DESIGN AND IMPLEMENTATION OF
NOVEL RADAR MODULATIONS FOR THE SUPERDARN
RADAR AT KODIAK ISLAND, ALASKA

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A

THESIS

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Abstract

The Kodiak SuperDARN (Super Dual Auroral Radar Network), located on Kodiak Island, Alaska, is a coherent-backscatter radar sensitive to Bragg scatter from ionospheric irregularities. SuperDARN transmitters send out a sequence of seven pulses that aid in the formation of complex autocorrelation functions (ACFs). These ACFs allow for estimating the power, velocity and the spectral widths of the scattering plasma waves. However, the multipulse sequence used currently has some characteristics that are not ideal for the intended purpose. In addition, the analysis technique for estimating the properties of the ACF assumes that there is only a single velocity component present in each range cell at one time. In this study, the aperiodic radar technique designed by Dr. John D. Sahr and Dr. Sathyadev V. Uppala was investigated to design an optimized transmission sequence that would have no repeated lags, a minimum number of inherently missing lags and no loss of lags due to Tx-on/Rx-off conflicts. With the designed transmission sequence, efficient analysis of data is possible through the use of a standard spectral estimator, the modified covariance technique. The design enhances the ability of the radar to discriminate targets in the same range bin.
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Chapter 1  Introduction

An important milestone in the study of upper atmosphere physics was the development of a multi-national network of high frequency (HF) coherent-scatter radars designed to study large-scale structure in the high-latitude ionospheric plasma convection. This process started with the design of the Goose Bay HF radar by Dr. Ray A. Greenwald and his team at the John Hopkins University Applied Physics Laboratory. The success of that original system led to the design of the network that is known as Super Dual Auroral Radar Network (SuperDARN). At this point of time, 18 radars are in operation in the northern and southern hemispheres.

The radar of concern in this thesis is located on Kodiak Island, Alaska, and started its operation in the fall of 1999. Research on enhancing the radar’s capabilities has made it an ideal tool to study not only the high-latitudes but the mid-latitudes as well [Parris, 2003]. This thesis is yet another step towards advancing the radar’s competence by improving its target discrimination capability and its ability to resolve the Doppler frequency due to target motion.

The frequency resolution obtainable from a pulse is proportional to the inverse of the length of the transmitted pulse while the altitude resolution is directly proportional to the length of the pulse. The shorter the pulse, the better its altitude resolution, but the worse its frequency resolution. Since the energy transmitted through a short pulse is less than that of a long pulse of equal amplitude, the signal-to-noise ratio is also reduced. This leads to a tradeoff in the choice of resolution in the different domains. This tradeoff can be eliminated if a sequence of short pulses is used rather than a single pulse. In such a case, the range resolution is still proportional to the length of the individual pulses, but the frequency resolution becomes inversely proportional to the length of the pulse sequence. The specific properties of a pulse sequence are dependent on the pattern in which the pulses are structured to generate most or all of the time lags for forming the autocorrelation function [Farley, 1969]. This scheme enables the study of several time delays simultaneously. Use of a sequence of pulses repeated at a uniform time interval
could derive all the time lags from an autocorrelation function, but would lead to range aliasing, which arises due to the computation of a time lag from a received signal that is a combination of pulse returns from more than one range. A well designed pulse sequence leads to minimum ambiguity in the ranges that can contribute to a given time lag. Additionally, power from unwanted ranges, called clutter, adds to the noise. The effective signal to noise ratio is greatly reduced by clutter, making it necessary for longer integration times to give satisfactory accuracy. Averaging over many pulses has therefore become an essential ingredient of any practical processing scheme.

The Kodiak SuperDARN, like all of its counterparts, uses a multipulse transmission scheme to resolve returns from different ranges. The data received from the transmission of the pulse sequence are processed using correlation techniques which allow the calculation of a number of time lagged products up to ~ 43.2 ms. The terms involving noise are minimized in the final estimate of the correlation function by averaging lag products from ten pulse sequences every second. The presence of a plasma drift in the direction of the radar beam causes the spectrum to become asymmetric and the correlation function estimated is complex in nature. The autocorrelation function is then used to derive the power, spectral width and mean Doppler velocity of the echoes for each beam direction and each range cell in the radar's field of view. This process is performed in real time using the 'FITACF' algorithm, which assumes a single spectral component in a range cell, implying that the phase of an autocorrelation function varies linearly with time lag. The mean Doppler velocity is a direct measure of the ExB drift of irregularities when they backscatter the HF signal. The existence of many irregularities moving at different ExB velocities in a range cell leads to a spread in the Doppler velocity whose estimate is given by the spectral width.

A problem that arises from the use of multipulse sequences is that any pulse sequence does not have the ability to produce an infinite number of time lags without having redundant pairs that would in turn lead to range aliasing [Farley, 1971]. If the correlation time of the target studied by the radar is greater than the longest time lag that can be generated by the pulse sequence, this could be a serious problem.
Decades of studies have revealed noteworthy discrepancies between the theoretical predictions and the observations in the ionospheric spectra [Sahr and Fejer, 1996]. These inconsistencies can be attributed to the existence of many spectral components in a range cell and the incapability of the SuperDARN to discriminate them due to the single spectral component assumption.

1.1 Objective of this research

The purpose of this research is to investigate the design of an optimum pulse sequence, which would be used to derive more accurate data from the SuperDARN. Design of a novel pulse sequence that has the ability to reduce the severity of the effect of bad lags of an autocorrelation function without introducing range aliasing would be a giant leap towards the perfection of these radars. The aperiodic transmission scheme introduced by Dr. Sahr J. D. and Dr. Uppala S. V. [Uppala and Sahr, 1994] for moderately overspread targets was studied and analyzed for this purpose. Sampling the signal from a desired range at a higher rate and under-sampling the signal adding up from ranges that lead to aliasing would keep the desired spectrum unharmed by the effects of range clutter. This is because under-sampling the clutter would make it appear like noise. The spectrum remains unchanged except for an increase in the noise floor. These pulse sequences have been used to study the auroral electrojet irregularities with the Very High Frequency (VHF) radars.

This research took a step farther into exploring a method of spectral analysis, called the modified covariance technique designed by Dr. S. L. Marple [Marple, 1987] for its ability to resolve the various spectral components in a range cell. This method has been extensively studied and successfully used for analyzing Synthetic Aperture Radar data [Marple, 1991].
1.2 Organization of the thesis

The outline of the thesis is as follows. The radar theories pertaining to the understanding of the thesis are presented in Chapter 2. The importance of over-the-horizon coherent backscatter radars in ionospheric studies is discussed in brief. A comment is made on the HF propagation modes as well. The principle of coherence is described briefly. In Chapter 3, the abilities, details of operation, methods of data collection and processing of data by the Kodiak HF radar are described. The need for a new pulse sequence is identified through an analysis of the 7-pulse sequence used by the radar. The process of merging the line-of-sight Doppler velocities from radars at the intersection of their beams is described and a sample convection plot is presented. The philosophy of design of aperiodic pulse sequences is discussed in Chapter 4 based on the type of radar target. The different types of aperiodic pulse sequences are discussed in detail. Chapter 5 involves comparing the merits and demerits of the various aperiodic pulse sequences. The design of a sequence of pulses whose pulse spacings were a combination of arithmetic, geometric and harmonic progressions has proved to be a good solution for the desired goal. Each of the pulse sequences was formed by an educated trial and error method subject to the restraints that no lag be repeated twice and generate short and long time lags simultaneously. The modified covariance spectral analysis technique was used to resolve the SuperDARN spectra whose details were difficult to see with the standard methods. A final pulse sequence was chosen and implemented on the radar. The data analysis procedures and the possible means of improving accuracy in determining the Doppler moments are discussed in Chapter 6. The thesis concludes with suggestions for further research and conclusions in Chapter 7.
Chapter 2  An introduction to radar principles

Knowledge of the principle of operation of radar is necessary for understanding the topics discussed in this thesis. Hence, an effort has been made to illustrate the essential areas.

The technique of sending out a signal and, based on the returning ‘echo’, judging the direction of the ‘target’ from the source of the signal has been used by animals such as bats since time immemorial. By processing subsequent echoes, the direction of travel and speed of the target are also sensed. This technique is the basis for Radio Detection And Ranging (radar). The radar of interest here receives reflection from discontinuities of the index of refraction of the atmosphere. A portion of the reflected power is collected, amplified, detected and displayed in a manner so as to determine the characteristics of the discontinuity.

2.1  What can radar do?

A radar helps us understand how easy it is to detect a target, how big and where exactly it is, and how it changes or moves.

![Diagram of radar range determination](image-url)

Figure 2.1: Illustration of radar range determination
In a radar system, the velocity of the radiation to and from the reflecting object is constant (the velocity of light). The range, or distance to a target, is found by measuring the time it takes for the radar signal to travel to the target and return back to the radar.

The target’s location in angle can be found from the direction the narrow-beamwidth radar antenna points when the received echo signal is of maximum amplitude.

If a target is in motion, there is a shift in the frequency of the echo signal due to the Doppler Effect. This frequency shift is proportional to the velocity of the target relative to the radar. However, the radar will only observe the component of velocity that is along the line between the target and the radar. This line is known as the ‘line of sight’. A target moving tangentially would produce a zero Doppler frequency shift.

Radar can be grouped into two broad categories, continuous wave radars and pulsed radars.

In the case of continuous wave radar, a continuous radio signal is sent by the transmitter, while the pulse radar transmits pulses. The radar of concern here is a pulsed-Doppler radar capable of extracting useful information to understand ionospheric convection. A brief introduction to the pulsed-Doppler radar follows.

2.2 Pulsed-Doppler radars

A pulsed-Doppler radar determines the range of a target by measuring the round trip delay pulsed signal returned by a target. Information about the target motion is contained in the received echo signal in the form of a Doppler shift of the carrier. Due to the target motion, the phase path of the echo changes from pulse-to-pulse and hence the phase differences also change by the same amount. The rate of change of phase, \(\frac{d\phi}{dt} = \omega_d = 2\pi f_d\), where \(f_d\) is the Doppler shift of the carrier. For a Doppler shift of frequency by \(f_d\), the phase difference changes linearly with a slope of \(f_d\). The pulse-repetition frequency (prf) of the pulses must therefore be \(\geq 2f_d\). If the electromagnetic wave transmitted by the radar has a phase \(\varphi_0\), the phase of the received echo will be,

\[
\varphi = \varphi_0 + \frac{2\pi}{\lambda} (2r),
\] (2.1)
where \( r \) is the range of the target and \( \lambda \) is the operating wavelength. Since the rate of change of phase is equal to the Doppler shift in frequency,

\[
\omega_d = \frac{4\pi}{\lambda} \frac{dr}{dt} = \frac{4\pi}{\lambda} v_r,
\]

\[
\Rightarrow f_d = \frac{2v_r}{\lambda},
\]

where \( v_r \) is the radial velocity of the target. The Doppler shift in frequency measured by the radar is hence related to the pulse-repetition frequency by the relation,

\[
\frac{2v_r}{\lambda} \leq \frac{prf}{2},
\]

\[
\Rightarrow v_{\text{max}} = prf \left( \frac{\lambda}{4} \right).
\]

Hence for a given \( prf \), larger radial velocities can be measured unambiguously using radars operating at lower frequencies. The unambiguous range measured by a pulse-doppler radar is given by the relation,

\[
r_{\text{max}} = \frac{1}{2} \left( \frac{c}{prf} \right) = \frac{c}{4f_d},
\]

where \( c \) is the velocity of light. Long unambiguous ranges can be observed using radars with low \( prfs \). This leads to the relation,

\[
r_{\text{max}} v_{\text{max}} = \frac{c\lambda}{8},
\]

which is referred to as the ‘Doppler dilemma’ in radar literature. There can be no one \( prf \) which optimizes both the maximum unambiguous range and the maximum observed radial velocity. Extensive studies have led to the conclusion that changing the inter-pulse period between successive transmitted pulses can help in receiving echoes from great ranges and from targets moving at high velocities without ambiguity.

A pulsed-Doppler radar can also provide information about the nature of the targets being observed. It has proven to be extremely efficient in detecting targets on the ground, in the sea, in the air, in space, and even below the ground.
The radar of interest here is used to observe the auroral and polar cap ionospheres. The next section will review the importance of ionospheric research and how SuperDARN radars are suited to perform their research tasks.

2.3 Why study the ionosphere?

The sun, the source of all life on our planet, emits radiation over a broad spectrum. Light at short wavelengths, ultraviolet wavelengths, impinging on the Earth’s upper atmosphere, ionizes a fraction of the atmospheric gases producing the ‘ionosphere’. In addition, the sun continually emits fluctuating clouds of highly ionized gas or plasma, called the ‘solar wind’. This wind carries with it a magnetic field called the ‘interplanetary magnetic field’. When the solar wind reaches the Earth, the interplanetary magnetic field interacts with the Earth’s magnetic field, causing a magnetic field cavity called the ‘magnetosphere’. The ‘magnetopause’ is the outer boundary of the magnetosphere.

The interaction of the solar wind and the magnetosphere leads to a potential difference across the geomagnetic field, generating electric fields perpendicular to the magnetic field of the magnetosphere. These electric fields map down to the ionosphere creating motion in the ionospheric plasma at the Hall drift velocity given by,

$$v = \frac{E \times B}{B^2}.$$  \hspace{1cm} (2.8)

This motion is called ‘convection’. The direction of convection can be obtained by applying the \(E \times B\) rule for the electric field and the Earth’s magnetic field. This also leads to plasma instabilities in the high-latitude ionosphere. The solar-terrestrial environment is illustrated in Figure 2.2.
2.4 Importance of radar in ionospheric studies

Decades-long data sequences accumulated from radars have proved to be scientifically sound and cost-effective to monitor processes in the ionosphere. One can hardly conceive of an instrument that can compete with a radar in furthering the advancement of knowledge in microphysics, kinematics, and the understanding of thermodynamic structures on scales ranging from a few tens of meters to several thousand kilometers. Radars have the ability to operate continuously while rocket and satellite measurements are limited to a specific trajectory, unique in time and space. Adding to these limitations there is also the fact that the use of satellites is an expensive exercise.

Several types of radars have excelled in this field. Incoherent scatter radars have been used extensively to understand the electron density structure, ion composition, and the temperature of the ionosphere, etc. Coherent scatter radars have been used primarily to investigate plasma physics and convection. MST radars were developed to observe radial components of the wind, turbulence and the stability of the atmospheric layer in the
troposphere (10 km), stratosphere (10 – 50 km) and the mesosphere (50 – 100 km) regions of the atmosphere. The radar of interest here is a high frequency over-the-horizon coherent backscatter pulsed radar.

2.5 Role of over-the-horizon coherent backscatter radars in ionospheric studies

The maximum operating range of a radar designed for use on the ground with operating wavelengths ranging from meters to millimeters, is limited by the curvature of the earth which determines the altitude observed along a direct line of sight. When waves propagate through a medium in which the index of refraction varies with height, the waves are refracted and the propagation path becomes curved. The index of refraction depends on the frequency of the radar signals, with low frequencies more strongly influenced than high frequencies. The propagation conditions encountered by HF (3 – 30 MHz) signals are strongly dependent upon the ionospheric plasma. Great interest was hence taken to develop HF radars since they could detect targets completely obscured by the horizon.

Over the years, over-the-horizon backscatter radars have been widely used to understand the physics of the ionosphere. When electromagnetic energy is radiated by the transmitting antenna at a low angle to the horizon, waves propagate until they reach the ionosphere in the first hop region. In the ionosphere, the waves may be scattered back by plasma irregularities, or may continue on a forward path and be refracted downward toward the ground [Headrick and Skolnik, 1974]. The density distribution with altitude in the ionosphere can lead to HF radio waves of different frequencies taking different trajectories. Research over decades has established that signals transmitted at an elevation angle greater than some critical value go all the way through the ionosphere and never return. When transmitted below the critical value of elevation angle, signals are reflected at the E or the F regions of the ionosphere, ranging in altitude from 90 – 150 km and > 150 km respectively.

The various propagation modes of an HF radio wave in the ionosphere are illustrated in the Figure 2.3. When a radio wave reaches orthogonality with the magnetic field of the E (or F) region, we have potential for direct ‘ionospheric backscatter’ from
the E (or F) region. This is shown in Figure 2.3 as $\frac{1}{2}E$ and $\frac{1}{2}F$ respectively. When we have high ionospheric densities, the radio wave may actually bend to such an extent that it strikes the ground and is then scattered back to the radar. This is termed as ‘ground scatter’; shown in the Figure as 1E, 1F and 2F modes. Ionospheric backscatter may result from the $1\frac{1}{2}$, $2\frac{1}{2}$ modes too.

Figure 2.3: Propagation modes through the ionosphere for HF radio waves

It is important to understand the principle on which the coherent radar is based to truly appreciate the importance of the SuperDARN radars. Oppenheim had demonstrated that many features of a signal are retained in the phase information but not in the amplitude [Oppenheim and Schafer, 1975]. For an HF radio wave plasma irregularity scattering process, momentum is conserved, hence, the wave vectors of the transmitted signal, the received signal, and the ionospheric irregularities follow the relation,

$$k_{\text{transmitted}} = k_{\text{received}} + k_{\text{irregularity}}.$$  \hspace{2cm} (2.9)

This leads to the Bragg’s scatter condition that is based on the coherent reinforcement of scattering from a periodic scatterer [Fejer and Kelley, 1980]. The ionospheric plasma density is inhomogeneous due to thermal fluctuations and
irregularities caused by plasma instabilities. The irregularities have some coherence spatially and temporally that can satisfy the Bragg condition. The scattered signal from such a disturbance can be characterized as scattering from that particular frequency component of the irregularity spectrum that is resonant with the radar frequency. This implies that the echo energy from each cycle of the sine wave gets added up coherently.

![Figure 2.4: Bragg Scatter from a sinusoidal component of the ionospheric irregularity](image)

The radar wavelength, \( \lambda_{\text{radar}} \), is twice that of the spectral component, \( \lambda_{\text{irregularity}} \) (irregularity wavelength), so that coherent addition takes place. The echoes returning from any spectral component that is not at the resonant wavelength will then add non-coherently and result in much smaller amplitude than the echo that experiences coherent addition from each cycle. However, there may be a spread of velocities present within a range cell and the scattered signal spectrum will not be a delta function at the Doppler velocity corresponding to \( \lambda_{\text{radar}}/2 \). Hence, we have a spectrum that has some finite width and centered around the average Doppler velocity.

The HF radio wave plasma irregularity scattering process also conserves energy leading to the relation,

\[
\omega_{\text{transmitted}} = \omega_{\text{received}} + \omega_{\text{irregularity}}.
\]  

(2.10)

The difference in the angular frequency of the transmitted and received radio wave supplies information on the phase velocity of the ionospheric irregularities. If \( \omega_{\text{irregularity}} = 2\pi f_{\text{irregularity}} \) is the Doppler shift measured by the radar, then the phase velocity of the detected ionospheric irregularities is given by the relation,
\[ V_{\text{phase}} = \frac{c}{2f_{\text{radar}}} f_{\text{irregularity}}. \] (2.11)

Extensive research has lead to a conclusion that the velocity of the irregularity determined by the coherent backscatter radars employing HF radio waves is equal to the bulk drift velocity of the plasma. When the radar echoes originate in the ionospheric F-region, the plasma bulk density is equal to the ExB velocity.
3.1 Overview of the SuperDARN

The zeal to study the phenomena occurring in the high latitude ionosphere motivated the design of an HF phased-array radar in the fall of 1983. The SuperDARN is a constellation currently consisting of 18 radars (11 in the Northern Hemisphere and 7 in the Southern Hemisphere). These radars are high frequency, over-the-horizon radars for conducting research in ionospheric physics and space physics [Greenwald et al., 1995]. The design of this network allows these radars to work in pairs with common areas of view that facilitate mapping of high latitude plasma convection over the auroral and polar cap ionosphere from 2-D Doppler velocity vectors. The Figure 3.1 shows the fields of view of the SuperDARN radars in the northern and the southern hemispheres.

![Figure 3.1: Fields of view of SuperDARN in the northern (Figure (a)) and the southern (Figure (b)) hemispheres](image)
These radars are maintained and operated by different organizations all over the globe. The Tables 3.1 and 3.2 tabulate the location of the radars and the organizations that operate and maintain them.

One objective of this research is to understand and improve the capability to better predict ionospheric changes and their impact on technologies. Adding radars at mid-latitudes to the current constellation of SuperDARN is being considered since the auroral oval often expands equatorward during geomagnetic storms.

Table 3.1: Essential information about SuperDARN in the Northern Hemisphere

<table>
<thead>
<tr>
<th>#</th>
<th>Field of View</th>
<th>Location</th>
<th>Operating Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Rankin Inlet, Nunavut, Canada</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 62.82° N</td>
<td>University of Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 93.11° W</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>King Salmon, Alaska, USA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 58.68° N</td>
<td>Communications Research Laboratory, Japan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 156.65° W</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Kodiak Island, Alaska, USA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 57.6° N</td>
<td>Geophysical Institute, USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 152.2° W</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Prince George, British Columbia, CANADA</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 53.98° N</td>
<td>University of Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 122.59° W</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.1(contd.): Essential information about SuperDARN in the Northern Hemisphere

<table>
<thead>
<tr>
<th>#</th>
<th>Field of View</th>
<th>Location</th>
<th>Operating Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td></td>
<td>Saskatoon, Saskatchewan, CANADA</td>
<td>University of Saskatchewan, Canada</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 52.16° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 106.53° W</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Kapuskasing, Ontario, CANADA</td>
<td>Johns Hopkins Applied Physics Laboratory, USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 49.39° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 82.32° W</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Goose Bay, Nfld, CANADA</td>
<td>Johns Hopkins Applied Physics Laboratory, USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 53.32° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 60.46° W</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>Stokkseyri, ICELAND</td>
<td>LPCE/CNRS, France</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 63.86° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 22.02° W</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>bykkvybær, ICELAND</td>
<td>University of Leicester, England</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 63.86° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 19.20° W</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Hankasalmi, Finland</td>
<td>University of Leicester, England</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 62.32° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 26.61° E</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Wallops Island, Virginia, USA</td>
<td>Johns Hopkins Applied Physics Laboratory, USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 37.93° N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 75.47° W</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2: Information and fields of view of the SuperDARN in the Southern Hemisphere

<table>
<thead>
<tr>
<th>#</th>
<th>Field of View</th>
<th>Location</th>
<th>Operating Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Halley Station, Antarctica</td>
<td>British Antarctic Survey, England</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 75.52° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 26.63° W</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Sanae, Antarctica</td>
<td>University of Kwazulu-Natal, South Africa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 71.68° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 2.85° W</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Syowa (South), Antarctica</td>
<td>National Institute of Polar Research, Japan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 62.82° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 39.58° E</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Syowa (East), Antarctica</td>
<td>National Institute of Polar Research, Japan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 69.01° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 39.61° E</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Kerguelen, Kerguelen Island</td>
<td>LPCE/CNRS, France</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 49.35° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 70.26° E</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>TIGER, Tasmania</td>
<td>LaTrobe University, Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 43.38° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 147.23° E</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>TIGER Unwin, New Zealand</td>
<td>LaTrobe University, Australia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Lat.: 46.51° S</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geographic Long.: 168.38° E</td>
<td></td>
</tr>
</tbody>
</table>
3.2 The Kodiak SuperDARN

The Kodiak SuperDARN radar is operated by the Geophysical Institute of the University of Alaska, Fairbanks. It is a monostatic, over-the-horizon coherent backscatter pulsed radar. It is located at 57.6°N (geographic latitude) and 152.2°W (geographic longitude) with a boresight heading 30° east of North. This radar is designed to detect ionospheric scatter and determine the echo power, apparent range (slant path), Doppler spectrum, and the angle of arrival. It is paired to have a common field of view with the radar located at Prince George in British Columbia, Canada. Table 3.3 summarizes the technical parameters of the Kodiak SuperDARN. Previous work done by Richard T. Parris has improved the radar’s ability in extracting valuable information from meteor echoes; thereby, providing a means of studying the mesosphere region of the atmosphere [Parris, 2003].

Table 3.3: Technical parameters of the Kodiak SuperDARN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuthal Coverage</td>
<td>(~ 52^\circ)</td>
</tr>
<tr>
<td>Beam Width</td>
<td>(2.5^\circ - 6^\circ)</td>
</tr>
<tr>
<td>Frequency Range</td>
<td>(8 - 20) MHz</td>
</tr>
<tr>
<td>Pulse Length (Typical)</td>
<td>(100 - 300) (\mu s)</td>
</tr>
<tr>
<td>Fundamental Pulse Separation</td>
<td>(2400) (\mu s)</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>(15 - 45) (km)</td>
</tr>
<tr>
<td>Time Taken To Transmit one Pulse Sequence</td>
<td>(100) (ms)</td>
</tr>
<tr>
<td>Number of Pulses Transmitted in a Second</td>
<td>(70)</td>
</tr>
<tr>
<td>Range</td>
<td>(180 - 3555) (km)</td>
</tr>
<tr>
<td>Scan Duration</td>
<td>(1 - 2) (minutes)</td>
</tr>
<tr>
<td>Total Transmit Peak Power</td>
<td>(9600) (W)</td>
</tr>
<tr>
<td>Matched Filter Bandwidth</td>
<td>(10) (kHz)</td>
</tr>
</tbody>
</table>

The Kodiak SuperDARN looks through a range extending from \(180 - 3555\) \(km\). Like its counterparts, the Kodiak HF radar relies on the Bragg’s backscatter of HF radio
waves from ionospheric irregularities with a size of 7.5 – 18.75 m to determine the characteristics of the received signals. Figure 3.2 walks through the steps involved in the operation of the Kodiak radar. A brief description of how every step is carried out will be presented in the sections that follow.

Figure 3.2: Steps involved in the operation of the Kodiak SuperDARN
3.2.1 Operating mode

The radar usually operates in the 'fast mode' or the 'common mode'. These modes scan the entire field of view of the radar every one minute (fast mode) or two minutes (normal mode), the dwell time in each beam position being 3 or 6 s respectively. Within a scan, beam 0 is the west-most beam and beam 15 is the east-most. The radar, like all its counterparts, has two types of operation, the 'common time' and the 'discretionary time'. Common time is the time when all the radars in the SuperDARN network operate in the same mode to collect data to map ionospheric convection. Discretionary time is when the radar can experiment with new experimental modes.

3.2.2 Operating frequency

The operating frequencies of the radar range from 8 – 20 MHz lying in the HF band of the electromagnetic spectrum. Since the SuperDARN radars are dependent on ionospheric refraction, the detection of echoes from ionospheric irregularities is highly dependent on the prevailing conditions of the ionospheric plasma. Usually high frequencies are used during the day, while lower frequencies are used at night since the ionosphere is generally less dense at night. Furthermore, since signals in the HF band can travel extremely long distances, it is important to know if there are any outside signals present in the operating band of the radar. The transmission frequency is chosen to minimize any interference from other transmitters in the band. This is taken care of by an algorithm specially written for this purpose - the 'clear frequency search'.

The Federal Communication Commission (FCC) license held by the university for operation of the radar determines the frequencies at which the radar can transmit and the bandwidth of the transmitted signal. The frequency bands within which the radar can transmit are given in Table 3.4. The signal bandwidth permitted by the FCC is 22 kHz.

Several modifications have been made to the radar control programs to be able to adapt to the changing conditions of the ionosphere. The ‘sounder mode’ decides at the end of the 16-beam scan as to which frequency will be used for transmission next depending on the amount of ionospheric backscatter received by the radar.
### Table 3.4: FCC frequency allocations for the Kodiak SuperDARN

<table>
<thead>
<tr>
<th>Band</th>
<th>Start Freq. (KHz)</th>
<th>Stop Freq. (KHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8000</td>
<td>8100</td>
</tr>
<tr>
<td>2</td>
<td>9040</td>
<td>9500</td>
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<td>9995</td>
</tr>
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<td>11175</td>
</tr>
<tr>
<td>5</td>
<td>11400</td>
<td>11650</td>
</tr>
<tr>
<td>6</td>
<td>12050</td>
<td>12230</td>
</tr>
<tr>
<td>7</td>
<td>13410</td>
<td>13600</td>
</tr>
<tr>
<td>8</td>
<td>13800</td>
<td>14000</td>
</tr>
<tr>
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</tr>
<tr>
<td>10</td>
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<td>18900</td>
<td>19680</td>
</tr>
<tr>
<td>15</td>
<td>19800</td>
<td>19990</td>
</tr>
</tbody>
</table>

#### 3.2.3 Transmission-reception system

The transmission-reception system consists of two parallel arrays of log-periodic, horizontally polarized antennas with the front array consisting of sixteen antennas and the back array consisting of four antennas. These arrays are separated by a distance of 100 m. The front array is used for both transmission and reception while the back array is used only as an interferometer to determine the vertical angle of arrival of the received signals. The main array of sixteen antennas has an overall length of ~228.6 m and scans through sixteen beam positions in ~3.24° steps across the radar’s field of view, covering 52° in azimuth and over ranges from 180 km to 3555 km. The vertical beam is ~30° wide. The beam is electronically steered by phasing the antennas in the front array. The beam
steering is independent of the frequency of operation. The geometry of the front and back arrays can be seen in Figure 3.3.

![Figure 3.3: Geometry of front and back arrays of the Kodiak HF radar](image)

All of the antennas are Model 608 log-periodic antennas manufactured by the Sabre Communications Corporation of Sioux City, Iowa. The antennas are specified to work over the frequencies 8 – 20 MHz and are able to withstand wind speeds up to 105 mph. They have a voltage-standing-wave-ratio of 2.5:1 or better over the band and a minimum front-to-back ratio of 12 dB. The input impedance to the antenna is 50 ohms. The sketch shown in the Figure 3.4 illustrates the geometry of the saber antenna.

Each antenna of the front array is equipped with its own transmitter able to generate 600 W. The total transmitted power of the array is then 9600 W. Since the typical operating mode consists of 7 pulses of width 300 μs every 100 ms, the average transmitted power is 201.6 W. The gain of the front array of 16 antennas is 256 times (24 dB) that of a single antenna. Each of the antennas has a gain of 12 dB. Hence the overall
gain of the front array is 36 dB. The effective radiated power (the sum of the overall gain and the transmission power of a single antenna) is 2.44 MW.

Figure 3.4: Geometry of the Model 608 log-periodic antenna used by the Kodiak SuperDARN

The NEC-Win Pro 1.6.2d software package, from the Nittany Scientific Inc. was used to analyze the electromagnetic response of the antennas used by the Kodiak HF radar. The current distribution, the azimuthal, and the elevation radiation patterns for a single antenna 50 feet above the ground were generated at 12 MHz. 0° is the forward looking direction of the antenna. The gain of the antenna at 12 MHz is 13.46 dBi. These results are presented in Figure 3.5.
Figure 3.5: The current distribution (Figure (a)), the normalized azimuthal (Figure (b)) and elevation (Figure (c)) radiation pattern of the Model 608 log periodic antenna used by the Kodiak HF radar at 12 MHz.
The front array of 16 antennas helps in directing the radiated power towards a particular direction. The front array normalized radiation patterns were plotted in elevation and azimuth at 12 MHz using NEC-Win Pro and are shown in Figure 3.6.

![Figure 3.6](image)

Figure 3.6: The normalized azimuthal (Figure (a)) and elevation (Figure (b)) radiation pattern of the front array of 16 antenna elements at 12 MHz

The steering of the antenna beam is achieved by changing the relative phases of the array elements. Introducing a phase delay of 78° between the antenna elements leads to Figure 3.7.

![Figure 3.7](image)

Figure 3.7: The normalized azimuthal radiation pattern of the front array at 12 MHz
3.2.4 Echo parameters determination

Studies made regarding the ‘Doppler Dilemma’ discussed in the previous chapter, have led to a conclusion that the use of multipulse sequences can help in receiving echoes from large ranges without ambiguity. The SuperDARN radars measure line-of-sight velocities of up to ~2000 m/s over distances up to a maximum of 3555 km. However, it is clear that this can’t be achieved with a single pulse transmission scheme since the time taken for a return to be detected from 3555 km is approximately 24 ms, which would allow a pulse repetition frequency of ~42 Hz. The maximum Doppler frequency shift that could be detected by the SuperDARN with such a pulse transmission scheme is only ~21 Hz, which translates to a velocity of 262.5 m/s at a frequency of 12 MHz. Typical ionospheric convection velocities have been observed to result in Doppler shifts of up to about 208 Hz. These velocities can be observed using a specially designed multi-pulse sequence of 7 pulses. The standard operating modes use this sequence to derive the power, spectral width, and mean Doppler velocity of the echoes for each beam range cell.

The use of a multi-pulse sequence allows discrimination of returns from different pulses and different distances. The 7-pulse sequence is repeatedly transmitted and the received signal is processed into complex autocorrelation functions (ACFs) dependent on the time lags. The pulses are separated by multiples of $T = 2400$ µs and capable of generating time lags up to $18T$ with the exception of $16T$. The transmitted pulses are typically 100 µs or 300 µs long giving 15 km or 45 km range resolution, respectively. The Nyquist velocity that could be measured by the Kodiak HF radar is given by the relation,

$$v_{Nyquist} = \frac{c}{4f_{radar}T},$$

where $f_{radar}$ is the operating frequency of the radar and $T$ is the fundamental lag separation. For a radar operating frequency of 12 MHz, the maximum aliasing velocity that could be measured by the Kodiak radar using a minimum lag spacing of 2400 µs is 2604 m/s.
Figure 3.8 illustrates the determination of a point in the ACF at a particular time lag from the signal received from different pulses. Let us consider a multi-pulse sequence of 2 pulses (P₁ and P₂) that are transmitted at times t₀ and t₀+ξ. The scattered signal is received at times t₁ and t₁+ξ. It is obvious that the signal received at t₁ is the sum of returns from pulses P₁ (S₁₀) and P₂ (S₂) backscattered from ranges d₀ and d, respectively. The same is the case with the signal received at time t₁+ξ which is the sum of the returns from pulses P₁ (S₁+) and P₂ (S₂₀) backscattered from ranges d⁺ and d₀ respectively. Clearly S₂ and S₁⁺ are undesirable components that get added up in the received signal,

\[
\begin{align*}
S(t₁) &= S₁₀ + S₂. \\
S(t₁+ξ) &= S₁⁺ + S₂₀.
\end{align*}
\]

For a complex random process \(x(t)\), the autocorrelation function is defined as [Lathi, 1989],

\[
R_x(t₁, t₂) = \overline{x^*(t₁)x(t₂)},
\]

where the over-bar indicates time averaging. However for a random process whose statistical characteristics do not change with time, a shift of time origin will be impossible to detect since the process will appear to be the same. Hence, the autocorrelation function \(R_x(t₁, t₂)\) must be a function of only \(τ = (t₂ - t₁)\) and is given by the relation,
\[ R_x(t_1, t_2) = R_x(t_2 - t_1) = R_x(\tau) = x^*(t)x(t + \tau). \]  

(3.4)

Hence, the autocorrelation function at lag \( \xi \) is given by the relation,

\[ R_x(\xi) = S^*(t_1)S(t_1 + \xi) = (S^*_{10} + S^*_{20})(S_{1+} + S_{20}) \]

\[ = S^*_{10}S_{20} + S^*_{10}S_{1+} + S_{20}S^*_{2.} + S^*_{2.}S_{1+}. \]

(3.5)

If the signals scattered from different ranges are uncorrelated, the terms \( S^*_{10}S_{1+}, S_{20}S^*_{2.}, \) and \( S^*_{2.}S_{1+} \) disappear on averaging these returns over a fair amount of time.

The SuperDARN 7-pulse sequence is shown in Figure 3.9 illustrating the extraction of time lags from it. The longest time lag that can be derived using this pulse sequence is 64.8 ms. However only lags up to 43.2 ms are considered for further analysis since several time lags (19T, 21T, 23T, 24T, 25T) are missing after 18T.

Figure 3.9: SuperDARN 7-pulse sequence
The duration of a pulse sequence transmission cycle is 100 ms. It takes 65.1 (64.9) ms to transmit one pulse sequence with pulses having a width of 300 (100) μs. The radar doesn’t transmit for 34.9 (35.1) ms after the final pulse in the sequence in order to allow all returns out to 3555 km range to have reached the radar before it starts transmitting another pulse sequence. Ten pulse sequences (70 pulses) are transmitted every second. The typical integration times are 3 or 6 s depending on whether a ‘fast’ or ‘normal’ mode is used.

The range-time plot of the 7-pulse sequence is shown in the Figure 3.10. Evidently the backscattered return received from the transmission of every pulse in the sequence may be corrupted by returns received from other pulses. However, since the received signals are averaged 30 (60) times (depending on the mode used) before the final autocorrelation function is recorded, the error in the lag calculation may be reduced.

Figure 3.10: Range-time plot of the SuperDARN pulse sequence
Another aspect that arises on observing the received signals from different pulses is the fact that they can interfere with each other if they arrive at the same time from different distances. The scattered signals from regions separated by $\frac{c\xi}{2}$ will overlap when pulses are transmitted at times separated by $\xi$. This phenomenon is known as ‘cross-range interference’ in radar literature. This could lead to improper deciphering of received data. Since the target of interest for the SuperDARN radars is the ionospheric plasma that extends over many hundreds of kilometers, the occurrence of this interference is natural. It is easy to determine the time lags that would be affected due to this phenomenon for a known multipulse sequence.

![Range-time plot of the SuperDARN pulse sequence](image)

Figure 3.11: Range-time plot of the SuperDARN pulse sequence that shows regions in the field of view that could lead to cross-range interference
For the pulse sequence used by the Kodiak HF radar, these regions that lead to cross-range interference are recognized in the Figure 3.11. The extent to which this interference affects the backscatter received by the radar is a matter of concern.

The Kodiak HF radar is a monostatic radar; hence it cannot receive signals while transmitting. However, for a known pulse sequence, it is easy to determine the ranges from which the returns would arrive when the radar is transmitting. These ranges are identified in Figure 3.12. Nothing can be done about the missing time lags due to transmitter-on-receiver-off conflicts.

Another significant problem that arises from the use of multipulse sequences is that no pulse sequence can generate an infinite number of lags without having some redundant pairs. Having redundant lags would again lead to range aliasing.

Figure 3.12: Range-time plot of the SuperDARN pulse sequence showing ranges that lead to transmitter-on-receiver-off conflicts
The Kodiak SuperDARN makes use of I/Q reception to extract the complex autocorrelation functions from the received signals. The backscattered echoes are directly sampled and converted to digital data. These data are fed to a numerical I/Q detector that splits this signal into two channels with the quadrature (Q) channel being phase shifted by 90° with respect to the inphase (I) channel. An I/Q receiver has an added advantage of being able to preserve the sign of the Doppler shift of the signal passed through it. The Doppler signals output by the I and Q channels have the same frequency, but, the phase relationship between the two channels determines the direction that generated the frequency shift.

This process is done for every beam and range bin. For a given beam direction \(b\) and range bin \(r\), the backscattered power is related to the I/Q outputs as,
\[
P(b,r) = V_I^2(b,r) + V_Q^2(b,r),
\]
where \(V_{\text{front}}(t) = V_I(t) + jV_Q(t)\) is the complex signal used to evaluate the real \(A_r(\tau)\) and imaginary \(A_i(\tau)\) parts of the complex autocorrelation function (ACF) for each beam direction and range bin. Since the target of interest here is the ionospheric plasma which changes rapidly with time, the real and the imaginary ACFs are not merely oscillating sinusoidal functions, but they are most often in fact damped cosine and sine waves, respectively. A sketch of how the real and imaginary autocorrelation functions appear is shown in Figure 3.13.

A data processing algorithm called FITACF is used for estimating the scattered signal power, mean Doppler frequency shifts, and the spectral width of the echoes received. This procedure is based on an assumption that the Fourier transform of the ACF has a single spectral component. This directly implies that the phase of the ACF changes linearly with increasing time lag. The ACF amplitude is assumed to decay either exponentially or as a Gaussian.
Figure 3.13: Real and imaginary autocorrelation functions

The line-of-sight Doppler velocities serve as a measure of the movement of ionospheric irregularities. The mean Doppler velocity depends linearly on phase for the single spectral component assumption. FITACF determines the rate of change of the ACF phase, \( \tan^{-1}(A_I(\tau)/A_R(\tau)) \) as a function of time lag (\( \tau \)). The slope of the fitted line gives the angular Doppler frequency which is related to the mean Doppler velocity by,

\[
\nu_{\text{doppler}} = \frac{c \omega_d}{4\pi f_{\text{radar}}},
\]  

(3.10)

where \( \omega_d \) is the slope of the fitted line and \( f_{\text{radar}} \) is the operating frequency of the radar.
A sketch of how the angular Doppler frequency is extracted from the phase of the autocorrelation function is shown in Figure 3.14. A similar processing is done for the signals received by the back array and $V_{\text{Back}}(t) = V_j(t) + jV_0(t)$ is computed. The real ($X_R(\tau)$) and imaginary ($X_I(\tau)$) parts of the complex cross-correlation function (XCF) for each beam direction and range bin are computed. The phase intercept at $\tau = 0$ gives the angle of arrival of the backscattered signal when the time averaged phase $(\tan^{-1}(X_I(\tau)/X_R(\tau)))$ is plotted as a function of time lags ($\tau$) (Figure 3.15).

In many studies, the backscattered power and the spectral widths have been used to identify and understand ionospheric signatures of magnetospheric regions or boundaries. The spectral width is an estimate of the spread in the Doppler velocity that arises because the various irregularities in a given range cell drift at different $ExB$ velocities. The rate of decay of the ACF power with time lag determines the FITACF estimate of the spectral width [Baker et al, 1995]. The Kodiak HF radar estimates the power and the spectral width by assuming a model for the rate at which the ACF amplitude decays with time lag.
For a Lorentzian spectral width determination, the ACF is considered to take the form,

\[ P(\tau) = A_L e^{-\lambda \tau}, \]  \hspace{1cm} (3.11)

where \( A_L \) is a constant and \( \lambda \) is the decorrelation coefficient that needs to be evaluated. The slope of the least square fitted to the natural logarithm of \( P(\tau) \) gives the decay constant \( \lambda \) and the y-intercept helps determine the value of the constant \( A_L \). This is illustrated in Figure 3.16.

Since the autocorrelation function and the power spectrum are Fourier transform pair (Weiner-Khinchine Theorem), the spectral width at half maximum can be evaluated as a function of the correlation time.

The Fourier transform of this model is given by the relation,

\[ \int_{-\infty}^{\infty} A_L e^{-\lambda |\zeta|} e^{-j\omega t} dt = \frac{2\lambda A_L}{\lambda^2 + \omega^2}. \]  \hspace{1cm} (3.12)
Figure 3.16: Lorentzian spectral width determination parameters

Figure 3.17 illustrates the model and its transform. The spectral width for a spectrum of this form is given by the relation,

$$\omega_d = 2\lambda \text{ rad/s.} \quad (3.13)$$

The Doppler velocity is given by the relation,

$$v_{\text{doppler}} = \frac{c\omega_d}{4\pi f_{\text{radar}}} = \frac{c\lambda}{2\pi f_{\text{radar}}}. \quad (3.14)$$

Figure 3.17: Fourier transform pair for the Lorentzian spectral width model

For a Gaussian spectral width determination, the ACF is considered to take the form,
where $A_c$ is a constant and $\sigma$ is the decorrelation coefficient that needs to be evaluated. The gradient of the parabola fitted to the natural logarithm of $P(\tau)$ gives the decay constant $\sigma$. This is illustrated in Figure 3.18.

![Figure 3.18: Gaussian spectral width determination parameters](image)

The Fourier transform of this model is given by the relation,

$$
\int_{-\infty}^{\infty} A_c e^{-\sigma^2 \tau^2} e^{-j\omega \tau} d\tau = \frac{A_c}{\sqrt{\pi}} \frac{-\alpha^2}{e^{4\sigma^2}}.
$$

(3.16)

The Figure 3.19 illustrates the model and its transform. The spectral width for a spectrum of this form is given by the relation,

$$\omega_d = \frac{4\sigma}{\ln(2)} \text{ rad/s.}
$$

(3.17)

The Doppler velocity is given by the relation,

$$v_{doppler} = \frac{c\omega_d}{4\pi f_{\text{radar}}} = \frac{c\sigma}{\pi f_{\text{radar}} \sqrt{\ln(2)}}.
$$

(3.18)
Figure 3.19: Fourier transform pair for the Gaussian spectral width model

The method of estimation of spectral width using model parameters is good; however, it is not effective if the spectrum has multiple peaks in it.

A common technique for estimating the frequency of a signal is by finding the Fast Fourier Transform (FFT) of the autocorrelation function. An FFT demonstrates the distribution of power at various frequencies and can be a powerful tool to analyze multi-component spectra. However, its computational intensity and lack of good spectral resolution that is totally dependent on the number of points in the FFT makes it an unlikely candidate for SuperDARN spectral estimation. For the current pulse sequence employed by the SuperDARN, the spectral resolution of an FFT would be ~100 m/s.

Previous studies of the SuperDARN spectra have revealed the existence of multiple peaks in the spectrum due to the existence of several scatterers in a range cell which lead to signal mixing. It is not possible to determine positively a physical mechanism that would lead to such spectra. However, some evidence leads to an understanding that this may be caused by low energy electron precipitation that generates regions of inhomogeneous increased F-layer ionization. This effect can also show its presence when echoes from E-region are received by the 1½F propagation mode. Several such combinations might lead to spurious peaks in the spectrum. Simultaneous echo reception from several heights can also be a reason for broader than usual echoes. SuperDARN’s assumption of a single spectral peak inhibits the radars’ ability to identify
multiple peaks in the spectrum. The assumption would also lead to over-estimation of the spectral widths when multiple peaks exist.

3.3 Velocity data merging to observe ionospheric convection

The SuperDARN radars are instruments used to study large scale dynamic processes in the high-latitude magnetosphere-ionosphere system. Most of the radars are designed to work in pairs with common fields of view. The Prince George radar shares its field of view with the Kodiak radar. The combination of the line-of-sight Doppler velocities at the intersection of the antenna beams of two radars allows estimation of the plasma drift velocity (Figure 3.20). When data from all the radars is mapped, it can generate a global-scale view of the ionospheric convection.

![Figure 3.20: Merging the line-of-sight Doppler velocities from radars at the intersection of their beams](image)

A sample convection pattern is shown in the Figure 3.21. The scale for the velocities is shown on the top-left corner of the diagram. The part of the auroral ionosphere that isn’t illuminated by the sun is shaded in the figure. The dots with directed
lines show the observed ionospheric convection velocities. Their length is proportional to the velocity. The solid and the dashed lines account for the equipotential contours. It is clear from the diagram that data from all the radars is not available always. Under such circumstances, a convection estimation algorithm called the Map Potential Approach designed by Dr. Baker and Dr. Ruohoniemi [Ruohoniemi and Baker, 1998] is used. The more radars that contribute to the ionospheric backscatter data, the more accurate the model will be.

Figure 3.21: Sample ionospheric convection pattern diagram
Developing a new pulse sequence that could help remove bad lags without introducing range aliasing would be a step towards the perfection of the radars. The purpose of this thesis project is to investigate the aspects that could lead to the design of an optimum pulse sequence that could help derive more accurate data to observe the ionospheric convection.
Great advantages can be derived from radar systems if their ability to distinguish different targets from each other is enhanced. Good target discrimination would be helpful to study various phenomena in the auroral and polar cap ionosphere. Considering the significance of the problem, a clear understanding of the theoretical problem is a prerequisite for any practical hardware or software improvements.

In order to clearly understand the implications of this problem, the simplest model of target is considered. The simplest target is defined as one whose characteristics are fixed during the time it is illuminated by the transmitted pulse (a narrowband signal centered around some carrier frequency). The target has small dimensions compared to the size of the radar resolution cell. Thus the only effect of the target on the envelope of the transmitted pulse is to attenuate and delay it. The carrier acquires a phase shift which is determined by the distance from the transmitter to the target. In simulating this, a random phase is used since differences in range of a few meters lead to large phase differences.

The delay calculation is made by measuring the round-trip time when echoes are received after the transmission of the SuperDARN pulse sequence. The pulse sequence transmitted by the radar is given by the function $s(t)$,

$$s(t) = a(t)\cos(\omega_c t + \phi_c),$$

where $a(t)$ can be defined in terms of the rectangular function given by the equation,

$$rect(t) = \begin{cases} 1, & -\frac{1}{2} < t < \frac{1}{2} \\ 0, & \text{elsewhere.} \end{cases}$$

$a(t)$ can be written in terms of $rect(t)$ as,

$$a(t) = A \left[ rect\left(\frac{t-\frac{1}{2}}{\tau}\right) + rect\left(\frac{t-9T-\frac{1}{2}}{\tau}\right) + rect\left(\frac{t-12T-\frac{1}{2}}{\tau}\right) + rect\left(\frac{t-20T-\frac{1}{2}}{\tau}\right) \\
+ rect\left(\frac{t-22T-\frac{1}{2}}{\tau}\right) + rect\left(\frac{t-26T-\frac{1}{2}}{\tau}\right) + rect\left(\frac{t-27T-\frac{1}{2}}{\tau}\right) \right].$$
Let us assume the target is located at a distance $d$. If $t_d$ is the round trip delay time from the target and the velocity of propagation is $c$ (velocity of light), then,

$$c = \frac{2d}{t_d}. \quad (4.4)$$

If we consider the target to be moving with a constant radial velocity $v$, the round trip time delay would vary with time. This motion introduces a shift in the carrier frequency given by the relation,

$$\omega_r = \left(\frac{c-v}{c+v}\right)\omega_c. \quad (4.5)$$

The returned signal can now be modeled as

$$r(t) = a_f s(t-t_d)\exp(-2\pi f_d(t-t_d)). \quad (4.6)$$

Here $a_f$ is some attenuation factor and $f_d (= 2v/\lambda)$ is the Doppler frequency shift. There are several factors that would determine the value of $a_f$. These include the geometry of the target, its area of cross-section, the reflective properties of the material, and the losses in the propagating medium.

This equation was modeled in MATLAB with a target placed at different ranges and assigning different velocities to it. The basic assumption in our model was that the
returns from disjoint intervals in range were statistically independent. The SuperDARN radars measure line of sight velocities of up to \(~2000\) m/s over distances up to a maximum distance of \(3555\) km. An example situation will be presented here.

Let the radar operate at a frequency of \(12\) MHz. Consider a point target at a distance \(1200\) km having a radial velocity \(625\) m/s. The time delay is determined to be \(8\) ms and the Doppler frequency shift is \(50\) Hz from the above equations. Let the transmitted pulses have a width of \(300\) \(\mu\)s thereby corresponding to a range resolution of \(45\) km. The pulse sequence transmitted is the present SuperDARN pulse sequence shown below in Figure 4.2(a). The pulses are separated by multiples of \(T = 2400\) \(\mu\)s as discussed in the previous chapter.

An attenuated and possibly distorted version of the reflected signal is returned to the receiver. The sources of interference could be additive Gaussian receiver noise and interference due to external noise sources. Hence, we considered a received signal-to-noise ratio (SNR) of \(3\) dB for the simulation. A complex amplitude is recorded at the receiver when it digitizes the echo. The Kodiak radar uses the I/Q receiver to analyze the received signal. The return signal would have 2 components,

1. the inphase component – component in phase with the receiver clock
   \[
   r_{\cos}(t) = a_s(t-t_d)\cos(-2\pi f_d(t-t_d)).
   \] (4.7)

2. the quadrature component – component \(90^\circ\) out of phase with the receiver clock
   \[
   r_{\sin}(t) = a_s(t-t_d)\sin(-2\pi f_d(t-t_d)).
   \] (4.8)

It is seen clearly in Figure 4.2(b) that the return signal is received only after a time delay of \(8\) ms.
Figure 4.2: (a) Transmitted pulse sequence and (b) received signal for a point target at a range 1200 km and moving at a radial velocity of 625 m/s

The time lags are calculated, so that the autocorrelation function can be computed for multiples of $T (1 - 18)$ with an exception of $16T$ as explained in the previous chapter. This can be seen in Figure 4.3(a). This autocorrelation function is then Fourier transformed to obtain the Doppler spectrum as shown in Figure 4.3(b). In this simulation, the Fast Fourier Transform was used to determine the frequency spectrum.

Figure 4.3: (a) Real and imaginary autocorrelation functions as a function of time lags and (b) FFT of the complex autocorrelation function for the target
Up to this point, a model for the return from a target at a particular point in the range-doppler plane has been designed. The returned signal differed from the transmitted signal in four ways:

- Random amplitude,
- Random phase angle,
- Doppler frequency shift,
- Delay.

The change in amplitude and phase was due to the reflective characteristics of the target. The Doppler shift and the delay were due to the velocity and range of the target. For SuperDARN, the pulse length may be greater than the correlation time of the reflection process. This would make the target fluctuate during the time the transmitted pulse is being reflected. Such a fluctuation leads to time-selective fading [Van Trees, 2001].

The ionosphere, however, presents us with a volume of plasma stretching over ~1000 km with small-scale irregularities. Hence SuperDARN is in fact looking at a distributed target. A distributed target is one that has large dimensions compared to the resolution-cell size, not allowing the individual scatterers to be discerned [Skolnik, 2001]. In the case of the SuperDARN radars, the bandwidth of the transmitted signal is greater than the reciprocal of the target extent. Such a target introduces frequency-selective fading [Van Trees, 2001]. The characteristics of a distributed target can be determined with sufficient resolution in the appropriate dimension using multipulse sequences. A serious situation arises when the pulse transmitted is not short enough to resolve individual scatterers from a complex target. This is a problem faced by SuperDARN. The range resolution is 15 km for a pulse width of 100 μs and 45 km for a pulse width of 300 μs. Hence resolving of scattering centers within the 15 km range bin will not be possible. Another significant problem is the constructive and destructive interference among the echo signals from individual scatterers that will lead to change in amplitude in the echo signal. This indicates changes in the relative locations of the individual scatterers of the
complex target. It arises when the returns of different pulses in a sequence arrive at the receiver simultaneously from different ranges.

The ionospheric sounding process leads to a great amount of cross-range interference as illustrated in the previous chapter. A clear way of enhancing the target discrimination within a single resolution cell is to try to improve the multipulse sequence currently transmitted by SuperDARN. Designing a multipulse sequence that can derive short and long lags simultaneously from a return signal from a complex target could help improve the accuracy of determining a target's velocity, irrespective of whether it generates high or low Doppler frequency shift. Increasing the number of pulses in the sequence is another logical step to look into. A large number of pulses would help generating a large number of lags. This will lead to reduction in the error generated while estimating the spectral width and the Doppler frequency shift. An intelligent design of a pulse sequence would hence be required to get rid of all the effects of bad lags, missing lags and the cross-range interference.

4.1 Types of radar targets

Radar literature speaks of two types of radar targets:

- Under-spread targets,
- Over-spread targets.

If the maximum range observed by a radar is $R_{\text{max}}$ and $B$ the bandwidth of the Doppler spectrum, the value of the term $B \frac{R_{\text{max}}}{c}$ decides the nature of the target. If the term $B \frac{R_{\text{max}}}{c}$ is less than 1, it is defined as an under-spread target, and if it is greater than 1, it is defined as an over-spread target [Van Trees, 2001]. Clearly, the target of importance for the SuperDARN is overspread ($B \frac{R_{\text{max}}}{c} = 9.875$), but moderately overspread. While the under-spread targets can be studied by transmitting pulses at uniform time intervals, the over-spread targets cannot be understood perfectly using this procedure.
A very interesting set of multipulse codes were designed by Dr. Sathyadev V. Uppala and Dr. John D. Sahr to observe auroral electrojet irregularities. These pulse sequences were used for a class of radar targets that couldn’t be studied by transmission of pulses at uniform time intervals. This motivated a study into analyzing if these sequences could work well for the SuperDARN environment. These sequences are used to sample the range of interest at a suitable rate, while under sampling the clutter ranges. This study exploits the fact that if the sampling rate of a signal is reduced, the time samples become progressively decorrelated and would hence behave as noise [Uppala and Sahr, 1994].

4.2 Aperiodic pulse transmission scheme

The phenomenon of ‘aliasing’ has a negative effect on recovering a signal from its digital samples. The two signals shown in Figure 4.4 have the same values at the sampling instants although their frequencies are different. Sampling at the rate shown in the figure isn’t useful to estimate the signal correctly.

![Figure 4.4: An example of aliasing in the time domain](image)

However, this feature has been used by Dr. Uppala and Dr. Sahr to reduce the effects of range aliasing. They designed a set of multipulse sequences for this purpose.
called the ‘aperiodic pulse sequences’. To truly appreciate the significance of these multipulse sequences, it is necessary to understand the problems encountered when a periodic pulse train is used to study an overspread target. Let us consider the target to lie between the ranges \( R_1 \) and \( R_2 \). Let the desired target range be \( r_0 \). Echoes returning from each pulse transmitted are corrupted by returns from another range \( r_1 \). Let the time samples corresponding to \( r_0 \) be \( r_0(nT) \) and those from \( r_1 \) be \( r_1(nT) \). The received signal is the sum of these signals. The ranges \( r_0 \) and \( r_1 \) are said to be aliased. The Figure 4.5 illustrates the situation.

\[
\tau(nT) = r_0(nT) + r_1(nT).
\] (4.9)

![Figure 4.5: Illustration of a uniform radar pulse transmission scheme](Uppala and Sahr, 1994)

For illustrating the aperiodic pulse transmission scheme, let us consider an aperiodic 3-pulse scheme. If pulses transmitted at \( T \) and \( 2T \) in the above figure are shifted to \( \frac{3T}{7} \) and \( \frac{9T}{7} \), respectively, and continue this process for every three pulses, a new pulse sequence is formed which repeats itself every \( 3T \). However, range aliasing arises from three different ranges \( (r_1, r_2 \) and \( r_3) \). Let the time samples corresponding to the desired range \( r_0 \) be \( r_0(T_3) \) and those from ranges \( r_1, r_2 \) and \( r_3 \), be \( r_1(T_3), r_2(T_3) \) and \( r_3(T_3) \) respectively.
The sample times are \( \{0, T_3/7, 3T_3/7, T_3, 8T_3/7, 10T_3/7, \ldots\} \) where \( T_3 = 3T \). The received signal is the sum of these signals.

\[
r(T_3) = r_0(T_3) + r_1(T_3) + r_2(T_3) + r_3(T_3). \tag{4.10}
\]

There are three times the number of samples from the range \( r_0 \) compared to the ranges \( r_1, r_2, \) and \( r_3 \). The individual clutter ranges are hence, sub-sampled. The situation is illustrated in the Figure 4.6.

![Figure 4.6: Illustration of a non-uniform radar pulse transmission scheme](Adapted from Uppala and Sahr, 1994)

When the time samples collected from the ranges that lead to clutter are separated by greater than the auto-correlation time of the scatterer, they have no correlation. In this scheme, though the clutter comes from multiple ranges, it is infrequently sampled. The clutter will get progressively more decorrelated when the number of pulses in the sequence is increased.

### 4.2.1 Features of aperiodic pulse codes

- For an aperiodic multi-pulse sequence repeating every \( T_N \), the pulse sequence can be defined as,

\[
\{ t_i + nT_N; \ 1 \leq i \leq N, \ n = 0,1,2,\ldots\ldots\} . \tag{4.11}
\]

The aperiodic pulse codes set \( t_1 = 0 \). The time samples are collected at times,
The spacing between pulses is cyclical in nature for these pulse sequences. If a circle of circumference $T_N$ is considered with the pulse transmission times $(t_i)$ to be the points on it, the spacings between the pulses would be defined as,

$$t_{ij} = t_i \Theta_N t_j,$$

where $\Theta_N$ is the difference - modulo $N$ operator. This can be seen in Figure 4.7.

![Figure 4.7: Wheel and spoke representation of an aperiodic pulse sequence that repeats every $T_N$](image)

The set of all these cyclical differences is denoted as ‘$D$’ which has $N(N-1)$ elements in it.

$$D = \{t_{ij} : i, j = 1, \ldots, N \ i \neq j\}.$$  

(4.14)

The set of differences for the pulse sequence shown in Figure 4.6 is given by,

$$D = \{\frac{T_3}{7}, \frac{2T_3}{7}, \frac{3T_3}{7}, \frac{4T_3}{7}, \frac{5T_3}{7}, \frac{6T_3}{7}\}.$$

(4.15)

This set doesn’t have any repetitions in it. Multiple occurrence of an element in the set above would lead to distortion in the power spectrum for a desired range.
- $T_N$ can be increased in order to increase the decorrelation between the samples arriving from the ranges that lead to clutter. However, $N$ also needs to be increased in proportion, or the spacing between the transmitted pulses increases, decreasing the sampling rate which would in turn lead to frequency aliasing [Farley, 1969].

- For a spectral analysis technique like the Fast Fourier Transform, if $T_{\text{avg}}$ is defined as the average pulse spacing given by, $T_{\text{avg}} = T_N / N$, then the Nyquist criterion that needs to be satisfied leads to the relation,

$$T_{\text{avg}} \leq \frac{1}{F},$$

where $F = 2\max (|f_+|, |f_-|)$ and $f_+$ and $f_-$ define the positive and the negative extremes of the signal's spectrum. The relation that defines the range of $T_N$ to prevent aliasing is given by,

$$T_N : \bigcup_{n \in Z^+} \left[ \frac{2R_1}{c} + T_N > nT_N > \frac{2R_2}{c} \right],$$

where $Z^+$ is the set of positive integers and $\bigcup$ is the logical union of several possibilities. The above inequality reduces to

$$T_N > \frac{2R_2}{c} = T_{\text{min}}.$$  

Combining the equations (4.16) and (4.17), the range in which $T_N$ should lie is determined.

$$T_{\text{min}} < T_N < \frac{N}{F}.$$  

4.2.2 Types of Aperiodic pulse codes

Dr. Uppala and Dr. Sahr introduced different types of codes to generate aperiodic pulse sequences. These include,

- Simple difference cover codes
- Arithmetic progression codes
- Arithmetic modulus codes
A code is defined using a set of integers \( S \) that can be represented as \( \{0, s_2, \ldots, s_N, S_N + s_2, \ldots\} \). The aperiodic transmission scheme is still defined by \( \{0, t_2, \ldots, t_N, T_N + t_2, \ldots\} \) and can be obtained by multiplying \( S \) by some scale factor \( c \). The set of differences, \( D \) is given by,

\[
D = \{s_{ij}; \ i, j = 1, \ldots, N \ i \neq j \},
\]

and is filled with elements formed using the relation,

\[
s_{ij} = s_i \Theta_N s_j,
\]

where \( \Theta_N \) is the difference – modulo \( N \) operator. All the codes have been designed in such a manner that no repetitions arise in the set \( D \) [Uppala and Sahr, 1994].

4.2.2.1 Simple difference cover codes

A set \( \hat{S} = \{s_1, s_2, \ldots, s_N\} \) is defined to constitute the aperiodic code that is repeated after every \( S_N \). If the difference set, \( D \), formed as described earlier from \( \hat{S} \), contains all the integers from 1 to \( (S_N - 1) \), without any repetitions, then the set \( \hat{S} \) is defined as a simple difference cover [Clinger and Van Ness, 1976]. For the pulse sequence defined with \( S_N = 13 \) and \( \hat{S} = \{0, 1, 3, 9\} \), the wheel and spoke diagram would appear as shown in Figure 4.8.

The number of segments in the wheel is \( S_N = 13 \) and the difference set \( D = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\} \). The difference calculation can be seen in Figure 4.9. Table 4.1 summarizes the simple difference cover codes for \( N = 1 \) to \( 8 \).

The parameter \( \sigma_{\text{diff}} \) (fourth column of Table 4.1) is defined to express the difference between a simple difference cover code and a standard periodic code. It can be calculated using the equation,

\[
\sigma_{\text{diff}}^2 = \frac{1}{N} \sum_{i=1}^{N} \left[ \frac{(s_{i+1} - s_i)N}{S_N} - 1 \right] ^2. \tag{4.22}
\]

For a periodic code the value of \( \sigma_{\text{diff}} \) is 0. The value of \( \sigma_{\text{diff}} \) can be seen to increase as the value of \( N \) is increased. The wheel size can be expressed in terms of \( N \) as \( [(N-1)N + 1] \).
Figure 4.8: Wheel and spoke representation of a simple difference cover with $N = 4$

Figure 4.9: Calculation of differences from a Simple Difference Cover sequence with $N = 4$, $S_N = 13$ and $\hat{S} = \{0, 1, 3, 9\}$
Table 4.1: Simple difference codes [Adapted from Sahr and Uppala, 1994]

<table>
<thead>
<tr>
<th>Cardinal Number ((N))</th>
<th>Spoke Positions ((\hat{S}))</th>
<th>Wheel Size ((S_N))</th>
<th>(\sigma\text{diff})</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{0}</td>
<td>1</td>
<td>0.3333</td>
<td>0.6667</td>
</tr>
<tr>
<td>2</td>
<td>{0, 1}</td>
<td>3</td>
<td>0.5345</td>
<td>0.4286</td>
</tr>
<tr>
<td>3</td>
<td>{0, 1, 3}</td>
<td>7</td>
<td>0.5909</td>
<td>0.3077</td>
</tr>
<tr>
<td>4</td>
<td>{0, 1, 3, 9}</td>
<td>13</td>
<td>0.7589</td>
<td>0.2381</td>
</tr>
<tr>
<td>5</td>
<td>{0, 1, 4, 14, 16}</td>
<td>21</td>
<td>0.7531</td>
<td>0.1935</td>
</tr>
<tr>
<td>6</td>
<td>{0, 1, 3, 8, 12, 18}</td>
<td>31</td>
<td>0.7540</td>
<td>0.1404</td>
</tr>
<tr>
<td>8</td>
<td>{0, 1, 3, 13, 32, 36, 43, 52}</td>
<td>57</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

During the course of studying these codes, another simple difference cover code was discovered with \(N = 5\), with \(S_N = 21\) and \(\hat{S} = \{0, 5, 6, 9, 19\}\). This sequence has a difference set \(D = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20\}\). The extraction of differences from the pulses is illustrated in Figure 4.10.

![Figure 4.10: Calculation of differences from a simple difference cover sequence with \(N = 5\), with \(S_N = 21\) and \(\hat{S} = \{0, 5, 6, 9, 19\}\)](image-url)
4.2.2.2 Arithmetic progression codes

Another set of codes, the arithmetic progression codes, was developed by Dr. Uppala and Dr. Sahr that has the unique property that the spacings between the pulses in a sequence are in arithmetic progression. Table 4.2 summarizes the properties of the various arithmetic progression codes. To understand these codes better, a brief introduction to arithmetic progression will be presented.

A sequence of numbers that has the characteristic that the difference of its successive terms is a constant is an arithmetic series. These numbers are said to form an arithmetic progression. An arithmetic series of ‘n’ terms can be represented as: $a, (a + d), (a + 2d), \ldots, [a + (n-1)d]$ where ‘$a$’ is a constant and ‘$d$’ is the common difference between the successive terms.

Table 4.2: Arithmetic progression codes [Adapted from Uppala and Sahr, 1994]

<table>
<thead>
<tr>
<th>Cardinal Number (N)</th>
<th>Spoke Positions ($\hat{S}$)</th>
<th>Wheel Size ($S_N$)</th>
<th>$\sigma_{\text{diff}}$</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>{0, 2, 5}</td>
<td>9</td>
<td>0.2772</td>
<td>0.3333</td>
</tr>
<tr>
<td>5</td>
<td>{0, 5, 11, 18, 26}</td>
<td>35</td>
<td>0.2020</td>
<td>0.1429</td>
</tr>
<tr>
<td>7</td>
<td>{0, 10, 21, 33, 46, 60, 75}</td>
<td>91</td>
<td>0.1538</td>
<td>0.0769</td>
</tr>
<tr>
<td>11</td>
<td>{0, 26, 53, 81, 110, 140, 171, 203, 236, 270, 305}</td>
<td>341</td>
<td>0.1020</td>
<td>0.0322</td>
</tr>
<tr>
<td>13</td>
<td>{0, 37, 75, 114, 154, 195, 237, 280, 324, 369, 415, 462, 510}</td>
<td>559</td>
<td>0.0870</td>
<td>0.0232</td>
</tr>
<tr>
<td>17</td>
<td>{0, 65, 131, 198, 266, 335, 405, 476, 548, 621, 695, 770, 846, 923, 1001, 1080, 1160}</td>
<td>1241</td>
<td>0.0671</td>
<td>0.0137</td>
</tr>
</tbody>
</table>

For an arithmetic progression code $\hat{S} = \{s_1, s_2, \ldots, s_N\}$ that repeats after every $S_N$, with a difference set ‘D’ defined as $\{a, (a + d), (a + 2d), \ldots, [a + (N-2)d]\}$, the $i$th term in the code can be written as,

$$s_i = a(i - 1) + \frac{d(i - 2)(i - 1)}{2}, \quad i = 1, 2, 3, \ldots, N \quad (4.23)$$
and the wheel-size of these codes is given by,

\[ s_i = aN + \frac{d(N-1)N}{2}. \] (4.24)

These codes have been found to exist only when \( N \) is a prime. For a particular value of \( N \), an arithmetic progression code exists only when,

\[ a > \frac{(N-1)^2}{4} d, \] (4.25)

where \( d \) is an arbitrary positive integer. Research into these codes was done with the value for \( d \) set to 1, since this would generate the aperiodic code with the lowest \( \sigma_{\text{diff}} \) [Uppala, 1993]. The \( \sigma_{\text{diff}} \) of these codes for a specific value of \( N \) is less than that of the simple difference cover codes.

For the pulse sequence defined with \( S_N = 35 \) and \( \hat{S} = \{0, 5, 11, 18, 26\} \) the wheel and spoke diagram would appear as shown in Figure 4.11.

![Figure 4.11: Wheel and spoke representation of an arithmetic progression code with \( N = 5 \)](image-url)
The number of segments in the wheel is $S_N = 35$ and the difference set $D = \{5, 6, 7, 8, 11, 13, 15, 18, 21, 26\}$. The difference calculation can be seen in Figure 4.12.

![Figure 4.12: Calculation of differences from an arithmetic progression sequence with $N = 5, S_N = 35$ and $\hat{S} = \{0, 5, 11, 18, 26\}$](image)

4.2.2.3 Arithmetic modulus codes

Codes similar to arithmetic progression codes discussed in the previous section, but not having the pulse spacings in arithmetic order, were developed and found to have the lowest value of $\sigma_{\text{diff}}$ for a specific value of $N$ [Uppala and Sahr, 1996]. These codes were termed arithmetic modulus codes since the spacings between the adjacent pulses formed an arithmetic progression modulo some prime number. Table 4.3 summarizes the properties of these codes for $N = 2$ to 15.

For an arithmetic progression code $\hat{S} = \{s_1, s_2, \ldots, s_N\}$ that repeats after every $S_N$, the difference set ‘$D$’ can be written as $\{a,(a+(d \mod(N))),(a+(2d \mod(N)),$ $\ldots\ldots\ldots\ldots[a+(N-1)d \mod(N)]\}$. These codes have been found to exist for all values of $N$ unlike the arithmetic progression codes. For a particular value of $N$, an arithmetic modulus code exists only when,
$$a > \frac{(N-1)^2}{4}.$$  
(4.25)

Table 4.3: Arithmetic modulus codes [Adapted from Uppala and Sahr, 1996]

<table>
<thead>
<tr>
<th>Cardinal Number (N)</th>
<th>Spoke Positions ($\hat{S}$)</th>
<th>Wheel Size ($S_n$)</th>
<th>$\sigma_{\text{diff}}$</th>
<th>Duty Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>${0, 1}$</td>
<td>3</td>
<td>0.3333</td>
<td>0.6667</td>
</tr>
<tr>
<td>3</td>
<td>${0, 2, 5}$</td>
<td>9</td>
<td>0.2722</td>
<td>0.3333</td>
</tr>
<tr>
<td>4</td>
<td>${0, 3, 7, 13}$</td>
<td>18</td>
<td>0.2485</td>
<td>0.2222</td>
</tr>
<tr>
<td>5</td>
<td>${0, 3, 8, 12, 18}$</td>
<td>25</td>
<td>0.2828</td>
<td>0.2000</td>
</tr>
<tr>
<td>6</td>
<td>${0, 5, 11, 20, 27, 37}$</td>
<td>45</td>
<td>0.2277</td>
<td>0.1333</td>
</tr>
<tr>
<td>7</td>
<td>${0, 5, 12, 21, 32, 38, 46}$</td>
<td>56</td>
<td>0.2500</td>
<td>0.1250</td>
</tr>
<tr>
<td>8</td>
<td>${0, 6, 16, 23, 31, 42, 55, 64}$</td>
<td>76</td>
<td>0.2412</td>
<td>0.1053</td>
</tr>
<tr>
<td>9</td>
<td>${0, 7, 16, 26, 38, 46, 59, 74, 88}$</td>
<td>99</td>
<td>0.2347</td>
<td>0.0909</td>
</tr>
<tr>
<td>10</td>
<td>${0, 10, 22, 37, 55, 72, 86, 97, 116, 129}$</td>
<td>145</td>
<td>0.1980</td>
<td>0.0690</td>
</tr>
<tr>
<td>11</td>
<td>${0, 10, 21, 34, 53, 73, 89, 101, 115, 130, 148}$</td>
<td>165</td>
<td>0.2108</td>
<td>0.0667</td>
</tr>
<tr>
<td>12</td>
<td>${0, 11, 23, 42, 57, 79, 97, 111, 132, 149, 162, 182}$</td>
<td>198</td>
<td>0.2092</td>
<td>0.0606</td>
</tr>
<tr>
<td>13</td>
<td>${0, 11, 27, 48, 61, 79, 102, 117, 137, 149, 166, 188, 202}$</td>
<td>221</td>
<td>0.2201</td>
<td>0.0588</td>
</tr>
<tr>
<td>14</td>
<td>${0, 15, 33, 61, 87, 108, 135, 151, 176, 200, 220, 239, 256, 279}$</td>
<td>301</td>
<td>0.1875</td>
<td>0.0465</td>
</tr>
<tr>
<td>15</td>
<td>${0, 17, 38, 69, 99, 117, 136, 158, 185, 214, 242, 265, 289, 315, 335}$</td>
<td>360</td>
<td>0.1800</td>
<td>0.0417</td>
</tr>
<tr>
<td>16</td>
<td>${0, 17, 43, 74, 104, 124, 146, 171, 192, 224, 247, 265, 284, 313, 340, 364}$</td>
<td>392</td>
<td>0.1882</td>
<td>0.0408</td>
</tr>
<tr>
<td>17</td>
<td>${0, 15, 35, 53, 75, 96, 126, 143, 170, 193, 212, 241, 257, 282, 306, 334, 360}$</td>
<td>391</td>
<td>0.2130</td>
<td>0.0435</td>
</tr>
</tbody>
</table>
For the pulse sequence defined with $S_N = 18$ and $\hat{S} = \{0, 3, 7, 13\}$, the wheel and spoke diagram would appear as shown in Figure 4.13.

![Image](image.png)

Figure 4.13: Wheel and spoke representation of an arithmetic modulus code with $N = 4$

The number of segments in the wheel is $S_N = 18$ and the difference set $D = \{3, 4, 6, 7, 10, 13\}$. The difference calculation can be seen in the Figure 4.14.

![Image](image.png)

Figure 4.14: Calculation of differences from an arithmetic modulus code with $N = 4$, $S_N = 18$ and $\hat{S} = \{0, 3, 7, 13\}$
4.3 Simulations in MATLAB

These aperiodic pulse sequences have proved to be useful to study targets having a correlation time comparable to their range. Code written in MATLAB was used to analyze these pulse sequences with different combinations of targets at different ranges and velocities. The chart shown in Figure 4.15 illustrates the flow of the program that examines the characteristics of aperiodic pulse sequences.

Figure 4.15: Flow of program that scrutinizes the performance of aperiodic pulse sequences
The user is given the option of using a graphical input, entering the range and velocity of the various targets himself, or using MATLAB to generate them. When MATLAB is used, the user has an option of choosing a distribution for the targets’ ranges and velocities which includes the beta, chi-square, exponential, F, Gamma, Log Normal, Normal, Poisson, Rayleigh and Weibull distributions.

The desired pulse sequence is generated and is used to generate the received signal as described in the first section of the chapter. The time lags are calculated by a program ‘time_lags’. This program keeps track of the pulses used to generate the respective time lags. The lag products are then computed from the received signal. The code is capable of adding the lags generated from different pulse sequences transmitted over the integration time. The real and imaginary parts of the ACF are then used to compute the phase plots and find the frequency spectrum.

A very important goal of this thesis was to develop a means of distinguishing various target velocities in the same range bin using the knowledge of aperiodic pulse sequences. This cannot be achieved easily. Therefore, different spectral estimation techniques were studied. Since the Fast Fourier Transform (FFT) is the most frequently used spectral algorithms, it was compared with the modified-covariance spectral estimation technique. This technique was developed by Dr. S. L. Marple [Marple, 1991]. It is a fast computation algorithm that utilizes the fact that linear prediction filters can be used to model the second order statistical characteristics of a signal. It fits an autoregressive linear prediction filter model to the signal by minimizing the forward and the backward prediction errors in the least squares sense [Marple, 1987]. This algorithm has an added advantage of sharper peaks which have less width compared to the Burg’s estimation method [Marple and Wei, 2005]. Another interesting feature of this memory efficient algorithm is its unbiased spectral estimation capability. Furthermore, it keeps track of all the intermediate parameter order values, allowing the user to choose an optimal order. Since the SuperDARN operating environment consists of highly variable plasma irregularities that vary constantly, it becomes difficult to determine the
appropriate order beforehand. Hence this dynamic algorithm would be an interesting addition towards the improvement of the radar's versatility.
Chapter 5  Pulse sequence design

The need for a new multipulse sequence for SuperDARN has clearly been identified in the previous chapters. A summary of all the features that would be warranted from an optimum transmission multipulse sequence are summarized below.

- The pulse sequence must generate a long maximum lag which determines the lowest observable velocity.
- The pulse sequence must generate short minimum lags for a given number of pulses, which would allow detection of high velocity targets.
- The pulse sequence must have low number of repeated lags. It would be ideal not to have any repeated lags.
- The pulse sequence must have a low number of lags missing due to Tx-on/Rx-off conflicts.

The development of the code used to design the pulse sequence will be discussed in detail in the following sections.

The steps involved in the design of an optimum pulse sequence included:

- Decide the optimum number of pulses in the pulse sequence.
- Simulate results and analyze the performance of the simple difference cover, arithmetic progression, and the aperiodic codes for the SuperDARN environment.
- Design a new sequence based on the above analysis.

5.1 Number of pulses in an optimum pulse sequence

A very important criterion in the design of a good pulse sequence is the number of pulses in the sequence, which determines the number of pulse returns that can be integrated in a second. The larger the number of pulse returns that can be integrated the better the SNR. Another important criterion to look for is the maximum lag that can be derived from the pulse sequence for some fundamental lag spacing. The spacing between
the pulse sequences is another important factor. This value needs to be more than 24 ms since we cannot have pulse returns coming from the last pulse in the pulse sequence before the transmission of the next sequence of pulses.

Let us first see how the number of pulse returns that can be integrated in a second is determined for sequences with different numbers of pulses. Let the number of pulses in the sequence be ‘n’ and the fundamental lag spacing be ‘T’. The time taken to transmit one pulse sequence will then be ‘nT’. The minimum spacing between each pulse sequence should not be less than 24 ms. The following equation now needs to be solved to derive the number of pulse sequences that can be transmitted in a second:

\[ \text{# Pulse sequences} = \frac{1}{(nT + 24 \text{ ms})}. \]

Figure 5.1: The number of pulse returns that could be integrated in a second as a function of the number of pulses in the sequence and the fundamental lag spacing

Taking the integer value of the number of pulse sequences from the above equation and substituting it in again, we get the exact spacing between pulse sequences.
The number of pulse returns that can be integrated in a second is given by the product of ‘n’ and the number of pulse sequences.

Figure 5.1 shows the number of pulses that can be integrated in a second as a function of the fundamental lag spacing and the number of pulses in the sequence. From this plot the best value for the number of pulses in a sequence for the specific fundamental lag spacing is chosen. Table 5.1 shows the best number of pulses suitable for deriving the maximum time lag for particular lag spacing.

Table 5.1: The best number of pulses suitable for deriving the maximum time lag for particular fundamental lag spacing

<table>
<thead>
<tr>
<th>#</th>
<th>Fundamental lag spacing (μs)</th>
<th>Best value of # pulses in a pulse sequence</th>
<th># of pulse returns in a second</th>
<th>Maximum lag that can be derived (ms)</th>
<th>Spacing between pulse sequences (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2400</td>
<td>16</td>
<td>256</td>
<td>38.4</td>
<td>24.1</td>
</tr>
<tr>
<td>2</td>
<td>3600</td>
<td>16</td>
<td>192</td>
<td>57.6</td>
<td>25.7333</td>
</tr>
<tr>
<td>3</td>
<td>4800</td>
<td>17</td>
<td>153</td>
<td>81.6</td>
<td>29.5111</td>
</tr>
<tr>
<td>4</td>
<td>6000</td>
<td>16</td>
<td>128</td>
<td>96</td>
<td>29.0000</td>
</tr>
<tr>
<td>5</td>
<td>7200</td>
<td>16</td>
<td>112</td>
<td>115.2</td>
<td>27.6571</td>
</tr>
<tr>
<td>6</td>
<td>8400</td>
<td>14</td>
<td>98</td>
<td>117.6</td>
<td>25.2571</td>
</tr>
<tr>
<td>7</td>
<td>9600</td>
<td>17</td>
<td>85</td>
<td>163.2</td>
<td>36.8000</td>
</tr>
<tr>
<td>8</td>
<td>10800</td>
<td>16</td>
<td>80</td>
<td>172.8</td>
<td>27.2000</td>
</tr>
<tr>
<td>9</td>
<td>12000</td>
<td>14</td>
<td>70</td>
<td>168</td>
<td>32.0000</td>
</tr>
</tbody>
</table>
It can be said that for a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs gives a maximum lag of ~170 ms which is approximately 4 times the maximum lag that can be derived from the current sequence.

5.2 Performance of aperiodic transmitter codes

5.2.1 Performance of simple difference cover codes

The design of simple difference cover codes was described in the previous chapter. Unfortunately, these codes will not work well for SuperDARN, which is explained by the principle behind their design. Their property of generating periodic time lags would explain why these codes wouldn’t work well for SuperDARN. To illustrate this, let us take a closer look at the design of the simple difference cover codes. Consider the case of a sequence having 5 pulses.

\[ N = 5 \]

Spoke positions = \{0, 1, 4, 14, 16\}

Wheel size \((S_N) = 21\)

![Graphical representation of N = 5, simple difference cover code](image-url)
The graphical representation of the simple difference cover for \( N = 5 \) is shown in Figure 5.2. The time lags that can be calculated from the sequence, \( \{0, 1, 4, 14, 16\} \) are

\[
\left\{ \frac{T_5}{21}, \frac{T_5}{21}, \frac{T_5}{21}, \frac{T_5}{21}, \frac{T_5}{21}, \frac{T_5}{21}, \frac{4T_5}{21}, \frac{2T_5}{21}, \frac{T_5}{21}, \frac{5T_5}{21}, \frac{10T_5}{21}, \frac{11T_5}{21}, \frac{4T_5}{21}, \frac{13T_5}{21}, \frac{2T_5}{21}, \frac{5T_5}{21}, \frac{16T_5}{21}, \frac{17T_5}{21}, \frac{6T_5}{21}, \frac{19T_5}{21}, \frac{20T_5}{21} \right\}
\]

where \( T_s = 5T \). Here \( T \) represents the time taken for a pulse to travel to and fro to the maximum range the radar can see.

Figure 5.3 illustrates the extraction of time lags from the pulse sequences.

![Figure 5.3: Time lags extracted from the 5 pulse simple difference cover sequence \( \{0, 1, 4, 14, 16\} \) with wheel size \( (S_N) = 21 \)](image)

Calculation of time lags \( \frac{T_5}{21} \) through \( \frac{20T_5}{21} \) involves the use of more than one pulse sequence. If two pulse sequences were used to find the time lags, we have an intrusion of repeated lags. Table 5.2 illustrates the lags that can be computed from this sequence.
Table 5.2: Time lags generated from the simple difference cover 5-pulse sequence \{0, 1, 4, 14, 16\}

<table>
<thead>
<tr>
<th>Lag Generated</th>
<th>Spoke Positions Used to generate lags</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>
Considering the general case in which a pulse sequence has ‘n’ number of pulses. The wheel-size would then be 
\[ S_N = \frac{nT}{[n(n-1)+1]} \]. Figure 5.4 plots the time taken to transmit a pulse sequence and the longest time lag that could be derived from it as a function of the number of pulses in the pulse sequence.

Values in Table 5.3 make it clear that if we aim to design a sequence that can generate long time lags, the time taken for transmitting the pulse sequence increases by a factor of \( \frac{n(n-1)+1}{n(n-1)} \), leading the number of returns from pulse sequences averaged in a second to drastically decrease. Hence the use of simple difference cover codes for HF studies would probably be a wrong decision.

Figure 5.4: Time taken to transmit the sequence of simple difference cover pulses and the longest time lag that can be derived from them as a function of number of pulses in the pulse sequence
Table 5.3: Time taken to transmit a pulse sequence and the longest time lag that could be derived from it as a function of number of pulses in the pulse sequence

<table>
<thead>
<tr>
<th># pulses in sequence</th>
<th>Maximum time lag (s)</th>
<th>Sequence length (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.061714</td>
<td>0.144</td>
</tr>
<tr>
<td>4</td>
<td>0.088615</td>
<td>0.192</td>
</tr>
<tr>
<td>5</td>
<td>0.11429</td>
<td>0.24</td>
</tr>
<tr>
<td>6</td>
<td>0.13935</td>
<td>0.288</td>
</tr>
<tr>
<td>7</td>
<td>0.16409</td>
<td>0.336</td>
</tr>
<tr>
<td>8</td>
<td>0.18863</td>
<td>0.384</td>
</tr>
<tr>
<td>9</td>
<td>0.21304</td>
<td>0.432</td>
</tr>
<tr>
<td>10</td>
<td>0.23736</td>
<td>0.48</td>
</tr>
<tr>
<td>11</td>
<td>0.26162</td>
<td>0.528</td>
</tr>
<tr>
<td>12</td>
<td>0.28583</td>
<td>0.576</td>
</tr>
<tr>
<td>13</td>
<td>0.31001</td>
<td>0.624</td>
</tr>
<tr>
<td>14</td>
<td>0.33416</td>
<td>0.672</td>
</tr>
<tr>
<td>15</td>
<td>0.35829</td>
<td>0.72</td>
</tr>
<tr>
<td>16</td>
<td>0.38241</td>
<td>0.768</td>
</tr>
<tr>
<td>17</td>
<td>0.40651</td>
<td>0.816</td>
</tr>
</tbody>
</table>

5.2.2 Performance of arithmetic progression codes

The design of arithmetic progression codes was described in the previous chapter. These codes are almost periodic codes allowing the use of the Fast Fourier Transforms for deriving the power spectrum. To understand the relevance of these codes for SuperDARN, let us consider an arithmetic progression pulse sequence with 7 pulses.

\[ N = 7 \]

Spoke positions = \{0, 10, 21, 33, 46, 60, 75\}

Wheel size \((S_N) = 91\)
Table 5.4: Time lags generated from the arithmetic progression code 7-pulse sequence \{0, 10, 21, 33, 46, 60, 75\}

<table>
<thead>
<tr>
<th>#</th>
<th>Time Lags</th>
<th>Spoke positions used to generate lags</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td>10</td>
<td>27</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>29</td>
<td>75</td>
</tr>
<tr>
<td>12</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>13</td>
<td>36</td>
<td>46</td>
</tr>
<tr>
<td>14</td>
<td>39</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td>16</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>17</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>54</td>
<td>75</td>
</tr>
<tr>
<td>19</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>21</td>
<td>75</td>
<td>75</td>
</tr>
</tbody>
</table>

The time lags that can be extracted from the arithmetic pulse sequence are tabulated in Table 5.4. The pulses generate six time lags i.e.,
\{ \frac{10T}{91}, \frac{11T}{91}, \frac{12T}{91}, \frac{13T}{91}, \frac{14T}{91}, \frac{15T}{91} \} \text{ where } T = 7T \text{ that are in arithmetic progression.}

Here } T \text{ is some fundamental time lag. However, this pulse sequence has a huge number of missing lags. The diagram shown below in Figure 5.5 illustrates this problem.

Figure 5.5: Time lags generated from the arithmetic progression code 7-pulse sequence
\{0, 10, 21, 33, 46, 60, 75\}

The gravity of this problem can be explained further with a MATLAB simulation for a target situated at a range 1200 km and moving at a velocity of 625 m/s. Let the radar
operate at a frequency 12 MHz. Transmitting the above pulse sequence with pulses of width 300 μs once every 100 ms will give a maximum lag of ~62.3 ms; hence, we integrate returns from 70 pulses per second using this scheme.

Figure 5.6 shows the real and imaginary autocorrelation functions derived from the received signal. The autocorrelation functions seem to lose their shape after the first few time lags. Considering the general case of an arithmetic pulse code sequence comprising ‘n’ pulses, we could have \((n-1)\) lags in arithmetic progression out of the \(nC_2\) lags generated by it. \(nC_2\) is the number of combinations of ‘n’ different pulses, taken 2 at a time in the calculation of a time lag and is given by, \(n!/(2!(n-2))!\).

Figure 5.6: Real and imaginary autocorrelation functions generated from the received signal
Figure 5.7: Total time lags and lags in arithmetic progression as a function of number of pulses in the pulse sequence

The Figure 5.7 illustrates that as the number of pulses in the sequence increase, the lags in arithmetic progression also increase linearly but the total number of lags increases exponentially leading to a large number of discontinuous lags.

Long time lags cannot be derived unless the fundamental time lag is increased. However, this choice would lead to reduction in the number of pulse returns that could be integrated in a second. Taking into account all the harm rather than good that these sequences might do, it wouldn’t be an encouraging option to use them for SuperDARN.

5.2.3 Performance of arithmetic modulus codes

The design of the arithmetic modulus codes was explained in detail in the previous chapter. An analysis of their relevance for use with SuperDARN will be presented in this section. These codes have been designed considering the generality that the pulse spacings could form an arithmetic progression. However, they are not explicitly
in the arithmetic order. These sequences give time lags that are almost periodic with few missing lags and are definitely sequences that could be used with SuperDARN. However to understand all the features of these codes and their applicability to SuperDARN, let us consider one of the arithmetic modulus pulse sequences.

\( N = 5 \)

Spoke positions = \{0, 3, 8, 12, 18\}

Wheel size (\( S_N \)) = 25

Figure 5.8 illustrates the extraction of lags from the pulse sequence considered above. It is clear that short time lags are not calculated in these pulse sequences, which will be a problem during the estimation of fast moving targets. The severity of this problem can be understood with a MATLAB simulation, with a target situated at a range 1200 km and moving at a velocity of 1875 m/s. Let the radar operate at a frequency 12 MHz. Transmitting the above pulse sequence with pulses of width 300 \( \mu \)s once every 62.5 ms will give a maximum lag of \(-28\) ms. Hence, we integrate returns from 80 pulses per second using this scheme.

![Diagram](image-url)

Figure 5.8: Time lags generated from the arithmetic modulus code 5-pulse sequence \{0, 3, 8, 12, 18\}
Figure 5.9: Real and imaginary autocorrelation functions generated from the received signal

Figure 5.9 plots the real and imaginary autocorrelation functions derived from the received signal. We see that there are no lag calculations made for values less than 4.32 ms. However, it’s evident in Figure 5.9 that the autocorrelation functions are deformed for targets moving at high velocities.

It may be possible to get long and almost periodic time lags using these pulse sequences but they definitely aren’t a good option for estimating targets moving at rapid speeds.

Considering the general case of an arithmetic modulo pulse code sequence composed of ‘n’ pulses, we could have at most \((n-1)\) lags in arithmetic progression out of the \(nC_2\) lags generated by it. Figure 5.10 illustrates that as the number of pulses in the sequence increase, the total number of lags increases exponentially while the lags in
arithmetic progression are only able to increase linearly leading to a large number of discontinuous lags.

Figure 5.10: Total time lags and lags in arithmetic progression as a function of number of pulses in the pulse sequence

If these pulse sequences could be modified in a way to generate both short and long time lags, they could be used with the radar. A combination of pulse spacings that could generate a sequence that would be a combination of arithmetic, geometric, and harmonic progressions appeared to be a plausible solution to the problem. An investigation was made in this regard and the following four classes of sequences of pulse spacings were analyzed.

(i) Sequence 1: \[ a \left( 1 + \frac{1}{a} \right), (a + d) \left( 1 + \frac{1}{(a + d)} \right), (a + 2d) \left( 1 + \frac{1}{(a + 2d)} \right) \] .................
(ii) Sequence 2:
\[
\left(a + \frac{1}{a}\right), \left(1 + \frac{1}{(a + d)}\right), \left(1 + \frac{1}{(a + 2d)}\right)
\]

(iii) Sequence 3:
\[
\left(a + \frac{1}{a}\right), \left(1 + \frac{1}{(a + d)}\right), \left(1 + \frac{1}{(a + 2d)}\right)
\]

(iv) Sequence 4:
\[
\left(a + \frac{1}{a}\right), \left(1 + \frac{1}{(a + d)}\right), \left(1 + \frac{1}{(a + 2d)}\right)
\]

Here ‘a’ and ‘d’ are constants.

Knowledge of the arithmetic, geometric and harmonic progressions is necessary to clearly understand the performance of the above sequences of pulse spacings. Since the arithmetic progressions were introduced earlier, only the geometric and harmonic progressions will be discussed here.

5.3 Progressions

5.3.1 Geometric progression

A sequence of numbers that has the characteristic that the ratio of successive terms is a constant is a geometric series. These numbers are said to form a geometric progression. A geometric series of ‘n’ terms can be represented as, \( a, ar, ar^2, \ldots, ar^{n-1} \) where ‘a’ is a constant and ‘r’ is the ratio of successive terms, the common ratio.

5.3.2 Harmonic progression

A sequence of numbers whose reciprocals form an arithmetic series are said to form a harmonic progression. A harmonic series of ‘n’ terms can be represented as, \( \left(\frac{1}{a}\right), \left(\frac{1}{(a + d)}\right), \left(\frac{1}{(a + 2d)}\right), \ldots, \left(\frac{1}{(a + (n-1)d)}\right) \) where ‘a’ is a constant and ‘d’ is the common difference in the arithmetic progression formed by the reciprocals of the terms in the series.
Since the above sequences depend on the values of ‘a’ and ‘d’, it would be best to see how they affect the maximum and minimum time lags derived from the pulse sequence. It would be interesting to see if any of the time lags derived from the pulse sequences are separated by more than 2400 ps. Another important factor to be considered would be the minimum difference between the calculated time lags.

Simulations were run in order to examine the behavior of the sequences for different values of ‘a’ and ‘d’. It was said earlier that a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs would give the best maximum lag. Hence, the pulse sequence was designed for 16 pulses.

5.4 Constraints on the design of a 16-pulse sequence

5.4.1 Criterion 1: Maximum time lag

The maximum time lag that could be derived from each of the 16 - pulse sequences designed using the above sequences of pulse spacings is determined for values of ‘a’ and ‘d’ ranging from 0.01 to 1. Values greater than 1 couldn’t help in the generation of long maximum lags.

<table>
<thead>
<tr>
<th>Sequence #</th>
<th>Longest Maximum Lag</th>
<th>Shortest Maximum Lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1616</td>
<td>0.1525</td>
</tr>
<tr>
<td>2</td>
<td>0.1530</td>
<td>0.1493</td>
</tr>
<tr>
<td>3</td>
<td>0.1716</td>
<td>0.1513</td>
</tr>
<tr>
<td>4</td>
<td>0.1578</td>
<td>0.0593</td>
</tr>
</tbody>
</table>

The Table 5.5 shows the longest and the shortest maximum time lags that can be derived from each pulse sequence designed using the sequences of pulse spacings considered above. The figures illustrating the maximum time lag that could be derived
from the different 16-pulse sequences with a fundamental lag spacing of 10800 μs are shown in Figure 5.11.

Figure 5.11: Maximum time lag that can be derived from sequence 1 (Figure (a)), sequence 2 (Figure (b)), sequence 3 (Figure (c)) and sequence 4 (Figure (d)) for a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs

5.4.2 Criterion 2: Shortest time lag

An important point of concern has been the estimation of fast moving targets, which required the calculation of short time lags. To see the performance of these codes,
similar simulations were run to find the shortest time lag generated by the above described four multipulse sequences with different ‘a’ and ‘d’ values ranging from 0.01 to 1. Figure 5.12 illustrates the shortest time lags that could be generated by these pulse sequences.

Figure 5.12: Shortest time lag that can be derived from sequence 1 (Figure (a)), sequence 2 (Figure (b)), sequence 3 (Figure (c)) and sequence 4 (Figure (d)) for a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs

Table 5.6 illustrates the range over which the shortest time lags that can be generated from these pulse sequences would extend.
Table 5.6: Range of the shortest time lags that can be derived from the four multipulse sequences

<table>
<thead>
<tr>
<th>Sequence #</th>
<th>Range of shortest time lag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0013 – 0.0104</td>
</tr>
<tr>
<td>2</td>
<td>1.3984e-005 – 0.022</td>
</tr>
<tr>
<td>3</td>
<td>7.1624e-006 – 0.0076</td>
</tr>
<tr>
<td>4</td>
<td>1.0156e-14 – 0.0031</td>
</tr>
</tbody>
</table>

5.4.3 Criterion 3: Number of time lags separated by more than 2400 μs

The present SuperDARN pulse sequence is comprised of 7 pulses separated by multiples of \( T = 2400 \) μs. The autocorrelation function is computed for the values of \( T \) from 1 to 18T with the exception of 16T. The time lags generated using this pulse sequence are 2400 μs apart. The pulse sequence schemes under consideration have to be tested to find the number of time lags separated by greater than 2400 μs. Simulations were run to test the sequences and Table 5.7 tabulates the results.

Table 5.7: Range of the number of time lags separated by greater than 2400 μs from the four multipulse sequences

<table>
<thead>
<tr>
<th>Sequence #</th>
<th>Range of # time lags greater than 2400 μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8 – 25</td>
</tr>
<tr>
<td>2</td>
<td>12 – 23</td>
</tr>
<tr>
<td>3</td>
<td>11 – 33</td>
</tr>
<tr>
<td>4</td>
<td>6 – 26</td>
</tr>
</tbody>
</table>

The figures illustrating the number of lags separated by greater than 2400 μs for different values of ‘a’ and ‘d’ ranging from 0.01 to 1 for a 16-pulse sequence with a fundamental lag spacing of 10800 μs are shown below.
5.4.4 Criterion 4: Minimum separation between time lags

The most important factor to be considered is the minimum separation between the time lags. The sequences in discussion are capable of generating lags which have no repetition at all. However, the radar will only be able to consider lags which are at least

Figure 5.13: Number of time lags separated by greater than 2400 μs in sequence 1 (Figure (a)), sequence 2 (Figure (b)), sequence 3 (Figure (c)) and sequence 4 (Figure (d)) for a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs
10 μs apart to be different as the fundamental timing unit used in the radar hardware is 10 μs. Lags closer than 10 μs will be considered to be repeated lags.

Figure 5.14: Least spacing between time lags that can be derived from sequence 1 (Figure (a)), sequence 2 (Figure (b)), sequence 3 (Figure (c)) and sequence 4 (Figure (d)) for a pulse sequence with 16 pulses and a fundamental lag spacing of 10800 μs.

The present pulse sequence schemes under consideration also need to be tested to find the least spacing between the time lags. Simulations were run to test the sequences and Figure 5.14 gives an idea about the range of the least spacing between the calculated time lags for different values of ‘a’ and ‘d’ ranging from 0.01 to 1 for a 16-pulse sequence with a fundamental lag spacing of 10800 μs.
5.5 Design of the 16-pulse sequence and its abilities

All four of the above constraints would lead to an optimized pulse sequence, if it satisfies the following properties:

- Generate long maximum time lags.
- Generate short minimum time lags.
- Have a low number of time lags separated by more than 2400 μs.
- Have a minimum spacing of 10 μs between the time lags.

A search was performed for the sequences that would satisfy the above norms from the 10000 combinations of sequences that would arise from the use of values of ‘a’ and ‘d’ ranging from 0.01 to 1 for a 16-pulse sequence with a fundamental lag spacing of 10800 μs. The investigation finally ended at 8 pulse sequences that proved to satisfy all the above criteria. The chart 5.8 tabulates all the information of these pulse sequences.

Table 5.8: Optimized hybrid progression sequences and their parameters for a 16-pulse sequence with a fundamental lag spacing of 10.8 ms.

<table>
<thead>
<tr>
<th>#</th>
<th>Sequence Type</th>
<th>a</th>
<th>d</th>
<th>Longest Lag</th>
<th>Shortest Lag</th>
<th># lags &gt; 2.4 msec</th>
<th>Minimum Lag Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.26</td>
<td>0.75</td>
<td>0.15318</td>
<td>0.0019765</td>
<td>12</td>
<td>4.7059e-5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.31</td>
<td>0.78</td>
<td>0.15318</td>
<td>0.001976</td>
<td>12</td>
<td>4.5251e-5</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.36</td>
<td>0.81</td>
<td>0.15318</td>
<td>0.0019755</td>
<td>12</td>
<td>4.3578e-5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.41</td>
<td>0.84</td>
<td>0.15318</td>
<td>0.0019751</td>
<td>12</td>
<td>4.2023e-5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0.04</td>
<td>0.04</td>
<td>0.14941</td>
<td>0.00044349</td>
<td>12</td>
<td>3.3066e-5</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>0.12</td>
<td>0.18</td>
<td>0.15812</td>
<td>0.0011679</td>
<td>11</td>
<td>1.805e-5</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>0.53</td>
<td>0.33</td>
<td>0.15283</td>
<td>0.00090598</td>
<td>12</td>
<td>1.0604e-5</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>0.56</td>
<td>0.35</td>
<td>0.15285</td>
<td>0.00094865</td>
<td>12</td>
<td>1.318e-5</td>
</tr>
</tbody>
</table>
From Table 5.8, it is clear that we need to go for a tradeoff for the best sequence. The pulse sequence formed with pulse spacings generated from the progression of the type \( a\left(1 + \frac{1}{a}\right)\left(1 + \frac{1}{a + d}\right)\left(1 + \frac{1}{(a + d)^2}\right)\), with \(a = 0.04\), \(d = 0.04\) with 16 pulses in it works pretty well as seen from the table. It generated the shortest time lag and a reasonably long maximum lag among all the above pulse sequences.

Simulations were run in MATLAB to test its performance and its ability to distinguish targets moving at different velocities in the same range bin. Targets were assumed to be placed at 2000, 2001, 2002, 2003 and 2004 km moving at 200, 500, 100, 1000 and 400 m/s velocity, respectively. Hence they would generate frequency Doppler shifts of 13.33, 33.33, 6.66, 66.66, 26.66 Hz, respectively. The pulse sequence would be transmitted at the times \(\{0, 0.00044349, 0.0017569, 0.0041535, 0.0077753, 0.012729, 0.0191, 0.026959, 0.047379, 0.060039, 0.074393, 0.090477, 0.10833, 0.12798, 0.14946\}\). The pulses transmitted had a width of 300 ps, thereby resulting in a range resolution of 45 km. The pulse sequence was transmitted once every 0.2 s. Pulses sent over one second only were integrated to illustrate the capability of the pulse sequence. Figure 5.15 illustrates the transmitted pulse sequences. Since the pulse sequence has 16 pulses, 120 time lags can be generated from it. The time lags that can be calculated from this pulse sequence are shown in Figure 5.16. These time lags ranged from a value \(4.4349\times10^{-4}\) to 0.14941. We have 4 time lags shorter than 2400 \(\mu\)s namely, \(\{0.00044349, 0.0013134, 0.0017569, 0.0023966\}\).
Figure 5.15: Transmitted pulse sequences in one second

Pulse returns from 5 pulse sequences were averaged in one second to find the real and imaginary time lags. 80 pulse returns were integrated in a second.

Figure 5.16: Time lags generated from the 16-pulse sequence
The real and imaginary autocorrelation functions were plotted at every time instant as the pulse returns were received. Figure 5.17 shows the imaginary and real autocorrelation functions plotted as a function of time and lag number.

Figure 5.17: Real and imaginary ACFs as a function of time and lag number

The complex autocorrelation functions were Fourier transformed to find the frequency spectrum. Figure 5.18 shows a plot of the frequency spectrum where the 5 targets are clearly identified in the spectrum.

Figure 5.18: Frequency spectrum of the complex autocorrelation functions
This analysis shows that the selected sequence provides good performance and satisfies the design criteria. Target discrimination is greatly enhanced using this sequence. Implementation of this pulse sequence on the Kodiak SuperDARN will be discussed in the next chapter to understand its performance practically.
Chapter 6  Implementation and analysis

6.1 Implementation process

The Kodiak HF radar system is run by the radar control programs that were written in ‘C’ programming Language (Robin Barnes, John Hopkins University Applied Physics Laboratory). The designed pulse sequence was implemented on January 26, 2007 from 0000 – 0106 UT. Various control programs were employed and modified slightly to adapt to the designed pulse sequence. The following paragraphs describe necessary changes in parameters in the radar control programs.

The parameter ‘ptab’ defines the time instants at which the pulses in a multipulse sequence are transmitted. It was tailored to accommodate the 16 pulses that needed to be transmitted in the sequence. The pulse sequence was modified slightly for transmission by the radar so as to make the pulse transmission times multiples of 100 μs. The process still leads to a pulse sequence that did not generate any repeated time lags. The time lags that could be calculated from the initial and the modified pulse sequences are shown in Figure 6.1. The initial and modified pulse positions are tabulated in Table 6.1. The difference between the time lags calculated from the initial and modified pulse sequences is shown in Figure 6.2.

The parameter ‘lags’, which specifies the pulse positions used to calculate all the time lags was modified to include all the 242 [121x2] elements. The number of pulses in the sequence and the number of time lags that could be calculated were defined by ‘mpul’ and ‘mplgs’, respectively, that were correspondingly set to 16 and 121. The transmitted pulse length ‘txpl’ was set to 100 μs with a range resolution ‘rsep’ defined as 15 km. The number of range gates ‘nrang’ was set to 225. The pulse set length was 0.175 s and an integration time ‘intsc’ for every beam direction was set to 7 s, implying that autocorrelation functions formed from returns from approximately 40 transmitted pulse sequences would be averaged to compile the statistics for that beam direction. The narrow azimuthal beam was scanned across the radar footprint in 16 steps covering 52°.
At the end of each 16 beam scan, the sounder mode, described in Chapter 3, was used to scan through the available frequency bands to determine the transmission frequency.

Figure 6.1: Time lags from the initial and the modified pulse sequences

Figure 6.2: Difference between time lags from the initial and the modified pulse sequences
6.2 Data analysis procedures

SuperDARN radars record data in many ways. At the most basic level, the raw data are collected as arrays of ASCII characters that include the inphase and quadrature components of the received signal collected every 100 μs. The data also included header information about the beam number, the operating frequency and the estimated noise value for samples collected from every transmitted sequence of pulses. The data analysis was done using MATLAB, with the ultimate goal of observing changes in key echo parameters like the backscatter power (Signal to Noise Ratio (SNR)) (dB) and the line of sight Doppler velocity (m/s).
The data were passed through a series of programs to finally create statistical plots of the Doppler characteristics of the echoes. The collected data had samples received from 20478 transmitted pulse sequences. By using the lags from the lag table, the complex ACFs were constructed from the received signal samples from every pulse sequence that was transmitted for each range gate. At this stage, a very important point of concern was to eliminate the lags calculated during the Tx – on, Rx – off times. A routine was written that removed the lags calculated at these times. The ACFs of the echoes at each range were then averaged over an integration time of seven s. For accomplishing this, a program was written that extracted the beam number, frequency of operation, and noise level from the header. When a change in the beam number was detected, it indicated the end of an integration period. In total there were 535 integration periods for the collected data. The resulting ACFs were saved as binary (.mat) files. An example normalized ACF is shown in the Figure 6.3 for 94\textsuperscript{th} range gate (1575 km) of the record 461. The plot illustrates that there was a single low velocity component in the range gate at that time.

![Normalized ACF for the 94\textsuperscript{th} gate (1575 Km) of the Record 461](image_url)

Figure 6.3: Normalized ACF for the 94\textsuperscript{th} gate (1575 Km) of the Record 461
6.2.1 Backscatter SNR profile

A measure of the SNR is given by the backscatter power. The lag 0 power derived from the complex ACF records gave the signal power that was used in the SNR calculation. For a signal to qualify as an echo, the SNR had to be greater than 3 dB. The resulting backscatter power profile as a function of range and time (Figure 6.4) was hence, derived.

The range-time plot clearly exhibits the significance of HF propagation environment in affecting the SuperDARN observations of the backscattered power. This is seen by the presence of a sizeable amount of echo power in the regions 1, 2, and 3 corresponding to range gates 65 – 85 (1140 – 1440 km), 90 – 125 (1515 – 2040 km) and 150 – 170 (2415 – 2715 km) respectively in Figure 6.4.

![Figure 6.4: Range time plot for the received SNR (in dB)](image)

It is seen that during the interval of operation there was not much ionospheric backscatter.
6.2.2 Derivation of the line of sight velocities from the data

The line of sight velocities would help determine the ExB drift in the plasma irregularities when an HF signal is backscattered by them. To achieve an understanding of the line of sight velocities, the ACFs were passed through the fft and the pmcov routines in MATLAB to find their frequency spectra using the Fast Fourier Transform and the Modified Covariance methods respectively. A routine written in MATLAB helped determine the Doppler frequency shift from the frequency spectra of all the records. The Doppler shift in frequency, $f_d$, is related to the operation wavelength, $\lambda$, and the line of sight velocity, $v_r$, by the relation,

$$f_d = \frac{2v_r}{\lambda}.$$  \hspace{1cm} (6.1)

This equation was used to derive a profile of the line of sight velocities along the range as a function of time. Figures 6.5 and 6.6 correspond to the range-time parameter plots for the radial velocities calculated using the FFT and the modified covariance techniques respectively. The fan plots for the modified covariance plots along the field of view of the Kodiak radar are shown in Appendix A. These plots were similar to the velocity fan plot plotted immediately after the usual pulse sequence transmission was resumed. This plot is shown in Appendix A as Figure A.34.

Figure 6.5: Range time plot for the estimated line of sight velocities using the FFT (m/s)
The plots also indicate the presence of low velocity backscatter from ionospheric irregularities in region 3. However, regions 1 and 2 only indicate ground scatter since there is clearly no dominant velocity component greater than 50 m/s.

6.2.3 Variance analysis in the estimation of the Doppler frequency shift and line of sight velocity using the linear least squares method

A very interesting observation is that the values of velocity determined from the FFT and the modified covariance techniques seem to be in agreement with those derived using the FITACF technique for the regions 1 and 2. This indicates that the backscatter was from a source that had a single component of velocity during the time of observation. There was a disparity between the values of velocity determined for the region 3. This lead to an investigation into the variance in estimating the slope of the phase found from the complex autocorrelation functions. For this purpose, idea behind the FITACF method was used. The phase determined from a complex autocorrelation function as a function of time lag number is wrapped between $-\pi$ to $\pi$. However, for an estimate of the Doppler
frequency to be established, the phase needs to be unwrapped as illustrated in Figure 6.7. Since the technique involves performing a least squares linear fit to the unwrapped phase, it wouldn’t lead to an accurate estimate if more than one Doppler component existed and the variance in estimating the fit would indicate the extent to which the Doppler frequency was miscalculated. The variance in estimating the line-of-sight velocity $v_{\text{LOS}}$ can be estimated from the relation:

$$v_{\text{LOS}} = \frac{c \omega_d}{4 \pi f_{\text{radar}}} ,$$

where $\omega_d$ is the Doppler frequency in radians/sec and $f_{\text{radar}}$ is the operating frequency of the radar.

![Figure 6.7: Doppler extraction procedure from the complex autocorrelation function](image)

The data was analyzed to find the variance in estimating the least squares line fit. This would be a direct measure of how far the Doppler frequency would deviate from its mean value. Figure 6.8 illustrates the results from the investigation. It is clearly seen in
the figure that the region 3 estimates of Doppler frequency often had high values of variance in spite of exhibiting high backscatter power. This could be an indication of the presence of multiple velocity components in those range bins.

![Variance in Estimation of Doppler Frequency](image)

**Figure 6.8**: Range time plot for the variance in estimating the Doppler frequency using linear least squares fit method (rad/s)

An example normalized ACF is shown in the Figure 6.9 for 154\textsuperscript{th} range gate (2475 km) of the record 40. The plot illustrates the possibility of existence of more than one velocity component in the range gate at that time. Also presented is a plot of spectrum found using the Fast Fourier Transform and the modified covariance method in Figure 6.10. The presence of two peaks can be seen in the frequency spectra. Similar spectra were observed for complex ACFs in several range gates of region 3. This instigated an interest to run simulations to understand such anomalies.
The applicability of the designed pulse sequence for such an analysis was an essential question that needed to be answered at this stage. A simulation was run in MATLAB to see if the designed pulse sequence was any better than the SuperDARN pulse sequence currently being used for this purpose. Multiple targets were placed in different range bins \{1080 km, 1095 km, 1695 km, 1700 km, 2500 km, 2505 km and 2510 km\} moving with different velocities \{10 m/s, 56 m/s, 200 m/s, 700 m/s, 510 m/s, 1005 m/s and 210 m/s\} and the variance in estimating the phase using the Linear Least Squares Fit was determined for the 7-pulse SuperDARN sequence, and the designed 16-pulse sequence. Since the designed sequence had more time lags that could be deduced from it for a longer period of time than the SuperDARN 7-pulse sequence, there are greater number of points available for estimating the linear fit. This implies that the variance in estimating the fit should be lower for the designed sequence. The Figure 6.11 exhibits the variances as a function of range. The values for the designed sequence were considerably lower than those for the 7-pulse SuperDARN sequence.
Figure 6.10: Frequency spectra calculated using the Fast Fourier Transform and the modified covariance method for the ACF in 154th gate (2475 Km) of the Record 40.

Figure 6.11: Variances in estimation of Doppler frequency calculated for targets at {1080 km, 1095 km, 1695 km, 1700 km, 2500 km, 2505 km and 2510 km} moving at velocities {10 m/s, 56 m/s, 200 m/s, 700 m/s, 510 m/s, 1005 m/s and 210 m/s} when the SuperDARN pulse sequence and the designed pulse sequence were transmitted.
6.2.4 Dependence of variance in estimation of line of sight velocity on the radar transmission frequency

Another simulation was designed to extract the variance in estimating the velocity as a function of radar operating frequency. Multiple velocity components were placed in range gates 154 – 177 and single low velocity components placed in other range gates. The backscatter power profile as a function of range was determined and can be seen in the Figure 6.12.

![Backscatter power profile as a function of range](image)

Figure 6.12: Backscattered power profile as a function of range (in dB)

![Variance in estimating velocity using the designed Pulse Sequence as a function of frequency](image)

Figure 6.13: Variance in estimating the LOS velocities from the Doppler frequency derived from the least squares fit method when designed pulse sequence was transmitted
The variance in the estimated velocity was plotted as a function of frequency ranging from 8 MHz to 20 MHz in steps of 50 kHz. It can be inferred from Figure 6.13 that range gates where multiple velocity components were present had clearly high values compared to other ranges, irrespective of the transmission frequency of the radar. However, it is seen that the variance in estimating the velocity of the targets decreases as the operating frequency increases.
Chapter 7  Summary, conclusions, and future work

7.1  Summary and conclusions

The Kodiak HF radar system has the potential to continuously map ionospheric convection in its field of view. In that way, it is a useful instrument to study processes occurring in the high-latitude magnetospheric-ionospheric system. Orthogonality of the refracted HF radio waves to the magnetic field-aligned irregularities leads to the detection of echoes, and in turn an understanding of what is happening in the ionosphere. Despite their relative simplicity, SuperDARN radars are beset by certain fundamental problems, the solutions to which are by no means trivial. A very interesting challenge faced by SuperDARN is to partition an echo by avoiding delay folding and Doppler aliasing of highly dispersed echoes from “range-spread targets” like the ionosphere, which is a randomly fluctuating medium, the temporal and spatial variation of which directly affects the ionospheric channel and the transmission of HF waves.

The SuperDARN radars perform the spectral analysis directly on the lagged product time series of the received signal, and in effect, perform the decoding and spectral analysis in a single step. Through direct analysis in real time, the complex ACF is calculated from the 7-pulse sequence used for transmission. These ACFs are further processed to obtain information about the Doppler spectrum and its moments. In an ideal case, the returned signal spectrum should be a delta function at the Doppler frequency shift corresponding to the plasma flow speed in the ionosphere. For a variety of reasons, however, the observed spectrum has a finite width and is centered on the expected Doppler frequency shift. To determine this frequency, the phase of the ACF is determined as a function of time lag from the inverse tangent of the ratio of the imaginary and real components. The Doppler frequency shift is established by fitting a line to the unwrapped phase using the least squares fitting technique. This method, however, is not effective if the spectrum has multiple peaks in it due to sharp velocity gradients or vortices contained within the scattering volume limits.
The most important factor dictating the reception of accurate data to observe ionospheric convection is the design of an optimum pulse sequence that could help in getting rid of the mathematical ghosts like the ‘bad lags’ and ‘missing lags’. For the design of such a sequence, the degree of dispersion of the echo, as quantified by the overspreading factor $F = TB$ (where $T$ is the target’s delay depth and $B$ is its Doppler bandwidth) needs to be taken into consideration. Targets are said to be either “under-spread” if $F < 1$ or “over-spread” if $F > 1$. A set of multipulse codes were designed by Dr. Sathyadev V. Uppala and Dr. John D. Sahr to observe auroral electrojet irregularities. The sequence design looked promising enough for the SuperDARN environment. The principle of the design of these sequences was to sample a range of interest at a suitable rate, while under sampling the other ranges. The features of these codes have been discussed in detail in Chapter 4.

The aperiodic pulse sequences have proved to be useful to study targets that have a correlation time comparable to their range. Hence, codes were written in MATLAB to analyze the complex ACFs derived from the received signals when these pulse sequences were transmitted with different combinations of targets at different ranges and velocities. Figure 4.15 describes this process in detail. A requirement of the sequence to be designed was to be able to discriminate multiple target velocities in an individual range bin. This requirement lead to the study of a rather interesting spectral estimation technique called the modified covariance method.

An in-depth analysis of the aperiodic pulse sequences lead to an understanding that many of the sequences that had been used by others couldn’t be used with SuperDARN due to reasons mentioned in Chapter 5. However, a combination of pulse spacings that could generate a sequence that would be a combination of arithmetic, geometric, and harmonic progressions appeared to be a plausible solution to battle the problem. A final pulse sequence for SuperDARN was chosen based on several factors that include a long maximum time lag, short minimum time lag, number of time lags separated by more than 2400 μs, and minimum separation between the time lags. Numerical simulations are presented to show the performance of the designed pulse
sequence and its ability to deeply enhance the target discrimination capability of SuperDARN.

The designed pulse sequence was implemented on January 26, 2007 from 0000 – 0106 UT. The radar control programs had to be modified and the pulse sequence had to be tailored to help the radar adapt to the designed sequence. Promising features were seen during the process of data analysis. However, when the spectra were calculated as a function of range and time, it was seen that the FFT and the modified covariance estimates for the Doppler velocity were different in a few range bins from those of the FITACF technique. Hence, a study of the variance during the estimation of the phase from the complex ACFs was made. The range bins that showed a difference in the estimates showed an interesting feature during this analysis. They had reasonably high values of variance which may have been due to the presence of multiple velocity components in the range bins. A look at the ACFs and their corresponding spectra of those range bins confirmed this. To understand the dependence of the variance in estimating the line of sight velocity on the operating frequency, simulations were run. It was deduced that the variance in estimating the velocity of the targets decreases as the operating frequency increases.

The research effort described in this thesis cannot be considered as complete in every detail. The analysis presented here does show some promising features, but more detailed, quantitative studies need to be done before one can talk about the reality of the efforts. Hence some possible extensions of the work are presented here.

7.2 Future work

The presence of double peaked spectra disturbs the normal ACF processing of the SuperDARN data. The inclusion of a double peaked spectral model into the current data analysis procedure of SuperDARN data will further improve the accuracy and quality of SuperDARN measurements.

It would be appropriate to devise an algorithm that would find the variance in estimating the Doppler frequency shift and the backscattered SNR from the complex
ACF and if both the values were above some threshold values, should use the Modified Covariance technique to determine the various velocity components in the range bin.

The numerical simulations show that the variance in estimating the velocity is dependent on the operating frequency. Hence an algorithm that would dynamically determine the variance threshold above which a range bin would be expected to contain multiple velocities would be an excellent addition.
Bibliography


Appendix

Fan Plots for the estimated velocity using the modified covariance technique along the field of view of the Kodiak SuperDARN when the designed pulse sequence was run. The figures were plotted every 2 minutes after a complete beam scan along the field of view of the radar. The Figures A.1 to A.33 correspond to the beam scans when the designed pulse sequence was run on January 26, 2007 and A.34 corresponds to the beam scan immediately after the SuperDARN pulse sequence resumed its transmission.

Figure A.1: 0000 UT to 0002 UT

Figure A.2: 0002 UT to 0004 UT
Figure A.3: 0004 UT to 0006 UT

Figure A.4: 0006 UT to 0008 UT

Figure A.5: 0008 UT to 0010 UT

Figure A.6: 0010 UT to 0012 UT
Figure A.7: 0012 UT to 0014 UT

Figure A.8: 0014 UT to 0016 UT

Figure A.9: 0016 UT to 0018 UT

Figure A.10: 0018 UT to 0020 UT
Figure A.15: 0028 UT to 0030 UT
Figure A.16: 0030 UT to 0032 UT
Figure A.17: 0032 UT to 0034 UT
Figure A.18: 0034 UT to 0036 UT
Figure A.19: 0036 UT to 0038 UT

Figure A.20: 0038 UT to 0040 UT

Figure A.21: 0040 UT to 0042 UT

Figure A.22: 0042 UT to 0044 UT
Figure A.23: 0044 UT to 0046 UT
Figure A.24: 0046 UT to 0048 UT
Figure A.25: 0048 UT to 0050 UT
Figure A.26: 0050 UT to 0052 UT
Figure A.27: 0052 UT to 0054 UT

Figure A.28: 0054 UT to 0056 UT

Figure A.29: 0056 UT to 0058 UT

Figure A.30: 0058 UT to 0100 UT
Figure A.31: 0100 UT to 0102 UT  
Figure A.32: 0102 UT to 0104 UT  
Figure A.33: 0104 UT to 0106 UT
Figure A.34: Estimated line of sight velocities along the field of view of the Kodiak SuperDARN immediately after the designed pulse sequence transmission was stopped and the SuperDARN pulse sequence transmission resumed from 0132 to 0134 UT on January 26, 2007