticed that WAM sensors have the same equipment as the LAM's, so it is reasonable to assume that they have approximately the same processing time, and also that the processing time between the reception of the information in the intermediate building and the forwarding to the fibre is not being considered.

According to Section 3.3, the geographical location of the sensors is also a parameter that influences delay, more specifically the distance between each of the sensors to the fastest one. Montejunto and TAR have already a defined communication link, but the TAR communication link is for sure faster than the Montejunto one, which has a higher channel delay, due to the higher length and smaller capacity. Being TAR the fastest sensor, all the synchronisation delays are defined by this sensor. The distances from every sensor to the fastest sensor, TAR, and also the elapsed time for a signal to propagate that distance are shown in Table 4-8.

Link delay NAV Portugal to $CP(t_{extra})$	0.014 ms
Link delay TAR (t <sub>Channel-airport</sub> )	0.017 ms
Maximum synchronisation time (t <sub>synch-max</sub> )	500 ms

Table 4-7 - Constants for VPN delay.	
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RU ID	Distance to TAR [km]	$\Delta  au_{air}[ms]$
Arrábida	33.83	0.113
Caparica	15.31	0.051
Espichel	37.99	0.127
Fanhões	13.93	0.046
Montargil	89.37	0.298

Table 4-8 - Distances to TAR.

Considering the fixed system time as a Gaussian distribution, with average  $(t_{fixed})$  9.992 ms and standard deviation  $(\overline{\sigma_{fixed}})$  0.355 ms, taking a confidence interval of 99.73% means that one has  $t_{fixed i} \in \overline{\tau_{fixed}} \pm 3 \times \overline{\sigma_{fixed}}$  [Corr09]. With this confidence interval, the difference in the system

processing time ( $\Delta t_{system}$ ) is  $6 \times \overline{\sigma_{fixed}} = 2.13$  ms. All the components of (3.22) have been calculated, except the extra time, due to the existence of an extra communication link connecting the NAV Portugal building to the CP.

To consider the extra delay due to the existence of another communication link in the WAM sensors, an extra delay is considered. The only processing time known is the MLAT sensors one, which includes, beside the basic operation, the time to forward and receiving a message from an optical link. To avoid any problems, this value can be subtracted from the VPN maximum delay to give a margin for the system. It must be noticed that considering this fixed time is certainly higher than the extra delay in a real system. Table 4-9 contains the VPN maximum delay with and without the correction value previously discussed.

Even with an exaggerated compensation for the delay introduced for routing the messages from the intermediate building to the CP, 487 ms is enough for every VPN links. This value is not meaningful by itself, but comparing with a well-known situation, the tolerable delay in voice communications, should be smaller than 100 ms [Corr09]. If the network service provider guarantees this delay for that service, it should not be a problem to negotiate a delay around 200 ms for the MLAT service.

RU ID	VPN maximum delay [ms]	VPN maximum delay compensated [ms]
Arrabida	497.76	487.77
Caparica	497.82	487.83
Espichel	497.75	487.75
Fanhões	497.83	487.83
Montargil	497.58	487.58

Table 4-9 - VPN maximum delay.

## 4.6 Latency Simulator Results

#### 4.6.1 Lisbon LAM

To analyse the delays involved in any MLAT system, besides the system description is also required to define the targets position, from which one estimates delays. In a LAM system, there are many sensors spread in a small area, so distances separating targets from sensors are very small.

Three possible airplane positions were chosen (airplane 1, 2 and 3), being shown together with available sensors in Figure 4-8. The test positions, airplane 1 and airplane 3, were intended to maximise the radio distance to the fifth sensor, because it is the one used to calculate the synchronisation time. Airplane 2 was chosen just to analyse one of the worst positions in terms of

coverage, which is only covered by 5 sensors, according to the coverage analysis in Figure D.1.

As explained in the Section 3.2, the individual coverage must be included to define the test file, besides the choice of the locations. The global input file for these test positions is shown in Table 4-10, and the coverage for each point was accomplished by comparing the test positions with the coverage maps from Figure D.2 to Figure D.4. For each sensor, if the column contains "1" it means that this position is covered, and "0" otherwise.

Adding the test file with the Lisbon LAM system description in Table 4-1, the simulator generates the output file, the most important information being summarised in Table 4-11. As expected with small radio distances and small link lengths, delays are very small compared to the maximum synchronisation time, which is 500 ms in this case. In practice, for a LAM, there is no influence from the communication link length and the distance from the airplane to the sensors.



Figure 4-8 - Test positions for Lisbon LAM

Test Position	Latitude [DD° MM'SS"]	Longitude [DD° MM'SS"]	01	02	03	04	05	06	07	08	09	10	11	12	13	14
airplane 1	38°46'36.40"N	9° 8'18.06"W	1	1	1	1	0	1	1	1	1	1	1	1	1	1
airplane 2	38°46'47.00"N	9° 7'47.02"W	1	0	0	0	1	0	0	0	0	0	1	1	0	1
airplane 3	38°47'8.95"N	9° 8'0.86"W	1	1	1	1	0	0	1	1	0	1	1	1	1	1

Table 4-10 - Lisbon LAM tests input file.

Table	4-11	-	LAM	results

<b>Test Position</b>	Fastest sensor	Slowest sensor	Synchronization
	[ID]	[ID]	time[ms]
airplane 1	7	1	0.016
airplane 2	14	11	0.016
airplane 3	7	2	0.020

This system has the specificity of having all communication links with the same capacity, 100 Mbps, so the link transmission delay is very small. For the delays calculated from this test positions, it may be assumed that even testing for every possible position in the airport, the maximum synchronisation time based on the propagation time in the air and optical fibre is irrelevant. The sensor's processing time was not considered, because it is assumed that they all are approximately the same.

#### 4.6.2 Lisbon WAM

As discussed in Chapter 3, there are differences between the LAM and WAM analysis. One of the differences is in the test positions, and another in the system's description. In this Section the delays expected in the Lisbon WAM system are calculated and discussed. To define the test positions of the airplanes in a WAM system, the flight routes must be defined. Figure 4-9 contains the representation of the positions to test, which are better described in Annex A. In Figure 4-9 and every airspace maps used in this thesis, the coordinates displayed start by the direction, meaning N/S or E/W and then degrees, minutes and seconds separate by a space.

Considering that a given test route, the declination angle must be estimated. For this, a random section was chosen in the map, between DEKUS and MAGUM, with coordinates 38°00'55" N, 10°00'00" W and 39°10'03" N, 8°23'33" W respectively, which has a magnetic angle of 51°. Using (3.27) the real angle is 47.5°, and from (3.26) the magnetic declination is approximately 3.5°W.



Figure 4-9- Tests for Lisbon WAM [NAV10].

Another test, not included in Figure 4-9, is the approach to the runway, in the most used one in the Lisbon airport, which is described not on the flight routes map but in Figure 3-8. With all the variables to describe the test positions, the file to include in the simulator is shown in Table 4-12. The description of this system is partially given in Table 4-2, and missing column from the description being the maximum latency of the VPN links.

Two results for the VPN maximum delay could be considered; the maximum latency calculated in Section 4.4, 487 ms, or a reasonable value that a service provider offers. The value of 487 ms is exaggerated, and this type of delay is only expected in satellite links. A reference value obtained from [NAV11] for a VPN link is a round trip delay of 50 ms with an average jitter of 25 ms. The total delay of the link is 50 ms taking into account the jitter deviation, because the delay is only one way and not a round trip time.

For the approach, two extra sensors are used, RU04 and RU13 from Lisbon LAM, and their coverage is set to approach, meaning that they only cover the approach test position. The output gives two results: the total link delay for each sensor without taking the overall MLAT processing time into consideration; the equivalent to the LAM analysis, giving for each position the covering sensors and the synchronisation time.

ID	Туре	Initial Latitude	Initial Longitude	Route	Final Latitude	Final Longitude	Altitude	Final Altitude	Descent angle	Test points
UN745	Route	38°00'55"N	10°0'0"W	51			195			20
Ateca	Single Point	38°39'30"N	8°37'21"W				195			1
Espichel	Single Point	38°25'27"N	9°11'9"W				195			1
UN975	Section	38°39'30"N	8°37'21"W		38°25'27"N	9°11'9"W	195			20
RWY03	Approach	38°38'24"N	9°12'41"W	27			30	3.31	5.2	20
UN870a	Section	38°32'42"N	10°0'0"W		38°53'16"N	9°9'46"W	195			20
UN870b	Route	38°53'16"N	9°9'46"W	69			195			20

Table 4-12- Tests input file for Lisbon WAM.

The channel delay for each sensor, given as an output of the simulator, is shown in Table 4-13. The link delays in WAM sensors are much larger than the delays for the LAM's. Comparing WAM sensors link delay with the ones used for the LAM, there is a noticeable increase in delay. If the sensor's processing time would be included with the correspondent standard deviation, only the difference between the VPN links to the proprietary links would be noticed.

Sensor ID	Link Delay
Sensorid	[ms]
Arrabida	50.02
Caparica	50.02
Espichel	50.02
Fanhões	50.02
Montargil	50.02
Montejunto	0.36
TAR (RU 11)	0.02
RU 04	0.03
RU 13	0.01

Table 4-13 - Lisbon WAM sensors channel delay

The results of the synchronisation time are shown in Figure 4-10. Synchronisation times are very close to the delay defined for the VPN, as expected. It is also noticed that usually as closer the airplane is from the faster's links, the synchronisation time increases. For instance, in the approach case, when decreasing the distance to the fastest airport links increases the synchronisation time.

The main result is that even in a WAM with distances around 30 NM there is still no impact of the propagation delays in the system. Also, this system does not have proprietary links with high delays, and the synchronisation time is defined by the VPN delays, which are more resilient to errors and are still very far from the maximum latency allowed.



Figure 4-10 - Synchronisation time results Lisbon WAM

#### 4.6.3 Azores WAM

Considering the Azores WAM, similar to the Section 4.6.2, the system and test positions must be defined. The major difference between Lisbon's and Azores' WAMs is that in Azores there is no need to calculate the magnetic declination, because there is no coverage radius to intersect with the flight route.

The airspace route map in Figure 4-11 has a visual description of the test positions chosen for test in this analysis. These test positions are converted into the test input file of Table 4-14, as an input of the simulator together with the system description in Table 4-3.



Figure 4-11 - Azores route maps with the test positions (extracted from [NAV10]).

Link delays for each sensor, Table 4-15, are much higher than the ones calculated for the Lisbon

airport, due to the larger distances and smaller capacity of the links. These calculations do not consider the multi-hop effect, and for instance GS\_06 and GS\_07 have five hops until reaching the CP. The extra delay in each hop is not be very large, but considering the small delays calculated in these analyses, it may have a large influence.

ID	Туре	Initial Latitude [DD/MM.MMM]	Initial Longitude [DD/MM.MMM]	Final Latitude [DD/MM.MMM]	Final Longitude [DD/MM.MMM]	Test points
Horta	Single Point	38°31'10"N	28°37'25"W			1
H153 (HRT-NMA)	Section	38°31'10"N	28°37'25"W	38°48'45"N	28°3'22"W	20
H101 (HRT-RDL)	Section	38°31'10"N	28°37'25"W	38°4'44"N	27°36'24"W	20
H123 (SLG-LJS)	Section	38°37'30"N	28°1'58"W	38°46'59"N	27°06'47"W	20
H114(HRT-SML)	Section	38°31'10"N	28°37'25"W	38°13'21"N	27°19'1"W	20
H131(HRT-IBL)	Section	38°31'10"N	28°37'25"W	38°29'43"N	30°0'0"W	20

Table 4-14 - Simulator input tests for WAM Azores

Table 4-15 - Azores sensors channel delay.

Sensor ID	link delay [ms]
GS_00	4.43
GS_01	2.21
GS_02	2.25
GS_03	6.70
GS_04	11.30
GS_05	6.78
GS_06	11.23
GS_07	11.55
GS_08	9.09
GS_09	9.22
GS_10	9.02

In this system, no coverage analysis has been performed, so the synchronisation time only takes into consideration the fastest sensors.

Figure 4-12 contains the test analysis performed with the corresponding synchronisation times. In this analysis, there is also no concern about the synchronisation delay, because it is much smaller than the maximum one allowed by the system. This system has a much higher link delay compared to Lisbon's LAM, because links capacities are much smaller, there is a higher number of hops in most of the links, and links capacity is much lower than optical fibres' 100Mbps. Furthermore, it must also be noticed that in this simulation all sensors in the network are able to forward the message within time to the CP.

This summarises the analysis of the different networks. To finalise the study of the delay influence in the system, Section 4.6.4 contains a global view of the different parameters that influence it.



Figure 4-12- Azores Synchronisation time results.

#### 4.6.4 Overall Multilateration Systems Analysis

After showing the results for the three systems considered, Lisbon's LAM and WAM, and Azores' WAM, an assessment of the overall MLAT concerning the delay analysis is in order.

The Latency requirements are easily accomplished with any system, but there are some parameters that also influence the synchronisation time and have not been considered, i.e., standard deviation of the MLAT system processing time, analysed in Section 4.2, and the extra delay when there are hops in the communication link. There are five different delay components, air and link propagation time, transmission time, standard deviation of the system processing time, and the influence of the number of hops.

The air propagation delay has a speed approximated by the speed of light, Figure 4-13 showing this delay as a function of distance. For Lisbon's LAM, air distances are very small, at most around 4.5 km, which is approximately the largest dimension in the airport; for this specific case, the propagation time is much less than 0.1 ms. In the WAM scenario, even having distances that can go above 200 km, the influence of the synchronisation time is limited by the distance between the sensors as shown in Section 3.3. For Lisbon's WAM, this limitation is worse between Montargil and Espichel, 112 km, and in Azores' WAM is approximately 120 km between GS\_00 and GS\_09. With these distances, the maximum air propagation delay difference is not higher than 0.5 ms.

The link propagation speed depends on the type of link, and can be approximately  $2 \times 10^8$  m/s for an optical fibre or the speed of light for a microwave link, but the situation is similar to the air propagation delay, considering that the links distances are also at most a few hundreds of kilometres. In the analysed scenarios, the highest link length is in Azores with 184.66 km, and the difference between the shortest and longest is less than 180 km. From Figure 4-13, in this last case, the maximum delay

difference is less than 1 ms. All delays are very small, except in the case of having a satellite link, in which the air distance is twice the height to the orbit of a GEO satellite, approximately 70 000km, in which case delays are higher than 200 ms. Unless this last case occurs, the effects of propagation delay in links are very small.



Figure 4-13- Influence of the propagation delay with the distance.

Transmission time could also be a limitation of the system; considering a 70 B message, the transmission time for different capacities is shown in Figure 4-14, which contains a capacity range from [0.2, 10] Mbps, the maximum value of the interval being a common value for a link capacity, while the minimum is the minimum capacity for a link. The worst case for the synchronisation time is having a fibre mixed in a network of other sensors with capacity around the minimum required, but even in that case, the difference in transmission time is not higher than 3 ms.



The average standard deviation of the system processing time for the Lisbon's LAM is 0.355 ms and it was obtained for the Lisbon's LAM system with only one optical fibre. Simplifying the problem by considering that this value is valid for every analysed system, and with the same confidence interval of 99.73% used in Section 4.3, the extra delay of 2.13 ms should be added to the results obtained in the analysis. This is more accurate for Lisbon's WAM rather than Azores', because in the former the manufacturer and equipment are the same, while in the second the manufacturer is different.

The last delay influence to consider is the number of hops in the link. The standard deviation and the

average processing time, besides the MLAT system processing time, also includes the delays of forwarding the information to the link and receiving it, in an optical link. It is not possible to separate these two parts of the delay, so they must be considered together, and there are three cases in which an error is made:

- only one hop is used, not being an optical fibre;
- more than one hop is used, but one of them is an optical fibre;
- more than one hop is used, and none of them is an optical fibre.

In the first case, the time difference should be very small, because the optical or microwave links transmitter/receivers do not differ a lot in terms of delay.

In the second case, it may be considered that the standard deviation and the average of the MLAT processing time considers the extra delays of one optical link and the system itself, but does not consider any other delay of the remaining links. For each hop, the time delay considered was calculated by the propagation delay and the transmission time in (2.6), but there is the extra delay of receiving the message in an intermediary point, and reading at least the headers to forward the message correctly.

Finally, the third case is approximately the sum of the last two, and even if no optical links are used, it may be considered that the delay in one of them is included in the average and standard deviation of the system processing time. Concerning the rest of the hops, an assessment of the delay not considered for each extra hop should be done.

For now, it is not possible to get delay results from MLAT systems implemented with more than one hop, so this value is not possible to estimate. If there were data available, it would be possible to compare two different links with a different number of hops, and from that to retrieve an estimation of the extra delay per hop. This extra delay would only be considered for the total number of hops minus one, because the delay of only one hop has already been considered.

It is arguable that the extra delay by considering the processing time on each hop is quite small, but so are the other delays involved in the system. Table 4-16 contains the summary of each of the components and its possible influence of the synchronisation time. The maximum delay is calculated as the difference between the minimum and maximum value of the considered values. All parameters that influence the delay are quite small compared to the synchronisation delay, except the satellite and only in this situation it is possible not to consider the hop effect.

On the one hand, every small delays need to be considered in order to have an accurate simulator but on the other, all of these values are extremely small, as expected, and will not have any influence in the MLAT system.

This Section summarised the complete assessment of the possible telecommunication links and their effect in the MLAT systems already installed or any other to be developed.

Delay component	Considered limit	Maximum delay
Air	[0, 150] km	~0.5 ms
Fibre/Microwave link propagation	[0, 200] km	~ [0.67, 1]ms
Satellite propagation	[0, 70 000] km	~233 ms
Transmission	[0.2, 10] Mbps	~2.7 ms
Standard deviation MLAT	99.73% (±3σ)	~2.13 ms
Hops	unknown	unknown

Table 4-16 - Summary of the delays involved.

## 4.7 North of Portugal Multilateration study

### 4.7.1 Study Data

A preliminary study for a MLAT WAM system is presented, for the North of Portugal, the area delimited by the red line in Figure 4-15, where Porto's airport TMA is also included the. The TMA is a very important area, because the surveillance has more restrictive requirements, including the requirements studied in Section 4.3 for the tracking probabilities. The defined area for the TMA can be retrieved from [NAV10].



Figure 4-15 - North region to cover.

The study considers some sensors location proposals with different coverage goals, and analyses the tolerable delay and the required capacity for the links. Altitude coverage requirements are different within the entire region, but this study, being preliminary, considers FL100.

The first step in the study was to collect information for possible sensors location, and complete an individual coverage analysis for each one of them. Twenty sensors obtained from [NAV11] were

tested, and the individual coverage maps, obtained from the coverage simulator, are shown in Annex E.

As explained in Section 3.5, two different methods to address sensors importance were proposed: qualitative and quantitative evaluations. Table 4-17 contains the qualitative evaluation for the tested sensors, while Table 4-19 contains the quantitative one.

RU ID	Viana do Castelo	Braga	Porto	Aveiro	Viseu	Vila Real	Guarda	Bragança	Porto TMA
Porto Locator	Total	Total	Total	Total	HalfSW	0	0	0	Total-NE
Porto NDB	Total	Total	Total	Total	Total-E	Total	0	HalfW	Total
Viseu VOR-DM	0	0	Total	Total	Total	0	Total	Half S	HalfSE
Braganca	0	0	0	0	0	0	0	Total-SW	0
Ovar Tacan	Total	Total	Total	Total	HalfW	HalfW	0	0	Total-NE
Sensor 1	Total	Total	Total	Total	Total	Total	Total-SE	HalfSW	Total
Sensor 2	Total	Total	Total	Total	Total-NE	HalfW	0	0	Total-NE
Sensor 3	Total	Total	Total	Total-W	Total-W	Total	0	Half NW	Total-SW
Sensor 4	Total	Total	Total	Total	Total	Total	Total	Total-NE	Total
Sensor 5	Total	Total	Total	Total	Total	Total-NE	Total	HalfSW	Total
Sensor 6	Total-NW	Total	Total	Total-S	Total	Total	Total	Total	Total-NW
Sensor 7	Total	Total	Total	Total	Total	Total	Total	Total	Total
Sensor 8	HalfE	0	0	0	HalfE	HalfNW	HalfNW	Total	0
Sensor 9	Total	Total	Total	Total	Total	Total	Total	Total	Total
Sensor 10	Total	Total	Total	Total	Total	Total	0	HalfW	Total
Sensor 11	Total	Total	Total	Total	Total	Total	Total	Total	Total
Sensor 12	0	Total	Total	HalfN	Total-SW	Total	Total	Total-N	HalfE
Sensor 13	Total-NW	Total	Total	Total	Total	Total	Total	Total	Total-NW
Sensor 14	Total-NE	Total	Total	Total	Total	HalfS	Total	Total-NW	Total-SW/N
Braganca VOR	0	0	0	0	0	0	Total-SW	Total	0

Table 4-17 - Qualitative evaluation of the sensors.

To define the quantitative evaluation, districts areas were taken from [IGP10], but for the districts of Aveiro, Viseu and Guarda, the considered area is the intersection between the desired coverage, Figure 4-15, and the district itself; the considered percentage of area covered in each of the districts was 75%, 85% and 40% for Aveiro, Viseu and Guarda, respectively. The considered areas for each district are shown in Table 4-18, which were the values used to calculate the percentage of coverage area, using (3.42). The parameter that gives the percentage of the total coverage area is in the last column of Table 4-18, under utility. The percentage of coverage in each district is also shown.

For both analyses, the evaluation was done by observation, being used to support the choice of locations. In order to have more accurate values for the covered area with a certain set of sensors, the coverage maps in Google Earth must be used. With this information concerning the coverage for some possible sites, four analyses with different goals are developed in the rest of Section 4.7.

District	Total area [km <sup>2</sup> ]	Considered area [km <sup>2</sup> ]
Aveiro	2801	2101
Braga	2706	2706
Bragança	6599	6599
Guarda	5535	2214
Porto	2332	2332
Viana do Castelo	2219	2219
Vila Real	4308	4308
Viseu	5010	4258

Table 4-18 - Districts areas.

Table 4-19 - Quantitative evaluation of the sensors.

RU ID	Viana do Castelo	Braga	Porto	Aveiro	Viseu	Vila Real	Guarda	Bragança	Utility
Porto Locator	100%	95%	100%	100%	70%	10%	0%	0%	47.25%
Porto NDB	100%	100%	100%	100%	95%	100%	5%	30%	74.06%
Viseu VOR-DME	0%	0%	100%	100%	100%	0%	100%	40%	50.66%
Braganca	0%	0%	0%	0%	0%	0%	0%	80%	19.74%
Ovar Tacan	100%	100%	100%	100%	70%	30%	0%	0%	50.98%
RU 1	100%	100%	100%	100%	100%	100%	95%	50%	87.25%
RU 2	100%	100%	100%	100%	90%	40%	10%	0%	56.61%
RU 3	100%	100%	95%	95%	70%	100%	0%	60%	76.24%
RU 4	100%	100%	100%	100%	100%	100%	100%	80%	95.06%
RU 5	100%	100%	100%	100%	100%	95%	100%	50%	86.85%
RU 6	95%	100%	100%	75%	98%	100%	100%	100%	97.30%
RU 7	100%	100%	100%	100%	100%	100%	100%	100%	100.00%
RU 8	30%	0%	0%	0%	20%	70%	50%	100%	45.77%
RU 9	100%	100%	100%	98%	100%	100%	100%	100%	99.84%
RU 10	100%	100%	100%	100%	100%	100%	20%	40%	78.57%
RU 11	100%	100%	100%	100%	100%	100%	100%	100%	100.00%
RU 12	0%	95%	100%	40%	90%	95%	100%	80%	79.15%
RU 13	90%	100%	100%	100%	100%	100%	100%	100%	99.17%
RU 14	80%	100%	100%	100%	100%	55%	100%	80%	86.15%
Braganca VOR	0%	0%	0%	0%	10%	15%	80%	100%	35.32%

### 4.7.2 First Proposal

It is a fact that the minimum number of sensors to execute the TDOA algorithm is at least 4 for a 3D localisation, as explained in Section 2.2. This minimum number of sensors is increased to 5, in order to have redundancy in this critical system. Considering these facts, an initial study is to know how many sensors are required to provide at least 5 sensors covering every location. The first coverage

study proposes a set of sensors to meet these requirements.

Considering the quantitative and qualitative analysis, Table 4-17 and Table 4-19, the difficulty to cover the Northeast sector of Bragança is obvious, since only a few sensors cover that area. The five sensors chosen to cover this area were sensor7, sensor9, sensor11, sensor13 and Bragança VOR. The choice of the first four sensors was that, besides covering the entire district of Bragança, they also have the highest utility in Table 4-19, which means the highest covered area. The last sensor, Bragança VOR, does not have a good total coverage even though Bragança is completely covered, but the main advantage of this location is that the site already contains NAV Portugal equipment and the installation would be much easier.

With the five sensors already chosen, there are two small areas in the northwest and southwest of the region that are only covered by 3 sensors; even though this is a small area, in order to respect the minimum requirements for this proposal, two more sensors that cover simultaneously the northwest and southwest areas are required. sensor4 and Porto NDB sensors were chosen, the former because it is the one with larger coverage, and the latter due to the fact that it is a NAV's location and the total coverage is not much worse than the other possibilities. Figure F.1 contains the chosen sensors and the respective global coverage for the considered area (this map was created by intersecting the sensor's individual coverage maps in Google Earth).

There is still a small area that is only covered by only four sensors, but this area does not intersect Porto's TMA and it is not relevant for the global coverage. Concerning the rest of the region, there is a predominant area covered by 6 or 7 sensors, which means that its majority has a good coverage, taking into consideration that only 7 sensors are being used.

A proposal for a set of sensors to provide at least 5 sensors per location is then: sensor 7, sensor 9, sensor 11, sensor 13, Bragança VOR, sensor 4 and Porto NDB. The possibility of replacing Bragança VOR by sensor 6, which has a much higher coverage, was considered, but even if sensor 6 was chosen, the same 7 sensors would be necessary. If the same number of sensors is required, it is preferable to have sensors in NAV Portugal locations that do not require site renting and preparation.

### 4.7.3 Second Proposal

One of the goals of this thesis was the evaluation of required number of sensors to comply with the localisation requirements. Considering 60% for the sensor's receiving probability, from Table 4-5 the minimum number of sensors in the TMA is 8. The second coverage study concludes how many sensors are required to meet the localisation requirements, and then analyse the coverage for the remaining areas.

From Table 4-17, there are only 8 sensors that cover the entire TMA, thus, 8 being also the minimum number of sensors to comply with the requirements: sensor 1, sensor 4, sensor 5, sensor 7, sensor 9, sensor 10 and sensor 11. This choice did not take into consideration that there are other sensors with higher coverage utility, but if they were to be used, the solution would have more than 8 sensors. The coverage result for this combination of sensors is shown in Figure F.2.

In this proposal, the intersection of Porto's TMA with the coverage is the most important result, which is why the TMA is overlapped with the global coverage. There is a small TMA area that is only covered by seven sensors, but it is negligible, so no more sensors were added to this proposal. Considering that this study only considers eight sensors, the area covered by eight or seven is very large, and the only area that does not meet the first proposal requirements is the Bragança Northeast.

The study to guarantee eight sensors covering the TMA cannot be final because not all requirements of a MLAT system are met, but it is helpful to complete the last study, which improves this second proposal.

### 4.7.4 Third Proposal

After presenting the first two proposals, it was defined that a useful study would be to add three sensors to the second proposal, increasing the total number of sensors to eleven. The sensors to add are the ones with more coverage utility from the remaining set.

The third proposal considers the sensors from the second and in addition will add sensors sensor 6, sensor 13 and sensor 14, which are the sensors with higher coverage area. Sensor 6 and sensor 13 cover the entire district of Bragança, and sensor 14 is the remaining sensor with the largest total coverage. Figure F.3 contains the global coverage of this proposal.

Including two sensors that cover Bragança entirely, and another that gives a partial coverage, improves a lot the global coverage of the North region. The TMA is also better covered with 11 or 10 sensors, except in a few small areas in the North border that are only covered by 9.

This proposal could be improved if the Porto NDB sensor was replaced by sensor 12, this way the system would have the eleventh best sensors in terms of total coverage. However, this replacement was not considered, because the difference in approximate coverage is around 5%. Another reason is that Porto NDB, besides being a NAV Portugal site, is also in a very strategic place to cover the area near the airport.

All requirements are met with this choice of sensors, every region has at least 5 sensors and the TMA is covered by more than 8 sensors. Except for small areas in the TMA and Bragança, the redundancy of this system is 2. This means that even if sensor sensor 7 and sensor 9 fail, whose coverage utility is 100%, the requirements are still fulfilled in the majority of the area to cover.

## 4.7.5 Fourth Proposal

In terms of global coverage the last proposal is better than any other arranged combination, but the fact is that Bragança is not a district with a high frequency of airplanes, on the contrary, the traffic in this region is very small and it is preferable to cover the coast and the TMA better rather than that region. Due to this fact, one analysed the possibility to place two sensors that provide the minimum coverage to Bragança, and another near the coast, even if it is not the one with the largest coverage.

Another motivation to replace one sensor from the last proposal by another in the coast is to have

more spatial diversity. This matter has not been discussed in this thesis, but the accuracy of the MLAT system depends on the sensors position in relation to the airplane. If an airplane is covered by 5 sensors but they are all in a straight line, the uncertainty of the calculated position is much higher than if the airplane is in-between the same number of sensors. Preventing this situation, whose effects have not been considered, a sensor placed in the coast increases the spatial diversity.

The sensor to replace must be one that does not cover the northeast sector of Bragança, and that does not have a high global coverage compared to the others, sensor 14 being chosen. The sensor to add in the southwest region with the largest global coverage is Ovar Tacan, which has two advantages: it is much separated from Porto NDB, which is also located in the coast, and it is located in a military site, which is probably better than having to rent the site from a telecommunications operator or even building a new one. Figure F.4 contains the global coverage for the last proposal.

By comparing Figure F.3 with Figure F.4, it is observable that the third proposal has a better overall coverage of the region, especially in Bragança. On the other hand, this last proposal improves the coverage in the cost and the TMA. Taking into consideration that the East area is not as important as the coast, this last proposal should be given more value.

This proposal finalises the coverage study of the North region of Portugal. Still, some more considerations in terms of communication links are discussed in the Section 4.7.6.

#### 4.7.6 Global Analysis

Four different sensors combinations with different objectives have been proposed, but the only complete proposal to consider for the final implementation are the third and fourth. Besides the coverage analysis, it is also important to assess other requirements considered in this thesis, like the maximum latency and the required capacity for the communication links.

The required capacity for the links is directly related to the expected traffic in the region. If the maximum expected traffic in the defined region is 250 airplanes, then, as concluded in Section 4.2, each link should have at least 275.7 kbps. Even though it is possible to define the maximum capacity required for 250 airplanes, it mainly depends on each sensor individually. The coverage figures in Annex E only contain the North area, but their coverage for FL100 is much wider than that, and considering that most of the airplanes travel in higher routes, then, this coverage will also increase.

The conclusion is that to determine the capacity required for each link, one should take the individual coverage of the sensor into account. The solution of reducing the sensor's range may not be effective, and may decrease the system's efficiency. In case the sensor is placed in the limits of the region to cover, reducing the range of the sensor the required capacity is also reduced, but at the cost of reducing their effective covered area. From Figure F.3 and Figure F.4, most of the sensors are in this situation, because many are located near the border with Spain. A solution not to limit the effective covered area is to use sector antennas, used often in mobile networks. Using sector antennas for the sensors places near the border, the sector including the area not to cover can have a minimum range, while the other sectors have the maximum range allowed. If this is possible to implement, it would

solve the link capacity problem, and also be energy efficient, because no energy would be spent covering a region that is not NAV Portugal's responsibility.

Concerning the maximum latency for the communication links, the analysis is the same used to assess the required latency for the WAM sensors in Lisbon. In this case, there is still no specific location for the CPS, but probably it will be located near Porto's airport. In this situation, the fastest link would be Porto NDB, because it is a station with surveillance equipment and is certainly connected to the airport by a fast private communication link. By using (3.22), it is possible to estimate the maximum delay for every other link compared to the fastest one. The extra delay in the air and the MLAT processing time are the only parameters that influence the delay, not depending on the communication link.

By using Google Earth, the maximum distance that separates a pair of sensors in that region is around 250 km, which corresponds to the distance from the Southwest end to the Northeast. According to Figure 4-13, the extra delay of this component is around 1 ms. The MLAT processing time standard deviation is the same used in the Lisbon VPN, and for a confidence interval of 99.73 %, the maximum difference in time is 2.13 ms.

As a final conclusion, there are no problems concerning the delays, and if a VPN connection is used for all sensors, the tolerable delay can be very close to the maximum allowed. Any service provider operator will easily supply a maximum delay of 200 ms, which is higher than the current values tolerable for mobile communications. All private links should be used, but in case none is available, renting a VPN link is a solution.

# **Chapter 5**

## Conclusions

This chapter finalises this work, summarising conclusions and pointing out aspects to be developed in future work.

This thesis consists of a study of multilateration systems requirements and limitations in Portugal, in Lisbon and Azores, and the design of a new system for the North of the country.

Chapter 2 focuses in four different subjects: messages used in air surveillance, introduction to multilateration systems, the state of the art, and the description of possible telecommunications links to use. Concerning the messages used, the most important information is concerning their size and sending rate which are used to calculate the capacity of the links. The multilateration system description is important to provide the basic knowledge of how multilateration works. Finally, the telecommunication links Section, used to develop the latency model, explaining the delays involved in each type of link.

In Chapter 3, two models were developed to estimate the delay in a multilateration system and to analyse the coverage of each sensor. For the latency model, the delays in the links and the possible distance between the airplane and sensors were implemented in a simulator, which estimates the delays for a given MLAT system considering the possible routes of the airplanes. The coverage model is based on the land profile surrounding the sensor and the height of the airplane, which enables the global coverage calculation. These models were also implemented in a simulator, which is able to request from the Google servers the information necessary to calculate the global coverage and represent it in Google Earth.

Beside the discussed models, Chapter 3 also includes some smaller models to estimate the capacity required in a link, to estimate the maximum allowed delay for a virtual private network link, and finally to assess the localisation requirements according to the number of sensors. These three models do not have a simulator, because the calculations are only using one or two equations.

In Chapter 4, by analysing the results in each Section, the overall conclusions from this work can be divided into two categories, the communication links and the multilateration sensors. The communication links conclusions are mainly three: the required capacity for the communication links to support 250 targets is 275.7 kbps, the synchronisation time is not close to the maximum tolerable delay of 500 ms, and the maximum delay for the VPN links in Lisbon is 487 ms. For a more detailed analysis of each conclusion:

- The average expected traffic is much smaller than the maximum one, but the capacity for it must at least cope with the traffic generated by the maximum number of targets plus a safety margin that should also be considered. Concerning the provided headers, for a usage ratio of 90%, a receiving probability of 40%, and 250 targets, links require 275.7 kbps. The main impact on links capacity is due to headers.
- The delay analysis for each of the implemented systems using the simulator did not presented any delay problems, as expected. Analysing all the components of delay, and not considering the large delay of using a satellite link, the largest influence is from the sensors processing time. This delay has been estimated from the equipment installed in the Lisbon airport, and it has an average fixed delay and standard deviation smaller than 10 ms and 0.4 ms, respectively.
- For the maximum tolerable delay in Lisbon's wide area multilateration VPN links, the result is that 487 ms is enough. For normal voice communications the tolerable delay is around 200 ms, which

the telecommunications operators have been guaranteeing for a large number of years, hence, with the technological advances, the maximum delay provided will be much smaller.

The calculated delays are not very accurate, because the standard deviation itself is around the same order of magnitude as every other component, so even a link that in theory is the fastest, it may be proven otherwise with real measures. Also, the effect of the processing time in the multi-hop could not be considered, because measures to conclude about its significance were not available.

Regarding the multilateration sensors, the work is split into two parts: to analyse the localisation requirements from Eurocontrol, and then to perform a coverage study for the Northern region of Portugal. Localisation requirements are two, concerning the tracking probability higher than 99 % in five update intervals, and the continuous tracking probability higher than 97% in one update interval.

The minimum number of sensors required to execute the time difference of arrival algorithm is 3 or 4, for a 2D or 3D localisation respectively. On the other hand, to comply with the Eurocontrol requirements and considering that the receiving probability of the sensors is not 100 %, more sensors are required. To calculate the two localisation requirements, it was considered that the minimum number of sensors to execute the localisation algorithm is 4 and that the track initiation can be performed with 2 or 3 consecutive messages. The conclusion is that 4 sensors are never enough to comply with the requirements in the terminal manoeuvring area and that the requirement more restrictive is the track initiation. If a 40 % receiving probability is considered, the minimum number of sensors to cover the terminal manoeuvring area is 8 if three consecutive messages are required to initiate the track or 7 sensors if only two messages are required.

Four different coverage studies for FL100 have been developed using some sensors locations. From them it was concluded that:

- To provide coverage of 5 sensors per location in the North of Portugal, which is the minimum requirements for the algorithm plus one extra sensor for redundancy, 7 sensors are required.
- To comply with the localisation requirements in the terminal manoeuvring area of Porto, with a 40 % receiving probability and for a track initiation with three messages, 8 sensors are required.

The first two coverage proposals were useful to analyse the impact of the minimum requirements of the system but a system cannot be implement only respecting the minimum requirements. Following NAV Portugal indications, two other coverage studies were made to have a more robust system with the total of 11 sensors. Both analyses guarantee a redundancy of one sensor and to have 8 sensors in the TMA a redundancy of two sensors.

The effects of the sensor's receiving probability affect two critical system requirements, the localisation probability and the link capacity. For this thesis the main receiving probability considered was around 40 %, but this parameter may change a lot depending on the equipment and conditions. The fact is that with a small receiving probability the required capacity is smaller, but the number of sensors to respect the localisation requirements increase. On the other hand, if the receiving probability increases, the links capacity must increase and the required number of sensors decreases. This parameter influences a lot the entire system, and it must be carefully analysed.

The last note concerns the range of the sensors. All manufacturers have sensors with the capability of covering 200 NM, meaning that with one sensor there is the possibility of covering almost the entire country. When an air navigation service provider defines the maximum number of targets, they are assuming that in the desired area the number of airplanes will not exceed that number. On the other hand, a sensor may have a large coverage area, and like in Lisbon for the most common flight levels, above 10 000 feet, the covered area is more than the double of the desired one. In conclusion, if the range exceeds the desired coverage, the capacity of the link should be increased, or the range can be limited.

This concludes the analysis performed in the thesis, but still there are future improvements and work to perform on this subject:

- If there are delay measures of a multilateration system, like the one installed in Azores, the effect of the multi-hop links in the total delay can be better estimated. To have accurate values, it is very important that this analysis is performed, especially because all delay components involved in this type of systems have very small values.
- Considering the coverage range for flight levels higher than 10 000 feet, it is possible to cover the entire country with a small set of sensors, instead of having each region independent between themselves. The multilateration systems analysed consider that the messages can be forward to different systems, which allows having a common control centre that is able to provide surveillance to the entire Portuguese airspace, and still have the possibility of forwarding messages to other control centres. This can become more efficient, because the sensors range can be maximised and cover a larger area. And it was also shown that the capacity to rent in a VPN link is small considering the bandwidth that is available nowadays.
- The influence of the delay has been discussed, but the accuracy of the system has not. There are
  two critical aspects to study the influence in the location accuracy: the sensors geographical
  disposition and the number of sensors. It is known that if 5 sensors are all in the same azimuth of
  the airplane, the error of the position is much higher than if they have different azimuths. It is
  important to quantify this effect, in order to have a better project of the system and reduce the
  dependency from the multilateration manufacturers.
- If there is the possibility of removing the limitation of the land profile requests used in the developed simulator, it may be used for lower flight levels and increase its accuracy.

Hopefully the work developed in this thesis is of value to a air navigation service provider. It can give deeper knowledge to evaluate the manufactures proposals, and compare their proposals with the expected performance.

All in all, the main goal of this thesis is to be one step forward in recent technologies and to understand that knowledge is the most powerful weapon that one has.

## **Annex A Latency Simulator Manual**

This Annex presents indications for the use of the simulator with examples of input files and description of the GUI, two different software were used, Matlab R2007b [MatL11] for the simulator and Microsoft Office Excel 2007 for the input/output files. The simulator code is only accessible in the Matlab files.

The application can be started by the executable file or by the Matlab file *multilateration.m* that contains the GUI and Figure A.1 is displayed.

Multilateration	
Multilateration Type	Parameters
Local Area Multilteration	Insert the cell Radius (default 30NM):
O Wide Area Multilateration	Insert declination in degrees(default 3.5):
	Note: Use '.' for decimal values
	Select Input File 1
	Select Input File 1 Select Input File 2

Figure A.1 - Simulator GUI.

There are three parameters to define, the cell radius, the declination of the area in question and the maximum allowed synchronisation time. All of these parameters have default values, mentioned on the GUI, and to insert a decimal value it must be used the '.'. The analysis type, WAM or LAM, is chosen by the option button in the upper left corner.

Pressing the button *Select Input File* 1 or *Select Input File* 2, a file select browser like Figure A.2 is displayed. The first input file must contain the system description and the second the test positions, some examples are given for both input files bellow.

To run the simulator the *Run* button must be pressed but it will only run if both input files are selected. After the second input file is selected it will appear in the GUI a note saying the output name and another note will appear while the simulator is running, Figure A.3. When the execution ends an information message is displayed.

Procurar em:	MATLAB	-	🗧 🔁 📸 🔻	
C.	Nome	Data modificação	Тіро	Tamani
<b>S</b>	line Air propagation time	12-05-2011 12:20	Pasta de Ficheiros	
recentes	📕 ChannelDelay	01-05-2011 16:31	Pasta de Ficheiros	
-	🃙 Define Path	06-05-2011 23:12	Pasta de Ficheiros	
	🍌 googleearth	30-06-2009 17:16	Pasta de Ficheiros	
Ambiente de	📙 Lixo	01-05-2011 16:04	Pasta de Ficheiros	
trabalho	📙 Read input files	01-06-2011 10:20	Pasta de Ficheiros	
	Testes	06-05-2011 22:39	Pasta de Ficheiros	
Joan Teixeira	Unit conversion	05-05-2011 00:19	Pasta de Ficheiros	
Pinto	🍌 Write output	07-05-2011 00:54	Pasta de Ficheiros	
	🕙 Descrição Sistema	01-06-2011 10:26	Microsoft Office E	1
	🕙 Descrição Sistema WAM	31-05-2011 18:10	Microsoft Office E	1
Computador	Manut2WAM	06-05-2011 22:31	Microsoft Office E	1
-	MAW2Wat Input2WAM	31-05-2011 18:11	Microsoft Office E	1
	•	III.		
Rede	Nome do ficheiro: Descrição Si	stema WAM	•	Abrir

Figure A.2 - Select file.

Output_Input2WAM.xlsx	Run
running	

Figure A.3 - Output name and simulator status.

The first input file contains the general description of the system, containing all the sensors in the network, and the complete description of the communication links. The CPS should also be included in the list of sensors because the cell radius is calculated from its position. The reference transmitters may be included or not. This description file must be able to fit any possible system if it would be used only for the Lisbon LAM the input file must contain the information of Table 4-1.

The simulator must considered all communication link types; satellite, optical fibre, microwave link and VPN. As explained in chapter 2, optical fibres and microwave links are described by its length and capacity, satellites by their orbit altitude and capacity, and finally VPN by a maximum delay, so the final input test must include some more categories than Table 4-1. The required headers to include in the LAM system description file are shown in Table A.1 while the headers for a WAM description file are shown in Table A.2.

Table A.1 - Headers to include in the LAM system description.

ID	Equipment Type	Latitude [DD°MM'SS.SS"]	Longitude [DD°MM'SS.SS"]	Required Communicati on Link	Link Capacity [Mbps]	Elevation AGL [m]	Link length [km]	Extra delay [ms]
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The WAM description file has three main differences from the LAM description. First there is the possibility of using an extra fibre link with a different capacity for any sensor. This difference is extremely important because the CPS is usually located in the middle of the airport and for WAM sensors it may be common that the data is received another place before being forward to the CPS. Second, the hops in a link are considered, and obviously the message must be processed in each hop. Finally a coverage column will be added for a more specific analysis.
#### Table A.2 - Headers to include in the WAM system description.

10	Equipment Type	Latitude [DD°MM'SS.SS"]	Longitude [DD°MM'SS.SS"]	Elevation MSL [m]	Coverage	Required Communication Link	Link Capacity [Mbps]	Total link length [km]	Number of link hops	Extra fibre length [km]	Extra fibre capacity [Mbps]	Extra delay [ms]
						LIIIK	[IMIDh2]	[Kiii]	nops	[KIII]	[INDD2]	luis

Each of the columns is given a more detailed explanation:

- *ID*: Name to identify the equipment, it is not important for the simulation.
- *Equipment Type*: Defines which equipment is represented in that line, it may be a RU6 (sensor), CPS or Reftrans. The Reftrans are not be used, the CPS is used to define the centre of the radius to cover and the RU6 are the different sensors of the network.
- Latitude: Latitude coordinates of the equipment position in degrees, minutes and seconds.
- Longitude: Longitude coordinates of the equipment position in degrees, minutes and seconds.
- *Required Communication Link*: Type of communication link used for the sensor which can be fibre, microwave, satellite (LEO, MEO, GEO) or VPN
- Elevation: Equipment height ASL for LAM and MSL for WAM.
- Link capacity: Capacity of the main link.
- *Link Length*: Total length of the main link, case it is a multi-hop link, the total length is the sum of all the hops length.
- *Extra delay*: Is used to consider any extra delays in the specified sensor or to specify the maximum allowed delay in a VPN connection.
- *Number of link hops*: Is more used in microwave links because the link may have one or more repeaters. These hops are only considered for the main link, the extra fibre that may exist is not included in this column.
- *Extra fibre length*: To consider extra fibre connections it is required to specify its length.
- Extra fibre capacity: Includes the capacity of extra link.

Coverage analysis is also important and somehow it must be possible to choose if a sensor is used or not. There is a big difference between LAM and WAM coverage as shown Section 4.1. While in a WAM system it can be considered that above FL100 each sensor covers the entire area in a LAM system the coverage is not regular at all. Two approaches have been defined to consider both cases. For WAM the coverage is included in the system description file and there are 4 possibilities which can be used separately or together:

- All: It does not matter the airplane position or altitude that it is covered by this sensor.
- Single: This sensor only covers single point's tests.
- Route: This sensor cover flight routes in the area, so every airplanes that circulate in normal airways.
- Approach: This sensor covers the airplanes that are approaching the landing runway.

The LAM coverage is more difficult and it is included in the test position input file and the coverage is explicit for every position to test. All of the headers are intuitive and the only that was not explained was the coverage that is explained in the second input file. The information contained in the

description file is the same as the tables explaining the multilateration system but the simulator must work independently of the input and that is the reason of the higher number of columns when comparing to the system description. One example of each system description, LAM and WAM, are shown in Table A.3 and Table A.4 respectively. For the WAM system description, the columns Equipment Type, Latitude and Longitude were hidden but they must appear in the file. Both examples illustrate most of the possibilities for the different columns and can be used as reference for future tests to run.

ID	Equipment Type	Latitude [DD°MM'SS.SS"]	Longitude [DD°MM'SS.SS"]	Required Communicati on Link	Link Capacity [Mbps]	Elevation AGL [m]	Link length [km]	Extra delay [ms]
SMR	CPS	38° 46'45.66"N	9° 8'22.56"W	None Required	N/A	N/A	N/A	N/A
X1	RefTran	38° 46'51.3"N	9° 7'55.74"W	None Required	N/A	N/A	N/A	N/A
RU01	RU6	38°46'51.30"N	9° 7'55.74"W	Fibre	100	33	1.784	0
RU02	RU6	38° 47'21.06"N	9° 7'49.26"W	Microwave	100	13	3.135	0
RU03	RU6	38°47'51.90"N	9° 7'50.34"W	VPN	N/A	3	N/A	400
RU04	RU6	38°47'57.18"N	9° 7'35.28"W	Satellite	0.2	3	N/A	0
RU05	RU6	38°46'51.78"N	9° 7'45.06"W	LEO	0.2	15	N/A	0
RU06	RU6	38°46'41.94"N	9° 7'53.52"W	MEO	0.2	20	N/A	0
RU07	RU6	38°46'45.66"N	9° 8'22.56"W	GEO	0.2	8	N/A	0

Table A.3 – LAM first input file example.

Table A.4 - WAM first input file example.

ID	Elevation MSL [m]	Coverage	Required Communic ation Link	Link Capacity [Mbps]	Total link length [m]	Number of link hops	Extra fibre length [km]	Extra fibre capacity [Mbps]	Extra delay [ms]
SMR	N/A	N/A	None Required	N/A	N/A	N/A	N/A	N/A	N/A
Arrabida	133	all	VPN	100	N/A	N/A	2.721	100	480
Caparica	105	all	VPN	100	N/A	N/A	2.721	100	480
Espichel	103	all	VPN	100	N/A	N/A	2.721	100	480
Fanhões	100	single	VPN	100	N/A	N/A	2.721	100	480
Montargil	112	route	VPN	100	N/A	N/A	2.721	100	480
MonteJunto	121	approach ; route ; single	microwave	100	47717	2	2.721	100	0
TAR (RU 11) airport	108	approach	fibre	100	3469	1	0	0	0

Beside the system description file it is also required to know the airplane test positions because the total delay of the system also depends on the airplane location. There is also a difference between LAM and WAM, in the first case airplanes have a very limited set of possible positions and the altitude is well known while in the WAM they can have flight routes with different altitudes.

The LAM test positions are only be given by a single point, meaning that the airplanes position is a latitude and longitude without having to add any information concerning the flight altitude. There is a slight error committed by not considering the transponder AGL height but as there is no fixed

transponder height it is not used. In the LAM test file the coverage must be included explicitly, meaning that for each test position it must include which of the sensors cover that position. An example of a LAM input test file is shown in Table A. 5. The test file contains three different test positions each one of them with latitude and longitude coordinates. The columns *01* to *14* represent each of the sensors ID in the network and the value "1" is used when the sensor covers the test position and "0" otherwise.

There are four different test positions for a WAM test file:

- Single point: It is required to specify the latitude and longitude of the point, the flight level of the airplane and contain "1" in the column *Test Points*, otherwise the test are not be performed.
- Route: It is required to specify, the coordinates for the initial point, the route angle, the altitude of the airplane and the number of test points.
- Section: It is required to specify, the initial and final point coordinates, the altitude of the airplane and the number of test points.
- Approach: It is required to specify, the coordinated of the beginning of the descent, the route angle, the initial and final altitude, the descent angle and the number of test points.

Table A.6 contains an example of a WAM test input file with every possible test positions considered. The coverage of the WAM sensors has been already considered in the system description file.

After running the simulator with both input files, the excel output is created in the same folder as the test position file under the name "Output\_" plus the name of the test position file name. This output file is also different if the user chose a LAM or WAM analysis. The output for the LAM test file in Table A. 5, is Table A.7. Because the LAM analysis is much smaller and only works with single points, all delays from the airplane to the CPS, through each of the sensors are presented. Furthermore the fastest and fifth fastest sensor with the correspondent synchronisation time is shown in the last columns of the output.

The output for a WAM test file is different from the LAM's and depends even though all the results are presented in the same file, each of the required test positions is presented separately. Table A.8, Table A.9 and Table A.10 contain the output of a single point, section and approach, respectively. The route output is not presented because it has the same structure as the section. Starting by the single point output, the information is equivalent to the LAM's but instead of presenting the calculated delay for each sensor it lists the sensors that arrive within the synchronisation time.

The section and route output are similar to the single point analysis considering each test point separately. The only difference is that in this output the each analysed point is numbered and its distance to the initial point is presented. Finally, the approach section differs from the section and route because it contains a column giving the altitude of the airplane in the correspondent position.

This Annex presented the user manual and the description of the parameters for a future use of the simulator. It gives a more detailed explanation of the interface but to make changes to it, the section with the correspondent model and simulator should also be consulted.

Table A. 5 - LAM test input file example.

Test Position	Latitude [DD/MM.MMM]	Longitude [DD/MM.MMM]	01	02	03	04	05	06	07	08	09	10	11	12	13	14
airplane 1	38°46'36.40"N	9°8'18.06"W	1	1	1	1	0	1	1	1	1	1	1	1	1	1
airplane 2	38°46'47.00"N	9°7'47.02"W	1	0	0	0	1	0	0	0	0	0	1	1	0	1
airplane 3	38°47'8.95"N	9°8'0.86"W	1	1	1	1	0	0	1	1	0	1	1	1	1	1

Table A.6 - WAM test input file example.

ID	Туре	Initial Latitude [DD/MM.MMM]	Initial Longitude [DD/MM.MMM]	Route [Degrees]	Final Latitude [DD/MM.MMM]	Final Longitude [DD/MM.MMM]	Altitude [ft $\times$ $10^{-2}$ ]	Final Altitude $[ft \times 10^{-2}]$	Descent angle [%]	Test points
UN745	Route	38°00'55"N	10°0'0"W	51			195			20
Ateca	Single Point	38°39'30"N	08°37'21"W				195			1
Espichel	Single Point	38°25'27"N	9°11'9"W				195			1
UN975	Section	38°39'30"N	8°37'21"W		38°25'27"N	9°11'9"W	195			20
RWY03	Approach	38°38'24"N	9°12'41"W	27			30	3.31	5.2	20
UN870a	Section	38°32'42"N	10°0'0"W		38° 53'16"N	9°9'46"W	195			20
UN870b	Route	38°53'16"N	9°9'46"W	69			195			20

Table A.7 - Example of result for a LAM analysis.

Test Position	01	02	03	04	05	06	07	08	09	10	11	12	13	14	Fastest sensor [ID]	Slowest sensor [ID]	Synchronisation time[ms]
airplane 1	0.02	0.03	0.04	0.04	NLoS	0.01	0.00	0.03	0.03	0.03	0.03	0.02	0.02	0.01	07	01	0.0162
airplane 2	0.02	NLoS	NLoS	NLoS	0.02	NLoS	NLoS	NLoS	NLoS	NLoS	0.03	0.03	NLoS	0.01	14	11	0.0156
airplane 3	0.02	0.02	0.04	0.03	NLoS	NLoS	0.00	0.03	NLoS	0.04	0.03	0.03	0.02	0.01	07	02	0.0197

#### Table A.8 - Results for a WAM single point.

Ateca	Single Point	Altitude:19500 ft				
Test number	Latitude	Longitude	Fastest	Slowest	Synch time	List of Sensors within sync time
1	38°39'30"N	08°37'21"W	TAR (RU 11) airport	Fanhões	50.0194868	TAR (RU 11) airport: MonteJunto: Arrabida: Caparica: Fanhões: Espichel: Montargil

Table A.9 - Results for a WAM section.

UN975	Section	Altitude:19500 ft					
Test number	Latitude	Longitude	Distance [km]	Fastest	Slowest	Synch time	List of Sensors within sync time
1	38°39'30"N	8°37'21"W	0.00	TAR (RU 11) airport	Fanhões	50.019	TAR (RU 11) airport: MonteJunto: Arrabida: Caparica: Fanhões: Espichel: Montargil
2	38°38'45.6316"N	8°39'7.9017"W	1.58	TAR (RU 11) airport	Fanhões	50.021	TAR (RU 11) airport: MonteJunto: Arrabida: Caparica: Fanhões: Espichel: Montargil
3	38°38'1.2632"N	8°40'54.7851"W	3.15	TAR (RU 11) airport	Espichel	50.021	TAR (RU 11) airport: MonteJunto: Arrabida: Caparica: Espichel: Fanhões: Montargil

Table A.10 - Results for a WAM approach.

RWY03	Approach							
Test number	Latitude	Longitude	Distance [NM]	Altitude [ft]	Fastest	Slowest	List of Sensors within sync time	Synch time
1	38°38'24"N	9°12'41"W	0.00	3000.0	RU13	Caparica	RU13: TAR (RU 11) airport: RU04: MonteJunto: Caparica: Espichel: Arrabida: Fanhões: Montargil	50.002
2	38°38'48.45"N	9°12'27.39"W	0.44	2859.5	RU13	Caparica	RU13: TAR (RU 11) airport: RU04: MonteJunto: Caparica: Espichel: Fanhões: Arrabida: Montargil	50.002
3	38°39'12.89"N	9°12'13.78"W	0.89	2719.1	RU13	Caparica	RU13: TAR (RU 11) airport: RU04: MonteJunto: Caparica: Espichel: Fanhões: Arrabida: Montargil	50.003

## **Annex B Latency Simulator Flowcharts**

With the latency model developed, to develop the simulator it must also be presented the flowcharts that created it. They are required to understand the steps of the simulator and its implementation. This Annex presents the flowcharts for the LAM and WAM simulator, but their description is given in Section 3.6. The LAM flowchart is presented in Figure B.1 while the WAM's is in Figure B.2.



Figure B.1 – LAM simulator flowchart.



Figure B.2 – WAM simulator flowchart.

# **Annex C Coverage Simulator Manual**

This Annex presents indications for the use of the coverage simulator with the description of the GUI and main indications for its correct use. The software used was Microsoft Visual Studio 2010 [MVS11] and the programming language C sharp. Google Earth software is also used to display the final results of the coverage analysis.

The simulator only requires an internet connection in case a new land profile request is made, otherwise it is not necessary. By double clicking the executable file the interface is launched as presented in Figure C.1. The black box is used to transmit information to the user, for example informing that all the land profile as been retrieved from Google servers.



Figure C.1 – Coverage simulator GUI.

There are four menus; File, Configurations, Run and View which are described with more detail, the file menu is presented in Figure C.1 while the rest is shown in Figure C.2. The file menu contains five functionalities:

- New Simulation: If the user as already performed any simulation if this button is pressed the simulator all the variables are reset and it is the same as closing and opening the application.
- Save Image As: If this button is pressed the image that is in the application, such as the plot in Figure C.4, is saved with name and location defined by the user.
- Import File: Import a complete profile of a location that has been already completed.
- Export File: Save the present land profile analysis that has been completed.
- Exit: Leave the application.

Configurations	Run	View
Flight Level	Run Elevation	Elevation Profile
Sensor	Run Coverage	Coverage profile

Figure C.2 - Menu's functionalities.

The configuration menu contains two buttons, *Flight Level* and *Sensor*, the first is used to configure the flight level for which the coverage analysis is being performed while the sensor button is to define the sensor location and other parameters for the land profile request. The correspondent configurations window for both functionalities is shown in Figure C.3.

🖳 Configurations 📃 💷 💌							
Simulation Name Default							
Latitude Degree Minutes Seconds N/S							
Longitude Degree Minutes Seconds E/W							
0 0 0 W Sensor Height (m) Sample Points							
Range Angles Sample Angles							
ОК							



Figure C.3 - Sensor and flight level configurations.

The sensor configuration defines the simulation name which is used to name the outputs generated by the simulator, the coordinates of the sensor in degrees, minutes and seconds and the above the ground height. Also in the sensor configuration it is defined the parameters for the land profile, meaning the number of sample points per azimuth, the range of the request and the number of sample angles. The standard analysis in the thesis has considered 500 sample points, from 0 to 360 degrees and 36 sample angles. These parameters need to be carefully chosen because of the Google server limitations which set that the maximum number of Sample points per azimuth must be less than 512 and that per day the maximum of points is 25 000.

The airplane configurations are simpler and the three parameters to define is the flight level of the airplane given in hundreds of feet, the range of the sensor in nautical miles and the colour to display the coverage analysis in Google Earth.

The run menu contains the main action of the simulator. The button *Run Elevation* uses the already defined sensor configuration to request the land profile elevation and display the result, while the *Run* 

*Coverage* uses the elevation profile elevation to get the final global coverage. Finally, the view menu allows to change between the view of a given azimuth profile, Figure C.4, or the coverage line of the same profile, Figure C.6.

This summarised a walkthrough of the functionalities available in the simulator for better understanding of the sequence of operations to perform in the simulator. The main goal of the simulator is first to have a land profile analysis and only then get the global coverage.

After starting the program, to get a land profile of a given sensor and to display it in the application there are two possible ways:

- Import a pre-saved file with a land profile and then click in the view elevation profile button. The text box will display "File successfully imported!" in case of success.
- Configure the sensors in the configurations menu and then run the elevation profile; the elevation profile of the first azimuth is automatically displayed. The text box will display "All points successfully downloaded!" in case of success.

Having the elevation profile displayed, Figure C.4, it is possible to navigate between azimuth by pressing the *Prev* and *Next* button and also to plot the height correction and remove it with the correspondent buttons. Pressing the height correction button, Figure C.5 is presented. In the previous situation it is also possible see the coverage line for the given azimuth by pressing view coverage profile and it is displayed as shown in Figure C.6.



Figure C.4 - Display of the land elevation profile.

It is in this situation, after the land profile request that there is enough information to export a file and store the information for future use. By pressing the *export file* in the file menu it is created a file with the simulation information whose name is the conjugation of "Output\_" with the simulation name. The structure of the file is; simulation name (enter), sensor's latitude (enter), sensor's longitude (enter), sensor's height (enter), number of azimuths in the file followed by a blank line. After the blank line

each azimuth samples are listed in order, starting by the number of samples of that azimuth, the correspondent azimuth and finally each sample point in a new line containing the height, latitude, longitude and distance from the sensor. The output file may be altered, to add information, change the simulation name, the sensor height or any other alteration as long as the file structure remains the same.



Figure C.5 - Display of height correction.



Figure C.6 - Display of the coverage line.

With the elevation profile is possible to travel through the azimuths and change the view according to the objectives, the simple land profile or the coverage angle. To perform the global coverage analysis first the airplane configurations must be defined in the configurations menu and the click on the run coverage button. When the simulator ends the complete global coverage, Figure C.7 is displayed.



Figure C.7 - Global coverage display.

Simultaneously with the coverage diagram a (\*.kml) file with the name of the simulation is created in the same folder as the executable file. The kml file can be opened using Google Earth software and an example of the image displayed is shown in Figure C.8.



Figure C.8 - Google Earth coverage display.

It should be noticed that the development of the simulator would not be possible without the worldwide contribution of Google in geographical systems technology, more specifically in the elevation data, the Google Earth software and the open information from Google codes. I am hereby showing my appreciation to their work.

This Annex presented a brief manual to use the coverage simulator whose source code and executable file is supplied together with the thesis.

### Annex D Lisbon sensors coverage

This Annex presents the coverage analysis for the Lisbon airport sensors, separating the LAM sensors from the WAM. While Figure D.1 represents the overall coverage in the Lisbon airport LAM system, giving the total number of sensors covering each area. The individual coverage is presented from Figure D.2 to Figure D.4.



Figure D.1 - Overall sensor's coverage Lisbon LAM (extracted from [Sns09c]).

The individual coverage map is represented with two colours, green for covered area and red from not covered. These results were measured on the airport grounds after the sensor's installation to show the coverage results.

The WAM sensors coverage was supplied by NAV Portugal but they were not measured, software was used to calculate the LoS for each sensor given the altitude to cover. In this case the altitudes are the typical flight levels; FL100, FL200 and FL300 that correspond to an altitude of approximately 10 000ft, 20 000ft and 30 000ft respectively. The output of the software draws different radius centred on the sensor but the goal of the WAM system is to cover the approach area of the Lisbon airport, due to that a red circle is approximately representing the desirable area to cover and not the circles around the sensor.

There are six WAM sensors located outside the airport; Arrábida, Caparica, Espichel, Fanhões, Montargil and Montejunto, an extra sensor to analyse was included, TAR, this is the sensor with ID RU11 in the LAM system and intends to show a coverage of a LAM sensor in the overall system. The WAM coverage is shown from Figure D.5 to Figure D.11.



Figure D.2 - Individual coverage of sensor RU1 to RU6 (extracted from [Sns09c]).



Figure D.3 - Individual coverage of sensor RU7 to RU12 (extracted from [Sns09c]).



Figure D.4 - Individual coverage sensor RU13 and RU14 (extracted from [Sns09c]).



Figure D.5 - Arrabida sensor coverage (obtained from [NAV11]).



Figure D.6 - Caparica sensor coverage (obtained from [NAV11]).



Figure D.7 - Espichel sensor coverage (obtained from [NAV11]).



Figure D.8 - Fanhões sensor coverage (obtained from [NAV11]).



Figure D.9 - Montargil sensor coverage (obtained from [NAV11]).



Figure D.10 - Montejunto sensor coverage (obtained from [NAV11]).



Figure D.11 - TAR sensor coverage (obtained from [NAV11]).

### Annex E North sensors coverage

To complete the MLAT study for the North region of Portugal the individual coverage for every sensor must be known. Using the coverage simulator to calculate the individual coverage's of all the sensors presented in Section 4.7 the results are shown bellow. All the figures from Figure E.1 to Figure E.10 are used in Section 4.7 to help determine the global coverage of the system.



Figure E.1 – Sensor 1 and sensor 2 individual coverage.



Figure E.2 – Sensor 3 and sensor 4 individual coverage.



Figure E.3 – Sensor 5 and sensor 6 individual coverage.



Figure E.4 – Sensor 7 and sensor 8 individual coverage.



Figure E.5 – Sensor 9 and sensor 10 individual coverage.



Figure E.6 – Sensor 11 and sensor 12 individual coverage.



Figure E.7 – Sensor 13 and sensor 14 individual coverage.



Figure E.8 - Bragança and Bragança VOR individual coverage.



Figure E.9 - Ovar Tacan and Porto Locator individual coverage.



Figure E.10 - Porto NDB and Viseu Individual coverage.

# Annex F – Global Coverage Study

This Annex presents the final global coverage results for the North MLAT system. The studies were performed using the coverage simulator developed in the thesis. Each of the studies is explained in Section 4.7. Figure F.1 provides 5 sensors coverage in the desired region. Figure F.2 to provide 8 sensors covering the TMA. Finally, Figure F.3 and Figure F.4 are two complete studies with 11 sensors.



Figure F.1 – First proposal global coverage.



Figure F.2 - Second proposal global coverage.



Figure F.3 - Third proposal global coverage.



Figure F.4 - Fourth proposal global coverage.

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