INTERFERENCE MITIGATION IN RADIO ALTIMETER

A Thesis

by

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ABSTRACT

Ever since its advent in the late 19th century, wireless technology has evolved substantially. Towards the end of 20th century, wireless system was being considered as a replacement for wired connections between digital avionic systems in an aircraft. Although it seemed to be a possible breakthrough in aviation, it came with its own set of challenges which included interference avoidance with aircraft electronics, dedicated reserved frequency band and many more. Hence, the existing wireless solutions could not be used directly and there is a need to develop specialized solutions.

The primary objective of this research is to devise a technique to manage the interference, arising due to the Wireless Avionics Intra-Communication (WAIC) System, in the radio altimeter present in an aircraft. The altimeter along with the in-flight environment has been simulated in MATLAB. Its performance has been evaluated for the scenario when the interference due to WAIC system is introduced. Also, various techniques which utilize vacant bandwidth of the altimeter to aid the avionics intra-communication, thus managing the interference for the altimeter, have been analyzed.

DEDICATION

To my parents

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NOMENCLATURE

WAIC	Wireless Avionics Intra-Communication
AVSI	Aerospace Vehicle Systems Institute
ICAO	International Civil Aviation Organization
ITU	International Telecommunication Union
EMI	Electro-Magnetic Interference
WRC	World Radio Communication
ARNS	Aeronautical Radio Navigation Service
RADALT	Radio Altimeters
AGL	Above Ground Level
GPWS	Ground Proximity Warning Systems
EM	Electro-Magnetic
FMCW	Frequency Modulated Continuous Wave
LFM-CW	Linear Frequency Modulated Continuous Wave
AWGN	Additive White Gaussian Noise
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
MAC	Medium Access Control
IM	Interference Management
PSD	Power Spectral Density

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Airplanes have been regarded as the one of the most important innovations in the history of transportation. They revolutionized the war scenario and aided in socio-economic growth in the post-war era. Over the past few decades, aviation technology has witnessed a rapid development. Today, aircrafts are capable of transporting goods and people from one part of the world to another in less than a day. They play critical roles in the events of disasters and medical emergencies. Hence, ensuring their safety and reliability becomes very important. The proper functioning of an aircraft is ensured partly by its avionics.

The term *avionics* is an amalgamation of the words *aviation* and *electronics*. It is a humongous network of electronic systems that perform individual functions on an aircraft. It is comprised of electronics that support communications, navigation, monitoring displays, flight control system, flight recording system, collision avoidance system and hundreds of other systems that are instrumental in the management of the aircraft.

In a modern-day aircraft, all the avionic systems are connected using wires. Although, these wires are critical to the functioning of the aircraft, they form a very complex system (see figure 1). A major reason for this complexity is the incorporation of redundant wiring. A wire may fail due to incorrect installation, wear and tear induced by the environment or manufacturing flaws at any given point of time. Therefore, in order to avoid a system paralysis due to failure in a communication wire, redundancy is introduced into the wiring system. Currently, for each wire, there exist two or three redundant wires. This leads to a huge number of wires to be installed in the aircraft. A modern twin-aisle aircraft like the Boeing 787 has about 100,000 wires which could extend for 470 kilometers. This is approximately the distance between Los Angeles and San Jose! These wires weigh nearly 5,700 kilograms, which accounts for almost 3% of the aircraft's weight [1]. Such an enormous amount of weight, in turn, affects the fuel efficiency of the aircraft.

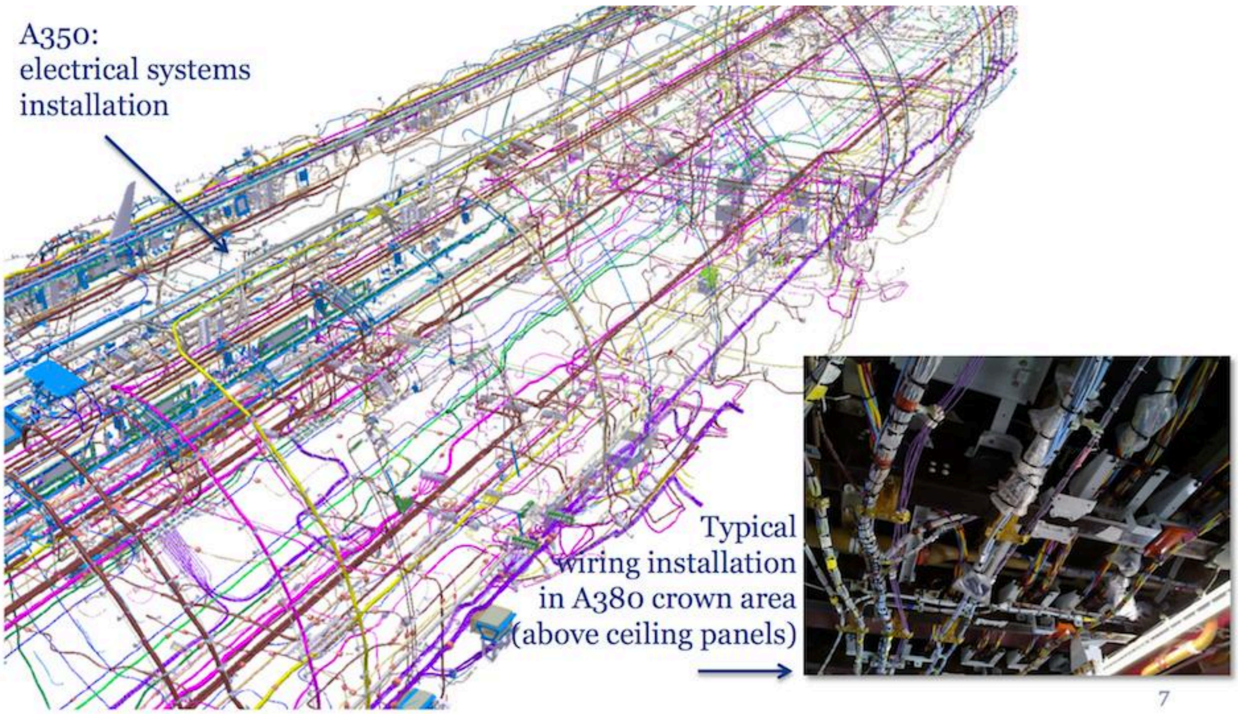

Figure 1: Wiring in a typical commercial aircraft (*Reprinted from* [2])

In order to enhance the efficiency, safety and reliability of the avionics intra-communication system, the Civil Aviation Industry came up with the idea of a Wireless Avionics Intra-Communication (WAIC) system.

1.1 Wireless Avionics Intra-Communication (WAIC) System

Towards the end of 20th century, aerospace researchers started to investigate the possibility of utilizing wireless connectivity to implement cable-less avionics for enhanced efficiency and reliability at reduced cost [3]. It has been estimated that around 30% (1,800 kilograms) of the wires could be potentially replaced by wireless links [4].

The aim of WAIC system is to provide radiocommunication between two or more stations on a single aircraft and constitute exclusive closed on-board networks required for the operation of an aircraft. These stations may be realized using integrated wireless components like wireless sensors. WAIC systems will not provide air-to-ground, air-to-satellite or air-to-air communications and will not be used for in-flight entertainment purposes. They will only be used for safety-related aircraft applications. [5]

The WAIC system layout may vary depending on the type of aircraft. It need not necessarily be limited to the interior of the aircraft structure. For example, the fuel gauge or the transmitter for fuel information will be present in the wing of the aircraft and receiver for this information will be in the cockpit. WAIC systems are currently planned to be installed on a variety of aircrafts which include regional, business, wide-body, two-deck aircraft and helicopters.

Since the WAIC systems are supposed to be installed on aircrafts, they need to follow international standards as aircrafts cross international boundaries quite often. Hence, national as well as international organizations are involved in the project. The WAIC system is currently being researched by AVSI (Aerospace Vehicle Systems Institute), ICAO (International Civil Aviation Organization) and ITU (International Telecommunication Union).

In addition to fuel reduction and subsequent environmental benefits, the use of Wireless Avionics Intra-Communications (WAIC) systems are anticipated to reduce the complexity of aircraft design. This will in turn improve an aircraft's performance over its useful lifetime through more cost-effective flight operations, reduction in maintenance costs and enhancement of aircraft systems that maintain or increase the level of safety. [6]

The prospective advantages of WAIC systems have been discussed in detail below.

1.1.1 Advantages of WAIC System

Wires and cables are gaining increasing importance more than ever in the data-centric architecture of modern aircraft.

On an average, wiring on a modern aircraft ranges anywhere between 70-300 miles. [7] They present the aircraft manufacturers and operators with a substantial expense, which is, in turn, levied on to the end customer. These expenses comprise of wiring harness designs, labor-intensive harness fabrication as well as maintenance and replacement costs of flying copper and connectors. Designing and installing a wiring harness consumes a lot of time as it requires explicit determination of routes for all the connections onboard an aircraft. It is necessary that redundant connections follow a separate path, in order to isolate the redundant circuits from issues affecting the main circuit. Being a tedious process, this shoots up the costs associated with wiring harness design and installation. Clearly, the use of wireless products would save a lot of time, effort and money for aircraft industry.

Additionally, with the wireless system providing the primary connection and only one redundant wired path in place, common mode failures could be avoided. Such a dissimilar redundancy promises higher reliability over the traditional wired architecture in which all the connections related to a particular system, could possibly fail for the same reason.

Wires also act as undesired transceivers, transmitting and receiving unwanted electromagnetic energy from the surrounding circuitry. Thus, additional resources need to be invested to ensure proper shielding from the electromagnetic interference (EMI). It is estimated that around 50% of EMI onboard an aircraft is a result of the wiring system. This encourages the need to find an alternative to the wired system.

An aircraft is operable for about 30 years on an average. [8] The avionics present onboard are expected to be functioning throughout the lifetime of the aircraft. However, due to the operating conditions, wear and tear is induced onto the electronic components, especially the monitoring sensors and hence, they undergo replacements. Sometimes, components are merely replaced to introduce updates. Given the complicated layout of the wiring, fault-finding and repairing/replacing the electronics becomes a very tedious task. On the contrary, the WAIC system provides considerable flexibility towards the modification of electronics systems and structural monitoring.

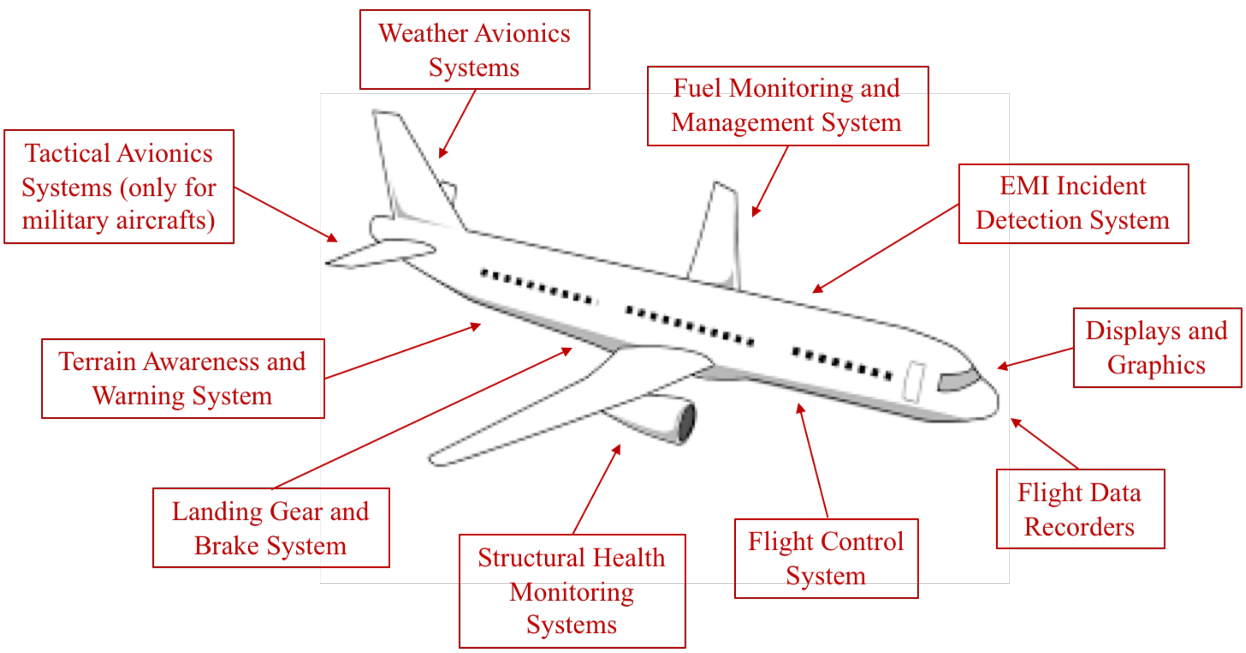

Figure 2: Potential WAIC Applications

As discussed earlier in 1.1, the WAIC system could help reduce the aircraft weight by more than 25%. This can be utilized to install new avionics, that can help provide better monitoring of the health of the aircraft. For example, sensors could be installed to monitor the temperature of the components, thus, curbing the attrition induced on the circuit due to heat. Also, additional functionalities could be implemented using wireless technology, which could not be achieved using wires. For example, sensors could be installed on moving or rotating parts and information regarding the rotor parameters could be transmitted to the desired location on the aircraft. Furthermore, with wireless technology, cabin reconfiguration would become adaptive, i.e., reconfiguring the seat layout would become relatively easy and quick.

Thus, the WAIC system ensures enhanced reliability as it rules out the losses induced due to wires as well as the need for maintenance to resolve issues arising due to wear & tear and aging of wires, which are unavoidable in the traditional wired architecture.

1.1.2 Challenges faced by WAIC system

Although the WAIC system seemed promising, it was not until recently that it could be realized due to a number of challenges faced in the past decade.

One of the major problems was the lack of a dedicated frequency band for WAIC system. Any communication system consists of a transmitting end, a receiving end and a channel. In case of wireless communication, the channel is characterized by a specific radio frequency or a band of radio frequencies, usually approved by an international regulatory committee for use.

Since, there are many other on-board wireless radio-communications services, it is necessary that these services do not interfere with the operation of WAIC system and vice-versa. Hence, the popular unlicensed frequency bands (2.4GHz and 5 GHz) were rejected for setting up wireless links in regard to safety-related applications. [9] Moreover, aircrafts often cross international territorial boundaries. Therefore, it was very important that the WAIC systems was allocated a dedicated frequency band, so as to avoid interference with any radio-communication service that could possibly function in its proximity.

[10] discusses the design issues of WAIC system ranging from physical layer to application and security layers. A few other notable challenges introduced by WAIC were,

1. Establishing highly secured communication
2. Avoiding interference with aircraft electronics
3. Enabling anti-jamming property

1.1.2.1 Spectrum Allocation for WAIC system

Several frequency bands were investigated for their compatibility to the WAIC system. [11] [12] [13] In the World Radio Communication (WRC) Conference 2015, the WAIC system was finally allotted a spectrum ranging from 4.2 GHz to 4.4 GHz.

However, unlike the requirement, the allocated band of frequencies was not explicit to WAIC applications. This spectrum was earlier allocated to Aeronautical Radio Navigation Service (ARNS) and was already being used by the radio altimeters (RADALT) installed on aircrafts.

This presented AVSI and the associated organizations, who were researching on WAIC, with a new challenge of 'Interference Management'.

1.2 Need for Interference Management

The WAIC system supports safety-related applications, which provide important statistics regarding the health of the aircraft and hence, it could not be disrupted for a long period of time. On the other hand, according to [14], the altimeter is a critical component of safety and thus, it cannot suffer from disruptions, even for short periods of time. Therefore, it becomes necessary that the signals of the two systems do not interfere with one another in a destructive fashion.

[15] discusses about the different interference mitigation techniques that could enable reliable operation of WAIC system in the presence of radio altimeters. Also, various researchers [11] [16] [17] have analyzed the effect of interference on the radio altimeters due to WAIC system. However, none have suggested solutions towards interference management in altimeters. The goal of this report is to propose efficient techniques to mitigate the interference experienced by the radio altimeter due to the WAIC system.

1.3 Radio Altimeter

According to [18], a radio altimeter is a radio navigation equipment, on board an aircraft, used to determine the height of the aircraft above the Earth's surface or another surface. The very first radio altimeter was invented by an American engineer Lloyd Espenschied in 1924. It was used by an aircraft for the very first time as a terrain avoidance system in 1938. [19]

Radar altimeter measures absolute altitude, also referred to as the height Above Ground Level (AGL). Depending on the type of aircraft, there might be up to 3 radar altimeters installed on-board. [19] All the three altimeters operate simultaneously and independent of one another. This is done to increase the accuracy of altitude measurement.

Normally, a radio altimeter can measure altitudes ranging from -20 feet (-6 meters) up to 19,685 feet (6000 meters) with an accuracy of 3 feet (0.9 meters).

Radio altimeters are a crucial component of Ground Proximity Warning Systems (GPWS). Commercial aircrafts mainly use altimeter during approach, landing and low-level or low-visibility flight conditions. It provides the necessary altitude information in regard to landing decision height. The safe altitude to land can be set beforehand. The altimeter sends a warning to the pilot when the aircraft reaches the predetermined altitude. Normally, landing is aborted if the pilot receives a warning and runway is not visible. Otherwise, the flare maneuver is initiated for a safe landing.

The ITU-R [18] considers the radio altimeter an essential component of aeronautical safety-of-life systems. For this reason, operation of radio altimeter should not be disrupted at any cost. So, it is crucial to protect it from interferences, including that arising from the WAIC signals. Before proceeding to the different interference mitigation techniques, it is important to understand the operating principle of a radar altimeter.

1.3.1 Operating Principle of Radio Altimeter

The underlying principle of a radio altimeter is radar. Radar is a system that uses high-frequency electromagnetic (EM) waves to determine distance, direction and velocity of other objects. The frequency of the EM waves used in an altimeter often belong to the radio or microwave domain of EM spectrum. Hence, radar altimeters are also known as *'Radio Altimeter'*.

A typical radio altimeter consists of a transmitter and a receiver. The transmitter is responsible for producing radio waves and transmitting them down to ground. These waves propagate in the atmosphere, hit the terrain and get reflected back to the receiver. The receiver then processes the received waves to compute the altitude. Typically, an altimeter measures the time taken for the transmitted radio wave to reach the receiving antenna and calculates the altitude (h) using speed of light as shown in the below equation.

$$h = \frac{c \text{ x } T}{2} \tag{1}$$

where, T is the time taken for the transmitted wave to reach the receiving antenna and c is the speed of light = 3×10^8 m/s

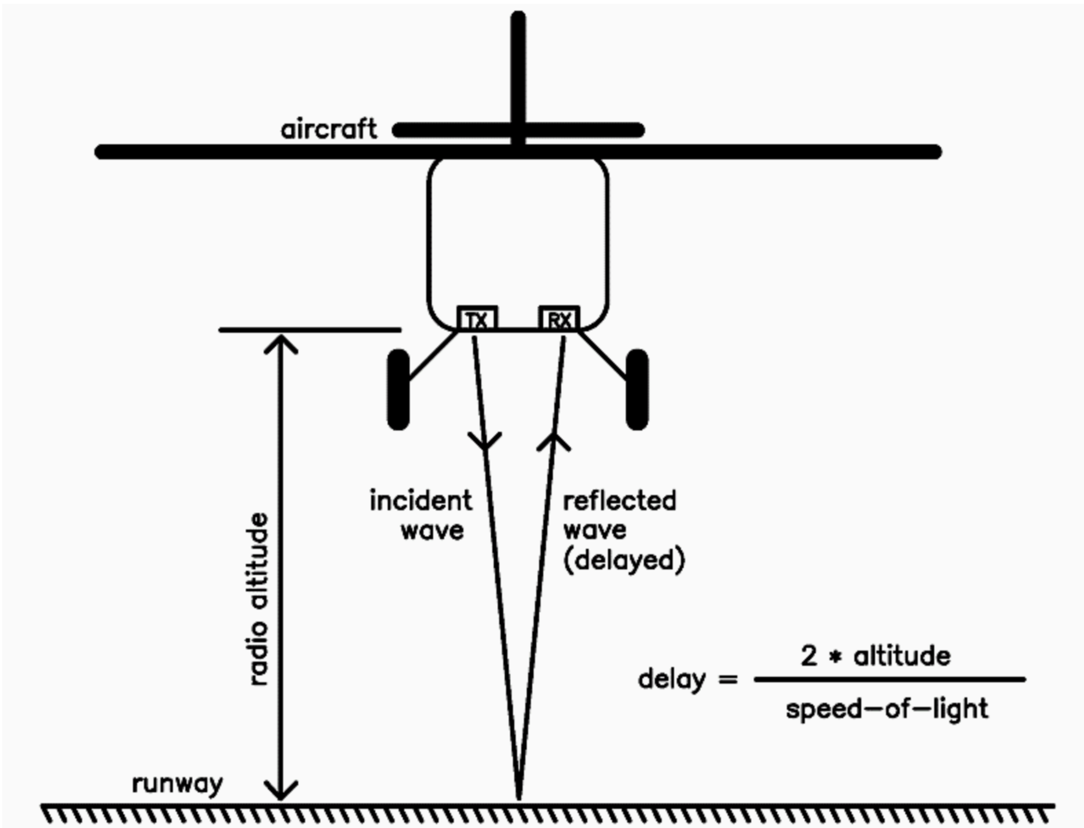

Figure 3: Operating Principle of a Radio Altimeter (*Reprinted from* [20])

Since, the radio waves propagate at the speed of light, the propagation time is usually very small, in the order of microseconds. A single antenna cannot switch between transmission and reception in a such a short period of time. Hence, two different antennas are installed in each altimeter for the purpose of transmission and reception of radio waves. To ensure proper operation of the altimeter, the receiving antenna should only pick up the reflected radio wave and avoid all other signals, including the transmitted wave. Hence, in order to avoid unwanted cross talk between the transmitted and receiving antennas, they are widely separated.

1.3.2 Frequency Modulated Continuous Wave (FMCW) Altimeter

Based on the modulation of the transmitted EM waves, radar altimeters are broadly classified into two categories,

- Pulsed Altimeter
- Linear Frequency Modulated Continuous Wave (LFM-CW) Altimeter

The LFM-CW altimeter, simply known as FMCW altimeter is identified to achieve higher accuracy over pulsed altimeter. Hence, FMCW altimeters are the industry standard. Today, all commercial aircrafts utilize FMCW altimeters. [21]

FMCW altimeters utilize large bandwidths to achieve the necessary accuracy levels. If the frequency bandwidth of an altimeter is reduced, the accuracy gets affected proportionately. [14]

FMCW altimeters use doppler effect in determining the altitude of the aircraft. The transmitter generates a linear frequency modulated signal, whose frequency varies continuously in

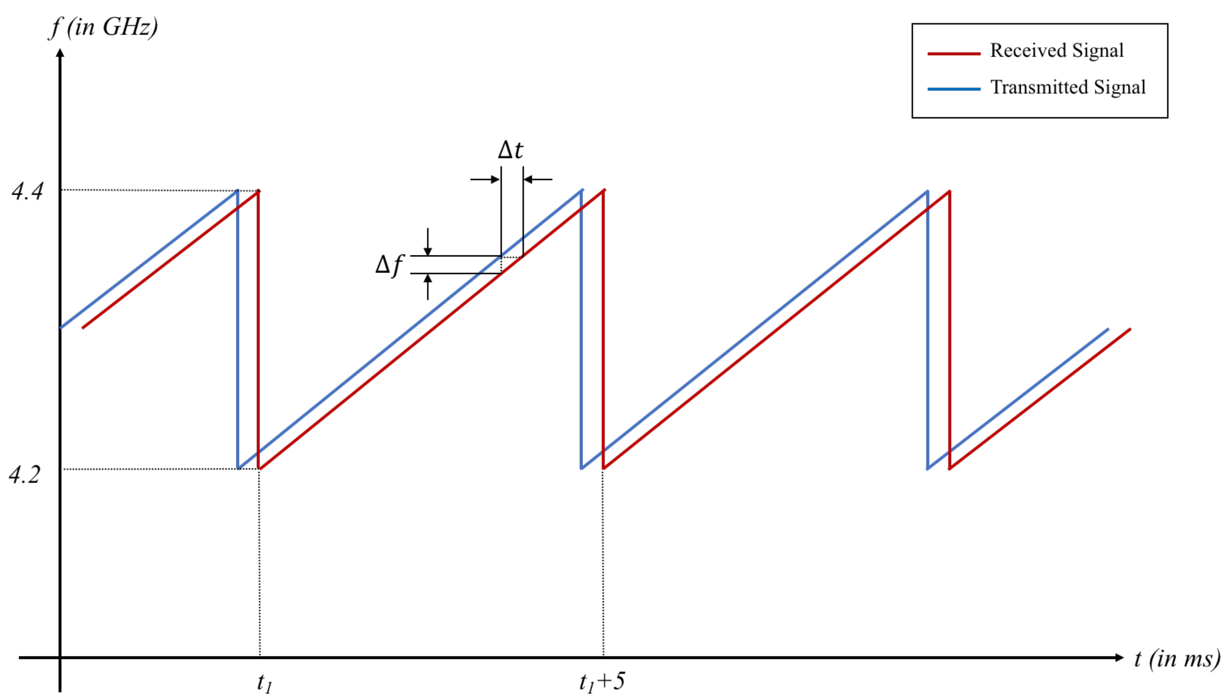

Figure 4: Frequency variation of FMCW altimeter waveform w.r.t time

the range of 4.2 – 4.4 GHz. As mentioned earlier in 1.3.1, the transmitted signal takes a short while to reach the receiving antenna. By the time the reflected EM wave reaches the receiver, the frequency of the signal at the transmitter is changed. FMCW altimeter works on the principle that the propagation time for the EM wave is directly proportional to the difference between the operating frequencies of transmitting and receiving antennas. [22] Thus, at any given instant of time, the altitude of the aircraft is directly proportional to the difference between the transmitter and receiver frequencies. From equation (1), the altitude *h* is given as,

$$h = \frac{c \text{ x } T}{2}$$

$$(or)\ \ h = \frac{c \text{ x } \Delta t}{2}$$

$$\Rightarrow h = \frac{c \text{ x } \Delta f}{2\left(\frac{df}{dt}\right)} \tag{2}$$

where, $\frac{df}{dt}$ represents the rate at which the signal frequency sweeps across the available bandwidth. (Typically, $\frac{df}{dt} = 200\ Hz$)

Here, it has been assumed that the signal frequency is not affected by propagation environment and it remains unchanged till it reaches the receiver.

Technical characteristics of typical analog and digital FMCW radio altimeters have been provided in Table 1 and Table 2.

Table 1: Technical Characteristics of typical Analog FMCW Altimeters (*Reprinted from* [14])

	ALTIMETER A1	ALTIMETER A2	ALTIMETER A3
Nominal Centre Frequency (in MHz)	4300	4300	4300
Transmitted Peak Power (in W)	0.6	1	0.1 to 0.25
Chirp Bandwidth excluding temperature drift (in MHz)	104	132.8	133
Altitude Measurement Range (meters/feet)	-4.6 to +2500 m (or) -15 to +8200 ft	-6 to +2438 m (or) -20 to +8000 ft	-6 to +6000 m (or) -20 to +19685 ft
Operational Altitude (in km)	12	12	20
Maximum Frequency Drift over Operational Temperature Range (in MHz)	±15	±15	±20
Centre frequency offset between individual radio altimeter systems (In MHz)	5	5	0
Waveform repetition frequency (Hz)	49 to 51	150	12 to 1623

Table 2: Technical Characteristics of typical Digital FMCW Altimeters (*Reprinted from* [14])

	ALTIMETER D1	**ALTIMETER D2**	**ALTIMETER D3**
Nominal Centre Frequency (in MHz)	4300	4300	4300
Transmitted Peak Power (in W)	0.4	0.1	0.1 to 1
Chirp Bandwidth excluding temperature drift (in MHz)	150	176.8	133
Altitude Measurement Range (meters/feet)	-6 to +1676 m (or) -20 to +5500 ft	-6 to +1737 m (or) -20 to +5700 ft	-6 to +6000 m (or) -20 to +19685 ft
Operational Altitude (in km)	12	12	20
Maximum Frequency Drift over Operational Temperature Range (in MHz)	±0.22	±0.129	±0.22
Average number of systems installed per aircraft	2 or 3	2 or 3	1 or 2
Waveform repetition frequency (Hz)	143	1000	100 to 4700

CHAPTER II

SIMULATION OF FMCW ALTIMETER

In order to analyze the proposed interference mitigation schemes, a test bed to emulate the FMCW altimeter under normal operating conditions was set up. This involved simulating,

- Altimeter Transmitter
- Channel (in-flight environment)
- Altimeter Receiver

Details pertaining to the simulation development have been discussed below.

2.1 Linear Frequency Modulated (Chirp) Signal

As mentioned in 1.3.2, the FMCW transmitter generates a linear frequency modulated signal, which is often also referred to as "Linear Chirp" or "Linear Sweep" signal in the literature. It owes its funny name due to its profound similarity to the chirping sound made by birds. [23]

The frequency of a chirp signal changes (either increases or decreases) with time. If the frequency of the signal increases with time, it is known as up-chirp signal (see figure 5). Similarly, if the frequency decreases with time, it is called down-chirp signal.

Let $s(t)$ be any sinusoidal signal with phase $\theta(t)$ as defined below.

$$s(t) = \sin\big(\theta(t)\big) \tag{3}$$

As mentioned above, $s(t)$ is a chirp signal if its frequency varies with time. The instantaneous frequency of a chirp signal is the rate of change of the signal phase as shown below.

$$f(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \tag{4}$$

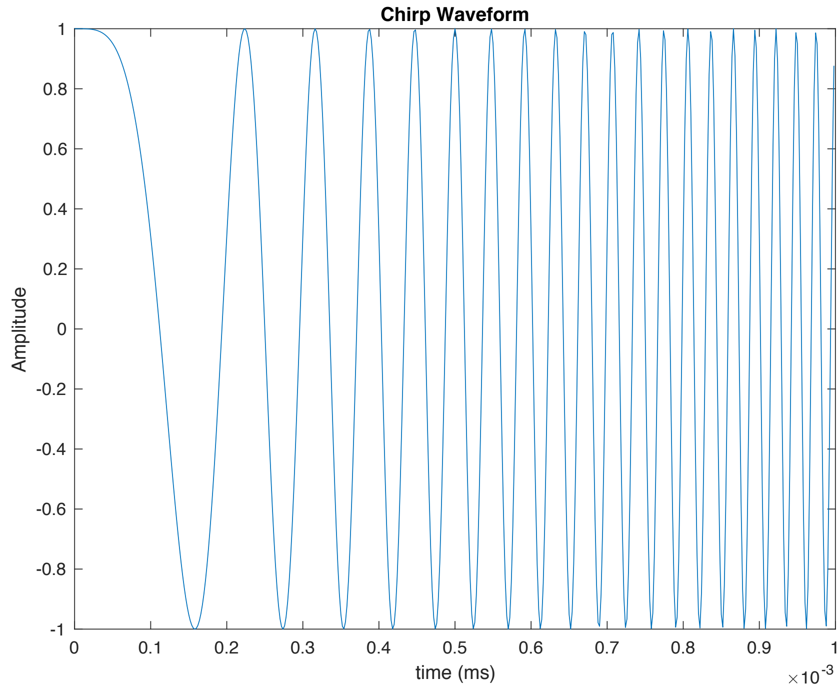

Figure 5: An Up-Chirp Signal Waveform

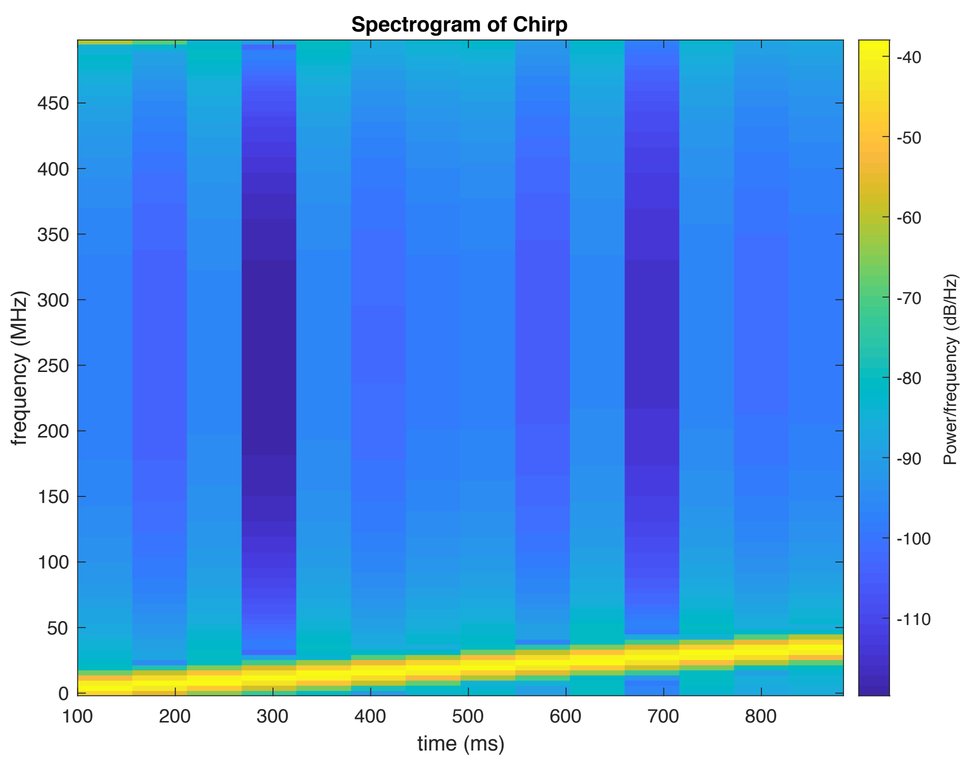

Figure 6: Spectrogram of the up-chirp signal shown in figure 5

For a linear chirp signal, the instantaneous frequency varies linearly with time and hence, could be formulated as,

$$f(t) = f_0 + kt \tag{5}$$

where, f_0 is the initial frequency (at time, t = 0)

and k is a scalar which represents the rate of change in frequency, also known as sweep rate or chirpyness and is given by,

$$k = \frac{df}{dt} = \frac{f_1 - f_0}{T} \tag{6}$$

f_1 is the final frequency (at time, t = T)

From (4), the instantaneous phase could be written as,

$$\theta(t) = \theta_0 + 2\pi \int_0^t f(\tau)d\tau \tag{7}$$

$$\theta(t) = \theta_0 + 2\pi \int_0^t (f_0 + k\tau)d\tau \tag{8}$$

$$\Rightarrow \theta(t) = \theta_0 + 2\pi \left(f_0 t + \frac{k}{2} t^2 \right) \tag{9}$$

where, θ_0 is the initial phase (at time, t = 0)

Thus, the linear chirp signal could be written as,

$$x(t) = \sin\left(\theta_0 + 2\pi \left(f_0 t + \frac{k}{2} t^2 \right) \right) \tag{10}$$

To keep things simple during simulation, a complex baseband equivalent of the band pass signal was considered. Hence, the initial phase and frequency were assumed to be 0 radians and 0 Hz respectively. k was chosen based on the value of waveform repetition frequency for the desired altimeter from Table 1 and Table 2.

Once a chirp signal was generated according to the specifications of the desired FMCW altimeter, the value of the altitude to be emulated was decided and the corresponding propagation time was computed using equation (1). The generated chirp signal was delayed by the calculated propagation time to reproduce the EM signal at the receiving antenna.

2.2 In-Flight Environment

The receiving antenna of an altimeter is surrounded by numerous electronic components, which contribute to thermal noise, shot noise, flicker noise, burst noise and transit time noise. The amount of noise produced varies greatly depending on the operating temperature and type of device. Most of these noises, especially thermal noise is unavoidable, given the altimeter operating conditions.

Thermal noise, also known as Johnson noise or Nyquist noise or Johnson-Nyquist noise, is in fact, one of the major sources of noise in electronic circuits. It is generated due to thermal agitation of charge carriers, usually electrons, within an electrical conductor at equilibrium. It occurs irrespective of the applied voltage because agitation in charge carriers is caused due to temperature. For high temperatures, the charge carriers experience greater levels of agitation and hence, the amount of thermal noise increases.

Thermal noise is quite random in nature. It has been found that the amplitude follows a Gaussian probability density function. [24] Furthermore, it is a white noise i.e., the power spectral density is almost constant throughout the frequency spectrum. Hence, it is frequently modelled as additive white gaussian noise (AWGN).

For purpose of simulation, AWGN corresponding to a SNR of 17 dB was generated. It could be seen from figure 8 that the altimeter could function correctly when its signal to noise ratio (SNR) was greater than or equal to 17 dB. Hence, in order to analyze the effects of interference on the altimeter, the least possible SNR for which the altimeter could function properly was considered.

Apart from component noise, the altimeter EM signal also suffers from interference, which occurs due to other signals propagating in the same environment. Interference takes place while the signal travels along the medium or more specifically, the channel. Interference affects the fidelity of the receiver's estimate of the desired signal in an adverse fashion. At the very least, it results in increased error rate. Although very rarely, it can also result in more severe situations like total loss of data.

Although a lot of on-board signals interfere with the altimeter, only the interference arising from the WAIC transmissions has been considered while simulating the in-flight environment. The reason being that WAIC applications are major sources of interference whilst rest of the on-board electricals signals, like electric power transmission are minor sources of interference.

For the purpose of simulation, a band-limited interference was generated by passing white gaussian noise through an ideal bandpass filter. The interference was assumed to be present only in the frequency band of 4.35 GHz – 4.37 GHz (baseband equivalent being 150 MHz – 170 MHz). There is no particular reason why the interference was modelled over that specific band. Since, the altimeter uses all the frequencies uniformly, the interference could be assumed to be present in any frequency band. Only the bandwidth of the interference influences the results.

2.3 Altitude Calculation

So far, details regarding simulation of the received signal have been discussed. The received signal could be viewed as time-shifted or delayed version of the originally transmitted signal, which is affect from noise and interference. The delay incurred by the signal is approximately equal to the propagation time. The propagation time needs to be estimated in order to compute the altitude. In extract information regarding the propagation time, correlation is used.

Correlation is a signal processing technique to measure of similarity between two signals. The cross-correlation, R_{xy} between two signals, $x(t)$ and $y(t)$ is given as,

$$R_{xy}(\tau) = \int x(t)y(t-\tau)dt \tag{11}$$

Alternatively, eq. (11) can also be written as,

$$R_{xy}(\tau) = \int x(t+\tau)y(t)dt \tag{12}$$

Here, τ denotes the lag or shift in the signal.

Now, if the originally transmitted and received signals are correlated, the resulting integral will contain a peak at $\tau > 0$. The value of τ represents the delay incurred into the signal after its transmission, which is equivalent to the propagation time. A simple example that describes this phenomenon is given below.

Suppose a periodic sequence is given as,

$$S = [10 \;\; 20 \;\; 30 \;\; 40 \;\; 50]$$

If this sequence is delayed by 1 time instant, the resulting sequence becomes,

$$S' = [50 \;\; 10 \;\; 20 \;\; 30 \;\; 40]$$

Since, the sequence was assumed to be periodic, any delay introduced into the sequence is projected as circular shifting of the sequence. The correlation of S with S' gives the following,

$$R_{SS'} = [900 \;\; 1100 \;\; 900 \;\; 800 \;\; 800]$$

It can be clearly observed that the correlation sequence contains the highest magnitude coefficient at the second position, which explains that the original sequence has suffered a delay of 1 time instant.

Figure 7 shows the correlation between the transmitted and received altimeter signal for a delay corresponding to exactly 5 milliseconds.

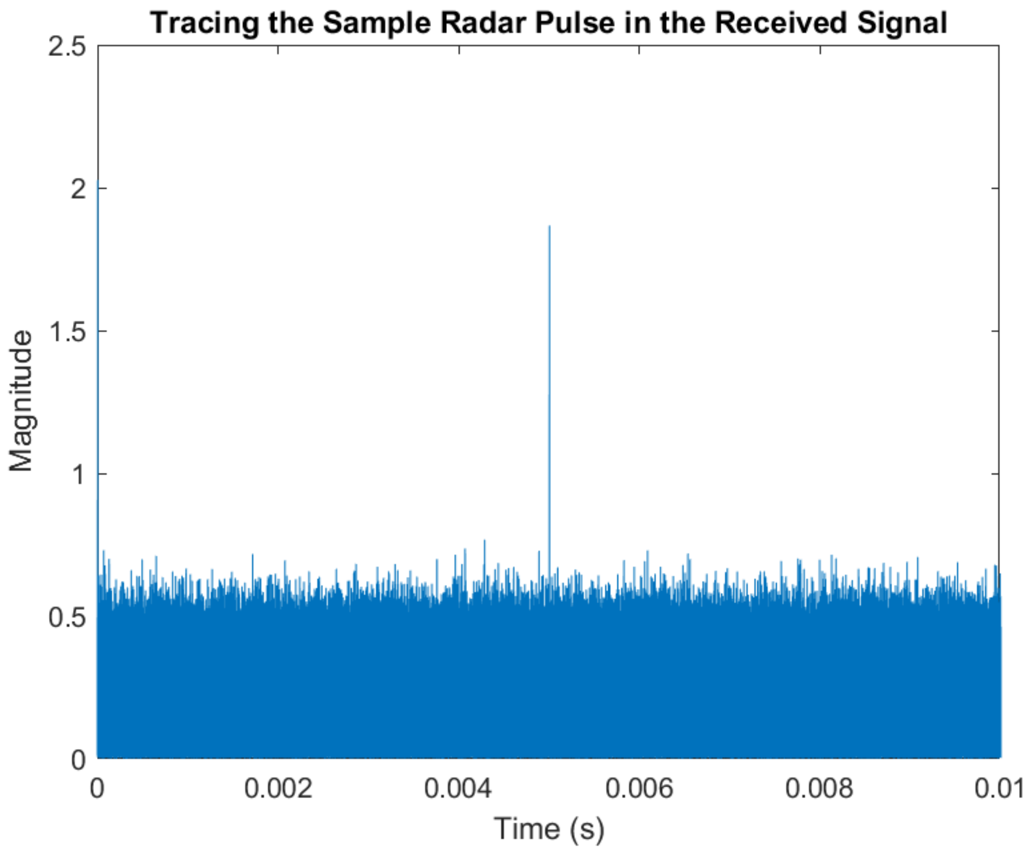

Figure 7: Correlation Peak at t ≈ 5ms, indicating that τ ≈ 5ms

However, in MATLAB, since all the mathematical operations are discrete, correlation results in a sequence. It is highly likely that the sequence might not contain the exact peak and instead, may contain the value of a sample (hereby, referred as pseudo-peak), which is close to the peak. The delay or propagation time estimated using the value of the pseudo-peak would not be accurate. Hence, the neighborhood of the pseudo-peak is isolated and vigorously reconstructed or interpolated to obtain a closer to actual peak value, thereby improving the accuracy of the altitude computation.

Reconstruction constructs a continuous-time bandlimited signal from a discrete sequence of real numbers. The ideal sinc interpolation formula is given by,

$$x(t) = \sum_{n=-\infty}^{\infty} x[n] sinc\left(\frac{t - nT}{T}\right) \tag{13}$$

where, $x(t)$ represents the reconstructed signal

$x[n]$ represents the discrete sequence

T denotes the sampling interval

Alternatively, eq. (13) can also be expressed as the convolution of a sinc function with infinite impulse train as shown below.

$$x(t) = \left(\sum_{n=-\infty}^{\infty} x[n]\delta(t - nT)\right) * sinc\left(\frac{t}{T}\right) \tag{14}$$

It could be observed that this is equivalent to filtering the impulse train with an ideal low pass filter.

Since, the *sinc* function consists of infinite samples in the time domain, the above-mentioned Shannon-Whittaker method could not be realized for practical implementations. Most of the practical implementations involve linear interpolation, wherein the interpolant i.e., the *sinc* function is replaced by a linear time-limited function.

Although the linear interpolation is quick and easy to realize, it does not provide an accurate estimate of the continuous time signal. Hence, a higher degree polynomial interpolant is used. This ensures a better accuracy over linear interpolation. Nonetheless, computational complexity becomes a point of concern again. Furthermore, polynomial interpolation suffers from Runge's phenomenon, wherein the interpolation oscillates at the interval limits/edges.

Spline interpolation is one method that avoids Runge's phenomenon and provides better accuracy even for lower degree polynomials. In MATLAB, this could be easily implemented using the command *interp1*, which allows the user to specify the interpolation method as one of the input arguments.

Depending on the efficiency of the reconstruction process, the actual peak or a pseudo peak with greater accuracy is identified. This yields an accurate estimate of the propagation time, which is, in turn, utilized to compute the altitude according to eq. (1).

2.4 Test Setup

It should be noted that the following assumptions were made in setting up the test bed,

- Channel does not exhibit fading
- Frequency of the EM signal remains unchanged during its propagation
- The interference caused by WAIC system is band limited to 20 MHz

The last assumption is not strong in the sense that the interference could occupy a different bandwidth and the techniques discussed in this report should still be applicable. However, the results presented in this report pertain to WAIC interference of 20 MHz.

Once the test bed (which comprises of simulation of altimeter and in-flight environment) was set up, the simulation was iterated for 1000 iterations for a pre-determined distance for different SINR values. Error values were computed (using equation 15) and analyzed to check if they occur due to noise or interference.

$$Error = |Computed\ Altitude - Actual\ Altitude| \tag{15}$$

For a fact, if an error occurs due to computational approximations, the magnitude of error is small i.e., the computed altitude is close to the actual value. The pilot of the aircraft could still navigate using the error-struck altitude value. These errors are categorized under *fine errors*.

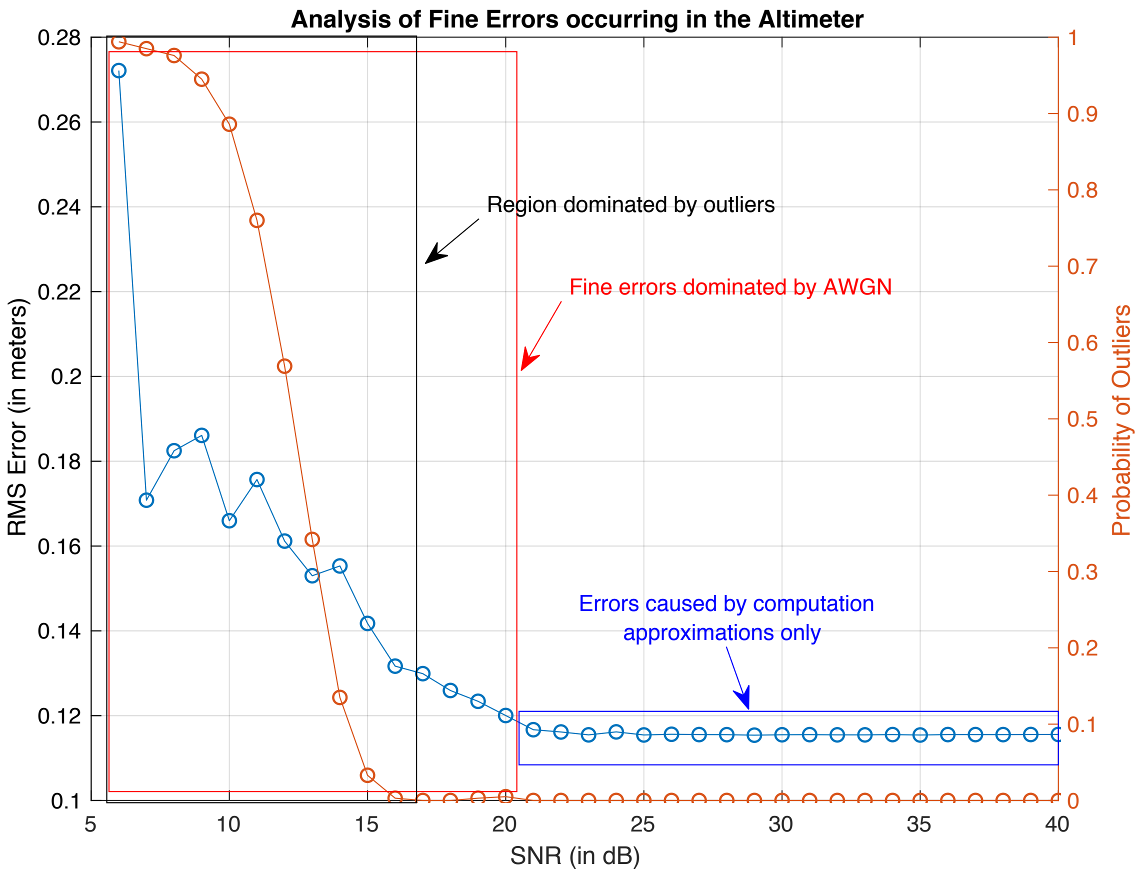

Figure 8: Analysis of Fine Errors occurring in an altimeter

Figure 8 shows the plot depicting the cause and nature of fine errors. The errors at lower SNR is of higher magnitude and mostly dominated by the noise present in the environment. As the SNR is increased, signal gets less affected by noise and thus, it could be said that the errors are solely due to computational approximations, which includes the interpolation inaccuracy involved in the estimation of the delay. This could be observed in the plot as the errors converge to a constant magnitude at higher SNRs.

However, if an error occurs due to interference or sudden bursts of noise, the computed altitude is off by a huge value. In such a case, the computed altitude is as good as absence of itself as the pilot would be navigating without any idea about how high the aircraft is flying. Such an error is called an *outlier*. Outliers dominate the scenario when SNR is very less (as could be seen in Figure 8).

The next important task was to separate the fine errors and the outliers and analyze the number of outliers occurring. Errors with absolute values greater than 10 meters were considered as outliers and the ones with absolute values less than or equal to 10 meters were considered as fine errors.

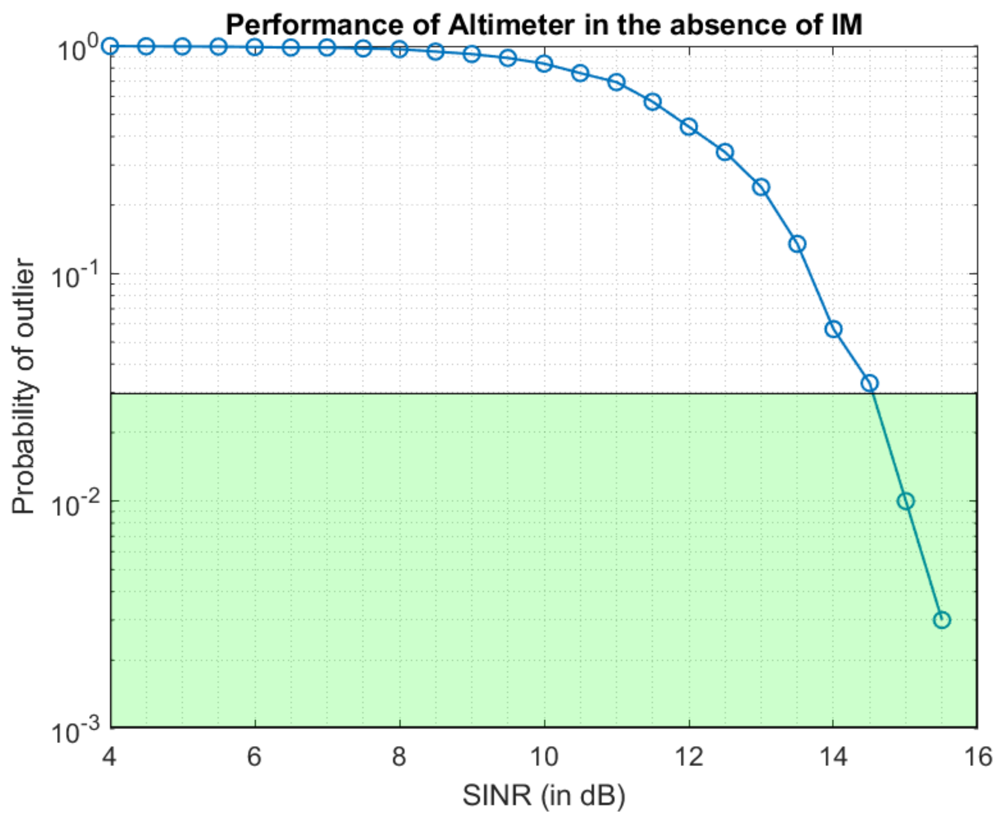

Figure 9: Performance of altimeter errors in the absence of interference management

Once the errors were classified, the empirical probability of the occurrence of outliers was computed. Figure 9 contains a plot depicting the probability of outliers at different SINRs, when no interference management technique is employed.

CHAPTER III

ANALYSIS OF INTERFERENCE MANAGEMENT TECHNIQUES

As discussed in Chapter I and II, the radio altimeter signal sweeps across the available bandwidth, utilizing only a single frequency at a time. This leaves the ARNS spectrum highly underutilized. Hence, it was suggested by WRC committee that ARNS share the spectrum with WAIC. Therefore, effective interference management is necessary for the co-existence of the two systems. Interference management techniques can be rooted in various aspects of system design from network planning, radio resource management, medium access control (MAC) to physical layer signal processing. The scope of this report is limited to the radio resource management and physical layer signal processing schemes for interference management (IM).

There exist many interference management schemes in the literature. Most of the traditional techniques attempt to exploit interfering transmitters' parameters like emission power, time or location. A few other techniques focus on managing the interference directly at the receiver. These techniques require real time interactions between receivers and interfering transmitters. This is achieved by either establishing some sort of synchronization between the receivers and interfering transmitters or by deploying spectral sensing at the receiver or at the interfering transmitters.

The altimeter is a standard equipment on the aircrafts and therefore, it is resistant to change in technology. In other words, it is not desirable to change the existing technology in an altimeter because any modification would require certification from the appropriate government entities, which is a tedious process. Rather, it is much easier to introduce new techniques in the WAIC system, since it is still in the proposal stage. Hence, the (altimeter) receiver-end IM techniques could not be considered.

[25] and [26] study the different interference management schemes that could be employed at the transmitter of the secondary system, which in this case is the WAIC system. Some of them have been briefly discussed here.

Table 3 provides a comparison of different IM techniques that could be implemented at the transmitter of WAIC system.

Table 3: Comparison of different transmitter-end IM techniques (*Reprinted from* [25])

	Spectral Shaping	**Spread Spectrum**	**Transmit Beamforming**
Co-channel Interference Suppression	Yes	Yes	Yes
Adjacent Channel Interference Suppression	Yes	No	Yes
Suppression Gain	High	High	High
Hardware Complexity	Medium	Low	High

These techniques will be discussed in detail in the following sections.

3.1 Transmit Beamforming Approach

The transmit beamforming approach uses the spatial characteristics to manage the interference. Since, the antennas of interfering system (WAIC system) and the primary system (altimeter) are located at different points in an aircraft, both the systems tend to have different spatial signatures.

This spatial diversity could be utilized to perform beamforming at the transmitter end of WAIC system.

In transmit beamforming, each WAIC transmitter is equipped with multiple antennas, which transmit signals in different directions. Each antenna is configured to either amplify or attenuate the received signal. The transmitting antennas apply weights to the transmitting signal adaptively, with an intention to suppress the signal in the direction of the primary system and enhance the signal in the direction of the secondary system.

However, transmit beamforming needs to incorporate a feedback to extract the instantaneous channel state information (CSI) so as to adapt its weights. It is capable of suppressing co-channel interference and adjacent channel interference, the approach is highly complex in terms of both computation and hardware. (Adjacent channel interference arises when a transmission from an adjacent band interferes with the transmission in the current band.)

3.2 Spectral Shaping Approach

In this technique, the waveforms of the interfering signals are designed such that they can dynamically respond to the spectral environment and have desired spectral shapes/notches. In other words, the spectral content of the interference is shaped so that its power leakage could be minimized in the frequency bands of primary system.

The main idea behind choosing this technique was to shape the spectrum of the WAIC system such that it does not interfere with the altimeter for most of the while. It seemed like if WAIC system signals are limited to a very narrow band of frequencies, then the altimeter will experience interference only when it passes through those narrow band of frequencies and for all other frequencies, the operation of altimeter would not be disrupted. Hence, the spectrum of the WAIC system was shaped as a notch.

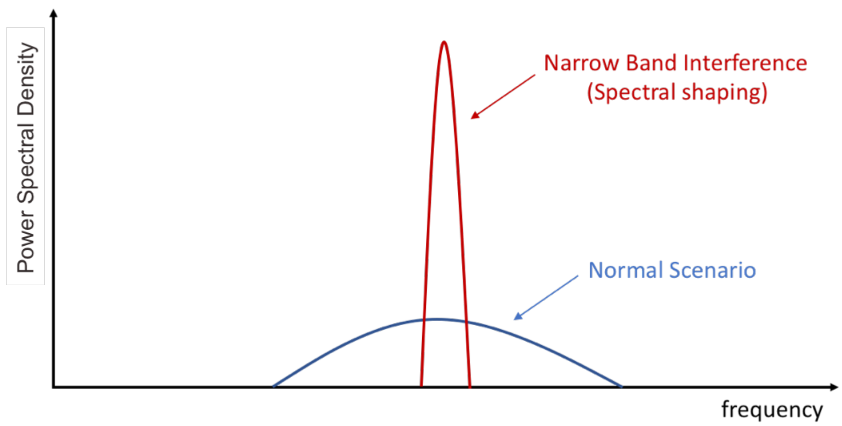

Figure 10: Characterization of Spectral Shaping

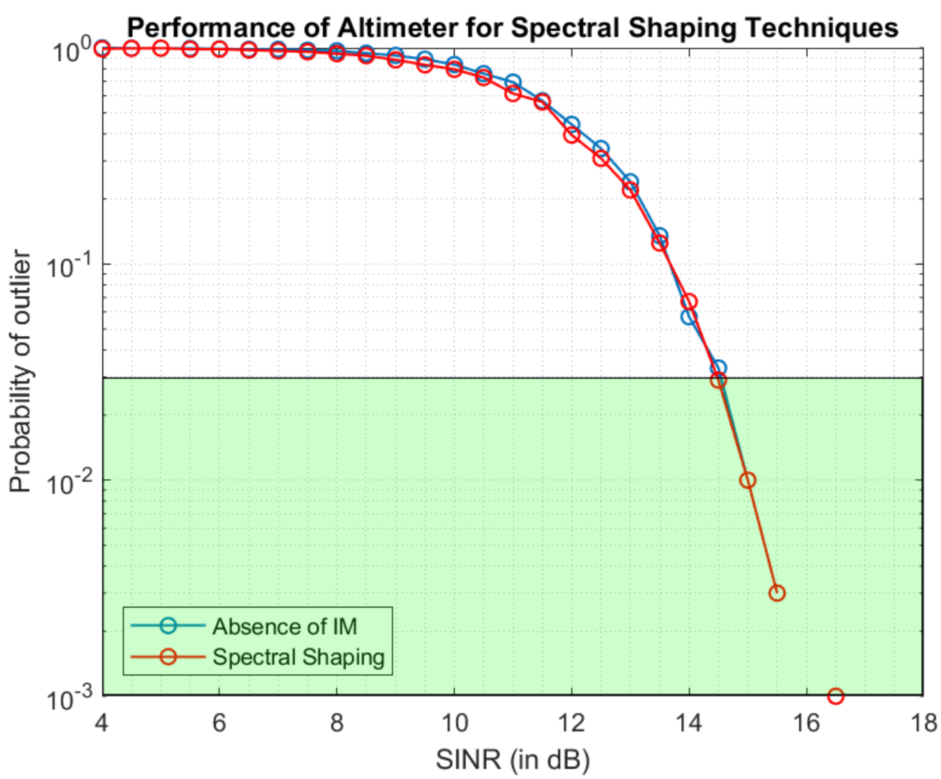

Figure 11: Performance of the altimeter when spectral shaping technique was used

In the simulation, the spectral content of the interference was designed as occupying very narrow band of frequencies (~ 2 MHz), which is very less compared to the originally assumed 20 MHz of interference. The power spectral density (PSD) of the interfering signals is increased by the same proportion such that the overall power is constant. This is done so as to ensure that the WAIC transmissions survive even when the altimeter utilizes that band of 2 MHz.

Figure 11 presents the observed behavior of the altimeter in the presence of spectral-shaped WAIC transmission. It could be observed that the performance of the technique is comparable to that in the absence of any interference management i.e., it seems to be as good as letting the two systems function without worrying about the transmission disruptions caused by WAIC interference. Hence, other techniques were explored with an aim of obtaining better performance.

3.3 Spread Spectrum Approach

The name itself suggests – *spectrum is spread*. In this technique, spectral content of the EM signal is *spread*, thus, resulting in an EM signal with wider bandwidth.

The principal interest behind choosing this technique was to keep the power levels of the WAIC system sufficiently low so that they do not interfere with the altimeter. It was speculated that a wideband interference with extremely low power spectral density could drastically reduce co-channel interference.

In the simulation, the WAIC system was allocated the entire available bandwidth of 200 MHz and the power spectral density was reduced to one-tenth of the original, again keeping the overall power constant. Figure 13 shows the plot depicting performance of the altimeter at different SINRs, when spread spectrum technique is employed at the interfering (WAIC) transmitters to manage the interference amongst the two systems.

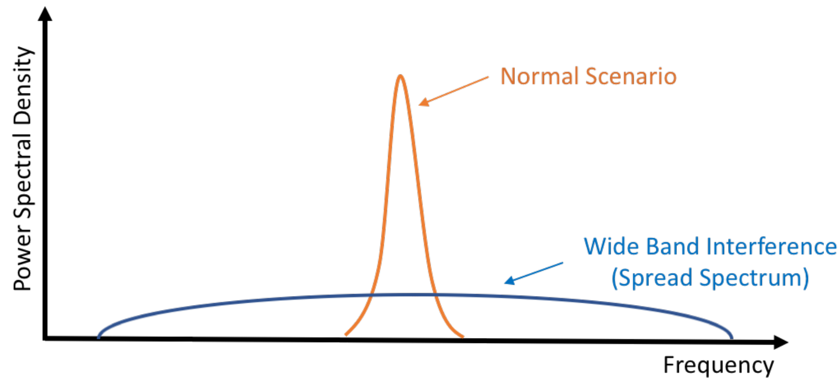

Figure 12: Characterization of Spread Spectrum

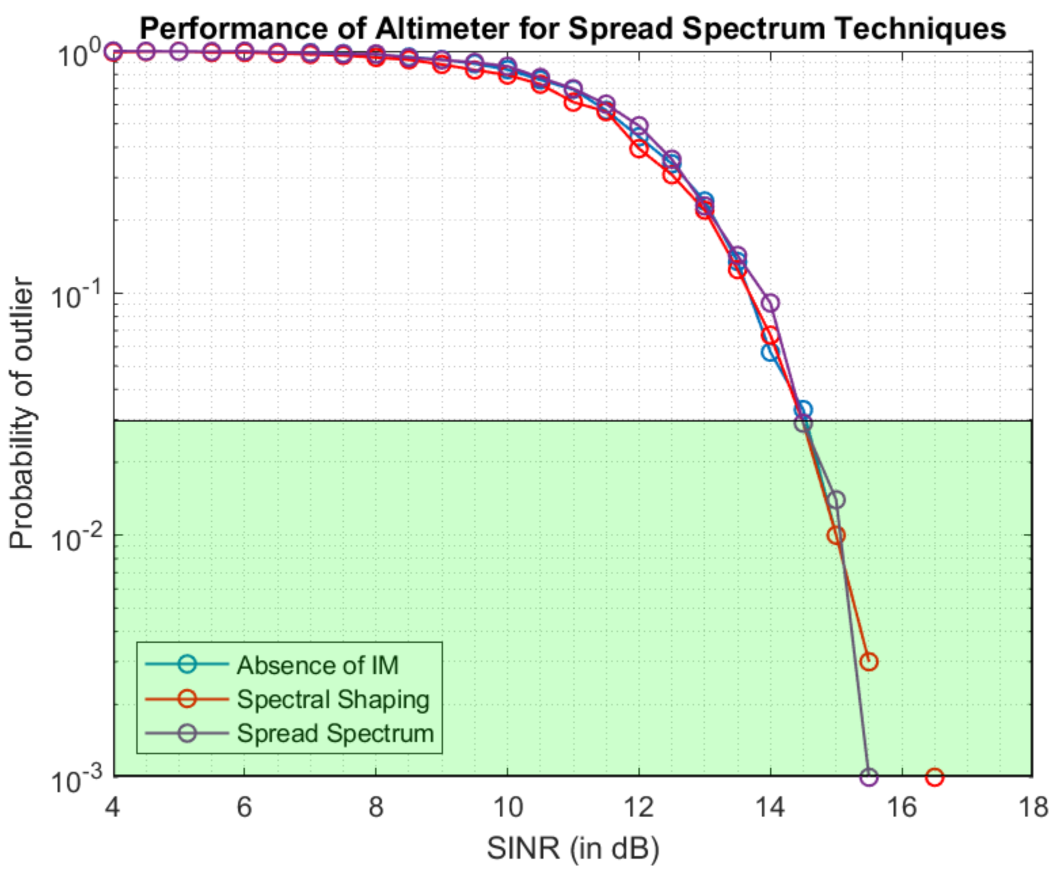

Figure 13: Performance of altimeter when spread spectrum technique was used

It can be observed that the number of outliers, and in turn the probability of outliers, in this case is higher when compared to the earlier scenarios (refer Table 4). The major reason for this is believed to be the unregulated adjacent channel interference. Hence, it became necessary to research for more efficient techniques.

3.4 Spectrum Sensing-based Approach

If only the interfering transmitter could somehow detect the spectrum utilization before it uses that frequency band for its transmission, the performance would improve drastically. There are many spectrum sensing techniques in the literature [26].

The most naïve and popular way is energy detection-based sensing. In this technique, the interfering transmitter detects the energy in the frequency band that it intends to use for its transmission. If the energy is found to be above a certain pre-determined threshold, the transmission is not initiated. At this point, the interfering transmitter could keep on checking the same band for vacancy (preferred in this case, since the altimeter never utilizes a single frequency for more than a few pico-seconds) or it could hop off to a different frequency band and check for its vacancy. When the transmitter does find a vacant frequency band, it starts its transmission and periodically checks for energy of primary signals.

Although the computational and hardware implementation complexities are low, this technique is not very useful for our scenario because the altimeter sweeps the spectrum at a very high rate (200 times in a second). So, the WAIC system needs to search, notify the receiver of the selected frequency, transmit information and quickly hop to another frequency very quickly (within 5 milli-seconds). However, this situation could be taken care of by the next technique, while achieving comparable performance.

3.5 Time-Synchronized IM Technique

If a synchronization could be established between transmitter and receiver, then, there would no need to sense the spectrum each time the interfering transmitter intends to transmit. In this technique, the radar altimeters are time-synchronized with the WAIC system. Hence, depending on the level of synchronization, the WAIC transmitters would know exactly when an altimeter is utilizing a particular frequency band. It would then, avoid transmitting in that particular interval. Since, the altimeter uses any frequency for a fraction of a nano-second, the WAIC transmitter could meanwhile process its signal internally and keep it ready for transmission.

A continuous transmission could not be achieved by the WAIC system over the same frequency band. Nevertheless, the WAIC system could quickly hop off to a different predetermined frequency to continue its transmission. But it is still bound to suffer from minute disruptions. However, as discussed in 1.2, it is permissible that the WAIC system transmissions be disrupted for short periods, if that helps achieve the goal of ensuring proper functioning of both the altimeter and the WAIC system in the same frequency band.

In order to simulate, the transmission of the WAIC system was again allocated a 20 MHz band of frequencies. The power spectral density was also the same as the one assumed originally. It is desired that the WAIC system enforces a guard interval in vacating and occupying any frequency band. However, in the initial simulation (result given by figure 14), a guard interval was not employed.

Figure 14 shows a plot depicting variation in the number of outliers encountered by the altimeter for different SINRs, when time-synchronized IM technique is employed to mitigate the interference arising due to WAIC transmission in the on-board altimeters. As could be observed in this scenario, the altimeter encounters < 3% errors (which fulfills the goal) for SINR higher than 14 dB.

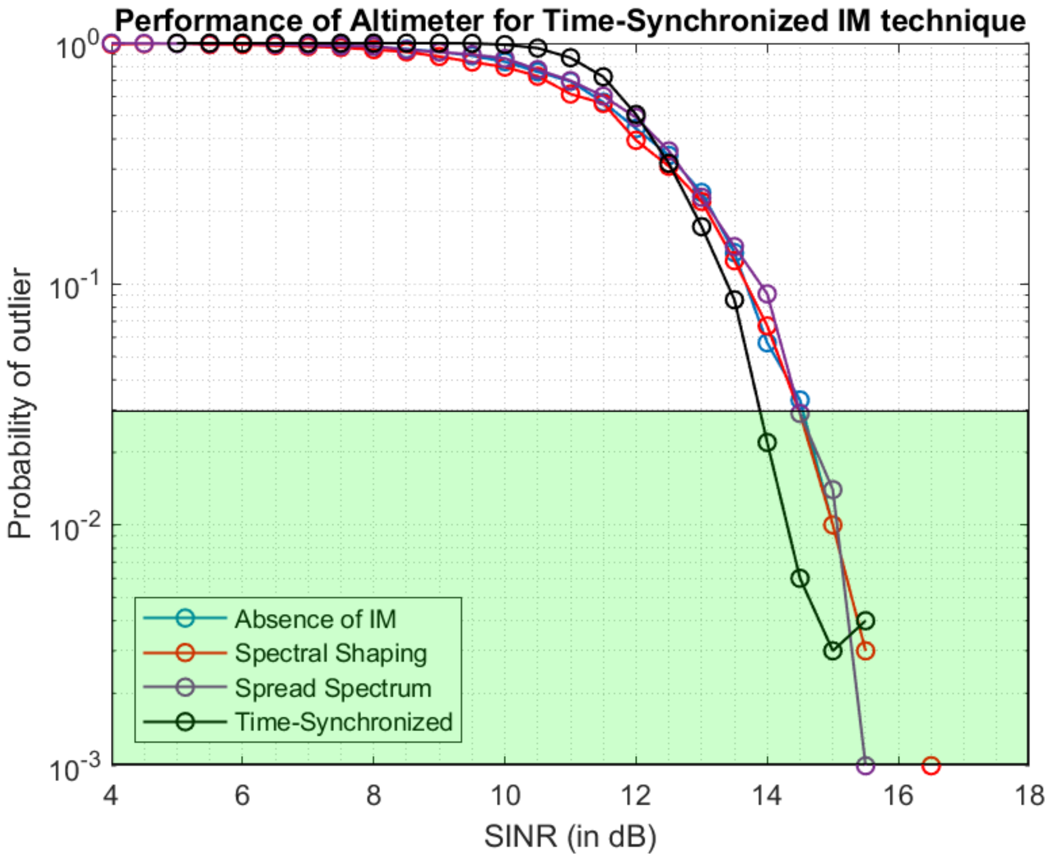

Figure 14: Performance of altimeter when time-synchronized IM technique was used

The performance could further be improved by imposing a guard interval. Figure 15 shows a plot which captures the performance of altimeter as the guard interval is varied from 0 to 2.25 milliseconds at SINR = 14 dB. At the first glance, it might seem that the performance is not stable, owing to the high number of fluctuations. However, on a closer look, it could be observed that in spite of the fluctuations, the performance is gradually improving as the probability of outliers converges to zero with increasing guard interval. Figure 16 is the same performance as figure 15 plotted on a logarithmic scale.

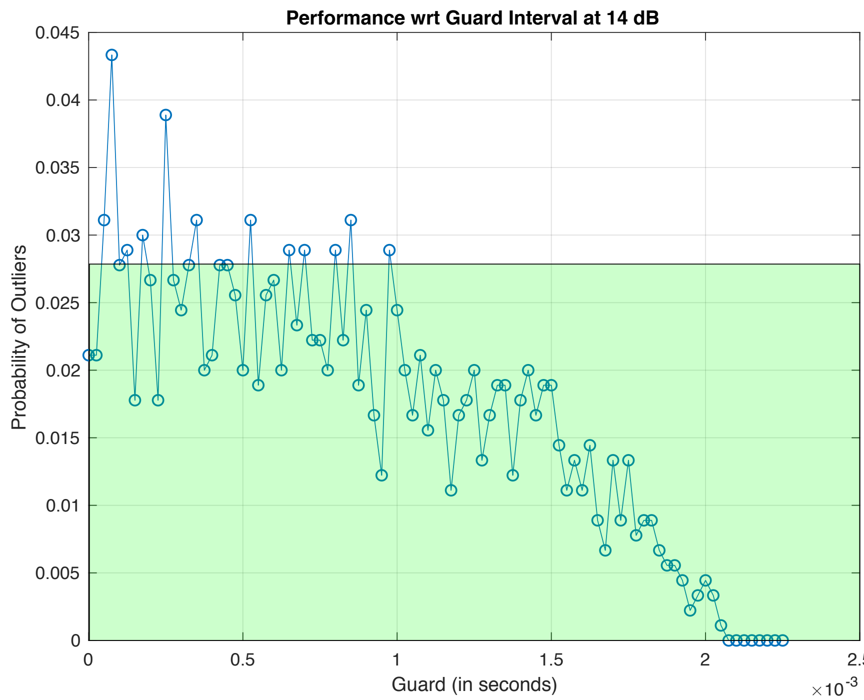

Figure 15: Performance of Altimeter at SINR = 14 dB for varying Guard Interval

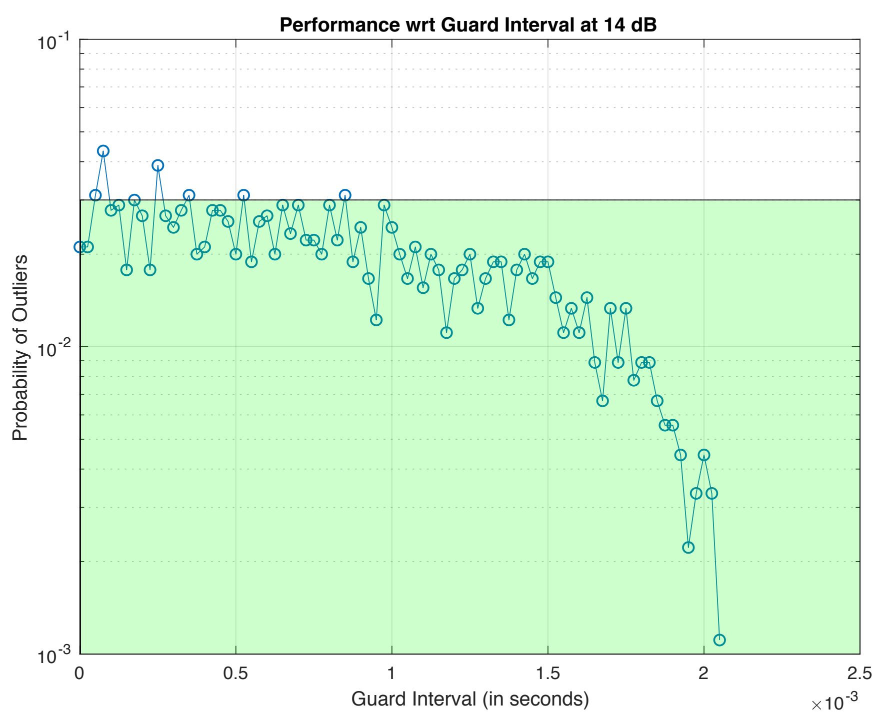

Figure 16: Performance of Altimeter for varying Guard Interval on a Logarithmic Scale

It is evident that the performance of this technique depends heavily on the timing module in both the systems. However, timing synchronization is a mature technology and thus, this requirement could be fulfilled using a variety of off-the-shelf products.

Table 4 comprises of the number of outliers (errors due to interference) observed for different techniques at different SINR.

Table 4: Number of Outliers observed for different Interference Mitigation Techniques

SINR (in dB)	**Interference Power (in dB)**	***Number of Outliers (out of 1000)***			
		Absence of IM Techniques	**Spectral Shaping**	**Spread Spectrum**	**Time Suppressed IC**
14	45.989	57	67	91	22
14.5	44.921	33	29	29	6
15	43.681	10	10	14	3
15.5	42.164	3	3	1	4
16	40.142	0	0	0	0
16.5	36.874	0	1	0	0
17	N/A	0	0	0	0

CHAPTER IV

CONCLUSION

It is possible to establish a secondary wireless system (WAIC) in the same frequency band as the one currently being utilized by commercial altimeters, without causing any disruption to the altimeters by incorporating good interference management techniques like the Time-Synchronized IM technique.

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