RFI Suppression in Low Frequency UWB SAR Using the RLS Algorithm

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This thesis is presented as part of Degree of Master of Science in Electrical Engineering with emphasis on Signal Processing

Blekinge Institute of Technology (BTH)
December 2010

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Abstract

Synthetic Aperture Radar (SAR) has many applications within ground image sensing and navigation. UltraWide Band(UWB) SAR operating at Ultra High Frequency /Very High Frequency(UHF/VHF) are usually affected by the Radio Frequency Interferences(RFI) from civilian communication bands which causes SIR(Signal to Interference Ratio) to go down. In response target detection is drastically affected in the system.

Therefore, mitigation of the dominating energy from Narrow Band(NB) broadcast and mobile communication sources is highly required. Which eventually speaks out demand for suppression of these RFI’s for effective SAR operation with such co-existing sources of UWB.

The accurate discrimination of target, from sources scattered around surrounding objects, is practical advantage of UWB SAR due to fine resolution in range and azimuth after pulse compression and SAR processing. But this advantage is weakened due to the RFI.

Mitigating RFI is the main aim of this thesis. For this, we have applied an adaptive filtering technique using Adaptive Line Enhancement(ALE) implemented with the Recursive Least Square (RLS) algorithm. The capability of fast tracking time varying signal and noise statistics is better in RLS compared to other adaptive techniques like LMS, NLMS etc. Due to which it is preferred for suppressing the mobile communication signal which is mixed with the SAR signal, due to operating in the same frequency ranges. ALE uses delayed received signal to de-correlate the SAR signal in order to do interference suppression. Thus it is being used for separating the desired SAR pulses for image formation. The results show that RFI has been reduced strongly in simulation and acquired real data using ALE with RLS. RFI suppression done by using this method, is also analyzed by testing in real laboratory environment.

**Keywords**: Aperture, Adaptive Line Enhancement(ALE), Chirp signal, Global BackProjection(GBP), Pulse compression, Radio Frequency Interference(RFI), Synthetic Aperture Radar(SAR), UltraWide Band(UWB)
Acknowledgements

All praises to Allah, the most merciful, the most gracious who has the strength of knowledge.

I would like to thank God who give me the ability and the chance to understand and learn the in-depth knowledge, who give me a chance to be a part of dept. of Electrical Engineering at Blekinge Institute of Technology, BTH.

I would like to show my gratitude for my honorable thesis supervisor and examiner, Thomas Sjögren and Viet Thuy for their guidance, feedback and support throughout my thesis work.

Specially I am really thankful to Thomas Sjögren being my supervisor for giving me his valuable time and guiding me in sorting out issues related with simulation in MatLab and mathematical manipulation. In fact I have no words of appreciation for the deep sincerity of Thomas and his great interest as a supervisor in my work. His deep interest and sincerity to deliver me knowledge and guidance gave me a unique strength and courage. His motivations made me confident to complete my work on time and deliver my tasks with honesty.

I am indebted to my colleagues and seniors as well, for their support and help in academic course work completion and for their guidance throughout my degree of Signal Processing. I would also like to acknowledge insight I had obtained from my friends and family. Their participation through financial and moral support which also gave me real strength to complete this thesis.

I am also grateful to the professors of BTH who broadened my knowledge in the area of Communication, Mathematics and Signal Processing.

I will conclude my thanking to reviewers, examiner and especially my supervisor Thomas Sjögren for his guidance.

Fazal Ullah Khan
2010, Sweden
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Contents

Abstract iii

Acknowledgements v

List of Figures ix

1 Introduction 1
  1.1 State of the Art ......................................................... 2
  1.2 Motivation for Thesis .................................................. 2
  1.3 Concept of RFI Suppression .......................................... 3
  1.4 Review of Chapters ..................................................... 4

2 Radar System Engineering 7
  2.1 Radar Classifications .................................................... 8
  2.2 Basic Components of Radar and Range Calculation ................. 9
  2.3 Target Detection and Estimation ...................................... 11
  2.4 Radar Limitations ........................................................ 11

3 Synthetic Aperture Radar(SAR)System 13
  3.1 How does SAR Works .................................................... 14
  3.2 SAR Applications ....................................................... 14
  3.3 SAR Systems .............................................................. 15
  3.4 Description of Imaging Radar ......................................... 15

4 SAR Image Formation and Processing 17
  4.1 UWB SAR ................................................................. 17
  4.2 Chirp Signal .............................................................. 18
  4.3 Pulse Compression and Matched Filtering .......................... 19
  4.4 SAR Raw Data Generation ............................................. 20
  4.5 SAR Signal Processing and Image Formation ....................... 23
    4.5.1 SAR Processing Algorithms ....................................... 23
    4.5.2 Global BackProjection(GBP) ...................................... 24
5 Radio Frequency Interference  
  5.1 Global System for Mobile communication(GSM) Model ....... 27  
  5.1.1 GSM Carrier Frequencies ..................................... 27  
  5.1.2 GMSK Modulation .............................................. 28  
  5.2 Adaptive Signal Processing and RLS Algorithm .......... 30  
  5.2.1 Exponentially Weighted RLS Algorithm .................. 30  
  5.3 Adaptive Line Enhancer(ALE) ................................. 32  

6 RFI Cancelation  
  6.1 Data Acquisition .................................................. 33  
  6.2 Noise Cancelation .................................................. 34  

7 Real Data Results and Conclusions  
  7.1 Data Acquisition in Real World Scenario ................... 37  
  7.2 Conclusions ......................................................... 38  

Bibliography  

## List of Figures

2.1 Radar System block diagram .......................... 10
2.2 Detection of Multiple Radar Targets .................. 11

3.1 Resolution Limits for SAR .......................... 14
3.2 Synthetic Aperture Radar Imaging Concept ............. 16

4.1 Transmitted Chirp Signal ............................ 19
4.2 FFT of Transmitted Chirp Signal ...................... 19
4.3 Signal for Matched Filtering .......................... 21
4.4 Uncompressed Received Signal ........................ 21
4.5 FFT of Uncompressed Received Signal ................ 21
4.6 Pulse Compressed Signal ............................. 22
4.7 FFT of Pulse Compressed Signal ...................... 22
4.8 SAR Raw Data ........................................ 22
4.9 SAR Signal Processing Diagram ....................... 23
4.10 Geometry of SAR System ............................. 24
4.11 SAR Image Processed by GBP ......................... 25
4.12 FFT of SAR Processed Image ......................... 26

5.1 GSM Transmitter ....................................... 29
5.2 GSM Transmitted Signal .............................. 29
5.3 RLS Algorithms Block Diagram ....................... 32
5.4 Adaptive Line Enhancer Block Diagram ................ 32

6.1 Disturbed Uncompressed Received Signal .............. 34
6.2 FFT of Disturbed Uncompressed Received Signal ...... 34
6.3 Disturbed Pulse Compressed Signal ................... 35
6.4 FFT of Disturbed Pulse Compressed Signal .......... 35
6.5 Distorted SAR Image Processed by GBP ............... 35
6.6 FFT of Distorted SAR Processed Image ................ 35
6.7 Pulse Compressed Signal after RFI Suppression ....... 36
6.8 FFT of Pulse Compressed Signal after RFI Suppression 36
6.9 RFI Suppressed SAR Processed Image ................ 36
6.10 FFT of RFI Suppressed SAR Processed Image ......... 36
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Agilent system configuration for data acquisition</td>
<td>38</td>
</tr>
<tr>
<td>7.2</td>
<td>Distorted compressed pulse in frequency domain</td>
<td>39</td>
</tr>
<tr>
<td>7.3</td>
<td>Disturbed SAR Processed Image</td>
<td>39</td>
</tr>
<tr>
<td>7.4</td>
<td>FFT of Disturbed SAR Processed Image</td>
<td>40</td>
</tr>
<tr>
<td>7.5</td>
<td>Pulse compressed signal after suppression</td>
<td>40</td>
</tr>
<tr>
<td>7.6</td>
<td>SAR Processed Image Interference Suppressed</td>
<td>40</td>
</tr>
<tr>
<td>7.7</td>
<td>FFT of SAR Processed Image Interference Suppressed</td>
<td>40</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The recognition of objects in air while flying like a bat or being able to know about their environment while swimming like dolphins do, are some impressive and appealing examples from nature which make us profound to think deep about the beauty of the nature. The history of evolution of such echolocation, by these mammals is million years old. This mechanism of hutting by processing of returns from time-frequency signatures of emitting waveform to environment, is really complicated and sophisticated. Such waveform sensing and adaptation to nature may have been the inspiration for man-made applications like radar and sonar.

Such sophistication and perfection will also consider issues concerning selection of transmitted and received waveform. At each time step the estimation errors can be reduced by adapting the waveform. This eventually results in optimization of collected data.

The process of information retrieval from their environment includes the update of transmitted waveform which supports the next step. This whole process is so sophisticated that it ultimately speaks out the manifestation of a higher power. The process in bio sonar like mammals is very interesting, where these waveforms with nonlinear time and frequency signatures are uniquely found more conductive to adverse environmental conditions.

It also looks quite interesting to note the similarities in concepts of these mammals and radar, as both of them detect their targets by wave transmission and reception from the surrounding environment which are further processed for acquiring desired data.

In this work radar and more specific Synthetic Aperture Radar (SAR) is the focus. SAR has the ability of imaging the surrounding and could be considered as an important sensor for aircraft, similar to echolocation for a bat.
1.1 State of the Art

It is illustrated in [1] that a UltraWide Band (UWB) radar system working at low frequencies is most probably effected by Radio Frequency Interferences (RFI) compared to Narrow Band (NB) radar. These interferences are from different radio links operating at that place or broadcasting systems like radio and television system. An other source of interference may be the wireless mobile networks like GSM systems. Different algorithms and techniques could be applied for estimation and removal of this sort of interference which are no doubt disturbance for a radar system. These interferences cause problems in accurate target detection.

In [2] and [3] Adaptive Line Enhancement (ALE) with Normalized Least Mean Square (NLMS) is proposed for RFI suppression. Both have introduced almost the same idea and tested on a real low frequency UWB SAR system. In [4] ALE with Least Mean Square (LMS) algorithm is proposed to eliminate the RFI from radar signals. Also [5] has proposed a scheme to remove RFI in frequency domain by using the method of Amplitude Normalization. In [6] an other method of RFI suppression is proposed, which is an adaptive technique of auto regression process, modeling the interference power spectral density further used for RFI estimation and suppression. The concept of [7] is something different from previous techniques, using the method of Maximum Likelihood (ML) estimation for RFI suppression.

1.2 Motivation for Thesis

Radars must have to operate in and combat with the presence of noise, the signals emitted from other systems operating around it such as jammers. In common practice, the main source of noise in electronic devices is thermal noise which is mainly due to thermal excitation of electrons caused by heat. The source of heat can be the environment (sun, earth, room temp., humans, etc.) or by electronic equipment itself. Mostly in radars the predominant source of heat is the electronic equipment.

Usually when radar transmits pulsed sinusoid and when signal comes back after reflection from target, the received signals usually have some problems like it doesn’t only have information but also some interfering signal in the form of noise, added to it. In some simple cases the only source of noise is Additive White Gaussian Noise (AWGN) but in most practical situations these interfering noises can be from different sources like other communication systems or may be unwanted reflections from targets. Then, the detection process is performed, to decide whether or not target is present at a particular location. From some parametric estimation, receiver processes the signal to measure the characteristics of the target e.g. range, velocity or acceleration. The signal processing aspect is also considered here. In this thesis, we have addressed issues like:
• Describing reflective characteristics of the target e.g for transmitted signal \( S_t(t) \), detecting reflected signal \( S_r(t) \).

• Effects of transmission channel on signal.

• And description and characterization of interference and for that we have to consider the interference sources or clutters in addition to receiver noise.

So in view of all these considerations, we will finally be able to design an optimum or sub optimum receiver and will evaluate its performance.

The main focus of this thesis is Synthetic Aperture Radar (SAR) which is a special kind of radar. SAR operating at UWB low frequency is effected by RFI signals of very high energy, which is an extremely serious issue.

In view of this problem, an efficient approach is needed to suppress RFI and retrieve a high quality SAR image. For this purpose an adaptive filtering technique with ALE using Recursive Least Square (RLS) algorithm is being proposed and implemented in this thesis work.

1.3 Concept of RFI Suppression

RFI is one major problem for low-frequency UWB SAR system which is operating in VHF/UHF- bands. The main reason is that the same spectrum is usually in use for different other services like television, mobile communications, radio and cellular phones. Now, the question arises how to suppress such interferences.

In [8] it is illustrated that such radio frequency suppression can be performed into step wise manner like:

• Developing a model for the interfering signals.

• From measured data, estimation of parameters of interfering signals.

• And finally using these parameters for suppression of interference

Where as the RFI suppression methodologies can be placed in following main categories [9]:

• Temporal domain rejection (most effective in case of dealing with strong and spiked bursts of RFI).

• Frequency domain rejection (effective for weak, SIR of -70 dB, and long-lasting RFI signals).

• Spatial filtering (using difference between direction of arrival of signal of interest and RFI)
The main goal of this thesis as illustrated before is the suppression of RFI that comes from a GSM system which is operating in same frequency range as used by the radar system. The whole work done is on a SAR system, which extract information from pulses received by the radar system to form a SAR image. Interfering Radio Frequencies (RF) are detected as noise sources and finally suppressed. Finally the experimental work is done in a laboratory environment.

1.4 Review of Chapters

Chapter 2: is about Radar systems in general, its design, different modules and how it works. Functioning of different components of a radar system is also explained. We also introduce a basic concept of radar transmit and received pulse. Further we discuss how the wave form scheduling is performed. If the reader has this much basic knowledge about radars he is recommended to move on to the next chapter.

Chapter 3: is about Synthetic Aperture Radar (SAR) systems. Principle of SAR and how SAR works are the main topics of this chapter. It also illustrates the SAR imaging geometry. This study will be proved helpful for the understanding of SAR image processing and further how SAR image is formed from raw SAR data.

Chapter 4: is one of the main chapters of this thesis which gives the detailed illustrations of how SAR data is collected and how Image Formation is done. Further, it gives some information about different algorithms applied on the SAR raw data. One of the important time domain SAR processing algorithms, Global Back Projection (GBP) is applied on raw SAR data and is discussed in detail.

Chapter 5: Studying the GSM signal modeling is also an important part of this thesis, because the main source of interference in the investigated SAR system is considered to be due to this wireless communication system for civil use. While it is also very important to know about adaptive algorithms and application that are going to be used for this Radio Frequency Interference (RFI) suppression. These two important topics makes the main sections of this chapter.

Chapter 6: gives the idea of data acquisition, addition of noise (interferences) in SAR Image for testing. Further data is acquired and added to the interference to create an RFI distorted SAR system. This is the main part of this thesis in which Recursive Least Mean Square (RLS) algorithm is applied for interference suppression. And finally results after interference suppression, are presented.
Chapter 7: The final chapter is the summary of my thesis work. In this chapter I have commented my work which is in fact a sort of analysis report of the work done. I have analyzed my results in context of expected results, based on laboratory work.
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Chapter 2

Radar System Engineering

The word RADAR is short for Radio Detection And Ranging. Radar is using modulated waveforms and directive antennas for the transmission and reception of electromagnetic energy in some specific direction or volume space for search of a target. If the object (target) is present within the search volume, it will reflect a portion of this energy (Radar echoes) back to the radar. These echoes are then used and processed by radar receivers for extraction of target information e.g. range, velocity, angular position or other required target identifying characteristics [10].

The range or distance is found by time, a wave took to hit the target and come back to radar. Angular location of the target is found with a directive antenna (with a narrow beamwidth), sensing the angle of arrival of echo signal [11]. The moving targets e.g. aircrafts induces a shift in frequency of received echo signal due to doppler effect.

Radar can also discern something about the nature of a target (size or shape) with sufficient resolution. We can obtain radar resolution in angle, range or both. Large bandwidth is required for high range resolution but large antenna is required for high angle resolution. If there is relative motion between individual parts of the target and radar, inherently resolution in doppler frequency can possibly be used for resolving the cross range dimensioning [12]. SAR azimuth resolution for the image sensing such as terrain could be explained as being due to resolution in doppler, although a SAR is usually thought of generating large synthetic antenna by sectoring received signal in memory.

Radar operates from few megahertz (HF, or high frequency electromagnetic spectrum) to optical region (laser radar). So the implementation of radar differs greatly over this range of frequencies, but basic principle remains the same.

RADAR was developed with the main aim to satisfy the needs of military surveillance and weapon control. Due to these applications radar technology has rapidly developed due to lots of funding. Apart from this application, radar has also significant civilian usage for safe travel of aircraft, ships and spacecrafts, also remote sensing of environmental situations, especially weather, law enforcement
and other applications.

2.1 Radar Classifications

There are many classifications for radar systems like ground based, air borne, space or ship borne system. Also there are some special categories based on specific characteristics, like frequency band, antenna type and waveform utility. Also depending upon mission and / or functionality, on the bases of which they can also be classified such as weather, acquisition and searching, tracking, track-while scan, fire control, early warning, over the horizon, terrain following and terrain avoidance radar. Phase arrayed or multi-functional multi-mode radars, are popular in usage. They usually has many radiator antennas from composite phase arrays. They are most important in applications like synthesis of narrow directive beams which may steer mechanically or electrically. By controlling phase of the electric current feeding to the array elements, electric steering is achieved thats why they are named phase array.

Mostly, radar is classified by types of waveforms or operating frequency they use e.g. Continuous Wave (CW) or Pulsed Radar (PW). CW radars uses separate transmit and receive antennas and may emit continuously electromagnetic energy. CW radar can accurately measure targets radial velocity (doppler shift) and angular position. These types of radar systems are most popular in usage for target velocity search and track, and missile guidance [11].

But target range information needs some form of modulation, for that reason this type of radars mostly are not good in such applications. In such application another type of radar systems is commonly introduced which are Pulse train Waveforms radar using pulsed radar which is usually modulated. But here in this category radar can be further classified based on Pulse Repetition Frequency (PRF); which is how much pulses are repeated per second in traveling along platform [13] e.g. low PRF, medium PRF and high PRF radars. For applications like target ranging where doppler shift target velocity is not of interest, the low PRF radar are used, on the other hand if high precision for measuring target velocity is required, high PRF is used. So, using different modulation schemes, both CW and PW radars measure target range and radial velocity.

Any device that can detect and locate a target via electromagnetic radiation and scattered echoes from target can be a radar [12]. Letter designation that used in the table 2.1 is of practical considerations for all radar engineers, to denote the general bands of frequency in which radar operates. These bands are universally used. These code letters (P,L,S,X and K) were introduced during World War II for the purpose of secrecy. And then they remained as it is, even afterward.

Principle of reflection from ionosphere for target detection over horizon is used in High Frequency (HF) radars. Very High Frequency (VHF) and Ultra High Frequency (UHF) bands are used in long range Early Warning Radars (EWR).
Table 2.1: Radar Frequency Bands

<table>
<thead>
<tr>
<th>Letter designation</th>
<th>Frequency (GHz)</th>
<th>New band designation (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.003 - 0.03</td>
<td>A</td>
</tr>
<tr>
<td>VHF</td>
<td>0.03 - 0.3</td>
<td>A&lt;0.25; B&gt;0.25</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3 - 1.0</td>
<td>B&lt;0.5; C&gt;0.5</td>
</tr>
<tr>
<td>L-band</td>
<td>1.0 - 2.0</td>
<td>D</td>
</tr>
<tr>
<td>S-band</td>
<td>2.0 - 4.0</td>
<td>E&lt;3.0; F&gt;3.0</td>
</tr>
<tr>
<td>C-band</td>
<td>4.0 - 8.0</td>
<td>G&lt;6.0; H&gt;6.0</td>
</tr>
<tr>
<td>X-band</td>
<td>8.0 - 12.5</td>
<td>I&lt;10.0; J&gt;10.0</td>
</tr>
<tr>
<td>Ku-band</td>
<td>12.5 - 18.0</td>
<td>J</td>
</tr>
<tr>
<td>K-band</td>
<td>18.0 - 26.5</td>
<td>J&lt;20.0; K&gt;20.0</td>
</tr>
<tr>
<td>Ka-band</td>
<td>26.5 - 40.0</td>
<td>K</td>
</tr>
<tr>
<td>MMW</td>
<td>Normally &gt;34.0</td>
<td>L&lt;60.0; M&gt;60.0</td>
</tr>
</tbody>
</table>

For example Ballistic Missile Early Warning System (BMEWS) search and track mono-pulse radar operate at 245 MHz. L band radar systems are mostly ground based and ship based systems which are usually used in long range military and air traffic control search operations. Also, most of the ground based or ship based radars are S-band systems like Air Surveillance Radar (ASR) that is used in air traffic control. In applications like weather detection, medium range search and fire control military radar uses C-band. Applications in which size of antenna constitutes physical limitations; including military multimode airborne radars, are using X-band. For fine detection with no tolerance for atmospheric attenuation of high frequency band X-band may also be used. Higher frequency bands (K and Ka) are more prone to the atmospheric attenuations that’s why they are used for limited and short range applications like police traffic radar. In short range Radio Frequency (RF) seekers and experimental radar systems the Milli-Meter Wave (MMW) radars are used.

2.2 Basic Components of Radar and Range Calculation

To have the knowledge of technical nature of radar is really important. This varies between application to application and make the topic of radar rather complex. Though the complete details of radar is highly complicated to understand exactly. The principle of operation are however essentially the same.

Figure 2.1 showed block diagram of the radar system. It is a basic functional diagram of the system, which comprises different components. The Timing Module act as synchronizer or modulation generator, timing the transmitted sig-
Time information ultimately plays an important role in range calculation for the radar system. The Transmitter, continuously generate the pulses to transmit high energy radio frequency pulses which eventually enters to Transmitting Antenna. Here note that for a monostatic radar system the same antenna act as transmitting and receiving antenna depending on mode, controlled by duplexer. Basically duplexer is responsible for same antenna to act as transmitter as well as receiver for different modes by using switching operations. Radar electromagnetic energy is directed towards antenna in transmission mode. While on the other hand radar is directed to receiver when reception mode is on. The pulses transmitted are always in highly directional mode and received echoes are passed to receiver, where after amplification these pulses are used as video pulses for location of target, displayed on indicator. In this block diagram, two important modules are not mentioned, but still they also have an important role to play for the system i.e indicator or displayer and power supply generators. Where power supply provide Ac-Dc voltages required for system component operation.

The amplified received pulses are further prepared to process in Signal Processing device module. Signal Processor performs the extraction of target information [11]. Targets range, R is computed by measuring $\Delta t$, time delay; time to take a pulse to travel two way path between radar and target.

$$R = \frac{c \Delta t}{2}$$

(2.1)

where $R$ is in meters, $\Delta t$ in seconds and the factor $\frac{1}{2}$ accounts for two way time delay and $c$ being the speed of light $3 \times 10^{8} m/s$.

Usually, pulsed radar transmits and receives a train of pulses. Which are $T_s$ seconds apart, called the Inter Pulse Period (IPP) or Pulse Repetition.

In general, the equation most popular with the name of radar range equation is:

$$P_r = \frac{P_t G_t \sigma A_e}{[4\pi R^2]^2}$$

(2.2)
Where $P_r, P_t$ are receive and transmit powers respectively, $G_t$ is transmitter antenna gain, $R$ is the distance or range of radar, while $\sigma$ is the radar cross section and $A_e$ radar antenna effective area respectively.

In fact the radar equation is the most useful description of factors influencing the radar performance and also characterizes radar received signal. Radar equation also form a good basis for preliminary system design which provide a guidance for possible tradeoffs among various parameters for radar performance.

2.3 Target Detection and Estimation

For range information of targets, the transmitting and receiving signals reflected from targets are the main means of working for a radar system. Also, the unique techniques of modulations used in radar systems for detection are really helpful for accurate location of target. In the Figure 2.2 concept of target detection is illustrated where the aircraft is moving along the platform. It is important that different targets are distinguished by the echoes returned at different times. A practical limitation here is distinguishing these points along the track of aircraft are difficult with small antenna. So to overcome this problem instead of using a huge antenna which also not possible practically, many pulses are combined as observation points which helps in making a large synthetic aperture, much larger than length of the antenna used. This concept of target detection finally leads to the SAR system development, discussed in the preceding chapter in detail.

2.4 Radar Limitations

It is also important to go through the limitation of radar. This section encompasses practical limitations of radar systems in a real world scenario which may
come in front of us as failure of radar system.

Some of radar systems operate based on the system transmitting high energy pulses in a certain direction, which after hitting a target, bounces back some of the transmitted energy. Such types of radar transmit its signals in all directions by rotating. Here comes some limitation that some time radar only detect moving targets around it, now if a target is moving across a circular path around the radar and radar will detect it range based on doppler effect. The range will be continuously the same, as the distance of each point of circle is same from center. So this scenario limits the radar operation because for radar the target range comes, is same all the time and thus it is not able to detect it. Also if a target is in a hilly area where mountain height is higher than the flight altitude, radar signals can’t reach to it. So in this case the radar will also not be able to detect the target but this limitation depends on radar frequency and may not occur for radars operating at low frequencies. The third biggest limiting factor in radar operation is rain. During rainy season, when it’s heavy rain, the water absorbs energy. But still it depends on operating frequency.

The basic aim of discussing these limitation are that as SAR is also based on radar’s principle of operation so the same limitations are also applied to SAR.

This chapter provides a baseline for preceding chapters. We get to know how radar echoes are transmitted by radar system, which is also giving a basic concept of how SAR image data is formed from radar received signals. It also gives the information about SAR signal power and energy because the SAR image is the collection of many radar pulses as is discussed in this chapter. It is also important that from radar equation the SNR of SAR signal can be derived so system information can be further enhanced.
Chapter 3

Synthetic Aperture Radar (SAR) System

Large and small scale information gathering, like done in remote sensing, is an active field of research over decades and even now a days. This sensing is mostly done via different means by using special equipments installed i.e remote sensors. Here medium might be any, mostly optical cameras or microwave sensors and by using altitude flights like aircraft, spacecrafts etc.

To meet the modern time challenges in peace and war, remote sensing also become more important. The environmental conditions of the earth and political situation of regions are undergoing rapid changes. In view of all these situations, remote sensing is getting much importance. To monitor the depletion and desertification of earth conditions and to keep look on land and territorial boundaries, all speaks out importance of the remote sensing applications.

After the first SAR invention in 1951 by Carl A. Wiley [14], who was a mathematician at Goodyear aircraft, it got much attention, using for military and civilian applications. It could produce a narrow effective beam and giving fine azimuth resolution.

It is also very important to know the main difference between SAR and common radar before going in further details of SAR and SAR processing. Which is also important for better understanding the proper functioning of a SAR system. In SAR many pulses are integrated together thus synthesized a theoretical longer aperture antenna.

SAR systems can be used in many form of configurations. It may be single antenna mounted on moving platform (airplane or spacecraft) imaging a target scene or may be many low directive small stationary antennas scattered near target area described in [15]. Target is identified by waveform echoes received and post processed.
3.1 How does SAR Works

SAR basically produces a two dimensional image, with two coordinates in the image i.e range the measure of line of sight distance from radar to the target and azimuth. This range and azimuth measurement in SAR is almost same as in other radars [15]. In this regard the precise measurement of time for transmission of pulses to receiving echos from target is really important. The range resolution is measured by measurement of pulse compressed signal’s pulse width. Thus mostly a narrow pulse will result in fine range resolution.

![Figure 3.1: Resolution Limits for SAR](image)

The azimuth is always perpendicular to the range. In SAR, azimuth distinguishes it from normal radar in terms of fine azimuth resolution. Physically larger antenna is required to focus transmitter and receiver energy to a sharp beam, which defines azimuth resolution. On the other hand also beamwidth plays an important role in synthetic aperture length. Narrow synthetic beam produces larger synthetic aperture. Figure 3.1 shows the parameters that effect SAR image resolution. Length of synthetic array, $L$ is dependent on beamwidth $\theta_B$ of antenna.

3.2 SAR Applications

SAR is useful for a wide range of applications like mining [16], sea and ice monitoring as illustrated in [17], oil pollution monitoring, oceanography [18], snow monitoring [19], and also in applications like earth terrain classification [20]. This is the reason due to which SAR systems are used in a number of airborne and space borne systems. Apart from these application a popular application of SAR now a days is exploration of other astronomical bodies in space like moon and other planets.
3.3 SAR Systems

NASA Jet propulsion Laboratory (JPL) developed a polarimetric airborne system that was loaded on CV-990 aircraft system [21] which got a lot of attention. It was operated at frequency of 12 MHz (L-band). In July, 1985 a new imaging SAR (AIRSAR) was built by JPL which incorporated all the characteristics of previous CV-990 L-band SAR. After that, NASA launched SEASAT for remote sensing of oceans, which was using the L-Band frequency of 1.175 GHz [14]. It is important to note that the polarimetric airborne system served as prototype for all imaging radars and space borne systems developed by NASA.

Brigham young university developed a less expensive and light weight SAR, who was easy to transport [22]. In this system a baseband chirp is generated by a low cost 200 MHz Arbitrary Waveform Generator (AWG). Also Double Side Band (DSB) modulation technique was used for chirp transmission and reception to reduce the cost.

Among the most popular commercial air borne SAR system, the STAR-1 and STAR-2, are X-band system [23]. European Earth Remote Sensing satellite (ERS-1), developed by European space agency is C-band with vertical polarization system. These all systems developed are mostly designed for scientific operations. The other most popular system like EnviSat was launched in 2001 by European Space Agency (ESA). Which was the largest earth observation satellite, orbiting around earth at an altitude of 790 km [24].

Recently working under Swedish Research Agency(FOI), researchers developed different highly efficient SAR systems, among which the most popular are CARABAS-II systems(20-90 MHz), LORA in VHF- and UHF band(200-800 MHz). While the US systems includes P-3 in 215-900 MHz with bandwidth of 515 MHz, ground based Boom SAR in 50-1200 MHz. While PAMIR operating in X-band with effective bandwidth of 1820 MHz [1], a German system.

In this thesis the same specification as LORA, a low frequency UWB SAR with operational frequencies in the range of VHF/UHF, has been used.

3.4 Description of Imaging Radar

In the Figure 3.2 the imagery radar geometry is shown. It shows a 3D geometry of SAR system. So combining the concepts of both Figures 3.1 and 3.2, we can get some idea that how SAR system construct SAR image. Almost all parameters that are used in SAR image formation are illustrated. Range, the distance between aircraft flying and the target. Azimuth, relating to aircraft positions and orthogonal to range. Where pulselength is the measure of how far the two pulses are received from each other which is usually in terms of samples. Also it is important to note that the range is varied with target angle or azimuth.

So these all parameters are used in construction of the final SAR image and
image is defined in terms of these parameters. Usually the radar map provides high resolution in both range and azimuth dimensions. Which is achieved by using Linear Frequency Modulation (LFM). So using the techniques of transmitting chirp signals and pulse compression. From [25] we find the cross range resolution $\Delta$ for SAR.

$$\Delta = \frac{R\lambda}{D}$$

where $R$ is the range, $D$ is the physical dimension of the antenna or length of synthetic aperture and $\lambda$ being the wavelength. From this equation we can easily guess that to achieve a fine cross range resolution of SAR it is necessary to increase length of Synthetic aperture as large as we can. So it is one of the theoretical limiting factor.

This chapter ends with this enough introductory information about the fundamental concepts of SAR system. In this chapter we have developed a baseline for the proceeding chapters, about chirp, pulse compression and data matrix formation for raw SAR data, followed by SAR processing by one of the suitable algorithms, which is chosen for this system.
Chapter 4

SAR Image Formation and Processing

Importance of imaging sensor systems, which is well established, is only effective when its sensed image is largely beneficial in contrast for detection. Same is applicable to SAR, being an important image sensory system due to fine gathering of information for target’s image formation and processing for refined sensing.

This chapter is about how image formation is performed from collected SAR raw data which is an important step towards proceeding further. In SAR, data processing algorithms are performed to get a high resolution image. High spatial resolution, an important parameter for any image sensing system, for SAR images are achieved through processing two dimensional images into azimuth or flight direction and distance or range directions. For this purpose along with the use of synthetic aperture antenna, the backscattering energy is integrated by SAR processing.

The SAR systems’s biggest advantage is that it gives images of good resolutions in day and night mode and also its effectiveness for any climatic conditions due to SAR processing. Keep in mind that the bandwidth of signal, system precision and post processing techniques plays an important role in image’s resolution through which we generate a suitable SAR image.

4.1 UWB SAR

Before going into details of SAR image construction it is required to first know ultrawide band SAR system. UWB SAR is a newly emerging technology that is in wide use these days. It is now an active filed for researchers. These ultrawide band systems using extremely large bandwidth i.e greater than 500 MHz, developed in last decade to provide finer resolution images.

UWB is high bandwidth communication system using larger portion of radio spectrum thus help to attain very high resolution. Due to these unique character-
istics, it is commonly preferred to use for non co-operative radar imaging, target sensor data collection, precision location and tracking applications.

4.2 Chirp Signal

A chirp signal is used in most radar systems because it allows long pulses with low output power from antenna to be transmitted or received that’s why much energy can be transmitted.

Generally, we define chirp signal in which frequency either increases with time called up – chirp or decreases with time called down – chirp. They can also be categorized as linear in which frequencies linearly increases or exponential chirp in which the rise or fall in frequency is exponential. We have used linear chirp technique in this thesis.

It is also important to note that signals in common practice, uses normal modulations i.e frequency changes over time but compare to it chirp signals are totally different. They are different because in these signals time varying over frequency is observed. Which means they sweep linearly or exponentially from low frequencies to high or vice versa. So to get such situation we usually needs to modify equation of sinusoid which are frequency varying thus if, [26]

\[ x(t) = Asin(\theta(t)) \]  

Where \( \theta(t) = 2\pi ft \). Then instantaneous angular frequency is :

\[ w_i(t) = \frac{d}{dt} \theta(t) \]  

Considering phase as quadratic instead of linear, an assumption from which we will finally find linearly varying chirp signal. So letting

\[ \theta(t) = 2\pi \mu t^2 + 2\pi f_c t + \phi \]  

\( \phi \) being phase of signal. So

\[ w_i(t) = \frac{d}{dt} (\theta(t)) = 4\pi \mu t + 2\pi f_c t \]  

From which we found the instantaneous frequency in \( Hz \)

\[ f_i t = 2\mu t + f_0 \]  

This expression shows that frequency is no longer constant but linearly varying over time. We now get that:

\[ f_t = f_c + kt \]  

So, then

\[ f'_t = f_c + kt' \]
From (4.1) we found that

\[ S_t(\tau) = \exp(j2\pi(f_0 + \frac{k\tau}{2})\tau) \]  \hspace{1cm} (4.8)

Where \( k \) is the chirp rate, “Rate of change of instantaneous frequency of input signal waveform”, is equal to

\[ k = \frac{B}{t_{dur}} \]  \hspace{1cm} (4.9)

Similarly for exponential chirp:

\[ S_t(\tau) = \exp(j2\pi f_0 \frac{k\tau}{\ln(k)} - \frac{1}{\ln(k)}) \]  \hspace{1cm} (4.10)

\( \tau \) is the time vector \([t_{p1} - t_{p2}]\) and \( f_0 \) is the lowest frequency used for generating chirp signal. Figure 4.1 shows the transmitted chirp signal using linear chirping

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{transmitted_chirp_signal.png}
\caption{Transmitted Chirp Signal}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fft_transmitted_chirp_signal.png}
\caption{FFT of Transmitted Chirp Signal}
\end{figure}

, while Figure 4.2 shows its frequency spectrum found by taking the Fast Fourier Transform (FFT) of the chirp signal.

4.3 Pulse Compression and Matched Filtering

To get much shorter pulses the next step performed on the chirp signal is pulse compression which is done for generating high energy pulses of very short time duration. Pulse compression is done by matched filtering.
This linear frequency modulated signal having reduced peak power provide an advantage. The signal amplitude should be constant at receiver, so by using pulse compression filter we obtain much shorter pulses for radar transmission.

Thus pulse compressed signal has obtained after derivation in [10], by matched filtering is:

\[
S_{pc}(\tau) = \int_{-\infty}^{\infty} e^{-2\pi i (\phi_0 + f_c (t' - \tau_d) + \frac{1}{2} (t' - \tau_d)^2)} e^{2\pi i (\phi_0 + f_c (\tau_d - t') + \frac{1}{2} (\tau_d - t')^2)} rect\left[\frac{(t' - \tau_d)}{T}\right] \, dt'
\]

(4.11)

An important feature to note here is about rectangular function used for rectification which is convolved with matched filter to find received final pulse compressed signal. Pulse compression could be done by convolving the delayed chirp signal with the time reversed conjugate of the transmitted pulse. This is easy to implement and quite accurate method for pulse compression mostly used in practical radar systems.

\[
m(\tau) = \text{conj}(S_t(-\tau))
\]

(4.12)

The above integral is solved for following four cases giving up final received pulse compressed signal:

\[
S_{pc}(\tau) = \begin{cases} 
0 & \text{for } \tau - \tau_d < -T \\
\int_{\tau_d - \frac{T}{2}}^{\tau_d + \frac{T}{2}} I \, dt' & \text{for } -T < \tau - \tau_d < 0 \\
\int_{\tau_d - \frac{T}{2}}^{\tau_d + \frac{T}{2}} I \, dt' & \text{for } 0 < \tau - \tau_d < T \\
0 & \text{for } \tau - \tau_d < T
\end{cases}
\]

(4.13)

Match filter will compress signal to a relatively narrow pulse. Which is significant in context to augment the range resolution as well as the Signal to Noise Ratio (SNR) during reception, thus improving the performance of system. Figure 4.3 shows the signal for Matched Filtering. Uncompressed signal is shown in Figure 4.4 while it is also shown in frequency domain in Figure 4.5, which is then convolved with signal for match filtering of Figure 4.3 to give results shown in Figure 4.6 whose frequency spectrum is shown in Figure 4.7.

The selection of this match filtering is in accordance with to attain a maximum SNR.

### 4.4 SAR Raw Data Generation

SAR system is continuously transmitting series of pulses for which the corresponding series of samples are collected from antenna. All samples are collected and arranged in a two dimensional data set or received matrix also called SAR raw data.

The arrangement of this data follows a special pattern, first data point from each range line always lies to the top while the last data received from range
Figure 4.3: Signal for Matched Filtering

Figure 4.4: Uncompressed Received Signal

Figure 4.5: FFT of Uncompressed Received Signal
Figure 4.6: Pulse Compressed Signal

Figure 4.7: FFT of Pulse Compressed Signal

Figure 4.8: SAR Raw Data
will lie to the bottom [27]. This pattern has also another information in it i.e.
strength of the received signal with reference to point target, for different points
and aperture positions. Figure 4.8 show SAR raw data plotted without making
any kind of process to data which is an image of unfocussed raw data.

For SAR raw data generation we have made some assumptions i.e Pulse Repet-
tition Frequency (PRF) is 100 pulse/sec when our airplane, on which SAR system
is installed, is moving at a height of 1000 m with a speed of 100 m/s. The syn-
thetic aperture length L is considered as 2000 m.

4.5 SAR Signal Processing and Image Formation

Main goal of SAR processing is the determination of range and azimuth where
target lies at the mid strip map or foot print area. Figure 4.9 roughly shows how

Figure 4.9: SAR Signal Processing Diagram

systematically this process is done.

4.5.1 SAR Processing Algorithms

Most of the early SAR systems were using frequency domain SAR processing
 techniques which were though computationally efficient but were only applicable
for linear cases like e.g the platform is straight, speed is constant and there is no up
and down motion of the aircraft. Among most important algorithms of this type
are Range Doppler Algorithm (RDA) a two dimensional correlating process [28],
Range Migration Algorithm (RMA) which are implemented in frequency domain.

The most practical approach now a days used in SAR processing is to perform
in time domain. The most important examples of time domain SAR processing
algorithms are Fast Backproject (FBP) and Global Backprojection (GBP) [17].
From GBP very accurate results are obtained. In [10] an other important time
domain approach is illustrated which is also a type of BackProjection (BP), the
Local Backprojection (LBP). While this thesis focus on implementation of GBP.
4.5.2 Global BackProjection (GBP)

Global Backprojection (GBP) is one of the important backprojection methods working in time domain. GBP operates in cartesian coordinates that's why the sub aperture and final image formed is in cartesian coordinate. From [3] and [29] we can have an idea how to implement the GBP algorithm. Figure 4.10 shows that how we implement this algorithm. We considered a footprint area of $N \times M$ where our target most probably lies, while in MatLab we will consider a 100 X 100 empty matrix and then fill it with data. Now each point in this area is each pixel of our SAR image $x_{image}$, that we found.

GBP work on all pulses together which are coming from different sub apertures. Each pulse is spaced $\frac{1}{f_s}$ samples apart from each other. It is also important that three dimensional coordinates of all pixels are known [30] which are arranged in rectangular cartesian grids. Now, the location of corner pixels and displacement vectors in range and angular direction are defined. In this way, distance of each pixel from our platform or flight is determined. We also found $\Delta x$ and $\Delta y$ to get our footprint area to (0,0) position. We have also considered that our synthetic aperture length is $L=2000$ m. Now by using equation (4.14), we found exact position of our target.

$$R = \sqrt{(x_a - x_p)^2 + (y_a - y_p)^2 + (z_a - z_p)^2}$$  \hspace{1cm} (4.14)

Where $x_a$ is the $x$-coordinates of air plane position that is continuously changing over $L$ and also $y_a$ and $z_a$ are $y$ and $z$ coordinates of airplane. Similarly $x_p$, $y_p$ and $z_p$ are $x$, $y$ and $z$ coordinates of the target in footprint area. Where $x_p = \Delta y + x_{image}$ and $y_p = \Delta x + y_{image}$. Where $x_{image}$ is the each pixel position in
NXM footprint area as illustrated before. SAR image is formed finally from the pulses received from each sub aperture which are arranged in the NXM matrix previously considered. By plotting range vs azimuth, will give the position of our target in terms of range and azimuth. GBP has importance to apply here as it is simple and easy to implement algorithm giving accurate and easy to understand positioning information of our target. Figure 4.11, image of the point target which is generated by using GBP algorithm. In this process we haven’t used any sort of interpolation. Instead we just applied round function. The FFT of SAR processed image as is shown in Figure 4.12. In these situations any of the interpolation method can be used as proposed in [10] and [28] which are applied for interpolation noise minimization in SAR image.

The process described can also be implemented by integrating all pixel’s position in foot print area over the range of target from plate form or flying air plane which is illustrated in [29] and [10].

With the generation of SAR image this chapter is closed. Now next we will discuss how to generate and acquire GSM transmitted signal in the next chapter. This GSM signal will add up to our received signals as a source of external interference from environment. Also adaptive filtering especially Recursive Least Square(RLS) is discussed which is applied for suppression of added interference to the SAR image.
Figure 4.12: FFT of SAR Processed Image
Chapter 5

Radio Frequency Interference

In the last chapter we have discussed SAR system simulations that generated a SAR image. Also in the start of the thesis we also have discussed about the RFI in SAR systems. We have illustrated some work done on RF interference cancelation by a number of researchers, using different methods and algorithms designed for this purpose.

This chapter is enlightening one of the biggest source of this interference i.e GSM signal. We can also say this chapter is dedicated to the preparation of RF interference module and also on the other hand the suppression module as well.

In the first part of chapter we have presented fundamentals of the GSM model while the second part is about the introduction to adaptive algorithms, which has special emphasis on RLS algorithm.

5.1 Global System for Mobile communication (GSM) Model

GSM is the most widely known standard communication technology now a days. Which is widely used in almost each corner of the world. Most of the statistics tells that about 4.3 billion people from more than 212 countries and regions of the world are using this technology. GSM is using a special kind of modulation scheme which will be further discussed in next sections i.e Gaussian Minimum Shift Keying (GMSK) a special kind of Frequency Shift Keying (FSK), is usually used in this system.

5.1.1 GSM Carrier Frequencies

GSM is a 2-2.5 G standard which is operating in different range of frequencies in different regions and environments of the world. The most popular band of frequencies used in most regions is standard 900/1800 MHz. While in some regions it may be 850/1900 MHz, in case the above band of frequencies are already
in use in some other communication systems. It is also important to note that in some regions of the world, usually desert areas, rarely 400-450 MHz frequency bands are also in use. 2100 MHz band of frequency is now in use, in most of the European countries.

GSM is somewhat different from previous generations of communication systems as being using an approach of Time Division Multiple Access with Frequency Division Multiple Access (TDMA/FDMA). Which means that each user is allocated a time slot along with a particular frequency to be used for making a connection. These TDMA frames might be eight full rate or sixteen half rate speech channels per radio frequency. The data rate for all channels are usually 270.83 Kbps which is exactly four times the RF frequency shift while the frame duration is 4.615 ms.

Apart from above specification the transmission power also matters. Usually the transmission power for 850/900 systems ranges in 2 watts while for 1800/1900 systems it is almost 1 watt.

Another unique feature of GSM which really important to note is that the uplink and downlink frequencies are always different i.e frequency with which Mobile Station (MS) transmits to Base Station Transceiver (BTS) and BTS to MS is always different. So it is relevant to note that what is the interfering signal frequency mixed with SAR signal. Generally the uplink frequency in GSM is always higher than down link frequency to prevent second channel interference problem.

5.1.2 GMSK Modulation

In [31] GMSK modulation is described for GSM system. Also Figure 5.1 shows the simplified block diagram of GSM transmitter. While [32] has illustrated the implementation and mathematical model of this GSM system. Here a(n) $a \in [0, 1]$ i.e dataIn may be a speech or data signal which is converted to four level antipodal sequence $b(n)$ and finally to rectangular pulse $r(t)$, which is passed through the gaussian filter. A special kind of filter with suitable impulse response, $h(t)$, is used for this purpose given in (5.3), while the transmitted GSM output signal is:

$$y(t) = \cos(\phi[t])$$  \hspace{1cm} (5.1)

where

$$\phi(t) = w_c t + 2\pi f_m \int_0^t g(t)d\tau$$  \hspace{1cm} (5.2)

$$h(t) = A_0/\sqrt{\pi\beta}e^{[t-(t_0)\beta]^2}$$  \hspace{1cm} (5.3)

GSM is also using a particular carrier frequency band which is already described in section 5.1.1. For transmission over channel the baseband GMSK signal is carrier modulated, attenuated and transmitted by antenna as is shown in Figure

\[ \text{Figure 5.1: Simplified block diagram of GSM transmitter.} \]
Chapter 5. Radio Frequency Interference

\[ (n) \quad r(t) \quad g(t) \]
\[ P(t) \quad \text{Gaussian filter} \quad \int \quad \phi(n) \quad y(n) \]

Figure 5.1: GSM Transmitter

![GSM Transmitter Diagram](image)

Figure 5.2: GSM Transmitted Signal

![GSM Transmitted Signal Graph](image)
5.2. Our signal of concern is the transmitted GSM signal as being a major cause of RF interference to our SAR signal. Thus we will use it to interfere with SAR signal on which the major part of the thesis concentrate i.e suppression of this interference by use of adaptive signal processing.

5.2 Adaptive Signal Processing and RLS Algorithm

Filtering is an important application in all communication systems that is used for finding desired spectral characteristics of signal. It can also reject unwanted signals like noises or interferences or may be reducing bit rate of signal, in some cases, in transmission.

Adaptive filtering is a filtering process in which parameters (filter coefficients) are altered according to signal shaping by using some algorithms that is done for tracking the signal shape [33]. They uses different application e.g. Adaptive Line Enhancer (ALE), Adaptive Noise Cancelation (ANC) etc. Apart from that it also uses many different algorithms like Least Mean Square (LMS), Normalized Least Mean Square (NLMS), Leaky Least Mean Square (LLMS), Recursive Least Square (RLS) etc.

Adaptive filters [5] are also being used in some radar applications. As illustrated in [2] and [3] they are used for interference cancelation by ALE with NLMS.

In this thesis we are using RLS for interference suppression. Like other Least Square Estimation (LSE) algorithms, RLS also estimate the coefficients of the filter to achieve the optimum filter update based on new observations. Where the statistical information related to the unknown process is estimated from acquired data as denoted by [34]:

\[ s[n] = [s(n), s(n-1), \ldots, s(n-p+1)]^T \]  \hspace{1cm} (5.4)

For which the corresponding time varying FIR filter at time \( n \) is:

\[ w(n) = [w_0(n), w_1(n), \ldots, w_{p-1}(n)]^T \]  \hspace{1cm} (5.5)

And the estimated error will be:

\[ e[n] = d[n] - w^T[n]s[n] \]  \hspace{1cm} (5.6)

5.2.1 Exponentially Weighted RLS Algorithm

Exponentially weighting RLS is the most widely used RLS algorithm which is based on weighting or forgetting factor adjustment i.e \( \lambda \), for growing window.
Chapter 5. Radio Frequency Interference

Let's assume we have received the interfered SAR signal given as:

$$s(n) = \sum_{k=0}^{n} x(n) + v(n + 1) \quad (5.7)$$

Where we considered $x(n)$ as transmitted radar pulse while $v(n)$ being interfering GSM signal. So our goal is to suppress the interfering signal and recover the desired echo that we should receive actually. For which we will use the $p$-tap FIR filter, $w$:

$$\hat{d}(n) = \sum_{k=0}^{p-1} w_n(k)s(n - k) = w_n^T s(n) \quad (5.8)$$

We estimate parameters of $w$ by estimating $\hat{d}(n)$.

Principally RLS desires to minimize the cost function $J$, being related to $e(n)$ and depends on filter coefficients.

$$J = \sum_{i=0}^{n} \lambda^{n-i} e^2(i) \quad (5.9)$$

Where $0 < \lambda \leq 1$ is forgetting factor with which weight exponentially decrease compared with last samples. The choice of $\lambda$ is really important here. For smaller $\lambda$ the contribution of previous samples is small. While in RLS $\lambda=1$ is preferred to be used. From [35] we follow that weighted sample correlation matrix by using Woodbury matrix identity is,

$$P(n) = \lambda^{-1} P(n - 1) - g(n)s(n)P(n - 1) \lambda^{-1} \quad (5.10)$$

where $g(n)$ is gain factor given as:

$$g(n) = P(n - 1)s(n)[\lambda + s^T(n)P(n - 1)s(n)]^{-1} \quad (5.11)$$

So we arrive to weight update equation:

$$w_n = w_{n-1} + g(n)[d(n) - s^T(n)w_{n-1}] \quad (5.12)$$

where $\alpha(n) = d(n) - s^T(n)w_{n-1}$ is the a priori error.

Finally [35] has given a stepwise comprehensive summary of RLS implementation for error estimation.

A similar concept and procedure is described in [34] and [35]. That also has explained RLS algorithm which minimizes least square error instead of mean square error. At the end a comprehensive summary about how to implement RLS is given. Figure 5.3 shows the block diagram of RLS adaptive algorithms. RLS operates the same way as it is described in this figure. So each time adaptive filter parameters are updated according to varying interfering signal statistics to suppress the interference completely.
5.3 Adaptive Line Enhancer (ALE)

Apart from the suitable choice of adaptive algorithm, it is also important to choose proper application mechanism. In [1], [2] and [3] Adaptive Line Enhancer (ALE) is used along with Normalized Least Mean Square (NLMS) for the RF interference cancelation. The Adaptive Line Enhancer (ALE) is also being used together with Least Mean Square (LMS) algorithm in [4].

Adaptive Line Enhancer (ALE) shown in Figure 5.4 is one of the important adaptive application which is basically derived from Adaptive Noise Canceler (ANC). In [1] is described how ALE is implemented by using NLMS and it is also driven for RFI suppression. In ALE, the reference signal is delayed replica of the input primary signal, received distorted radar pulse in this case. So that if the auto correlation coefficient of the interference decay faster than that of the signal, but still the appropriate delay will ensure that signal component of the primary and secondary (delayed primary) will only be correlated but interference is not. And which ultimately helps to cancel out interference.

In the next chapter, the results of distorted single and multiple pulse, SAR image and the results after applying filtering are presented.
Chapter 6

RFI Cancelation

This chapter is dedicated to present the main work of my thesis i.e RFI suppression in SAR system. The chapter is mainly comprising of two sections with different sort of results from SAR system to be discussed. Mainly the chapter has summarized results and work done for RFI suppression in SAR. First of all we have seen how data acquisition is done, to show distorted SAR image with interfering signal. Then results are presented of RFI suppression by adaptive filtering using ALE mechanism applied by RLS algorithm.

6.1 Data Acquisition

In chapter 4 the results of SAR system are shown which are ideal and without any interference both for single and multiple pulses. The results of interfered and disturbed SAR system for same single and multiple pulses received are now given here.

Figure 6.1 shows disturbed single received radar signal whose amplitude seems to be more than hundred times than the original radar echo. The frequency domain plot is shown in Figure 6.2 where the dominance of RFI power spectrum is clear. Further, from this received signal we found pulse compressed signal shown in Figure 6.3 and its frequency spectrum in Figure 6.4.

The next series of figures are for distorted SAR image formed from multiple received signals. Which are pulse compressed signals received from different sub apertures. The output processed by GBP is shown in Figure 6.5 Whose frequency domain plot shown in Figure 6.6 give much detailed information that how much SAR image is effected by interfered signal’s frequency contents. Finally we see that the output image is not so good because it’s no more high resolution image.
Chapter 6. RFI Cancelation

6.2 Noise Cancelation

In this section the results of the interference canceled single and multiple radar signals are given. Adaptive filtering using RLS is applied on distorted received signal to suppress the interference. For this purpose an ALE mechanism is applied with filter order $M=32$. While for UWB radar signal and interference decorrelation, input reference signal with delay, $d_0=1$, is selected. The forgetting or exponential weighting factor $\lambda = 0.99$ and step size $\Delta = 0.009$ for RLS is being used. Final results are shown in Figure 6.7 to Figure 6.10. Which shows our success to suppress the GSM interfered signal in SAR system.

It is also important to note that it might be possible in some case that the estimated received signal has some loss of frequency components. It can be noticed that the characteristic RFI pattern has almost completely suppressed and thus point target can easily be located. Thus, these results show that using ALE mechanism with RLS algorithm, the interference added from GSM system has been removed. So we finally get a high resolution SAR image back. It is also important to note that RLS compare to other adaptive algorithms has high convergence speed and short learning time due to which it is faster. So to be used for eliminating such degradations it could be a better choice.
Chapter 6. RFI Cancelation

Figure 6.3: Disturbed Pulse Compressed Signal

Figure 6.4: FFT of Disturbed Pulse Compressed Signal

Figure 6.5: Distorted SAR Image Processed by GBP

Figure 6.6: FFT of Distorted SAR Processed Image
Figure 6.7: Pulse Compressed Signal after RFI Suppression

Figure 6.8: FFT of Pulse Compressed Signal after RFI Suppression

Figure 6.9: RFI Suppressed SAR Processed Image

Figure 6.10: FFT of RFI Suppressed SAR Processed Image
Chapter 7

Real Data Results and Conclusions

All knowledge we have is based on doing experiments and making measurements which is the main idea behind error analysis. The extraction of meaningful conclusion from acquired data is really important. So for that reason we consider the issue of understanding cruciality in the uncertainty of the physical quantities which needs attention. It is important what we measure is exactly accurate. But in some cases it becomes so difficult. But we have to do our effort to minimize the error to our best extent.

This chapter present analysis of main work done in thesis. These error analysis of results are done via testing results through lab experimentation. Which is performed at radar lab, Signal Processing Department, BTH. Based on the whole text and results of thesis I have finally presented the conclusion in the last section of this thesis.

7.1 Data Acquisition in Real World Scenario

Agilent E5071C ENA network analyzer has been used for testing purpose in the laboratory environment [36]. Using receive antenna connected to network analyzer we have acquired real time data of GSM system. By making a call and putting mobile phone in front of receive antenna. This data is saved as .csv files in network analyzer as is shown in Figure 7.1, which are generated equal to no. of samples we have in our SAR system. We then added this data with our SAR signal to generate RFI effected SAR image. Which is then passed through designed adaptive filter to suppress these interferences of GSM system. The observations of experimental results are some what different compared to simulation results. Because in simulation we have a very small spectrum i.e 890-890.0001 MHz with which received pulses are effected. But in laboratory, during acquisition of GSM data, the selected spectrum was in range of 700-950 MHz.
The real time data corresponding to range of 700-950 MHz frequencies is then being mixed (interfered) with SAR signal generated by simulation. We saw that this data has effected a large portion spectrum of our SAR signal i.e 450-975 MHz. Thus we observed the effects of RFI on SAR received pulses are worst.

Figure 7.2 to Figure 7.7 shows the interference effected and suppression results for SAR image before and after applying adaptive filtering on effected SAR image.

7.2 Conclusions

We have simulated low frequency UWB SAR system operating at UHF band in 450-975 MHz. Which has been interfered by P-GSM-900 system, locating around point target, with an Uplink frequency of 890 MHz in simulations. It is really important to consider these issues of interference and to nicely cater with because usually radiated power of RFI source is higher than reflected power of received back signal in SAR system.

So thinking in this direction the thesis has proposed a new fast and fine technique based on [3] using RLS algorithm implying adaptive filtering concept. Which has been finally tested via laboratory experimentation. The mechanism of ALE using RLS algorithm is being used. The visual inspection of the effected and refined results, clearly shows that the characteristic RFI pattern added to the image has almost been completely disappeared and the point target can easily be located.

During my thesis work I also come across some new ideas for future imple-
Chapter 7. Real Data Results and Conclusions

Figure 7.2: Distorted compressed pulse in frequency domain

Figure 7.3: Disturbed SAR Processed Image

mentation. By which the performance can be improved while the complexity of the research work can be reduced. RLS, though one of the fastest adaptive filtering algorithm but still has some minor issues in terms of complexity which is some what non practical solution for implementation in real system. It is only suitable for research and laboratory work but when we talk about practical solution for RFI suppression in real time SAR systems, in my opinion, I come across a new idea. This improved and practical technique is Kalman filtering, to be precisely an enhanced version of RLS, providing a more practical adaptive filtering approach.

During my research I also get to know that in some Voice Communication Systems(VCS) and practical radar systems these techniques of kalman filtering is common.
Figure 7.4: FFT of Disturbed SAR Processed Image

Figure 7.5: Pulse compressed signal after suppression

Figure 7.6: SAR Processed Image Interference Suppressed

Figure 7.7: FFT of SAR Processed Image Interference Suppressed
Bibliography


