AC 2009-2426: A STATUS REPORT ON A COLLABORATIVE PROGRAM FOR HANDS-ON LEARNING, SEVERE WEATHER, AND NEXT-GENERATION MULTIFUNCTION RADAR

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Dr. Mark Yeary is an Associate Professor in the School of Electrical and Computer Engineering and a member of the Atmospheric Radar Research Center (ARRC). He has many years of experience as a teaching assistant, lecturer, and faculty member. Since January of 1993, he has taught many students in various laboratories and lecture courses, culminating in approximately 14 years of teaching experience. For the 1999-00 academic year, he received the Outstanding Professor Award, given by the Texas A&M student chapters of IEEE and Eta Kappa Nu, and IBM in Austin. His research and teaching interests are in the areas of customized embedded DSP systems and digital signal processing as applied to radar signal processing, image processing, adaptive filter design, and real-time systems. He currently serves as the faculty advisor for the AISES student group at OU and is involved in many IEEE student activities.

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Robert Palmer, University of Oklahoma

Dr. Robert Palmer has published extensively in the general area of radar remote sensing of the atmosphere, with emphasis on the use of multiple frequencies/receivers for interferometry and generalized imaging problems. His has taught courses from the freshman to the graduate level in signals and systems, random processes, and weather radar for 13 years. He has won the University of Nebraska-Lincoln (UNL) College of Engineering Faculty Teaching Award and has twice been recognized by the UNL Teaching Council for contributions to students. Prof. Palmer moved to the University of Oklahoma (OU) in the summer of 2004. After coming to OU, he led the development of a cross-disciplinary curriculum in weather radar and instrumentation between the School of Meteorology and the School of Electrical and Computer Engineering. This program has seen heavy enrollments since its inception and is currently expanding and evolving to meet the needs of both undergraduate and graduate students. He recently received the Teaching Scholars Initiative (TSI) award from the University of Oklahoma.

James Sluss, University of Oklahoma

Dr. JAMES J. SLUSS, JR. is Director of Electrical and Computer Engineering at the University of Oklahoma. His research and teaching interests are in the areas of optical communications and photonics. He has been awarded seven U. S. patents and has authored/co-authored numerous journal and conference publications. He is a member of the IEEE Education Society, IEEE Communications Society, OSA, and ASEE.

Guifu Zhang, University of Oklahoma

Dr. Guifu Zhang is an associate professor in the School of Meteorology at the University of Oklahoma and is a member of the Atmospheric Radar Research Center on campus. His main interest is to develop remote sensing techniques for understanding and quantifying weather and earth environments. His research and education interests also include wave propagation and scattering in geophysical media subjected to turbulent mixing and filled with hydrometers and other objects. He is currently teaching and researching in the areas of cloud and precipitation microphysics, electromagnetics, radar polarimetry and phased array radar interferometry for weather applications. He has taught many courses and published over 40 journal papers. Prior to joining OU, Dr. Zhang was a scientist at the National Center for Atmospheric Research (NCAR).

Phil Chilson, University of Oklahoma

Dr. Phil Chilson received a PhD in Physics from Clemson University in 1993. The focus of his studies was the use of radar for the investigation of precipitation. He then spent three years at a Max-Planck Institute in Germany, where he continued his atmospheric research using radar. In 1997, he became a research scientist at the Swedish Institute of Space Physics as part of the Atmospheric Research Programme. In 2000, Dr. Chilson returned to the US to begin work in Boulder, CO, where he was appointed as a Research Scientist with the Cooperative Institute for Research in Environmental Sciences (CIRES). Since 2005, he has been an Associate Professor in Meteorology at the University of Oklahoma. He is also a member of the Atmospheric Radar Research Center at OU. Throughout his career, Dr. Chilson has been heavily involved in the development and use of radar and radar technologies for the investigation and study of the Earth's atmosphere.

Mike Biggerstaff, University of Oklahoma

Dr. Michael Biggerstaff is the lead scientist behind the Shared Mobile Atmospheric Research and Teaching (SMART) radar program, a collaborative effort between the University of Oklahoma, Texas A&M University, Texas Tech University, and the National Severe Storms Laboratory that built and successfully deployed two mobile radars to enhance storm research and to improve meteorological education. Dr. Biggerstaff has received awards in teaching and advising. He received several invitations for short courses in the U.S. and abroad. He is a faculty member in the School of Meteorology and a member of the Atmospheric Radar Research Center (ARRC).

A Status Report on a Collaborative Program for Hands-On Learning, Severe Weather, and Next-Generation Multi-Function Radar

This paper describes the details of an on-going NSF Department of Undergraduate Education (DUE) project that commenced in the fall of 2004. This multi-year project offers a new active-learning and hands-on laboratory program that is interdisciplinary, in which engineering and meteorology students are encouraged to actively participate. As discussed in a report by the Bureau of Economic Analysis, about a third of the nation's $10 trillion dollar economy is influenced by weather. Storm cells, tornados, and hazardous weather cause damage and loss that could be minimized through enhanced radar and longer warning lead times. To study these topics, the program has generated a unique, interdisciplinary research-oriented learning environment that will train future engineers and meteorologists in the full set of competencies needed to take raw radar data and transform it into meaningful interpretations of weather phenomena.

A key element of the program is the development, implementation and refinement of a set of several undergraduate courses and laboratory modules that are offered by the Schools of Meteorology and Electrical & Computer Engineering, that provides hands-on experiences in the special knowledge and skills necessary for organizing real-time weather data, improving and preparing that data for display, and interpreting its meteorological and scientific significance. In addition, programs for middle school teachers have been generated for the purpose of increasing their students' interest in science and engineering prior to entering college. The principal investigators have partnered with a major statewide climatology office for five summers to adapt and implement project materials directly to middle school teachers via its EarthStorm outreach program. This experience and the team's growing community of scholars will be combined to offer a comprehensive national workshop in the April of 2009.

There are several special features in this research-oriented teaching program, including: (1) it involves partners from several universities and government agencies, (2) it is the only program in the country with a full and equal collaboration between the School of Meteorology and the School of Electrical & Computer Engineering for the purpose of adding strength to an existing, successfully integrated curriculum on weather radar, (3) it has access to weather data from the recently constructed National Weather Radar Testbed (NWRT). Students have a unique opportunity to take advantage of the weather data derived from the new phased array radar, specifically suited for weather observations. To broaden the richness of the students' learning experiences, data from other remote sensors, such as profilers, conventional dish antennas, mobile radars, and the like are available. In-situ sensors, such as distrometers, also play an important role in the overall suite of atmospheric instrumentation. To reach diverse and off-campus populations, a wide variety of data and their associated learning modules are available on the team's website and are also accessible via the NSF Digital Library.

Introduction

General Educational Philosophy and Goals: The future of radar meteorology is critically dependent upon the education and training of students in both the technical and scientific aspects of this sub-discipline of meteorology. Not only should meteorology students be knowledgeable in the use of radar for studies of the atmosphere, but should also be comfortable with topics which may have previously been considered in the realm of engineering. Furthermore, engineering students who choose to work in this exciting field should have enough background in the atmospheric sciences to effectively communicate with the radar system users. Only through such an interdisciplinary approach can true leaps forward in both technology and science be achieved. To guide the development of the team's university educational radar program [1], the following three overarching goals were created.

- Provide a comprehensive interdisciplinary education in weather radar at both the undergraduate and graduate levels
- Provide extensive hands-on experience
- Combine the talents of faculty members from different departments across campus with those of local scientists and engineers

To implement a curriculum to realize the goals, a taxonomy of learning was employed. In particular, the classic Bloom's Taxonomy of Learning was used. Well known in the educational community, this model is based on six successive levels or categories of learning –knowledge, comprehension, application, analysis, synthesis and evaluation – that ascend in difficulty from factual knowledge to evaluation. This model serves as the glue that strengthens the bonds of our pedagogical goals and the team's curiosity driven class projects. More importantly, it helps to establish a logical framework for a group of interdisciplinary faculty. Scientific Motivations: Severe and hazardous weather such as thunderstorms, downbursts, and tornadoes can take lives in a matter of minutes. For instance, the tornado paths that are depicted in Figure 1 occurred in residential neighborhoods had a duration of approximately 30 to 60 minutes each, and they caused 10's of millions of dollars in damage. In order to improve detection and forecast of such phenomena using radar, one of the key factors is fast scan capability. Conventional weather radars, such as the ubiquitous NEXRAD (Next Generation Radar developed in the 1980's), are severely limited by mechanical scanning. Approximately 175 of these radars are in a national network to provide the bulk of our weather information. Under the development for weather applications, the electronically steerable beams provided by the phased array radar at the NWRT can overcome these limitations of the current NEXRAD radar. For this reason, the phased array radar was listed by the National Research Council as one of the primary candidate technologies to supersede the NEXRAD [2]. By definition, a phased array radar is one that relies on a two-dimensional array of small antennas. Each antenna has the ability to change its phase characteristics, thus allowing the overall system to collectively locate specific interesting regions of weather. The NWRT is the nation's first facility dedicated to phased array radar meteorology. In addition, the demand for students trained in this area will be high as new radar technologies replace the ones designed 20 years ago, and as weather radar usage extends into areas such as homeland security. From the Federal Aviation Administration's (FAA) perspective, the phased array radar technology developed at the NWRT will be used to enhance the safety and capacity of the National Airspace System. Moreover, this paper is consistent with one of NOAA's Mission Goals for the 21st Century: to serve society's needs for weather information [3].

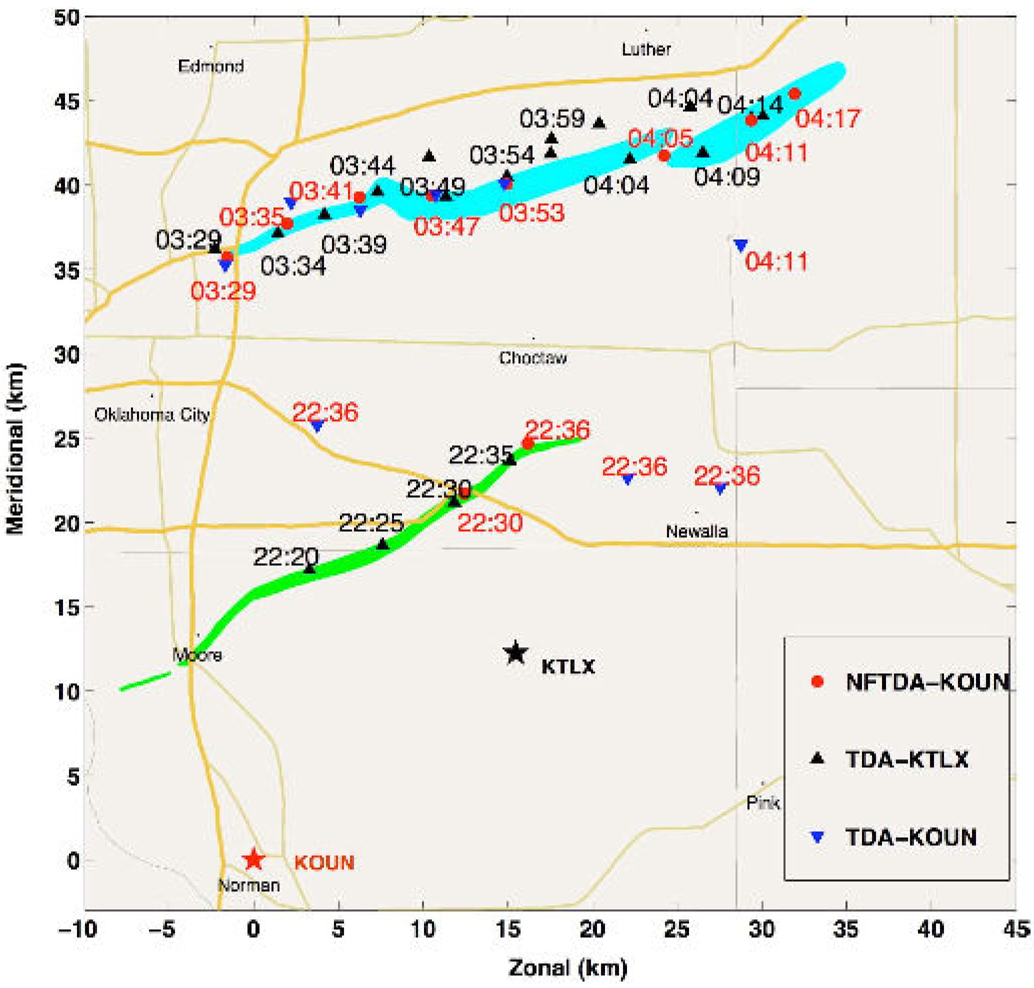

Figure 1: *This figure depicts several tornado paths that occurred in residential areas [4]. Helping students to learn more about innovative detection technologies for improved warning decisions is one tenet of the program. In the courses, students practice various signal processing techniques on a variety of radar data sets.*

In order for students and researchers to study the characteristics of the NEXTRAD and the NWRT, resources are available on campus for experiments. In addition to these radars, other radars are available for a wide variety of atmospheric investigations. Five radars are discussed here, as depicted in Figure 2. To begin, students have an unprecedented opportunity to take advantage of a unique federal, private, state and academic partnership that has been formed for the development of the phased array radar technology at the NWRT, as depicted by panel 1 in Figure 2. Eight participants contributed to the installation of the new radar, including: NOAA's National Severe Storms Laboratory and National Weather Service Radar Operations Center, Lockheed Martin, U.S. Navy, Federal Aviation Administration, and BCI, Inc.

Panel 2 in Figure 2 depicts a mobile radar known as the Shared Mobile Atmospheric Research and Teaching Radar or SMART-R [5]. This research and educational portable enterprise is a coalition of scientists from the University of Oklahoma (OU), National Severe Storms Laboratory (NSSL), Texas A&M University (TAMU), and Texas Tech University (TTU) who embarked on a project to build and deploy two mobile C-band Doppler weather radars for storm-scale research and to enhance graduate and undergraduate education in radar meteorology. This project culminated in the successful development and deployment of the first mobile C-band Doppler weather radar, radars capable of accurately measuring both clear-air circulations and damaging winds in heavy rain.

Panel 3 in Figure 2 depicts a snapshot of a NEXRAD radar. This radar is also known as a Weather Surveillance Radar, model 1988 or WSR-88D. 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 raw time series data over many hours. In general, weather surveillance radars, particularly the WSR-88D, have shown to be an important tool to observe severe and hazardous weather remotely, and to provide operational forecasters prompt information of rapidly evolving phenomena. Panel 4 depicts one node of a networked radar system. With the advances in networking technology, a new paradigm of networked radars is on the verge of becoming a reality. The many advantages offered by these networks of radars is manifested by their ability to offer the opportunity to make innovative improvements to the science of radar meteorology. The NSF sponsored Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is a prime example of emerging distributed collaborative and adaptive systems [6, 7]. The University of Oklahoma is a partner of CASA initiative, with three other universities. The vision of the CASA is to expand scientist's ability to observe the lower troposphere through Distributed Collaborative Adaptive Sensing (DCAS), improving the ability to detect, understand, and predict severe storms, floods, and other atmospheric and airborne hazards. Finally, as depicted in panel 5 of Figure 2, vertically pointing radars provide height profiles of fundamental quantities such as wind vectors, precipitation microphysics, and the intensity of clear-air turbulence, and are powerful observational and

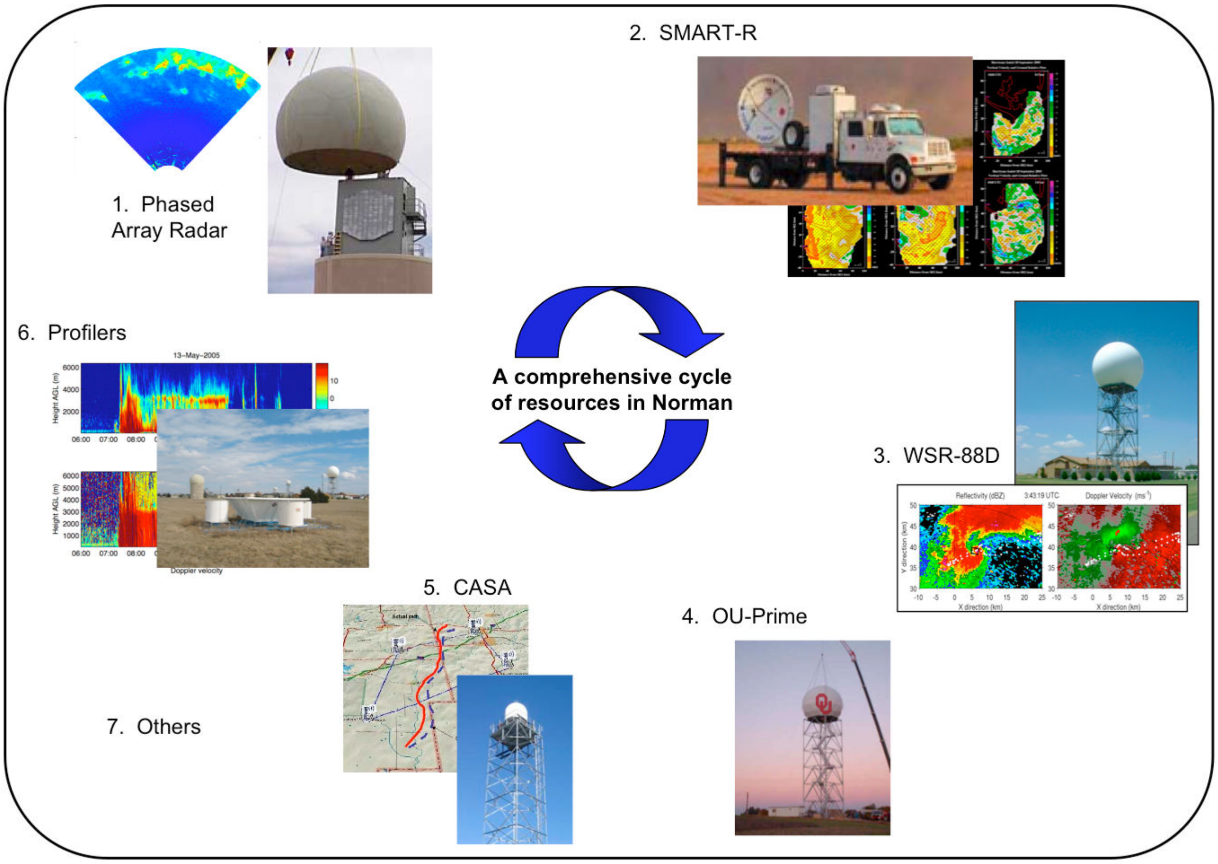

Figure 2: *To address the general problem that "students are not exposed to enough hands on data," the university faculty team has a rich variety of atmospheric data sources on its north and south research campuses, in close collaboration with their federal and corporate research partners.*

research tools within the meteorological community. These instruments are capable of routinely providing estimates of the wind flow aloft while also facilitating studies of turbulence, atmospheric stability, and precipitation. The complementary use of profiling radars together with NWRT and the WSR-88D offer exciting and unique research opportunities. Radar systems, like the ones previously mentioned, offer researchers and students the capability to make a variety of measurements of the atmosphere, which can then be used to develop forecasts. Long-term warnings have improved greatly over the last five years and are now being used for critical decision making [8]. Further improvements are being aimed at providing longer warning lead times before severe weather events, better quantification of forecast uncertainties in hurricanes and floods, and tools for integrating probabilistic forecasts with other data sets. Many other industries, groups, and individuals use weather information. For example, the construction industry uses weather information to schedule specific activities and to purchase materials. K-12 teachers use weather data to develop math and engineering skills in their students, which is essential for the future [9, 10, 11].

Researchers at the University of Syracuse surveyed faculty and administrators at 47 research universities all over the United States several years ago, as discussed in [12] and [13]. In the survey, 17 percent felt that their institutions should emphasize research, 34 percent said teaching, and 50 percent said the two duties should be balanced. Similarly, this comprehensive teaching and research program has followed a tight integration of teaching and research that has led to a pedagogical model that focuses on student retention, high-quality student learning, assessment, hands-on experiments, exportable teaching modules, and refinement. In addition, by following the spirit of the classic Boyer Report, it is very important that no gap exists between teaching and research [14]. In addition, faculty members who creatively combine teaching with research are essential to the improvement of undergraduate education [15, 16, 17, 18]. With this in mind, we now introduce the model that governs and sustains the teaching and research mission of our university laboratory. The synergistic interaction between teaching and research, their drivers and end-results is also illustrated. These drivers can be classified into those of resource needs (e.g. qualified personnel) and technology related issues. Resource needs can be further classified into three types – (1) design and application engineers, (2) radar system integrators and managers, and (3) research and development scientists. These needs are met by BS, MS, and PhD graduates, respectively. Thus our undergraduate and graduate educational initiatives have been developed to provide an appropriate level of training at the BS, MS, and PhD levels in this lab. The foundational key to the entire endeavor is the undergraduate educational process – these students are the first ones to enter our cycle that stresses lifelong learning, creativity, global awareness, and interdisciplinary collaborations. Sharing exciting projects with students will occur naturally here, since the authors have collaborative research projects at the NWRT. The team's laboratory/teaching program provides abundant opportunities for individuals that may concurrently assume responsibilities as researchers, educators, and students. The NWRT and other nationally prominent radar that are locally available facilitate joint efforts that infuse education with the excitement of discovery and enrich research through a diversity of learning perspectives.

A detailed description of the team's evaluation plan is given in [19], while a general overview of the project's goals are given below.

1. *Develop student knowledge and skills related to all phases of creating sophisticated weather radar.*

2. *Develop sufficient student interest that they enroll in additional courses in the program.*

3. *Increase the number of middle school students interested in weather science when they enter college.*

4. *Encourage relevant departments in other universities to implement similar programs in weather radar.*

The project is truly a cross-disciplinary effort between the School of Meteorology and the School of Electrical and Computer Engineering. This cross-fertilization between engineering and meteorology is also exemplified in efforts currently underway at our university to develop the cross-disciplinary Weather Radar and Instrumentation Curriculum (see more in [20]). The investigators, along with other colleagues at the university, have developed a unique curriculum which provides an in-depth education in meteorological radar and instrumentation with emphasis on a hands-on experience. This aspect of the program directly addresses a major concern among leaders in the meteorological community about the lack of expertise in the use of instrumentation [21]. The classroom exposure to radar theory, with supportive real radar data projects, is greatly enhancing the educational experience of the students and will more thoroughly prepare them for active scientific careers. A suite of courses has been developed, and where prudent, the courses were cross listed between the two departments; for instance, Radar Engineering is cross listed, while Electromagnetic Fields is not. Cross listing has been shown to strengthen the bonds of these types of collaborative efforts, while welcoming, attracting, and retaining students [22, 23, 24]. The team's courses are listed in Figure 3, and they are reinforced by specific laboratory modules, as described in the next section.

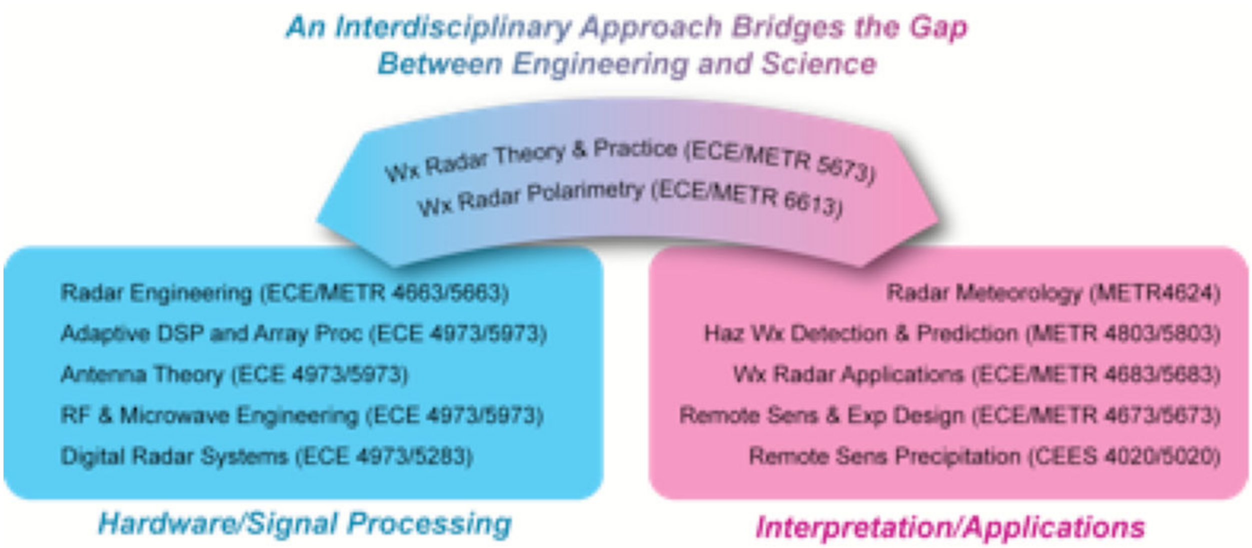

Figure 3: *List of courses which make up the interdisciplinary weather radar program [1]. By providing background materials in a just-in-time format, emphasis has been placed on making it possible for both engineering and meteorology students to succeed in all courses.*

Figure 4 depicts the course evaluations that have benefitted from the inclusion of modules. This data summarizes the results of our Phase I grant NSF-0410564, and our Phase II grant is still in progress. Here, the basis of this analysis is the average of the Student Faculty Evaluation (SFE) scores that are used at OU as a single score to rate the effectiveness of a professor's class (with 5 is the highest and 1 is the lowest). From the graph, it is seen that the average scores of the classes with the modules is typically above the average scores in the college. As one example of how the modules help the classes, the "Weather Radar Theory and Practice" class may be analyzed. Beginning with its inception in the fall of 2005, its class SFE scores have consistently increased.

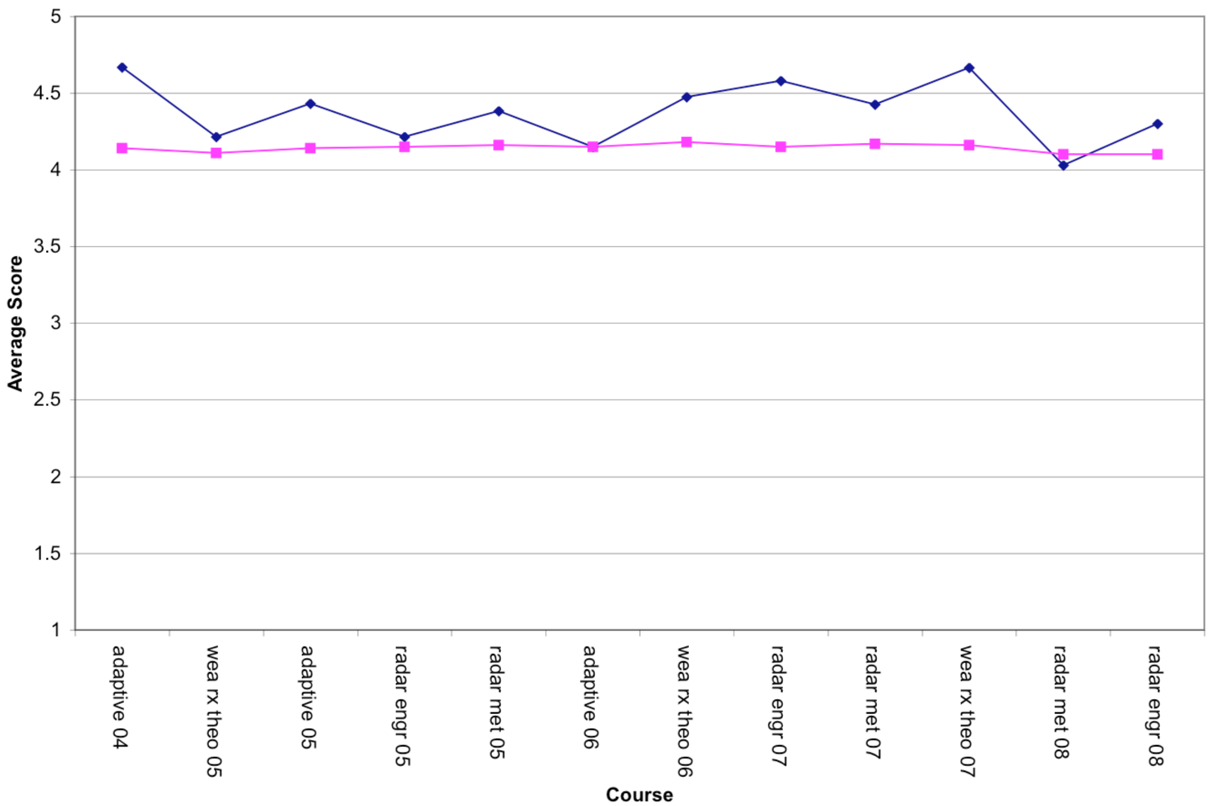

Figure 4: *The blue line with the diamond symbols represent the average Student Faculty Evaluation (SFE) scores that are used to rate the effectiveness of a professor's class at OU. The cyan line with the square symbols represents the average SFE scores from the college. In the rubric, 5 is the highest and 1 is the lowest.*

Hands-on Laboratory Exercises:

Figure 5 depicts the layout of the team's teaching modules in view of content; level of difficulty; and degree of engineering or meteorology emphasis. On a national basis, teaching modules have proven to be an effective means of introducing new material into an existing curriculum, without adding new courses [25, 26]. Moreover, the development of modules allows for the easy implementation at other institutions of learning [27]. As noted by [28], modularity allows a program to be easily transportable in full or in parts, thus allowing faculty to customize based on class structure, project design, and course material. There are many advantages to encapsulating a focused amount of material in a modular fashion, and modules were the educational cornerstone of DARPA's $150M Rapid Prototyping of Application Specific Signal Processors program [29]. At our university, the new modules, instruction, and assessment have been designed in accordance with the ABET Criteria 3 parts (a)-(k) [30]. They have also been carefully constructed to facilitate their adoption at other institutions. Within the sequence of courses, the learning of scientific phenomena, such as interesting atmospheric events, is greatly enhanced when students are allowed to make measurements and construct mathematical models that govern their behavior [31]. Several teamwork-oriented laboratory modules have been integrated into each of the courses. These modules are organized around four themes: 1.) data collection: developing different scanning patterns, 2.) data processing: computing and enhanced algorithms to extract weather information from the raw radar data, 3.) data display: placing the composite weather information on a user-friendly computer display, 4.) data interpretation: scientific understanding and discovery of the displayed data – this includes the locations and dynamics of storms, precipitation, tornadoes, downbursts, and the like. Each of the four items complement and build upon one another – thus solidifying the interaction between the courses. In terms of the course outlines, the unifying themes that integrate the courses are: (i) introduction and detailed study of the Science of weather radar, (ii) the modern-day Technology of displaying and interpreting weather phenomena on a conventional computer screen, (iii) the Engineering of data acquisition and analysis techniques, and (iv) the Mathematics of weather radar processing. Thus strengthening the bonds that comprise STEM education.

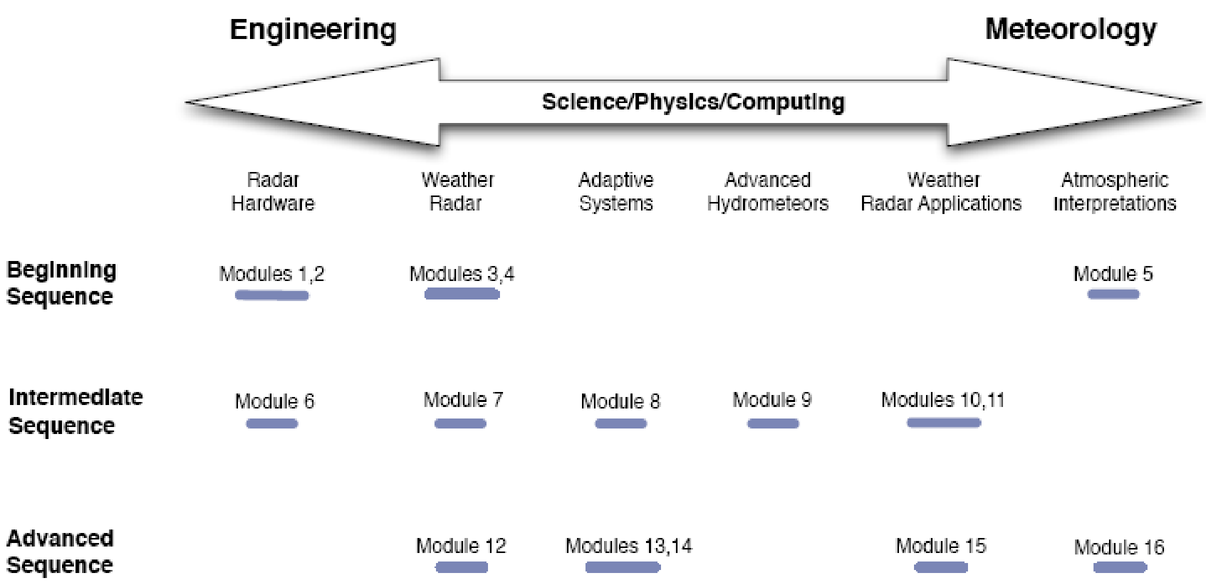

Figure 5: *Layout of the modules. A strong emphasis on fundamental science, physics, and computational computing bridges the gap between engineering and meteorology to create a united foundation that serves as the bedrock for the modules.*

As pointed out by Bourne, Harris, and Mayadas in [32], "providing self-paced modules to students allows additional time for participants in instructor-led courses to engage in interactive exercises." Short, instructional modules have been helpful for lifelong learning, project management, teaming, and time management [33]. Moreover, in a recent paper by Shuman and his colleagues [28], they campaign for the philosophy that, "one of the primary methods created to help integrate team learning into the engineering classroom is the development of formal curricular modules that could be used by various faculty planning to have students work on team projects." In fact, universities in remote locations, such as in Puerto Rico, have relied on teaching modules for especially difficult courses [34] in the past and are eager for more. In addition, such modules have also been a stimulus to increased retention for women in engineering at this university [35]. As such, compelling evidence exists that indicates that students do have a positive reaction to teaching modules. As noted in [36], survey data indicates a positive student reaction to this type instructional material. By observing other successful pedagogical programs in the US, such as the Clark School of Engineering at the University of Maryland and their modular team training program that was funded by the National Science Foundation, we can assess their strengths, while avoiding known pitfalls – thus helping to complete the cycle of innovation. The goal of their "Building Engineering Student Team Effectiveness and Management Systems (BESTEAMS)" was to provide a team curriculum that can be easily adopted by engineering faculty from various schools and at different levels of the undergraduate curriculum [37].

At the current time, student activities are numerous. Computing algorithms are studied and implemented that convert radar data from the phased array radar into environmental measurements known as spectral moments – very similar to previous researchers associated with conventional rotating weather radars [38, 39, 40]. Spectral moments (reflectivity, radial velocity, and spectrum width) are the essential, required radar meteorological measurements that are used to make decisions about cloud locations, storms, rain fall, tornadoes, downbursts, hail and other interesting weather phenomena. Microbursts are strong downbursts of air from evolving rain-clouds which can develop in a matter of minutes and cause windshear. These present hazards for aircraft, especially when taking off or landing. These windshears or strong downbursts are especially dangerous to aircraft [41, 42, 43]. Through appropriate configuration of the phased array radar at the NWRT, it can be designed to provide this windshear information [41, 42, 43, 44, 45]. Detecting windshear is a classic problem for aircraft, but our work will also provide an image of the atmosphere surrounding the radar. This will provide aircraft and other vehicles in the future an ability to make reasonable short term weather forecasts and improved situational awareness. Prior to collecting the weather data, it is imperative that the transmit waveforms of the phased array antenna be properly designed for this activity [42, 44, 45], which does include pulse compression. Similar to current work on the conventionally rotating WSR-88D, staggered pulse repetition times (PRTs) will also be explored to improve the data quality and increased scan rates [46]. In the dual-use mode, of collecting weather information while tracking targets of homeland interest, the scan strategy of the radar will need to be devised to accommodate both targets – that is, an adaptive multiplexing operation that visits each target differently. With respect to weather, the radar does not have to radiate the entire volume every scan or sweep of the beams. Weather targets are much larger than aircraft and move at a slower rate. Updates every minute is adequate. The problem for the radar is that weather targets can have a very small reflectivity and the algorithms will require good Doppler resolution [47]. This requires longer dwells where data is collected.

Summertime Outreach:

Fifty years of research on scientific literacy reveals a recurrent theme – that a basic understanding and appreciation of science are key ingredients of a well-educated and healthy society [48, 49]. Concurrently, Simons and Sutter in 2005 showed that today's operational weather radar systems have resulted in a 45% drop in tornado fatalities and a 40% reduction in injuries due to hazardous weather [50]. In addition, television weathercasters are often the most visible representatives of scientists in U.S. households [51], and more than 90% of television viewers indicate that weather information is the most important reason for watching a newscast [52]. Therefore, it is evident that scientific literacy and weather are inextricably linked, and a tremendous opportunity exists to improve scientific literacy through the use of a sophisticated research and operational tool that requires excellence in science, technology, engineering, and mathematics (STEM) – weather radar.

Figure 7: *A photo of the 2007 Earthstorm participants at the National Weather Center building. Offering 244,000 square feet, this building is home to a variety of activities. The primary authors of this paper and the OCS are both housed in this interdisciplinary facility.*

Today, weather radar imagery is routinely available for purposes ranging from operational forecasting and decision-making to education and recreational applications. Weather radar imagery is available from broadcast media outlets and through hundreds of Internet web sites via computers and cellular phones. In areas where hazardous weather is expected or imminent, it is likely that weather radar will be the tool of choice used by meteorologists to inform the public on the risk at hand and to advise the public on appropriate safety precautions to take. Because of the general public's exposure to weather radar imagery, as well as the commitment by the National Science Foundation to fund weather radar research, there is fertile ground to integrate weather radar as an important multi-disciplinary component in K-12 math and science courses.

Each summer, the Oklahoma Climatological Survey (OCS) in Norman, OK hosts a professional development workshop for teachers called Earthstorm [53]. Spanning nearly two decades, and serving over 250 teachers, Earthstorm has been an annual service to K-12 teachers committed to integrating weather content into their math and science curricula. OCS has successfully implemented a plethora of real time datasets into the K-12 classroom, including surface-based observations, satellite observations, and radar observations. The integration of weather radar content into the Earthstorm workshop includes both classroom and hands-on laboratory sessions on electromagnetic radiation, the Doppler effect, how radars work, and how to interpret weather radar imagery.

The classroom content portion of the radar outreach module provides each teacher with the basic principles of remote sensing, addresses the concept of resolution, and explains pixels and voxels as the building blocks of remotely sensed imagery. Substantial time is spent on how weather radar works, with analogies to household items such as microwave ovens. The classroom portion culminates with a study of radar beam behavior (e.g. beam broadening, earth curvature effects, ducting, etc.) and the implications of that behavior on radar imagery interpretation. The hands-on laboratory includes a field trip to see radars, an outdoor activity using hand-held radar guns, and a tabletop activity using radar imagery. The field trip includes visits to radar assets located at the NationalWeather Center (NWC) in Norman, OK. These assets include the Multi-function Phased Array Radar (MPAR) and the Shared Mobile Atmospheric Research and Teaching Radar (SMART-R) facilities. Each teacher has the opportunity to see how the radar operates, and how the data are collected, processed, and visualized. Scanning strategies are also discussed.

> *Post-workshop evaluation surveys indicate that the radar portion of the summer workshop is always one of the most popular, and many teachers have purchased radar guns for their schools and reproduced this activity with their students.*

To help the teachers understand how Doppler radar works, hand-held radar guns were provided for an outdoor experiment. After the radar guns were calibrated, the teachers were placed strategically along a roadway that is adjacent to the NWC. Each teacher was given instructions on the various angles to point their radar gun relative to the roadway. Workshop staff drove vehicles at controlled speeds back and forth on the roadway while the teachers recorded their observations. After the data were collected, trigonometric principles are applied to determine the actual vehicle speeds from the “inbound” and “outbound” components of the velocities measured by the radar guns. As mentioned above, post-workshop evaluation surveys indicate that this radar portion of the Earthstorm workshop is always one of the most popular, and many teachers have purchased radar guns for their students and recreate this activity. Teacher comments consistently claim that weather radar is a technology that their students are exposed to on a daily basis, and the students’ familiarity with the imagery allows the teacher to teach math and science in a way that is not intimidating to the teacher or student. Once the teacher has used these modules in the classroom, further conversations with them indicate that their students seem to grasp the relevance of applying weather radar for the protection of life and property. The hands-on activities culminate with a radar imagery interpretation laboratory that can be reproduced in the K-12 classroom using a variety of reflectivity and velocity data sets. The summer workshop lesson included instructions on detection of severe thunderstorms with characteristic “three-body scatter spikes” and “hook echoes,” the identification of boundaries using “thin lines,” the assessment of the reflectivity characteristics of liquid and frozen precipitation, identifying “rotation couplets” in velocity imagery, finding ground clutter and anomalous propagation and distinguishing non-precipitating echoes such as bats and birds. Convective storm cells, like the localized region of intense reflectivity that is depicted in the lower panel of Figure 6, and precursors to hazardous weather are also studied. Depending on the confidence level of the teacher, he/she can use these same cases in his/her classroom, or can substitute real-time radar imagery provided via a web site dedicated to Earthstorm participants.

Acknowledgement

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