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

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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 processing station. 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 $\{5, \ldots, 10\}$ being necessary to do so.

Keywords: Surveillance, Multilateration, Requirements, Delay, Coverage.

I. INTRODUCTION

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 [1]. In June 2011, Portugal had 25 991 flights [2], 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.

One of the three fundamental surveillance principles defined by Eurocontrol is the 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.

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 that besides providing surveillance for large areas, like the SSR, it also enables to monitor the airplanes on the grounds of an airport.

There are four main areas in which research has and is being made, the sensors synchronisation, the algorithm for the TDOA, the accuracy of the system and the sensors location.

The basis for the MLAT is the Time difference of Arrival (TDOA) algorithm which has been improving since the late 80’s when Smith and Abel [3] proposed the spherical interpolated method. Many other methods have been proposed since, such as Chain and Ho in [4] or Savage et. al. in [5]. 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 [6], 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.

[7] 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.
• 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 in the MLAT system itself has been mainly driven by the MLAT manufacturers, the European Organisation for the Safety of Air Navigation (Eurocontrol) and the European Organization for Civil Aviation Equipment (Eurocae). Most of the research available is concerning 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 [8] after a workshop with an international group of experts stating, “Wide Area Multilateration – A surveillance technique that is ready for use”.

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

This paper is composed of 5 sections, including the present one. In Section II, the technical principals of multilateration and the description of the most common telecommunication links to be used use in a multilateration system will be described.

In Section III, the two developed models for the latency and coverage analysis are presented. Both this models resulted in the implementation of a simulator. Finally the multilateration requirements and their implication in the overall system are shown.

In Section IX, 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. Other small results are presented that are important to understand this system such as the required telecommunication system capacity and the how to meet the regulator recommendations.

The final Section of the thesis will briefly resume every conclusion drawn from the work but also gives a more global analysis of the problem under study. This Section presented a brief introduction to the problem under study and the main work will be shown in the next Sections.

II. MULTILATERATION

As explained in Section I, Mlat can replace the SSR. The technology behind it is much different from the SSR. Mlat working principle is based on separated sensors that receive the signal sent from an airplane and crossing the information are capable of detecting the airplane position, which is basically the same function as the SSR. Knowing the coordinates of at least three different sensors and the signal TDOA the mathematical solution of the system gives the airplane location.

A major part in the MLAT systems are the telecommunication links. Their role, even not being part of the surveillance technique, is the backbone of the surveillance. Information must be distributed usually to more than one place and that is accomplished by many links spread through the network. In the multilateration 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 sensor but in more than five, whose information will have to be forward to the Central Processor (CP).

There are two sub types of multilateration, the Local Area Mlat (LAM) and Wide Area Mlat (WAM). The first is for airplanes and vehicles surveillance in the airports area and obviously is not enough to replace the SSR because of the difference in surveillance range. On the other hand the WAM is the chosen option to replace the SSR because this is a wide area system, meaning that the sensors are widely spread to provide coverage of an area the same size or wider than the SSR.

MLAT is defined by the method used to calculate the TDOA and by the method used to synchronise the sensors, depending on the method chosen there will be implications in the system architecture.

The architecture of the system depends on the method of synchronisation used. Since all the sensors will have to timestamp the message received, to calculate the TDOA, they all need to be synchronised and there are two possibilities, common clock systems and distributed clock system. The first is not commonly used because the time stamping is always performed in the CPS and only fast links with small random delay can be used [7].

The most common type of synchronization used is in fact the distributed clock systems. The receivers will be more complex because they will need to handle the digitalization and timestamp of the message before forwarding it to the CP, but on the other hand there is much more flexibility for the communication link because they will support a much higher delay. Each of the local clocks must have the same time base. This can be achieved by using Reference Transmitters (Reftrans), which send SSR transponder messages with clock information, or satellite. The main disadvantage of the reftrans is that it is necessary to have Line of Sight (LoS) to every sensor.

III. THEORETICAL MODELS

A. Capacity for the Communication Links

Before choosing a communication link to implement in a MLAT system the capacity required must be estimated. Each type of message used has a certain sending frequency which also depends on the target position. This means that a target stationary, moving on the ground or airborne sends different messages rates. Beside the message rate and the message size itself, the overhead applied to the message in the communication link also influences the capacity.

For an actual system implemented in the Lisbon airport by NAV the values to estimate the capacity may be drawn, but they will always depend on the manufacturer. This specific system uses a total overhead of 50 B. The different message rates with the correspondent sizes are resumed in Table I.

The final capacity required for a link, depending on the number of airplanes, is given by the sum of (1) and (2) which individually correspond to the traffic of the two types of system compatible with Mlat, ADS-B and SSR mode S.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS-B</td>
<td>DF17</td>
<td>14</td>
<td>64</td>
<td>Moving: 4 Stationary: 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>DF17</td>
<td>14</td>
<td>64</td>
<td>Moving: 4 Stationary: 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>DF18</td>
<td>14</td>
<td>64</td>
<td>Airborne: 1</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Mode S</td>
<td>DF4/ DF5</td>
<td>7</td>
<td>57</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>DF20/ DF21</td>
<td>14</td>
<td>64</td>
<td>0.25</td>
</tr>
</tbody>
</table>
\[ T_{\text{bpa}} = N_{\text{air}} \times (V_{\text{SL}}[\text{msg}]/s) + N_{\text{veh}} \times V_{\text{SS}}[\text{msg}]/s + N_{\text{veh}} \times V_{\text{SS}}[\text{msg}]/s \times \lambda_{\text{SS}}[\text{msg}]/s \times \lambda_{\text{SS}}[\text{msg}]/s, \] \quad (1)

\[ T_{\text{ADS}}[\text{bpa}] = (N_{\text{air}} + N_{\text{veh}}) \times V_{\text{SL}}[\text{msg}]/s + (r_{\text{air}} \times \lambda_{\text{ADS-air}}[\text{msg}]/s) + r_{\text{veh}} \times \lambda_{\text{ADS-veh}}[\text{msg}]/s, \] \quad (2)

where:

- \( T_c \): Traffic for mode S messages.
- \( T_{\text{ADS}} \): Traffic for ADS-B messages.
- \( N_{\text{air}} \): Number of airplanes at range.
- \( N_{\text{veh}} \): Number of vehicles at range.
- \( \lambda_{ai} \): Messages arrival rate for long mode S.
- \( \lambda_{ss} \): Messages arrival rate for short mode S.
- \( \lambda_{\text{SS}} \): Message arrival rate for ADS-B for airborne, moving or stationary targets.
- \( r_{\text{air}} \): Percentage of targets airborne, moving or stationary.
- \( V_{\text{SL}} \): Long messages with 14 B.
- \( V_{\text{SS}} \): Short messages with 7 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 this obviously reduces the traffic expected in the link but also decreases the probability of the success of the TDOA algorithm. This is because, in theory, to have a successful 3D localisation in the CP 4 sensors must receive the message.

**B. Latency Model**

The latency in a MLAT system may be critical and therefore it must be analysed before the implementation, mainly to study the influence of having mixed links in the system. To study the latency impact, a model is developed to analyse the global delays involved in a MLAT system, which depend on the communication links used and the airplane position. Two different scenarios will be analysed, LAM and WAM systems. The model will be separated into two components, the air interface and the link, which will then be used to calculate the synchronisation time.

The synchronisation delay is related with the maximum time difference between the receptions of the multilateration 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 is calculated from (3). Figure 1 shows the schematic for the latency model.

\[ t_{\text{sync}}[s] = \max \left\{ \left( t_{\text{air}}[s] + t_{\text{link}}[s] \right) - \left( t_{\text{air}}[s] + t_{\text{link}}[s] \right) \right\}, \quad n \in [1, N_{\text{sensor}}], \] \quad (3)

where:

- \( t_{\text{sync}} \): Synchronisation time for the specific position.
- \( t_{\text{air}} \): Propagation delay in the air.
- \( t_{\text{link}} \): Total delay in the telecommunication link.
- \( i \): Fastest sensor for the specific position.
- \( N_{\text{sensor}} \): Number of sensors.

The distance on the ground, separating the airplane from the antenna is given by [10]:

\[ \cos \theta_{[\text{rad}]} = \cos \phi_{[\text{rad}]} \cos (\Delta \phi_{[\text{rad}]} \cos \phi_{[\text{rad}]} + \sin \phi_{[\text{rad}]} \sin \phi_{[\text{rad}]}) \]

\[ d_{[\text{NM}]} = R_{\text{Earth}}[\text{NM}] \times \theta_{[\text{rad}]} \]

where:

- \( d \): Ground distance separating sensor from airplane.
- \( \phi_A \): 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.
- \( R_{\text{Earth}} \): Earth effective radius in nautical miles.
- \( \theta \): Angle between point A and B.
- \( \Delta \lambda = \lambda_A - \lambda_B \)

In order to calculate the length of the direct ray, three hypotheses have been tested: flat Earth, 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 [7]. Earth radius should be taken into account for large distances, namely beyond the radio-horizon [Corr09]. The flat Earth model solution is given by (6):

\[ \text{Direct ray}[\text{NM}] = \sqrt{(\theta_{[\text{NM}]} - h_{\text{air}}[\text{NM}])^2 + d_{[\text{NM}]}}. \]

where:
- \( h_{\text{air}} \): Airplane’s altitude.
- \( h_{\text{sensor}} \): Sensor’s height.
- \( \text{Direct ray} \): Distance separating the airplane from the sensor.

The spherical Earth model is not used because of the higher complexity of the solution. The simplified 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. Using this simplification, the effective heights of the airplane and sensor is given by (7) and (8). Using the corrected heights in the flat Earth model, (6), the distance between the airplane and the sensor is known.

\[
\begin{align*}
\text{Dis}_\text{ef,Radio} &= d_{\text{Radio}} \\
\text{Dis}_\text{ef,air} &= d_{\text{air}} \\
\text{Dis}_\text{ef,flat} &= d_{\text{flat}} \\
\end{align*}
\]

These two models are enough to calculate the propagation delay. The second part of the model calculates the delay in the telecommunication link. If the link is an optical fibre or microwave link, the delay is given by (9). The only difference between the fibre link and the microwave is that the speed in the first case is considered 2/3 of the speed of light while in the second it is exactly the speed of light. In the case of being a satellite link or a VPN, the delays are given by an average delay summed to a jitter delay. This is because type of links are mainly rented.

\[
\begin{align*}
\text{delay}_{\text{link}} &= \text{delay}_{\text{transmission}} + \text{delay}_{\text{propagation}} + \text{delay}_{\text{jitter}} \\
\end{align*}
\]

where:
- \( t_{\text{link}} \): Total link delay.
- \( t_{\text{transmission}} \): Transmission time.
- \( t_{\text{propagation}} \): Propagation delay.
- \( t_{\text{jitter}} \): Random jitter delay.
- \( t_{\text{fixed}} \): Fixed delay.
- \( R_{\text{bps}} \): Transmission rate.
- \( V_{\text{msg}} \): Size of the message to transmit.

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.

\[
\begin{align*}
\text{delay}_{\text{link}} &= t_{\text{transmission}} + t_{\text{propagation}} + t_{\text{jitter}} \\
\end{align*}
\]

\[
\begin{align*}
\text{delay}_{\text{link}} &= V_{\text{msg}} / R_{\text{bps}} \\
\end{align*}
\]

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. 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. 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.

\[
\begin{align*}
\text{Probability of continuous tracking} &= 1 - \left( 1 - p_{\text{TDOA}} \right)^{N_{\text{sens}}} \\
\text{Probability of the CP receive i messages} &= C_i^{N_{\text{sens}}} p_{\text{rec}}^i (1 - p_{\text{rec}})^{N_{\text{sens}} - i} \\
\end{align*}
\]

where:
- \( p_{\text{TDOA}} \): Probability of having enough sensors to execute the TDOA algorithm.
- \( p_{\text{rec}} \): Probability of a sensor 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:

\[
\begin{align*}
\text{Probability of continuous tracking} &= 1 - \left( 1 - p_{\text{TDOA}} \right)^{N_{\text{sens}}} \\
\end{align*}
\]

\[
\begin{align*}
\text{Probability of the CP receive i messages} &= C_i^{N_{\text{sens}}} p_{\text{rec}}^i (1 - p_{\text{rec}})^{N_{\text{sens}} - i} \\
\end{align*}
\]

where:
- \( p_{\text{TDOA}} \): Probability of continuous tracking.
- \( \lambda_{\text{msg}} \): Rate of messages sent by an airplane airborne.
- \( \Delta_{\text{interval}} \): Update time interval, in this case its 5 seconds.

C. 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:

- 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.
The coverage analysis is to get the land
up, the goal being to determine the
n which there is no
ich is located at a
(14)
16
11
tan
(15)
(18)
tan
1
(16)
\[
\tan \psi_{\text{obs},i} = \frac{h_{\text{eff,obs}}(\text{NM})}{d_{\text{obs}}(\text{NM})},
\]

Figure 4 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.:
\[
\tan \psi_{\text{obs},i} = \frac{h_{\text{eff,obs}}(\text{NM})}{d_{\text{obs}}(\text{NM})},
\]

The effective height of the airplane is calculated in the same way as used for obstacles, (15), but it also depends on the distance between airplane and sensor. Replacing (15) in (16) and simplifying:
\[
\frac{d_{\text{eff,air}}}{2R_{\text{Earth}}(\text{km})} + \frac{d_{\text{air}}}{2R_{\text{Earth}}(\text{km})} \cdot \tan \psi_{\text{air}} = \frac{d_{\text{eff,air}}}{2R_{\text{Earth}}(\text{km})} - h_{\text{air}}(\text{km}) = 0,
\]

The solution of (18) 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°].

Each sensor has the range for which it was con-
(2)
where:
\[
d_{\text{Rl}}(\text{km}) = \sqrt{h_{\text{air}}(\text{km})^2 + 2R_{\text{Earth}}(\text{km})},
\]

IV. RESULTS ANALYSIS
A. Communication Links Required Capacity
As explained in Section IIIA, the assessment of the
(1) and
(2) and the considered overheads per message provided by
NAV Portugal are: Ethernet Frame with 14 B, Internet Protocol
(IP) with 20 B, User Datagram Protocol (UDP) with 8 B
and Internet Group Management Protocol version 2 (IGMP V2)
with 8 B. The total considered overhead per message is 50 B.
Concerning the maximum capacity, the first row of Table II 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 II.

### Table II. Capacity for different airplanes distribution.

<table>
<thead>
<tr>
<th>( r^e ) [%]</th>
<th>( r^m ) [%]</th>
<th>( r^{mv} ) [%]</th>
<th>Traffic without overhead [kbps]</th>
<th>Traffic with overhead [kbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>142.1</td>
<td>712.1</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>25</td>
<td>78.4</td>
<td>383.4</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>15</td>
<td>Not calculated</td>
<td>274.7</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>10</td>
<td>Not calculated</td>
<td>220.4</td>
</tr>
</tbody>
</table>

This table illustrates the impact of the overhead in the messages, which itself is responsible by around 77 % of the exchanged content, 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 %.

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.

### B. Latency assessment

This Section analyse the latency in a MLAT system. The latency in a communication link is explained in Section III.B but, the processing time has been assumed has constant, so it would take the same exact time independent of the sensor, this is not true in a real system. It is possible to gather information to estimate the sensors processing time in the Lisbon LAM.

The value for the average fixed time \( \bar{\tau}_{\text{fixed}} \) is 9.992 ms and the value for the average standard deviation time \( \sigma_{\text{fixed}} \) 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.

To estimate the synchronisation time of a system, it must be described and also the airplane test positions defined. Only one system is described and their results presented, the Azores WAM. The locations of the sensors are shown in Figure 5 and their description in Table III. The CPS is located in the Horta airport and there is an auxiliary repeater to forward the data to the CPS, represented as a triangle in Figure 5.

![Figure 5. Azores WAM sensors.](image)

### Table III. Azores WAM system description (calculated from [9]).

<table>
<thead>
<tr>
<th>ID</th>
<th>Elevation [m]</th>
<th>Communication link</th>
<th>Communication link capacity [Mbps]</th>
<th>Communication link length [km]</th>
<th>Number of hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS_00</td>
<td>1.052</td>
<td>Microwave link</td>
<td>0.256</td>
<td>17.26</td>
<td>2</td>
</tr>
<tr>
<td>GS_01</td>
<td>1.040</td>
<td>Microwave link</td>
<td>0.256</td>
<td>7.86</td>
<td>1</td>
</tr>
<tr>
<td>GS_02</td>
<td>1.122</td>
<td>Microwave link</td>
<td>0.256</td>
<td>18.60</td>
<td>1</td>
</tr>
<tr>
<td>GS_03</td>
<td>1.351</td>
<td>Microwave link</td>
<td>0.256</td>
<td>41.46</td>
<td>3</td>
</tr>
<tr>
<td>GS_04</td>
<td>0.862</td>
<td>Microwave link</td>
<td>0.256</td>
<td>110.06</td>
<td>5</td>
</tr>
<tr>
<td>GS_05</td>
<td>0.483</td>
<td>Microwave link</td>
<td>0.256</td>
<td>64.06</td>
<td>3</td>
</tr>
<tr>
<td>GS_06</td>
<td>0.845</td>
<td>Microwave link</td>
<td>0.256</td>
<td>86.54</td>
<td>5</td>
</tr>
<tr>
<td>GS_07</td>
<td>0.193</td>
<td>Microwave link</td>
<td>0.256</td>
<td>184.66</td>
<td>5</td>
</tr>
<tr>
<td>GS_08</td>
<td>0.382</td>
<td>Microwave link</td>
<td>0.256</td>
<td>103.26</td>
<td>3</td>
</tr>
<tr>
<td>GS_09</td>
<td>1.028</td>
<td>Microwave link</td>
<td>0.256</td>
<td>140.76</td>
<td>4</td>
</tr>
<tr>
<td>GS_10</td>
<td>1.178</td>
<td>Microwave link</td>
<td>0.256</td>
<td>81.56</td>
<td>4</td>
</tr>
<tr>
<td>Repeater</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TWR-Horta</td>
<td>65</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The airplane test positions are shown in Figure 6 and the calculations for the synchronisation time in Figure 7. All the airplane test routes have been defined from the left to the right. All the synchronisation times for the different test positions are small compared with the maximum allowed by the system, 500 ms. It is also noticed that usually as closer the airplane is from the slower links, the synchronisation time decreases. For instance, all the routes, except the yellow, are decreasing the synchronisation time because the slower links are located in the route direction.
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, 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. Their overall impact is shown in Table IV.

### Table IV. Overall delay impact.

<table>
<thead>
<tr>
<th>Delay component</th>
<th>Considered limit</th>
<th>Maximum delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>[0, 150] km</td>
<td>~0.5 ms</td>
</tr>
<tr>
<td>Fibre/Microwave link propagation</td>
<td>[0, 200] km</td>
<td>~ [0.67, 1]ms</td>
</tr>
<tr>
<td>Satellite propagation</td>
<td>[0, 70 000] km</td>
<td>~2.33 ms</td>
</tr>
<tr>
<td>Transmission</td>
<td>[0.2, 10] Mbps</td>
<td>~2.7 ms</td>
</tr>
<tr>
<td>Standard deviation MLAT</td>
<td>99.73% (±3σ)</td>
<td>~2.13 ms</td>
</tr>
<tr>
<td>Hops</td>
<td>unknown</td>
<td>unknown</td>
</tr>
</tbody>
</table>

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 IV 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.

### C. Localisation Requirements

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 III, and the effect of the receiving probability in these requirements must be analysed.

Figure 8 shows the probability of a message being received by 4 or more sensors, using (11), in a network of 20 sensors, considering the number of sensors at LoS ∈ [4,20]. Different values for the error probability were also considered, including the value considered in Section IV.A, 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.

![Synchronization time results.](image)

**Figure 7. Azores synchronisation time results.**

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, 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. Their overall impact is shown in Table IV.

![Localisation Requirements](image)

**Figure 8. TDOA execution probability.**

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 I, the frequency of messages sent by an airborne airplane is 5.7 msg/s.

Using (13) and (14), the continuous tracking probability and the track initiation are calculated. 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 controllers.

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 V contains the summary of the impact of each requirement. The limitations are imposed by the track initiation and not by the continuous tracking.

Table V. Overall MLAT requirements in terms of airplane detection

<table>
<thead>
<tr>
<th>Error probability</th>
<th>Continuous tracking (&gt; 97%)</th>
<th>Track initiation (&gt; 99%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 messages</td>
<td>3 messages</td>
</tr>
<tr>
<td>40%</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>50%</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>60%</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>70%</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

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.

D. North of Portugal Multilateration Study

A preliminary study for a MLAT WAM system is presented, for the North of Portugal, the area delimited by the red line in Figure 9, where Porto’s airport Terminal Maneuvering Area (TMA) is also included. The TMA is a very important area, because the surveillance has more restrictive requirements, including the requirements studied in Section IV.C for the tracking probabilities. The defined area for the TMA can be retrieved from [11].

![Figure 9. New MLAT study area.](image)

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. The approximate percentage of covered area of the sensor’s for each district in the TMA is shown in Table VI. The final column, under utility, is a approximation to the percentage of covered are but for the all area of the MLAT system.

<table>
<thead>
<tr>
<th>RU ID</th>
<th>Viana do Castelo</th>
<th>Braga</th>
<th>Porto</th>
<th>Aveiro</th>
<th>Viseu</th>
<th>Vila Real</th>
<th>Guarda</th>
<th>Bragança</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porto Locator</td>
<td>100%</td>
<td>95%</td>
<td>100%</td>
<td>100%</td>
<td>75%</td>
<td>10%</td>
<td>0%</td>
<td>0%</td>
<td>47.25%</td>
</tr>
<tr>
<td>Porto NDB</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>95%</td>
<td>100%</td>
<td>5%</td>
<td>30%</td>
<td>74.06%</td>
</tr>
<tr>
<td>Viseu VOR 04</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
<td>100%</td>
<td>100%</td>
<td>50.66%</td>
</tr>
<tr>
<td>Bragança</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Ovar Tacan</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>96%</td>
<td>54%</td>
<td>87.25%</td>
<td></td>
</tr>
<tr>
<td>RU 1</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>90%</td>
<td>40%</td>
<td>10%</td>
<td>56.61%</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>90%</td>
<td>70%</td>
<td>0%</td>
<td>20%</td>
</tr>
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<td>RU 3</td>
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<td>95%</td>
<td>95%</td>
<td>75%</td>
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<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>76.24%</td>
</tr>
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<td>RU 4</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>80%</td>
<td>95.06%</td>
</tr>
<tr>
<td>RU 5</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
<td>85.85%</td>
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<tr>
<td>RU 6</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>98%</td>
<td>100%</td>
<td>100%</td>
<td>97.32%</td>
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<td>RU 7</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
<td>100%</td>
</tr>
<tr>
<td>RU 8</td>
<td>0%</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
<td>20%</td>
<td>100%</td>
<td>50%</td>
<td>100%</td>
<td>45.77%</td>
</tr>
<tr>
<td>RU 9</td>
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<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RU 10</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RU 11</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>RU 12</td>
<td>0%</td>
<td>95%</td>
<td>40%</td>
<td>0%</td>
<td>50%</td>
<td>100%</td>
<td>80%</td>
<td>79.11%</td>
<td></td>
</tr>
<tr>
<td>RU 13</td>
<td>90%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>99.56%</td>
</tr>
<tr>
<td>RU 14</td>
<td>80%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>80%</td>
<td>85.15%</td>
</tr>
<tr>
<td>Bragança VOR</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>10%</td>
<td>15%</td>
<td>80%</td>
<td>100%</td>
<td>45.31%</td>
</tr>
</tbody>
</table>

Table VI. Sensor’s global coverage.

It is a fact that the minimum number of sensors to execute the TDOA algorithm is at least 4 for a 3D localisation. 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 Table VI, 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 RU7, RU9, RU11, RU13 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 VI, 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. RU4 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.

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.

Another conclusion of this thesis was the evaluation of required number of sensors to comply with the localisation requirements. Considering 60% for the receiver’s receiving
probability, from Table V 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 VI, there are only 8 sensors that cover the entire TMA, thus, 8 being also the minimum number of sensors to comply with the requirements: RU1, RU4, RU5, RU7, RU9, RU10 and RU11. 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.

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.

V. CONCLUSIONS

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.

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.

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.

Two 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 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 ft, 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.

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REFERENCES
