Curriculum Materials for an Interdisciplinary Program on Multi-Function Radar

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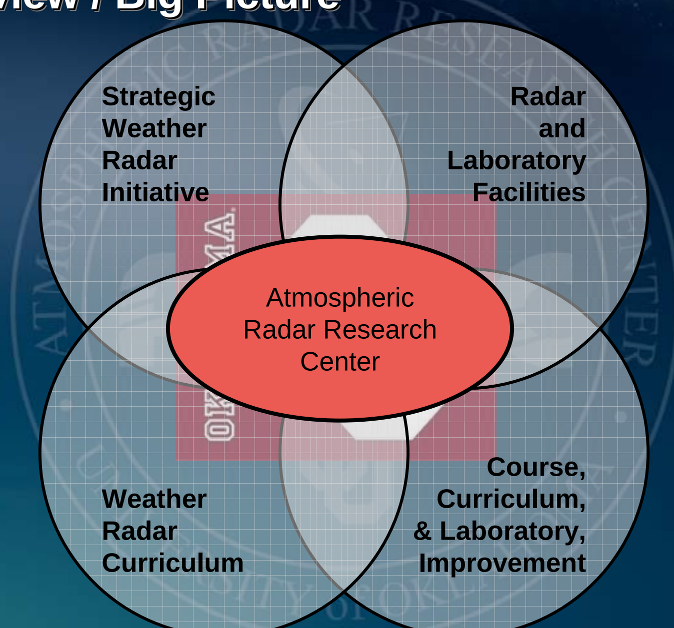
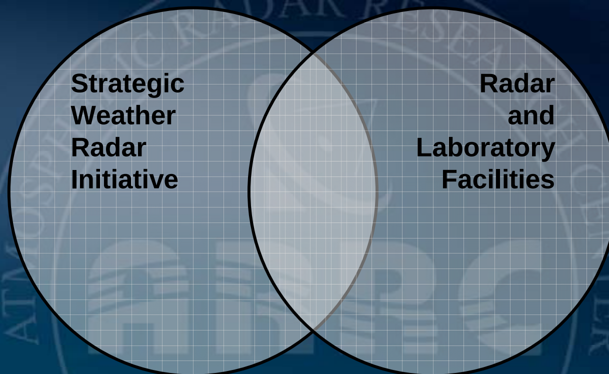
Overview / Big Picture





10 new faculty lines … so far

Name	Current Title	Department	Start Year
Mark Year	Assoc. Professor	Elect. Comp. Eng.	2002
Tian-You Yu	Assoc. Professor	Elect. Comp. Eng.	2002
Rovert Palmer	Professor	Meteorology	2004
Amy McGovern	Asst. Professor	Computer Science	2005
Phillip Chilson	Assoc. Professor	Meteorology	2005
Guifu Zhang	Assoc. Professor	Meteorology	2005
Yan Zhang	Asst. Professor	Elect. Comp. Eng.	2007
Yang Hong	Assoc. Professor	Civil Eng. & Env. Sci.	2007
Chris Weaver	Asst. Professor	Computer Science	2008
Xuguang Wang	Asst. Professor	Meteorology	2009

Laboratory Facilities: Current & Planned

Radar Innovations Lab (RIL)

- $1.3M value of test equipment and software
- Up to 50 GHz test and fabrication capability
- Shielded screen room and EM chamber
- Dedicated to radar technology R&D

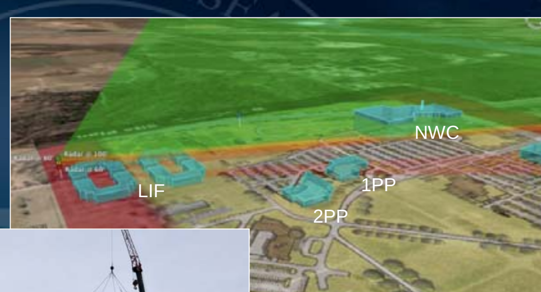
Electromagnetics & Microphysics Lab (EML)

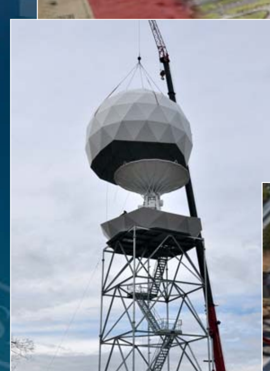
- Need for an environmentally controlled anechoic chamber to perform scattering experiments – *unique in the world!*
- Development of innovative radar designs – polarimetric phased arrays, passive radar, cognitive radar
- Polarimetric radar signatures of man-made (e.g., wind turbines) and natural hydrometeors
- In-door measurements to verify out-door in-situ measurem

OU-PRIME

Polarimetric Radar for Innovations in Meteorology and Engineering

- Operates on OU's Research Campus
- C-band, 1 MW peak power
- 0.5 degree beamwidth
- Flexible design for student projects
- Platform for advanced signal processing and hardware innovations





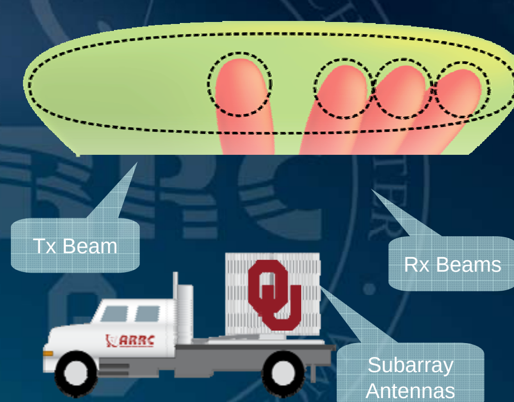
Phased Array Radar (PAR)

Operated by NSSL on North Campus. Integral component of radar class projects and NSF CCLI grants.

Atmospheric Imaging Radar (AIR)

Next Generation of Remote Sensing

- Mobile imaging radar for weather sensing
- Built by students in the ARRC
- Ideal for situations that require high temporal resolution… tornadogenesis
- Digital Beam Forming (DBF) techniques allow for high-speed data collection while maintaining spatial resolution of conventional radars



TUTOR (proposal pending)

- Designed by students during capstone experience
- Expanded design for education
- Mobile classroom facilities
- Reconfigurable for student projects/classes

Weather Radar Curriculum

Over-Arching Educational Goals

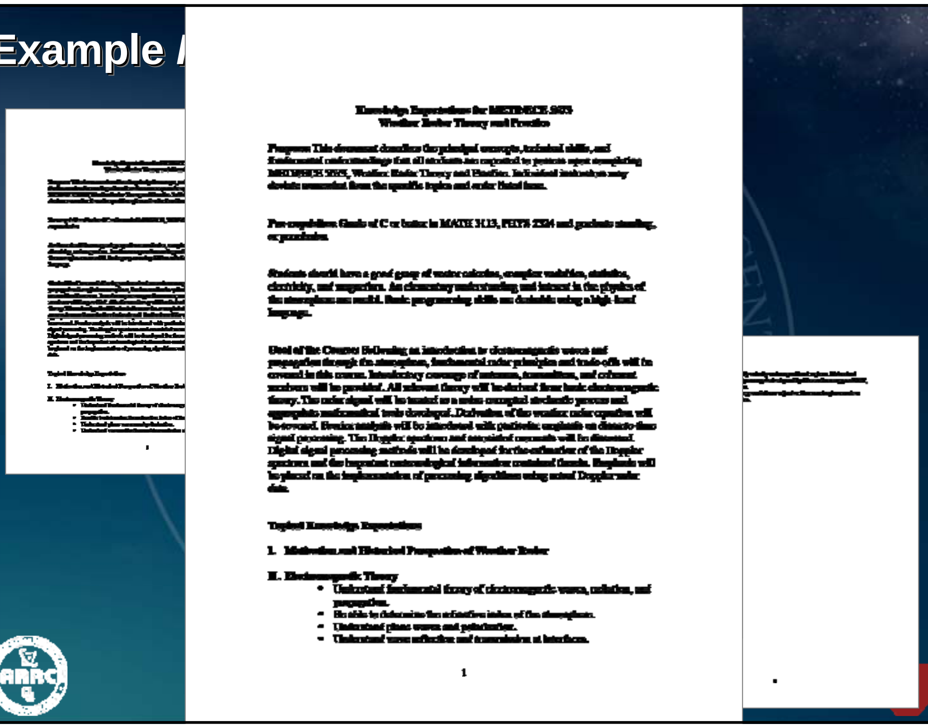
- Provide a comprehensive interdisciplinary education in both the theoretical and practical aspects of radar meteorology at both undergraduate and graduate levels
- Combine talents of faculty in School of Meteorology, School of Electrical/Computer Engineering, and local Norman scientists
- Extensive hands-on experience for students

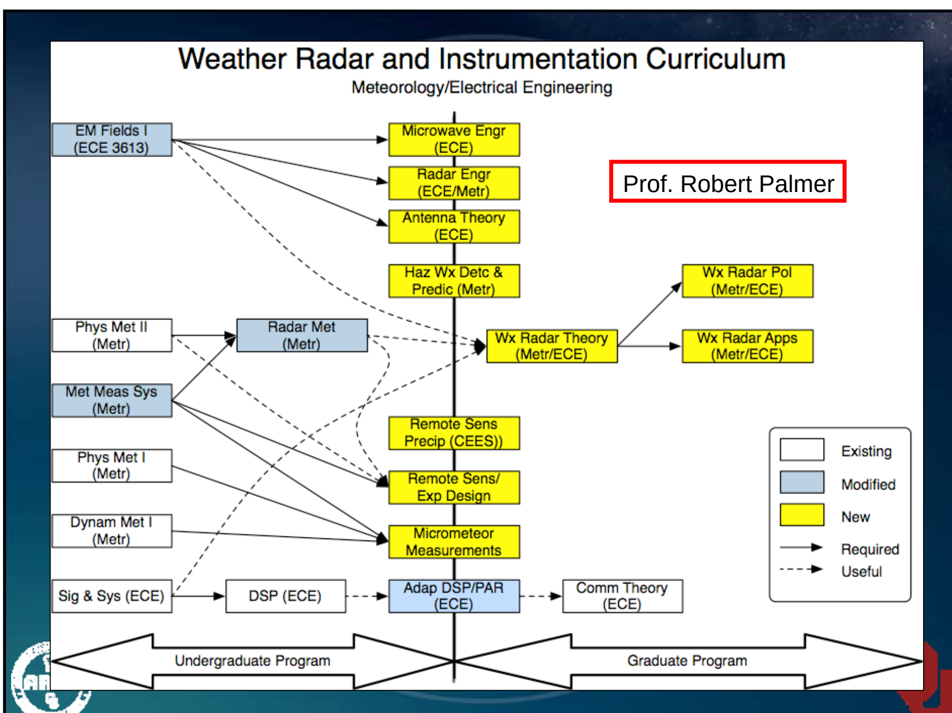
Design of *Knowledge Expectations*

- **Started with *clean slate (Fall 04)***
  - 1 existing Radar Meteorology course (SoM)
  - 1 existing Weather Radar Signal Processing course (ECE)
- **Assessed backgrounds of prospective students (Meteorology and ECE)**
  - Mathematics same (DEQ + 1)
  - Physics same
  - ECE students need basic physical meteorology
  - Meteorology students need electromagnetics and signal processing
- **Fundamental Question:**

What should an expert in weather radar know?

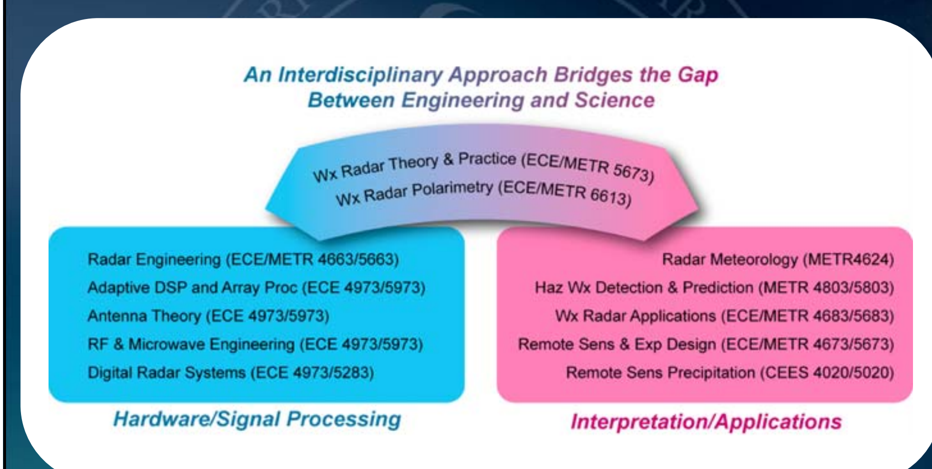
Example /




Weather Radar and Instrumentation Curriculum
Meteorology/Electrical Engineering
EM Fields I (ECE 3613)
Microwave Engr (ECE)
Radar Engr (ECE/Metr)
Antenna Theory (ECE)
Prof. Robert Palmer
Haz Wx Detc & Predic (Metr)
Wx Radar Pol (Metr/ECE)
Phys Met II (Metr)
Radar Met (Metr)
Wx Radar Theory (Metr/ECE)
Wx Radar Apps (Metr/ECE)
Met Meas Sys (Metr)
Remote Sens Precip (CEES))
Phys Met I (Metr)
Remote Sens/ Exp Design
Dynam Met I (Metr)
Micrometeor Measurements
Sig & Sys (ECE)
DSP (ECE)
Adap DSP/PAR (ECE)
Comm Theory (ECE)
Existing
Modified
New
Required
Useful
Undergraduate Program
Graduate Program

Course List … evolving with time

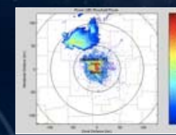
Course Name	Course #	Department	Semester
Weather Radar Theory and Practice	4673/5673	ECE/METR	Fall
Digital Radar Systems	4973/5283	ECE	Fall
Adaptive Digital Signal and Array Processing	4973/5283	ECE	Fall
Weather Radar Polarimetry	6613	ECE/METR	Fall
Radar Meteorology	4624	METR	Spring
Radar Engineering	4663/5663	ECE/METR	Spring
Hazardous Weather Detection and Prediction	4803	METR	Spring
RF and Microwave Engineering	4973/5973	ECE/METR	Spring
Weather Radar Applications	5683	ECE/METR	Spring
Antennas	5973	ECE	Spring
Remote Sensing of Precipitation	5020	CEES	Spring

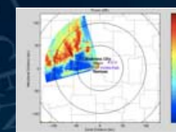


Example Course

Weather Radar Theory & Practice (METR/ECE 4673/5673)

- Motivation and Historical Perspective
- Electromagnetic Waves and Propagation - *introduction to basic physical meteorology*
- Weather Radar Design Principles
- Signal Statistics and Weather Radar Equation - *introduction to random processes*
- Doppler Spectra of Weather Signals - *introduction of Fourier theory*
- Doppler Moment Estimation - Time & Frequency Domain
- Techniques for Improved Data Quality





This graduate-only course has had significant interest from students: Fall 05 (25 met, 5 ECE), Fall 06 (11 met, 9 ECE), Fall 07 (8 met, 9 ECE, 1 CEES), Fall 08 (8 met, 10 ECE)

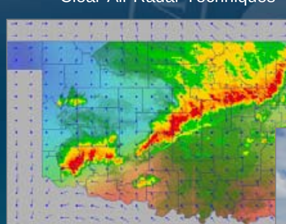
Emphasize interdisciplinary team projects using raw radar data

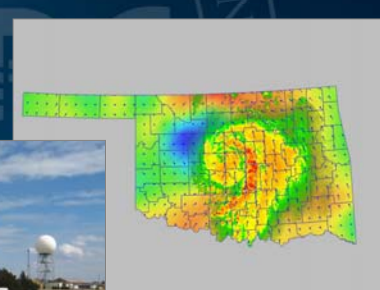
Example Course

Weather Radar Applications (METR/ECE 5683)

- Background and Review of Radio-wave Scatter
- Principles of Precipitation Measurements with Radar
- Basics of Radar Polarimetry
- Wind Measurements with Doppler Radar
- Higher-Level Radar Products
- Weather Radar and Meteorological Data Visualization
- Clear-Air Radar Techniques

Students engage in theoretical and programming based assignments using actual radar observations and pursue an independent radar related research project, which results in a paper and oral presentation.



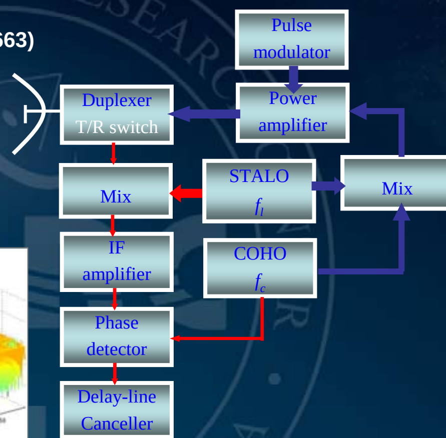


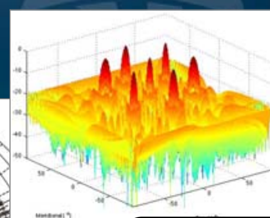
Example Course

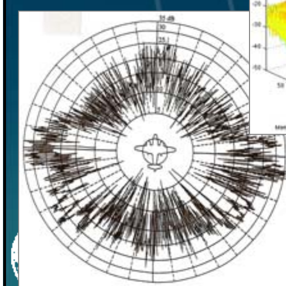
Radar Engineering (ECE 4663/5663, METR 5663)

An Introduction to Radar
The Radar Equation
Phased Array Radar
MTI and Pulse Doppler Radar
Detection of Signals in Noise
☐Information from Radar Signals

Tracking Radar







The course introduces various radar system designs and their applications. Radar system architecture and the functionalities and limitations of subsystems are discussed. Existing technologies and advanced techniques to improve radar performance are provided. Hands-on projects are designed enhance student's learning experience.

Active Integration with NOAA Partners

During the 2005 - 2008 academic years our students within OU's Weather Radar Program have received extensive lectures from:

Dick Doviak (NSSL)
Alexander Ryzhkov (CIMMS/NSSL)
Sebastian Torres (CIMMS/NSSL)
Rich Ice (ROC)
Kurt Hondl (NSSL)
Terry Schurr (CIMMS/NSSL)

NSSL: National Severe Storms Laboratory (NOAA)
ROC: Radar Operations Center (NOAA)
CIMMS: Cooperative Institute of Mesoscale Meteorological Studies

Student Feedback

Meteorology Graduate Student

"I think that the curriculum provides a solid foundation for those students who want to use radar to further meteorological research. I do think that it covers a broad swath of topics that are appropriately geared towards current research and does prepare the student well for a career in this area whether in the public or private sector… In all, I believe that the curriculum has provided me the tools to be successful in the job market."

Electrical Engineering Graduate Student

"From the perspective of a current electrical engineering student in this program, this curriculum provides a balanced study of both fields without compromising the science and fundamental knowledge of either one. Additionally, this curriculum graduates students with the skill to communicate the needs between meteorologists and radar engineers that cannot be obtained anywhere else."

Meteorology Graduate Student

"OU's Weather Radar Curriculum has opened my eyes to a wide field of weather radar technologies and techniques that I had no idea existed before I started. This curriculum combined with my exposure to the variety of radar research projects that are ongoing here will no doubt prove invaluable in my future job search."

Course, Curriculum, & Laboratory, Improvement

Course, Curriculum, and Laboratory Improvement (CCLI)

University of Oklahoma
School of Meteorology &
School of Electrical and Computer Engineering

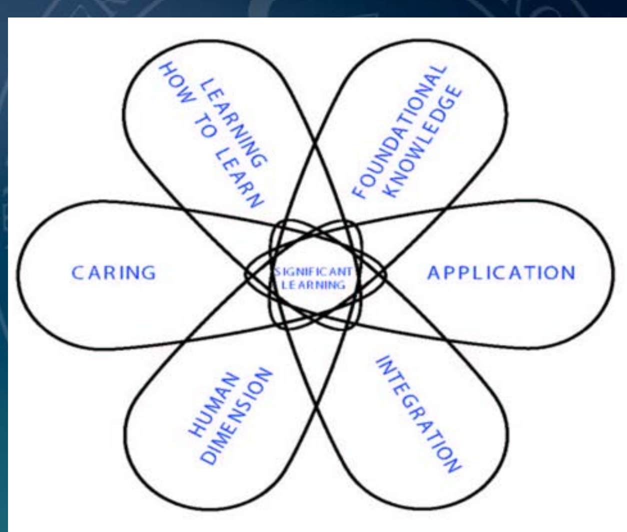
NSF CCLI Phase I
Hands-On Interdisciplinary Laboratory Program: An Approach to Strengthen the Weather Radar Curriculum

NSF CCLI Phase II
MOVING TO THE NEXT LEVEL: Refining and Disseminating a Pedagogical Taxonomy and Hands-On Curriculum
Materials for an Interdisciplinary Program and Multi-Function Weather

Prof. Mark Yeary (PI)

Taxonomy of Significant Learning

Creating Significant Learning Experiences:
An Integrated Approach to Designing College Courses
L. Dee Fink, 2003



Learning Modules

Learning Objectives:

- Retrieving and analyzing weather radar data is crucial to accurately predicting everyday weather and natural disasters such as tornadoes and supercell storms.
- Modules are used in the 11 weather radar classes at OU. In general, the modules may be used in a stand alone basis.
- The modules use data that are available for downloading with each module.
- Explore the utility of incorporating alternate data sources into your weather radar analysis.
- The modules appear below:

Engineering ← *Science/Physics/Computing* → *Meteorology*

	Radar Hardware	Weather Radar	Adaptive Systems	Advanced Hydrometeors	Weather Radar Applications	Atmospheric Interpretations
Beginning Sequence	Module 1	Modules 2,3				Module 4
Intermediate Sequence	Module 5	Module 6	Module 7	Module 8	Module 9	Module 10
Advanced Sequence	Modules 11,12	Module 13	Modules 14,15	Module 16	Module 17	

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1. Phased Array Antennas

- Learn about antenna patterns for linear and phased arrays
- Design trade-offs (beamwidth, sidelobes, etc.)
- SPY-1A antenna study

Phased Array Antenna

1 Learning Objectives:

- *Students will learn about the antenna pattern for linear and planar phased array.*
- *Students will learn about the design of linear array antenna (uniform and non-uniform spacing, aperture, and tapering function)*
- *Students will learn about the tradeoff in the design of linear array antenna (mainlobe beamwidth, sidelobe level, and grating lobes).*
- *Students will learn about the SPY-1A Phased Array Radar on the OU north campus.*

2 Introduction

A phased array antenna is a directive antenna made of a number of individual radiation element. It can steer the radar beam electronically by varying the phase of each element for both transmission and receiving. Electronically steered phased array radar was developed in mid-1960s mainly for military applications. It has the capability of instantaneously and adaptively controlling beam position on a pulse-to-pulse basis, which allows a single radar to perform multiple tasks such as surveillance, target tracking, and weapon controls.

In this module, we will learn and exercise the fundamental of phased array antenna. The antenna pattern is defined by the product of array factor and element factor. Here we assume that each element is isotropic to simply the problem. The electrical field produced by a number of sub-array and pointing at $\mathbf{a}_0$ can be obtained by the following equation.

$$E(\theta_x, \theta_y) = \sum_{n=0}^{N-1} w(n) e^{jk(\mathbf{a}_r - \mathbf{a}_0)\cdot \mathbf{d}_n} \quad (1)$$

where $w(n)$ is the tapering function, $k = 2\pi/\lambda$ is the wavenumber, $\mathbf{d}_n = \mathbf{a}_x d_{nx} + \mathbf{a}_y d_{ny} + \mathbf{a}_z d_{nz}$ is the location of the nth sub-array, $\mathbf{a}_r = \mathbf{a}_x \sin\theta\cos\phi + \mathbf{a}_y \sin\theta\sin\phi + \mathbf{a}_z \cos\theta$ is the angular location where $E(\theta_x, \theta_y)$ to be calculated, and $\theta_x = \sin\theta\cos\phi$, $\theta_y = \sin\theta\sin\phi$, $\theta_z = \cos\theta$. The array factor is obtained by $|E(\theta_x, \theta_y)|^2$. Note the general representation of (1) can be applied to both 2D and 1D array. It is suggested to use this equation for the following hands-on activities.

3 Hands-On Activities

You are required to write computer codes to plot the antenna pattern and analyze the results. You should turn in your code, discussions of the results, and figures. Proper labels

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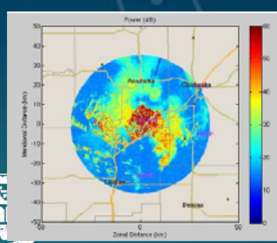
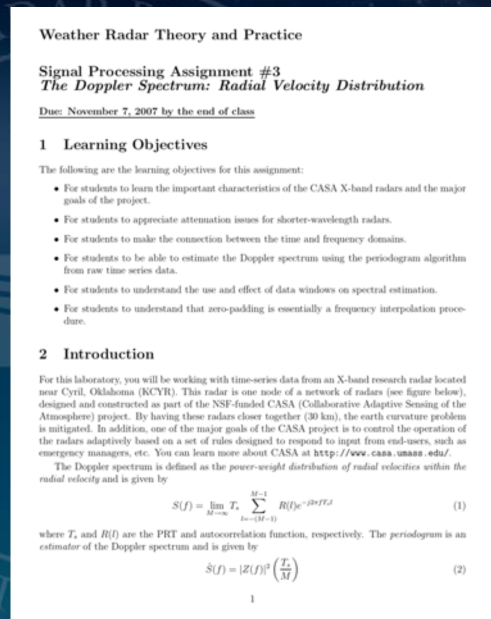
2. Doppler Spectrum

- Compute Doppler spectra
- Understand zero-padding and windowing





Weather Radar Theory and Practice

Signal Processing Assignment #3
The Doppler Spectrum: Radial Velocity Distribution

Due: November 7, 2007 by the end of class

1 Learning Objectives

The following are the learning objectives for this assignment:

- For students to learn the important characteristics of the CASA X-band radars and the major goals of the project.
- For students to appreciate attenuation issues for shorter-wavelength radars.
- For students to make the connection between the time and frequency domains.
- For students to be able to estimate the Doppler spectrum using the periodogram algorithm from raw time series data.
- For students to understand the use and effect of data windows on spectral estimation.
- For students to understand that zero-padding is essentially a frequency interpolation procedure.

2 Introduction

For this laboratory, you will be working with time-series data from an X-band research radar located near Cyril, Oklahoma (KCYR). This radar is one node of a network of radars (see figure below), designed and constructed as part of the NSF-funded CASA (Collaborative Adaptive Sensing of the Atmosphere) project. By having these radars closer together (30 km), the earth curvature problem is mitigated. In addition, one of the major goals of the CASA project is to control the operation of the radars adaptively based on a set of rules designed to respond to input from end-users, such as emergency managers, etc. You can learn more about CASA at `http://www.casa.umass.edu/`.

The Doppler spectrum is defined as the *power-weight distribution of radial velocities within the radial velocity* and is given by

$$S(f) = \lim_{M\to\infty} T_s \sum_{l=-(M-1)}^{M-1} R(l) e^{-j2\pi f T_s l} \qquad (1)$$

where T_s and $R(l)$ are the PRT and autocorrelation function, respectively. The *periodogram* is an *estimator* of the Doppler spectrum and is given by

$$\hat{S}(f) = |Z(f)|^2 \left(\frac{T_s}{M}\right) \qquad (2)$$

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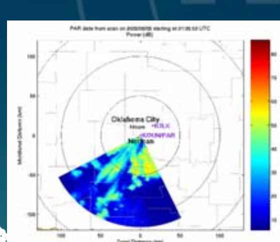
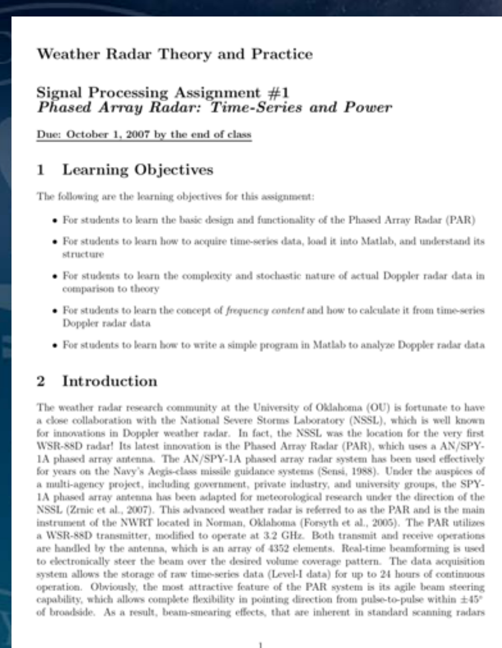
3. Time Series & Power

- Learn about I & Q data and how to compute the power and Doppler velocity.





Weather Radar Theory and Practice

Signal Processing Assignment #1
Phased Array Radar: Time-Series and Power

Due: October 1, 2007 by the end of class

1 Learning Objectives

The following are the learning objectives for this assignment:

- For students to learn the basic design and functionality of the Phased Array Radar (PAR)
- For students to learn how to acquire time-series data, load it into Matlab, and understand its structure
- For students to learn the complexity and stochastic nature of actual Doppler radar data in comparison to theory
- For students to learn the concept of *frequency content* and how to calculate it from time-series Doppler radar data
- For students to learn how to write a simple program in Matlab to analyze Doppler radar data

2 Introduction

The weather radar research community at the University of Oklahoma (OU) is fortunate to have a close collaboration with the National Severe Storms Laboratory (NSSL), which is well known for innovations in Doppler weather radar. In fact, the NSSL was the location for the very first WSR-88D radar! Its latest innovation is the Phased Array Radar (PAR), which uses a AN/SPY-1A phased array antenna. The AN/SPY-1A phased array radar system has been used effectively for years on the Navy's *Aegis*-class missile guidance systems (Sensi, 1988). Under the auspices of a multi-agency project, including government, private industry, and university groups, the SPY-1A phased array antenna has been adapted for meteorological research under the direction of the NSSL (Zrnic et al., 2007). This advanced weather radar is referred to as the PAR and is the main instrument of the NWRT located in Norman, Oklahoma (Forsyth et al., 2005). The PAR utilizes a WSR-88D transmitter, modified to operate at 3.2 GHz. Both transmit and receive operations are handled by the antenna, which is an array of 4352 elements. Real-time beamforming is used to electronically steer the beam over the desired volume coverage pattern. The data acquisition system allows the storage of raw time-series data (Level-I data) for up to 24 hours of continuous operation. Obviously, the most attractive feature of the PAR system is its agile beam steering capability, which allows complete flexibility in pointing direction from pulse-to-pulse within ±45° of broadside. As a result, beam-smearing effects, that are inherent in standard scanning radars

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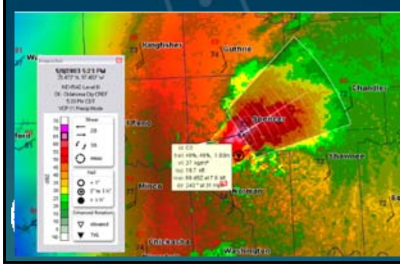
4. Visualization of WX data

- Learn about WeatherScope and the NCDC Java Viewer
- Plot WX data at specific locations



Visualization and processing of weather radar data

1 Learning Objectives

The following are the learning objectives for this assignment:

- Learn how to request and retrieve NEXRAD data from the NCDC data server
- Use the NCDC Java NEXRAD Viewer to display NEXRAD data
- Familiarize yourself with the WeatherScope GUI and how to plot multiple fields on one map.
- Explore the utility of incorporating alternate data sources into your weather radar analysis

2 Introduction

Data from the network of WSR-88D weather surveillance radars (NEXRAD) operated by NOAA are available from the National Climate Data Center (NCDC). These data are provided in Level II and Level III formats. Basically, Level II data contain the radar moments (reflectivity, radial velocity, and spectrum width) contained on a coordinate grid consistent with the particular volume coverage pattern (VCP) used for data collection. Level III data are processed products, which can be displayed as images. For more information see:
http://www.ncdc.noaa.gov/oa/radar/radarresources.html.
The data are stored in a NEXRAD Information Dissemination Service (NIDS) format. Visualization software are available and two of these are described below.

2.1 WeatherScope

The WeatherScope program, written and distributed by the Oklahoma Climatological Survey (http://climate.ok.gov/software) provides a user-friendly, cross-platform framework for the visualization of meteorological data. It is also highly customizable, allowing users to generate datasets for their own needs for use inside of the program.

Installing WeatherScope
Inside a web browser, visit the address listed above and you will see two software packages available for download. The WxScope Plugin allows you to view animations of Oklahoma Mesonet data inside your browser window, but is not necessary for the operation of WeatherScope itself. Select the platform on which you desire to install the program, and the download will begin immediately (.dmg file for Macintosh, .exe file for Windows). **Note**: WeatherScope is not currently available for UNIX/Linux distributions. If you do not have access to either a Mac or a Windows PC, the student computer lab on the 5th floor has WeatherScope installed already.

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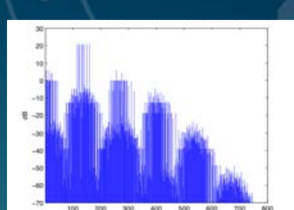
5. Intermods

- Learn about compressive amplifiers
- Compute location and strength of intermodulation products
- Use measured lab data



Intermodulation Product Computing Techniques for Broadband Active Transmit Systems

1 Learning Objectives

- From downloadable laboratory data, students will learn about compressive amplifiers for use in wideband systems.
- Students will learn about intermodulation products, harmonics, and fundamentals.
- Students will learn how to model an amplifier based on collected laboratory data.
- Students will learn about the discrete Fourier transform and its fast Fourier transform (FFT) implementation.
- Parseval's Theorem will be explored to determine the power of a signal in the time and frequency domains.

2 Introduction

The determination of intermodulation products is an ever pervasive problem to the radar and satellite community – its eminence will continue to manifest itself as data rates increase, as transmitters are required to handle increasing numbers of multiple carriers, and as amplifiers are pushed to operate closer to their non-linear regions (to circumvent the need of adding the extra weight and cost of a more linear amplifier). To study the intermodulation effects, FFT-based techniques are often employed. By definition, $\Delta = F_s/N$ defines the frequency resolution for the discrete Fourier transform. It is typically desired to design Δ to be as small as possible, to allow for a very fine frequency resolution. Doing this requires that F_s be minimized and/or N be selected as large as possible.

As reported in the literature, the ability to determine the amplitude and location of intermodulation products is of prime importance. Non-linear amplifiers lead to the generation of unwanted signal components that are mathematically related to the frequencies of input signals. It takes at least two tones at unique frequencies to generate these unwanted frequency components, known as intermodulation products. A few moments are taken here to visit the classic two-tone test; that is, when the input signal is defined by $v(t) = \cos(\omega_1 t) + \cos(\omega_2 t)$. The first order products are known as the frequencies of the original signals. The second order products are known as the second harmonics $\omega_1 + \omega_1$ and $\omega_2 + \omega_2$, and the sum and difference terms, $\omega_1 + \omega_2$, $\omega_2 + \omega_1$, $\omega_1 - \omega_2$, $\omega_2 - \omega_1$. The DC-terms $\omega_1 - \omega_1$ and $\omega_2 - \omega_2$ from the second-order distortions should be included in the list. The third order products are numerous, but the most vexing ones are the ones that occur close to or within the specified bandwidth of the transmission channel, since they are extremely tedious to remove by filtering and these are: $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$. Continuing in a similar fashion, higher order products do exist.

In a gem of a paper, Hemmi explored the intermodulation product calculation problem oriented around the classic non-linear amplifier studies of Ha [5], but only considered the effects of a third order system [1]. Moreover, the upper bound of this work considered only exploring two tones. In his paper [3], Real also applied third order models to study the occurrence of intermodulation frequencies which result from amplifier non-linearities, but with more emphasis on

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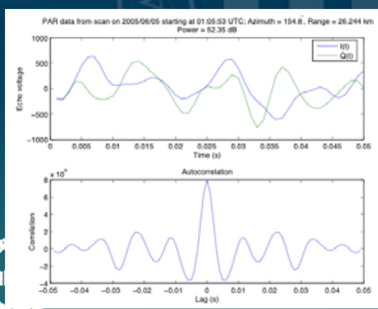
6. Reflectivity & Statistical Properties

- The radar equation and reflectivity factor
- Simple rainfall estimates
- Correlation sequences and PDFs.



Weather Radar Theory and Practice

Signal Processing Assignment #2
Reflectivity Factor and Statistical Properties of Weather Radar Data

Due: October 31, 2007 by the end of class

1 Learning Objectives

The following are the learning objectives for this assignment:

- For students to learn how *reflectivity factor* relates to received radar power.
- For students to learn how to conduct a rudimentary radar calibration.
- For students to learn the challenges of using reflectivity factor for estimation of rainfall rate and its associated uncertainties.
- For students to investigate the statistical characteristics of weather radar signals, including probability density functions and correlation structure.

2 Introduction

The *Weather Radar Equation* describes the relationship between transmitted power of the radar and the expected returned power, under certain assumptions. Given this equation, it is possible to design radar characteristics to obtain particular levels of sensitivity. The weather radar equation is given by

$$E[P_r] = \frac{P_t g^2 \lambda^2 \eta c \tau \pi \theta_1^2}{(4\pi)^3 r^2 l^2 16 \ln 2} \quad (1)$$

where P_t, g, η, τ, θ_1, and l are the transmit power, antenna gain, reflectivity, pulse length, beamwidth, and loss factor, respectively. One of the more important parameters is the reflectivity, which is given by

$$\eta = \frac{\pi^5}{\lambda^4}|K_w|^2 \int_0^\infty D^6 N(D)\, dD \quad (2)$$

where $N(D)$ is the dropsize distribution and K_w is the complex dielectric factor of water. The integral factor is defined as the *Reflectivity Factor*

$$Z = \int_0^\infty D^6 N(D)\, dD \quad (3)$$

and is usually given in units of dBZ relative to 1 $mm^6\ m^{-3}$. Z can vary from negative values to as high as 60 dBZ for large hail.

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7. NN for Tornado Detection

- Learn about the LMS algorithm and neural networks
- Network design via Matlab toolbox
- Tornado detection

Adaptive Pattern Recognition for Tornado Detection

1 Learning Objectives:

- *Students will learn how to develop a simple three layer neural network consisting of: a two node input layer, a one node output layer, and a hidden layer that connects the two and is governed by the least mean squares (LMS) algorithm. From these principles, Matlab's neural network toolbox will then be used to design meaningful, large-scale neural networks for realistic weather radar data senarios.*
- *Students will learn about the features need to detect a tornado using Level I data, which differs from conventional Level II techniques. The broad and flat spectra of the Level I data will be explored.*
- *Students will train a large-scale neural network to recognize the broad and flat Doppler spectrum associated with tornadoes. The students will examine a diverse class of artificial neural networks for the most efficient candidate. To do this, the students will look at their architecture, choice of kernel, training time, and the generalization ability of the classifier (how well it responds to new inputs).*

2 Introduction

Enhanced tornado detection and tracking can prevent loss of life and property damage. The research WSR-88D (weather surveillance radar) locally operated by the National Severe Storms Laboratory (NSSL) in Norman has the unique capability of collecting massive volumes of time series data over many hours which provides a rich environment for evaluating new post-processing algorithms. With the advent of more memory and computing power, new state-of-the-art algorithms can be explored. In this laboratory, an approach of identifying tornado vortices in Doppler spectra is proposed and investigated through the use of neural networks. Once the coordinates of the tornado has been established, the research question becomes: how can students apply target tracking algorithms to a volume of radar data to make estimations about where the tornado is going?

2.1 Remote Sensing: the Weather Surveillance Radar

About one-third of the nation's $10 trillion economy is sensitive to climate variability and weather [1–3]. Networked remote sensor systems, such as the ubiquitous WSR-88D (Weather Surveillance Radar - 1988 Doppler) in Figure 1, comprise the approximately 150 weather radars in the continental U.S. that are in a national network to provide the bulk of the nation's weather information [4,5]. The research WSR-88D (known as KOUN within the national network) operated by the National Severe Storms Laboratory in Norman has the unique capability of collecting massive volumes of Level I time series data over many hours. A unique feature of the KOUN is that it has a dual polarization capability and hence the two receivers. It can change modes from dual to single polarization. It should also be mentioned that there are 47 more terminal Doppler

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8. Scattering RCS

- Learn about radio wave scattering, absorption, and WX radar cross sections.
- Rayleigh and Mie regimes

Rayleigh & Mie scattering cross section calculations and implications for weather radar observations

1 Learning Objectives

The following are the learning objectives for this assignment:

- Familiarize yourself with some basic concepts related to radio wave scattering, absorption, and radar cross sections
- Become acquainted with some of the fundamental definitions and foundations connected with the Mie theory
- Explore under what conditions the Rayleigh approximation can be applied and to what extent it accurately represents radio wave scatter and absorption
- Study the dependence of various radar cross sections on wavelength and temperature

2 Introduction

As electromagnetic radiation propagates though our atmosphere, it interacts with air molecules, dust particles, water vapor, rain, ice particles, insects, and a host of other entities. These interactions result primarily in the form of scatter and absorption, both of which are important for remote sensing studies of the atmosphere. Typically, the degree to which a "target" can scatter or absorb electromagnetic radiation is described through its cross section σ. When a target is illuminated by a wave having a power density (irradiance) given by S_i, it will scatter/absorb a portion of the wave. The cross section represents an apparent area, used to describe by what amount the radiation interacts with the target. An observer located at a particular location (described by θ and ϕ with respect to the wave's propagation vector) will be detect radiation scattered by the target with a power density given by by S_r. Assuming that the target has scattered the incident electromagnetic radiation *isotropically*, then the cross section σ can be directly calculated using

$$\sigma(\theta,\phi) = 4\pi r^2 \frac{S_r(\theta,\phi)}{S_i}, \quad (1)$$

where r is the distance between the target and the observer. In general, the scattering cross section will depend the angles θ and ϕ. That is, the scatter is not truly isotropic. Also note that the value of σ does not in general correspond to the geometric cross section of the target.

Here we will consider four different types of cross sections, which are commonly used in connection with radar. They are the scattering cross section σ_s, the extinction cross section σ_e, the absorption cross section σ_a, and the backscattering cross section σ_b. The scattering cross section multiplied by the power density of the incident wave is equivalent to total amount of energy

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9. Z-R Relationships

- Learn about single parameter rainfall estimation
- Z-R relationships for different regions
- Comparison to ground truth

Z-R Relationships

Weather Radar Applications
ECE / METR 5683
Spring 2008
Prof. Chilson

1 Learning Objectives

The following are the learning objectives for this assignment:

- Learn how NEXRAD data stored in the NIDS format can be converted to the popular netCDF data format.
- Familiarize yourself with the netCDF data format and how it is manipulated.
- Discover how netCDF data can be imported into MATLAB
- Explore and understand the errors and benefits associated with single-parameter rainfall estimation.

2 Introduction

Remote measurement of the rainfall rate R is of considerable practical interest. For many years meteorologists have attempted to find a useful relation between the radar reflectivity factor Z and the rainfall rate R. Unfortunately, there is no single relation that can satisfy all meteorological phenomena - Battan (1973) lists no fewer than 69 separate $Z-R$ relationships that have been proposed by various investigators. More importantly, observed drop size distributions, of which both Z and R are functions, can be expressed in an indefinite number of parameters. Single-parameter measurement of rainfall constrains the DSD to one free parameter, which may vary strongly in both space and time, and as a result most $Z-R$ relationships are expressed as a power law:

$$Z = aR^b \quad (1)$$

in which Z is expressed in linear units (mm^6 m^{-3}) and R is in mm hr^{-1}.

Your task is to investigate the appropriateness (or lack thereof) of various $Z-R$ relations which are implemented for the WSR-88D network. You will also begin to familiarize yourself with the netCDF data format, which is widely used in scientific applications because of its ability to embed metadata into the file itself, and its ease of integration with MATLAB. Finally, the WeatherScope

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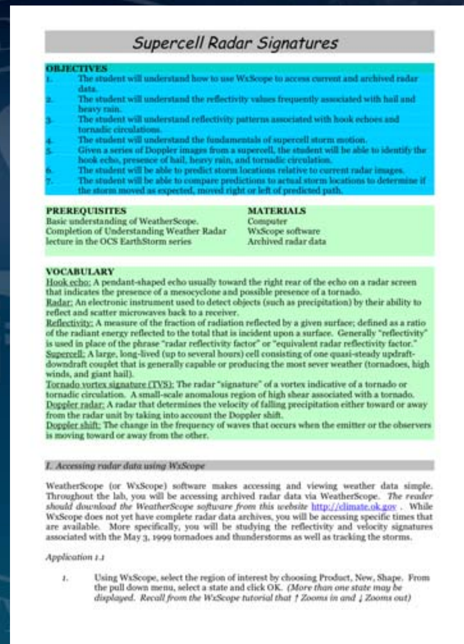
10. Supercell Signatures

- WeatherScope and the NCDC Java Viewer
- Hail, heavy rain and radar reflectivities



Supercell Radar Signatures

OBJECTIVES

1. The student will understand how to use WxScope to access current and archived radar data.
2. The student will understand the reflectivity values frequently associated with hail and heavy rain.
3. The student will understand reflectivity patterns associated with hook echoes and tornadic circulations.
4. The student will understand the fundamentals of supercell storm motion.
5. Given a series of Doppler images from a supercell, the student will be able to identify the hook echo, presence of hail, heavy rain, and tornadic circulation.
6. The student will be able to predict storm locations relative to current radar images.
7. The student will be able to compare predictions to actual storm locations to determine if the storm moved as expected, moved right or left of predicted path.

PREREQUISITES
Basic understanding of WeatherScope.
Completion of Understanding Weather Radar lecture in the OCS EarthStorm series

MATERIALS
Computer
WxScope software
Archived radar data

VOCABULARY
Hook echo: A pendant-shaped echo usually toward the right rear of the echo on a radar screen that indicates the presence of a mesocyclone and possible presence of a tornado.
Radar: An electronic instrument used to detect objects (such as precipitation) by their ability to reflect and scatter microwaves back to a receiver.
Reflectivity: A measure of the fraction of radiation reflected by a given surface; defined as a ratio of the radiant energy reflected to the total that is incident upon a surface. Generally "reflectivity" is used in place of the phrase "radar reflectivity factor" or "equivalent radar reflectivity factor."
Supercell: A large, long-lived (up to several hours) cell consisting of one quasi-steady updraft-downdraft couplet that is generally capable or producing the most sever weather (tornadoes, high winds, and giant hail).
Tornado vortex signature (TVS): The radar "signature" of a vortex indicative of a tornado or tornadic circulation. A small-scale anomalous region of high shear associated with a tornado.
Doppler radar: A radar that determines the velocity of falling precipitation either toward or away from the radar unit by taking into account the Doppler shift.
Doppler shift: The change in the frequency of waves that occurs when the emitter or the observers is moving toward or away from the other.

I. Accessing radar data using WxScope

WeatherScope (or WxScope) software makes accessing and viewing weather data simple. Throughout the lab, you will be accessing archived radar data via WeatherScope. *The reader should download the WeatherScope software from this website* http://climate.ok.gov . While WxScope does not yet have complete radar data archives, you will be accessing specific times that are available. More specifically, you will be studying the reflectivity and velocity signatures associated with the May 3, 1999 tornadoes and thunderstorms as well as tracking the storms.

Application 1.1

1. Using WxScope, select the region of interest by choosing Product, New, Shape. From the pull down menu, select a state and click OK. *(More than one state may be displayed. Recall from the WxScope tutorial that ↑ Zooms in and ↓ Zooms out)*

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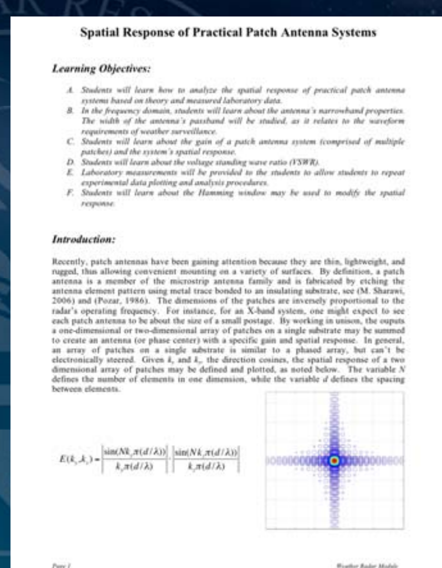
11. Patch Antennas

- Learn about patch antennas
- Plot antenna patterns
- Study chamber data



Spatial Response of Practical Patch Antenna Systems

Learning Objectives:

A. *Students will learn how to analyze the spatial response of practical patch antenna systems based on theory and measured laboratory data.*
B. *In the frequency domain, students will learn about the antenna's narrowband properties. The width of the antenna's passband will be studied, as it relates to the waveform requirements of weather surveillance.*
C. *Students will learn about the gain of a patch antenna system (comprised of multiple patches) and the system's spatial response.*
D. *Students will learn about the voltage standing wave ratio (VSWR).*
E. *Laboratory measurements will be provided to the students to allow students to repeat experimental data plotting and analysis procedures.*
F. *Students will learn about the Hamming window may be used to modify the spatial response.*

Introduction:

Recently, patch antennas have been gaining attention because they are thin, lightweight, and rugged, thus allowing convenient mounting on a variety of surfaces. By definition, a patch antenna is a member of the microstrip antenna family and is fabricated by etching the antenna element pattern using metal trace bonded to an insulating substrate, see (M. Sharawi, 2006) and (Pozar, 1986). The dimensions of the patches are inversely proportional to the radar's operating frequency. For instance, for an X-band system, one might expect to see each patch antenna to be about the size of a small postage. By working in unison, the ouputs a one-dimensional or two-dimensional array of patches on a single substrate may be summed to create an antenna (or phase center) with a specific gain and spatial response. In general, an array of patches on a single substrate is similar to a phased array, but can't be electronically steered. Given k_x and k_y, the direction cosines, the spatial response of a two dimensional array of patches may be defined and plotted, as noted below. The variable N defines the number of elements in one dimension, while the variable d defines the spacing between elements.

$$E(k_x,k_y) = \left|\frac{\sin(Nk_x\pi(d/\lambda))}{k_x\pi(d/\lambda)}\right| \cdot \left|\frac{\sin(Nk_y\pi(d/\lambda))}{k_y\pi(d/\lambda)}\right|$$

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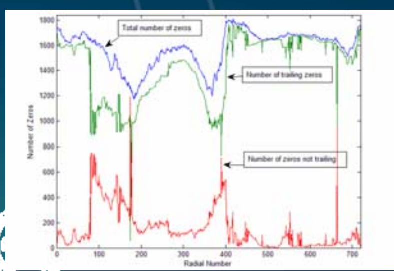
12. Data Compression

- Learn about compression techniques
- Importance of compressing WSR-88D data
- Various forms of pre-processing are studied



Real-Time Adaptive Data Compression for Weather Radars

1 Learning Objectives:

- *Students will learn about the importance of compressing radar data and how it is accomplished in the modern governmental, industrial, and educational environments.*
- *Historical perspectives will be discussed. Students should understand the genesis of how various compression algorithms have evolved during the last twenty years: from tape drive storage to Internet transfer.*
- *Students will develop their own compression algorithms, which will be a simplified version of the compression algorithms that were developed in the early days of the WSR-88D. Advanced versions of compression algorithms will also be studied.*
- *Students will learn about the spatial correlation of radar data and its relationship to compression. Students will also learn about how different elevations in VCPs may influence the amount of compression associated with each radial.*
- *Various forms of pre-processing will be studied. One example involves setting a threshold so that very weak echoes in the presence of convective storms or other significant events may be zero padded to help maximize compression.*
- *High Resolution (Hi-Res) and Dual Polarization WSR-88D data cases will be studied and analyzed by the students.*
- *Scalability of the techniques will be covered. This will span procedures for the existing, large-scale operational radars to small-scale, futuristic FPGA based digital receivers.*

2 Introduction

A bit (either 0 or 1) is the smallest, most basic form in which information can be measured. The objective of compression is reduce the number of bits required to represent a signal by removing redundant or unnecessary information to reduce the signal.s storage requirements, yet allow its reconstruction [1]. The term "compression ratio" is the key metric that describes the bit savings. It is the ratio of (number of bits employed after compression)/(number of bits before compression). Two different types of compression exist: lossy and lossless. Lossy compression provides the highest level of compression, but the reconstructed data set will have a slightly reduced fidelity since some of the less meaningful bits are actually deleted during the compression scheme. However, in lossless compression, the reconstructed signal will be an exact replica of the original signal. In general, researchers have been experimenting with various compression algorithms for many years, especially in the communications community. A description of a variety of compression techniques applied to radar data can be found in [2–5] and others.

13. DBF

- Learn about digital beamforming
- Digital, complex coefficient design for beam formation.

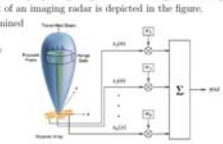
Digital Beamforming and Imaging Radar

1 Learning Objectives:

- *Students will learn about the antenna pattern for planar phased array.*
- *Students will learn about digital beamforming (DBF) technique, which is the main idea behind an imaging radar.*
- *Students will learn about how to implement Fourier-based DBF from a practical system.*

2 Introduction

An imaging radar can produce a snap-shot of the scene, illuminated by a wide transmitting beam, using digital beamforming (DBF) techniques. In other words, a number of receiving beams can be formed simultaneously by weighting the received signals from spatially separated sub-arrays. The concept of an imaging radar is depicted in the figure.



Those weights can be pre-determined or adaptive to the scene the radar perceived to maximize performance such as clutter/interference mitigation. In this project, only the Fourier-based DBF is introduced, where the receiving pattern is determined from the configuration of sub-arrays. The output of a beamformer is given by

$$y(n) = \mathbf{w}^H \mathbf{x}(n) \tag{1}$$

where the superscript H is the Hermitian (conjugate transpose), $\mathbf{x}^T(n) = [x_1(n)\, x_2(n) \cdots x_N(n)]$ is a vector consisting of received signals from N sub-arrays (can be linear or planar array) at time n, and $\mathbf{w}^T = [e^{jk\mathbf{a}_r \cdot \mathbf{d}_1}\, e^{jk\mathbf{a}_r \cdot \mathbf{d}_2} \cdots e^{jk\mathbf{a}_r \cdot \mathbf{d}_N}]$ is the vector of weights for each received signals. Moreover, the position vector of the i^{th} sub-array is denoted by $\mathbf{d}_i$, and the beam pointing direction is defined by $\mathbf{a}_r$. As a result, the output power of the beamformer is obtained by

$$P(n) = \mathbf{w}^H < \mathbf{x}(n)\mathbf{x}^H(n) > \mathbf{w}. \tag{2}$$

Note that $P(n)$ is implicitly a function of pointing angle $\mathbf{a}_r$.

The data used in this project was collected by the UMASS Turbulent Eddy Profiler (TEP) with 56 sub-arrays on June 14, 2003. The data can be downloaded from the following website http://www.ou.edu/radar/tep_iqdata.mat. Note that the data from only one range

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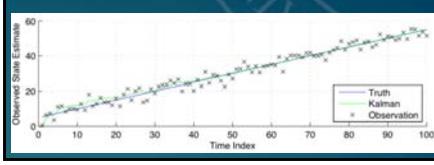
14. Signal Modeling

- For level I data
- AR modeling
- PSD is based on the AR model
- Use the KF to adaptively yield more accurate estimates of the model.



Level I Signal Modeling and Adaptive Spectral Analysis

1 Learning Objectives

- Students will learn about autoregressive signal modeling as a means to represent a stochastic signal. This differs from using a transform, such as the Fourier transform or wavelet transform, which is used to map a signal from one domain to another.
- The well known Kalman estimator will be briefly studied, since a variation of it can be viewed as a parametric estimation process which relies on an autoregressive (AR) model in its internal the signal estimation process.
- Students will learn about parametric modeling of Level I data for each range gate of a radars sample volume. As storage capabilities become more prevalent, such as KOUN, massive amounts of Level I data can be stored and analyzed.
- Students will learn how autoregressive parameters are related to spectral analysis. Such all-pole modeling is very effective in representing peaks or bumps in a signals spectrum.
- Students will learn how to develop an adaptive technique that relies on autoregressive signal modeling to estimate the spectrum for a range gate of data. In particular, when a range gate has more than one type of scatterer, multiple peaks in the Doppler spectrum may appear. Thus the autoregressive parameters can be used to represent the peaks in the spectrum, which is very similar to the modeling of voice data.

2 Introduction

Signal modelling is a broad class of processing techniques where a stochastic signal of interest is modelled as a certain type of process, such as an autoregressive moving-average (ARMA) process or as a collection of sinusoids. In fitting the signal to the model, several parameters are obtained which can then be used in a variety of ways, including spectral analysis, frequency estimation, and adaptive signal processing. The focus here will be on modelling a signal as an autoregressive (AR) process, also known as an all-pole model, which is a special class of the more-general ARMA process model. Using the AR model, the location of multiple peaks within the frequency spectrum can be obtained, which can be used in a weather radar to estimate the velocity of meteorological targets in the presence of moving biological clutter. The AR model can also be used within the framework of the Kalman filter, a powerful adaptive filter that is employed in a wide variety of applications.

2.1 Autoregressive Modelling

In digital signal processing, the input-output relation of a linear time-invariant (LTI) system is given (in the z domain) by

$$Y(z) = \frac{B(z)}{A(z)}X(z) = H(z)X(z) \quad (1)$$

where $H(z)$ is called the filter response. In an LTI system, $A(z)$ and $B(z)$ are polynomials, so $H(z)$ can be written as

$$H(z) = \frac{\sum_{i=1}^{n} b_n z^{-n}}{\sum_{j=1}^{m} a_m z^{-m}} \quad (2)$$

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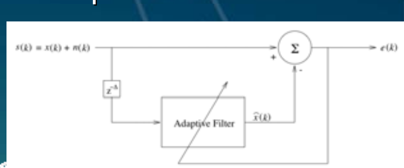
15. Adaptive, Temporal Clutter Filtering

- Discussion of adaptive noise cancellation architectures
- LMS and RLS algorithms
- Leverage differences in autocorrelation sequences



Temporal Clutter Filtering via Adaptive Techniques

1 Learning Objectives:

- *Students will learn about how to apply the least mean squares (LMS) and the recursive least squares (RLS) algorithm in order to build an adaptive digital filtering architecture that will remove clutter from radar returns. Complexity and convergence comparisons will be made for the two techniques.*
- *Students will learn how differentiation between the clutter and the useful signal is obtained by exploiting the different auto-correlation functions of the two signals. Students will learn how to devise a cost function so that the clutter may be recursively miminized on a sample by sample basis (i.e., for each point that comprises a range gate's spectrum).*
- *Most adaptive algorithms rely on using a statistical framework. Students will be exposed to new techniques in which theory necessary to consider adaptive signal processing using a recursive least squares algorithm – which does not depend on the ensemble statistics of a signal. This unique feature allows a broad class of signals to be filtered without regard to a particular signal model.*
- *After this module and classroom discussions, the student should also be in a position to describe various sources of ground based and sea based clutter. The statistical distributions of each are different and do influence the design of radar's receiver.*

2 Introduction

Radar (RAdio Detection And Ranging) was refined during World War II to counter enemy military forces, particularly airborne forces. Broader utility of radar was quickly recognized and the technology was soon applied to civilian aviation to meet its growing requirements. As the technology matured it became evident that radar could also be used in surveillance of weather phenomena [1], aiding immeasurably the meteorological and aviation safety communities. There have been many significant improvements to aircraft and weather radar systems since their initial fieldings that benefit mankind. As eloquently articulated in the passages of the book titled *Engineer of the 2020* [2], students will be expected to have a better understanding of the "natural world." Although natural disasters are beyond man's control, man's ability to predict them and adapt accordingly are essential to minimize impact, especially with observing systems such as radar.

2.1 A Discussion of Noise Cancellation and Adaptive Filters

This section summarizes a progression of the development of the adaptive filters. It is well known that the Wiener filter is the optimum filter for determining a desired signal in the mean squared sense, assuming that the signal is stationary. Here the objective is to explain how the Wiener filter structure may be augmented so that a filter architecture may be developed that is

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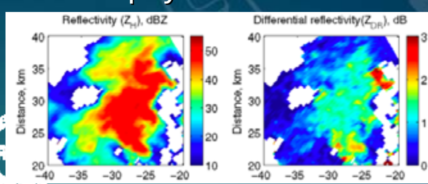
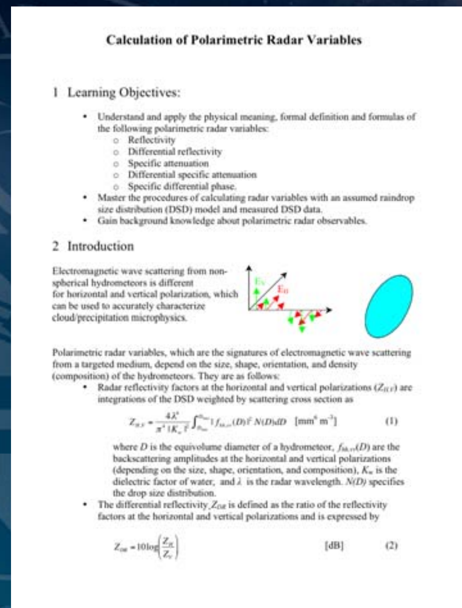
16. Polarimetric Radar Variables

- Reflectivity, differential reflectivity, specific attenuation, differential specific attenuation, specific differential phase
- Measured DSDs
- T-matrix calculation
- Hydrometer classification
- Microphysics retrieval





Calculation of Polarimetric Radar Variables

1 Learning Objectives:

- Understand and apply the physical meaning, formal definition and formulas of the following polarimetric radar variables:
  - Reflectivity
  - Differential reflectivity
  - Specific attenuation
  - Differential specific attenuation
  - Specific differential phase.
- Master the procedures of calculating radar variables with an assumed raindrop size distribution (DSD) model and measured DSD data.
- Gain background knowledge about polarimetric radar observables.

2 Introduction

Electromagnetic wave scattering from non-spherical hydrometeors is different for horizontal and vertical polarization, which can be used to accurately characterize cloud/precipitation microphysics.

Polarimetric radar variables, which are the signatures of electromagnetic wave scattering from a targeted medium, depend on the size, shape, orientation, and density (composition) of the hydrometeors. They are as follows:

- Radar reflectivity factors at the horizontal and vertical polarizations ($Z_{H,V}$) are integrations of the DSD weighted by scattering cross section as

$$Z_{H,V} = \frac{4\lambda^4}{\pi^4 |K_w|^2}\int_{D_{min}}^{D_{max}} |f_{hh,vv}(D)|^2 N(D)dD \quad [\text{mm}^6\ \text{m}^{-3}] \qquad (1)$$

where D is the equivolume diameter of a hydrometeor, $f_{hh,vv}(D)$ are the backscattering amplitudes at the horizontal and vertical polarizations (depending on the size, shape, orientation, and composition), K_w is the dielectric factor of water, and λ is the radar wavelength. $N(D)$ specifies the drop size distribution.

- The differential reflectivity Z_{DR} is defined as the ratio of the reflectivity factors at the horizontal and vertical polarizations and is expressed by

$$Z_{DR} = 10\log\left(\frac{Z_H}{Z_V}\right) \quad [\text{dB}] \qquad (2)$$

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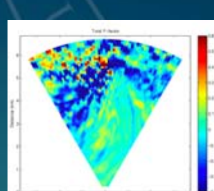
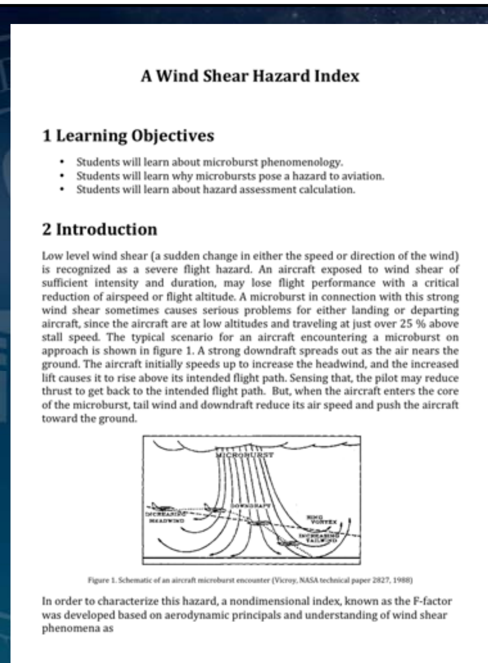
17. F-Factor

- Learn about how to compute the F-Factor
- Importance of wind shear
- Compute hazard map





A Wind Shear Hazard Index

1 Learning Objectives

- Students will learn about microburst phenomenology.
- Students will learn why microbursts pose a hazard to aviation.
- Students will learn about hazard assessment calculation.

2 Introduction

Low level wind shear (a sudden change in either the speed or direction of the wind) is recognized as a severe flight hazard. An aircraft exposed to wind shear of sufficient intensity and duration, may lose flight performance with a critical reduction of airspeed or flight altitude. A microburst in connection with this strong wind shear sometimes causes serious problems for either landing or departing aircraft, since the aircraft are at low altitudes and traveling at just over 25 % above stall speed. The typical scenario for an aircraft encountering a microburst on approach is shown in figure 1. A strong downdraft spreads out as the air nears the ground. The aircraft initially speeds up to increase the headwind, and the increased lift causes it to rise above its intended flight path. Sensing that, the pilot may reduce thrust to get back to the intended flight path. But, when the aircraft enters the core of the microburst, tail wind and downdraft reduce its air speed and push the aircraft toward the ground.

Figure 1. Schematic of an aircraft microburst encounter (Vicroy, NASA technical paper 2827, 1988)

In order to characterize this hazard, a nondimensional index, known as the F-factor was developed based on aerodynamic principals and understanding of wind shear phenomena as

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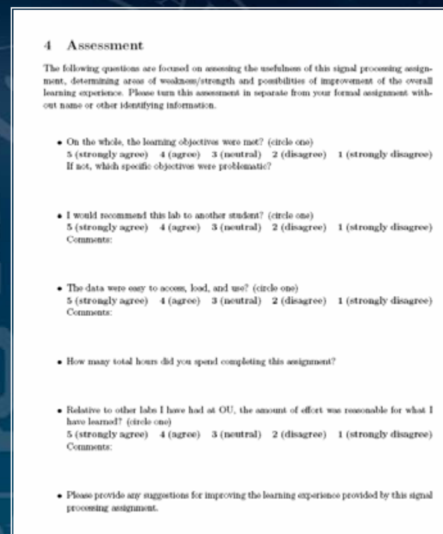
Module Assessment

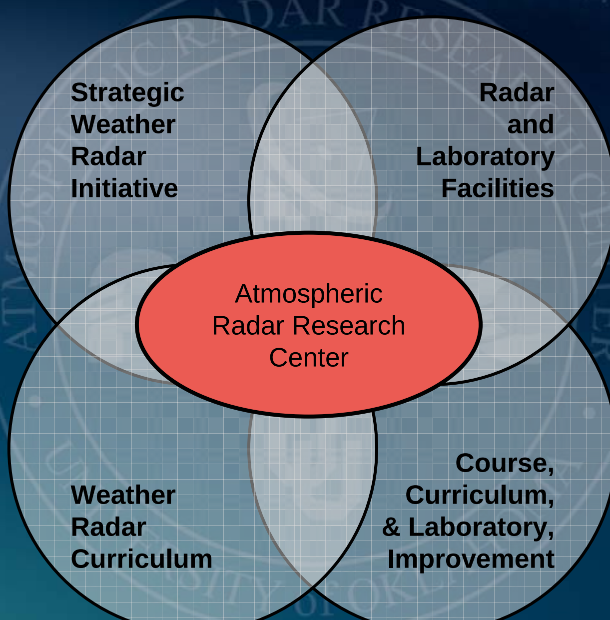
- For all of the modules, a standard one-page assessment tool has been prepared. It was prepared via three principles:
  - a.) with compliance and annual oversight by OU's Institutional Review Board (IRB);
  - b.) to be relatively simple so that a standard instrument could be implemented for all of the modules; and
  - c.) under guidance by the team's external assessment specialist.



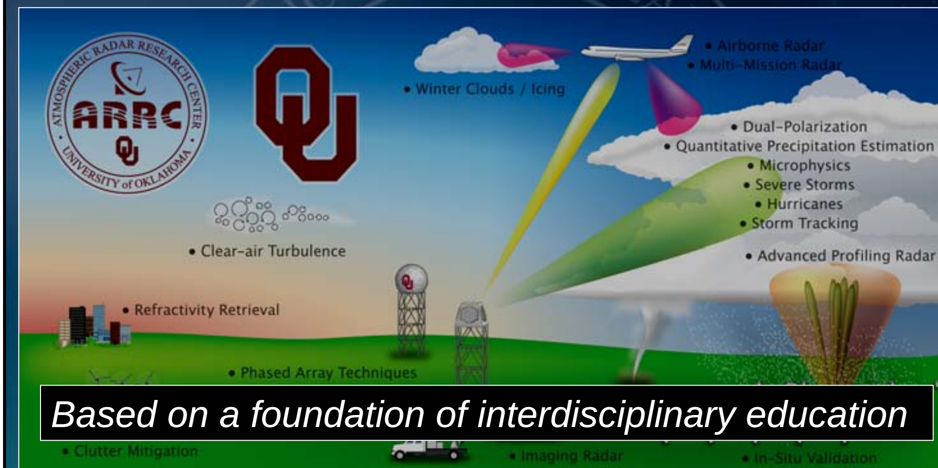
4 Assessment

The following questions are focused on assessing the usefulness of this signal processing assignment, determining areas of weakness/strength and possibilities of improvement of the overall learning experience. Please turn this assessment in separate from your formal assignment without name or other identifying information.

- On the whole, the learning objectives were met? (circle one)
  5 (strongly agree) 4 (agree) 3 (neutral) 2 (disagree) 1 (strongly disagree)
  If not, which specific objectives were problematic?
- I would recommend this lab to another student? (circle one)
  5 (strongly agree) 4 (agree) 3 (neutral) 2 (disagree) 1 (strongly disagree)
  Comments:
- The data were easy to access, load, and use? (circle one)
  5 (strongly agree) 4 (agree) 3 (neutral) 2 (disagree) 1 (strongly disagree)
  Comments:
- How many total hours did you spend completing this assignment?
- Relative to other labs I have had at OU, the amount of effort was reasonable for what I have learned? (circle one)
  5 (strongly agree) 4 (agree) 3 (neutral) 2 (disagree) 1 (strongly disagree)
  Comments:
- Please provide any suggestions for improving the learning experience provided by this signal processing assignment.



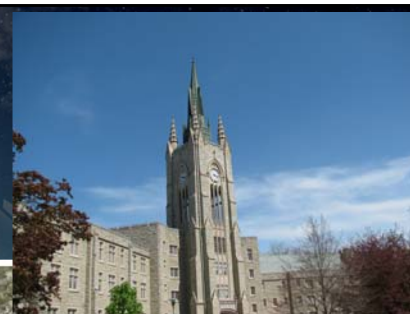
Atmospheric Radar Research Center



Based on a foundation of interdisciplinary education

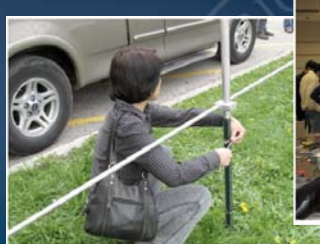
From OU to Canada

MST12 Radar School
University of Western Ontario
London, Canada

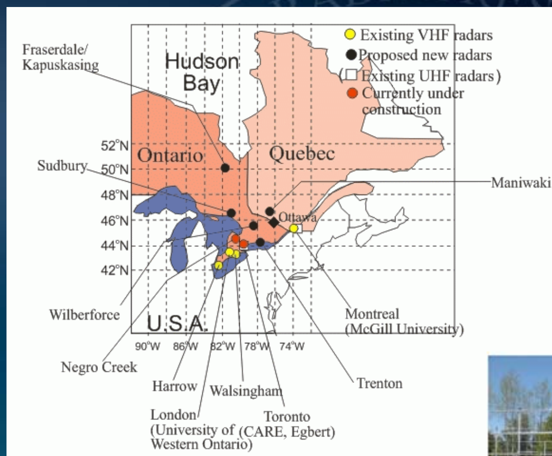


May 12-16
2009

Building a Radar !!

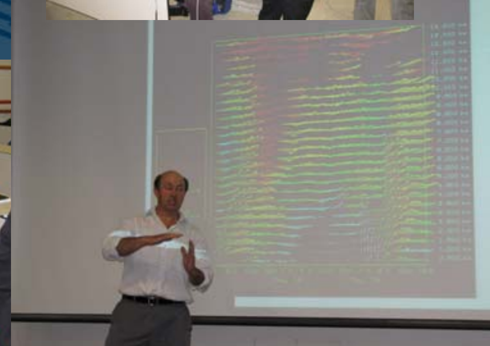


Visiting a Radar Site

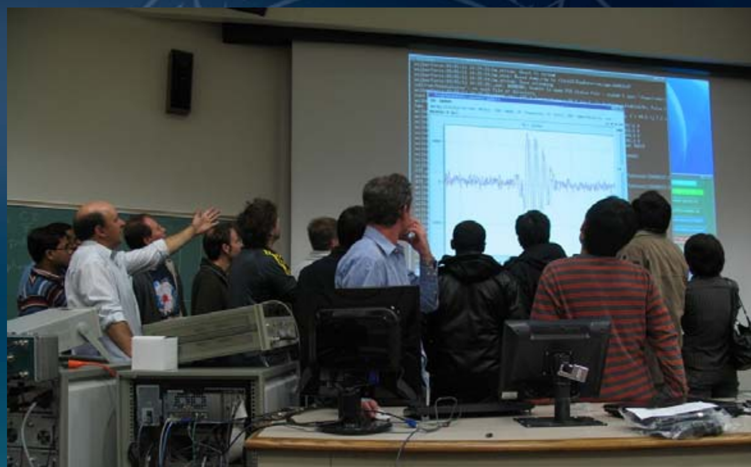


O-QNet

Analyzing the Radar Data



Bringing It All Together



Meteor Echo Observed Using the “School Radar”

Build a Radar

- **What was your impression of the radar building exercise?**
  - “Brilliant. Helps to show to a theoretical guy it’s not such a big deal getting your hands ‘dirty’”
  - “Best part of conference”
  - “I was amazed how well it worked – good fun.”
  - “This was an excellent idea. I learned a lot and had fun”

Visit a Radar Site

- **Did you find the radar visits useful / informative?**
  - "It was the first radar I had seen"
  - "This is one of the main reasons I enrolled."
  - "Yes. It was also nice to get out of the lecture theatre and see some of Canada"
  - "Meteor radar visit was very useful, informative and gave me an understanding of where I get my data. Really enjoyed it"

Most enjoyed / helpful

- **What did you enjoy most / find most helpful?**
  - "The diversity of fields and speakers helped me to get the big picture."
  - "Dedication and energy of Prof. Hocking"
  - "Interacting with so many learned and experienced teachers and students from the field from all over the world made it a very unique experience. I am impressed by the enthusiasm and motivation of the teachers in the school."
  - "Discussion with the lecturers as well as the students about the different interests in MST."

Overall impressions

- **What is you overall impression of the school?**
  - “If you are working or planning to work with radars this school is a must have.”
  - “Absolutely brilliant would definitely go again.”
  - “Quite useful it is nice to be able to discuss topics with students from different research groups and backgrounds.”
  - “Great atmosphere, putting all these people together, learning a lot about each others fields. A big “thank you” to the organizers for running this so smoothly and for the vast amounts of time you invested to make this pay off big time.”
  - “The university environment was a comfortable setting for the school.”
  - “Brilliant. Would recommend it for other students.”

Summary

“Education is what remains after one has forgotten what one has learned in school.”