



TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

Thesis NO: 070/MSI/616

A Thesis Report On
“An Adaptive Filter For
Clutter Suppression In Doppler Radar System”

By

Suhaag Shakya (070/MSI/616)

ERN:66365

SUBMITTED TO

Department of Electronics and Computer Engineering
Masters of Science in Information and Communication Engineering

November, 2015



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SUBMITTED TO THE DEPARTMENT OF ELECTRONICS AND COMPUTER
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DEGREE OF MASTER OF SCIENCE IN INFORMATION AND COMMUNICATION
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The undersigned certify that it has been read and recommended to the Department of Electronics and Computer Engineering for acceptance, a thesis entitled "**An Adaptive Filter For Clutter Suppression in Doppler Radar System**", submitted by **Mr. Suhaag Shakya** in partial fulfillment of the requirement for the award of the degree of "**Masters of Science in Information and Communication Engineering**"

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DEPARTMENT ACCEPTANCE

The thesis entitled "**An Adaptive Filter For Clutter Suppression in Doppler Radar System**", submitted by **Suhaag Shakya** in partial fulfillment of the requirement for the award of the degree of "**Masters of Science in Information and Communication Engineering**" has been accepted as a bonafide record of work independently carried out by him in the department.

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ABSTRACT

The clutter return presents a severe problem in detection of target in radar systems. Conventional frequency selective filter fails to distinguish clutter and echo from target since they have same frequency spectrum. This paper proposes an adaptive clutter suppression scheme. An adaptive digital filter processes a signal by employing an architecture having time varying parameters. The approach used in this paper is able to overcome the inherent limitations of conventional clutter cancelling techniques (e.g. Moving target indicator, delay line canceler etc.) having predefined filter coefficients. A LMS algorithm based adaptive FIR filter has been implemented for filtering in order to suppress clutter. Matlab simulation has been done to compare the performance of the adaptive filter with that of delay line cancelers. The result shows that the adaptive filter has better frequency response in the pass band than that of delay line cancelers. The filter have been tested with real micro rain radar data using two different scenarios, using rain phenomenon once as target and then as clutter. In both scenarios the filter has been able to cancel clutter.

Keywords: Radar, Clutter, Adaptive Filter, LMS Algorithm, Micro Rain Radar

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LIST OF ABBREVIATIONS

CA	Clutter Attenuation
FMCW	Frequency Modulated Continuous Wave
FIR	Finite Impulse Response
LMS	Least Mean Square
MTI	Moving Target Indicator
MRR	Micro Rain Radar
PRF	Pulse Repetition Frequency
PRT	Pulse Repetition Time
PSD	Power Spectral Density
PW	Pulse Width
RADAR	RADio Detection And Ranging
RCS	Radar Cross Section
SNR	Signal to Noise Ratio

1. INTRODUCTION

1.1 Background

The word radar is an abbreviation for RAdio Detection And Ranging. This technique is used to detect a remote object and find necessary information about it. RADARs are widely used in many applications like remote sensing, air traffic control, aircraft safety and navigation, law enforcement in highway traffic, ship safety, space applications, military and many more. The ability of RADAR in providing repeated information about the target(s), by repeatedly sending the transmitting signal, helps the operator to obtain detail information, like range, velocity, direction etc., about the target.

In general, radar systems use modulated waveforms and directive antennas to transmit electromagnetic energy into a specific volume in space to search for targets. Objects (targets) within a search volume will reflect portions of this energy (radar returns or echoes) back to the radar. These echoes are then processed by the radar receiver to extract target information such as range, velocity, angular position, and other target identifying characteristics [1].

Clutter is a term used to describe any object that may generate unwanted radar returns that may interfere with normal radar operations. Parasitic returns that enter the radar through the antenna's main lobe are called main lobe clutter; otherwise they are called side lobe clutter. Clutter echoes are random and have thermal noise-like characteristics because the individual clutter components have random phases and amplitudes. In many cases, the clutter signal level is much higher than the receiver noise level. Thus, the radar's ability to detect targets embedded in high clutter background depends on the Signal-to-Clutter Ratio (SCR) rather than the SNR [1].

In recent years, there has been a significant increase in the requirement for superior performance of radar in all areas of civil as well as military applications. One of the main areas of progress in a radar system today is its signal processing. With the advent of Very Large Scale Integration technology and FPGA, implementation of Digital Signal Processing algorithm on a single chip has become a reality. Radar signal processor (RSP) manipulates the received radar signal for extraction of desired information of moving target whilst rejecting unwanted clutters. The process of target detection becomes a challenge

when the strength and statistical properties of the interfering signals are unknown a priori [2]. The target detection which estimates and detects the target from an ever changing clutter environment is called adaptive moving target detector (AMTD).

For optimal detection of known signal in such a clutter with great level of power relating to the signal it is necessary to create an optimal filter of which frequency characteristic is inverse of the clutter spectrum. The classical methods of power spectral estimation use Fourier transform operations on windowed autocorrelation function. Windowing makes the implicit assumption that the unobserved data outside the window are zero that is not realistic [2].

An adaptive system performs the processing by using an architecture having time-varying parameters on the received signals. Adaptive noise canceling is based on the noise canceling by subtracting noise from a received signal, an operation controlled in an adaptive manner for the purpose of improved signal-to-noise ratio [3]. An adaptive clutter canceller is a dual input system illustrated in Figure 1.1. The first input is a time channel which receives signal corrupted by clutter. The second input is a mean value of others time channels which receive clutter only. Because of environment is changing during observation it is necessary to adapt the filter parameters to new characteristics of the clutter.

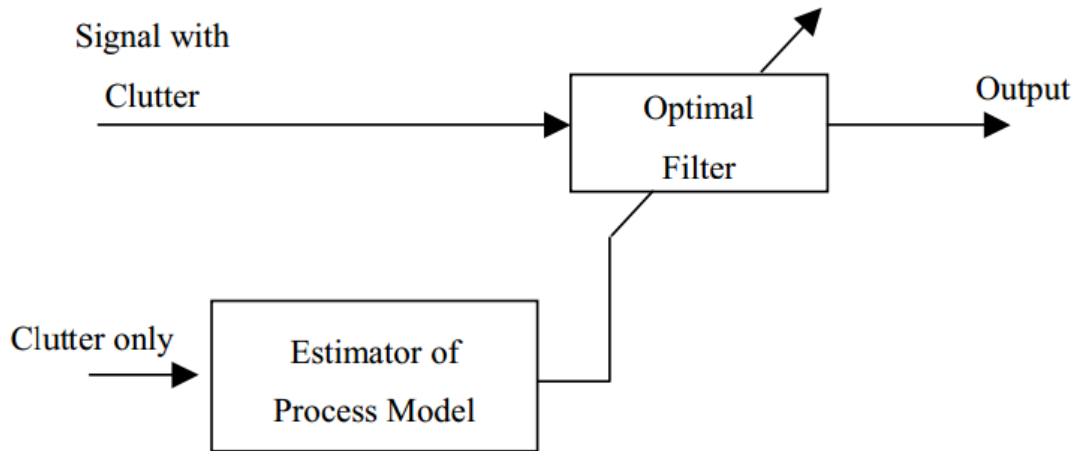


Figure 1.1 Adaptive clutter canceller

1.2 Objectives

The main objectives of this thesis are:

1. Clutter suppression in Doppler radar using adaptive filter
2. Comparison of performance parameters of adaptive filter against conventional cancellers

1.3 Applications

Clutter suppression or cancellation technique is inherent part in all radar systems. In air traffic controller (ATC) radar ground clutter from nearby mountains, building or tower can limit the sensitivity of a radar receiver. In severe weather conditions clutter due to cloud, hailstone or rain may create difficulty in detection of aircraft. Stationary or slow moving clutter can be suppressed by conventional moving target indicator filters having predefined filter coefficients. However for suppression of moving clutter adaptive filters are required. In case of weather radar precipitation is the desired target whereas ground structures and aircrafts act as clutter. Clutter due to ground structure can be cancelled by conventional moving target indicator filters but suppression of clutter due to aircrafts may require adaptive filters.

2. LITERATURE REVIEW

James Clerk Maxwell (1831 – 1879) predicted the existence of radio waves in his theory of electromagnetism. Hertz (1857 – 1894) confirmed by experiment that electromagnetic radio waves have the same velocity as light and can be reflected by metallic and dielectric bodies. A.H. Taylor and L.C. Young (1922) of the Naval Research Laboratory in the USA demonstrated detection of a wooden ship using a CW wave-interference radar, at a wavelength of 5 m. The first detection of aircraft using the wave-interference effect was made in 1930 by L.A. Hyland of the Naval Research Laboratory in the USA. Watson Watt (1935) had been asked by the UK Air Ministry to investigate the feasibility of electromagnetic ‘death rays’ to disable aircraft. He concluded, in an elegantly-reasoned piece, that it would not be feasible, but that detection of aircraft using radio waves should be possible. The same year he demonstrated detection of aircraft at a range of up to 8 miles in what has become known as ‘the Daventry experiment’, and by June 1935 he had demonstrated the pulsed radar technique to measure aircraft range.

Galileo (1632) has originated a theory of estimation, which he developed to minimize various functions of errors. However, it was Gauss who was given credit for the development of linear estimation theory. This was based on his invention of the method of least squares that he developed in 1795 to study the motion of heavenly bodies. Legendre invented the method of least squares independently of Gauss and actually published before Gauss in 1805 and was therefore subsequently given equal credit for the invention. Kolmogorov and, Krein and Wiener (1940s) originated the first studies of minimum mean square estimation in connection with stochastic processes. Kolmogorov (1939) developed a comprehensive treatment of the linear prediction problem for discrete-time stochastic processes. Krein (1945) subsequently extended Kolmogorov’s results to continuous-time by using a bilinear transformation. Wiener (1949), working independently of either Kolmogorov or Krein, had formulated the continuous-time linear prediction problem but in a different context to the other two. He derived an explicit formula for the optimum predictor as well as solving the filtering problem of estimating a process corrupted by added noise. This required

the solution of the integral equation known as the Wiener-Hopf equation, which was developed in 1931. Levinson (1947) formulated the Wiener filtering problem in discrete-time in the form of a transversal filter structure. From earlier work in the 1950s the LMS algorithm for adaptive transversal filters emerged in 1959. It was developed by Widrow and Hoff (1960) for their ADALINE pattern recognition system. The family of RLS algorithms saw its beginnings with the work of Plackett (1950). After much work by many researchers, Godard (1974) presented the most successful application of the Kalman filter theory used to derive a variant of the RLS algorithm. It wasn't until 1994 that Sayed and Kailath exposed the exact relationship between the RLS algorithm and Kalman filter theory opening the way for the full exploitation of the vast literature on Kalman filtering for solving linear adaptive filtering problems. They showed that QR-decomposition-based RLS and fast RLS algorithms were simply special cases of the Kalman filter.

In the paper published by Yong Huang (2012) a new adaptive clutter suppression scheme named FFT processing method in frequency domain (FPMFD) is presented. The scheme integrates the moving target indication (MTI) with the MTD processing and has low computational burden [4].

Priyabrata Karmakar (2013) has done a comparative analysis of different types of MTI filters for radar clutter rejection with a conclusion that with the increase in delay line cancelers in MTI filters, increases clutter rejection ability and the feedback path increases the response of MTI filters [5].

The problem of clutter cancellation when the clutter is due to two sources such as coexisting land and weather clutter system has not been explored in as much detail as the conventional problem. A novel method for joint land-weather clutter cancellation has been presented by Ulakbim Uasl. Its performance has been compared with the optimal and some other alternative methods [6]

3. THEORY

3.1 Fundamental Principle of Radar

The basic operation of RADAR is based on transmission an electromagnetic signal of specified pattern (continuous wave, continuous wave modulated, pulsed etc.) and reception the corresponding echo signal from the target. The radar transmits a short radio pulse with very high pulse power. This pulse is focused in one direction only by the directivity of the antenna, and propagates in this direction with the speed of light. If there is obstacle in this direction then a part of the energy of the pulse is scattered in all direction and a very small portion is reflected back to the radar antenna. The radar antenna receives this energy and evaluates the contained information.

A simple RADAR system consists of a transmitting and a receiving antenna that are connected to the transmitter and receiver. The transmitting antenna transmits a high power microwave signal, a part which is intercepted by the “target”. The target then reradiated it in all directions. The receiving antenna then receives a part of this echo signal and processes it to detect the presence of the target, its range, velocity etc. In most of the RADAR systems the transmitting and receiving antennas are same and the transmitting and receiving signals are separated with the help of a duplexer.

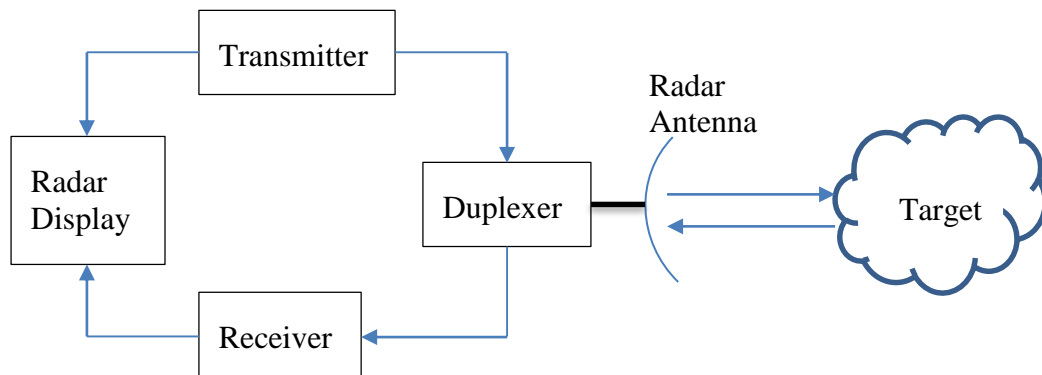


Figure 3.1 Block diagram of Radar system

The fundamental application of all Radar systems is to measure the distance of an object from the Radar site by measuring the time a pulse of radio energy takes to travel to the object and back again. Since the radio wave propagates at constant speed (the speed of light

c) the distance of the target is determined from the runtime of the high-frequency transmitted signal. The actual range of a target from the radar is known as slant range which is given by:

$$R = \frac{c \cdot t}{2}, \quad (3.1)$$

Where,

c = speed of light= 3×10^8 m/s,

t =measured running time(s),

R =slant range (m).

Since the wave travel to a target and back, the round trip time is divided by two in order to obtain the time the wave took to reach the target.

3.2 Radar Range Equation

The radar range equation represents the physical dependences of the transmit power (P_t) and received power (P_r) of the radar with other parameters such as range (R), reflection characteristics of the target (radar cross section σ), wavelength (λ) and the gain of the antenna(G).

For mono static radar, range is given by

$$R = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_r}}. \quad (3.2)$$

The minimum detectable received power ($P_{r, \min}$) corresponds to the maximum range (R_{\max}) of the target.

$$R_{\max} = \sqrt[4]{\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_{r, \min}}}. \quad (3.3)$$

3.3 Radar Cross-Section

Radar cross-section (RCS) is a measure of how detectable an object is with radar. A larger RCS indicates that an object is more easily detected.

Informally, the RCS of an object is the cross-sectional area of a perfectly reflecting sphere that would produce the same strength reflection as would the object in question. (Bigger

sizes of this imaginary sphere would produce stronger reflections.) Thus, RCS is an abstraction: The radar cross-sectional area of an object does not necessarily bear a direct relationship with the physical cross-sectional area of that object but depends upon other factors.

Somewhat less informally, the RCS of a radar target is an effective area that intercepts the transmitted radar power and then scatters that power isotropically back to the radar receiver.

Mathematically the radar cross section is defined as the ratio of the power reflected (P_r) back to the radar to the power density (P_D) incident on the target,

$$\sigma = \frac{P_r}{P_D} \quad (3.4)$$

3.4 Detection of Targets

The detection of a target in presence of noise signals depends on the establishment of a threshold detection level at the output of receiver. If the output of the receiver exceeds this threshold level then the target is said to be present whereas if the output of the receiver falls below this threshold level then only noise is said to be present. Such procedure is called threshold detection.

If the threshold level is properly selected then the receiver output should not cross it until the presence of the target. If the threshold level is set too low, noise might exceed it and may be mistaken as an echo from a target. This is called as “false alarm”. On the other hand if the threshold level is kept too high then the echoes from a weak target may not be able cross it and hence the target is not detected. This is known as “missed detection”. One of the ways out of the above problems is to set two threshold levels – one low and the other high.

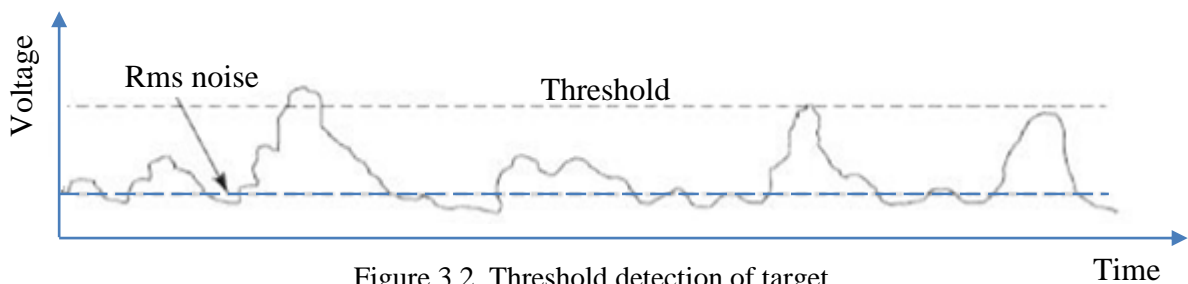


Figure 3.2 Threshold detection of target

If the echo signal is below the lower level then it is considered as noise whereas if the echo signal is above the upper threshold level it is assumed that target is present. However, if the echo signal is in between the two levels more careful observation is required. The fluctuations in voltage are due to random receiver and clutter noise. When the strength of the echo signal is equal to or just above the threshold level, the noise present in the system will be added to the signal or subtracted from the signal depending on whether its amplitude is positive or negative. If the noise signal is added to the echo signal then the total signal will cross the threshold level and the target will be detected. On the other hand if the noise signal is subtracted from the weak echo signal then the total signal will fall below the threshold level and will result in missed detection. In military applications the missed detection may cause a severe problem and hence in such case the threshold level is kept low. On the other hand in traffic RADAR false alarm may cause hazard and hence in such case the threshold level is kept high.

3.5 Doppler Shift

It is known that when there is a relative motion between a source and a listener, an apparent shift in the carrier frequency of the received signal results. This is known as Doppler Effect. In a RADAR system, when the target moves relative to the antenna, this effect comes into play. Radars use Doppler shift in frequency to extract target radial velocity, as well as to distinguish between moving and stationary targets or objects such as clutter. The Doppler phenomenon describes the shift in the center frequency of an incident waveform due to the target motion with respect to the source of radiation. Depending on the direction of the target's motion this frequency shift may be positive or negative. Doppler frequency shift for a target moving with velocity v at an angle Θ from radar antenna is given by

$$f_D = \frac{2v \cos \theta}{\lambda} \quad (3.5)$$

Above equation reveals that the Doppler shift is maximum when $\Theta=0^\circ$ and is equal to zero when $\Theta=90^\circ$.

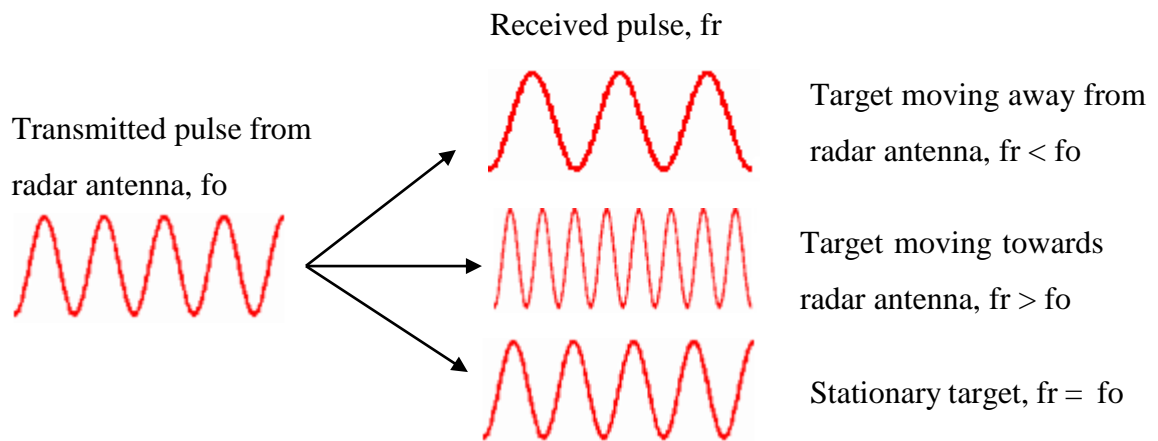


Figure 3.3 Illustration of Doppler shift

The magnitude of Doppler shift is same regardless of whether the target is moving towards the RADAR or outward the RADAR, provided the velocity is constant. However in the former case the sign of the Doppler shift will be positive whereas in the latter case the sign will be negative. Thus if the target is moving towards the RADAR, the received signal frequency will be higher than the transmitted signal frequency whereas if the target is moving outwards the RADAR, the received signal frequency will be lower than the transmitted signal frequency. The transmitter generates a continuous wave of frequency f_0 whereas due to the Doppler shift the received signal is of frequency $(f_0 \pm f_D)$.

3.6 Frequency Modulated Continuous Wave Radar

Continuous wave (CW) radar transmits a continuous and stable frequency radio wave signal. CW radars are simple, inexpensive and can be used to compute relative velocity of the target by measuring the Doppler shift in the received signal. However it cannot determine the range of the target.

In frequency modulated continuous wave (FMCW) radar frequency of the transmitted signal is varied over a fixed period of time by a modulating signal that could be sine wave, saw-tooth wave, triangular wave or square wave. Frequency difference between the receive signal and the transmit signal increases with delay, and hence with distance.

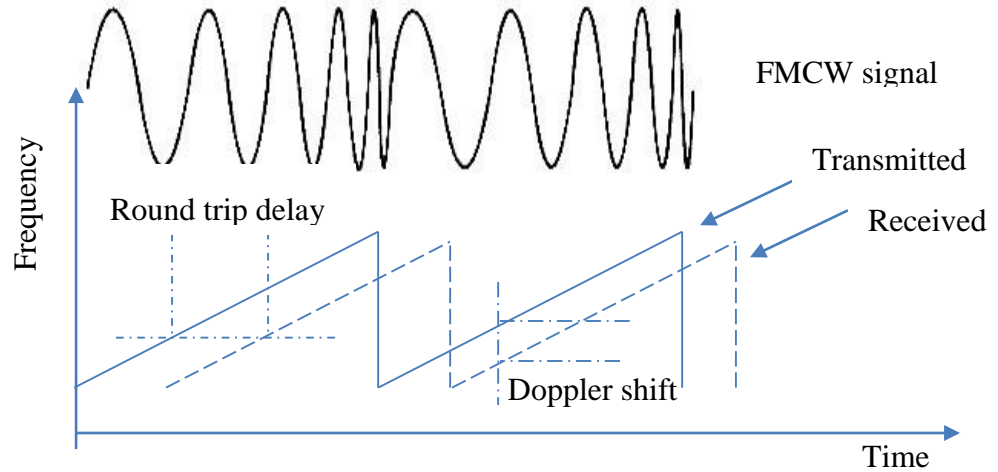


Figure 3.4 Principle of operation of FMCW

In a FMCW RADAR the frequency of the transmitted signal is changed with time in a known manner. Due to this, unlike Doppler CW RADAR, the frequency of the echo signal and transmitted signal, at the instant echo is received, is not same. In practice this frequency difference will be proportional to the transit time. Since the change in transmitter frequency with time is known therefore from the frequency difference the transit time of the signal and hence the range of the target can be calculated. In FMCW RADAR a greater transmitter frequency deviation in a given time interval corresponds to greater measurement accuracy.

3.7 Pulse Radar

Pulse radar transmits a train of modulated pulses and waits for the echo. Unlike CW radar in which transmitter is always on, in pulse radar the transmitter is off during reception. . Range is extracted from the two-way time delay between a transmitted and received pulse. Pulsed radar waveforms can be completely defined by the following:

- carrier frequency
- pulse repetition time (PRT)
- pulse width (PW)
- modulation

Carrier frequency depends of the design requirement and radar mission. Pulse repetition time (PRT) is the time required to complete one transmission cycle. It is the time from the beginning of one radar pulse to the beginning of the next one. The reciprocal of PRT is called pulse repetition frequency (PRF)

Pulse width is duration for which radio signal is transmitted and usually measured in microseconds. Pulse width is directly proportional to the average power transmitted by radar which is given by

$$P_{av} = PW * PRF * \text{Peak power} \quad (3.6)$$

Pulse width should be large enough to ensure that reflected pulse is detectable by its receiver. It is inversely proportional to the bandwidth. It also defines the range resolution that is the capacity of the radar to distinguish between two targets fairly close together which is given by

$$\Delta R = \frac{c.PW}{2} \quad (3.7)$$

Rest time is the time between the end of one transmission and the start of the next. It can be divided into two parts: recovery time and listening time. Recovery time represents the time immediately following the transmission of RF energy during which the radar is unable to process the echo. Listening time is the part of the rest time that radar can receive and process the echo.

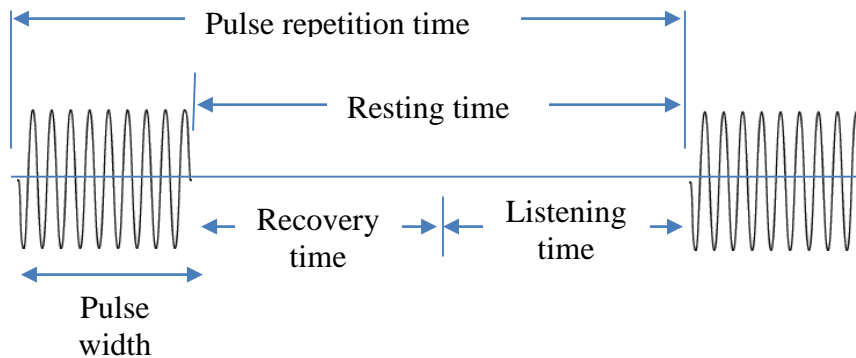


Figure 3.5 Radar pulse and its parameters

3.8 Clutter

Clutter is a term used to describe any object that may generate unwanted radar echo that may interfere with normal radar operation creating difficulty in the detection of wanted targets. When clutter echoes are sufficiently intense and extensive, they can limit the

sensitivity of a radar receiver, and thus determine the range performance [6]. The definition of clutter depends on the function of the radar. For ATC radar weather is clutter whereas in case of weather detecting radar it is not clutter.

White noise normally introduces the same amount of noise power across all radar range bins, while clutter power may vary within a single range bin.

Since clutter returns are target-like echoes, the only way a radar can distinguish target returns from clutter echoes is based on the target RCS. Clutter RCS can be defined as the equivalent radar cross section attributed to reflections from a clutter area.



Figure 3.6 PPI screen of an ATC-radar with targets and clutter
(Courtesy: Radar Surveillance Division, TIA, Kathmandu, Nepal)

3.8.1 Volume clutter

Volume clutter includes rain (weather), birds, chaff etc. For ground based radar system such as ATC radar volume clutter is major issue than the surface clutter. For such system, the return from a desired target is contaminated by the returns from both a land system having zero Doppler frequency and a weather system having a non-zero Doppler frequency [6].

Weather or rain clutter can be viewed as perfect small spheres. We can use the Rayleigh approximation of perfect sphere to estimate the rain droplets' RCS. The Rayleigh approximation, without regard to the propagation medium index of refraction, is

$$\sigma = 9\pi r^2 (kr)^4, \quad r \ll \lambda \quad (3.8)$$

where $k=2\pi/\lambda$.

RCS per unit resolution volume η is computed as the sum of all individual scatters RCS within the volume,

$$\eta = \sum_{i=1}^N \sigma_i, \quad (3.9)$$

Where N is the total number of scatters within the resolution volume. Thus, the total RCS of a single resolution volume (V_W) is

$$\sigma_W = \sum_{i=1}^N \sigma_i V_W \quad (3.10)$$

A resolution volume as shown in Figure 3.7 is approximated by

$$V_W = \frac{\pi}{8} \theta_a \theta_e R^2 c \tau \quad (3.11)$$

Where θ_a , θ_e are, respectively, the antenna beam width in azimuth and elevation, τ is the pulse width in seconds, c is speed of light, and R is range

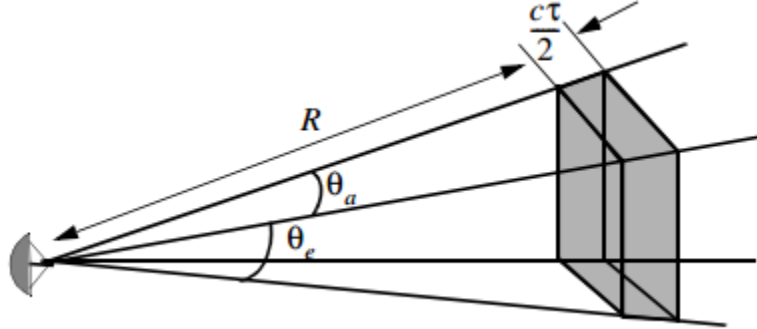


Figure 3.7 Definition of resolution volume

Consider propagation medium with an index of refraction. The rain droplet RCS approximation in this medium is

$$\sigma_i = \frac{\pi^5}{\lambda^4} K^2 D_i^6, \quad (3.12)$$

Where,

$$K^2 = \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 \quad (3.13)$$

m is the refractive index of the medium, D_i is the i^{th} droplet diameter.

$$\eta = \sum_1^N \sigma_i = \frac{\pi^5}{\lambda^4} K^2 \sum_1^N D_i^6 = \frac{\pi^5}{\lambda^4} K^2 Z , \quad (3.14)$$

Where, Z is the reflectivity factor which is defined as

$$Z = \sum_1^N D_i^6 . \quad (3.15)$$

In general, a rain droplet diameter is given in millimeters and the radar resolution volume is expressed in cubic meters, thus the units of are often expressed in mm^6/m^3 .

Z is related to the size distribution of the raindrops in the radar sample volume according to

$$Z = \int_0^\infty N(D).D^6 dD, \quad (3.16)$$

where $N(D)$ represents the mean number of raindrops with equivalent spherical diameters between D and $D + dD$ (mm) present per unit volume of air.

Although Z is called the radar reflectivity factor, it is a purely meteorological quantity that is independent of any radar property. Because in practice the variations in radar reflectivity may span several orders of magnitude, it is often convenient to use a logarithmic scale. By dividing Z with the equivalent return of a 1 mm drop in a volume of a meter cube (Z_0) one obtains the dimensionless quantity dBZ The logarithmic radar reflectivity is defined as

$$Z(\text{dBZ})=10 \log(Z/Z_0). \quad (3.17)$$

3.9 Micro Rain Radar

The MRR Micro Rain Radar is a compact 24 GHz FM-CW vertically pointing radar for the measurement of profiles of drop size distributions and derived from this rain rates, liquid water content and characteristic falling velocity.

Due to the high sensitivity and fine temporal resolution very small amounts of precipitation below the threshold of conventional rain gauges are detectable. Due to the large scattering volume (compared to in situ sensors) statistically stable drop size distributions can be derived within few seconds.

Unlike conventional weather radars the MRR does not provide areal coverage as it is operated only as a vertically looking profiler. The advantage of this operation mode is that the measured Doppler spectra can be transformed into number concentration versus drop size using the known relation between drop size and terminal fall velocity [9].

The backscatter cross section of rain drops increases with the fourth power of the radar frequency, if the target diameter is small compared to the wavelength (Rayleigh scattering). This is why a high frequency is useful in order to increase the sensitivity with respect to small drops.

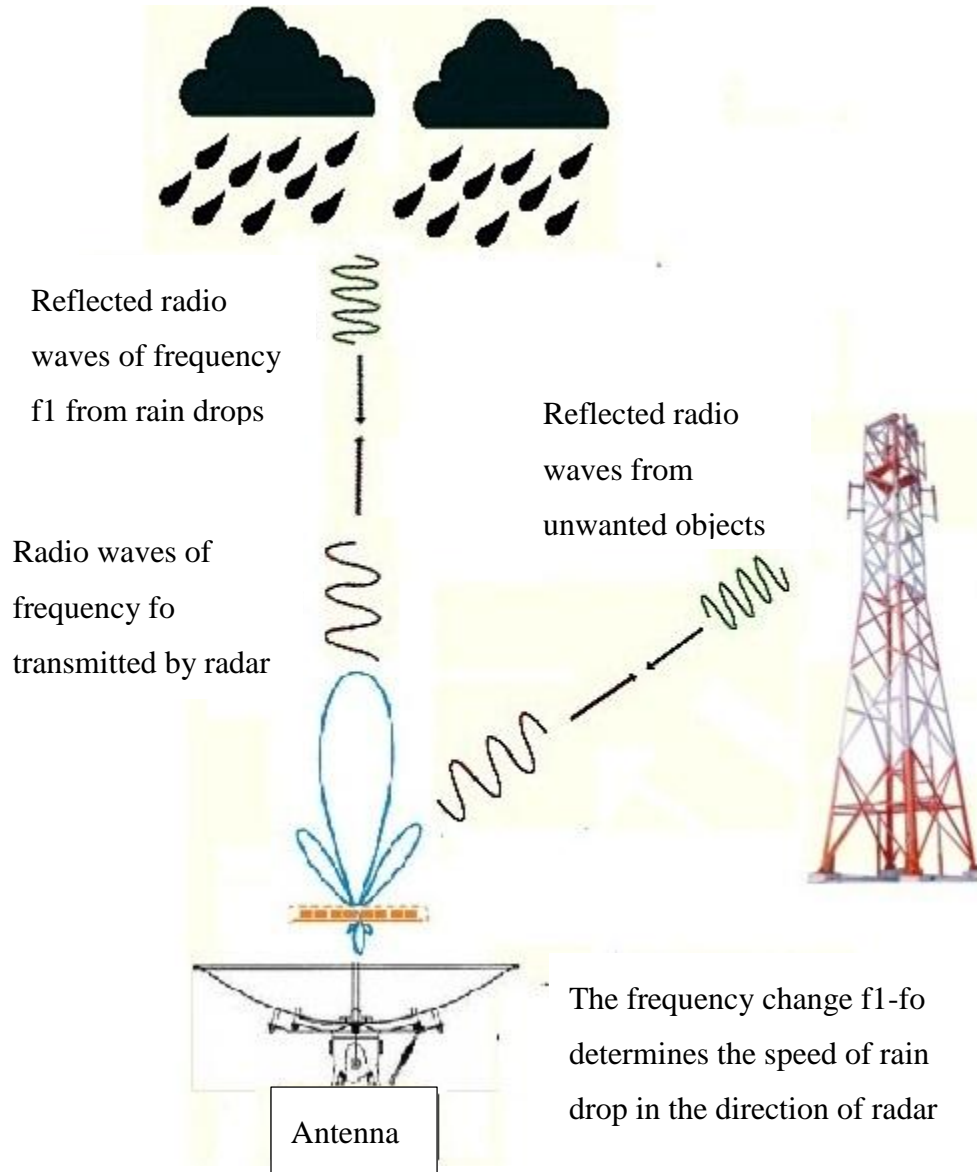


Figure 3.8 Illustration of working principle of MRR

For land based weather radars, clutter consists primarily of returns from ground targets such as trees, buildings and orographic features. Unfortunately, these targets possess radar cross-sections which are typically much larger than the aggregate radar cross-section of the

particulates within a radar resolution volume. Clutter of a given radar cross-section assumes different equivalent dBZ values as a function of range.

The relationship between the received power, the properties of the radar, the properties of the targets and the distance between the radar and the targets is given by the weather radar equation

$$P_r = C \frac{|k|^2}{R^2} Z, \quad (3.18)$$

Where P_r (W) is the mean power received from raindrops at range R (m), C is called radar constant and $|K|^2$ is a coefficient related to the dielectric constant of water (~ 0.93). The above equation is used to convert weather radar measurement into reflectivity as

$$Z = \frac{R^2 P_r}{C |k|^2}. \quad (3.19)$$

Estimates of Z obtained with this equation will only be perfect if the Rayleigh scattering approximation is met which requires that the water drops have diameters no larger than about one-tenth the radar wavelength [10]. If particle are not in the Rayleigh limit and/or non-spherical (e.g., ice crystals), the effective radar reflectivity factor, Z_e , is introduced.

$$Z_e = \frac{\pi^5}{\lambda^5 |k|^2} \int_{D_{min}}^{D_{max}} \sigma(D) N(D) dD \quad (3.20)$$

The differential rain rate $rr(D)$ is equal to the volume of the differential droplet number density $(\pi/6) \cdot N(D)D^3$ multiplied with the terminal falling velocity $v(D)$. From this product the rain rate is obtained by integration over the drop size:

$$Rain Rate = \frac{\pi}{6} \int_0^{\infty} N(D) v(D) D^3 dD \quad (3.21)$$

3.10 Moving Target Indicator

Moving Target Indicator RADAR (or MTI RADAR) utilizes Doppler Effect for its operation and is capable of reducing clutter due to stationary objects. Its basic principle is to compare the received echoes with the echoes that were received during previous sweep and thereafter to cancel out those echoes whose phase has remained unchanged. For moving targets the phase of successive echoes, in general, changes and hence they are not cancelled. For stationary targets, however, the phase of successive echoes does not change and hence they are cancelled.

Clutter spectrum is normally concentrated around DC ($f=0$) and multiple integers of the radar PRF f_r . In CW radars, clutter is avoided or suppressed by ignoring the receiver output around DC, since most of the clutter power is concentrated about the zero frequency band. Pulsed radar systems may utilize special filters that can distinguish between slowly moving or stationary targets and fast moving ones. This class of filters is known as the Moving Target Indicator (MTI). The purpose of an MTI filter is to suppress target-like returns produced by clutter, and allow returns from moving targets to pass through with little or no degradation. In order to effectively suppress clutter returns, an MTI filter needs to have a deep stop-band at DC and at integer multiples of the PRF. Figure 3.9(b) shows a typical sketch of an MTI filter response, while Figure 3.9(c) shows its output when the PSD shown in Figure 3.9(a) is the input.

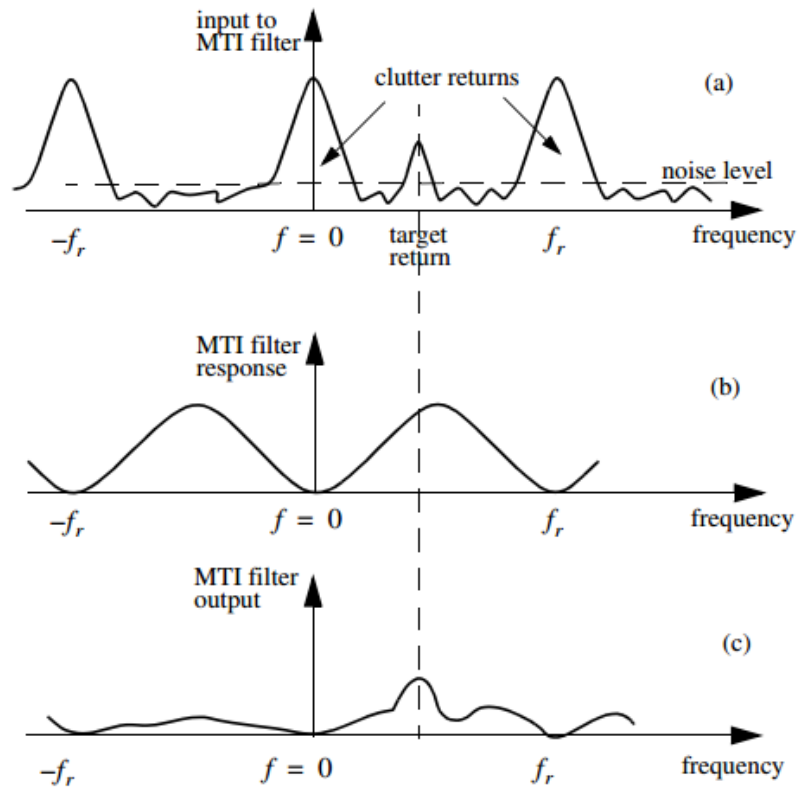


Figure 3.9 Typical radar return PSD

(a) Input to the filter. (b) MTI filter frequency response. (c) Output from an MTI filter.

3.10.1 Single delay line canceler

MTI filters can be implemented using delay line cancelers. The basic idea of MTI filtering is that repeated pulses from a stationary target yield the same echo amplitude and phase. Thus successive pulses should cancel when subtracted from one another.

Cancelers reject frequency bands centered at zero frequency and at multiple of sampling rate. The width of the notch must be sufficient to remove moving components of clutter without occupying so much of the spectrum that a large part of moving targets are also filtered out by them.

A single delay line canceler can be implemented as shown in Fig. 9.10. The canceler's impulse response is denoted as $h(t)$. The output is equal to the convolution between the impulse response and the input. The single delay canceler is often called a "two-pulse canceler" since it requires two distinct input pulses before an output can be read. The delay is equal to the PRI of the radar.

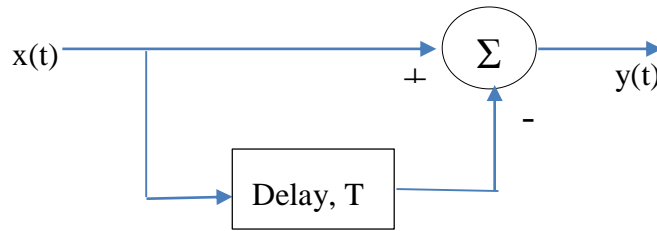


Figure 3.10 Single delay line canceler

The output signal is

$$y(t) = x(t) - x(t-T) \quad (3.22)$$

The impulse response of the canceler is given by

$$h(t) = \delta(t) - \delta(t-T) \quad (3.23)$$

It follows that the Fourier transform of $h(t)$ is

$$H(\omega) = 1 - e^{-j\omega T} \quad (3.24)$$

In z-domain,

$$H(z) = 1 - z^{-1} \quad (3.25)$$

In most radar applications the response of a single canceler is not acceptable since it does not have a wide notch in the stop-band.

3.10.2 Double delay line canceler

Double cancelers are often called “three-pulse cancelers” since they require three distinct input pulses before an output can be read. A double delay line canceler has better response in both the stop- and pass-bands, and thus it is more frequently used than a single canceler.

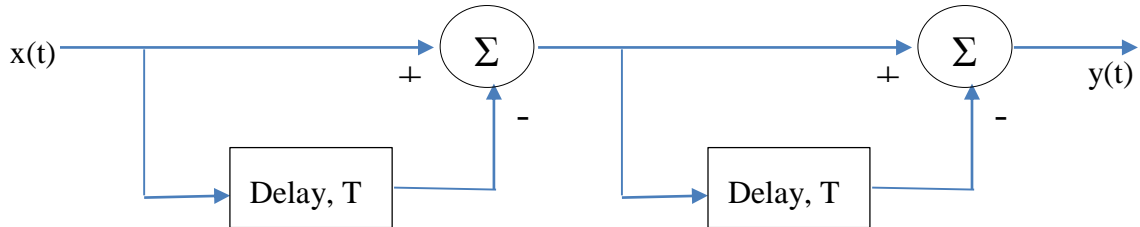


Figure 3.11 Double delay line canceler

The output signal is

$$y(t) = x(t) - 2x(t-T) + x(t-2T) \quad (3.26)$$

The impulse response of the canceler is given by

$$h(t) = \delta(t) - 2\delta(t-T) + \delta(t-2T) \quad (3.27)$$

It follows that the Fourier transform of $h(t)$ is

$$H(\omega) = 1 - 2e^{-j\omega T} + e^{-j2\omega T} \quad (3.28)$$

$$|H(\omega)|^2 = 16(\sin(\omega T/2))^4 \quad (3.29)$$

In z-domain

$$H(z) = (1 - z^{-1})^2 = 1 - 2z^{-1} + z^{-2} \quad (3.30)$$

3.11 Finite Impulse Response Filter

On the basis of the duration of impulse response, digital filters are categorized into finite impulse response (FIR) filter and infinite impulse response (IIR) filter. Compared to IIR, FIR filter has many unique advantages that can satisfy the requirement of frequency response with strict linearity in phase characteristics and high stability. IIR filter suffers from non-linear phase response, frequency dispersion and instability.

The transversal filter, also referred to as a tapped-delay line filter, consists of three basic elements:

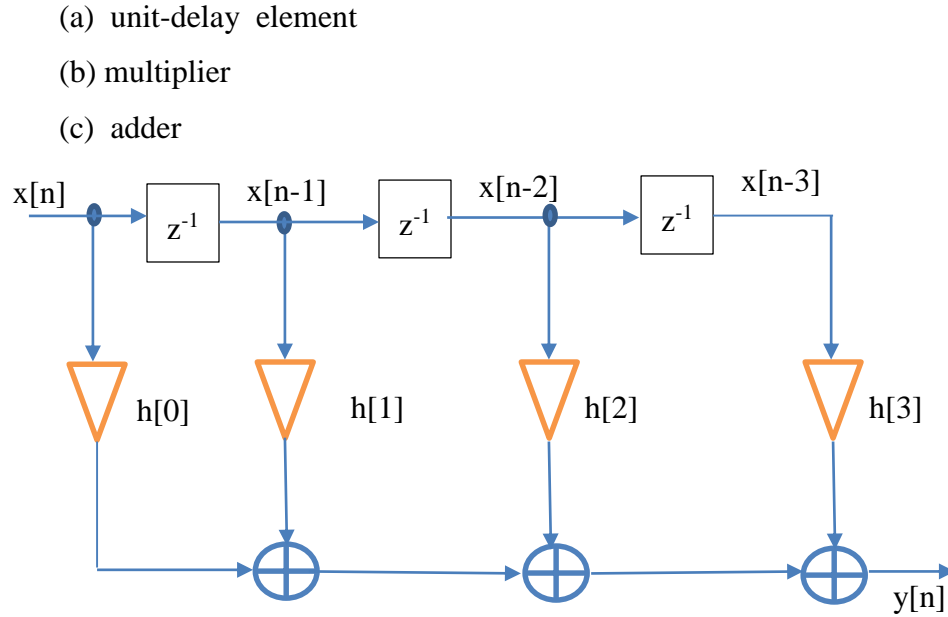


Figure 3.12 Direct form of FIR filter

An FIR filter has an impulse response that is zero outside some finite interval of time, so the convolution formula for such system reduces to

$$y[n] = \sum_{i=0}^{M-1} h[i]x[n - i], \quad (3.31)$$

where,

- $x[n]$ is the input signal,
- $y[n]$ is the output signal, and
- $h[i]$ is filter coefficient

The number of delay elements, $M-1$ is commonly referred to as the filter order

3.12 Adaptive Filter Theory

Adaptive filter is the filter with adjustable coefficients that attempts to model the relationship between two signals in real time in an iterative manner. It incorporates algorithm to adjust the filter coefficients to adapt to the signal statistics. Hence it doesn't require priori information about the statistics of the data to be processed. The parameters of an adaptive filter are updated according to some algorithm, so adaptive filter in reality is non-linear. The algorithms starts from some predetermined state of initial condition and

in a stationary environment, it converges to the optimum wiener solution whereas in non-stationary environment, it offers a tracking capability.

The operation of a linear adaptive filtering algorithm involves two basic processes:

- A filtering process designed to produce an output in response to a sequence of input data
- An adaptive process, the purpose of which is to provide a mechanism for the adaptive control of an adjustable set of parameters used in the filtering process

These two processes work interactively with each other. Naturally, the choice of a structure for the filtering process has a profound effect on the operation of the algorithm as a whole. The basic filter structure is transversal filter.

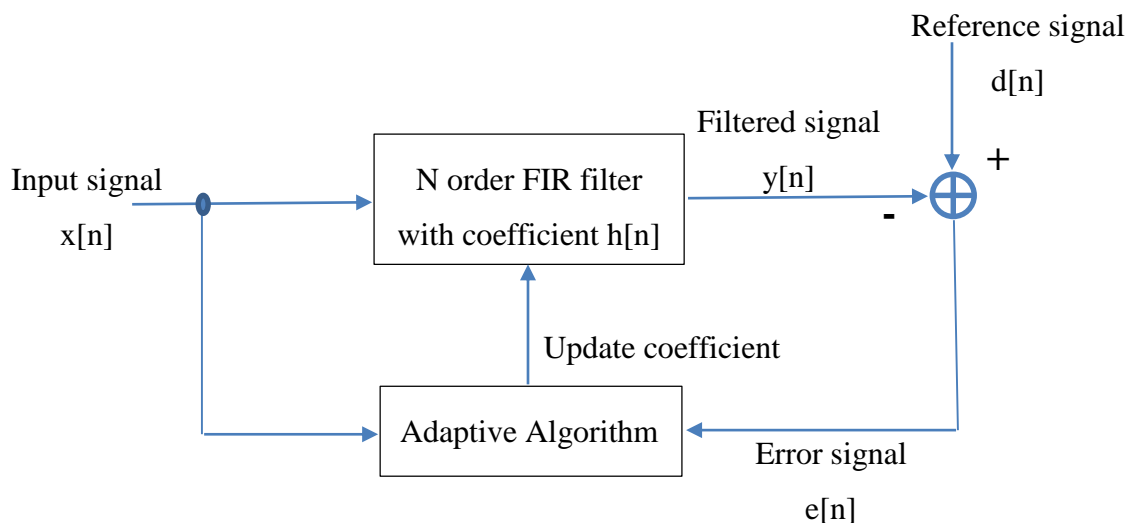


Figure 3.13 Adaptive filter system

3.13 Least Mean Square Algorithm

Least-mean-square (LMS) algorithm was developed by Widrow and Hoff (1960). The LMS algorithm is an important member of the family of stochastic gradient algorithms. A significant feature of the LMS algorithm is its simplicity. For an N-tap filter, it requires $2N$ multiplications and N additions per coefficient update [3]. Moreover, it does not require measurements of the pertinent correlation functions, nor does it require matrix inversion.

The LMS algorithm is a linear adaptive filtering algorithm, which consists of two basic processes

- A filtering process
- An adaptive process

A filtering process involves computation of the output of a linear filter in response to an input signal and generating an estimation error by comparing this output with a desired response. An adaptive process involves the automatic adjustment of the parameters of the filter in accordance with the estimation error. The combination of these two processes working together constitutes a feedback loop.

4. METHODOLOGY

The first part of the thesis work is to implement adaptive filter. Direct form of FIR filter has been used as filter structure. The coefficients of the filter are updated using LMS algorithm. Target echo and clutter signals are generated for FMCW radar. Clutter suppression is done by adaptive filtering. The effect of filter parameters namely step size and order of filter is studied. The performance of adaptive filter is compared with that of delay line cancelers. In the next part the filter is tested using real data.

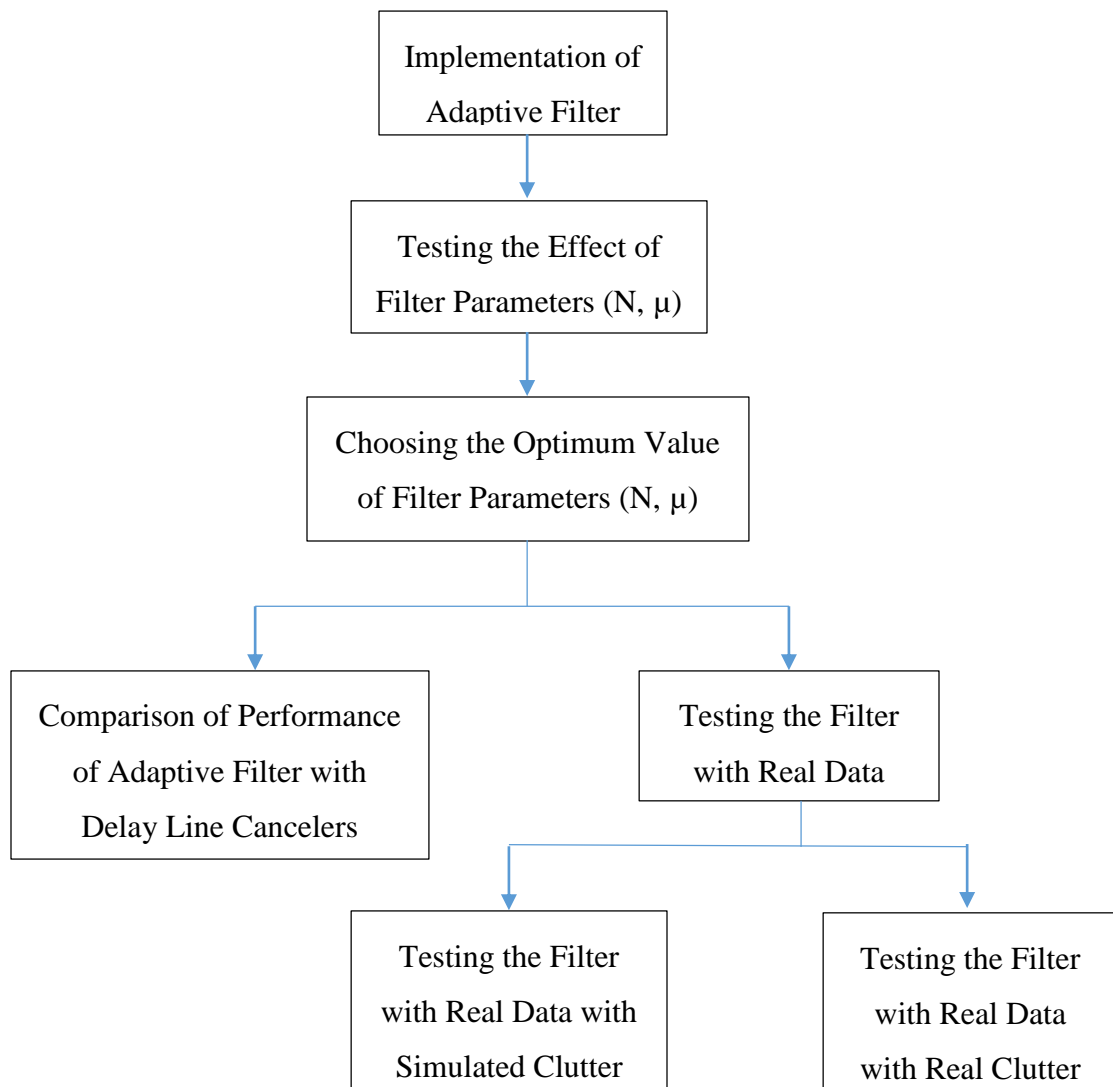


Figure 4.1 Block diagram of methodology

4.1 Generation of Simulated Data

Adaptive filter is used for suppression of clutter in Doppler radar system. In order to generate radar data, fmcw radar signal is generated. Both echo from the target and clutter are derived from transmitted fmcw signal. Phase shifted and attenuated fmcw signal is used as clutter. Besides phase shift and attenuation some doppler component and random noise is also added to generate echo signal from the target. Doppler component is added to model the motion of the target and random noise is used to model receiver noise. Clutter and echo from the target is added to generate the signal that is one of the input to the filter. Another input to the filter is pure echo signal from the target which is our desired signal.

The adaptive filter will compare the filter output with the desired signal. The difference between filter output and desired signal is termed as error signal which is used to update the coefficient of FIR filter. Filter coefficients are updated using Least Mean Square algorithm. This process is repeated until the mean square value of the error signal converges to a fixed value.

4.2 Filtering Using LMS Algorithm

The LMS algorithm is described by the following equation:

Filter output:

$$y[n] = \mathbf{h}[n] \cdot \mathbf{x}[n] \quad (4.1)$$

Estimation error or error signal:

$$e[n] = d[n] - y[n] \quad (4.2)$$

Tap-weight adaptation:

$$\mathbf{h}[n+1] = \mathbf{h}[n] + \mu \mathbf{x}[n] e[n] \quad (4.3)$$

4.3 Testing Filter Parameters and Performance

The filter has mainly two parameters namely order of the filter(N) and step size(μ). The performance of the filter is examined using different values of N at certain fixed value of μ . Similarly the performance of filter is checked for various values of μ for some constant

value of N . Also the optimum value of μ is determined so that the filter converges to some specified value of mean square error with least number of iterations.

Further frequency response of the adaptive filter is compared with that of conventional cancelers. Adaptive filter should give better clutter suppression in the pass band.

4.4 Testing With Real Data

The performance of the filter is also be verified by using real data. These data are derived from Micro Rain Radar (MRR). It operates with electromagnetic radiation at a frequency of 24 GHz with a modulation of 0.5 - 15 MHz depending on the height resolution (e.g. 300 m - 10 m). It is a type of FM-CW-radar which is for the measurement of vertical profiles of Doppler spectra and derives drop size distributions, rain rates, liquid water contents, radar reflectivity factors, Doppler velocities, path integrated attenuation simultaneously on vertical profiles up to several kilometers above the radar. The data consists of set vertical profile of reflectivity factors taken at regular interval of time. There are two types of data. The first data is MRR data without any clutter. In this data simulated stationary clutter data has been added. This real MRR data with simulated clutter is applied to the filter. The simulated clutter is suppressed by the filter. Next data is MRR Doppler spectra consisting of vertical profile of falling velocity of rain drops and radar reflectivity factor. This data contains real clutter as well. This data is also used test the clutter suppression capability of the filter.

5. SIMULATION RESULTS AND DISCUSSION

Adaptive filter has been implemented using matlab coding. FMCW radar signals have been generated to simulated target echo signals and clutter. Clutter suppression capability of the filter is tested using this simulated radar data. Further the performance of the filter has been tested using different values of filter parameters namely step size (μ) and order of the filter (N). The optimum value of step size parameter has been determined. The performance of the filter has been compared with that of different delay line cancelers. The filter has been tested with real MRR data in different scenarios. At first rain is considered as the desired target and returns from stationary ground objects as clutter. In the second case rain is considered as clutter whereas stationary ground objects as target.

5.1 Generation of Radar Data

FMCW radar signal is generated by modulating 24GHz sinusoidal signal with 15MHz periodic ramp signal. Phase shifted and attenuated FMCW signal is used to model clutter. Delay and attenuation has been estimated using fundamental radar range equations. This signal has no Doppler component since it is an echo from stationary object. Another weak FMCW signal is used as echo from the target. It has some Doppler component to model moving target. A random signal with exponential distribution is also added to it in order to model receiver noise. Reflected signal from the target and clutter are summed which is fed to the filter. These simulated radar signals are shown in Figure 5.1.

The frequency spectrums of transmitted FMCW signal, clutter, and echo signal from target and input signal to the filter are shown in Figure 5.2. Here the spectrum of transmitted signal and clutter is same. The spectrum of echo from the target is also similar but its spectrum is slightly shifted due to Doppler Effect i.e. motion of the target. It also has some noise component. Frequency selective filters cannot distinguish between clutter and echo from the target because both of them fall in the same band. Also we cannot evaluate the performance of the filter by observing the filter output signal in frequency domain because it has also similar spectrum except the noise component which has been cancelled in the filter output.

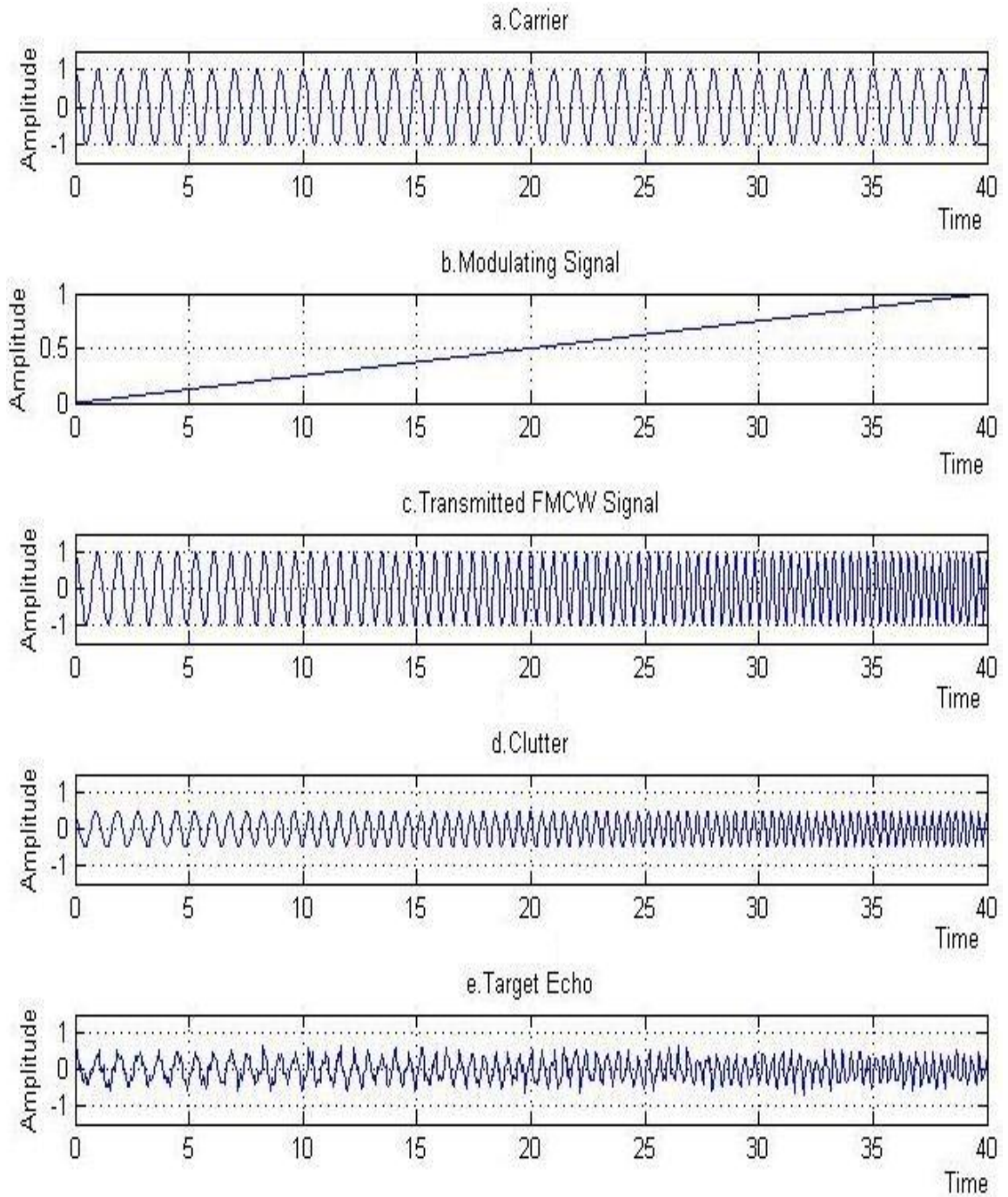


Figure 5.1 Simulated radar signals

(a) Carrier (b) Modulating signal (c) Transmitted FMCW signal (d) Clutter (e) Target echo

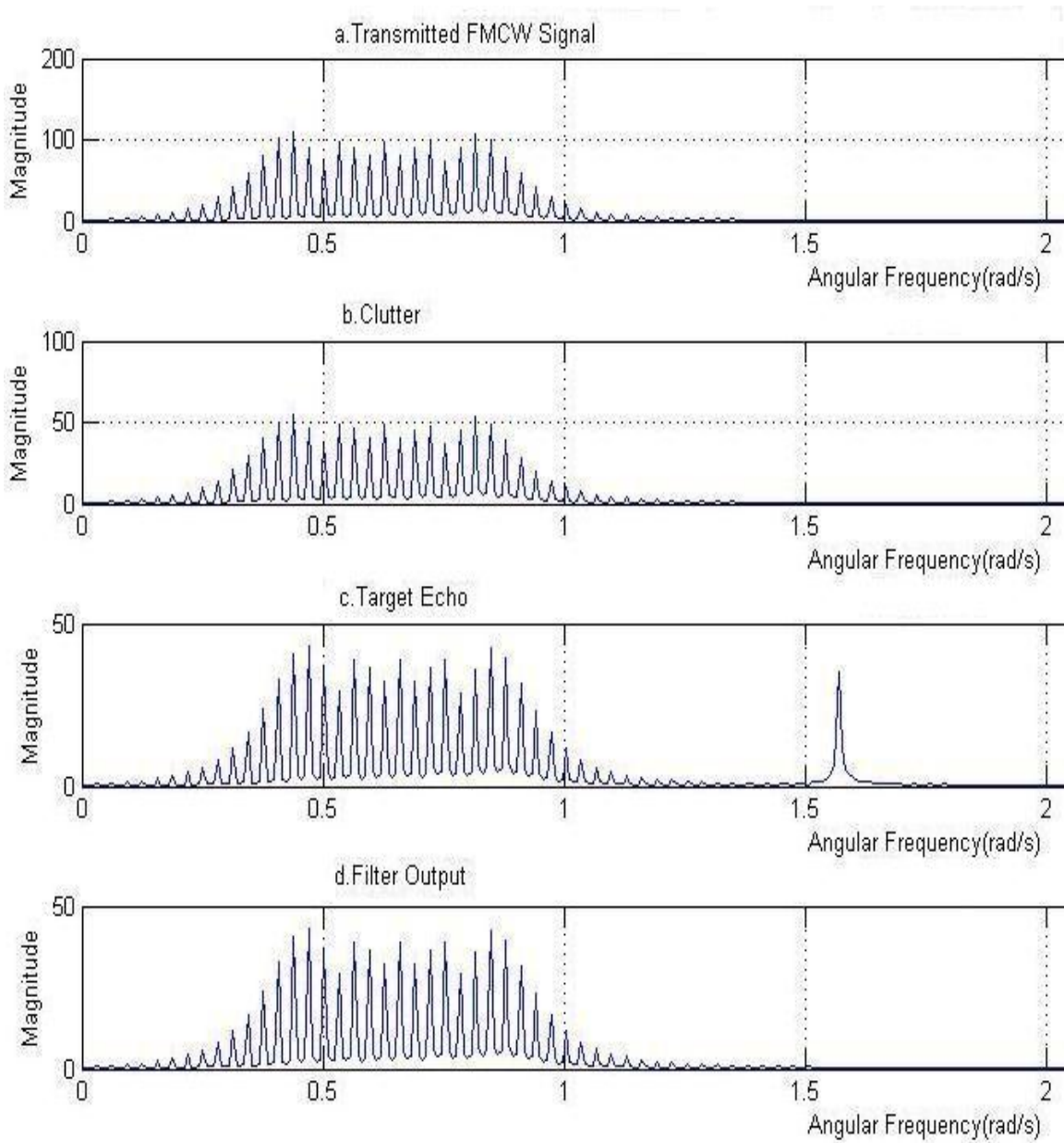


Figure 5.2 Spectrum of different signals

(a) Transmitted FMCW (b) Clutter (c) Target echo (d) Filter output

5.2 Adaptive Filtering

Performance of the filter can be analyzed by observing the time domain signal as shown in Figure 5.3. The results has been obtained for filter order $N=8$ and step size $\mu=0.05$. Here input signal to the filter consists of echo from the target, clutter return and noise. First few cycles of the filter output illustrates the adaptation process of the filter whereby the filter coefficients are updated in order to cancel clutter and noise. Error signal means the difference between target echo signal and filter output which is gradually diminishing. It means the filter output is gradually converging towards the echo signal from the target which is in fact our desired signal. The clutter and other noise signal are gradually getting suppressed.

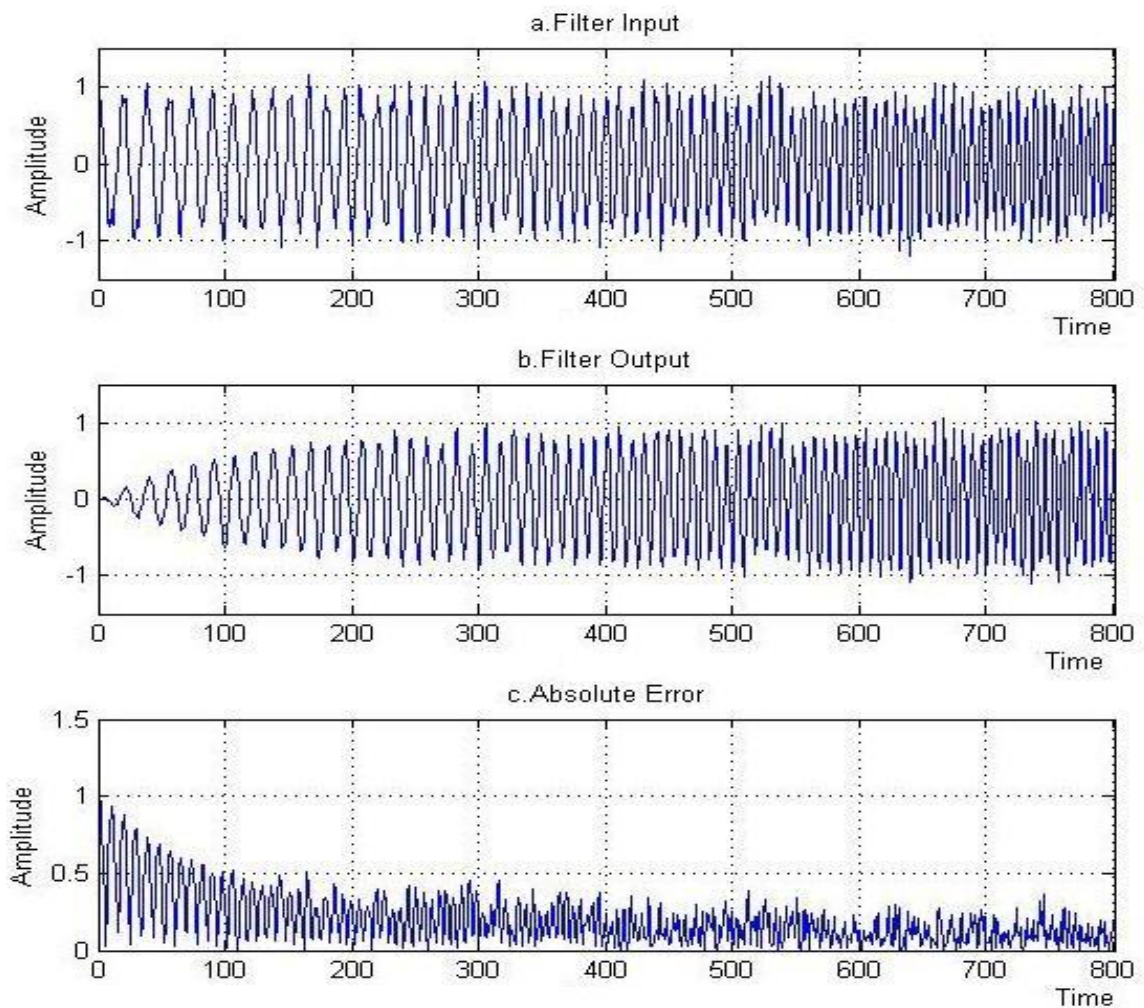


Figure 5.3 Input and output signals to the filter

(a) Filter input. (b) Filter output (c) Error signal.

5.3 Effect of Order of Filter

In order to study the effect of order of filter on filtering process mean square value of the error signal is calculated in each iteration. Iteration is carried over few cycles and graph of mean square error vs. number of iteration is plotted. This process is repeated for different values of filter order (N=4, 6 and 8). It is observed that in an adaptive filter mean square error decreases and approaches a steady value as the number of iteration increases. Higher the order of filter faster the convergence of mean square error to the steady value with smaller value of steady state mean square error. Obviously the transfer function of FIR filter approaches the ideal as the filter order increases. For better performance higher order filter is desired. But, higher order means higher computational complexity thus increasing the complexity and amount of time needed for processing. In order to handle higher computational complexity high performance processor will be required which demands for higher cost.

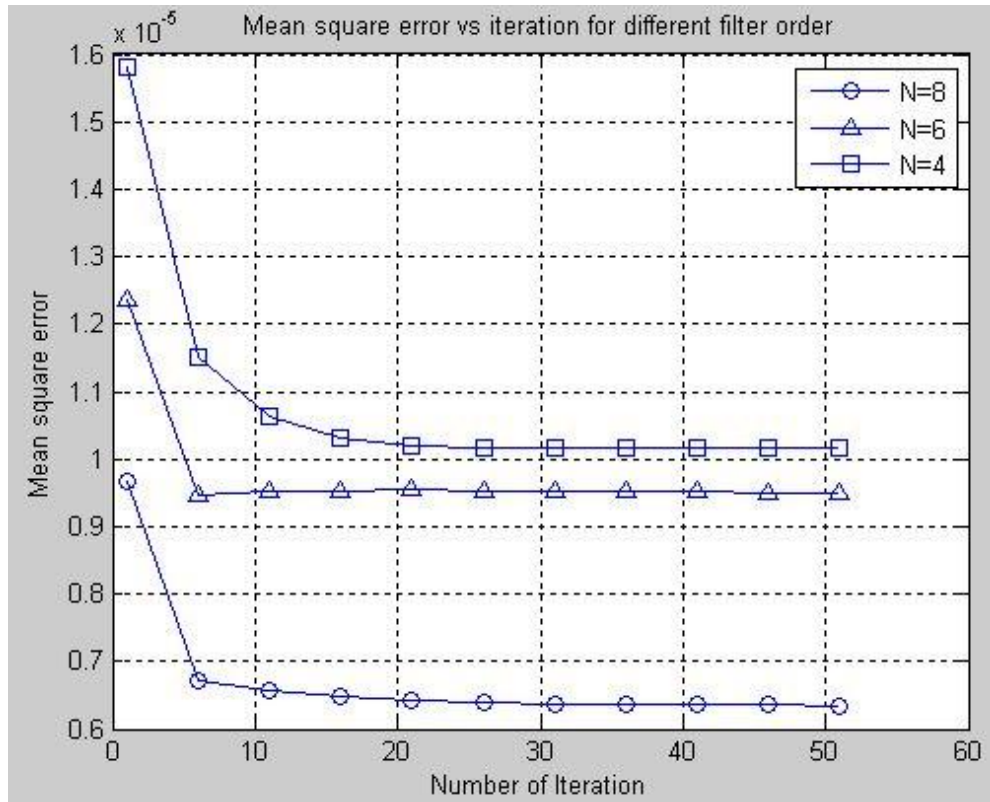


Figure 5.4 Mean square error vs. Iteration for different order of filter

5.4 Effect of Step Size Parameter

In order to study the effect of step size parameter of filter on filtering process mean square value of the error signal is calculated in each iteration. Iteration is carried over few cycles and graph of mean square error vs. number of iteration is plotted. The same process is repeated for different values of step size ($\mu=0.04, 0.08$ and 0.1). The result shows that the step size μ control the performance of the algorithm. If μ is large the convergence speed is fast. It means that the difference between the filter output and the desired signal decreases rapidly, but at the same time mean square error in the steady state is larger. On the other hand if μ is smaller, mean square error decreases slowly with iteration, but the value of steady state error is smaller. Hence the selection of proper value of step-size for specific application is important to get better results.

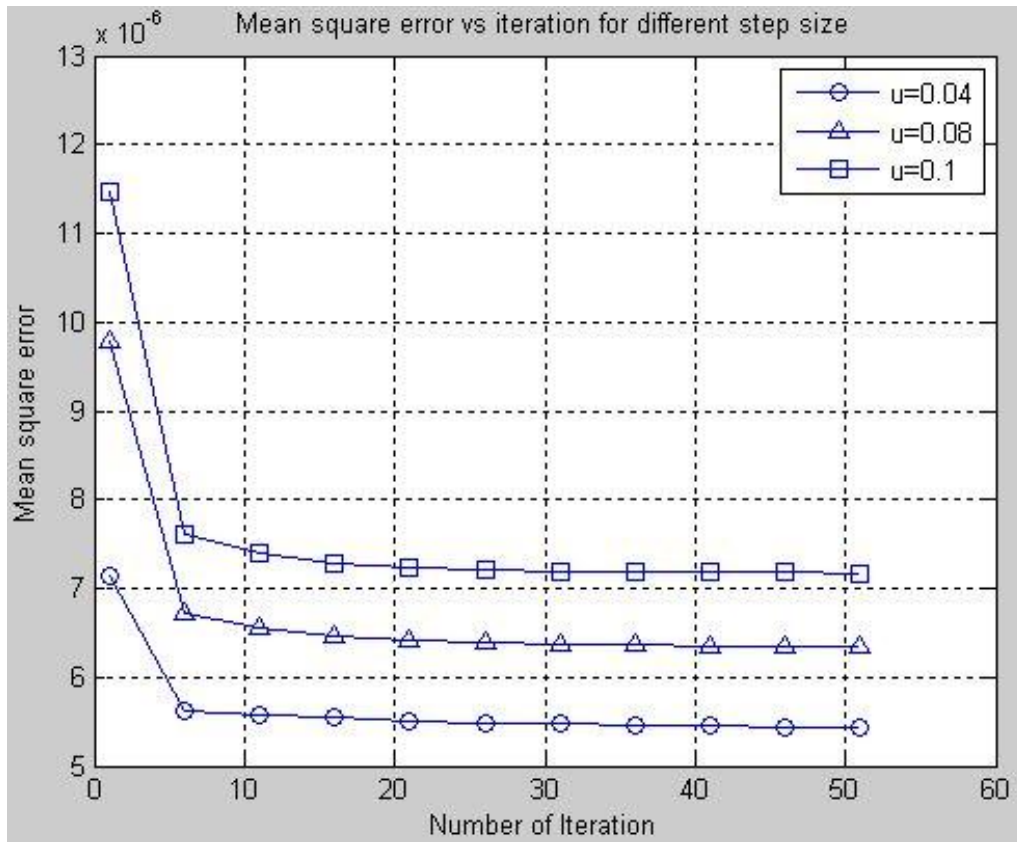


Figure 5.5 Mean square error vs. Iteration for different step size

5.5 Optimum Value of Step Size

Optimum value of the step size μ is that value of μ which leads to the specified value of mean square error in the least number of iteration. In order to determine the optimum value of μ a permissible value of mean square error is set (10^{-3}). The number of iteration required to achieve the specified value of mean square error for different value of step size is calculated for different values of step size from 0.01 to 0.1 in steps of 0.005. These values are plotted as shown in Figure 5.6. As the value of μ increases, at first, the number of iteration is decreased and then it becomes minimum for certain value of μ . If the value of μ is further increased, then the number of iteration increases. From the figure it is found that the optimum value of μ is between 0.04-0.05

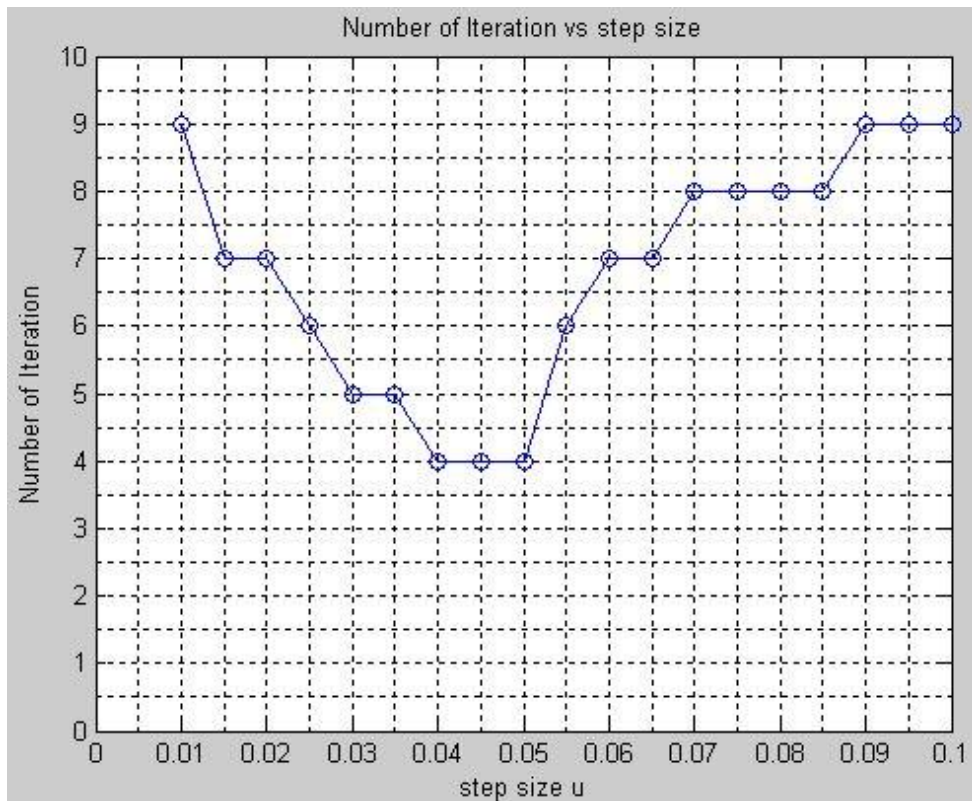


Figure 5.6 Number of iteration vs. step size

5.6 Performance Comparison with Delay Line Cancelers

Performance of adaptive filter is compared with that of different delay line cancelers. Higher order delay line cancelers have better frequency response both in the pass compared to lower order delay line cancelers. Double delay line canceler has better response than single delay line canceler, triple delay line canceler has better response than double delay line canceler. From the Figure 5.7 it is clear that adaptive filter has even better frequency response than delay line cancelers in the pass band. This is achieved at the cost of some ripple in the stop band. The stop band ripple in adaptive filter is less than half of the peak value i.e. below 3dB threshold value.

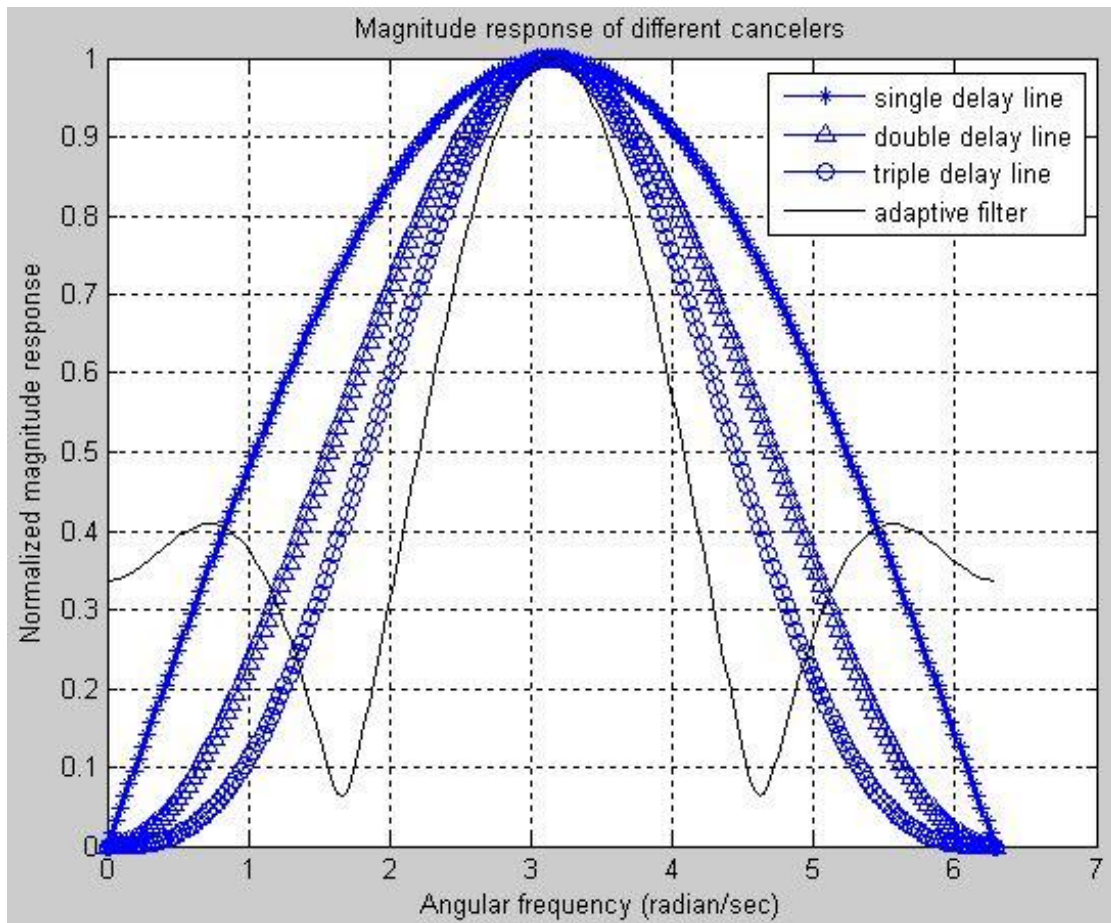


Figure 5.7 Magnitude response of delay line cancelers and adaptive filter

The adaptive filter has been implemented using direct form fir filter and LMS algorithm. Better results can be obtained by using lattice structure filter and more advanced adaptive algorithms such as Recursive Least Squares (RLS), variable step size LMS algorithm etc.

5.7 Testing the Filter Using Simulated Data

The performance of the filter has been tested using MRR data with simulated clutter. The data consists of vertical profile of radar reflectivity factor factors taken at regular interval of time. Certain range of data in each time frame are made constant so as to model clutter i.e. echo from the fixed stationary structure as shown in the first plot of Figure 5.9. Reflectivity from the clutter is constant i.e. -105 dBZ. This data has been applied to the filter. Second plot is the output of adaptive filter. In this case simulated clutter has been suppressed.

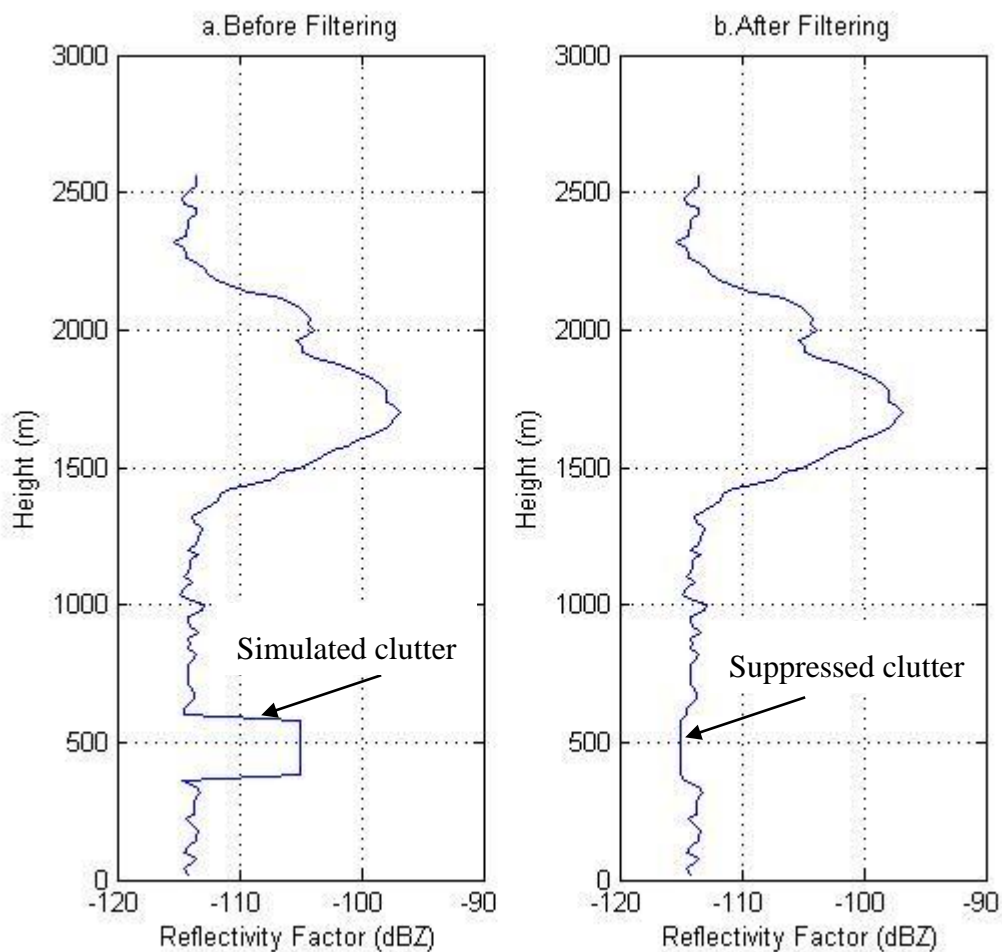


Figure 5.8 Simulation result with simulated data

(a) Before filtering (b) After filtering

5.8 Testing the Filter Using Real Data

The performance of the filter has been tested using real micro rain radar data. The data consists of vertical profile of falling velocity of rain drops and radar reflectivity factor taken at 10 minute interval of time [10, 11, 12]. The data is in animated gif format consisting of 48 image frames which are included in appendix E. A snapshot of Doppler spectra is shown in Figure 5.9. Different color bands have been used to represent different level of reflectivity. From the figure it can be interpreted that as the rain droplets descends downwards their falling velocity increases. Mean fall velocity has been represented by white curve.

In the top right part of the figure there are some strong and persistent radar return whose intensity is almost constant over the observation period. That may be due to echo from nearby tall buildings or tower. This portion of the data has been considered as a clutter.

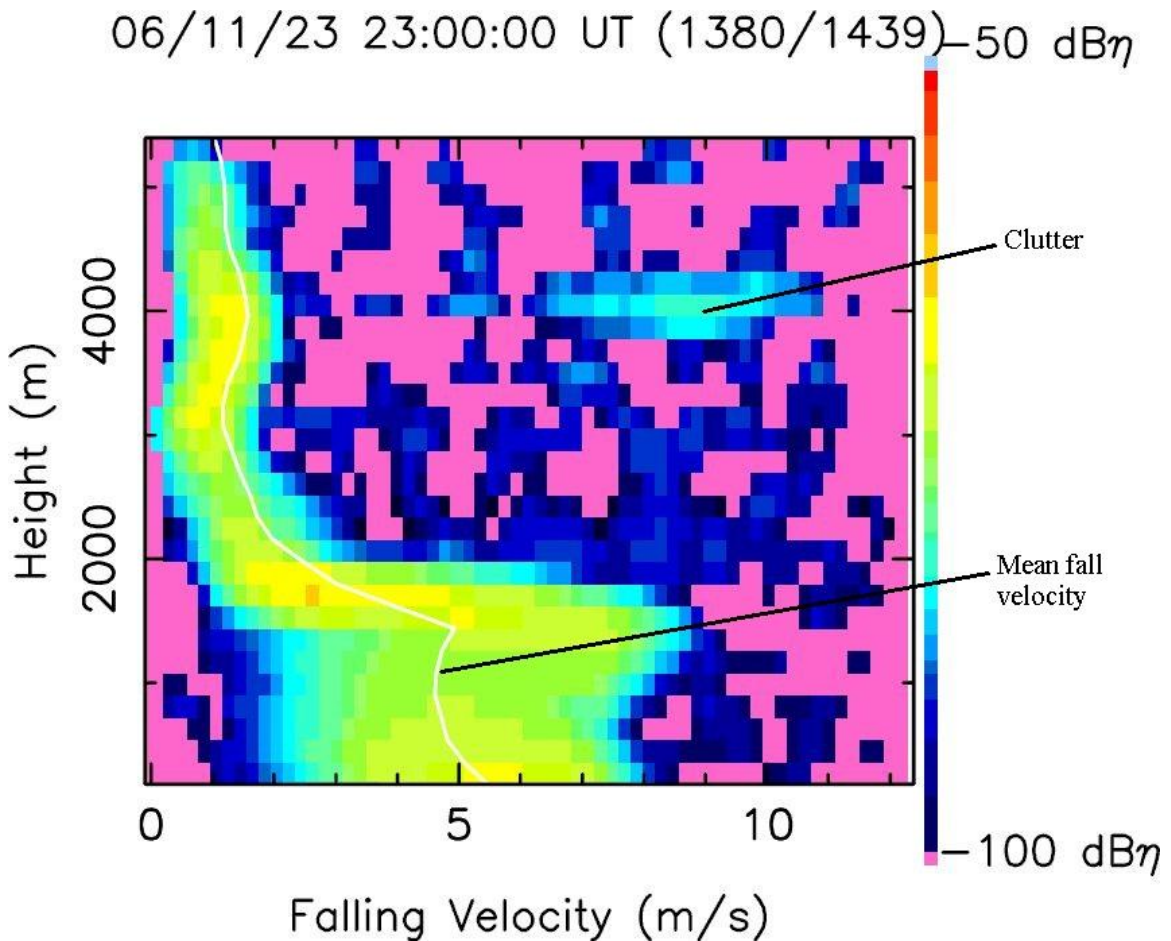


Figure 5.9 MRR Doppler spectra before filtering

This MRR data is applied to the adaptive filter. In an adaptive filter one input to the filter is the data to be filtered and the other one is desired data which is ideally noise free or clutter free data. In practice this desired data is generated by prediction filters. In this thesis desired data for the adaptive filter has been generated by using double delay line canceler which suppresses clutter due to stationary objects. A snapshot of Doppler spectra after filtering is shown in Figure 5.10. All gif frames are included in appendix F. Before filtering reflectivity from clutter is around $-80\text{dB}\eta$ whereas after filtering reflectivity from clutter is suppressed to minimum detectable level i.e. -100η .

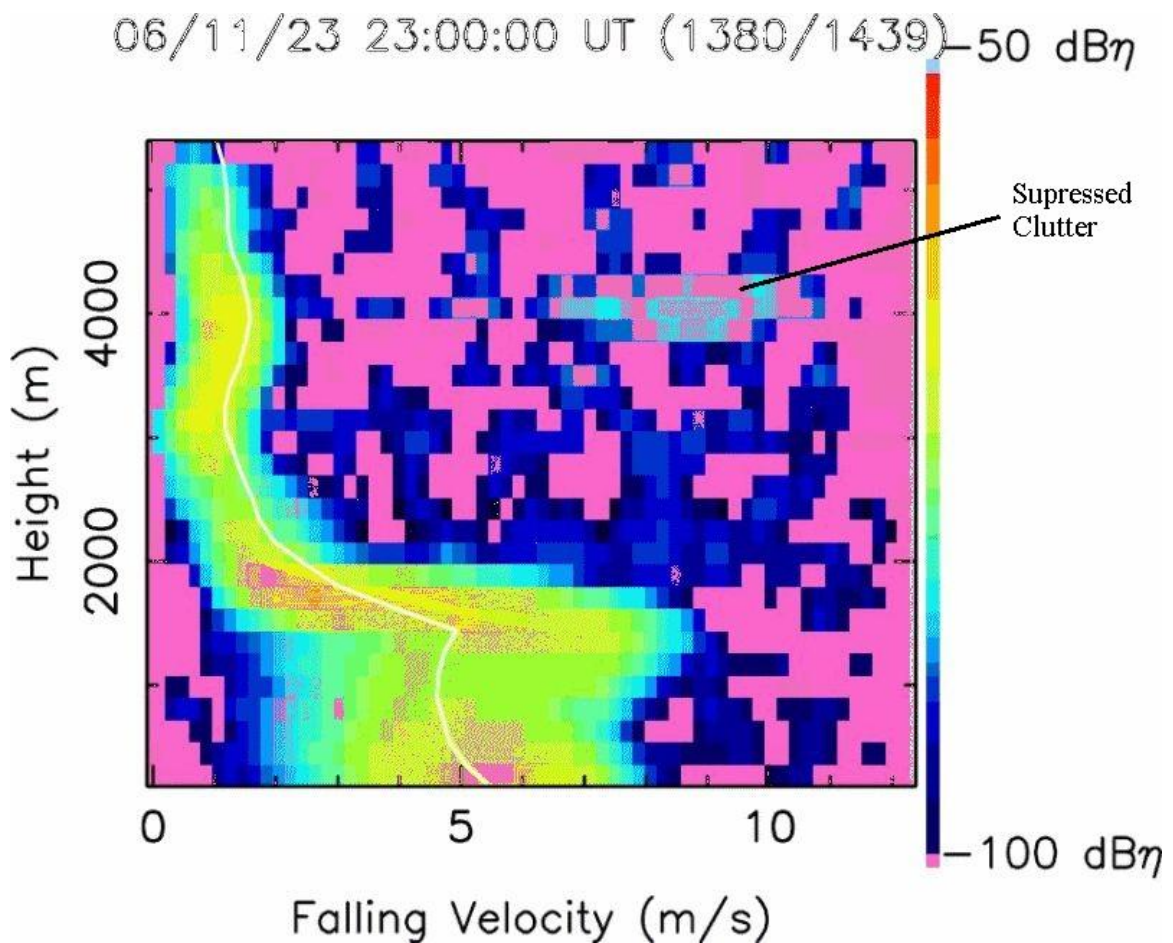


Figure 5.10 MRR Doppler spectra after filtering with weather phenomenon as target.

The filter is again tested with the same data but with reverse conditions i.e. now the weather phenomenon is considered as clutter and the object from which the persistent echo is being received is taken as our desired target. A snapshot the filter output for this case is shown in Figure 5.11. All gif frames are included in appendix G. The figure shows that the weather clutter has been suppressed considerably.

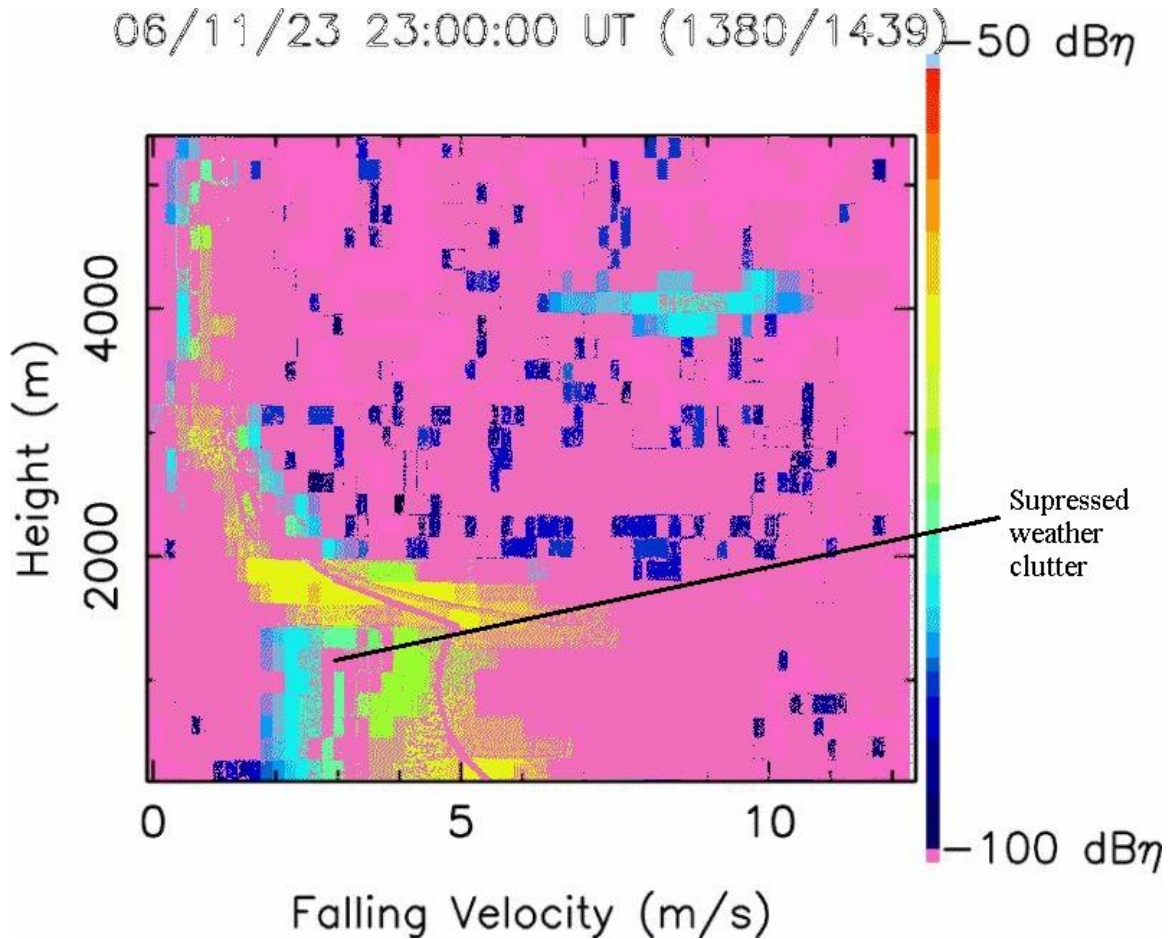


Figure 5.11 MRR Doppler spectra after filtering with weather phenomenon as clutter.

Thus the filter has been tested in different scenarios with same data treating some portion of data as target in one case and the same portion of data as clutter in the another case. The result shows that the filter is able to adapt to different environment by adjusting its coefficients.

6. CONCLUSION

Adaptive filter has been implemented in matlab for clutter suppression in Doppler FMCW radar. Performance has been studied for different values of its parameter namely step size (μ) and order (N). Higher order of filter provides better filtering but at the cost of higher computational complexity. At smaller value of μ filtering process is slow whereas at larger value the system may be unstable or oscillatory. The optimum value of μ has been determined so that the number of iterations required to achieve the specified value of mean square error is minimum. The optimum value of step size is found to be in the range 0.04 to 0.05 for filter order N=8. Frequency response of the filter has been compared with delay line cancelers of first, second and third order. The result shows that the adaptive filter has superior frequency response in the pass band which is achieved at the cost of some ripple in the stop band. The performance of filter has been examined using MRR data, once with weather as target and then with weather as clutter. It has been observed that the filter has clutter suppression ability in different scenarios.

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12. Adhikari N.B and K. Nakamura, *Detectable rain range of spaceborne Ka-band radar estimated from TRMM precipitation radar data*, J.Atmos oceano technol 19,173,180,2002.

APPENDIX

Appendix A: Radar Frequency Bands

Letter Designation	Frequency Range (GHz)
HF	0.003 – 0.03
VHF	0.03 – 0.3
UHF	0.3 – 1.0
L-band	1.0 – 2.0
S-band	2.0 – 4.0
C-band	4.0 – 8.0
X-band	8.0 – 12.5
Ku-band	12.5 – 18.0
K-band	18.0 – 26.5
Ka-band	26.5 – 40.0
V-band	40.0 – 75.0
W-band	75.0 – 110.0

Appendix B: Typical RCS of Different Targets at X band

Target Type	RCS(m ²)
Pickup truck	200
Jumbo jet	100
Large bomber or jet	40
Medium bomber or jet	20
Cabin cruiser boat	10
Large Fighter aircraft	6
Small fighter aircraft	2
Adult male	1
Conventional winged missile	0.5
Bird	0.01
Insect	1x10 ⁻⁵

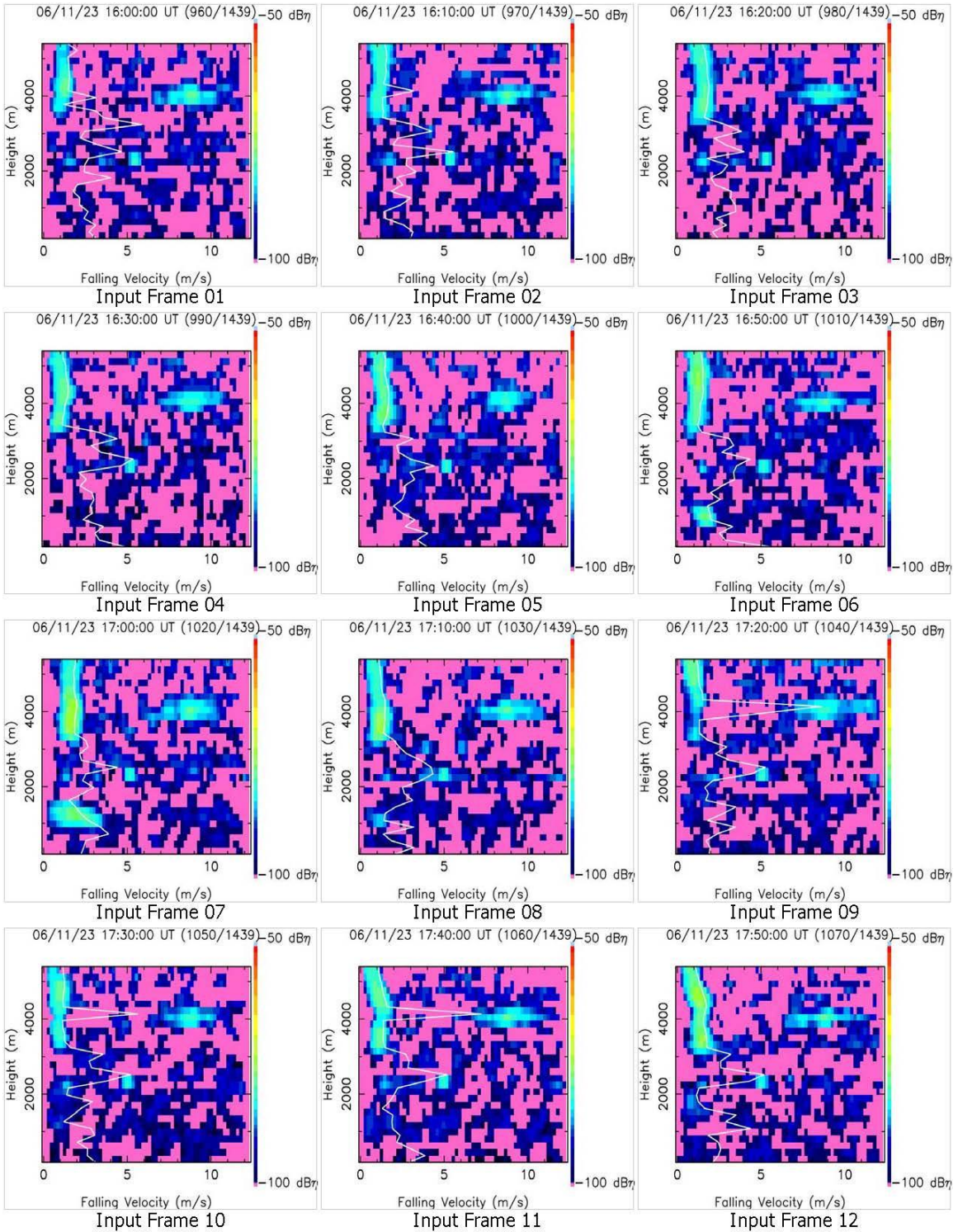
Appendix C: Typical MRR Specification

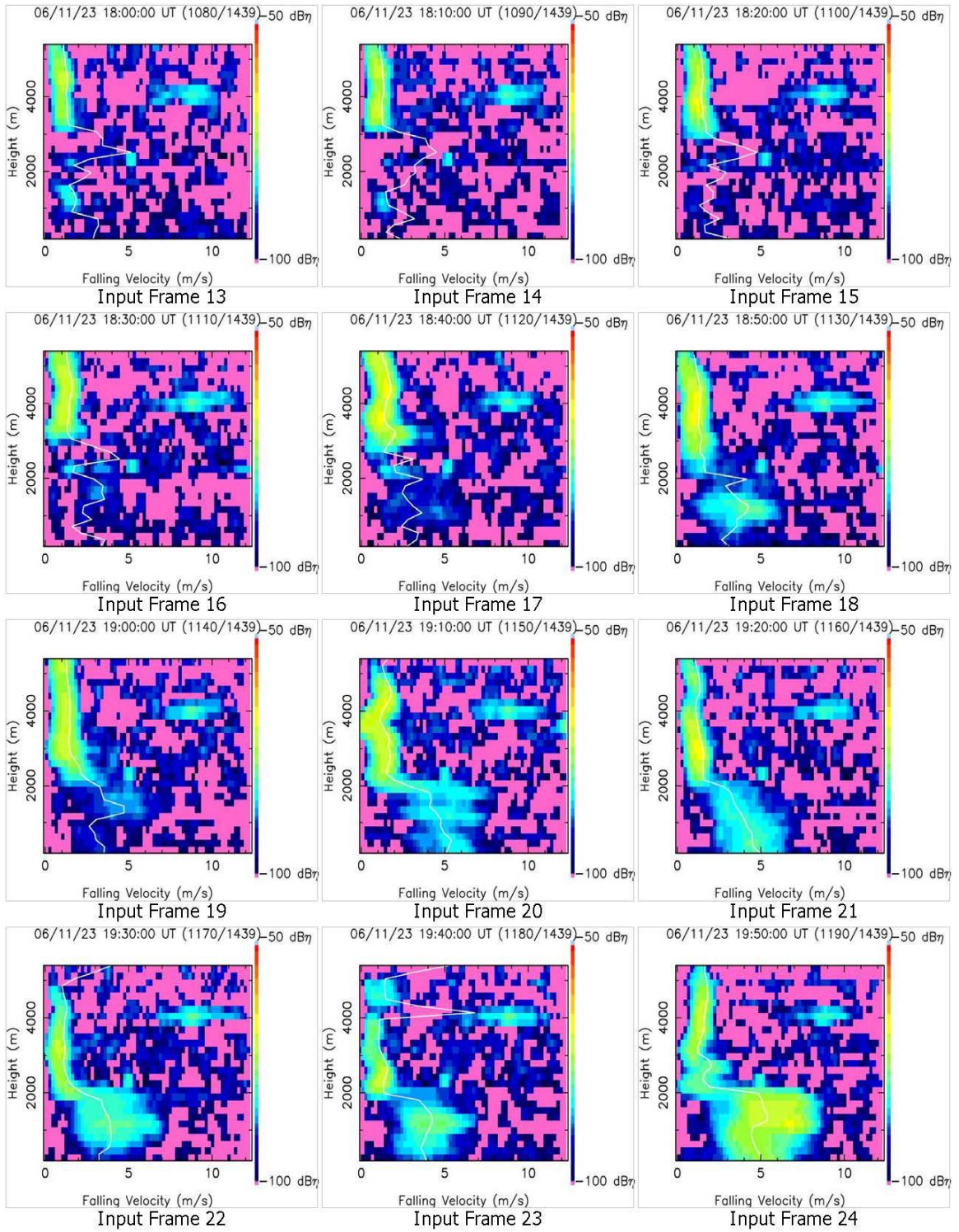
Operating Frequency:	24.23 GHz
Operating Mode:	FMCW
Modulation:	1.5 – 15MHz
Output Power:	50mW
Height Range:	30-6000m, max 30 height intervals
Antenna Type:	Parabolic
Antenna Diameter:	60cm
3 dB Beam width:	1.5 ⁰ (approximately)
Antenna Gain:	40.1dBi

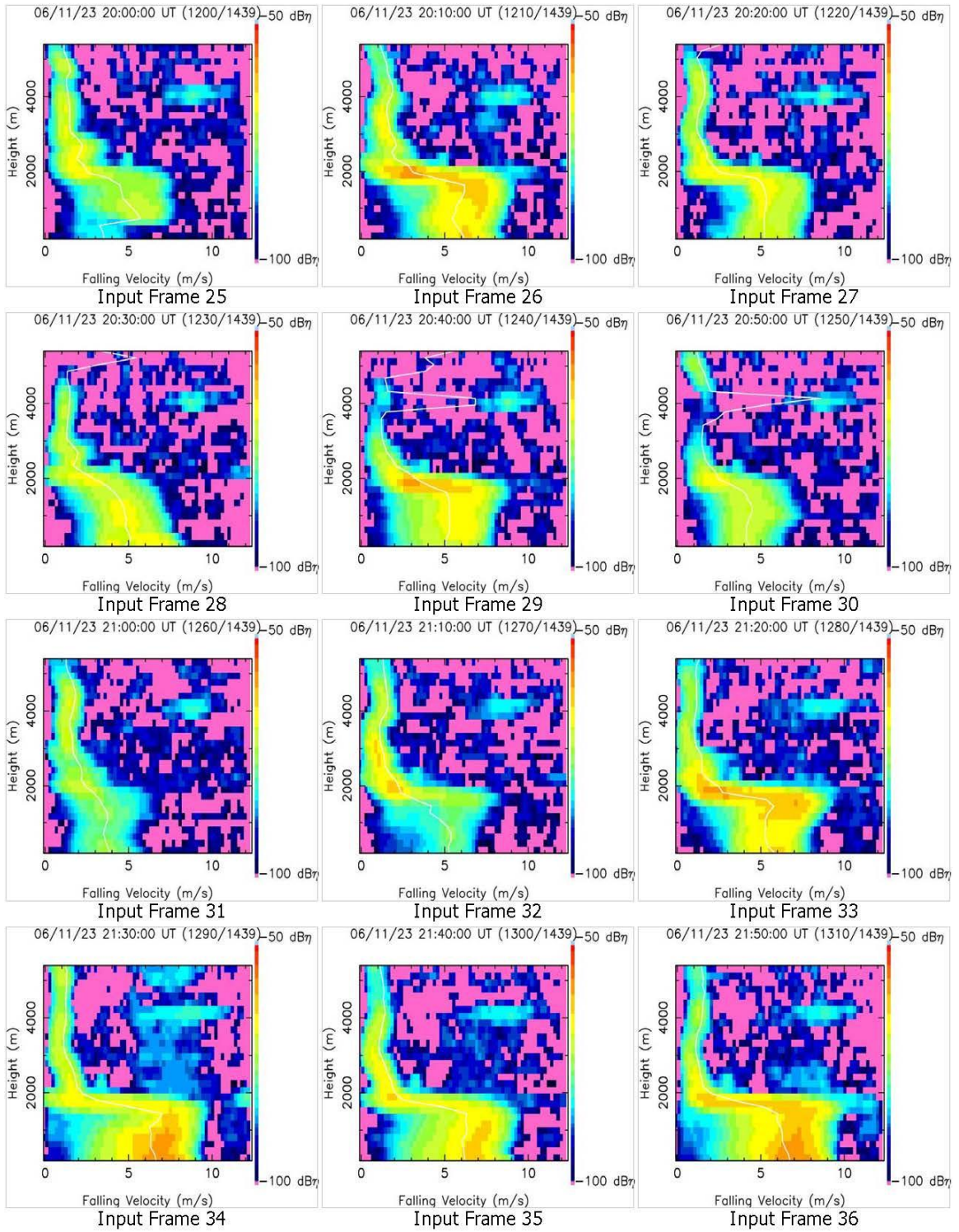
Appendix D: Reflectivity vs. Rain Rate

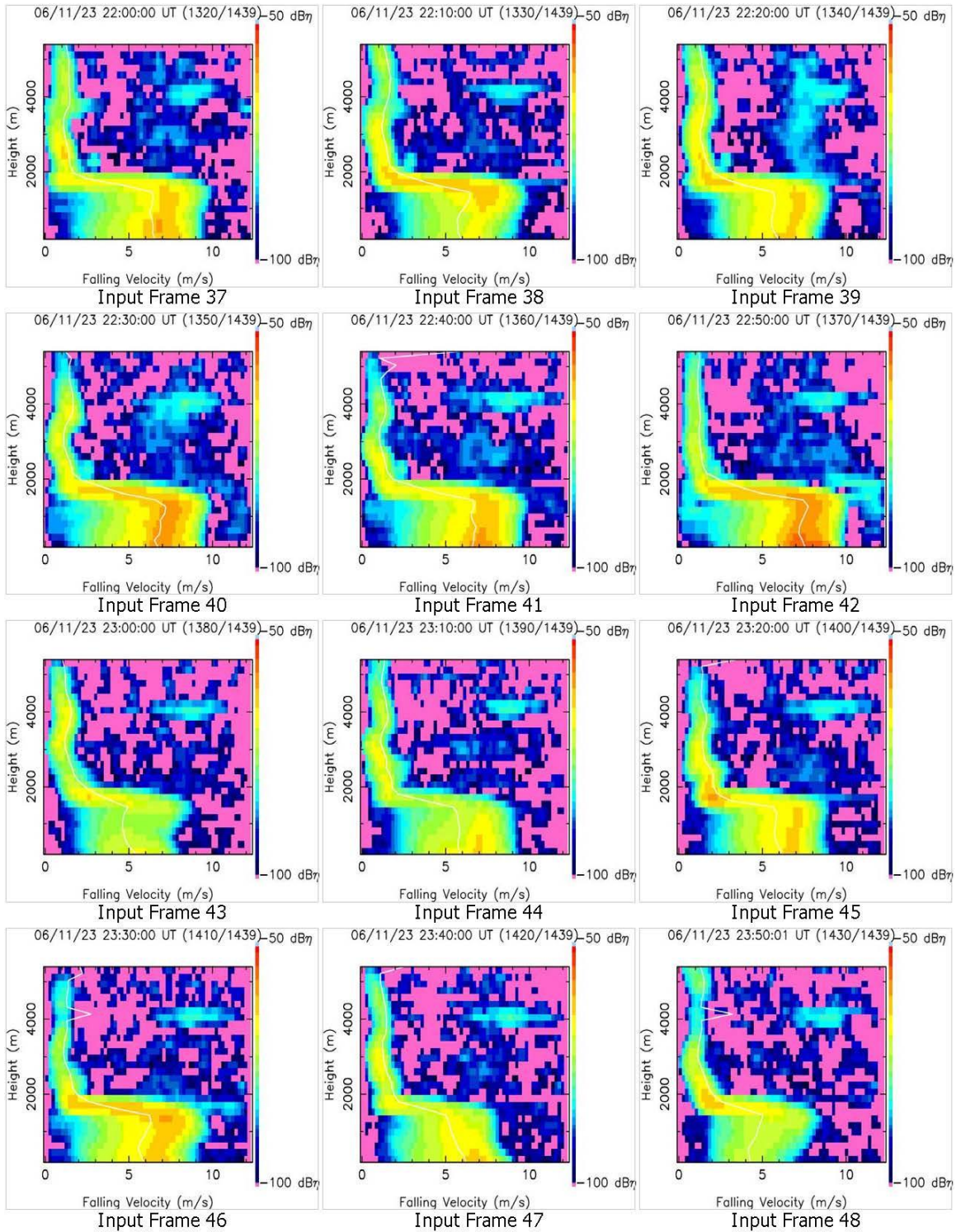
Reflectivity (dBZ)	Rain Rate (mm/hr)	Intensity
5	0.07	Hardly noticeable
10	0.15	Light mist
15	0.3	Mist
20	0.6	Very light
25	1.3	Light
30	2.7	Light to moderate
35	5.6	Moderate rain
40	11.53	Moderate rain
45	23.7	Moderate to heavy
50	48.6	Heavy
55	100	Very Heavy / small hail
60	205	Moderate hail
65	421	Extreme / large hail

Appendix E: MRR Input Data Frames

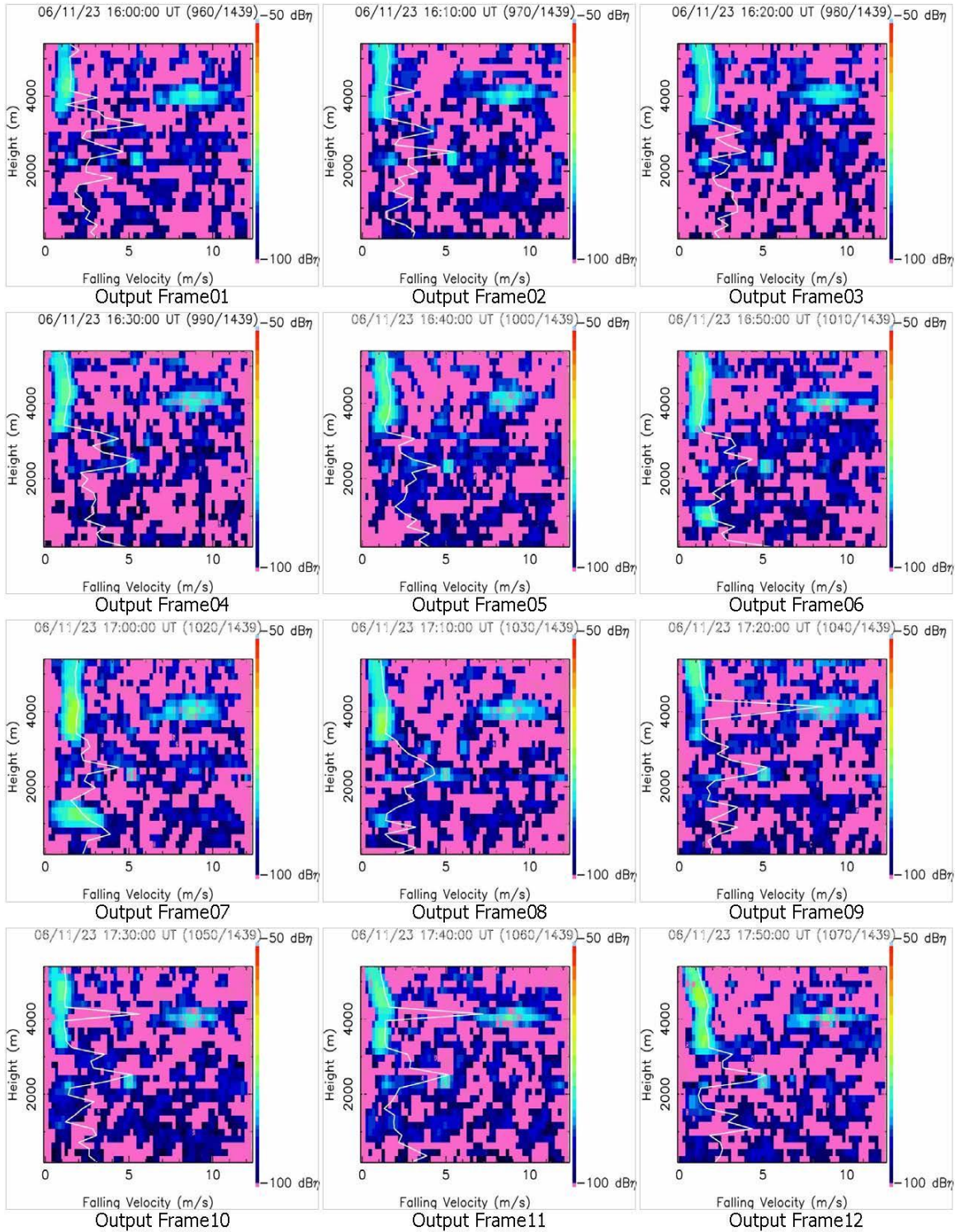


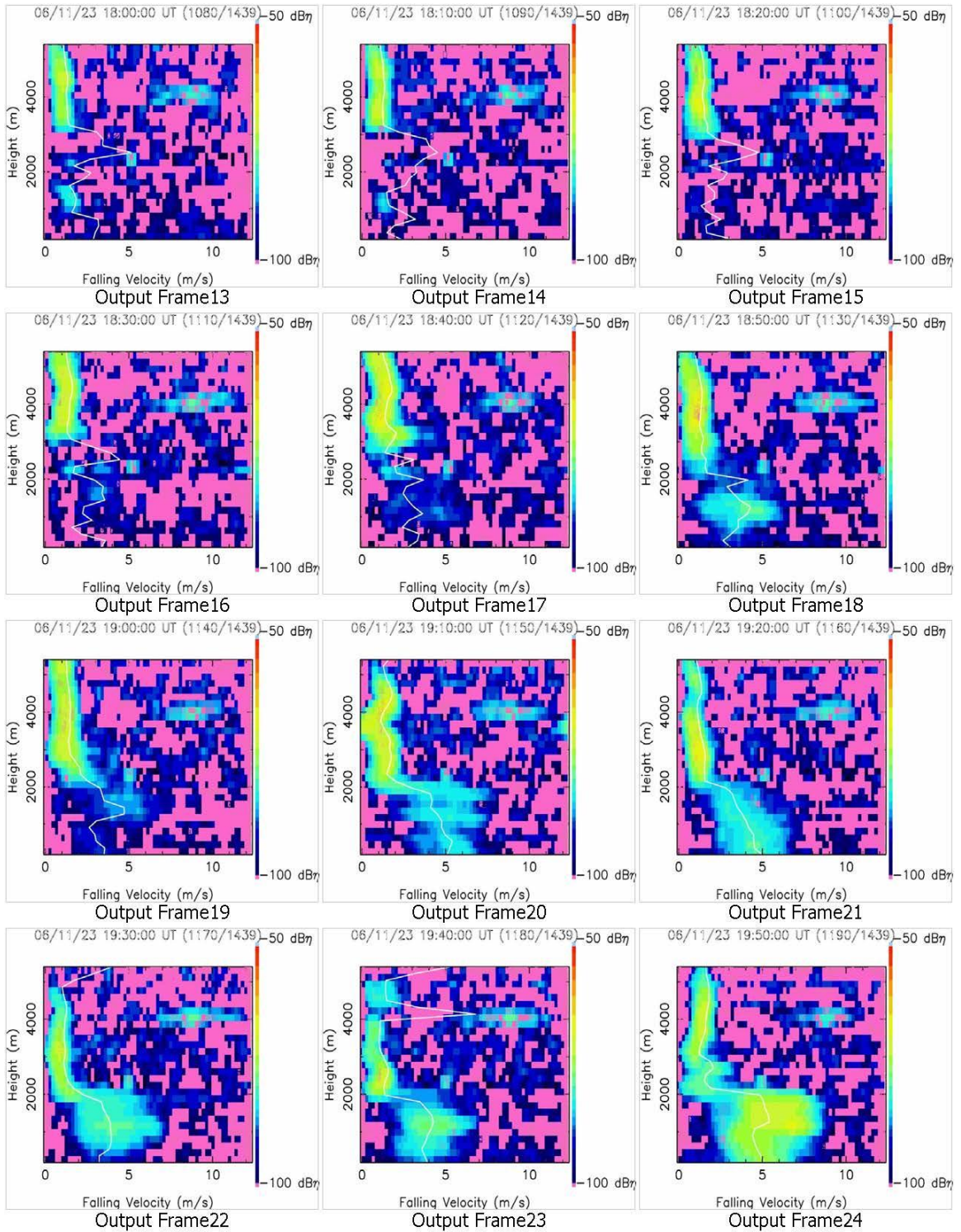


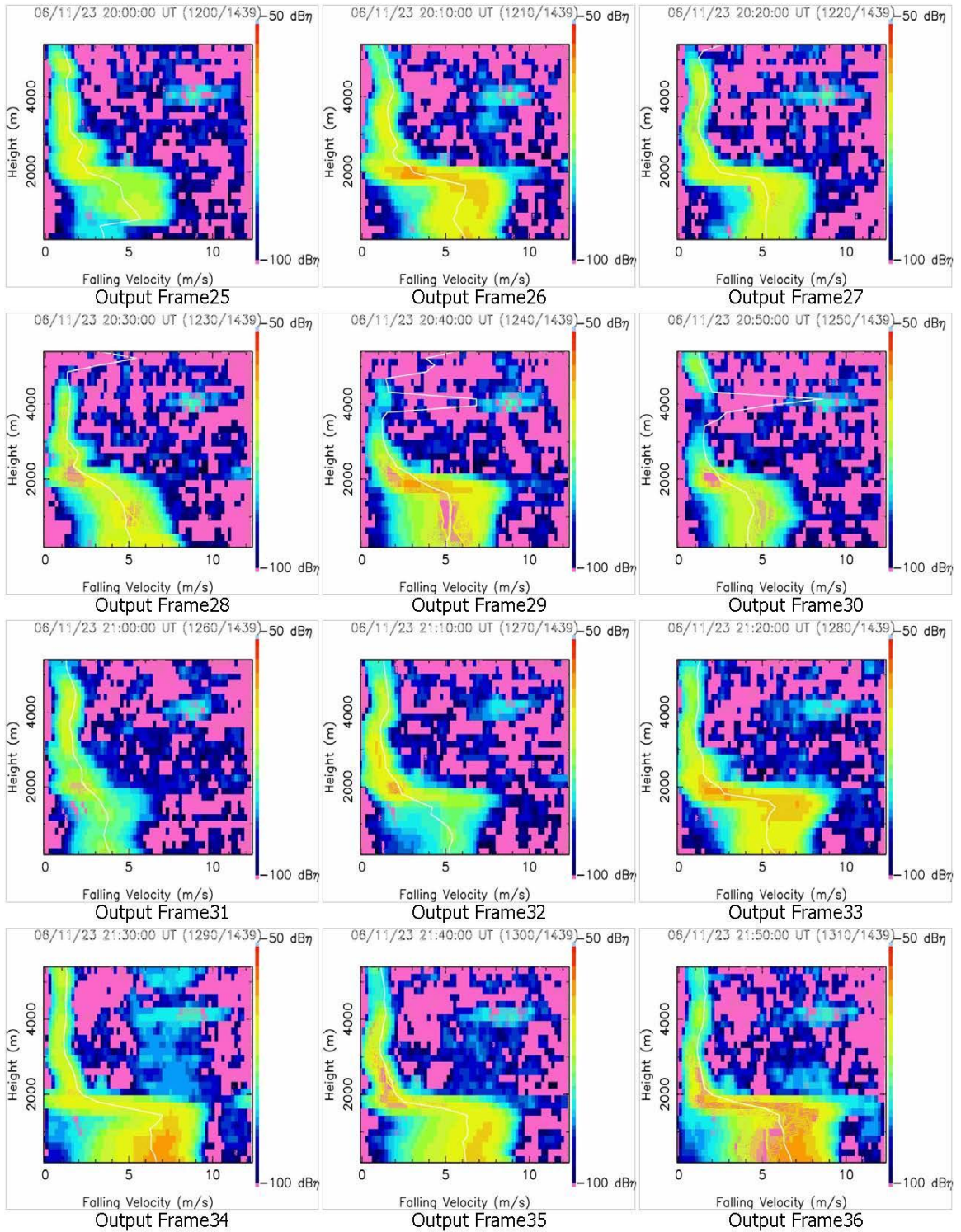


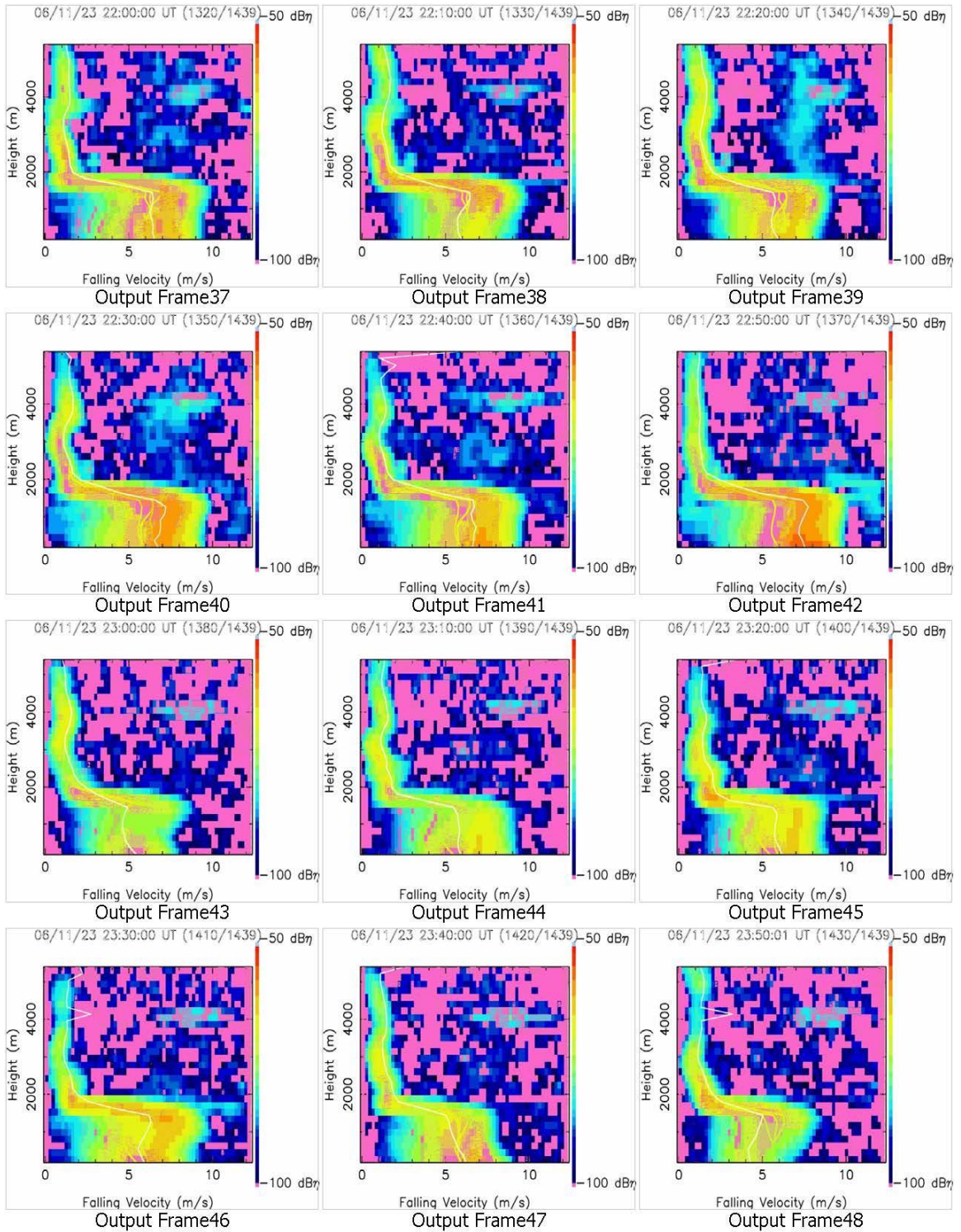


Appendix F: MRR Data Frames after Filtering with Weather as Target









Appendix G: MRR Data Frames after Filtering with Weather as Clutter

