ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

Feasibility study on Aircraft Location Accuracy using Multilateration System in the case of Addis Ababa Bole international Airport

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SCHOOL OF GRADUATE STUDIES
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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Place: Addis Ababa

Date of Submission: ________________

This thesis has been submitted for examination with my approval as a university advisor.

Dr. Murad Ridwan ______________

Advisor's Name Signature

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Abstract

The aviation sector must be safe. Information errors which are provided from ground aids Communication, Navigation and Surveillance (CNS) systems can put the aircraft at risk. Therefore, all ground-based flight aids should always be accurately calibrated. In addition, flight delays can lead to unnecessary fuel consumption and air pollution. Accordingly, in order to provide an efficient air transport system, it is important to have modern, fast and accurate ground based flight aids that provide real and timely information.

Air Navigation Aeronautical multilateration systems enable the localization of an aircraft based on the Time Difference of Arrival (TDoA) of its signal to three or more strategically placed receiving ground station antennas, located around an area of interest, providing continuous air traffic surveillance.

The main objective of this thesis is to show how to install an optimized multilateration system that can provide an aircraft information (position & identification) and to study the performance analysis of approach type multilateration systems in Ethiopia, specifically in Addis Ababa Bole international airport approach and terminal maneuvering area concerning radio coverage and aircraft location accuracy by considering ground stations' location, their antennas radiation patterns, transmitted power, receiver sensitivity, and the corresponding parameters for the aircraft.

Line of Sight situation is assessed by taking into considerationof Digital Elevation, Fresnel's Ellipsoid, and the Effective Earth's Radius Models. The Free-Space Path Loss Model is likewise used, with fading margins being set to model power oscillations due to multipath and the airplane orientation uncertainty. The position accuracy of the aircraftis estimated from the system's Geometric Dilution of Precision, taking into considerationof error components due to troposphere delay, multipath, receiver noise, quantization, and clock bias. The model will be implemented in a simulator with results in agreement with data from the literature and previously implemented systems.

Keywords: MLAT, PSR, SSR, TDoA, ADS-B

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List of Abbreviations

ASMGCS	Advanced Surface Movement Guidance and Control Systems
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATM	Air Traffic Management
ECAA	Ethiopian Civil Aviation Authority
CPS	Central Processing Station
CRLB	Cramer-Rao Lower Bound
ECAC	European Civil Aviation Conference
FAA	Federal Aviation Administration
FIR	Flight Information Region
Eurocontrol	European Organization for Safety of Air Navigation
GDOP	Geometric Dilution of Precision
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GS	Ground Station
HDOP	Horizontal Dilution of Precision
HPA	Horizontal Position Accuracy
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
LAM	Local Area Multilateration
LoS	Line of Sight
MLAT	Multilateration
PDF	Probability Density Function
PoD	Probability of Detection
PSR	Primary Surveillance Radar
RMS	Root Mean Squared
RMSE	Root Mean Squared Error
RTD	Round-Trip Delay
SSR	Secondary Surveillance Radar
TDOA	Time Difference of Arrival
TDOP	Time Dilution of Precision
TOA	Time of Arrival
VDOP	Vertical Dilution of Precision
WAM	Wide Area Multilateration

List of Symbols

ρ	Slant range from the ground radar antenna up to the target
φ	Angular distance measured from the geographic North and the segment connecting the radar antenna and the target
$\sum$	Sum of Mono pulse radar
Δ	Difference of Mono pulse radar
θ	Off-Bore sight Angle
$D_{i[m]}$	distance between the ground station receiver and the target
X_i	X coordinate location in the i^{th} ground station
Y_i	y coordinate location in the i^{th} ground station
Z_i	z coordinate location in the i^{th} ground station
d_a	Largest dimension of the antenna
λ_o	Carrier wavelength
F_o	Carrier frequency
D_0	Difference in distance from the target to the reference
D_m	Difference in distance from the target to the ground station m
d_{m0}	Distance difference from ground station m to reference
M_I	implementation margin
N_{GS}	Number of Ground station receivers
t_i	Signal travel time
R_{nr}	Non reference ground station receivers
R_r	Reference ground station receivers
τ_{m0}	TDoA from ground station m to the reference
Δd_{ToA}	RMS ToA accuracy associated with a GS
C	Speed of light
B_w	Bandwidth in Hz
P_1, P_3	SSR Interrogation pulse
P_2	SSR Suppression pulse
A^{-1}	Inverse Matrix A
A^T	Transpose of Matrix A
A^+	Pseudo inverse of Matrix A
E	Expectation or mean value
$RDoA_{m0}$	Range Difference of Arrival from the GS_m to the reference
$\widehat{RDoA}_{m0}$	Estimated Range Difference of Arrival from the GS_m to the reference
$\delta \mathrm{RDoA}_{\mathrm{m0}}$	Error Range Difference of Arrival in measurement
δP_{xyz}	Effect of position accuracy
$Cov\delta P_{xyz}$	Covariance of position accuracy
$Var\delta P_{xyz}$	Variance of position accuracy
$GDoP$	Geometric dilution of precession

List of Software

CASPER software	Coverage simulation tool
AIRNAS	Radio Tracer
DPTMLAT	MLAT testing tool
CPF	Central Processing Function
Google Earth	Geographical information system
ImageJ	Java script image processing program
QGIS	open source Quantum Geographic Information System
Microsoft Word 2010	Word Processor
Microsoft Excel 2010	Spreadsheet application
Microsoft power Point 2010	Presentation Application
Paint	Image editing tool

Chapter 1

1. Introduction

1.1. Background

Worldwide, air traffic has increased by 50 percent in the past decade, and forecasts going to say that it will continue to do so in the future, increasing by nearly five percent every year. This growth in demand is continuously paving a new path for engineers to take. New challenges will have to be solved regarding capacity, fuel emissions, speed, and interoperability with an ever-increasing number of aircraft in the sky, the task to survey them efficiently has become a technological challenge for air space companies [1].

Engineers are looking into new methods of tracking aircraft among congested skies while minimizing infrastructure cost, but also increasing range in safety levels. The aeronautical sector is characteristic of the few changes that are carried out to its existing technologies. Communication and navigation are slowly changing shape. The surveillance system has been used in aging technologies for quite a while.

This revolutionary new surveillance system is considered to be the next step for air navigation service providers, allowing seamless integration between air traffic management systems. Its use began with primary radar, which is considered to be a passive device that is no additional information is given by the targets that only reflects the signal. A high-powered transmitter emits a radar beam, which is subsequently reflected by the aircraft and then again received by the radar. This allows the measure to time of the interval, and so did this position. However, this system has major disadvantages, such as the high power, clutter's sensitivity, and no aircraft densification or altitude. Due to this and many other reasons, its role has been taken over by more modern systems like the secondary surveillance radar. Secondary radar was designed to be an improvement in terms of cost, reliability, and performance. It functions thanks to a ground component, but also an airborne component, also known as a transponder. More information can be found like the identification or the barometric altitude.

One of the main disadvantages of secondary radar is its requirement for line of sight visibility between the transponder and the ground receiver when the path is obscured by either a building or a mountain. The strength of the signal deteriorates very quickly. The secondary surveillance radar was further improved with the addition of Mode S. This offers a number of significant advantages when compared to its predecessor. Although it operates on the same frequencies, it allows for selective interrogation. It directs itself to the desired aircraft using a 24 address unique for each airplane. With time, this system is becoming more and more common among commercial airliners, and in the coming years, all aircraft will be equipped with Mode S transponders [2].

Multilateral action is a system that makes use of signals transmitted by aircraft in order to calculate their position, since it makes use of currently existing transmissions, multilateration systems can be deployed with no need for changes in the airborne infrastructure. However, to receive and process all the signals, ground stations are required. A signal is emitted from an aircraft that is received through several antennas, though each receiver gets a signal at a different time. This time difference of arrival is the one that allows the position of the aircraft to be calculated at the central processing unit geometrically. The time difference between two antennas corresponds to a hyperbola along which the aircraft is located. When superimposing all of the hyperboloids, the point of intersection gives the location of the aircraft with four antennas. When more than four antennas are present, then the information can serve as verification to other measurements. In order for all of these systems to function correctly, all stations must be synchronized so that all the measurements are relative to the same reference, one being compared. This is a key concept for the system and a very difficult task.

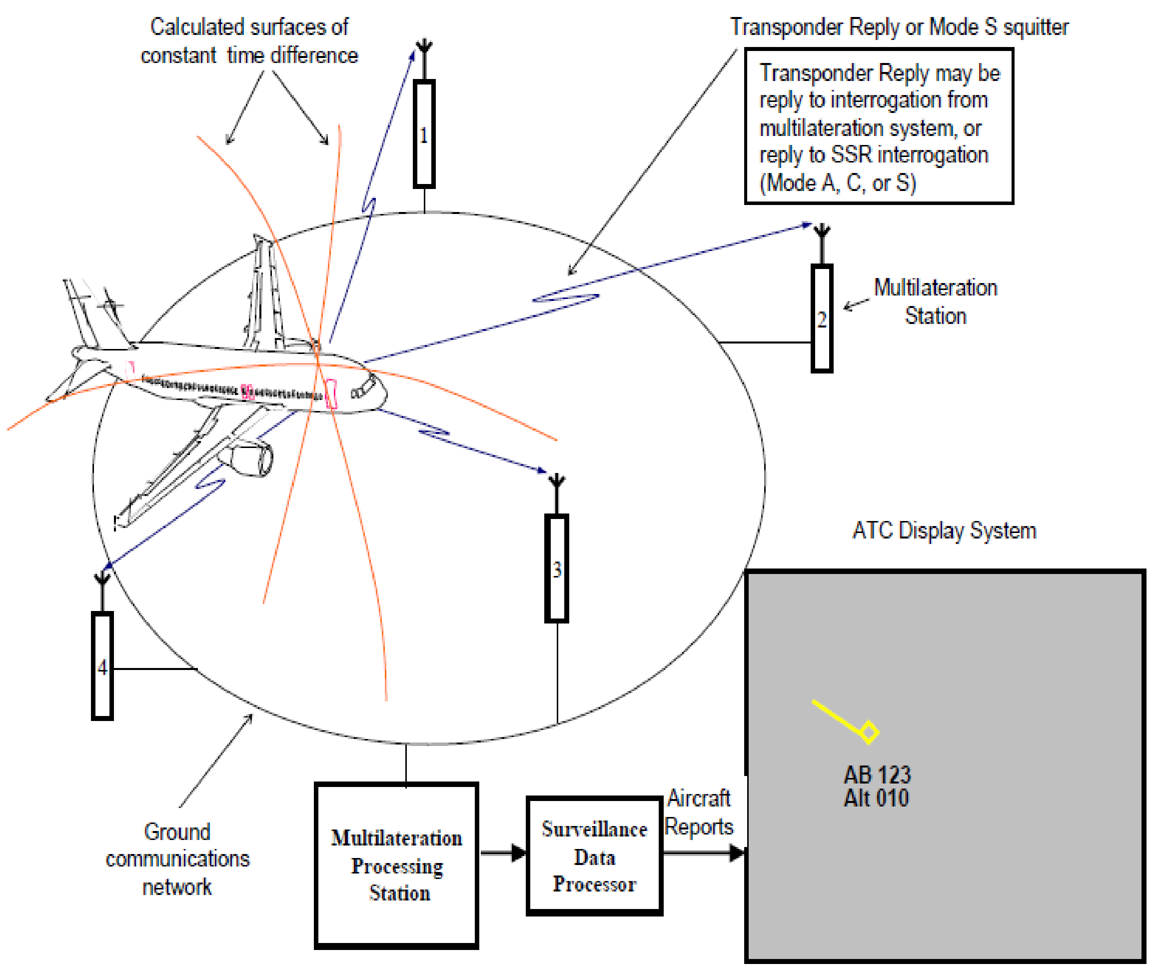


Figure 1. 1 Overview of multilateration system

1.2. Statement of the problem

Today most of the world air traffic control infrastructure relies on radars; these radars send out high-power interrogation signals and receive responses from a device on the airplane called a transponder. When the transponder receives the signal from the radar, it replies back with information such as four-digit aircraft identification code and altitude. The ground personnel then use this information to determine the exact location of the aircraft. This approach worked well when radar was invented in the 1940's. However, as skies around the world become more crowded, it is very likely that aircrafts will overwhelm the current air traffic control system, which will lead to increases in delays, higher costs, and greater environmental impact [3].

In order to address this challenge the International Civil Aviation Organization (ICAO) and Federal Aviation Administration (FAA) in collaboration with universities, airline industry among others is introducing new technologies. One the system which is specified on the Next Generation (NextGen) plan is aeronautical multilateration, which is used to get a fast, reliable & an accurate aircraft information target than the existing PSR and SSR radars [4].

Ethiopian Civil Aviation Air Navigation service has a plan in order to install this new technology called Multilateration. Though the technology is nice, if not properly located it poses network delay and because of these, data exchanged between aircraft and control tower could easily be spoofed and manipulated. In other words, there is no mechanism in place to protect the confidentiality, integrity, and availability of information. Adequate measures must be implemented along with appropriate set of receiver sensors location otherwise unwanted delay and risk may arise and jeopardize the NextGen technology. Furthermore, understanding the implications of the system is fundamental.

Thesis questions

- Does the aeronautical Multilateration give better target than the Secondary Surveillance Radar (SSR)?
- How the aeronautical multilateration system detect the targeted aircraft using TDoA?
- How many receiver sensors needed to get the required accurate, reliable & better target?
- How the appropriate & optimized location of the receiver sensors selected?
- At what rate the delay time is minimized as compared to the ordinary SSR & PSR radars?

- How the multilateration receiver sensors are detect when more than two aircrafts appear on the same signal area?

1.3. Objectives

1.3.1. General objective

The main objective this thesis is to address and come up with a viable optimized location solution on the design of sensors during the deployment of multilateration system in the city of Addis Ababa, Bole international airport by considering demographic and geographic data of the city.

1.3.2. Specific objectives

Specifically, the objectives of this thesis work can be outlined as,

- Detail literature study for the concept of aeronautical multilateration system.
- Analyzing how multilateration increase target performance than ordinary radars especially with SSR. This will also be an input for further improvement for another area.
- Analyzing how many ground receiver sensors are needed to get good3D flight information.

1.4. Methodology

The methods employed to achieve the objectives of the research are:

- Literature review: includes reading books, articles, white papers, simulation tools and other resources related to the topic.
- Doing observational studies to
    - ✓ know the good estimate of peak-hour flight traffic in the busiest day in Addis Ababa air space;
    - ✓ know the relative traffic density in different air space routes so that the distribution of flights will be designed accordingly;
    - ✓ Get the topological and demographical data of the area. The demographical data include the different services required in

different parts of the area and the size, material and distribution of buildings and other infrastructures;

- ✓ Choose the best option to connect with the main network;

- ➢ Doing analytical studies to
  - ✓ Decide the best test algorithm and propagation modeling for the selected installation area;
  - ✓ Choose the best RF technology to address the need;
  - ✓ Determine the best network topology;
  - ✓ Do the appropriate link budget and other calculations;
  - ✓ Determine the quantity and quality of hardware devices like the number and capacity of receiver sensors, access points, etc.;
- ➢ Doing experimental studies to
  - ✓ Investigating whether the analytical design is sufficient for the actual need;

1.5. Related Works

Multilateration (MLAT) implementations are an opportunity to provide useful ATC surveillance where it is required and concurrently introduce ADS-B for partial use. This forms a graduated transition from the current global environments to a future ADS-B based system. To come up with these strategies different academies and companies are doing researches and some have already deployed networks.

This particular area of research is not an intensely explored one in the context of a thesis work or an academic research as this area is mostly dealt with by International Civil Aviation Authority and state aviation companies prior to deployment. To the best of my knowledge, there are some other theses and research papers related to this thesis.

To mention some of the researches done and tools developed, on one of the paper presented for ICAO at Montreal, Canada in 2014 for aeronautical Multilateration research titled 'MULTILATERATION & MAGS' described how the multilateration sensors are optimally located and algorithm of TDOA works [6].

On the research of Era Systems Corporation, 'Multilateration - Executive Reference Guide', mentioned the actual difference between ordinary radars and multilateration [5].

And also EUROCONTROL, 'Guidance Material on Comparison of Surveillance Technologies (GMST)' [2] from a processing point of view, the radar data processing chain is undoubtedly the most complex element of the ATM system. This is due to its many complex constituent elements and also to the important influence of the radar environment, be it mono- or multi- radar environment. Obviously the final accuracy of the displayed position is a function of the performance characteristics of all radar sub – systems.

The main point that every research and development works that I have seen agree on the idea that air space congestion and a fast & accurate air traffic information are becoming a challenge and a means solving this congested air space is the best means to alleviate the problem; and they all suggest that the best effective way is to use properly allocated surveillance system specially multilateration.

1.6. Contribution

As mentioned in prior sections, this thesis work conducts all the capacity signal coverage and radio network planning steps needed for deployment of multilateration in the city of Addis Ababa, particularly at bole international airport. This thesis will serve as a good resource when multilateration is deployed in Addis bole international airport. In addition,to present it as a starting point for future similar studies.

1.7. Scope/Limitations

The performance analyses in this thesis work will be based on simulation of the proposed solutions using MATLAB and radio propagation model simulator. Thus, implementation is beyond the scope of this thesis. The geographic and terrain analysis of data used on this paper is entirely that of the city of Addis Ababa, specifically bole international airport. Therefore, the scope of this research is limited to capacity, coverage and radio network planning for the city of Addis using computer aided simulations.

1.8. Thesis Organization

The thesis is divided into five chapters, including this Introductionpart.Chapter 2 provides the theoretical background of aeronautical surveillance, focusing on multilateration systems, and its state of the art. Chapter 3 concerns the proposal, TDOA model and description on Aeronautical Multilateration, and assessment of the model for the analysis of aircraft accuracy location in aeronautical multilateration systems. Chapter 4 provides the description of the scenarios for the performance analysis, and the analysis of solutions and of their implementation. Chapter 5 finalizes the thesis, providing the main results from the work, conclusions from the various chapters are presented, and recommendations for future implementations of aeronautical multilateration systems provided. Additional material and information related to this study may be found in the appendices of this thesis.

Chapter 2

2. Theoretical background on Aeronautical Surveillance

2.1. Overview

In the previous session, introduction and literature review of works related to aeronautical multilateration system were briefly discussed. In this session, basically a relationship and comparison of multilateration with other aeronautical surveillance systems are explained. In addition to these different modes of uplink and downlink interrogation and replay surveillance signal are presented.

What comes to our mind when we hear the term RADAR? Maybe the envision a large antenna pointed at the sky like we see at the airport, or for fast car driving, we may think of that when a police officer hiding in a speed trap waiting to give us a penalty ticket or when we think of a bad weather report or any other thing. There are different radar systems all around us and they touch our lives more than we often realize.

The term RADAR is an acronym that stands for RAdio Detection And Ranging that tells us how we are using radio waves to detect objects in the world around us and range or determine how far away they are.Radar uses electromagnetic energy pulses in order to detect objects which will refer to as targets by using an antenna to transmit the radio signal in a specific direction. Figure 2.1 shows how a target becomes reflective to the transmitted radio waves and returns back some portion of reflected energy back to the radar set as an echo. The radar set uses this echo in order to determine the distance and direction of the reflecting target [3].

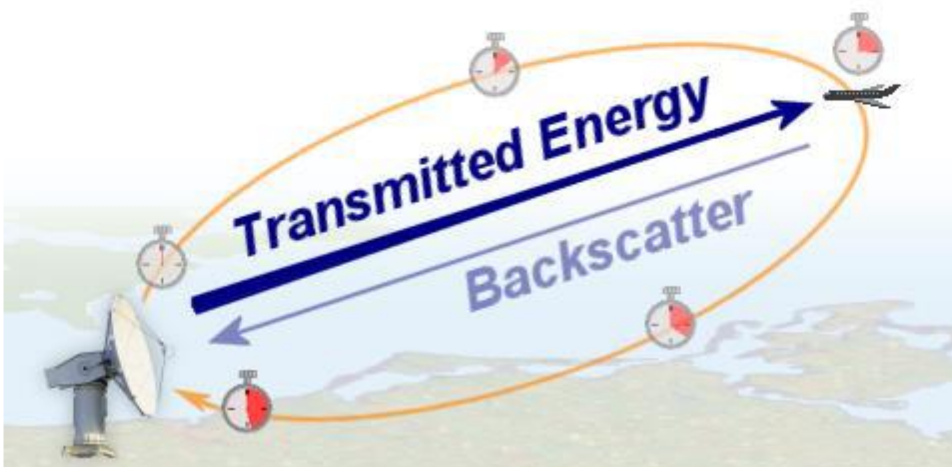


Figure 2. 1: Radar Principle

Radar sets can be roughly classified into two categories: **Imaging radar techniques (imaging radar) and non-imaging radar techniques (non-imaging radar)**. Within this broad classification, figure 2.2 below shows different types of radars which are categorized according to their specific functionality.

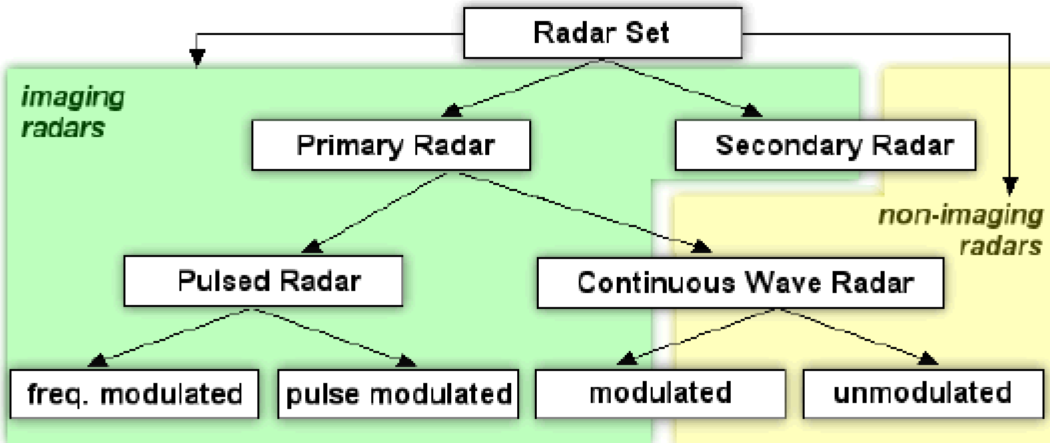


Figure 2. 2: Radar systems classified according to specific function

2.2. Primary Surveillance Radar

The first air space surveillance system used simple radar, because it allows the finding of distant objects (such as airplanes), being named Primary Surveillance Radar (PSR), Figure 2.3. PSR is a kind of echo radar. In our case, it simply detects aircraft without any special functions. In terms of energy, these radars have very high consumption, and there is a possibility that the received signal will be lost.

Primary radar equipment has an important feature: it can use passive echo. The transmitted high-frequency pulse is reflected by the target and then received by the radar unit itself. Then, the direct cause of the reflected echo is the pulse sent by the radar.

The PSR is a ground-based, centralized, non-cooperative, independent, surveillance system; based on the estimation of the round-trip delay, between the transmission of a pulse, and the reception of its reflection from a passive reflecting body. The coverage volume is usually segmented into cells, with spatial resolution defined by two components; the range resolution, inversely proportional to the pulse width; and, the angular resolution, defined by the product between the main-lobe beam width and the object range [2].

The main goal of PSR systems is to ensure the airplane's landing and taking-off. These systems can only detect and position the airplane. Like any other system, the PSR has advantages and limitations. On the one hand, there is not one single object in the air space that can be invisible to the 'eyes' of air traffic controllers, and in addition no other equipment is necessary, hence, it is only needed one site per installation and the infrastructure costs are low. On the other hand, it has its cons, since it cannot provide the airplane's identification, and because it uses an echo, it has a limited range and can only work in Line of Sight (LoS), so no installation in mountainous areas is possible.

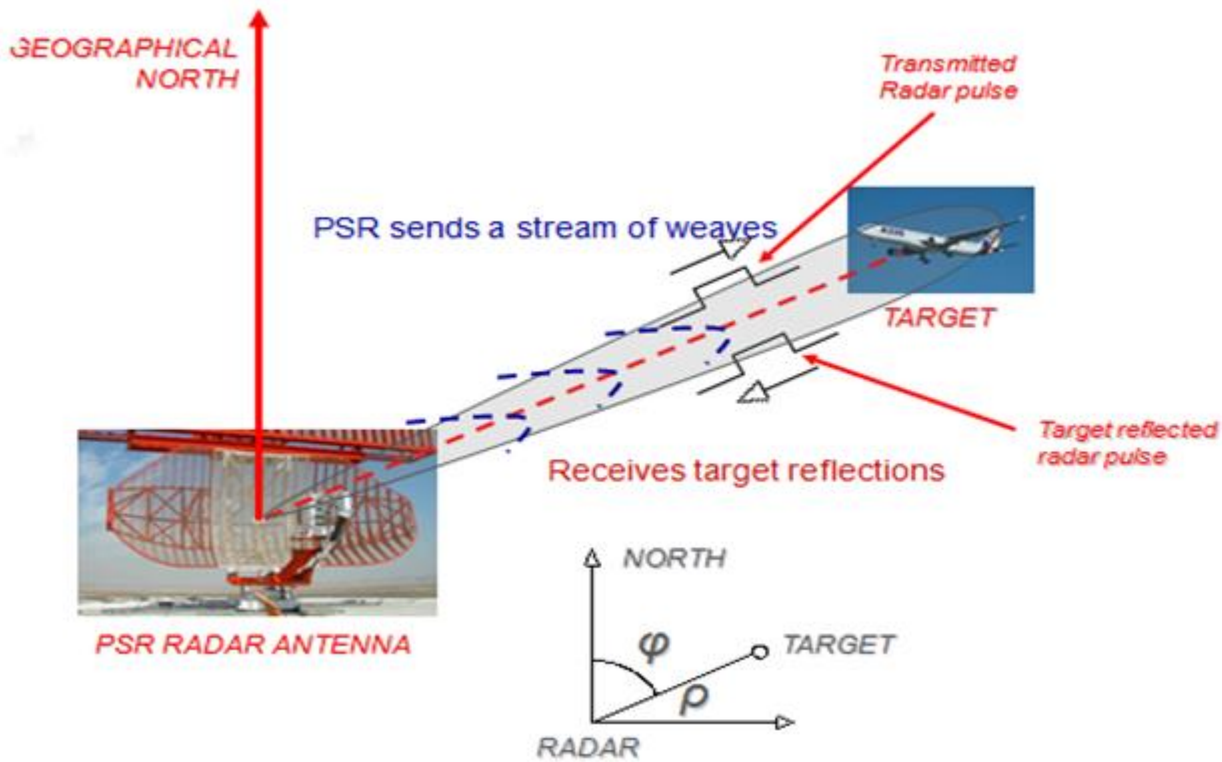


Figure 2. 3: PSR overview

Where:

ρ is Distance from the radar antenna up to the target and

φ Angular distance measured from the geographic North and the segment connecting the radar antenna and the target.

From the above figure, target reflection of PSR determines:

- the distance of the target
- intensity of the eco
- polar coordinates

The system should operate at a frequency where geometrical optics is valid; in other words, the electrical size of the object to be detected should be much larger than the signal wavelength. Three different frequency bands are used, depending on the type of airspace and associated path-loss limitations: the L-band, [1215, 1350] MHz, is usually reserved for en-route (~200 NM); the S-band, [2.7, 3.1] GHz, is usually used for approach (~60 NM); the X-band, [8.0, 12.0] GHz, is used for airport surveillance and landing (~10 NM). The system is particularly vulnerable to interference due to the detection of unwanted backscatter, also known as radar clutter, from the terrain, sea surface, rain, and wind farms. The PSR system is mostly used for airspace intruder protection, and non-cooperative aircraft management and detection, due to its interference sensitivity, lack of aircraft identification, and lack of precise altitude information [5].

2.3. Secondary Surveillance Radar

In order to solve the limitations shown on PSR, regarding costs, reliability and performance, the Secondary Surveillance Radar (SSR) was created, Figure 2.5. Secondary Surveillance Radar provides identification as additional information from even a small aircraft from a long range and at great height using the support of aircraft transponder.

The SSR is a ground-based, centralized, cooperative, independent, surveillance system, based on the transmission and subsequent reception of a reply from an airborne transponder. The system differs from the PSR radar in the sense that an active response is required; the transmission and reception are performed at distinct frequencies; and, the round-trip delay estimation must now account for a standardized delay that is set in the aircraft transponder.

Unlike PSR, the SSR works on a large coverage, which is up to ~200NM& provides an identification of aircraft as additional information. One of the things that the PSR does not need, and that is fundamental to SSR, is a transponder on-board the airplane. The ground station radar interrogates to the airplane’s transponder at 1030 MHz, which triggers the transponder on-board to reply at 1090 MHz with the airplane’s identification and altitude. Most of the time the PSR & SSR are installed in a collocated way & the SSR appears to be on the top of the PSR antenna & both antenna scan the area simultaneously in a synchronization way [2].

As shown in figure 2.4, SSR Interrogator transmits two pulses (P1 and P3) with the same duration and the same amplitude and with 1030 MHz (Up-Link) frequency. The simplest signal which might be used for interrogation is a single pulse. To avoid interrogation from hazard or random pulse, the transponders are designed to replay only to specified pair of pulse and this is known as Mode. As table 2.1 shows, there is a time interval between pulses of each pair which determines the various modes now available for use with secondary radars. Thus a pulse basing 8µs gives mode A & a pulse basing of 17µs gives mode B. The replay from transponder triggered by mode A and B are used by air traffic controlling for identification and tracking of aircraft. A pulse basing of 21µs gives mode C and this has been designed for use and initiating automatic pressure altitude request. Furthermore, a spacing of 25µs provides mode D and the use of mode D has not been decided [7].

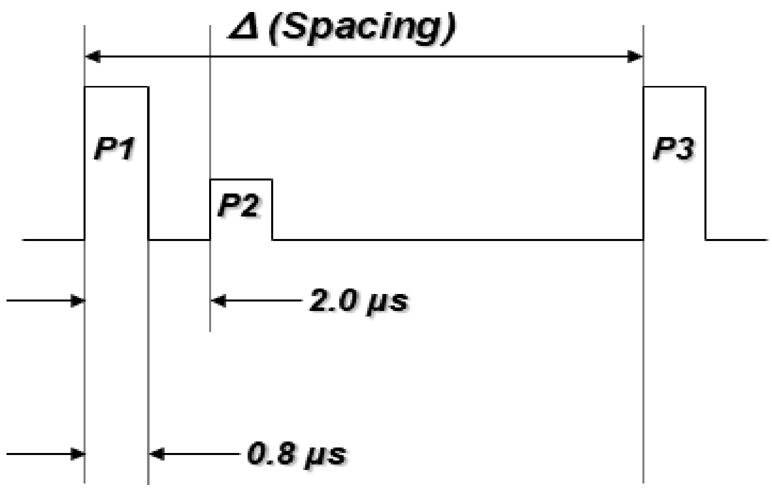


Figure 2. 4: SSR interrogation signal

Table 2. 1: Spacing (Δ) between interrogation pulses for different modes

MODE	Δ (μs)	USE	USER
1	3	IDENT.	MIL.
2	5	IDENT.	MIL.
3/A	8	IDENT.	CIV./MIL.
B	17	N.U.	CIV.
C	21	ALTIT.	CIV.
D	25	N.U.	CIV.

Mode S was developed as an improvement to Modes A and C; it allows selecting a specific aircraft to enquire, reducing interference, and enabling a higher bit rate communication channel. By doing so, besides the standard information from Modes A or C, the Mode S transponder reply can also carry several aircraft parameters through the data link, including the aircraft unique 24 bit address (over 16 million individual identity codes), barometric altitude with a resolution of 25 ft (7.62 m), aircraft status, bank angle, magnetic heading, and track angle [8].

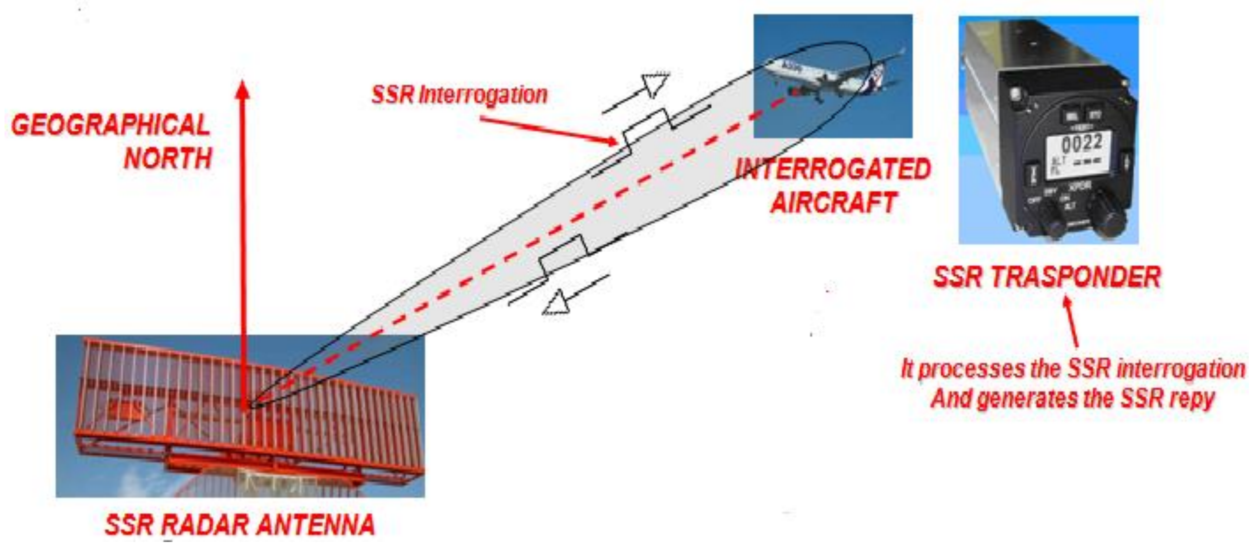


Figure 2. 5: SSR Overview

The two basic elements of **SSR**:

SSR Interrogator

- In-ground installed, provides the related Airspace surveillance through interrogations

SSR Transponder

- On-board installed, replies through the generation of reply coherent with the interrogations

The ground system consists of a rotating directive antenna, usually placed together with the en-route or approach PSR radar, which transmits interrogation messages at 1030 MHz, and receives transponder replies at 1090 MHz .The interrogation, and replies messages, is used to locate the cooperative aircraft, and to exchange relevant information.

The **SSR** is a surveillance system, in accordance with the **ICAO** (**I**nternational **C**ivil **A**viation Organization) regulation, which provides the related **ATC** (**A**ir **T**raffic **C**ontrol) Centers with the following cooperating aircrafts detected data:

- Azimuth
- Distance
- Identity
- Altitude

The **SSR** shows the following characteristics:

- Range: up to 200 NM
- Altitude: up to 30480 m (100000 feet), for elevation angles between 0,5°÷ 45° and for an azimuth angle of 360°
- Aircraft position detection without decoding equipment
- Aircraft identification with coding/decoding equipment
- Derivation of the aircraft altitude code (from the on-board altimeter)

- Identification of a single aircraft through the **SPI** (**S**pecial **P**ulse **I**dentification) *reply*, if requested
- Indication of an aircraft in emergency conditions or with failed radio communication.

SSR systems, despite being a great evolution compared to PSR, the following unwanted replies problems (replies which are not time correlated to the interrogations) are appeared:

✈ MULTIPATH

- Because of reflectance phenomena, unwanted replies are received

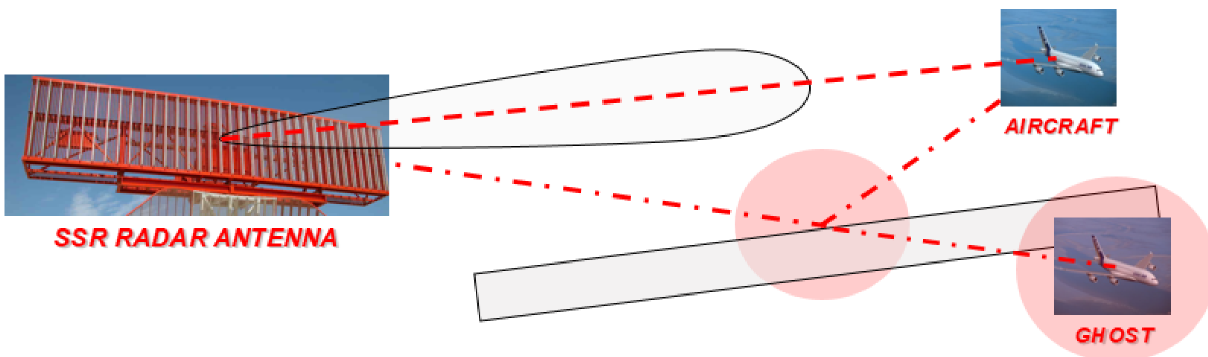


Figure 2. 6: Multipath Phenomenon

✈ FRUIT (False Reply Unsynchronized In Time)

- The FRUIT phenomena occur when a SSR radar receives replies generated after interrogations coming from other SSR radars (the inboard transponders transmit the replies in a Omni-directional manner)

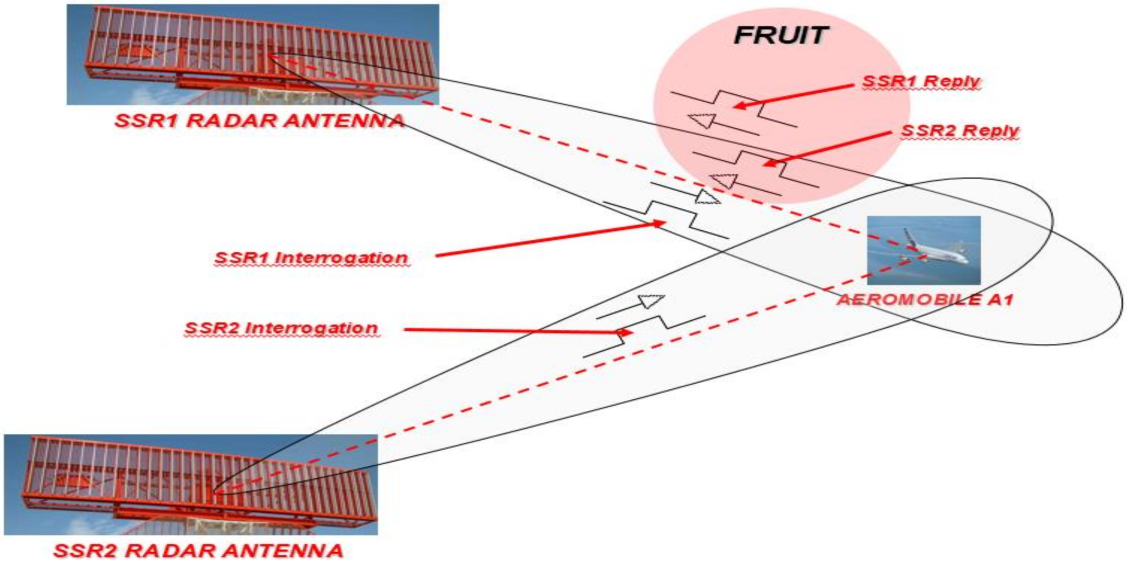


Figure 2. 7: False Reply Unsynchronized In Time (FRUIT)

As Figure 2.7 shows The SSR2 reply, which is received by the SSR1 radar, is asynchronous with respect to the PFR (Pulse Repetition Frequency)

- ✈ GARBLE
  - The GARBLE phenomenon occurs when two aircrafts have a distance lower than 3 Km (20.3 μs → reply length generated by the Transponder) within the main interrogation beam of the SSR radar Antenna; in this case, the possible aircrafts replies overlap causing a wrong decoding.

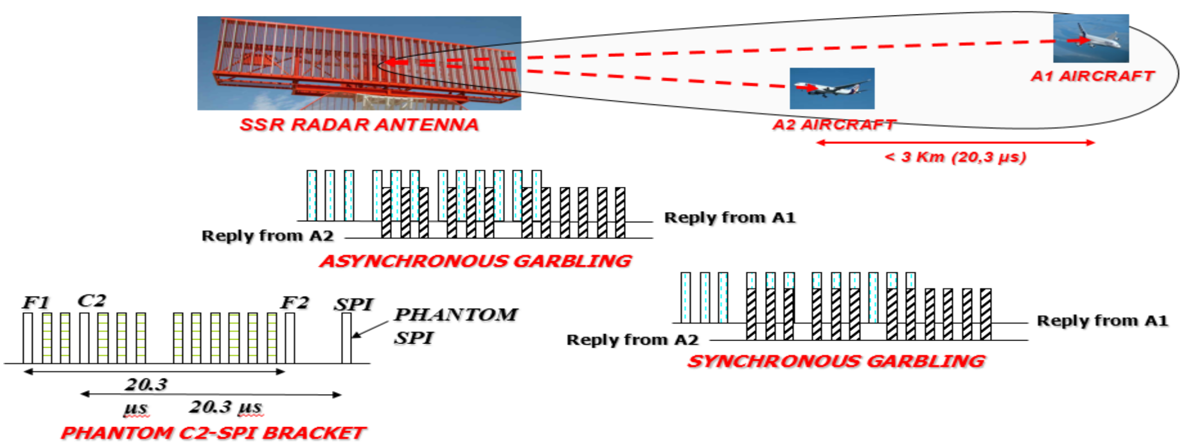


Figure 2. 8: GARBLE phenomenon

2.3.1. Mono pulse SSR technique

Mono-pulse SSR radars are another kind of radars types used to alleviate the problem like multipath, FRUIT and garbling. The SSR Monopulse radar uses the same signals (interrogation and reply) of those of the traditional model but different from the traditional one in the receiver which implements the monopulse techniques in the azimuth plane. With only one reply (monopulse radar) the azimuth aircraft measurement is obtained with a precision sensibly better with respect to the traditional techniques (with the traditional techniques at least 6-8 replies are necessary to obtain the correct azimuth position)

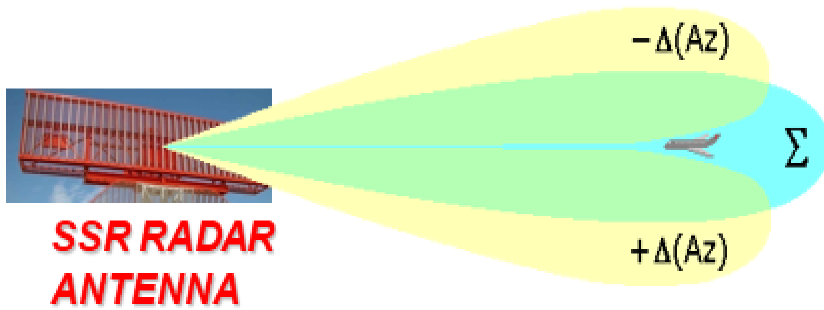


Figure 2. 9: Monopulse radar technique

The antenna of a Monopulse SSR interrogator consists of two separate antennas, with the ***d*** representing the distance between their phase centers. Usually ***d*** is approximately halve the horizontal size of the antenna.

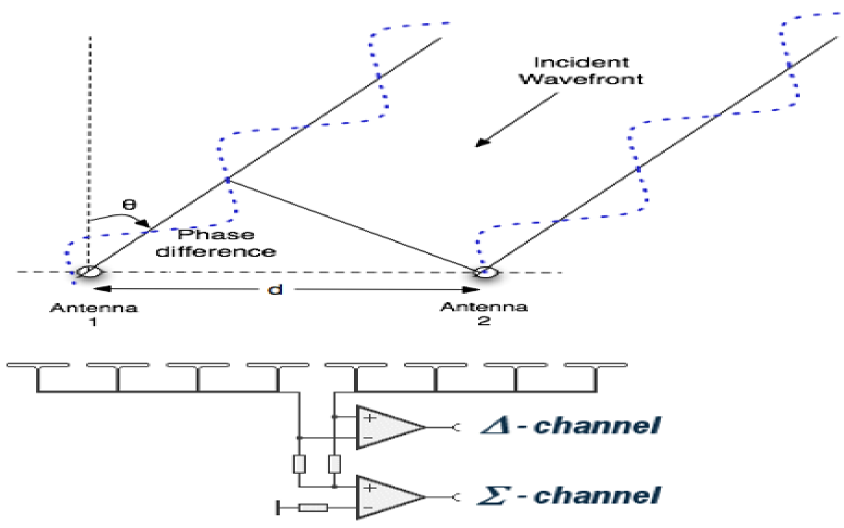


Figure 2. 10: Sum (∑) and difference (∆) of monopulse antenna

From the figure 2.11θ represents the Off-Boresight-Angle (**OBA**) of the target.

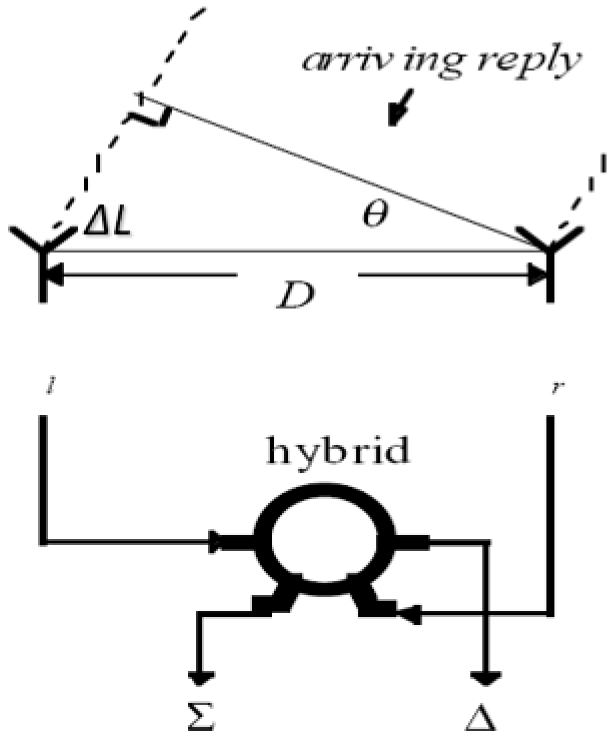


Figure 2. 11:

The signal **S** that arrives at the antenna is:

$$\boldsymbol{S = As_0(t)e^{j\omega t}} \text{ ……… (2.1)}$$

Due to the propagation *delay* difference the signal at the left antenna arrives later in time, which results in a phase difference between the $S_l$signals andS_r.

$$\boldsymbol{S_l = AG_l(\theta)s_0(t)e^{j(\omega t-\varphi)}} \text{ ……… (2.2)}$$

$$\boldsymbol{S_r = AG_r(\theta)s_0(t)e^{j\omega t}} \text{ ……… (2.3)}$$

The difference of path ΔL is calculated:

$$\boldsymbol{\varphi = \frac{2\pi D}{\lambda}\sin\theta} \text{ ……… (2.4)}$$

$$\sum = S_l + S_r = AG(\theta)s_0(t)e^{j(\omega t-\varphi)} + AG(\theta)s_0(t)e^{j\omega t} \quad \text{.................... (2.5)}$$

$$= AG(\theta)s_0(t)e^{j\omega t}(e^{-i\varphi} + 1)$$

$$\Delta = S_l - S_r = AG(\theta)s_0(t)e^{j(\omega t-\varphi)} - AG(\theta)s_0(t)e^{j\omega t} \quad \text{....................... (2.6)}$$

$$= AG(\theta)s_0(t)e^{j\omega t}(e^{-i\varphi} - 1)$$

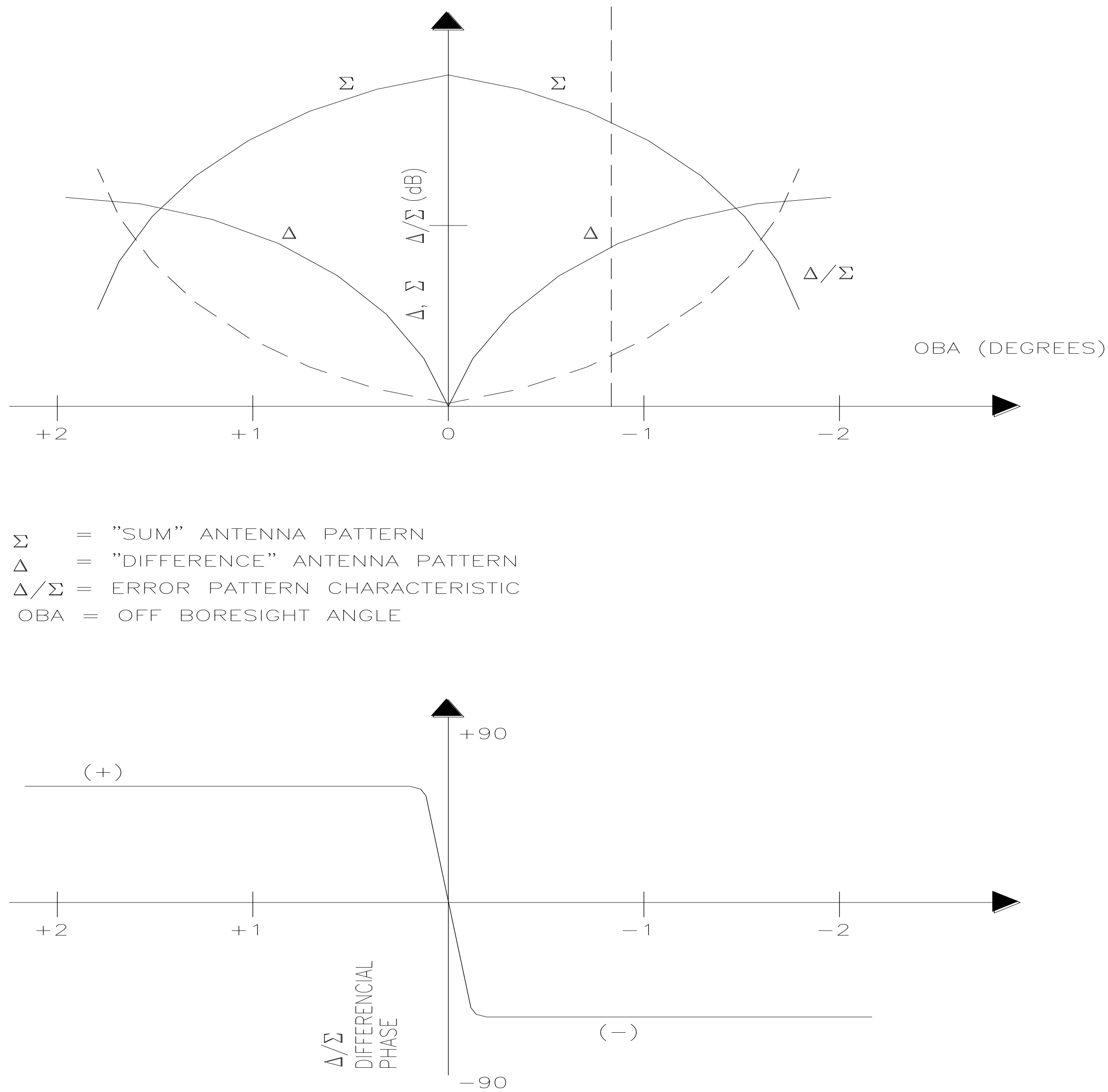


Figure 2. 12: Sum and Difference phase pattern

$$|\Sigma| = \left|AG(\theta)e^{j\omega t}\left(e^{-j\varphi}+1\right)\right| = AG(\theta)\left|e^{-j\varphi}+1\right| = AG(\theta)\sqrt{2(1+\cos\varphi)}$$

$$|\Delta| = \left|AG(\theta)e^{j\omega t}\left(e^{-j\varphi}-1\right)\right| = AG(\theta)\left|e^{-j\varphi}-1\right| = AG(\theta)\sqrt{2(1-\cos\varphi)}$$

$$\left|\frac{\Delta}{\Sigma}\right| = \sqrt{\frac{1-\cos\varphi}{1+\cos\varphi}}$$

The phase relation between **Δ** and **Σ** is:

$$phase = \arg(\Sigma) - \arg(\Delta) = \begin{cases} = +\frac{\pi}{2} \text{ if } \theta > 0 \\ = -\frac{\pi}{2} \text{ if } \theta < 0 \end{cases}$$

The SSR (Secondary Surveillance Radar) Monopulse radar shows the following characteristics:

- *LOW SENSITIVITY TO WEAK IRRADIATION DIAGRAMS*

As the monopulse technique calculates the positions of the airplane on each single reply, the problem is reduced.

- *REDUCTION (DIMINUTION) OF FRUITS (False Replies Unsynchronized In Time)*

As only few replies per scan are necessary, it is possible to reduce considerably the transmission PRF (Pulse Repetition Frequency). As a result, there will be a lower number of false signals (FRUITS) for the SSR systems nearby. The main result is a minor code pollution and a lower load on the processing systems.

- *EFFICIENT DEGARBLING*

Another improvement given by the monopulse technique is the ability to distinguish two or more aircrafts emitting garbled replies, moreover reducing the garble effect given by the temporary reception.

Another best modified technology of SSR radar is selective mode secondary surveillance radar (S-mode SSR).

2.3.2. S –Mode SSR

The SSR (Secondary Surveillance Radar) radars evolution radar has developed the Selective (S-Mode) SSR radar. The S-Mode SSR radar uses the selective interrogation and unique identification code of each aircraft given by the state at registration and this interrogations include the aircraft identification code to be interrogated so that the aircraft replies only if the interrogation includes the identification code.

The identification code includes 24 bits, therefore more than 16 million identities related to the S-Mode Transponder-equipped aircrafts are available and the unique identification code (IC: Interrogator Code) is also assigned to the S-Mode SSR interrogators.

By using S-Mode SSR, the FRUITS (False Replies Unsynchronized In Time) and de-garbling capabilities are enhanced.

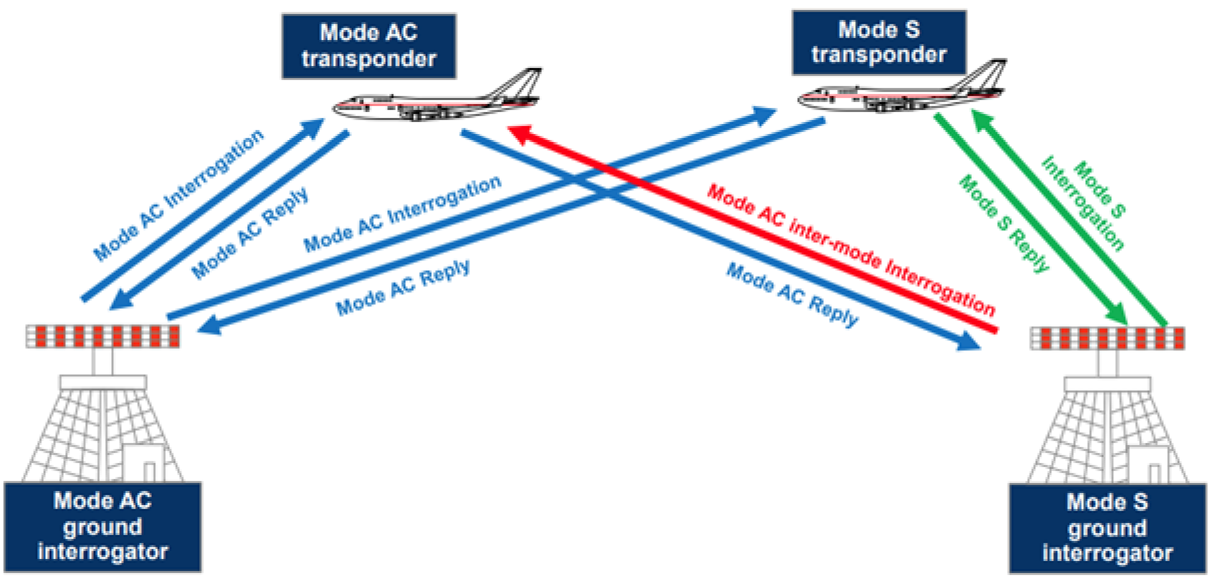


Figure 2. 13: Mode AC and Mode S interrogation and replay

Mode AC and Mode S operates on the same frequencies, it interrogations on 1030MHz replies on 1090MHz.

Compatibility between conventional and *S-Mode* is achieved by the following steps:

- The frequencies used in the *S-Mode* activity are the same as conventional (mode A/C)
- *S-Mode* Transponders can reply to conventional (mode A/C) *interrogations*

- The *S-Mode* sensors waveforms are such to prevent the mutual interference with signals relevant to the conventional *interrogations.*

Even if S-Mode SSR is best and advanced technology of surveillance system, it has some drawback that its functioning is also based on the rotation of the radar antenna, which limits the refresh rate of aircraft position to the rotation frequency of the antenna and the moving parts involved in SSR makes the system more complicated to install and costly to maintain [8].

2.4. Automatic Dependent Surveillance

Unlike the above mentioned methods, there is no need to interrogate and replay questions when using ADS, because the aircraft itself can determinate its position using GNSS support & navigation system on-board. ADS is a passive, cooperative and dependent surveillance system which works in association with GNSS. ADS is a satellite-based technology, and there are three different modes of using this type of surveillance, ADS-Address (ADS-A), ADS-Broadcast (ADS-B) and ADS-Contract (ADS-C).

ADS-A works based on a negotiated one-to-one peer relationship between aircraft providing ADS information and a ground facility requiring receipt of ADS messages, ADS-C works by using the aircraft navigation system and determine its position, velocity, and meteorological data, but as the name indicates, it works by contractual agreement between the aircraft & the ground station system. This technology is used in areas (e.g. Mountainous or marine areas), because the radar has no range and cannot be used. ADS-B is a surveillance system that allows for an aircraft to continuously broadcast several information parameters to the ATC on the ground (ADS-B Out), and to other suitably equipped aircraft in range (ADS-B In).

ADS-B differs from ADS-A in that the latter is based on a negotiated relationship between an airplane providing the information and a ground facility requiring receipt of ADS messages. For example, the ADS-A report will be used in future flight navigation systems. Using the Aircraft Communication Addressing and Reporting System (ACARS) as communication protocol. When flying over an area that is not covered by radar (e.g. oceanic and polar), Ocean and Polar) reports are regularly or periodically sent to the air traffic control area.

The standard transmission signal may include the aircraft's unique 24 bit address, its velocity, pressure-altitude information, and geographical position. ADS-B depends on pre-established systems to gather and broadcast this information: the geographical position information is retrieved through the on-board Global Navigation Satellite System (GNSS) receiver, and the information broadcast may be done through the ATC Mode S transponder. As shown in the Figure 2.14, a simple dipole antenna is a appropriate receiving GS, thus making this system rather easy and low-cost compared to radars. Additionally, ADS-B allows for higher refresh rate, contrary to PSR and SSR, for which the radar sweep rotational speed constrains the refresh rate of information.

Figure 2. 14: 1090/1030 dBs 620 omnidirectional antenna

Space-based ADS-B is an emerging technology for global satellite coverage of ADS-B Out, based on the Low Earth Orbit (LEO) Iridium NEXT constellation. Similar to ground-based ADS-B, the system relies on on-board navigation systems to determine, amongst other data, the aircraft's position, velocity, and predicted route; reporting this information to the ATC center in charge, through a satellite link, with bearable delay and refresh rate.

The ADS-B has a very good update rate, high accuracy, better resolution, and lower installation cost.

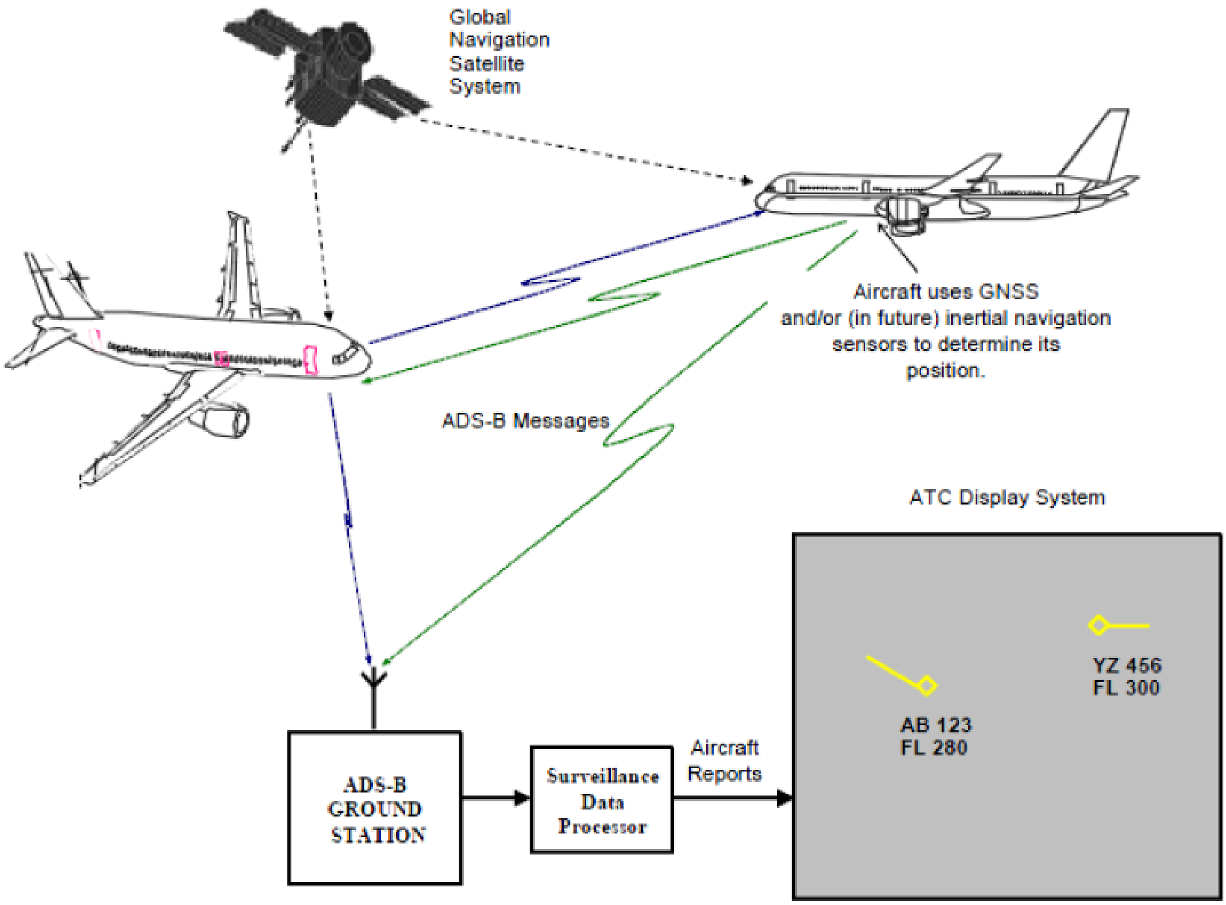


Figure 2. 15: process of ADS-B

In general, the SSR has a better performance compared with PSR. With SSR, it is possible to have a very accurate location of the airplane, to cover large areas; furthermore, SSR is less sensitive to interferences [8, 9]. Although even SSR has many advantages than PSR, it cannot provide ground surveillance and the requirements of latency and update rate need to be improved. Due to continuous improvement of the technology, a multilateration systems has been developed to rectify the limitations shown on SSR. The MLAT systems do everything that the SSR does and with more additional features; one can know the exact location of an airplane.

2.5. Overview of Aeronautical multilateration systems

Like ADS-B, Approach Multilateration, is a co-operative identification and surveillance system for en-route, terminal maneuvering area and airport surface traffic. The system employs multilateration based on Secondary Surveillance Radar (SSR) protocol and Mode A/C/S signals.

Position calculation by multilateration requires measuring the reception time or time of arrival (TOA) of the same signal at different locations. Ground station receivers placed in a suitable geometry on geographically identified earth surface perform these measurements simultaneously.

A central processing station collects and processes the data provided by the ground stations, and calculates target positions using the correlated Time Difference of Arrival (TDoA) [10].

The results are kept in a target list together with other target information that was obtained via the Mode A/C/S data link. In addition to the always-present Mode A address (SSR code) and/or Mode S address these data include the aircraft registration, call-sign, aircraft type, barometric altitude, etc.

On a periodic base, target reports will be output over the LAN interface in Eurocontrol Asterix formats for further processing by other air traffic control systems.

Due to the applied hyperbolic and elliptical principle of multilateration, the position strongly depends on the geometry between the contributing ground stations and the target. A detailed and optimized site planning and identification is therefore mandatory for system performance taking into account:

- The System geometry
- Line of sight restrictions
- Operational constraints, e.g. obstacle clearance limits
- Potential obstacles for signal propagation (e.g. terrain, buildings...)

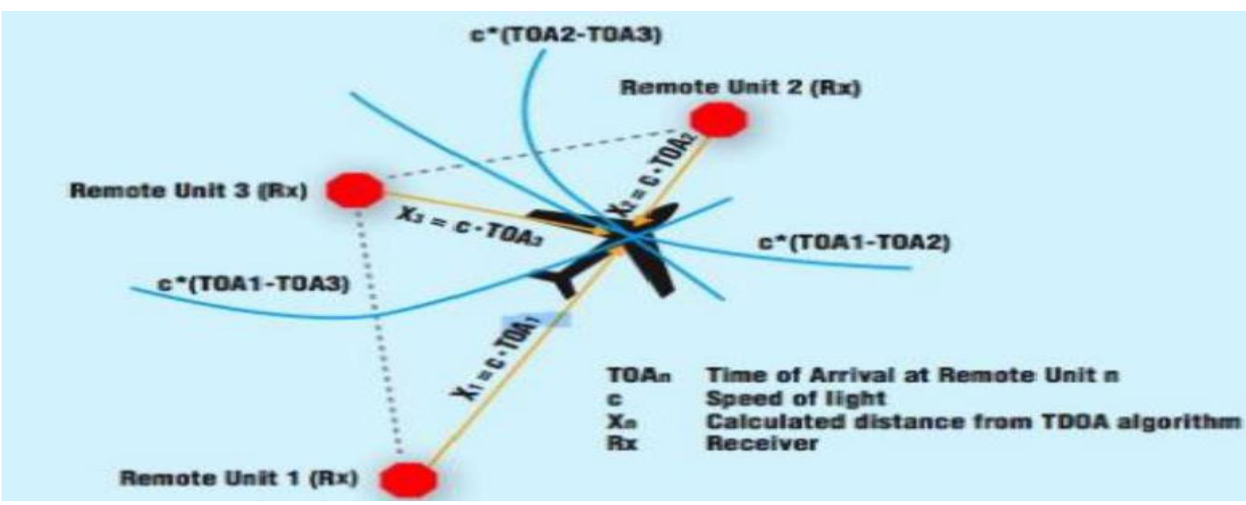


Figure 2. 16: TOA Synchronization

There are two options to calculate TDOA for these systems, cross correlation and Time of Arrival (TOA)[12, 13].The former can be used for any signal, and TDOA is calculated by cross-correlation between signals, in the latter, the process is the same as the SSR transponder, the time of arrival being measured in waveforms signals. The TOA system is most commonly used for multi-point positioning, so only this method is described below:

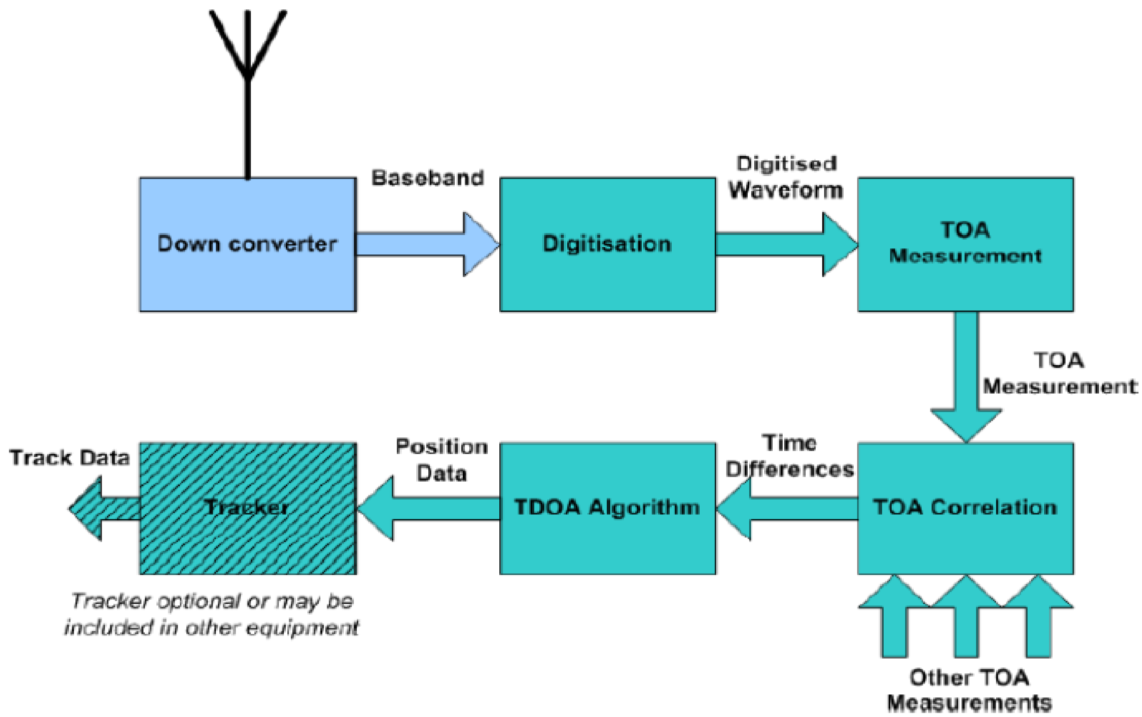


Figure 2. 17: TOA data flow

Explains the TOA process, the different elements are:

- Down-converter: Convert radio frequency to baseband signal.
- Digitization: the baseband signal is digitized.
- TOA measurement: Every message has its own time.
- TOA correlation: Calculates the time difference between signals.
- TDOA algorithm: used to determine the processing time difference of the aircraft position.
- Tracker: Use the xyz map to provide the ATC team with updated aircraft location information

The concept of the TDOA algorithm is based on knowing the time of arrival of the signal. The aircraft position is calculated by measuring the TOA signal between the aircraft transponder and the ground station. Each of the signals is processed by the TDOA algorithm, being transformed into a hyperbola, and the intersection of all these hyperbolas provides the target’s location, Figure 2.18.

There are different methods used on sensors' synchronization, which can be common clock or distributed clock systems [11]. This synchronization is necessary, because when the signals arrive from the different sensors, and are then transformed into time differences, they are time stamped during the digitization process. But in this process there are delays, which can compromise the accuracy of this technology, so to prevent this situation, synchronization techniques are implemented.

In common clock systems, the digitization occurs at the central site, which means that there is no need to synchronize each of the sensors. This technology uses a simple receiver, putting most of the complexity in the central multilateration processor, Figure 2.17. When there is an analogue link, as a distance increases, the delay of the system also increases. So in order to minimize the link distances the multilateration processor is usually at the center of the system.

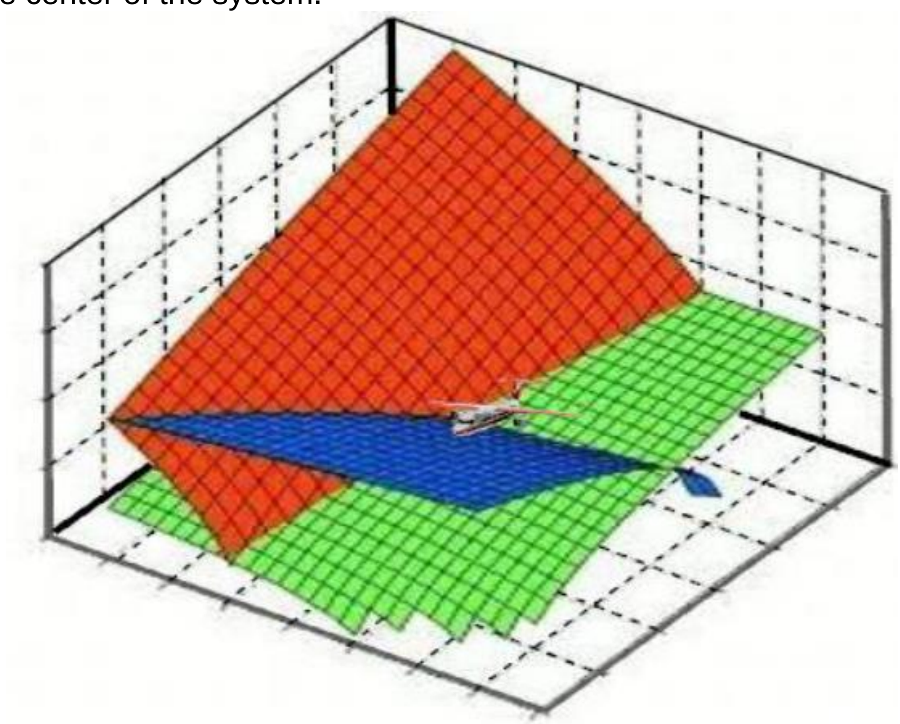


Figure 2. 18: MLAT hyperbola intersection

The distributed clock system has a different architecture from the centralized common clock system.. In these systems, a local clock is applied to each of the digitization, and the TOA measurement block increases the complexity of the system. The signal is converted to baseband, and then suffers a digitization followed by the TOA measurement. This method provides the necessary flexibility in the presence of high latency. Each sensor has its own local clock, and its synchronization is achieved by using the following methods:

- Transponder synchronized systems.

- GNSS (Global Navigation Satellite System) synchronized systems: standalone and common view GNSS synchronization.

All these methods have their own characteristics in terms of accuracy, baseline distance, communication parameters, and whether to provide line of sight or not. Therefore, every existing manufacturer uses the method that best suits their needs.

In the MLAT system, the baseline (i.e., distance between adjacent sites) of sensors is directly related to the minimum height that enables the communications between airplane and ground stations. The highest baseline between sensors is calculated based on the horizontal range of the sensors. As said earlier, one needs 4 or more sensors [17, 18, 19].
The aircraft is equipped with transponders that continuously transmit information; using these signals, by measuring the TDoA of these waveforms for ground receivers, the transmitter location can be estimated. Aeronautical multilateration systems exploit the radio interface of existing technologies, such as the SSR and ADS-B Out systems; integrating the Mode A/C/S/ES data transfer capabilities, with an independent method for locating the aircraft, and validate its reported position.

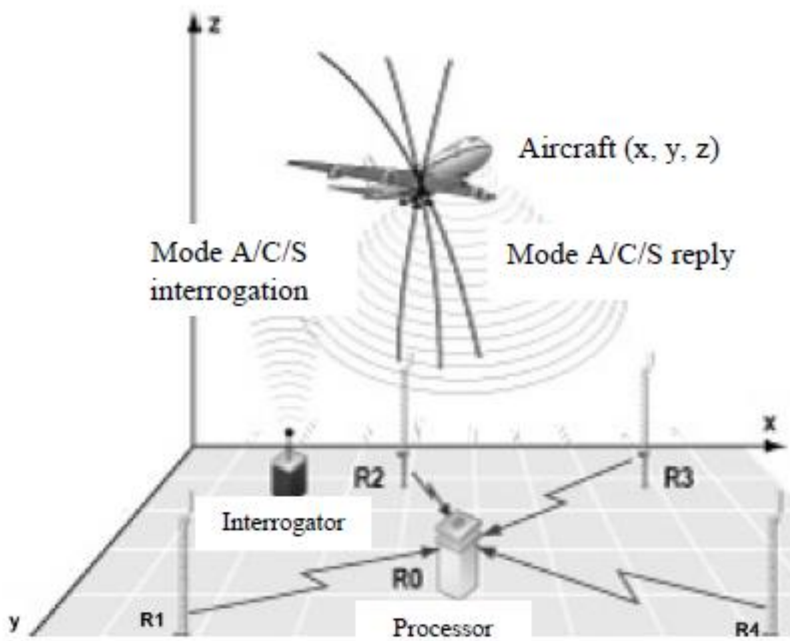


Figure 2. 19: Active MLAT operating concept

The uplink interrogation channel operates on a 1030 MHz carrier with a 21.5 MHz emission mask for cooperative aircraft in interrogation range [9, 10]. Different modulation schemes are used according to the selected query mode.
The interrogation of modes A and C consists of two pulses with a width of 0.8 µs; GS uses the distance between the two pulses to inform the interrogating transponder about the selected mode. For mode A, the range of spacing between pulses is 8 ± 0.2 µs, and

for mode C, the range is 21 ± 0.2 µs. In these operating modes, the request message will be unaddressed and all aircraft in range will be requested. Mode S can perform discrete interrogation of the aircraft; for this purpose, an additional DPSK modulated data block containing the address of the selected aircraft is sent after the two-pulse preamble [10]. This mode can significantly reduce channel interference. The transmit power depends on the expected coverage area and is usually not specified by the manufacturer; however, a value should be expected to ensure balance with the downlink.

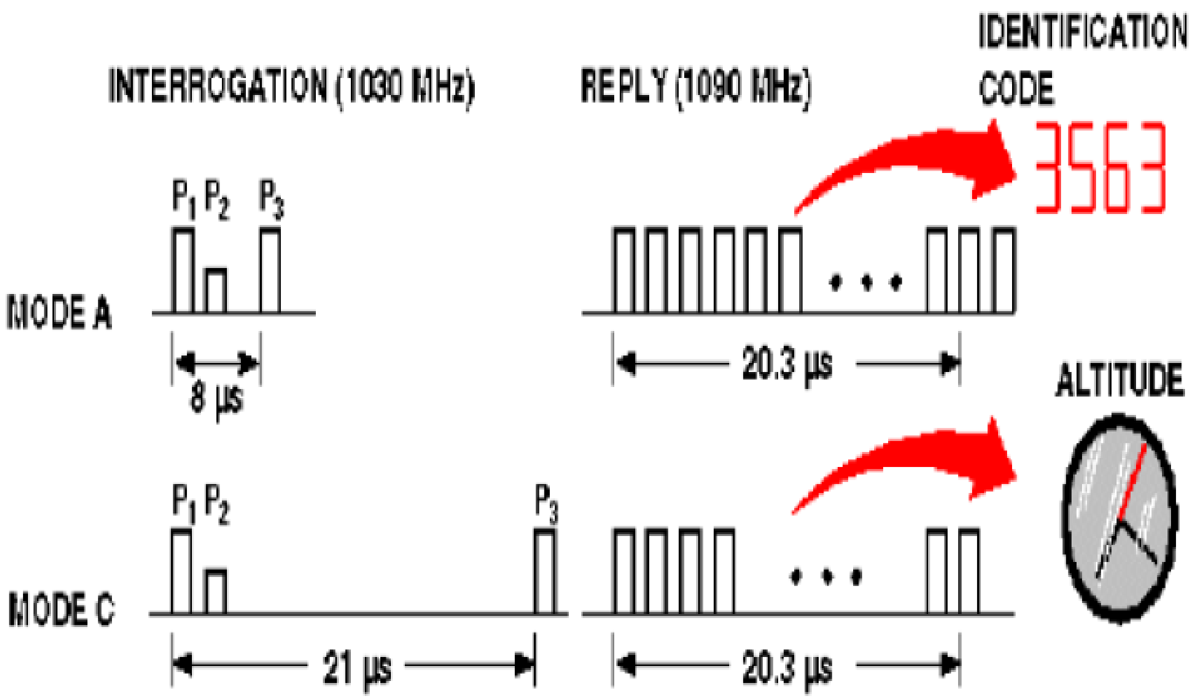


Figure 2. 20: Mode A/C interrogation

The downlink response channel operates at a frequency of 1090 MHz, with a -20 dB band width of 14 MHz, and is used to locate and identify communicating aircraft within range [4]. The response message of the transponder is the same for all operating modes and consists of a preamble with four 0.5 µs rectangular wave pulses and a pulse position modulation (PPM) data block. The length of the data block in bits depends on the operating mode: 12 bits in modes A and C, and for mode S, it can be 56 bits or 112 bits. Depending on the aircraft class, the transmission power varies from 48.5 to 57 dBm.

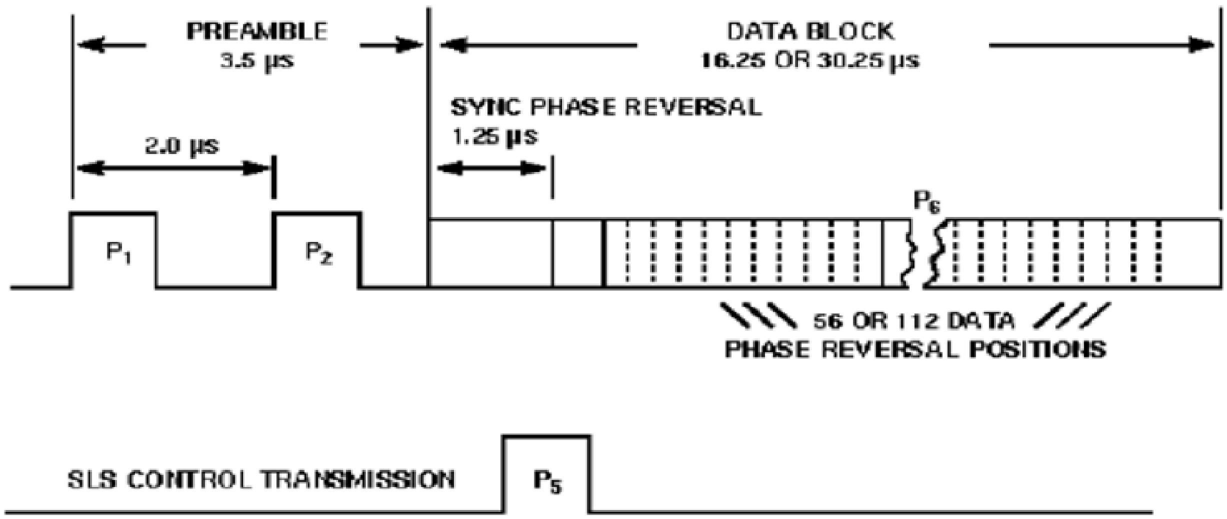


Figure 2. 21: Mode S interrogation waveform

- Differential Phase Shift Keying(DPSK) Modulation
- Data rate 4 Mb/s

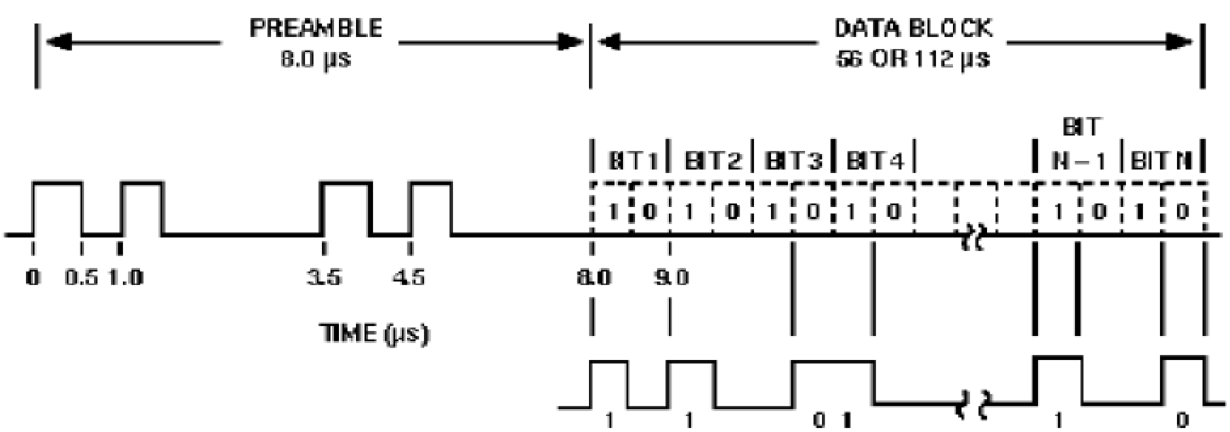


Figure 2. 22: Mode S replay waveform

- Pulse Position Modulation (PPM)
- Data rate 1Mb/s

The multilateration positioning system locates and recognizes the responding aircraft transponder based on the downlink pulse; in addition, the GS receiver; the telecommunication network that supports the system; and a central processing unit in which to estimate the position and track the target; these are all factors that affect the system's coverage, furthermore; an important component of performance in terms of accuracy and capacity.

Hyperbolic positioning involves measuring TDoA signals between strategically distributed sensor pairs; in aeronautical multilateration localization, this positioning method is used as follows. The aircraft transponder transmits the signals moving along different propagation paths to the distributed sensor network corresponding to the ground sensors of the MLAT system. The signal is converted to baseband and digitized at each receiver. The receivers IF filter bandwidth, noise figure, and quantization resolution play an important role in the theoretical accuracy of the system. In the N_{GS} GS system, independent nonlinear TDoA equations can be defined for $N_{GS} - 1$, and each equation is a hyperboloid.

Generally, the system of equations is redefined, that is, there are at least three hyperbolic equations associated with four receptors, which allows one to estimate the three unknown coordinates of the plane. It can also be calculated by using only three receptors by replacing one of the hyperboloids with a horizontal plane [5, 6]. The system must record the altitude of the airplanes air pressure, because the altitude of the target determines the altitude of the horizontal plane; this information is usually available in mode C or S messages.

The hyperbolic positioning is done with random values, which means that the TDoA of the GS pair does not provide a surface, but provides a confidence range around the hyperboloid surface; therefore, the intersection of these areas does not provide a single space in which the aircraft can be positioned, but provides a certain degree of trust. The exact position of the aircraft using multi-point positioning depends on the geometry of the problem, and GS needs to be used for each position calculation, so that position errors can be minimized. Periodic synchronization of the receiver clock is necessary to minimize errors related to the clock drift of each receiver; in addition, an accurate estimation of the position of the GS is a key point in defining the nonlinear hyperbolic equations [17, 18, 19, 20, and 21].

Table 2. 2: Shows overall comparison of PSR, SSR, ADS-B, and the MLAT system.

No.	Surveillance System	On-board equipment required?	Interrogation required?
1	PSR	No (non-cooperative)	Yes (active)
2	SSR	Yes (cooperative)	Yes (active)
3	Mode A/C MLAT	Yes (cooperative)	Yes (active)
4	Mode S MLAT	Yes (cooperative)	No (passive)
5	ADS-B	Yes (cooperative)	No (passive)

Chapter-3

3. TDOA model and description on Aeronautical Multilateration

This chapter concerns the proposal, description, implementation, and assessment of the model for the analysis of aircraft accuracy location in aeronautical multilateration system. The chapter starts with a theoretical model and offering an overview of its purpose and assumptions. Subsequently, a more detailed description of the sub-models is provided, followed by the development of the statistical model for the positioning error. Finally, the chapter ends with a thorough assessment of results from the model by comparison with data from the literature, and from previously implemented systems.

3.1. Model Development

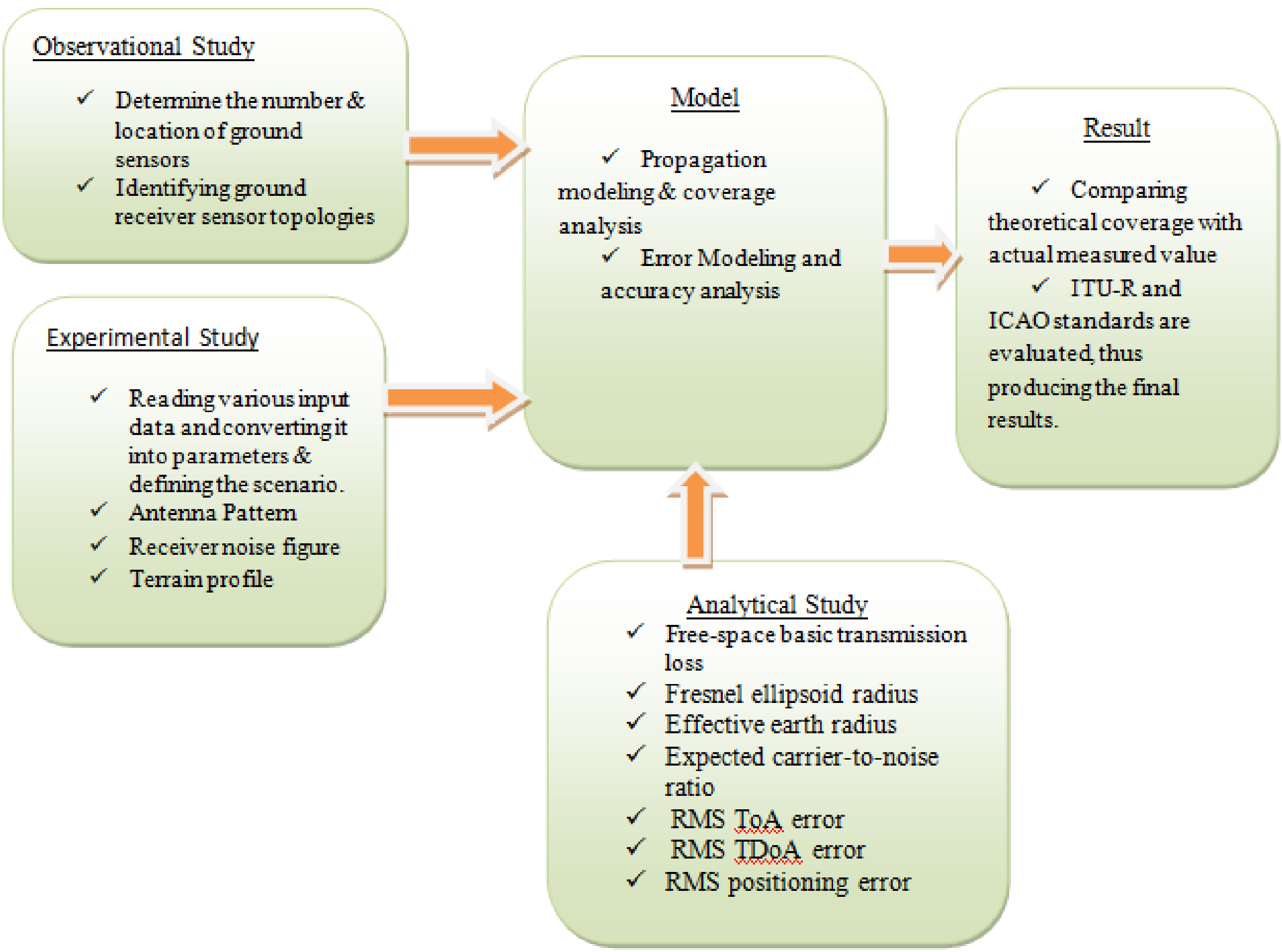


Figure 3. 1: Project model development

3.2. TOA/TDOA Principle

The performance of the multilateration localization system is measured by the operating coverage specified in its quality of service specification. The QoS arrangement for multilateration positioning consists of some mandatory specifications, such as accuracy, detection probability, throughput, and processing delay.

The MLAT Surveillance System calculates the position of the aircraft in two steps [7]. The first step is to estimate the time difference of arrival (TDOA) of the signal between the antenna pairs. The second stage involves using the estimated TDOA measurements from the first stage as input to the position estimation (PE) algorithm, called lateration. As mentioned in the previous chapter, the estimated position of the aircraft in 2D or 3D depends on the number of receiver antenna used [9].

At least 4 antennas are required for the 3D positioning of the aircraft. Literature [13, 14, and 15] describes several methods of evaluating TDOA, but the classic method of air traffic control is the TOA method. Using the TOA method to estimate TDOA means the pair wise difference between the TOA measurements of the estimated signal on each antenna. The signal TOA is the time required for the signal sent by the aircraft to be detected by one of the antennas. Various TOA estimation methods are described in the literature [13, 14, 15, 16 and 17], but the focus of this work is to use these TOA measures for the location estimation process. Therefore, the focus of this thesis is on the lateration algorithm

When converted to distance, the TDOA measurement results in a hyperbolic equation. The number N of TOA measurements leads to the N-1 hyperbolic equation [15]. Based on the hyperbolic equation, there is a non-linear relationship between the TDOA measurement and the aircraft position. In order to determine the position of the aircraft, it is necessary to obtain a linear relationship between two parameters (the TDOA measurement and the aircraft position). Many articles reported how to obtain this linear relationship, resulting in different types of lateration algorithms. Different types of lateration algorithms are divided into open and closed form [16]. The open form algorithm includes the use of linearization techniques, such as the Taylor series method, which is used to linearize the hyperbolic equation and the random initial position of the aircraft, input and then use an iterative method for refinement [18-23]. When the original position of the incoming aircraft is far from the actual position of the aircraft, this method will encounter convergence problems [17]. The closed form algorithm linearizes these two parameters through the algebraic processing of the hyperbolic equations [18, 19, 20, 21, and 24]. This method does not require the initial aircraft position, so it will not encounter convergence problems. To this end, this thesis uses a closed delay algorithm. Reference [26& 27] discusses the use of multiple reference antennas to improve the position estimation accuracy of the delay algorithm. TDOA estimation techniques.

There are two ways for estimating time difference of arrival, ToA correlation &Cross-correlation. ToA correlation is a suitable filtering method to estimate ToA on each sensor, and then transmit the stamped time to the CPU. The TDoA is just the analytical difference between a pair of ToA [23 & 24]. This method is suitable for signals that are easy to measure on one edge of the pulse; it is like the leading pulse in an aircraft transponder signal. The Cross-correlation is a signal which received by each sensor then digitized, labeled, and transmitted to the central processing unit, where the correlation function estimates the time difference between the pair of sensors. The accuracy of this estimation depends on the type of signal which is transmitted by the target and the distortion of the channel signal; that is, the effect of multipath propagation. This system can be applied to any signal and is widely used in sensor networks, wireless positioning systems, and electronic warfare support. The transponder signal in A/C/S mode does not have good auto or cross-correlation characteristics; therefore, MLAT ground systems based on cross-correlation must use algorithms designed to avoid false or ambiguous results. Figure 3.2 shows the simplified principle of a TDoA system & multiple hyperbolas for optimal position.

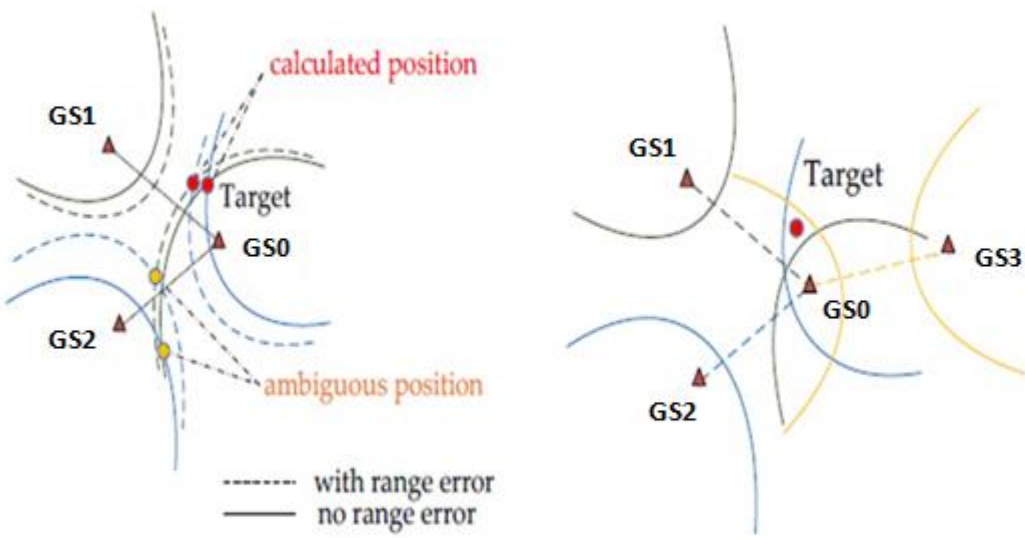


Figure 3. 2: Principle of TDoA measurement when there are three basic sensors of TDoA and multiple hyperbolas for the optimal position.

3.3. Determination of the airplane´s position

As we mentioned in the previous section, the aircraft position localization using multilateration system works based on the TDOA algorithm to accurately determine the position of the aircraft. For this reason, it is necessary to measure the TOA signal exchanged between the ground station and the aircraft. This method can also be called hyperbolic positioning because it is based on the intersection of the hyperbola as a direct result of the TDOA algorithm. Each hyperbola corresponds to the time difference of arrival between the signal sent by the aircraft and the signal received by one of the ground stations. After obtaining all the hyperbolas, the intersection point will give the exact position of the target at that particular point in time. It is assumed that the TOA measurement of the received signal has been evaluated on each antenna. Accordingly, the distance between the ground station and the target is then calculated:

$$D_{i[m]} = \sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2},\ i \in \{1,2,3,4 \ldots, N_{GS}\} \ldots\ldots\ldots\ldots \text{(3.1)}$$

Where:

- $(x_i,\ y_i,\ z_i)$: *coordinate Location of the* i^{th} *ground station in meter*
- (x, y, z): *coordinate Position of the airplane in meter*
- N_{GS}: *total Number of ground station receivers*

In order to achieve the hyperbolas intersection, it is necessary to have an equation for each of the hyperbolas [25]

$$\sqrt{(x-x_i)^2+(y-y_i)^2+(z-z_i)^2} - \sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}$$

$$= D_i - D_1 = c.(t_i - t_1) \ldots\ldots\ldots\ldots \text{(3.2)}$$

Where:

- $D_i -$ *Distance (in meter) from the position of aircraft to the ground station i*
- c: *Speed of light in* $\frac{m}{s}$
- $t_i -$ *Signal travel time from the aircraft to the ground receiver i*

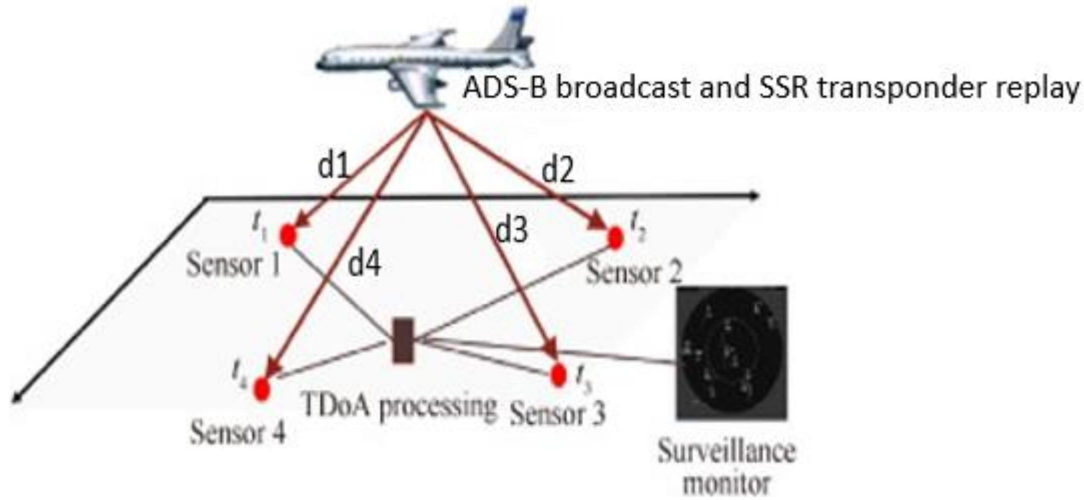


Figure 3. 3: Illustration model of MLAT TDOA system

3.3.1. Closed form basic algorithm derivation

The receiver of the ground station $R_m$is located at the coordinate point $(X_{m,}Y_{m,}Z_m)$ and the target $P$is located at the coordinate (x, y, z). Let C be the speed of light at free space, R_{nr} be the number of non-reference ground stations in the receiver group, and R_r be the number of reference ground station receivers, so there are a total of $R_{nr} + R_r$ground station receiver groups. To test the basic algorithm, let us assume that there is a reference ($R_r = 1$) at ground station 0 or point R_0. Then we define the distance from the target to the ground station receiver m as D_m. The TDoA that we derive from the data, τ_{m0}, for ground station m ∈ [1, r_{nr}], relative to the reference ground station R_0 is :

$\tau_{m0} = {(D_m - D_0)}/{C}$………………………………………………………………… (3.3)

$d_{m0} = \tau_{m0}C = D_m - D_0$ ………………………………………………………………… (3.4)

As shown, for a constant value of the speed of free space, the TDOA yields the distance difference of arrival, as follows:

$D_m = d_{m0} + D_0$ ……………………………………………………………………………… (3.5)

Let's assume that distance difference of arrival for 4 additional receivers using receiver 0 as the reference. And further assuming that all the receiver positions P_m. As in [26], we form for receiver m:

$D_m^2 - D_0^2 = |R_m - P|^2 - |R_0 - P|^2$………………………………… ………….. (3.6)

The right side can be extended to extended,

$$D_m^2 - D_0^2 = (x_m - x)^2 + (y_m - y)^2 + (z_m - z)^2 - (x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2 \quad (3.7)$$

By expanding again with some cancellation of the squared target coordinates and grouping

$$D_m^2 - D_0^2 = x_m^2 - x_0^2 - 2x(x_m - x_0) + y_m^2 - y_0^2 - 2y(y_m - y_0) + z_m^2 - z_0^2 - 2z(z_m - z_0) \quad (3.8)$$

The left side can be rewritten using (3) as:

$$D_m^2 - D_0^2 = (d_{m0} + D_0)^2 - D_0^2 \quad (3.9)$$

$$D_m^2 - D_0^2 = d_{m0}^2 - 2D_0 d_{m0} \quad (3.10)$$

Equating both sides:

$$d_{m0}^2 - 2D_0 d_{m0} = x_m^2 - x_0^2 - 2x(x_m - x_0) + y_m^2 - y_0^2 - 2y(y_m - y_0) + z_m^2 - z_0^2 - 2z(z_m - z_0) \quad (3.11)$$

We next group all the known terms together and divide by 2 defining w_{m0} as

$$w_{m0} = {}^{1}\!/_{2}\,(d_{m0}^2 - x_m^2 + x_0^2 - y_m^2 + y_0^2 - z_m^2 + z_0^2) \quad (3.12)$$

With some rearrangement and substitution, we get the result:

$$D_0 d_{m0} - (x_m - x_0)x - (y_m - y_0)y - (z_m - z_0)z = w_{m0} \quad (3.13)$$

The unknowns are x, y, z, D_0 and all these are seen to be linear in Equation (11). For the 4 unknowns, we need to have 4 equations,

$$\begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 & D_{10} \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 & D_{20} \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 & D_{30} \\ x_0 - x_4 & y_0 - y_4 & z_0 - z_4 & D_{40} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ D_0 \end{bmatrix} = \begin{bmatrix} w_{10} \\ w_{20} \\ w_{30} \\ w_{40} \end{bmatrix} \quad (3.14)$$

If the matrix in Equation (3.14) is not singular, then the Cartesian coordinates for the target and the distance from it to the reference are solved simultaneously by solving the linear system of Equation (3.14).

It should be noted that there are some useful arrangements of ground station receivers for which the matrix is singular. The most notable arrangement of receivers is keeping a line of uniformity on a specified geographical place. Such kind of configurations is very difficult on a practical arrangement of ground receiver arrays. Therefore, for receivers with random spacing, for example, the matrix is virtually always nonsingular

3.3.2. Extension of the algorithm for more ground station receivers

There are two possible useful generalizations of the basic algorithm. First, the number of non-referenced ground station receivers' R_{nr} need not be limited to four, and second, the number reference receivers' R_r need not be limited to one. In the case of more ground station receiver arrangements, we continue to use the matrix notation as:

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 & d_{10} \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 & d_{20} \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 & d_{30} \\ \vdots & \vdots & \vdots & \vdots \\ x_0 - x_m & y_0 - y_m & z_0 - z_m & d_{m0} \end{bmatrix} \ldots\ldots (3.15)$$

$$P = \begin{bmatrix} x \\ y \\ z \\ D_0 \end{bmatrix} \ldots\ldots (3.16)$$

$$w = \begin{bmatrix} w_{10} \\ w_{20} \\ w_{30} \\ \vdots \\ w_{m0} \end{bmatrix} \ldots\ldots (3.17)$$

Thus,

$$AP = w \ldots\ldots (3.18)$$

If m>4 and each row is linearly independent, then we can derive [12]

$$A^{+} = (A^T A)^{-1} A^T \ldots\ldots (3.19)$$

And in generate a least-squares error result, where T is transpose and + is the Pseudoinverse

$$P = wA^{+} \ldots\ldots (3.20)$$

A second generalization is to use multiple references for a single solution, as demonstrated in the following for $R_r = 2$ and$R_{nr} = 8$, using a total of 10 ground station receivers with receivers 0 and 9 as reference

$$A = \begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 & d_{10} \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 & d_{20} \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 & d_{30} \\ x_0 - x_4 & y_0 - y_4 & z_0 - z_4 & d_{40} \\ \vdots & \vdots & \vdots & \vdots \\ x_0 - x_8 & y_0 - y_8 & z_0 - z_8 & d_{80} \\ x_9 - x_1 & y_9 - y_1 & z_9 - z_1 & d_{19} \\ x_9 - x_2 & y_9 - y_2 & z_9 - z_2 & d_{29} \\ x_9 - x_3 & y_9 - y_3 & z_9 - z_3 & d_{39} \\ x_9 - x_4 & y_9 - y_4 & z_9 - z_4 & d_{49} \\ \vdots & \vdots & \vdots & \vdots \\ x_9 - x_8 & y_9 - y_8 & z_9 - z_8 & d_{89} \end{bmatrix} \ldots\ldots (3.21)$$

$$P = \begin{bmatrix} x \\ y \\ z \\ D_0 \\ D_9 \end{bmatrix} \ldots\ldots (3.22)$$

$$w = \begin{bmatrix} w_{10} \\ w_{20} \\ w_{30} \\ w_{40} \\ \vdots \\ w_{80} \\ w_{19} \\ w_{29} \\ w_{39} \\ w_{49} \\ \vdots \\ w_{89} \end{bmatrix} \ldots\ldots (3.23)$$

In the previous section the Range Difference of Arrival (RDoA) between the target and the ground sensor position m is calculated:

$$d_{m0} = \tau_{m0} C = D_m - D_0 = RDoA_{m0}, \ldots\ldots (3.24)$$

And estimated Range Difference of Arrival would be,

$$\widehat{RDoA}_{m0} = \left|\widehat{D_m} - \widehat{D_0}\right| = \sqrt{(x_m - x)^2 + (y_m - y)^2 + (z_m - z)^2} - \sqrt{(x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2} \quad \text{(3.25)}$$

Hence, the vector $\delta\mathrm{RDoA}_{\mathrm{m0}} = RDoA_{m0} - \widehat{RDoA}_{m0}$ is error in measurements.

The accuracy of the estimated position of a target (X, Y, Z) is affected by various system and environmental factors, such as measurement uncertainty, system noise, and target transponder geometry. However, the effects of noise and other factors can be reduced by using various error reduction techniques and positioning algorithms. The only way to avoid geometric influences is to position the sensor in correct geographical location. This task can be performed by analyzing GDOP configuration for different sensor configurations.

3.4. Effect of ground sensor geometry on Target position accuracy

Position accuracy is defined as the degree of closeness of estimated position to the true position [30] or is defined as the error in estimated position [31]. It depends on ground sensor geometry and measurement error. The equation below describes their relationship where, Estimated Range Error or represents Root Mean Square Error in range (RMSE).

$$\text{Estimated Target Position Accuracy} = \text{sensors to Target geometry} * \text{Estimated Range Error} \quad \text{(3.26)}$$

Measurement and position errors are usually assumed to be random variables with a mean value of zero and a variance of 1 (standard normal distribution). Therefore, its RMSE is calculated based on the error covariance matrix, and Equation (3.26) is modified accordingly and given in Equation (3.27).

$$\text{Estimated Target Position Accuracy} = \text{sensors to Target geometry} * \mathrm{Trace}\{\mathrm{E}[(\delta\mathrm{RDoA}_{\mathrm{m0}} - \mathrm{E}(\delta\mathrm{RDoA}_{\mathrm{m0}})(\delta\mathrm{RDoA}_{\mathrm{m0}} - \mathrm{E}(\delta\mathrm{RDoA}_{\mathrm{m0}}))^{\mathrm{T}}]\} \quad \text{(3.27)}$$

It is clear from Equation (3.26) that the geometric shape affects the position accuracy, although there is no uncertainty in the measurement (ie Estimated Range Error = identity matrix). This is shown in Figures 3.4 a and b, and the further deterioration of positioning accuracy due to the combined influence of measurement errors and geometric shapes is shown in Figures 3.4 c and d. This phenomenon is called Geometric Dilution of Precision (GDOP). Equation (3.26) also describes that the accuracy of the estimated position increases as the GDOP decreases, and vice versa. Therefore, it is very important to determine the best & optimized geometry configuration of the ground sensor to improve positioning accuracy, and this thesis also aims to achieve this goal.

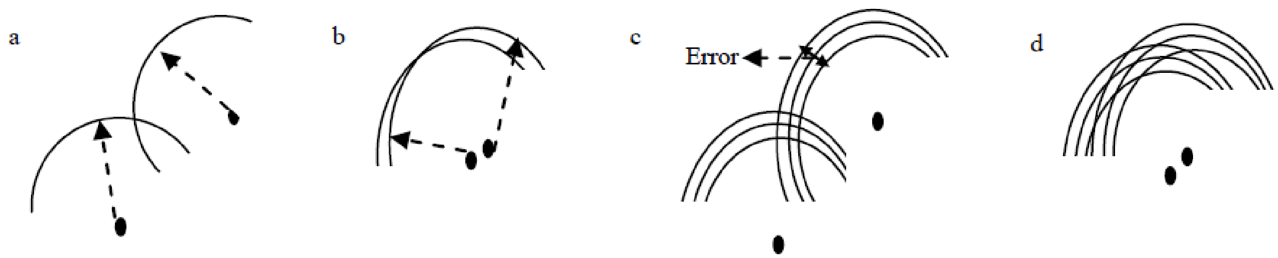


Figure 3. 4: The influence of sensor geometry on position accuracy (a) Long-distance high-precision sensors; b) Short-distance sensors with low accuracy; c) High-precision large-range sensors, inaccurate measurement; d) Short-distance sensors with poor accuracy and inaccurate measurement .

3.4.1. GDOP Coefficient for TDOA base Target systems

As it is mentioned previously, GDOP is defined as the coefficient that provides the effect of target sensor geometry on the relationship between RMSE in position estimate, δP_{xyz} to RMSE in measurements, $\delta RDoA_{m0}$ [29, 30]. The calculation of GDOP includes determining the effect of ground sensor geometry on position accuracy, δP_{xyz} and hence this thesis begins with Position Error Covariance matrix in deriving it. The term, $Cov\delta P_{xyz}$ in Equation (3.28) represents the position error covariance matrix.

$$Cov\delta P_{xyz} = E((\delta P_{xyz} - E(\delta P_{xyz}))(\delta P_{xyx} - E(\delta P_{xyz}))^T) \ldots\ldots \quad (3.28)$$

Here, E is the expectation (mean) operator and on assuming that mean of position error is zero, equation (3.28) written as:

$$Cov\delta P_{xyz} = E((\delta P_{xyz})\left(\delta P_{xyz}\right)^T) \ldots\ldots \quad (3.29)$$

Since,

$$\delta P_{xyz} = A^{-1}x\delta RDoA_{m0} = (A^TA)^{-1}A^Tx\delta RDoA_{m0} \ldots\ldots \quad (3.30)$$

Using equation (3.30) into (3.29) the Covariance matrix becomes:

$$Cov\delta P_{xyz} = E(((A^TA)^{-1}A^T\delta RDoA_{m0})(A^TA)^{-1}A^T\delta RDoA_{m0})^T \ldots\ldots \quad (3.31)$$

$$Cov\delta P_{xyz} = E(A^TA)^{-1}A^T\delta RDoA_{m0}\delta RDoA_{m0}{}^T((A^TA)^{-1}A^T)^T) \ldots\ldots \quad (3.32)$$

As the elements in matrix A are measured values, the expectation operator is only applied to measurement error matrix, $\delta RDoA_{m0}$ and equation (3.32) is represented as

$$Cov\delta P_{xyz} = (A^T A)^{-1} A^T ((A^T A)^{-1} A^T)^T E(\delta RDoA_{m0} \delta RDoA_{m0}{}^T) \ldots\ldots\ldots\ldots \text{(3.32)}$$

Here, $E(\delta RDoA_{m0} \delta RDoA_{m0}{}^T)$ represents the measurement error covariance matrix, $COV_{\delta RDoA_{m0}}$ with the assumption that mean of the measured error is zero. It is obvious from equation (3.14) that A is the only matrix that holds the information of target sensor geometry and therefore is also called as Geometry matrix. On further simplification equation (3.32) can be rewritten as:

$$Cov\delta P_{Rs} = (A^T A)^{-1} E(\delta RDoA_{m0} \delta RDoA_{m0}{}^T) \quad \text{Where, } (A^T A)^{-1}(A^T A) = 1 \ldots\ldots\ldots \text{(3.33)}$$

For the considered target localization system, any size of matrix A represented by nxm and hence the resultant matrix for $(A^T A)^{-1}$ becomes a square matrix. The trace of this matrix defines the GDOP coefficient, with estimated position error variances provided by diagonal elements.

$$Where\ ((A^T A)^{-1}) = \begin{bmatrix} Var_X & Cov_{XY} & Cov_{XZ} \\ Cov_{YX} & Var_Y & Cov_{YZ} \\ Cov_{ZX} & Cov_{ZY} & Var_Z \end{bmatrix} \ldots\ldots\ldots\ldots \text{(3.34)}$$

On comparing equation (3.32) with (3.27), the effect of sensor geometry or the coefficient of GDOP can be calculated as

$$GDOP = trace((A^T A)^{-1}) = \sqrt{Var_X + Var_Y + Var_Z} \ldots\ldots\ldots\ldots \text{(3.35)}$$

Elements outside the diagonal of the above matrix are considered independent and zero.

3.4.2. Multilateration error characteristics – analysis of geometrical error

In general, here practical horizontal and vertical components of the DOP are distinguished: the horizontal DOP (HDOP) describes the ratio of Horizontal position error to the TOA error, while the vertical DOP (VDOP) does the same for the vertical direction. A GDOP factor integrates all components into one figure.
As for the HDOP, it will achieve best results if the ground stations form a larger baseline & gives a better VDOP too.
The following figures illustrate the effect, different receiver geometries have on the distribution of the horizontal position error. Figure 3-5 shows two basic configurations as a triangle and a square. Ground stations are marked by a circled blue cross; the color corresponds to different DOP ranges (as defined within the legend below each picture).

The area of good coverage is generally located in the center. It extends slightly beyond the lines connecting the ground stations. Outside the surrounded area, accuracy degrades, along the extended connecting line beyond each ground station and the multilateration solution becomes inaccurate quickly.

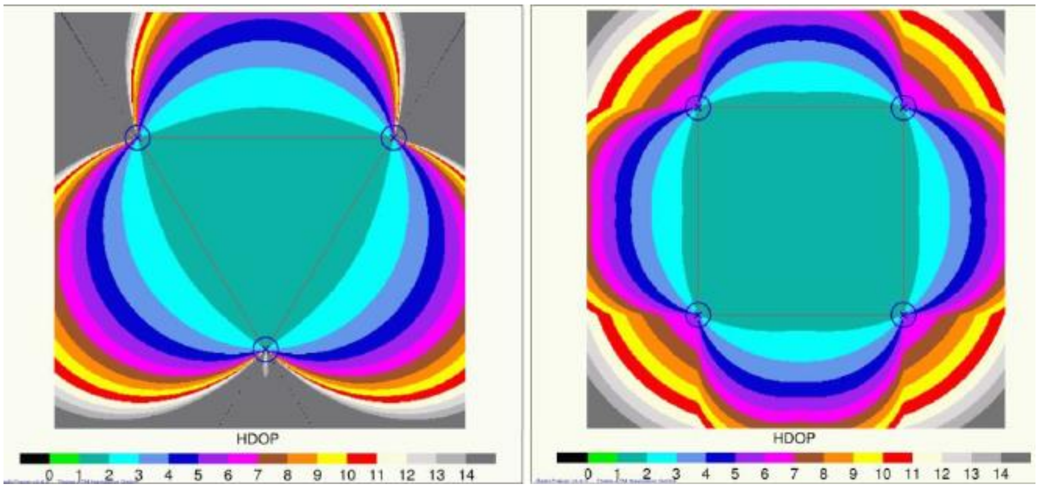
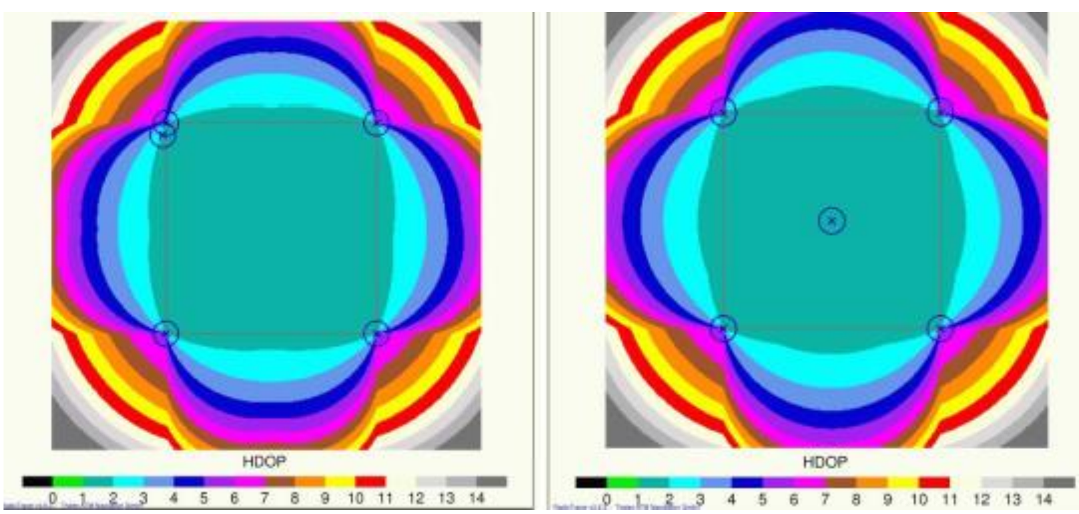


Figure 3. 5: Basic HDOP distribution in case of a triangular or square receiver setup

Additional ground stations have a potential to improve the coverage only if they are placed in a suitable geometry as illustrated in Figure 3-6. They contribute to an improved or larger coverage significantly only if they are placed outside the common environment. For redundancy reasons it may be certainly useful to have additional ground stations also inside this area.

Larger baselines between ground stations generate better results into the direction perpendicular to the baseline.



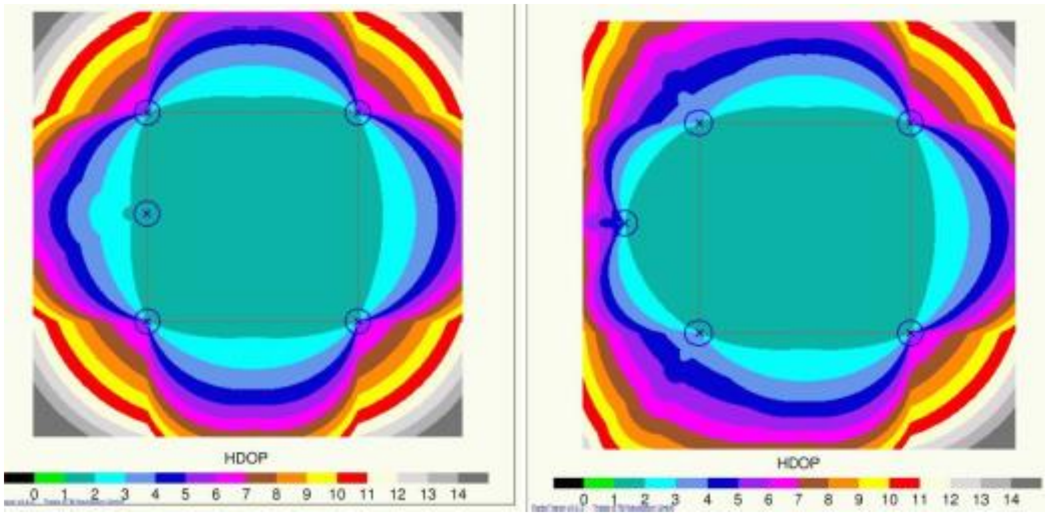


Figure 3. 6: Square configurations with a fifth ground station

If one of the ground stations cannot provide a valid contribution, e.g. because it is hidden behind a temporary obstacle (holding aircraft) or there is an equipment failure, the coverage could change exceptionally as shown in Figure 2.7.

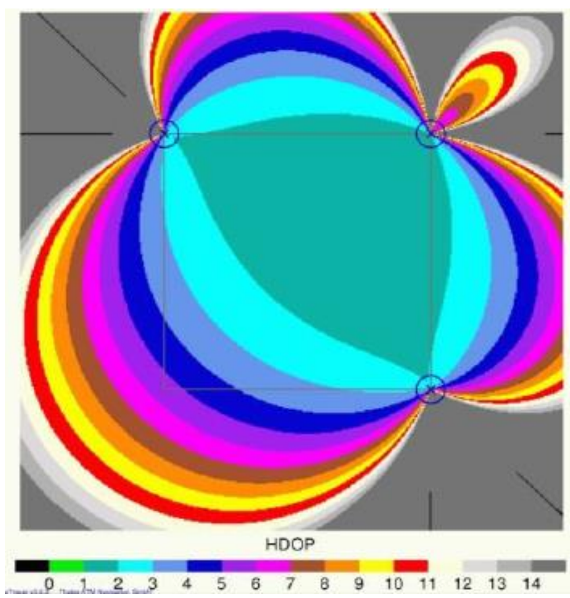


Figure 3. 7: DOP distribution of square setup in case of one receiver not contributing

Chapter 4

4. Simulation results and discussion

In this chapter, different MLAT simulation results in the case of Addis Ababa are presented. The chapter starts with the description of the GSs and simulation parameters for the scenarios under study. Then, the simulation and analysis of results of the signal coverage are presented on different scenario, especially on flight level ASL150ft, 1000ft, 2000ft, 4000ft, 5000ft, 10000ft, 20000ft, 30000ft and 40000ft.from the model for a set of different scenarios found in the literature is provided.

The system design and a provisional performance analysis were carried out using 'Radio Tracer' and other computer simulation tools. 'Radio Tracer' is an interactive computer simulation tool based on ray-tracing algorithms and a coarse environment model (terrain model or airport buildings model).

4.1. Target location and plot extraction

The target position is calculated in Cartesian coordinates, and the X, Y coordinates are calculated using either the measured height or an assumed target height and apply a stereographical projection technique for the final 3D to 2D conversion.

The operational status of the sensors is also taken into account for this function: if a sensor becomes non-operational (for any reason), this is removed from the available sensor list to be used by the plot Extraction thus the functionality and integrity of the extraction function is preserved. In addition, if enough measurements are available, the CPF can enable a specific Fault Detection and Exclusion (FDE) method to evaluate at run-time the target plot solution integrity and identify/isolate the faulty measurements (due to multipath or only reflected signal received). This procedure allows the system to obtain the highest position accuracy in the lowest computation time while guaranteeing the continuity of target plot generation.

Furthermore, when hybrid Multilateration is being used in Active mode (Multistatic ranging functionality), this function is able to perform SSR-like distance measuring and improve target accuracy in zones with bad geometry (e.g. far from the sensor array). The distance from the sensor array in which the Hybrid Multilateration is used can be configurable. The hybrid technique consists on implementing an innovative algorithm that considers each interrogator/receiver pair like a bi-static radar and using the corresponding weighted elliptical/round trip delay equation into the hyperbolic sets of equation together with the estimation of other parameters limiting the position accuracy; this will allow to limit the bad accuracy trend with the distance from the sensor array. A comparison graph showing how this improved technique will mitigate the geometry effects on the target accuracy is shown in the following picture.

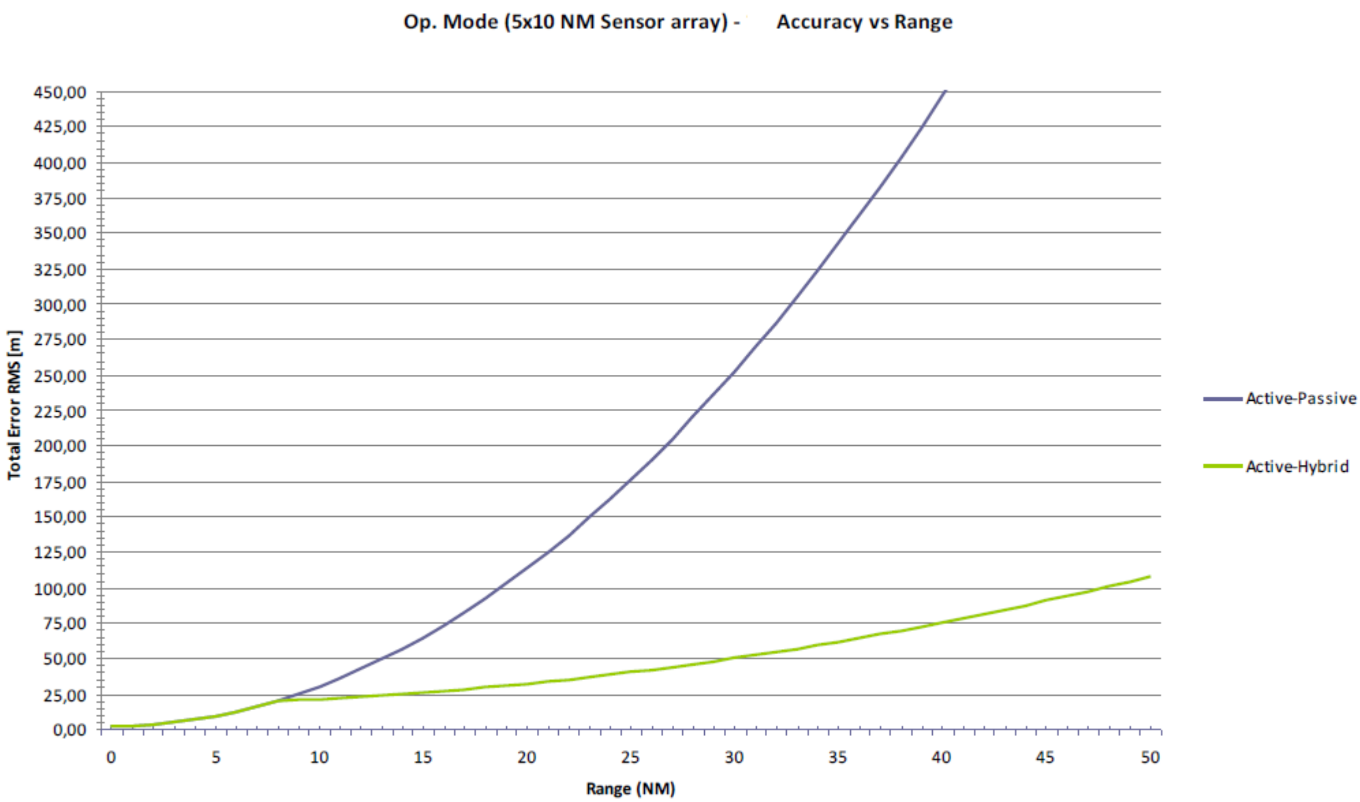


Figure 4. 1: MLAT accuracy Vs Range

4.2. Possible influence of near-field obstacles to ads-b receiver coverage

The optimal location of multilateration and ADS-B ground surveillance antenna is the top position at an antenna mast. In real installations ideal antenna positions are sometimes not available due to site constraints (e.g. the top position is occupied by other equipment such as rotating SSR antenna etc.).

In such cases the multilateration and ADS-B ground surveillance antennas can be mounted at an arm of 1 – 1.5 m length on a side of the tower. Anyhow such installation may have drawbacks since the mast will be in the near-field of the antenna and may adversely influence the antenna pattern. A theoretical example of the influence of the antenna pattern through a nearby mast is shown in Figure (below). The undisturbed antenna pattern is Omni-directional. The red, blue and yellow patterns show the changed antenna pattern if installed on a side of a lattice mast in a shape of a triangle of 50 cm leg length.

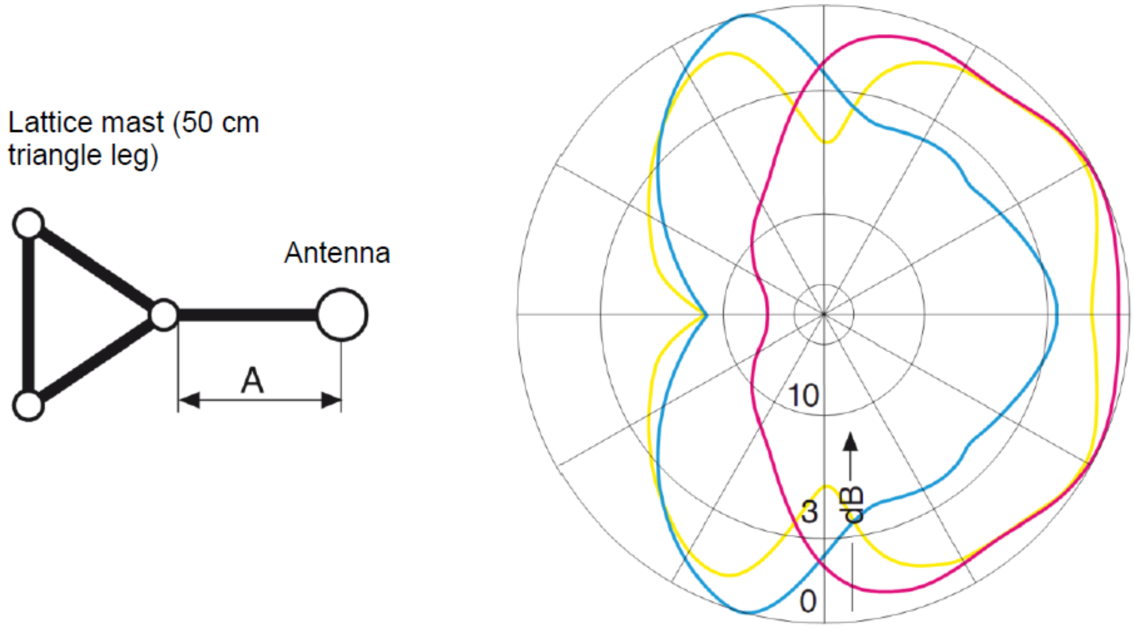


Figure 4. 2: Examples of antenna pattern change for omni-directional antennas mounted on a side of a lattice mast (red pattern: A = 0.25λ, blue pattern: A=0.5λ, yellow pattern: A=0.75λ)

The influence of the near-field obstacles cannot be modeled in a computer simulation with maintainable efforts. The computer simulations of the ADS-B coverage are to be understood as macro-type simulations which consider terrain and atmospheric constrains with human-made structures like buildings, masts etc. being not considered.

4.3. MLAT site selection criteria

The main function of every MLAT system is the location function allowing accurate position information to be calculated for cooperative targets equipped with Mode A/C/S SSR transponders.

The location function of a MLAT system strongly depends on the selection of the sites for the remote sensors/ground stations. The site selection is a stepwise process based upon a detailed visual and graphical topography analysis as well as upon computer simulations of the multilateration performance. In a first step a pre-selection of possible receiver sites (Ground Station – Receiver, GSR) has to be done.

The second step is aimed at optimization of the receiver sites by simulation of different configurations of the receiver sites and provides a short list selection of GSR sites. An optimal ground station configuration should provide a direct (multiple) line of sight (LOS) to each point of the coverage volume from the ground stations. The LOS can be affected by shadowing effects due to terrain or large objects such as buildings. As a rule, if the LOS is provided to each point of a height level, it is also provided to all higher levels up to the limit of the antenna coverage. Therefore the present sitting samples demonstrates the fulfillment of this thesis for the lowest required height levels. The LOS and the MLAT performance for higher levels can be assumed as better or at least equal.

The third step but not more focused on this thesis provides the decision what sites should be used for aircraft transponder interrogation within the required coverage volumes. These interrogator ground stations are called GST (Ground Station – Transmitter). Again, an optimal GST configuration should provide a direct (multiple) line of sight (LOS) to each point of the coverage volume from the GSTs.

4.3.1. Link budget for MLAT simulations

The following table presents the minimum transponder, interrogator & GSR capability and link budget used to model the system performance.

Table 4. 1: Minimum Transponder Model

Description	**Assumption**
Effective RX azimuth aperture	360 °
Receiver Antenna Gain	3 dB (6 dB on off airport sites)
Receiver Cable Loss	Site Specific
Interrogator Output Power	1000 W
Interrogator Antenna Gain	3 dB (6 dB on of airport sites)
Interrogator Cable Loss	Site Specific
Transponder Output Power	125 W
Transponder Antenna Gain	0 dB
Transponder Sensitivity (MTL)	-73 dBm

The above budget calculation is a worst case. For strong Mode A/C/S signals and for stable time calibration data links, the factors “TOA measurement accuracy” as well as “time synchronization accuracy” can be expected to be significantly smaller.
In addition plot validation techniques during the multilateration target processing especially at lower output rates will lead to a better MLAT location performance than that expected for single shot location measurements.

4.3.2. System Coverage Analysis

Here the coverage's analysis presented on this thesis is by considering the requirement for surveillance, assessing the constraints and the exploitation of in-site logistic infrastructures that can impact on the definition of a multilateration layout and then drive the baseline assumptions to be taken to propose a specific sensor and multilateration Processing deployment in the coverage area.
The proposed coverage analysis that has been evaluated on this thesis takes into account the requirements and assumption of choices according to the table 4.2.
The same accuracy as defined above shall be maintained during system degradation by loss of one receiver station (N-1).
According to researches and standard EUROCONTROL documents like ED-117 and ED-142, MLAT/ADS-B surveillance service in the Terminal Management Area (TMA) to a distance of 60 NM, at a height greater than 10000 m (32,800 feet) ASL (line of site permitting) and aircraft and other mobile units like vehicles on the airport surface within a full 360 degrees circumference should work with the following performances [2, 32]:

Table 4. 2: MLAT Position accuracy Requirements

Application	AREA	Horizontal position Error (HPE)	Confidence Level	Probability of Detection (Pd)
Airport	Maneuvering (APRON, TAXIWAY, RUNWAY)	< 7.5 m	95%	>99.9% (2 sec. period)
		< 12 m	99%	>99.9% (2 sec. period)
	Stand	< 20 m (any 5 second period)	95%	>99.9% (5 sec. period)
	Approach up to 2.5 NM from RWY	< 20 m	95%	>99.9% (2 sec. period)
	Approach up to 2.5 NM - 5NM from RWY	< 40 m	95%	>99.9% (2 sec. period)
TMA	Up to 60 NM from Airport	< 150 m	RMS	>97% (4 sec. period)

The following diagrams show an evaluation of the results of a test drive over the maneuvering area and parking stands of Addis Ababa bole international airport.

Figure 4. 3: AA Bole International Airport

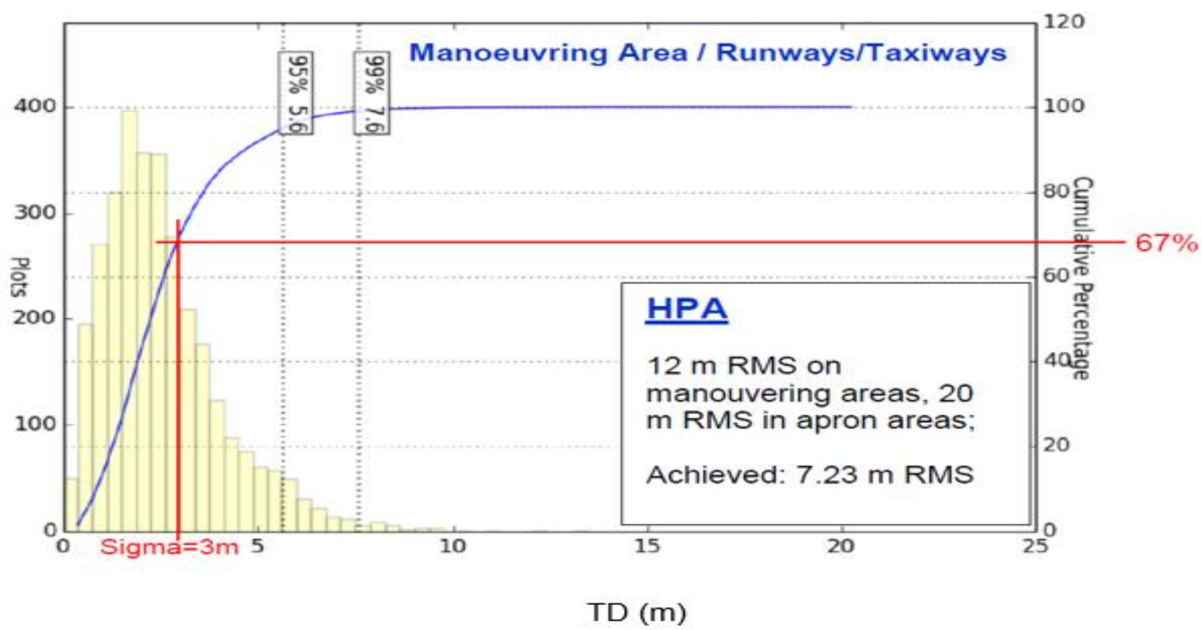


Figure 4. 4: Horizontal Position Accuracy (HPA) Evaluation – Maneuvering Area / Runways/Taxiways

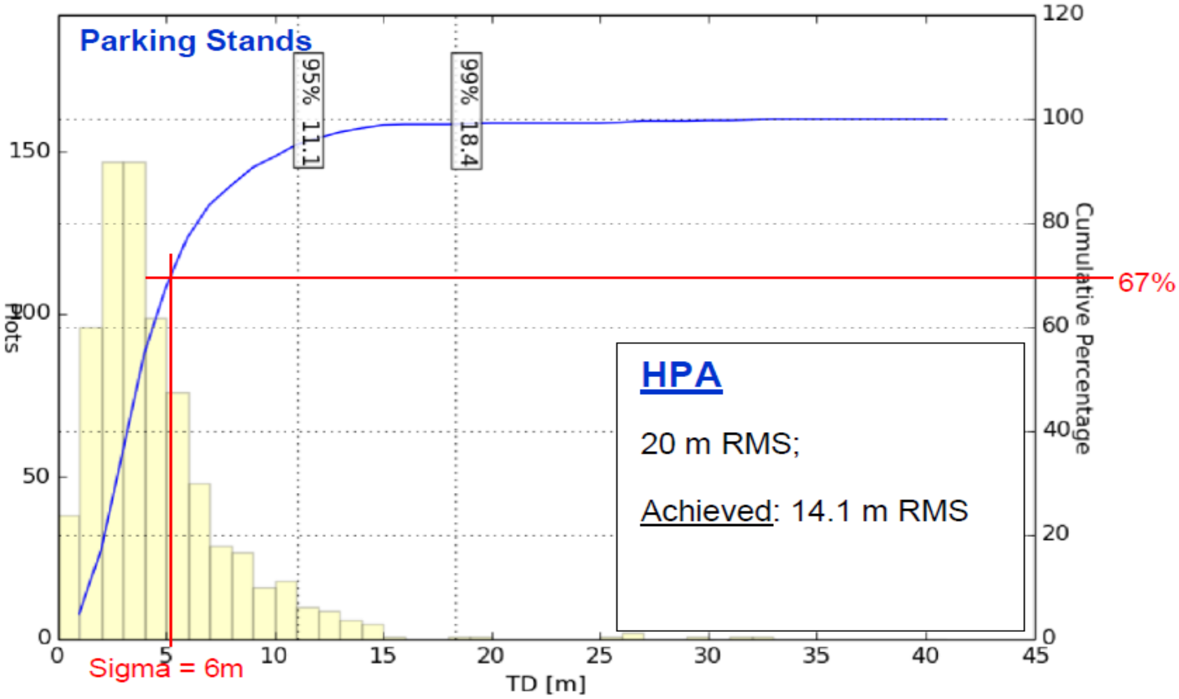


Figure 4. 5: HPA Evaluation – Parking Stands

This thesis uses **digital terrain model tool** data according to **SRTM3** (90 x 90 m cell) for a MLAT simulation.

The simulations presented on this thesis have been done by considering the following parameters:

- 'K Factor' (Earth Radius Correction) equal to 1.33333;
- A total cable loss of 3 dB for each MLAT sensor site;
- dBs-5100A high gain antenna pattern for each MLAT sensor site;
- The MLAT receivers downlink budget in the simulations considers the worst case minimally compliant SSR transponder transmission power, i.e. 70 W (48.5 dBm) below 150 FL and 125 W (51 dBm) above 150 FL, with 0 dB airborne antenna gain;
- The MLAT interrogators uplink budget in the simulations considers the worst case minimally compliant SSR transponder receiver sensitivity, i.e. -69 dBm, with 0 dB airborne antenna gain;

Another simulation tool which is used for MLAT simulations is Air Navigation and Airport System simulation (AIRNAS) framework is a multi-disciplinary integrated design environment based on CAD and simulation techniques capable of concurrently dealing with problems related to flight procedure design, airspace management, performance evaluation and deployment of C/N/S systems. Furthermore, other MLAT and ADS-B supporting tools like DPTMLAT CSCI java script software tool and CPFEMU also used

to configure the communication parameters (network and RX parameters) of the ground sensors.
The values to be set on the sensors must correspond with those in the Central Processing Facility (CPF) configuration files.

The related 3D modelingof Addis Ababa bole international airport used in the simulation tool is depicted in the following picture.

Figure 4. 6: Modeling used in the simulations

In this thesis aeronautical multilateration system of the Addis Ababa region is composed of 10 ground stations, Table 4.3, shows their positions.
For this thesis, the proposed Coverage Analysis investigates the optimum signal coverage required by the standard for a better performance and accuracy.
The following table used to show the proposed geographical location of ground station receivers presented by this thesis.

Table 4. 3: Sensors (Antenna) site location

Sensor site name	Antenna type	GPS Coordinate	Altitude (feet)
S01 – TWR	dBs-5100A	8°58'54.94"N; 38°47'37.40"E.	2329
S02 Hangar	>>	8°58'45.01"N; 38°47'3.56"E.	2331
S03 – GP25R	>>	8°58'57.80"N; 38°48'30.48"E.	2323
S04 – GP25L	>>	8°58'44.17"N; 38°48'39.84"E.	2313
S05	>>	8°59'5.31"N; 38°48'56.02"E.	2302
S06	>>	8°58'52.47"N; 38°49'8.76"E	2300
S07 – LOC25L	>>	8°58'17.46"N; 38°46'47.71"E.	2296
S08 - Radar	>>	8°58'12.26"N; 38°47'29.82"E.	2320
S09 - Furi	>>	8°52'59.83"N; 38°41'10.93"E.	2835
S10 - Entoto	>>	9°6'17.00"N; 38°49'1.00"E.	3174

The maximum error calculation associated with the multilateration system at the Addis Ababa airport fits the situation in which all the information related to the used ground stations and the flight routes from MLAT and ADS-B systems are available, as explained in Chapter 3.

4.3.3. MLAT System Surface Coverage Accuracy

The following figures show the coverage and accuracy of the preliminary sites study of the ground sensors with the proposed deployment in N-1 scenario.

This pictures shows the worst case study, this means that in case of failure of any receiver station the coverage is guaranteed with this accuracy.

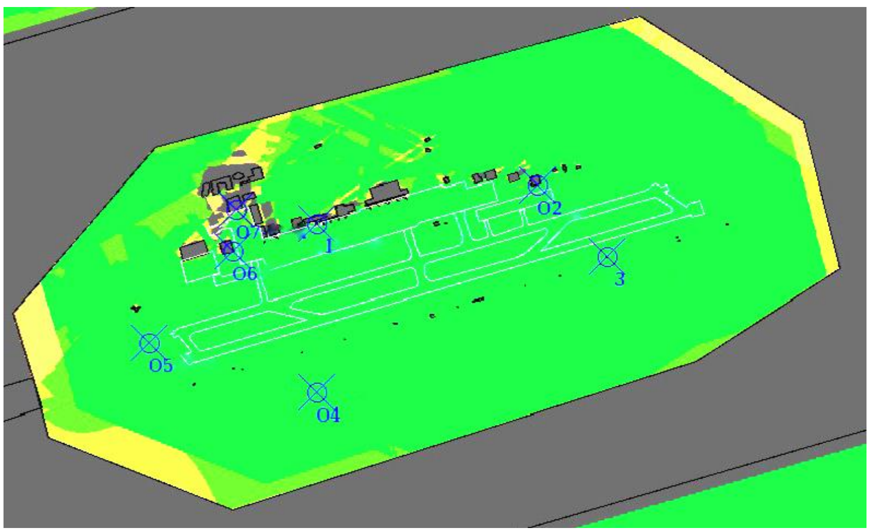


Figure 4. 7: Accuracy coverage at 4 m AGL

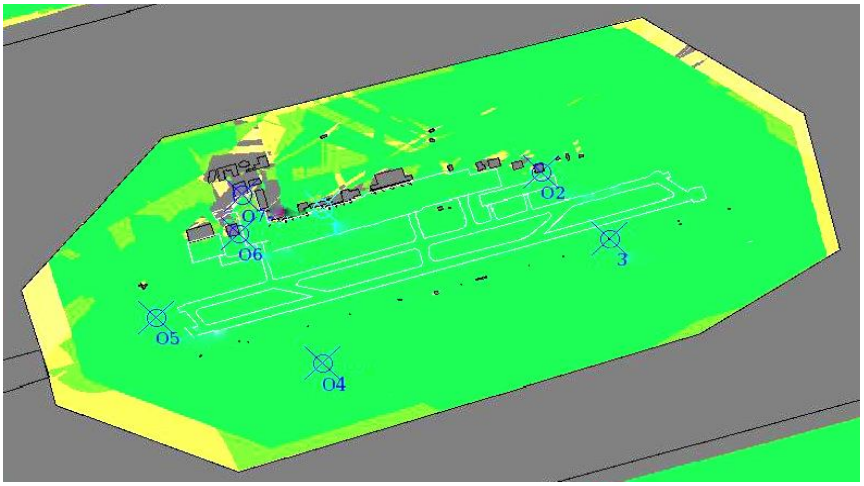


Figure 4. 8: Accuracy coverage at 4 m AGL – GS01 out Of Operation

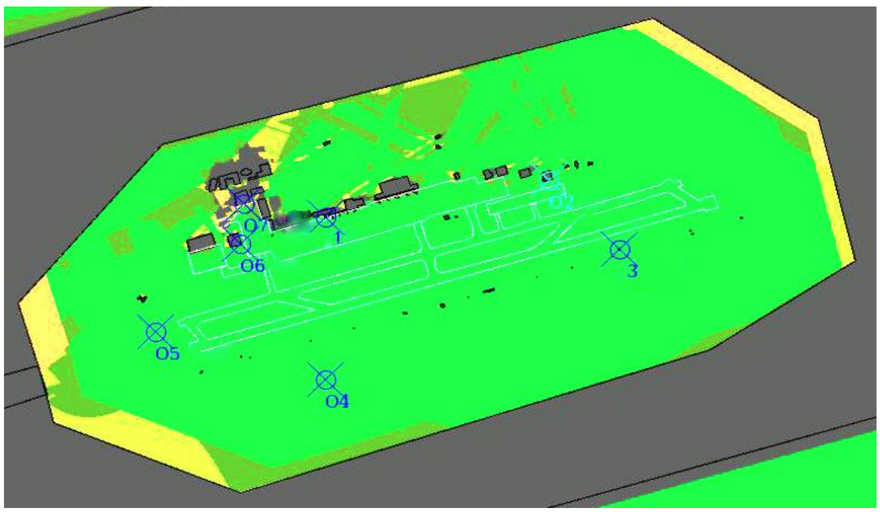


Figure 4. 9: Accuracy coverage at 4 m AGL – GS02 out Of Operation

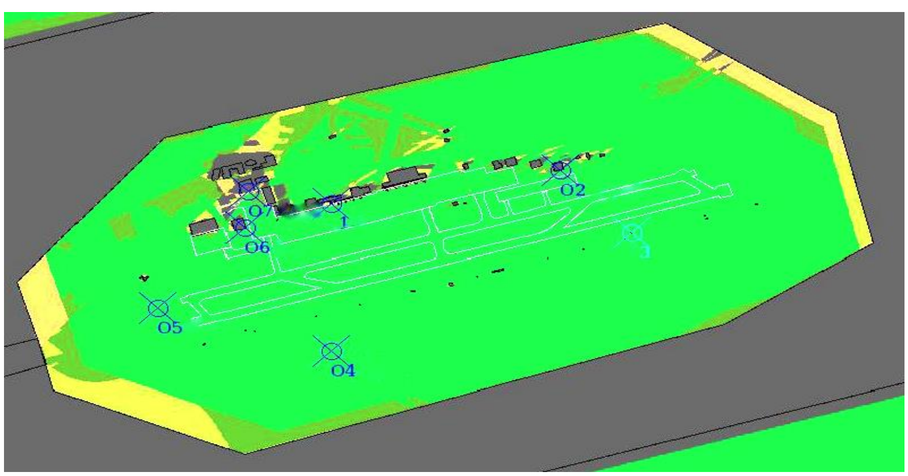


Figure 4. 10: Accuracy coverage at 4 m AGL – GS03 out Of Operation

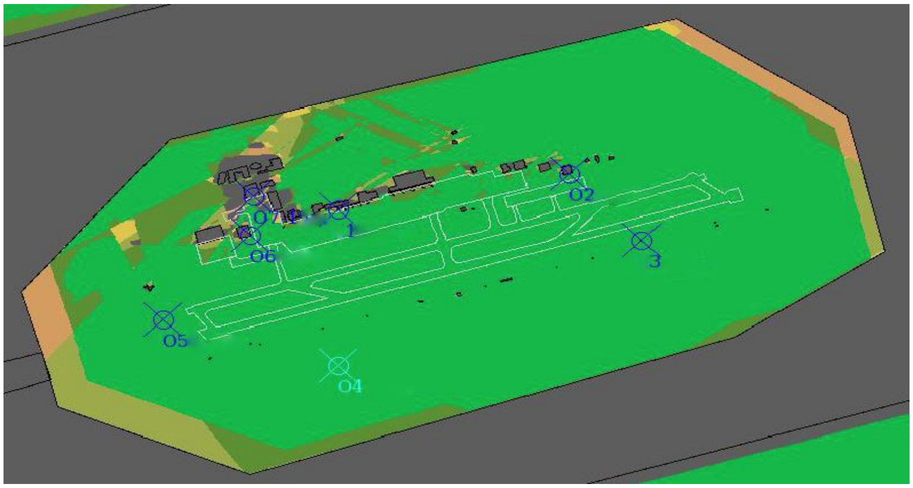


Figure 4. 11: Accuracy coverage at 4 m AGL – GS04 out Of Operation

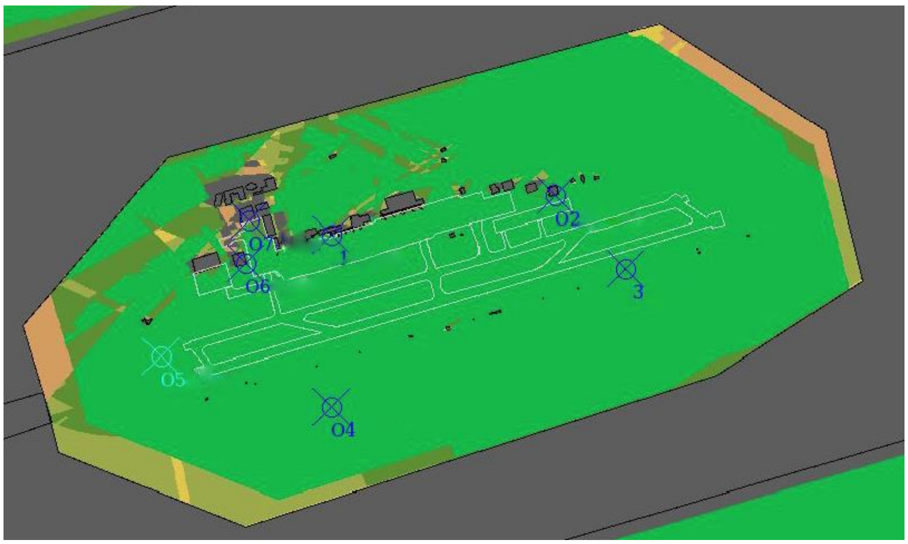


Figure 4. 12: Accuracy coverage at 4 m AGL – GS05 out Of Operation

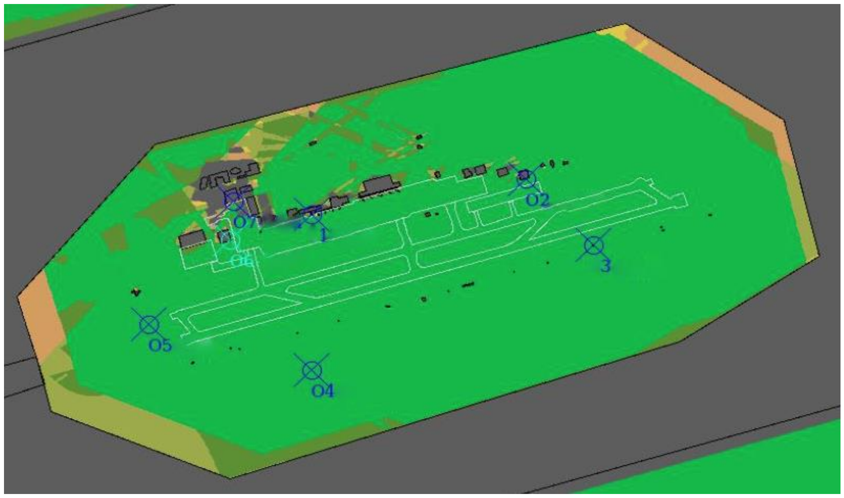


Figure 4. 13: Accuracy coverage at 4 m AGL – GS06out Of Operation

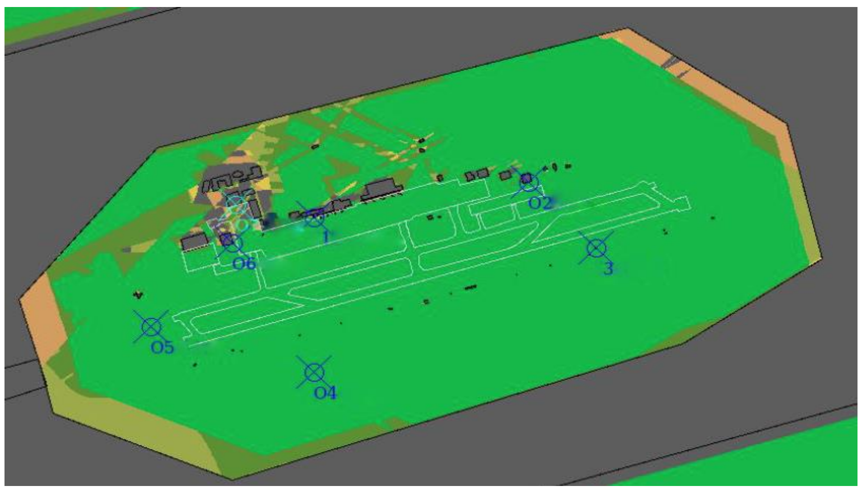


Figure 4. 14: Accuracy coverage at 4 m AGL – GS07 out Of Operation

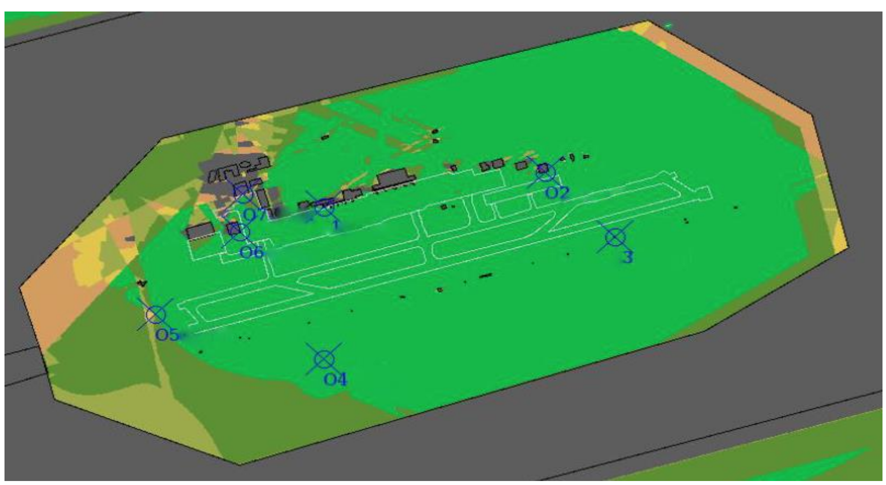


Figure 4. 15: Accuracy coverage at 4 m AGL – GS08 out Of Operation

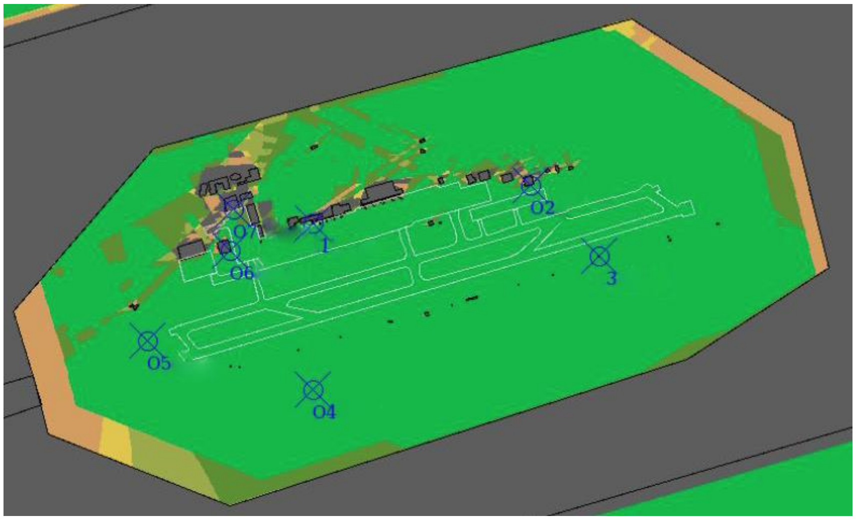


Figure 4. 16: Accuracy coverage at 4 m AGL – GS09 out Of Operation

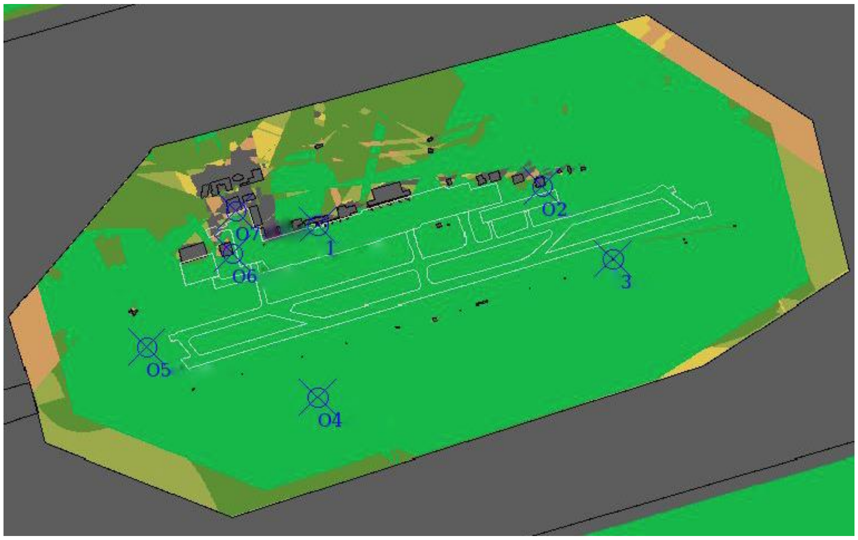


Figure 4. 17: Accuracy coverage at 4 m AGL – GS10 out Of Operation

4.3.4. MLAT COVERAGE DIAGRAMS

As shown in the figure below, relevant air route structure available from Jeppesen charts have been overlaid to multilateration coverage diagrams at 10000 feet ASL.

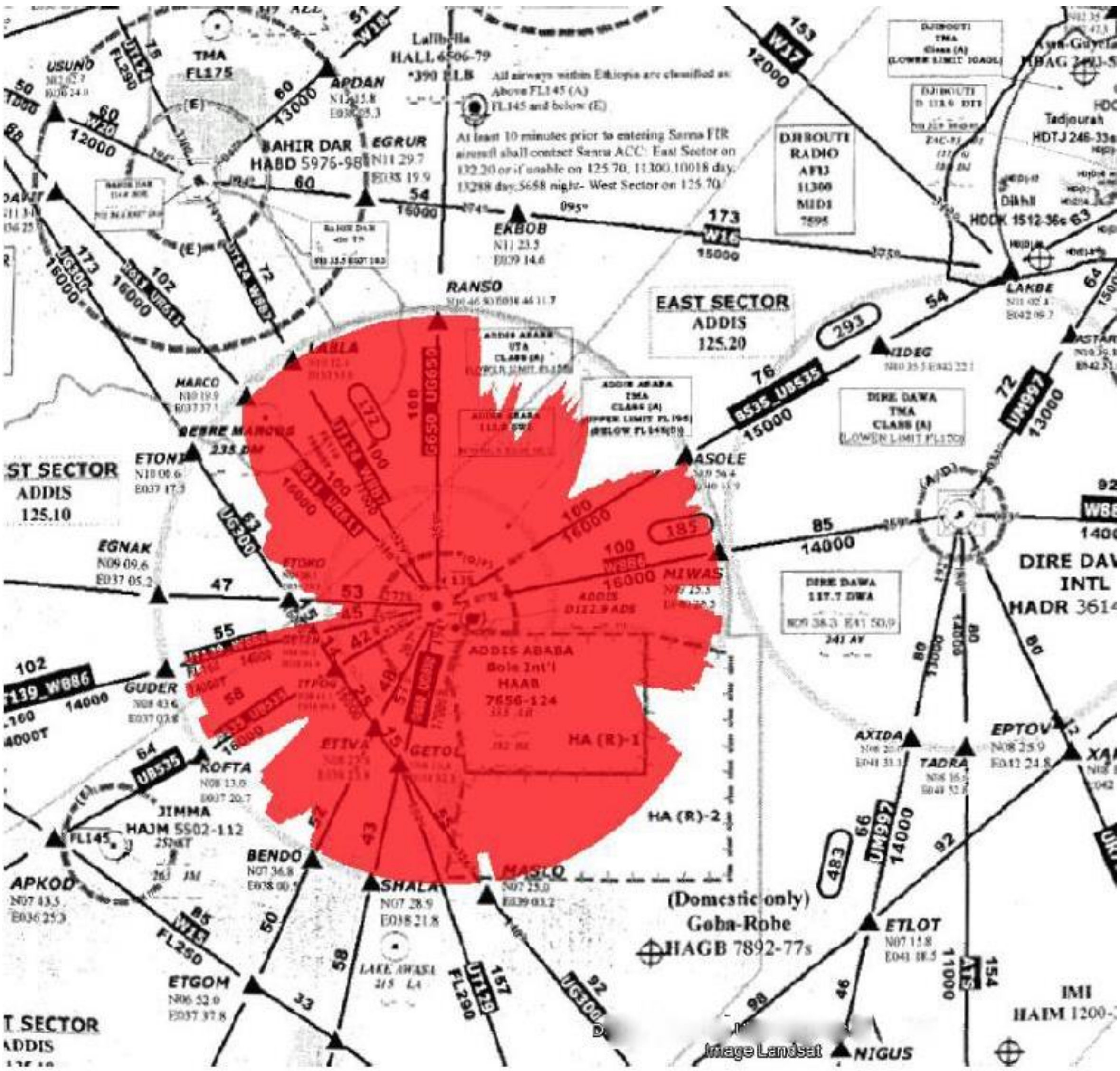


Figure 4. 18: MLAT TMA coverage @ 10000 feet ASL (Jeppesen overlaid)

The MLAT coverage diagrams have been overlapped to the existing SSR coverage in order to compare with multilateration and current SSR coverage; SSR coverage is displayed as white color style contour in the diagrams, from 250 feet to 30000 feet ASL according to the requirement.

Where applicable final approach paths and range rings at 60 NM from the airport, as black color style contour in the diagrams, are also overlapped to the multilateration relevant diagrams.
For the Airport and TMA application performances provided in the below coverage diagrams see Table 4.2 MLAT Performance Requirement

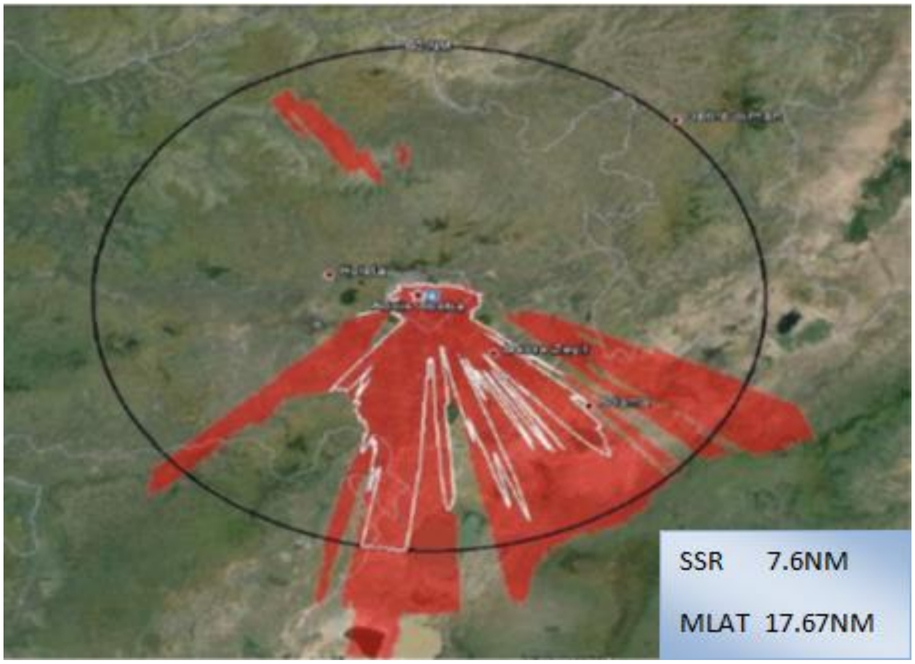


Figure 4. 19: Coverage at 250 feet ASL

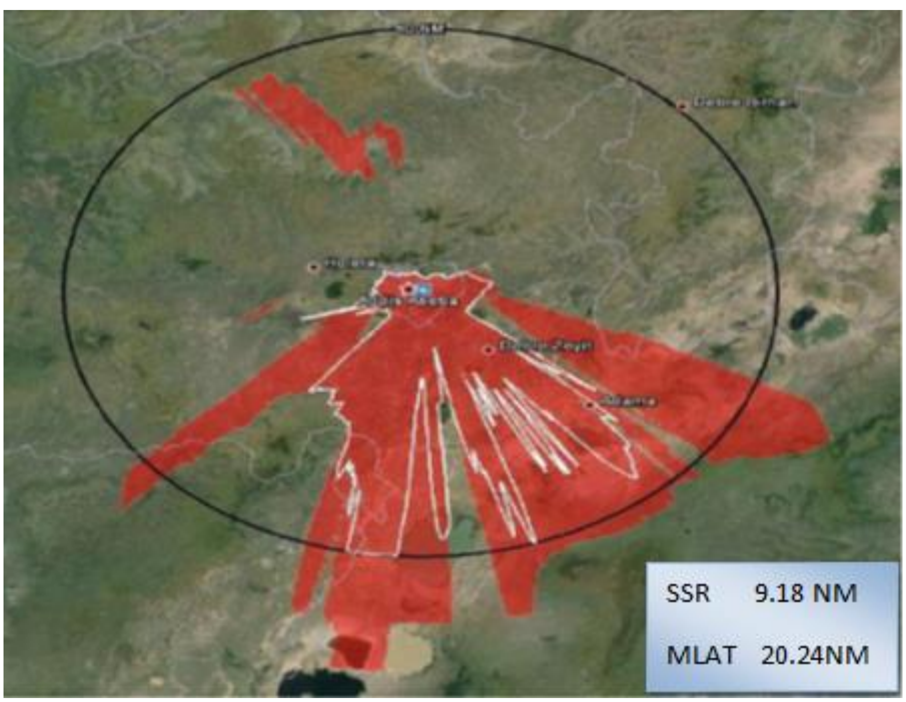


Figure 4. 20: Coverage at 500 feet ASL

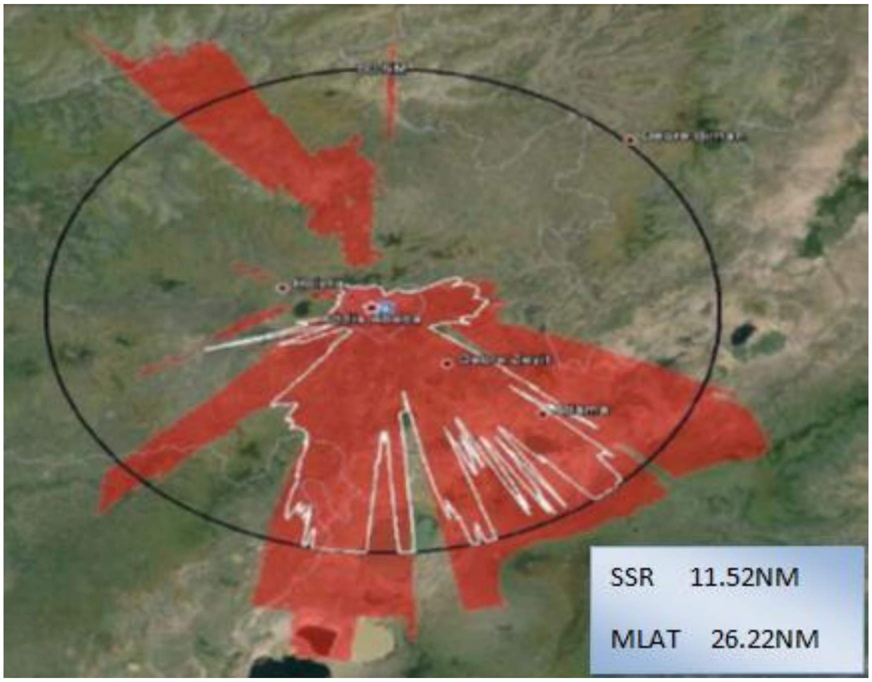


Figure 4. 21: Coverage at 1000 feet ASL

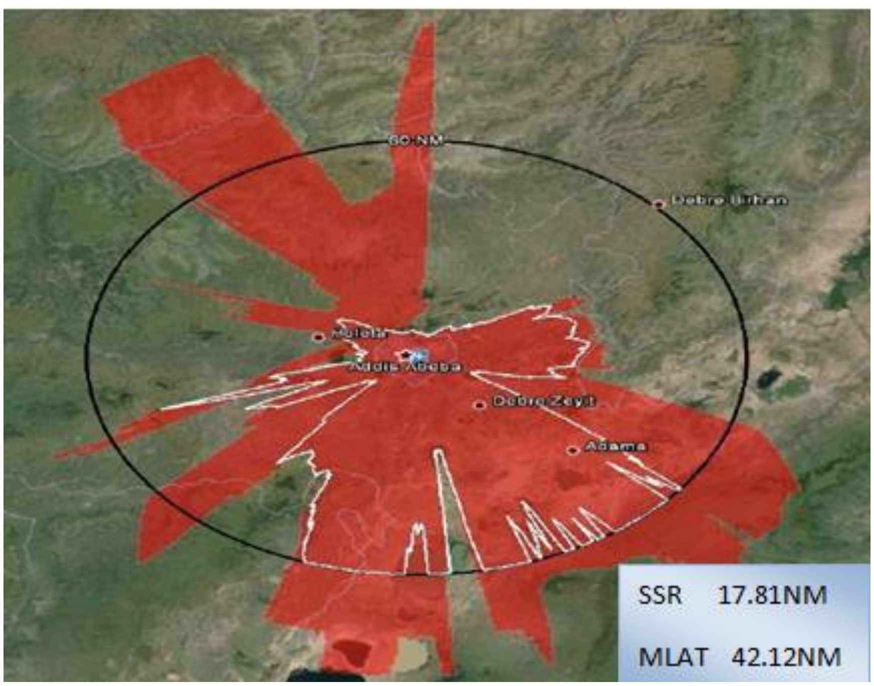


Figure 4. 22: Coverage at 2000 feet ASL

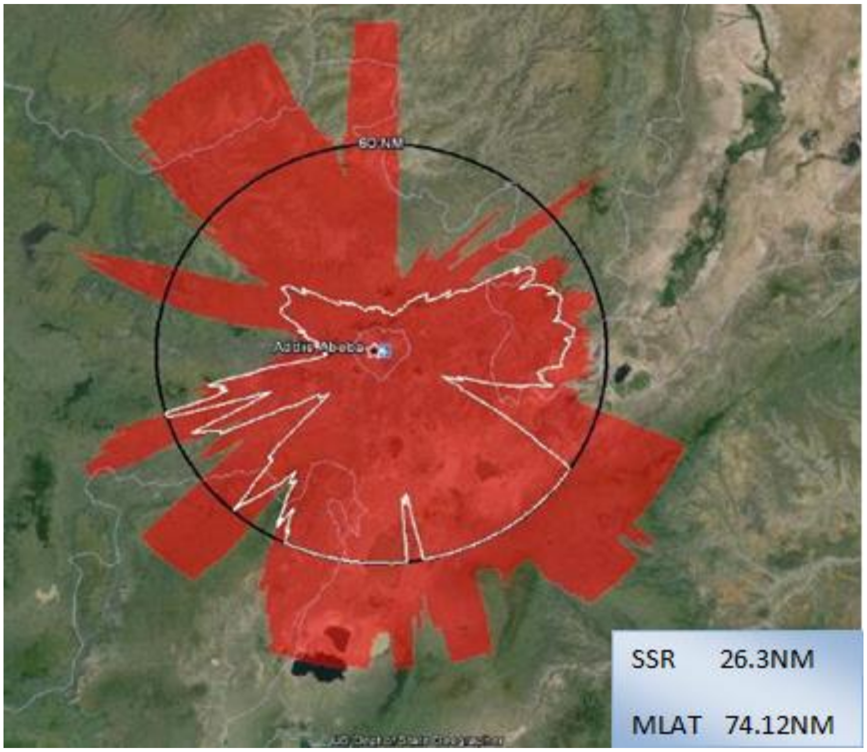


Figure 4. 23: Coverage at 4000 feet ASL

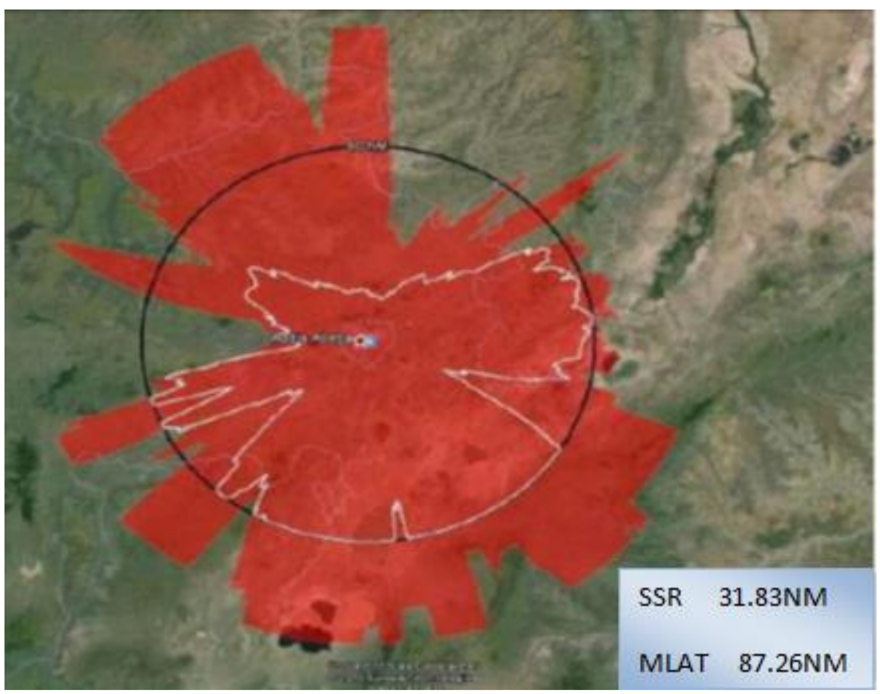


Figure 4. 24: Coverage at 5000 feet ASL

Fig. 8d: Coverage at 2000 feet ASL

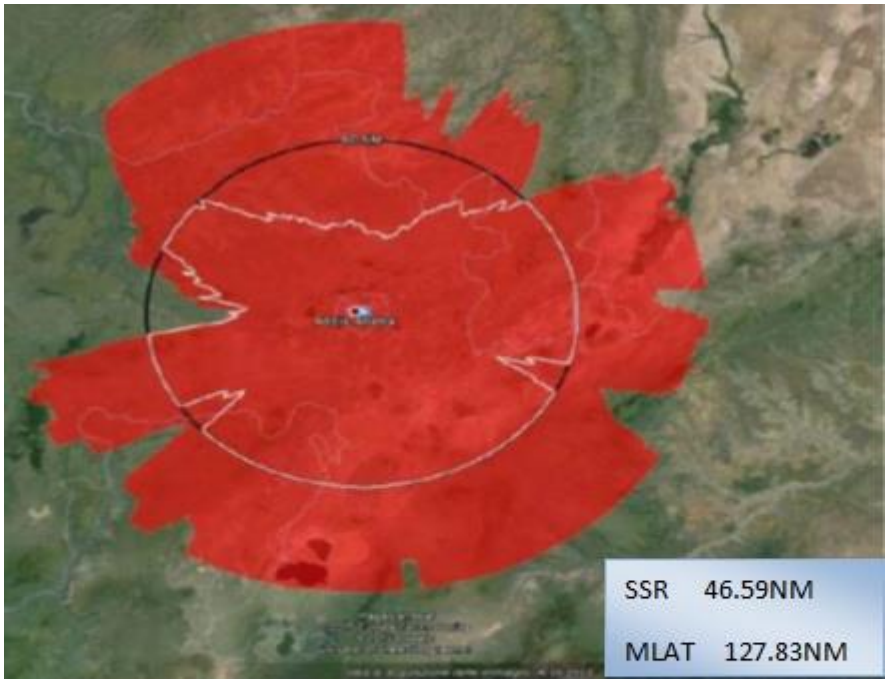


Figure 4. 25: Coverage at 10000 feet ASL

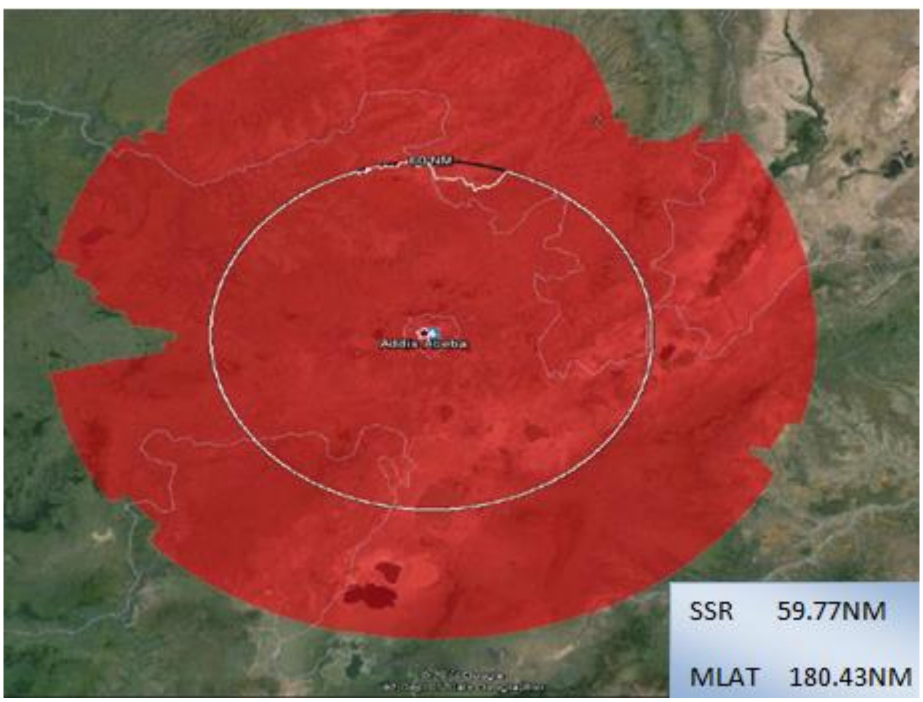


Figure 4. 26: Coverage at 20000 feet ASL

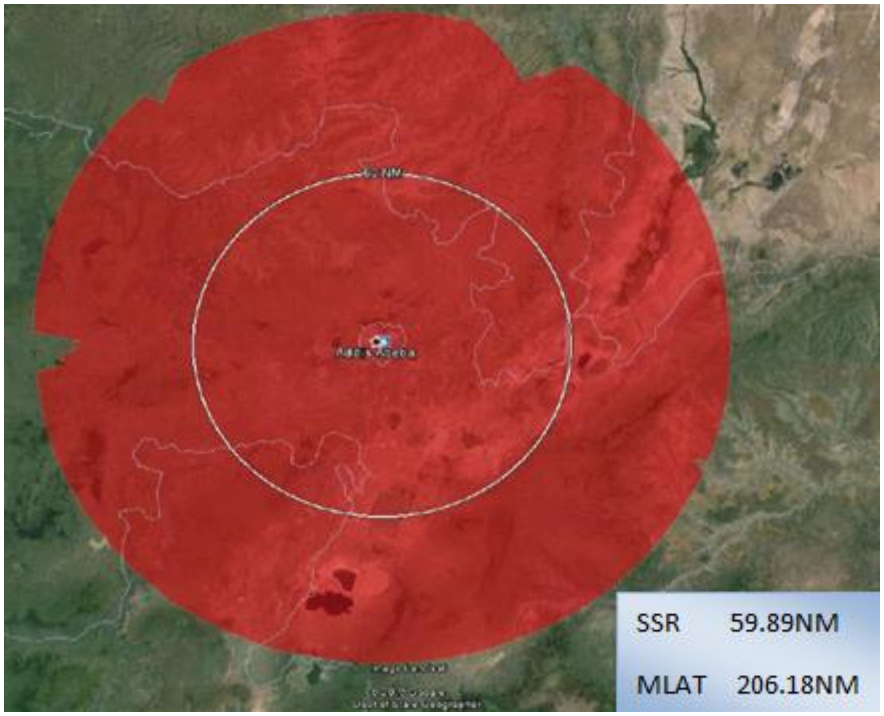


Figure 4. 27: Coverage at 30000 feet ASL

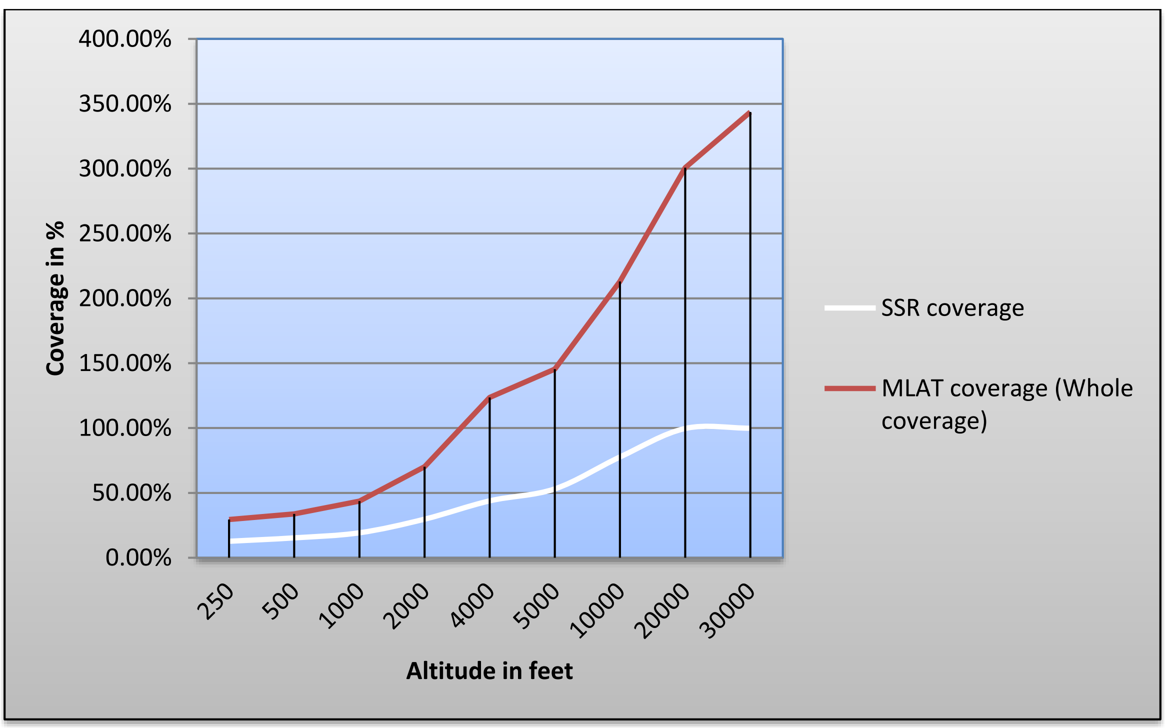


Figure 4. 28: Statistical analysis between altitude of an aircraft & coverage in percentage

Table 4. 4: Comparison of coverage for different flight levels

	Aircraft altitude (in feet)								
	250	500	1000	2000	4000	5000	10000	20000	30000
SSR coverage in NM	7.6	9.18	11.52	17.81	26.3	31.83	46.59	59.77	59.89
MLAT coverage (within 60NM)	16.5	17.7	21.19	29.33	45.52	50.39	57.06	60	60
MLAT (Whole coverage)	17.67	20.24	26.22	42.12	74.12	87.26	127.83	180.43	206.18

The above coverage analysis modeling assessment is done by considering the heights of the major buildings around the airport terminal area and terrain as an obstacle.

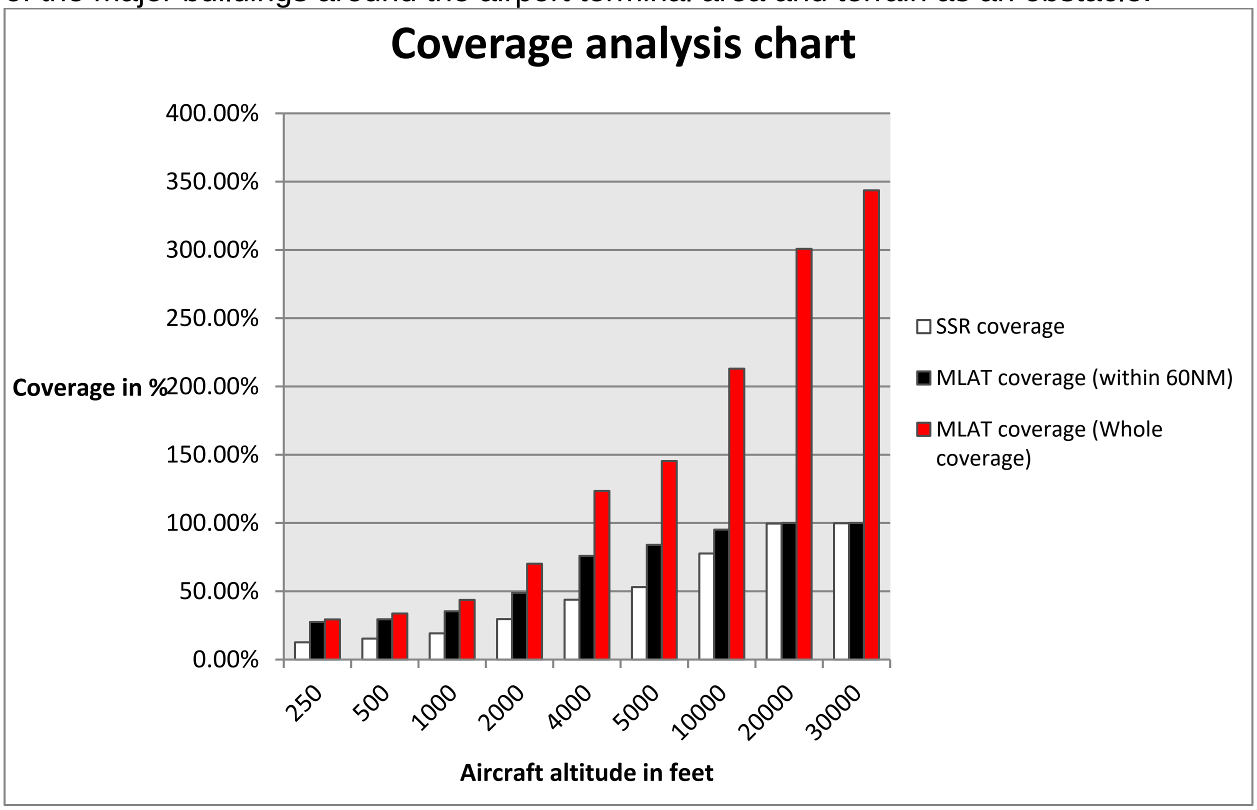


Figure 4. 29: Coverage analysis chart between SSR & MLAT

According the Figure 4.29, MLAT has better coverage than SSR, and it shows that as the height of flight the increases, more area will be covered.

Since this study is focused on approach MLAT, 60 NM of the air space should be covered at 10000 ft. On table 4.4 at 10000 ft. the SSR covers 46.59 NM, while the MLAT covers 127.83 NM.

Chapter 5

5. Conclusions and Recommendations for Future Work

5.1. Conclusions

This thesis is aimed to examine the feasibility study of aeronautical MLAT and has shown its potential benefits by using simple ground station dipole antennas, ADS-B and other passive interrogators as it provides an attractive and practical solution in order to get high performance with lesser cost on detecting an aircraft on approach area especially on TMA of Addis Ababa Bole international airport.

The diversity is realized by positioning a number of ground station receivers around the terminal area of the airport and other additional two selected areas around AA city. Passive type PSR and an active SSR used in hybrid way for interrogation signals specifically for A/C/S mode aircraft transponders.

Regarding the set of ground stations analysis for the Bole international airport, we can conclude that the number of ground receiver stations used for the implementation of the TDOA algorithm varies throughout the flight route, but this variation follows with the same fashion: the number of ground receiver station increases as the distance between the airplane and the reference ground station deceases.

On this thesis we can also observe that if the MLAT sensors were be sited with (n-1) redundancy so that it is possible to ensure the required level of accuracy & good probability of detection during the time of failure or outage of sensor for maintenance.

Even if the scope of this thesis is basically focused on the approach area of surveillance system (≤ 60 NM coverage area), the observed analysis shows that using this 10 ground receiver sensors, it is possible to detect the target which is found up to 200NM.

According to the coverage analysis shown in chapter 4, the capability to detect and process in all movement areas around the approach of Addis Ababa Bole International Airport critical zones, such us runways, taxiways and apron area has more coverage even on N-1 scenario.

The result from the analysis observed that, because the goal is to determine the set of ground stations that provide the best result for each of the airplane's positions in the route under analysis. We can conclude that the number of ground stations has a direct influence on the volume of the uncertainty area, since as the number of ground stations increases, the size of the uncertainty area decreases. Furthermore, as the distance between the airplane and the reference ground station decreases, the error value also decreases.

The location of the ground station receivers is crucial to the performance. Even if it is ideal, the best performance was achieved when the ground station receivers are located at equal distance from the source and the destination or slightly closer to the source. In general the ground receivers should not be too far from the source and the center to get good position estimation.

In general, from the result of the analysis, it is possible to validate the following hypotheses:

- ✈ The bigger the number of ground stations receiver sensors, the wider the range of the system and the smaller the error associated with it.
- ✈ The terrain typology, the building surrounding the airports, the mountainous areas are all factors that influence system's performance by increasing probability of false position detection, process delay (Latency), probability of false code detection and other type of error.
- ✈ Since this research is basically focused on the analysis of approach MLAT, it is necessary to use more ground station receivers around the airport terminal area so that, as the airplane gets closer to the reference ground station, due to the spatial or 3D resolution problem. As the distance gets smaller, angle of the ground stations or the beam width also gets narrower creating the necessity to use more ground stations.

5.2. Recommendations

Recommendations for future work are listed below:

- ✈ In this thesis, the coordinates and geographical location of all ground sensors has been assumed based on the terrain analysis software and Google earth tool as well. Since this assumption is impractical, the performance and coverage analysis has a limitation therefore, further practical study may be needed.

- ✈ This research work has only considered coverage area for deployment. In future works, other metrics of deployment such as routing and efficient power management can also be taken into consideration in deployment of sensors.

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