A Thesis
entitled
Quantification of Bird Migration Using Doppler Weather Surveillance Radars
(NEXRAD)

by
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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Master of Science Degree in Electrical Engineering

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An Abstract of

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Wind Energy is an important renewable source in United States. Since past few years, the growth of wind farms construction has significantly increased, due to which there is an increase in number of bird deaths. Therefore, ornithologists began to study the bird's behavior during different migration periods. So far ornithologists have used many methods to study the bird migration patterns in which the radar ornithology has been used in an innovative way. However, many studies have focused using small portable radars and recently researchers have proved that the migration events can be studied through large broad scale radars like NEXRAD. Throughout the United States, NEXRAD has 160 Doppler Weather Surveillance Radars. The advantage of NEXRAD is that it can provide bird migration movements over a broad geographical scale and can be accessed free of charge.

In this thesis, an algorithm has been designed to observe the bird migration patterns in aerosphere using NEXRAD. However, unfortunately, there is some bias in the radar measures due to its operational characteristics. Therefore, the designed algorithm has

been used to adjust the radar measures using radar beam geometry and increase the efficiency of the results from clutter using image processing techniques. In addition, the algorithm also reduces the computational time.

The NEXRAD used in the study is from KCLE station, Brook park, Ohio. The thesis used three study areas which are located towards West and North-West direction from the station KCLE, to observe the bird migration patterns according to the adjusted beam height (AGL). The study area # 1, # 2 and # 3 are located in Ohio at Ottawa National Wildlife Refuge, Sandusky, and Vermilion respectively.

At Study area #1, observations from NEXRAD were compared and correlated with independent observations using Marine Radar. The method discussed in this thesis was limited to the radar range up to 80 km. The work will be useful to wildlife biologists, wind farm developers and policy makers. It can be used within 80 km range of any of the NEXRAD in the country.

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Chapter 1

Introduction

Wind energy has gained economic variability due to major technological advancements, and it is one of the fastest growing renewable energy resources. In the United States, wind energy is an important component for future renewable technologies. Recent developments in wind energy technologies increase the economics of wind energy by reducing the cost. As a result, by the end of 2010 in the United States, wind plants have been constructed in 38 states. Top five wind energy production states are Texas, Iowa, California, Minnesota, Oregon and Washington [1]. The growth in wind energy has been incredible for the past ten years. However, due to this wind energy production, there is a potential impact of wind turbines on birds and bats in everyday life. The U.S. Fish and Wildlife Service has estimated that building window strikes may account for 97 to 976 million bird deaths per year, while communication towers may account for 4 to 5 million bird deaths per year and 100,000 bird deaths per year due to wind turbines [2,3].

There has been reported environmental risk to wildlife from wind turbines, communication towers and other structures. Therefore, from the mid-1980s, in the United States, ornithologists started observing and documenting environmental impacts on bird and bat species. The Department of Energy (DOE) is also concerned about the impacts on

migratory birds. These species are protected under Migratory Bird Treaty Act (MBTA) (16 U.S.C.703) [4].

Figure 1-1: Interaction of Birds with Wind Turbines [5]

The Potential Impacts of Wind turbines on Birds:

Usually the wind farms are installed where wind speeds are high such as upland, coastal and offshore areas. Thus, habitats for wintering, breeding and for migrating birds and bats are affected by the wind farms.

The installment of wind turbines in a particular area depends upon the following factors [6]:

- Height of the turbines.
- Rotor swept area of the turbine.
- Wind speed
- Cooperation with land owners and cities/townships

- Flight behavior of birds and bats in that particular area.
- The altitude range of wind turbines and birds and bats.

Four main reasons of bird mortalities due to wind turbines are [6]:

Figure 1-2: Bird mortalities due to wind turbines

- Collision:

The bird migration mortality not only depends upon the collisions with rotors but also with towers, nacelles and its associated structures. This depends on the factors such as the number and behavior of bird species, weather conditions and topography, as well as the nature of the wind farm.

- Displacement due to disturbance:

This occurs due to the disturbances such as noise, vibration impacts and visual intrusion of the wind farms. This effect may occur during both construction and operational phases of the wind farm.

- **Barrier effect:**

This effect occurs when birds are avoiding the wind farms during migration or local flight paths. This depends on the type, movement and altitude of the bird species, time of day, wind speed and direction of either the day or night.

- **Habitat Loss:**

This happens when wind farms and its associated infra-structures are being constructed, which depends on the size of the project.

Today, many studies are performed to investigate the bird migration patterns and the results of the studies are being taken into the consideration before constructing the wind farms [1- 10]. Of all the studies, radar ornithology is considered as the one of the best method available and is used in this thesis.

1.1. Preface to Thesis

Since mid-twentieth century, radar ornithologists are investigating the behavior of bird species using different types of radars during bird migration periods [11-32]. Generally researchers have used small portable radars covering small geographical areas and are getting finer resolution. After performing many experiments on large broad scale surveillance radars, researchers have obtained qualitative data. This result encourages the possibility of studying the bird migration patterns using these radars.

Today, NEXRAD (Network of WSR-88D) has opened new doors for the scientific community for the study of bird migration patterns. NEXRAD has much supplanted visual observations of nighttime bird migration patterns. NEXRAD provides amazing information irrespective of time and direction of bird patterns especially as they relate to

existing weather patterns. It provides ornithologists an easy free of cost tool that is appropriate for bird migration study.

Throughout the United States, 160 Doppler Weather Surveillance (WSR-88D) radars are deployed. Most of the radars are in the United States and some in overseas locations. Data can be easily accessed from any of the station from a network of 160 Doppler weather radars with no charge. These radars provide information in the range up to 230 km from a single radar station.

Many investigators began using the NEXRAD data in an increasing manner and conducted many experiments in order to obtain the behavior of biological targets in the atmosphere [17, 19- 27, 30-33]. However, these echoes have some bias and an algorithm has been developed in this thesis that separates the biological echoes from non-biological echoes and reduces the bias in biological measures.

1.2. Scope

In the current work, an algorithm is designed that differentiates the biological echoes from non-biological echoes using image-processing techniques. To reduce bias from biological measures, mean Vertical Profile of Reflectivity (VPR) technique has been incorporated using radar beam geometry. The algorithm also reduces the computational time.

1.3. Outline of Thesis

Chapter 2 of this thesis provides a brief review regarding background information and previous studies on radar ornithology. Chapter 3 provides a detailed description on

NEXRAD and its meteorological products. Chapter 4 discusses various algorithms available in the literature and various parameters that can be extracted. A new algorithm has been developed for processing of NEXRAD data. Chapter 5 discusses the study areas used to observe the bird migrations patterns, performs data analysis and shows data that will be useful for wildlife biologists. Chapter 6 provides conclusion and future research.

Chapter 2

Literature Review

On our planet, environmental conditions for most living beings are characterized according to the geophysical cycles: annual periodicity and diurnal periodicity. Earth's rotation, changes in sun position according to the altitude and periodicity results in migration. Aristotle observed bird migration and Emperor Frederick II gave valid precise observations and interpretations of bird migration. However, intensive studies of bird migration were started in the nineteenth century [7]. Migration is a cyclic behavior during which the living beings can travel regularly, seasonally or annually from one place to another and return back again. This process can take place for each species or group of species that can travel a long distance. Main reasons to migrate are food, nesting and reproduction opportunities [8-10].

Each year during migratory periods there are several millions of birds travelling between Canada, United States and southern points. During the migratory period, birds migrate from the northern hemisphere northward during spring to take advantage of insect populations, budding plants and abundant nesting locations. During fall, they return south due to drop in resources. The exact timing of the migration varies for different parts of the world and for different species. The spring migration generally starts from mid-

February until April or May and the fall migration starts as early as mid-July to early September or early November [8 - 10].

Birds can navigate during the migration by using variety of skills such as navigation by stars, navigation by sun, following landmarks, by sensing changes in the earth's magnetic field and even through smell. Usually the altitude of birds depends on many factors such as bird species, weather conditions, time and day of the year and geographic weather conditions. However, the majority of birds flight altitudes are at a height of 304 m to 509 m Above Ground Level (AGL). Some migratory flights also occur at 1500 m to 1850 m AGL and in unusual conditions may go up to 3600 m AGL [19].

2.1. Factors that influence the Bird Migration [8, 9, 10, 12]:

Many factors affect the bird migration patterns such as meteorological conditions, day length, intensity of sun and environmental factors. The major factor that can affect birds during migration is wind direction. If the winds blow in the direction that the birds move then the migration tend to be high when compared to head winds. Another factor that affects migration is temperature. During spring, birds can select warm temperatures and during fall, they prefer lower temperatures. Most birds migrate at night when the conditions are more favorable such as cool temperatures and calm air.

2.2. Techniques used to study Bird Migration [8]:

Researchers have spent decades, in trying to determine how birds migrate, how one can observe and how high and fast do they fly. Therefore, to determine this data, many traditional methods and new methods have been used in the study of bird migration. Methods used for bird migration studies are briefly discussed in the next section.

- Direct Observation:

Initially, it was not apparent how migration really happens. The simplest, oldest and frequently used method to study bird migration is by direct observation. After so many observations, there is significant information that most of the migration takes place across the face of the full moon. So, counting number of birds and their direction of flights through a telescope has become well-known technique named as the Moon-Watching method [8]. It is a modified version of direct-observation. The disadvantage of this method is its limitation to night time observations.

- Aural :

This method is used for species identification. In this method, a parabolic reflector with attached microphones is used. This device is equipped with a tape-recorder to record calls during a full moon and no moon days with altitude of up to 11,000 feet. The main disadvantage is that, it cannot specify the direction that a bird is travelling and the difficulty of finding different chip notes of night migrants.

- Radio Tracking :

Generally birds are tagged with a radio transmitter. The transmitter gives off a periodic signal that can be tracked when a receiving system receives signals from birds with attached transmitter. This technique is also called Telemetry. The main advantage of this method is its ability to track their flying path or flying behavior. Disadvantages of this approach are that birds need to have transmitter attached, the range of the signals can be limited and they may also have low period of survival.

- Radar:

Radar has been an important tool in detecting, monitoring and quantifying the bird migration. It can be used to observe, identify and track bird targets at nights when visibility is poor. Many researchers have used wide variety of radars such as marine radars, tracking radars, small and large surveillance radars [14-24]. Basically, these radars are divided into classes according to frequency or wavelength. Radar Ornithology uses only X, C and S band radars. Among all, X-band radars have the lowest wavelengths in the range of 2.4 to 3.8 cm, with operating frequencies of 8 to 12 GHz. C-band radars operate with wavelengths in the range of 3.8 to 7.5 cm, and with frequencies of 4 to 8 GHz. S-band radars operate with wavelengths of roughly of 7.5 to 15 cm, with operating frequencies of 2 to 4 GHz.

Some examples of various radars that have been used are:

Doppler-traffic radar is a small and low-powered and was used to study birds by measuring their ground speeds within a 1 km area. Military tracking radars provide the altitude and density information. Their wing-beat patterns can also be measured. Large satellite radars operated by National Aeronautics and Space Administration (NASA) can be used to track bird targets within a 10 km range. Low powered surveillance radars are used to study bird migration patterns within a few kilometers. High-resolution marine surveillance radars can detect and quantify bird species. Long-range surveillance radars are commonly available as NEXRAD/weather sites. They can also be used to detect bird flight information ranging up to 230 km.

Advantages of NEXRAD/weather radar over other types of radars are:

- The detection range of radar is extended.
- Over large spatial scales, weather radar provides constant coverage area.
- The data is collected continuously and is archived.
- The data usually can be accessed instantly free of cost.

Sidney A. Gauthreaux from Clemson University [11] showed appearance of birds on base reflectivity, base velocity, Velocity Azimuth Display (VAD) of WSR-88D products. They gathered data directly from the Principal User Processor (PUP) workstation at the KHGX station in Houston, Texas in the spring of 1992. They also used the moon-watching or direct observations methods for correlation purposes. He showed a calibration curve, which relates the decibel values of reflectivity to the Migration Traffic Rate (MTR) of Birds. The correlation developed in this paper can be used with any WSR-88D reflectivity data throughout the United States. This is possible as the intensity is the same at any given precipitation level. The paper also discusses that migrating birds introduce bias in to the wind measurements of WSR-88D, and can be automatically mapped on national mosaic displays.

A. M. Dokter and I. Holleman from the Royal Netherlands Meteorological Institute [25] have developed an automated method for the detection and quantification of bird migration. The weather radar observations were collected in the Netherlands, Belgium and France during autumn 2007 and spring 2008. Their algorithm was developed for a network of operational C-band radars to measure bird density, speed and direction for each altitude level. The data obtained from their weather radar was validated with

independent high accuracy dedicated pencil-beam X-band radar named as bird radar. The echo detected from X-band radar then is used to detect wing-beat pattern. It is then used to filter out non-bird echoes such as insects, ground clutter, rain, snow and other clutter. In weather Radar, bird scattered signals are detected using radial velocity. They have developed a Volume Velocity Processing (VVP) technique and computes altitude profile of average speed and direction using a constant velocity model. As the paper indicated, standard deviation of radial velocity is a good indicator of the presence of birds and therefore computes the standard deviation of radial velocity. Authors have proposed a cell-finding algorithm for removal of non-bird echoes in the reflectivity image. To convert the weather radar reflectivity to bird density, the algorithm uses a constant bird radar cross-section of 11 cm^2 . According to the results obtained, there is a strong correlation between bird densities measured by weather radar with the bird density measured by bird radar. He also observed mesoscale variations with the weather conditions. Authors proposed that their work can be extended for use with polarimetric weather radar, X-band and S-band radar observations.

Felix Liechti from the Swiss Ornithological Institute [26] proposed use of Sensitivity Time Control (STC) filter for removing clutter. This method includes discriminating bird echoes from insect echoes and estimating the detection probabilities by classifying birds according to their radar cross-section. Main critical factors necessary for proper quantification is to estimate the surveyed volume and make appropriate distinctions between insect echoes and bird echoes. This work provides computational steps and results using their own radar data. Their procedural solutions can be applied to any radar for quantification of bird migration data.

Roberto Nebuloni, Carlo Capsoni and Vittorio Vigorita proposed a method [27] for detection and counting of migratory bird patterns using S-band radar. The weather radar measurements were collected at Spinod'Adda (Northern Italy) and observations started before sunset and ended the next day at sunrise. In base reflectivity product, they observed that the bird echoes appeared as spotty patterns. Precipitation echoes were spread over a large area in a spatially homogeneous manner. The algorithm is mainly developed to count bird echoes using Poisson distribution method and estimates bird density with respect to the time and height. The method discussed in this paper is only suitable to broad-front migration. The accuracy of the bird count algorithm was tested using Monte Carlo simulations. To estimate the bird number in WSR-88D observations, the data was calibrated through an independent set of data using visual observations and high-resolution pencil-beam X-band radar. The paper quantifies bird echoes by estimating volume density according to height, cumulative density and daily Migration Traffic Rate (MTR). A reliable algorithm was not used for distinguishing between birds and insects. If a particular pulse volume includes insects then birds are overestimated. Their work could be extended by incorporating distinctions between birds and insects and that could be applied to a network of radars.

Todd J. Mabee and Peter [28] prepared a study report on fall season nocturnal bird and bat migration characteristics using marine radar. The report discusses flight information and migration passage rates within the rotor swept area of the proposed wind project. To differentiate between birds and bats, mostly foraging bats exhibit erratic flight patterns, and if any bats were exhibiting these patterns, those were excluded from the data. To filter out the insects, small targets of weak reflectivity within the 500 m range and also

the targets having air speeds less than 6 m/s were excluded from the data. This study also discussed the influence of weather on bird migration flight altitudes and passage rates.

Francois Gagnon from the Canadian Wildlife Service [29] detected bird migration patterns using Canadian Weather Surveillance Radar (CSWR) and through visual observations. The C-band radar was used to carry out these observations. The data was collected at Val d'Irene (XAM) at Gaspé Peninsula. The paper discussed a relationship between the radar reflectivity collected from CSWR and passerine counts collected by visual observers. Radar Data Analysis, Processing and Interactive Display (RAPID) software was used for analysis of raw radar reflectivity data. Visual observers used a technique called Minimum Individual Passing (MIP) to detect the bird count during the migration period. To correlate observations between weather radar reflectivity and visual observations, Pearson product moment correlations and linear mixed effects models were used. Their future work includes extension of bird migration observation in St. Lawrence-Great Lakes basin using NEXRAD. Bird density data from marine radars will be correlated with the NEXRAD reflectivity data. With weather radars, an acoustic study can also provide a better indication of flow of birds within the radar beams.

Robert H. Diehl [30] investigated the migratory behavior of land birds during flight and stopover over the Great Lakes using ten NEXRAD radars and two portable three cm radars. Diehl followed the work of Black and Donaldson [17] to estimate the bird density. An average radar cross-section of a bird was considered as 17.5 cm^2 . Examination of bird echoes from WSR-88D indicated that bird densities over water are always greater than the bird densities over land. The ratio of bird densities over land to

water is 1.3 to 3.9. By analyzing the bird echoes, a large number of birds were found to cross the Great lakes and some were found to avoid the lake crossings.

Han Van Gastern and Iwan Holleman [31] assessed the bird flight information using C-band Doppler weather radar. Observations were taken from Operational Programme for the Exchange of weather Radar Information (OPERA) in the Netherlands. To validate the result, three cm tracking bird radar was used. The altitude information of birds from the bird radar was not reliable with the weather radar altitudinal profiles. To correlate both the densities, Vertically Integrated Reflectivity (VIR) was calculated for Doppler radar measurements, and Vertically Integrated Density (VID) was calculated for Bird radar measurements. Integration of reflectivity from weather radar over altitude gives the Vertically Integrated Reflectivity (VIR), which is an index of migratory density over altitudes. Similar to weather radar, the integration of reflectivity over altitude from marine radar provides the Vertically Integrated Density (VID). However, in weather radar, the integration takes place over larger area and for bird radar, the integration takes place over a small area. Authors followed two approaches to estimate the migratory densities. First approach is to compare the Doppler radar bird density according to the altitude with the X-band radar bird density, and the second approach is to compare the Vertically Integrated Reflectivity measurements of Doppler radar with the Vertically Integrated Density measurements of bird radar. Their future work includes use of their algorithm for a network of weather radars. They will also need to improve their algorithm for discrimination between various targets.

Robert H. Diehl and Jeffrey J. Buler [32] proposed a bias-adjustment algorithm and used mean Vertical Profile of Reflectivity (VPR) technique to adjust the bias in reflectivity

measures. The algorithm was derived for five lowest elevation angle sweeps, which integrates the radar reflectivity. Validation of the results was done using vertically oriented portable marine radar. This algorithm will be further studied and modified in this work.

Chapter 3

Next Generation Radar (NEXRAD)

A brief history of radar, development of NEXRAD, its operation, technical details and meteorological products are presented in this chapter.

3.1. Introduction to NEXRAD

Robert Alexander Watson Watt and Arnold F. Wilkins used radio waves to detect the aircraft during pre-World War-II period. In the year 1935, Watson Watt was awarded as the ‘Father of Radar’. Officially, the idiom RADAR was coined as an acronym in the year 1940 by Samuel M. Tucker and F. R. Fruth and the term RADAR stands for Radio Detection and Ranging [33].

AN/CPS-9 was developed after World War-II; it was the first specifically designed radar for meteorological purposes for detection of storms. Weather Bureau installed 25 AN/APS-2F radars in Florida and Ohio. They were modified and were named as Weather Surveillance Radar (WSR)-1s, 1As, 3s and 4s. Here ‘s’ represents the S-band Radar. These radars are similar but differ in control and display mechanisms. On March 12, 1947, the first WSR was installed at National Airport, Washington, D.C. This was the beginning of the development of U. S. Basic Weather Radar Network.

Currently there are 160 S-band radars commonly called 1988 Doppler (WSR-88Ds) or Next Generation Radars (NEXRAD) deployed in the United States. They form a network of Weather Surveillance Radars. The NEXRAD (WSR-88Ds) is the backbone of the national network of weather radars operated by the National Weather Service (NWS), Federal Aviation Administration (FAA), the Department of Defense (DOD), the Department of Transportation (DOT) and other users. The data resolution in WSR-88D is up to the range of 230 km. This system is much more sensitive and is able to see inside a storm. This system is in use since 1980 and provides data in the form of reflectivity, velocity, and spectrum width of an atmospheric disturbance. It is a valuable national resource and is instrumental in saving lives.

Figure 3-1 shows an example of NEXRAD radar site, located at WSR-88D Operations Center in Norman, Oklahoma and dated November 21, 2007.

Figure 3-1: NEXRAD site, Norman. Oklahoma [35]

3.2. Weather Surveillance Radar (WSR-88D): [33, 36, 37, 38, 39, 40]

Principle:

The weather radar transmits and receives electromagnetic pulses repeatedly similar to any other radar. Electromagnetic pulses travel in air with the speed of light. In between each pulse, the radar station acts as a receiver and receives returned signals scattered from various targets. The NEXRAD transmits pulses for short period of time and it is in a listening mode for relatively longer period of time. Figure 3-2 shows coverage of NEXRAD throughout the US. Table 3-1 provides technical data of NEXRAD.

Figure 3-2: Doppler Weather Radar (WSR-88D) coverage throughout United States [41]

3.3. Technical Details of WSR-88D

Table 3-1: Technical Parameters of NEXRAD (www.noaa.gov)

Technical Details of NEXRAD	
Transmitter	
Type:	S-band, klystron Tube amplifier
Frequency:	2700 to 3000 MHZ
Wavelength :	8 to 15 cm
Power:	750 KW
Pulse width:	1.57 and 4.71 μ s
Pulse Repetition Frequency (PRF) :	318 to 1304 Hz (for short pulse) and 318 to 452 Hz (for long pulse)
Antenna	
Gain :	45.5 dB
Beam Width:	0.925 ⁰
Maximum rotation rate :	Azimuth: 30 ⁰ /sec Elevation: 30 ⁰ /sec
Normal Scan:	Azimuth: 360 ⁰ Elevation: 0.5 ⁰ to 19.5 ⁰
Data Generated from Radar Product Generator (RPG)	
Reflectivity	
Maximum Range :	460 km
Computation :	Linear average return power
Range increment :	1000 m
Azimuth increment :	1 ⁰
Velocity	
Maximum Range :	230 km
Computation :	Complex covariance argument or (Pulse Pair estimator)
Range increment :	250 m
Azimuth increment :	1 ⁰
Spectrum Width	
Maximum Range :	230 km
Computation :	autocorrelation
Range increment :	250 m
Azimuth increment :	1 ⁰

The WSR-88D is an S-band Doppler radar system, with the wavelength of 8 to 15cm and frequency is ranging from 2700 MHz to 3000 MHz. The peak power of the transmitter is 750KW and klystron tube amplifier transmitter is used. The beam width is 0.925° and beam pattern is in narrow Gaussian shape. The pulse width of the signal is 1.57 μs (for short pulse) and 4.71 μs (for long pulse). For short pulse, the Pulse Repetition Frequency (PRF) is 318 to 1304Hz and for long pulse, it is 318 to 452 Hz. The antenna gain is 45.5dB and the antenna maximum rotation speed is 30° /second [42]. NEXRAD provides data in the form of reflectivity, velocity, spectrum width and commonly referred as meteorological products.

The Base Reflectivity product is computed using linear average return power method. For Reflectivity Base product, the range is incremented at 1000 m and the azimuth is incremented at 1° . The maximum range of Base Reflectivity product is 460 km. For Doppler Measurements, the range is incremented at 250 m and the azimuth is incremented at 1° . The maximum range of Base Velocity product is 230 km. To compute velocity product, complex covariance argument or pulse pair estimator is used. For computing Spectrum Width Base product, autocorrelation method is used. The maximum range of Spectrum Width Base product is 230 km. The range is incremented at 250 m and the azimuth is incremented at 1° .

The WSR-88D system has mainly three functional units as shown in Figure 3-3:

- Radar Data Acquisition (RDA)
- Radar Product Generation (RPG)

- Principal User Processor (PUP)

Radar Data Acquisition (RDA)

Figure 3-3: Functional Components of the NEXRAD System

Radar Data Acquisition (RDA):

This unit consists of transmitter, receiver, antenna and associated circuitry. Its main task is to transmit and receive pulses at a specified pulse rate.

Radar Product Generation (RPG):

The RPG unit converts the data from RDA into hydrological and meteorological products. The data is generated to produce reflectivity, velocity and spectrum width. The unit uses various estimators, ground clutter cancellers, data formatting, quality checking and other radar control processing tools.

Principal User Processor (PUP):

The system consists of meteorological analysis processor, product generator, associated color displays and communication ports. This system displays the meteorological and hydrological products generated by the RPG unit.

3.3.1. Volume Coverage Patterns

Throughout the United States, NEXRAD has a network of 160 WSR-88D radar sites. The range of WSR-88D radar is 230 km. It has a dish antenna with a 28ft. diameter. Dish antenna and the design of the system is the same for all radar sites, however, certain parameters may vary from location to location. The dish antenna can rotate 360° in azimuth, 20° in elevation and it covers a wide range of area.

The NEXRAD performs multiple scans with multiple elevation angles. Number of slices and elevation angles depend on the type of Volume Coverage Pattern (VCP) used. The radar continuously collects data, by rotating the antenna through 360° . Figure 3-4 shows volume coverage pattern.

Figure 3-4: NEXRAD- Volume Coverage Pattern [43]

Scanning starts at 0.5° elevation angle. It is incremented for subsequent scanning and continues until all the desired elevations are completed. The total scanning process comprises a Volume Coverage Pattern (VCP). After the VCP is obtained, the data is processed and images are generated. Generally, to scan the atmosphere, WSR-88D employs different types of volume coverage pattern strategies. They depend upon various modes of operation [43].

3.3.2. Modes of Operation

WSR-88D operates in two modes of operation clear air and precipitation modes depending upon weather conditions.

Clear Air Mode:

In this mode, the radar operation is very sensitive as the antenna rotation rate is very slow. Due to this, it is easy to find small particles in the atmosphere. This mode gives the

accurate measurements of low-level signals. In this mode, the radar images are updated every 10 minutes. Figure 3-5 shows volume coverage area for different elevation angle, range and height.

Figure 3-5: Volume Coverage in Clear Air Mode [42]

There are number of Volume Coverage Patterns (VCP) available in this mode and two of them are as follows:

VCP 31: This pattern is used for clear air mode and NEXRAD operates in pulse mode. This pattern uses a long pulse, which transmits the pulse for every $4.71 \mu\text{s}$. It consists of five elevation angles of 0.5° , 1.5° , 2.5° , 3.5° and 4.5° . It takes 10 minutes to complete one elevation angle.

VCP 32: This pattern is used for clear air mode. VCP 32 uses a short pulse, which transmits the pulse for every $1.57 \mu\text{s}$. It consists of five elevation angles of 0.5° , 1.5° , 2.5° , 3.5° and 4.5° . It takes 10 minutes to complete one elevation angle.

Precipitation Mode:

This mode is used during any kind of precipitation. In this case, the radar needs not be as sensitive as in clear air mode. Compared to the clear air mode, the rotation rate is high. It gives the information of vertical structure of the storms. In this mode, the radar images are updated every 4 to 6 minutes. Figure 3-6 shows volume coverage area for different elevation angle, range and height.

Figure 3-6: Volume Coverage in Precipitation Mode [42]

There are number of Volume Coverage Patterns (VCP) available in this mode and four of them are as follows:

The Volume Coverage Patterns available in this mode are:

VCP 12: This pattern is used for severe weather. It consists of fourteen elevation angles that starts at 0.5° and ends at 19.5° . It takes 4 minutes and 6 seconds to complete each

elevation angle. The pattern provides a denser vertical sampling at lower elevations, which is used to improve the detection capability.

VCP 21: This pattern is used for non-severe weather. It consists of nine elevation angles that starts at 0.5° and ends with 19.5° and it takes 6 minutes to complete each elevation angle.

VCP 121: This pattern is used for severe weather. It consists of fourteen elevation angles that starts at 0.5° and ends with 19.5° . It takes 5 minutes to complete each elevation angle. This pattern has the ability to detect wind velocity and gives information on second trip echoes.

VCP 11: This pattern is used for both severe weather and non-severe precipitation events. It consists of sixteen elevations that start at 0.5° , ends with 19.5° . It takes 5 minutes to complete each elevation angle. This pattern provides better sampling of vertical structure of storm clouds and temporal resolution.

3.4. Radar Imagery

NEXRAD data is archived by number of organizations for multiple purposes. National Oceanic and Atmospheric Administration (NOAA) (<http://www.noaa.gov/>) archives NEXRAD data. National Climatic Data Center (NCDC) provides a special software called NOAA's Weather and Climate Toolkit (NCDC Radar Software). This toolkit provides simple visualization and data export capabilities. Archived data is available to scientific community and others at no cost.

NEXRAD data from NCDC is available mainly in three formats (Level I, II and III). Level I provides the raw radar data, which is the output of the Radar Data Acquisition

(RDA). Level II data is also called as base data and is obtained after removing clutter and performing certain radar signal processing operations. The NEXRAD Level II provides three base meteorological products such as reflectivity, Doppler velocity and spectrum width. Level II data is also called as Super Resolution data due to its higher resolution. NIDS format is used for displaying NEXRAD Level III data. It is a processed version of Level II data. It has 15 colors, 41 meteorological products and its resolution is low. Comparison of Level II and Level III data is shown in Table 3-2.

Table 3-2: Comparison between Level II and Level III data

Comparison between Level II and Level III data	
Level II	Level III
Level II data is also called base data or Super Resolution data	Level III data is also called NIDS data
Archived from Radar Product Generator (RPG)	Archived from Principal User Processor (PUP)
Provides three meteorological products	Provides 41 meteorological products
Represents the image using 128 colors	Represents the image using 15 colors
Data resolution is high	Data Resolution is low
Data is incremented in 0.5 dBZ	Data is incremented in 5 dBZ

The WSR-88D characterizes the echoes according to the mode of operation in three base meteorological products: Reflectivity, Radial Velocity and Spectrum Width. Most people use Level II data as it has as super resolution, provides 128 colors and data is incremented in 0.5 dBZ.

3.4.1. Reflectivity:

Reflectivity is a measure of an echo signal and a predictor of size of the target. If the transmitted signal intercepts a target, some energy will be reflected back. The amount of the reflected energy can be converted into power of the signal, which gives an estimate of the number of targets presents and their sizes in that area. The reflectivity is represented in decibels (dB), a standard measure from radar meteorology. NEXRAD specifies reflectivity in decibels (dBZ). The higher dBZ value indicates larger or stronger object [44].

Figure 3-7 shows an example of one of the base meteorological product, Reflectivity data from NEXRAD Level-II scan. This data was extracted from NOAA Weather and Climate Tool kit May 4, 2011 at 03:16 GMT.

Figure 3-7: Example of Reflectivity Image from NEXRAD Level-II Scan

The linear measurement of reflectivity is transformed to its logarithmic scale using $Z = 10^{dBZ/10}$. The range of reflectivity values (dBZ) depends on the mode of operation. The range of scale is -28 dBZ to +28 dBZ for clear air mode and from +5 dBZ to +75 dBZ for the precipitation mode.

3.4.2. Radial Velocity:

Radial Velocity specifies the speed of the moving target and its direction. NEXRAD is a Doppler radar. When the radar transmits the signal, the system keeps track of the phase shift of the echo signal. Phase shift value is used to determine the target's radial velocity by comparing the power of transmitted pulse with its echo signal. Therefore, if the phase shift is positive, then the target is moving towards the radar which is represented in green color else it is moving away from the radar and it is represented in red color. If the phase shift increases, then the radial velocity will also increase.

Figure 3-8: Example of Radial Velocity from NEXRAD Level-II Scan

Figure 3-8 shows an example of Doppler velocity of NEXRAD Level-II Scan. This data was extracted from NOAA Weather and Climate Tool kit on May 4, 2011 at 03:16 GMT.

If the target flies along or away from the radar antenna, it is its true ground speed. If the target flies at 60° relative to the antenna then it will be 50% of true ground speed. If the target flies perpendicular to the antenna then the radial velocity will be zero, which implies no data. The radial velocity is represented in Knots (KTS).

The velocity information can be used to distinguish or separate various kinds of targets. This work is focused on monitoring and tracking of birds using readily available NEXRAD data. Therefore radial velocity can be used as one way to separate birds from other moving targets. It is well known that generally birds fly with speed in the range of 8 m/s to 12 m/s [24, 45]. Therefore if one is interested in movement of birds than anything moving outside this range is considered as clutter and can be removed.

3.4.3. Spectrum Width:

The third child of meteorological product from WSR-88D is the Spectrum Width. Following definition is given by NOAA website:

“Spectrum Width depicts a measure of velocity dispersion. It provides a measure of the variability of the mean radial velocity estimates due to wind shear, turbulence, and/or the quality of the velocity samples. It is used to estimate turbulence associated with boundaries, thunderstorms and mesocyclones.”

The distribution of velocities provides a measure of spectrum width. If there is small variation in velocity then the spectrum width will be low indicating uniform or smooth

flow. On the other hand if variation in velocity is high then the spectrum width will also be high indicating that there is larger activity or turbulence. If insects are present in the data as they have lower air speeds and low variation then this will result in low spectrum width values. For birds, high spectrum width values are shown because of their high travelling airspeeds and higher variation. If the data contains different types of biological targets, which are at different radial velocities, then the spectrum width will also be high.

Figure 3-9 shows an example of the third base meteorological product, Spectrum Width data from NEXRAD Level-II Scan. This data was obtained from NOAA Weather and Climate Tool kit May 4, 2011 at 03:16 GMT.

Figure 3-9: Example of Spectrum Width Image from NEXRAD Level-II Scan

3.5. Data Downloading Steps from NOAA [46]:

Figure 3-10: Flowchart to download NEXRAD data

A flowchart for downloading the NEXRAD data is shown in Figure 3-10. NEXRAD data can be accessed from the National Oceanic and Atmospheric Administration (NOAA) and its National Climatic Data Center (NCDC) from the following website.

<http://www.ncdc.noaa.gov/oa/wct/>

Detailed step by step procedure for downloading the NEXRAD data are as follows:

- First of all download and install NOAA's Weather and Climate Toolkit from the above specified link.
- Select – order NEXRAD data
- Image of Figure 3-11 will be shown.
- Select desired NEXRAD site shown in the image (Figure 3-11)
- Image of Figure 3-12 will be shown.
- Select date of the desired data (Day, Month and Year)
- Select Level II data
- Image of Figure 3-13 will be shown.
- Provide email address and order data.
- NOAA/NCDC will send desired data to the specified email address after 5 – 20 minutes.
- Save received data for further processing.
- Open the toolkit
- Select the appropriate folder containing the received data as shown in Figure 3-14.
- Load the desired file.
- Select one of three options (Reflectivity, Radial Velocity and Spectrum Width).
- Specify elevation angel and load the data.
- Image of the data will be shown.

Figure 3-11: Example Image of ordering NEXRAD data

Figure 3-12: Example Image of ordering data from NEXRAD data Inventory Search

Figure 3-13 shows NEXRAD Level-II for March 3, 2010.

Figure 3-13: Example Image of ordered NEXRAD data.

Figure 3-14 shows NEXRAD data selector window and place to select name of the received data folder.

Figure 3-14: Example Image of ordered NEXRAD data with data selector

The second dialog box will show elevation angle and one of the three selected data (Reflectivity, Radial Velocity and Spectrum Width). Figure 3-15 shows the image of the Base Reflectivity Product at an elevation angle of 0.5° with name of NEXRAD location, date and time.

Figure 3-15: Example of ordered Reflectivity data from Radial Properties dialog box

The research work in this thesis is concerned with monitoring of bird migration pattern via NEXRAD. The data obtained using above procedure can be processed so that it will be useful for wildlife biologist to determine any behavioral pattern. Processing of the obtained data is discussed in the next chapter.

Chapter 4

Radar Data Processing

A radar data processing algorithm needs to be developed for extracting bird activity from NEXRAD data. Generally radar data consists of desired target information, clutter in the form of background and noise. The NEXRAD data is available in the form of images. An appropriate technique for processing this type of data is to use widely available image processing techniques. There is image processing toolbox available in the MATLAB that can be used for rapid development of this algorithm. Robert Diehl and others [25, 26, 27, 32] has provided an algorithm for quantification of bird activity using reflectivity data from NEXRAD. Image processing technique is proposed to enhance quantification of bird activity.

NEXRAD data can be obtained from NOAA Satellite and Information Service and its National Climatic Data Center (NCDC) using NOAA's Weather and Climate Tool kit. It is available free of cost. Level-II NEXRAD data is available as images in Portable Network Graphics (PNG) format. Once these images are brought into MATLAB environment then they simply become matrices. Image-processing techniques can be used to read images and filter out unwanted radar echoes. Background subtraction techniques can be applied to filter unwanted radar echoes. There are many methods to achieve this goal such as frame difference, rationale, selectivity, kernel density estimators and mean-shift based estimation [39]. However, one appropriate mechanism for

background subtraction on radar images is through eigen backgrounds. Principal Component Analysis (PCA) followed by noise subtractions, target filtering are used in this work [47]. Proposed radar data processing algorithm is shown in Figure 4-1.

4.1. Algorithm

- Collect NEXRAD data from NOAA Satellite and Information Service.
- Read images into MATLAB.
- Resize images as necessary.
- Perform background subtraction using PCA
- Apply noise removal techniques
- Perform target filtering
- Compute the Beam-Area Weighted mean Reflectivity for all pulse volumes
- Calculate mean Vertical Profile of Reflectivity (VPR).
- Use adjustment factors as desired or necessary.
- Adjust reflectivity values.
- Estimate reflectivity of birds in selected airspace.
- Quantify results.

Flow Chart:

Figure 4-1: NEXRAD Data Processing Algorithm

4.2. Description

Principal Component Analysis (PCA):

Principal Component Analysis (PCA) is a statistical technique that separates the target pixel from original radar images. The advantage of this method is, it identifies the patterns in the data and shows the similarities and differences in the images. Another advantage is, this method is used to compress the data without the loss of much information [47]. Following are its computational steps:

PCA Computation:

- Form a data matrix
- Subtract the mean from each value in the matrix
- Calculate the covariance matrix
- Calculate the eigenvectors and eigen values of the covariance matrix
- Order the eigenvectors from highest to lowest. Therefore, according to the order of the significance, the least desired data can be ignored. The eigenvectors with the highest eigen values are known as principal components of the data set.
- Eigenvectors are formed in a column and are considered as feature vectors.
- Final data set is obtained by using transpose of the feature vector and transpose of the mean adjusted original data matrix.

PCA operations performed on original data are basically equivalent to background subtraction.

Noise Removal:

The next step is the application of noise filtering techniques on the processed images. This method is also used to remove the noise and clutter from the images. The noise filtering algorithm consists of median filtering, image segmentation and morphology (image erosion and dilation). A flowchart of this technique is shown in Figure 4-2.

Figure 4-2: Noise Filtering Techniques

Median filtering is a non-linear digital filtering technique used to remove noise without blurring sharp edges. Image segmentation is a process of partitioning an image into multiple segments. It represents an image in a more meaningful way. It locates objects and boundaries in the image and makes it easier for further analysis.

Image erosion and dilation are considered as morphological operations in image processing techniques. These are used to process the images based on the shapes. Dilation is used to add pixels to the boundaries of the objects in the image while the erosion removes the pixels on the boundaries. MATLAB provides built in functions for

median filtering, image segmentation and morphology in their image processing toolbox and have been used in this work.

Most of the clutter has been removed from images using the background subtraction and noise filtering techniques as previously described. Target filtering will be the next step that needs to be performed. The target filtering is done according to a threshold created based on pulse volumes data. Currently images are in Cartesian coordinate system and needs to be converted into Polar form. This is necessary to obtain the target information in the form of Range and Azimuth angle. Following computational steps will be performed:

To find the range of the target from the center:

- Find the center pixel of the image.
- From the center pixel, find the distance of each pixel using:

$$D = \sqrt{x_2 - x_1^2 + y_2 - y_1^2} \quad (4-1)$$

- Convert each pixel into 0.5 km.

To find the Azimuthal Angle of the target:

- Convert the Image into four Quadrants.

$$\text{Quadrant 1: Angle} \quad (4-2)$$

$$\text{Quadrant 2: } 90^0\text{-Angle} \quad (4-3)$$

$$\text{Quadrant 3: } 180^0\text{+Angle} \quad (4-4)$$

$$\text{Quadrant 4: } 270^0\text{-Angle} \quad (4-5)$$

$$\text{where Angle} = \tan^{-1}((y_2 - y_1)/(x_2 - x_1)).$$

Data matrix is further transformed and considered as cell matrix. Therefore, according to the range and angle values, the values need to be assigned as pulse volumes format using cell matrix basis. The resolution of each cell is 0-1 km and $0-1^0$. That is, the spatial alignment is with 1^0 resolution in azimuth and 1km resolution in range. For example, the target that is in the range 0-1 km and $0-1^0$ is in one cell matrix. According to the above spatial alignment, mean intensity values in a particular volume can be obtained.

Target Filtering:

Target filtering is performed according to the threshold created based on pulse volumes data. If the reflectivity in a given pulse volume is greater than seven times the half of the immediately surrounding pulse volumes reflectivity then the reflectivity of a given pulse volume has to be filtered out [32]. This step is necessary as at a lowest elevation angle there will be reflectivity due to vehicles or other structures. The selected threshold is very conservative and will retain reflectivity due to biological echoes [32].

The next is the computation of the mean Vertical Profile of Reflectivity (VPR). It is an estimation of error and is also used to reduce the bias in the radar reflectivity measures.

The mean VPR is performed using following two steps:

1. Compute beam-area weighted mean reflectivity
2. Calculate mean VPR.

Figure 4-3: Flow Chart to Reduce Bias

Compute Beam-Area weighted mean Reflectivity:

Calculate the beam-area weighted mean reflectivity for all the pulse volumes according to the range using the following relation [32]:

$$\overline{Z}_i D_i = \sum_{c=1}^{n_c} \overline{Z}_c \beta_{ci} \quad \sum_{c=1}^{n_c} \beta_{ci} \quad (4-6)$$

where β_{ci} = Beam-cross section within a height interval for a given range.

$\overline{Z}_c$ = Mean-Reflectivity for a particular range.

$\overline{Z}_i D_i$ = Beam- Area weighted mean reflectivity for a particular range.

n_c = number of ranges.

To find the Radar Beam cross-section for each pulse volume:

$$\text{Beam Cross-section: } \pi r^2 \theta. \quad (4-7)$$

where r = range, $\theta= 0.95^\circ$.

To find Beam-height at each Range using (AGL):

$$\text{Beam Height} = \sqrt{r^2 + ke * a^2 + 2 * r * ke * a * \sin \theta} - ke * a + ha \quad (4-8)$$

Where r = range, $ke = 4/3$, $a = 6371$ km,

θ = elevation angle

ha = height of the antenna above ground level.

Mean Vertical Profile of Reflectivity (VPR):

The mean VPR according to the range can be calculated [32] as:

$$Z_i = \overline{Z_c} D_i \left(n_z \sum_{i=1}^{n_z} \overline{Z_i} D_i \right) \quad (4-9)$$

Where n_z = Number of height Intervals

Z_i = Mean VPR at each Range.

To estimate the error in the data, it is required to find the beam blockage occultation using beam interception function that gives percentage error and shows the amount of reflectivity that needs to be added to the original reflectivity data [48, 49].

Radar Beam Occultation:

When the radar transmits a signal, the energy may or may not be intercepted by the surrounding topography. There are two possible scenarios of blockages. First is the partial beam blockage which implies that only part of the beam cross-section area is intercepted by topography. The second scenario is the total beam blockage. It means that the total beam cross-section area has been blocked by topography or certain tall

structures. Bech et. al. [48-49] has provided various algorithms and formulas for computation of beam occultation. They consider the beam height with respect to the topography. If there is any beam blockage, the correction has to be applied on radar pixels. The correction varies from 10% to 60% that is 1-4 dB of reflectivity added to the original pixel data and depends up on the type of beam blockage.

The observations used in this work are from Cleveland (KCLE), Ohio. Therefore, according to the radar site information, there is no terrain part that surrounds the radar detections in the data. That is, there is no blockage and the percentage of reflectivity does not need any adjustment. An adjustment factor for the beam area weighted mean VPR is given by Diehl [32]:

$$z_{d,g,o} = \sum_{i=1}^{n_z} z_i \beta_i \quad (4-10)$$

where $z_{d,g,o}$ = Adjustment factor at each range

z_i = Mean VPR at each Range

β_i = Beam-Cross section at each Range

Since there is no occultation in the study area so occultation factor is ignored. If this work is used in an area where there is partial or total blockage then occultation factor needs to be considered. Number of birds in the air space can be estimated by dividing total raw reflectivity in each pulse volume by its corresponding adjustment factor for each range. The final step of the algorithm is to present results in a form that will be useful for wildlife biologists. Next section describes quantification of bird data.

4.3. Quantification:

The WSR-88D base reflectivity is directly related to the number of birds rather than the flow of birds within the radar beam. Wildlife biologists would like to see number of parameters that may be useful in determining behavior of birds in the vicinity of wind turbines or major geographical diversity. Parameters considered in this work are as follows:

- Bird Density (Birds/km²) according to range and altitude Above the Ground Level (AGL) at different areas.
- Volume Density (Birds/km³) according to range and altitude (AGL) at different areas.
- Percentage of bird density.
- Variance of bird density

Bird Density (Birds/km²):

This parameter represents the average number of birds according to range and altitude (AGL) at evening civil time, night time and morning civil twilight time. Evening civil twilight time is considered as one hour after sunset. Morning civil twilight time is one hour before sunrise, and in between these two timings, it is considered as night time observations. Bird density is then computed according to these timing and presented both in tabular or graphical forms.

$$\text{Bird Density in a pulse volume} = \frac{\text{Reflectivity in a pulse volume}}{10} \quad (4-11)$$

Volume Density (Birds/km³):

This parameter represents the average number of birds per cubic kilometer according to the range and altitude (AGL) at evening civil time, night time and morning civil twilight time. There are two methods that have been described by other researchers for computation of the volume density. First method computes volume density by taking into account complex dielectric scatters, wavelength of the radar and reflectivity. Volume density can be computed as [25, 50, 51]:

$$\eta = \frac{10^3 \pi^5}{\lambda^4} |k_m|^2 Z_e \quad (4-12)$$

where, η = Radar reflectivity

λ = wavelength of the NEXRAD = 10.2 cm

$|k_m|^2 = 0.93$ for water.

$$k_m = (m^2 - 1) / (m^2 + 1)$$

Where m = complex refractive index of the scatters.

Z_e = Radar Reflectivity factor.

A more general and approximate method has also been proposed by John E. Black [20] Diehl and Gauthreaux [11, 17, 30]. An approximate volume density can be computed as:

$$3.0 * Z = \text{Average Volume Density} * \text{Average Cross-section of a bird} \quad (4-13)$$

where, Z = Reflectivity in each pulse volume

Average Cross-section of a bird = 10 cm².

Computation of volume density was performed using above two methods and results indicates that they seem to provide similar results. First method seems to be more practical and has been adopted in this work.

$$\text{Volume Density in a pulse volume} = \frac{\text{Radar reflectivity } \eta \text{ in a pulse volume}}{10} \quad (4-14)$$

Percentage of Birds:

The Percentage of bird density is calculated by dividing the total number of bird density to the maximum number of bird density and converting into percentage.

Variance of Bird Density:

Variance of bird density at each range can be calculated using standard formulas.

4.4. Quantifying Bird Density (Buler and Diehl) [32]

Buler and Diehl have developed a methodology for quantification of bird density during migratory stopover. They have written their algorithm using SAS 9.1. Their algorithm reduces the bias in reflectivity measures caused by operational characteristics of the radar and any occultation due to geographical topography. Their algorithm performs following operations:

4.4.1. Buler and Diehl Algorithm:

1. Obtain NEXRAD Reflectivity data.
2. Compute Beam Area Weighted Mean Reflectivity
3. Compute Mean VPR.
4. Calculate Adjustment factor.
5. Target filtering, to remove clutter.
6. Reflectivity values adjusted using adjustment factor.
7. Estimates the reflectivity in air space.

The algorithm uses one filter to remove undesired clutter. That is, an appropriate threshold is used to filter out the clutter. The dimension of the NEXRAD image is $1,210 \times 654$, that is approximately 791,340 pixels. Analysis was performed using the NEXRAD data taken on April 27, 2011. The NEXRAD was operating in a precipitation mode and VCP 121 was used. However, on April 27, for one-day data there are 133 images present. Therefore, for 133 images, the total pixels need to adjust before filtering is $133 \times 791,340$ pixels. This pattern is used for severe weather cases like heavy rain, snow, fog and more. Therefore, the birds will not fly in this climate. Moreover, the algorithm needs to adjust $133 \times 791,340$ pixels before threshold filtering. This approach will result in higher computational time and may introduce undesired approximation.

NEXRAD data was processed for Ottawa National Wildlife Refuge location. A bird density of 2,225 birds/km² was obtained. A marine radar was also operated at this location for the same duration. Bird density from marine radar was only 3 birds/km².

Therefore, in order to improve the results and reduce the computational time algorithm, a new improved algorithm is proposed. Proposed algorithm uses additional computational steps inspired by the image processing literature and also lowers computational burden.

4.4.2. Proposed Algorithm:

The original method of Buler and Diehl [32] is modified by inserting image processing based filtering operations which eventually reduces computational burden and improves quality of results. A flowchart of this algorithm is shown in Figure 4-4.

This algorithm adjusts the reflectivity measures after filtering techniques are applied. The algorithm reduces number of pixels in the images resulting in reduced computational time. The algorithm was implemented in MATLAB.

Flow Chart:

Figure 4-4: Flowchart of Improved Algorithm.

The background subtraction and noise filtering techniques reduce noise in data. Target filtering is performed before the computation of VPR resulting in reduction in the computation time. Table 4.1 shows a comparison between Buler and Diehl and proposed algorithm. It also includes comparison with the marine radar for data collected on April 27, 2011 near Ottawa National Wildlife Refuge. Bird density computed from marine radar data was 3 birds/km². Results are compared and correlated with marine radar observations. If the correlation is high, then it is more precise than the other. Proposed algorithm provides better correlation between observations from marine radar data and NEXRAD.

Table 4.1: Comparison between Buler and Diehl and Proposed Algorithm

	Buler and Diehl Algorithm	Proposed Algorithm
Computation Time	No. of images = 133 6 days 58 minutes	No. of images = 133 12 hours 23 minutes
Pixels adjusted for bias due to operational characteristics of radar	1210*654 pixels	652*652 pixels
Bird Density	2225 birds/km ²	25 birds/km ²
Bird Density on Land	1007 birds/km ²	12 birds/km ²
Bird Density on Water	1218 birds/km ²	13 birds/km ²
Correlation with marine radar	0.0090158	0.158114
Error Rate between the algorithm and Marine Radar	1111.11	11

Chapter 5

Data Analysis

Proposed algorithm for quantification of bird migration using NEXRAD has been simulated. Data analysis needs to be performed and converted into a form that will be most useful for wildlife biologists. Its results also need to be compared with those of Furuno Model FR-1525 MKIII marine radar. During the 2011 spring bird migration period, nightly observations were collected at Ottawa National Wildlife Refuge, Ohio. Data was collected for approximately 27 nights. Marine radar data collected on April 27, 2011 was used as the test data for comparison purposes. NEXRAD data was also downloaded for the same time and date. NEXRAD observations were used from WSR-88D (KCLE; 41.4131 N, -81.8597 W or 41⁰ 24'47.41" N, 81⁰ 51'34.94"W) located at NASA, Glenn Research Center, Brook park Road, Cleveland, Ohio. This location was selected as it was the nearest to the Ottawa National Wildlife Refuge and had clear topography. Figure 5-1 shows the topographical view of NASA, Glenn Research Center and NEXRAD (KCLE) Cleveland. The elevation of the station is 763 feet from Mean Sea Level (MSL).

Figure 5-1: Map of KCLE station located at Glenn Research center, Ohio (From Google Earth).

The distance between NEXRAD at KCLE and marine radar location is approximately 114 km. Unfortunately NEXRAD was operating in precipitation mode during nights when data from marine radar was being collected. NEXRAD data from the night of April 27, 2011 was used to obtain quantification data for bird migration and for comparison with that of marine radar data. Figure 5-2 shows a Google map of marine radar and NEXRAD (KCLE) locations.

Figure 5-2: Map of Study Area 1 and NEXRAD (KCLE), Ohio (From Google Map)

A 13*13 km area was identified for simulation and quantification purposes as shown in Figure 5-3. The selected study area has both land and water areas.

Figure 5-3: Location of Marine Radar (Study area #1) (From Google Earth).

The study area #1 is the Ottawa National Wildlife Refuge (UTM: Zone 17; Northing 11396, Easting 316748 or 41.633 N,-83.200 W) which is located exactly at 114.479 km towards North-west at an azimuthal angle of 282.77° from the KCLE station.

Figure 5-4 shows the coverage height of NEXRAD with respect to the range and height. The range is represented in kilometers and the beam height is in meters. The NEXRAD beam height is calculated at 0.5° elevation angle and it will be approximately 1715 m Above Ground Level (AGL) at the marine radar location in Ottawa National Wildlife Refuge.

Figure 5-4: Beam Height coverage of NEXRAD with respect to range

Most wind turbines have a height between 100 to 300 m. Most birds also migrate close to 500 m height. There will be fewer birds at higher heights. Buler and Diehl [32] in their paper recommended the use of NEXRAD radar up to 80 km and in clear mode. Original

goal of this work was to correlate marine radar data with the NEXRAD (KCLE) data. But due to its long distance from NEXRAD location and its high beam height, it may not be very feasible to have good comparison of these two radar data sets. Moreover, NEXRAD was operating in precipitation mode at that time and date making comparison more difficult. Therefore, two other study area sites were selected for data analysis purposes. This will also allow the use of this work where any nearby NEXRAD station can be used to provide bird quantification data for possible wind turbine locations.

The study area # 2 is within the sampling area of KCLE and is near to Sandusky (Latitude: 41.4211 N, Longitude: 82.601 W). It is sited exactly at 62.0197 km towards west at an azimuthal angle of 271.09° from the KCLE station. The Study area is surrounded with land and water as shown in Figure 5-5. A study patch area for study area # 2 is also 13*13 km.

Figure 5-5: Map of Study Area 2 near to Sandusky, Ohio (From Google Earth).

Study area # 3 is about 33 km from KCLE and is near Vermilion (Latitude: 41.437 N, Longitude: 82.252 W). It is 32.9044 km towards west at an azimuthal angle of 274.92° from the KCLE station. The Study area is surrounded by land and water as shown in Figure 5-6. A study patch area for study area #3 is also 13*13 km.

Figure 5-6: Map of Study Area 3 near to Vermilion, Ohio (From Google Earth).

5.1. Study Design:

This study collected observations from the KCLE station for the night of April 27, 2011. Night data is split according to three times that are generally used by wildlife biologists and are as follows:

- ❗ Observations within an hour after sunset are considered as evening civil twilight time observations.

❗ Observations within an hour before sunrise are considered as morning civil twilight time observations.

❗ Observations in between these two timing are considered as nighttime observations.

On April 27, 2011 the evening civil twilight time was 7:48 PM and the morning civil twilight time on April 28 was 4:57 AM. The region considered for study area #1 is ranging from 108 km to 120 km with azimuthal angle ranging from 277^0 to 289^0 . The water and land has angle of 284^0 to 289^0 and 277^0 to 283^0 respectively.

The region considered for study area # 2 is from 56 km to 68 km and consists of both water and land with respect to angle from 269^0 to 277^0 and 265^0 to 268^0 respectively. The region considered for study area # 3 is from 27 km to 39 km and consists of both water and land with respect to angle from 274^0 to 281^0 and 269^0 to 273^0 respectively.

Simulation Algorithm:

The following detailed steps was used to propose a modified algorithm by incorporating image processing techniques. The proposed algorithm used base reflectivity product from one of the meteorological products of NCDC data, which was used to simulate the data on April 27, 2011. The algorithm was written in MATLAB.

- Read .png (Portable Network Graphics) format Images from a directory and folder
- Resize the images to 652*991 using MATLAB function.
- Compute Principal Component analysis for all stored images.

❗ Size of each image is 652 rows and 991 columns.

- ❗ Use for loop to read each column of the image and place it into a row. It will result in a single row of 646132 columns.
 - ❗ Use for loop to convert each image into a row of 646132 columns, the output of the loop is 133*646132. Each image is stored in a row.
 - ❗ Transpose the rows into columns and calculate mean for each column of the image.
 - ❗ Use for loop, subtract the mean from each point of the image. Compute the covariance matrix.
 - ❗ Compute Eigen values and Eigen vectors of the covariance matrix.
 - ❗ Compute adjusted value for each data point by subtracting the mean from each row in the image.
 - ❗ Compute new data for each data point set by multiplying the transposed Eigen vector to the adjusted value.
 - ❗ Resize the image to 652 by 652. The resized image is used for subtracting the background for all images.
- Apply background as resized new data set to all images.
 - Use for loop to read each column of the image and place it into a row. It will result in a single row of 646132 columns.
 - Use for loop to convert each image into a row of 646132 columns, the output of the loop is 133*646132. Each image is stored in a row.
 - ❗ Resize the images into 652*652.
 - ❗ Use for loop to subtract background using new data set from each image.
 - ❗ Apply median filtering to each image.

- ❗ Apply image segmentation to each image.
 - ❗ Apply image erosion and dilation to each image.
- Convert each image from Cartesian form into Polar form:
 - ❗ Calculate center of the pixel in each image (x_{11}, x_{12})
 - ❗ Calculate distance for each pixel from the center of the pixel.
 - ❗ Convert distance matrix to range matrix by assigning each pixel to 0.5 km.
 - ❗ Calculate azimuthal angle for each pixel using $\tan^{-1}(d_{12}/d_{11})$ and assigned each angle according to the classification of quadrants. Now the pixel location values are in the form of angles and ranges.
 - ❗ The data matrix of range and angle is transformed into pulse volume or cell matrix by assigning a spatial alignment and calculate the mean intensity values according to the assigned cell matrix. The output of the mean intensity matrix has 230 rows and 360 columns as ranges and angles respectively.
 - ❗ By using assigned threshold, use for loop to filter out the mean intensity values at each range and angle. The output is in the form of matrix with 230 rows and 360 columns.
 - ❗ Now calculate the mean intensity at each range, which implies, averaging the data values in each row. The result is in the form of matrix with 230*1 dimensions for each image.
- Compute beam area weighted mean reflectivity and Mean Vertical Profile of Reflectivity (VPR) for each image.

- ❗ Compute beam cross sectional area and beam height at each range for each image.
 - ❗ Compute beam area weighted mean reflectivity at each range for each image.
 - ❗ Compute Mean Vertical Profile of Reflectivity (VPR) at each range for each image.
 - ❗ Calculate adjustment factor at each range for each image.
 - ❗ Apply adjustment factor to the reflectivity at each range and angle.
- Quantification
 - ❗ Average the reflectivity in a row for each range in an image. It provides the averaged reflectivity according to the time period for each image. Average the reflectivity for each image in a row will provide the averaged reflectivity for entire day/night. The output is in a matrix form with the mean reflectivity according to the range.
 - ❗ To convert into bird numbers, divide the average reflectivity according to the range by a factor 10 (RCS of bird).
 - ❗ Compute volume density according to the range.
 - ❗ Calculate standard deviation and standard error.
- Quantification according to the Study area
 - ❗ Average the reflectivity values according to the required patch area. For example, if the data needs to select from Ottawa (108 to 120 km in range and 277^0 to 289^0 in angle). The mean intensity values need to extract in between these values.

- ❗ Convert the reflectivity values into bird numbers by divide the reflectivity with a factor 10 (RCS of bird).
- ❗ Compute volume density according to the range.
- ❗ Calculate standard deviation and standard error at each range.
- ❗ Similarly, division of matrix needs to be performing for land and water at a particular study area.

Following parameters are used in the simulation program:

❖ Radar Beam cross-section for each pulse volume: $\pi r^2 \theta^2$.

where r = range, $\theta = 0.95^\circ$.

❖ Beam-height at each Range using (AGL):

$$\text{Beam Height} = \sqrt{r^2 + ke * a^2 + 2 * r * ke * a * \sin \theta} - ke * a + ha$$

where r = range, $ke = 4/3$, $a = 6371$ km,

θ = elevation angle

ha = height of the antenna above ground level.

❖ To compute Bird Density in a pulse volume:

$$\text{Bird Density in a pulse volume} = \frac{\text{Reflectivity in a pulse volume}}{10}$$

❖ To compute Volume Density in a pulse volume:

$$\eta = \frac{10^3 \pi^5}{\lambda^4} |k_m|^2 Z_e$$

where, η = Radar reflectivity

λ = wavelength of the NEXRAD =10.2 cm

$k_m|^2 = 0.93$ for water (used for birds).

$$k_m = (m^2 - 1) / (m^2 + 1)$$

where m = complex refractive index of the scatters.

Z_e = Radar Reflectivity factor.

5.2. Simulation Results:

Figure 5-7 shows the average bird density (birds/km²) according to the beam height from the study area #1. It is observed that there are few birds detected in this range/height as it is far from KCLE and its beam is also too high from the ground.

Figure 5-7: Bird Density at Study Area #1

Figure 5-8 shows the average bird density according to the beam height from study area #2. It can be seen that bird migration activity is relatively higher.

Figure 5-8: Bird Density at Study Area #2, near Sandusky, Ohio

Figure 5-9 shows the bird density according to the range/height from study area #3. Usually birds start their migration during evening civil time that means birds will fly at low altitude. During evening civil twilight, the bird density is high compared to Study area #2 because of its low altitude level.

Figure 5-9: Bird Density at Study Area #3, near Vermilion, Ohio

Figures 5-10 to 5-12 show the total bird density at various times in three study areas.

Figure 5-10: Total Bird density at Study area # 1

Figure 5-11: Total Bird density at Study area # 2

Figure 5-12: Total Bird density at study Area # 3

Figures 5-13 to 5-15 show the percentage of bird density at various times in three study areas.

Figure 5-13: Percentage of Bird density at Study Area # 1

Figure 5-14: Percentage of Bird density at Study Area # 2

Figure 5-15: Percentage of Bird density at Study Area # 3

Figure 5-16 shows the bird density variation and standard error as the error plots for study area #1. The standard deviation for total bird density is 0.27735 and the standard error for total bird density is 0.076923.

Figure 5-16: Variance of Bird density at Study Area # 1

Figure 5-17 shows the bird density variation and standard error as the error plots for study area #2. The standard deviation for total bird density is 27.4151 and the standard error for total bird density is 7.0635. The standard deviation for total bird density is 11.0592 and the standard error for total bird density is 3.06729 for study area # 3 as shown in Figure 5-18.

Figure 5-17: Variance of Bird density at Study Area # 2

Figure 5-18: Variance of Bird density at Study Area # 3

Figures 5-19 to 5-24 show bird density for both land and water for three different study areas. Bird density is higher on water than land. Breakdown of bird densities on land and water may be useful for biologists.

Figure 5-19: Bird Density on Land at Study area #1

Figure 5-20: Bird Density on Water at Study area #1

Figure 5-21: Bird Density on Land at Study Area # 2

Figure 5-22: Bird Density on Water at Study Area # 2

Figure 5-23: Bird Density on Land at Study Area # 3

Figure 5-24: Bird Density on Water at Study Area # 3

Figures 5-25 to 5-27 represents the total bird density according to land and water. It can be seen that the bird density is higher on water than on land.

Figure 5-25: Total Bird Density at Study Area # 1

Figure 5-26: Total Bird Density at Study Area # 2

Figure 5-27: Total Bird density at Study Area # 3

Figures 5-28 to 5-33 show the total percentage of bird density on land and water for three study areas.

Figure 5-28: Percentage of Birds on Land at Study Area # 1

Figure 5-29: Percentage of Birds on Water at Study Area # 1

Figure 5-30: Percentage of Bird density on Land at Study Area # 2

Figure 5-31: Percentage of Bird Density on Water at Study Area # 2

Figure 5-32: Percentage of Bird Density on Land at Study Area # 3

Figure 5-33: Percentage of Bird density on Water at Study Area # 3

Figures 5-34 to 5-39 show variance of bird density according to land and water. The standard deviations and standard errors for various cases are shown in Table 5.1.

Figure 5-34: Variance of Bird Density on Land at Study Area # 1

Figure 5-35: Variance of Bird Density on Water at Study Area # 1

Figure 5-36: Variance of Bird Density on Land at Study Area # 2

Figure 5-37: Variance of Bird Density on Water at Study Area # 2

Figure 5-38: Variance of Bird Density on Land at Study Area # 3

Figure 5-39: Variance of Bird Density on Water at Study Area # 3

Table 5.1: Variation of Bird Density on Land and Water

	Variance of Bird Density on Land and Water			
	Land		Water	
	Standard Deviation	Standard Error	Standard Deviation	Standard Error
Study Area #1	0.2	0.07	0	0
Study Area #2	14.7	4.0	18.0	5.0
Study Area #3	5.5	1.5	9.2	2.6

Figures 5-40 to 5-42 show the total volume density on land and water for different study areas.

Figure 5-40: Volume Density at Study Area # 1

Figure 5-41: Volume Density at Study Area # 2

Figure 5-42: Volume Density at Study Area # 3

Figures 5-43 to 5-45 show the relationship between reflectivity observations and bird density.

Figure 5-43: Relation between NEXRAD Reflectivity and Bird Density at Study Area #1

Figure 5-44: Relation between NEXRAD Reflectivity and Bird Density at Study Area # 2

Figure 5-45: Relation between NEXRAD Reflectivity and Bird Density at Study Area # 3

Validation

Marine radar was placed in Ottawa National Wildlife Refuge (study area 1) and bird migration data was collected during spring 2011. Bird density was computed using both marine and NEXRAD nighttime data and is shown in Figure 5-46. It can be seen that there is discrepancy between these two data sets. It is due the fact that the study area happen to be far from the nearest NEXRAD station in terms of range and NEXRAD beam. The overlap between two beams is very small as shown in Figures 5-47 and 5-48.

Figure 5-46: Bird Density comparison between NEXRAD and Marine Radar at
Study area #1

Figure 5-47 : Coverage area of NEXRAD and Marine Radar signals at Study area #1

Figure 5-48 : Validation area covered by NEXRAD and Marine Radar beam

Figure 5-49 shows the correlation between NEXRAD and Marine Radar bird density observations. The factor shows the data correlation between the NEXRAD and Marine Radar observations as 0.158114.

Figure 5-49: Correlation between NEXRAD and Marine Radar Observations

Detailed Comparison between NEXRAD and Marine Radar Observations :

Bird density of both marine and NEXRAD for different periods is shown in Table 5.2.

Table 5.2: Comparison between NEXRAD and Marine Radar Observations

NEXRAD	Marine Radar
During Night, at 1693 m , 2 birds/km ²	During Night, at 1693 m , 1 bird/km ²
During evening civil time, no data present.	During evening civil time , no data present
During morning civil time, no data present.	During morning civil time, no data present.

Chapter 6

Conclusion and Future Work

The goal of the research was to provide quantification data for nightly bird migration patterns using NEXRAD. It will be a useful tool for wildlife biologists, wind turbine developers and policy makers. The work uses previously developed quantification algorithm, incorporates image processing techniques and proposes a new algorithm. The use of image-processing techniques removes clutter and can also reduce various biases in reflectivity measures. One of the reflectivity products of NCDC data is used in the proposed algorithm.

Marine radar was collecting data during 2011 bird spring migration near Ottawa National Wildlife Refuge Park. Observations from NEXRAD (KCLE) in Cleveland, Ohio were used for the same time and date. NEXRAD (KCLE) is about 114 km from marine radar site and was also operating in precipitation mode. NEXRAD data is only useful within 80 km range and operating in clear mode. There may not be one to one comparison of data of two radars as the NEXRAD beam is too high at this location, operating in precipitation mode and was farther than the 80 km the recommended range. The proposed algorithm will be useful for locations within 80 km diameter of any NEXRAD location.

This study conducted experiments on observations according to the civil twilight timings of April 27, 2011. The bird migration patterns were observed from the reflectivity data,

which is one of the base meteorological products. By using reflectivity observations, the algorithm has been designed to observe the bird migration patterns in an effective way and also reduces the bias in reflectivity measures due to operational characteristics of the radar.

The study was conducted in three main areas located towards the west of the NEXRAD KCLE Station. These three study areas have been selected with different ranges and beam heights. The Study areas#1, #2 and #3 are located approximately at 32 km, 62 km and 144 km respectively from the NEXRAD KCLE station. Compared to three study areas, the beam height is very high for study area # 1. Therefore, at this height, the bird migration is very low when compared with other study areas. In study area #1, NEXRAD observations were compared with the Marine Radar observations. The research can be extended to include velocity and spectral width data. It will be useful for comparing quantification bird migration data with any radar operating within recommended 80 km range. The proposed algorithm effectively quantifies bird measure, reduces clutter and computation time.

Future Work:

Perform comparison study between marine radar and NEXRAD data with marine radar is within 80 km range of NEXRAD. NEXRAD should be operating in clear mode. Study MATLAB code and make it computationally more efficient by stream lining various matrix operations. The study can also be extended for comparison with C-band radars operating in Europe and Canada.

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