Recent Advances in Radar Technology for Environmental Applications

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Ⅰ. Introduction

Radar is an acronym from the early 1940s that stands for RAdio Detection And Ranging. Radars use electromagnetic waves to determine the distance, direction and type of objects (or scatterers) encountered in the path of an electromagnetic wave. The early introduction of radar was for military applications. Since then, radars have found wide variety of applications ranging from radio astronomy, law enforcement, environment and weather monitoring,marine collision avoidance, space surveillance, rendezvous systems, missile guidance and ground penetrating radar for archeological applications. Radar is a "system", that consists of several major subsystems, such as the antenna, antenna positioner, transmitter, receiver, and display. Each of these areas has enjoyed tremendous technological growth since the early days of radar and hence the radar system as a whole has evolved into numerous application areas. This article specifically focuses on the recent technological advances in environmental radar systems. In addition to hardware improvements, fundamental advances have been made in the area of radars based on physical principles such as polarization diversity, and multiple frequencies. Moreover the information age has also advanced radars with the introduction of concepts such as Cognitive radar and Multiple Input Multiple output (MIMO) radar systems. This article provides introduction to these concepts for environmental applications.

Ⅱ. Radar System Elements

Radar system are composed of a transmitter, antenna, receiver, signal processor and display subsystems. Radars operate in the environment that they intend to monitor rain, snow, or even harsh windy conditions such as hurricanes or typhoons. Therefore these radars have to be able to function in inclement weather. ⟨Figure 1⟩ shows the concept phenomenology of a radar for environmental applications. ⟨Figure 1⟩ also shows that radar waves have to penetrate through rain/snow conditions to observe rain and snow.

⟨Figure 2⟩ shows the CSU-CHILL radar, an advanced radar system currently deployed in Colorado. The figure also shows the storm clouds often found in the environment in which such a radar often has to function.

⟨Figure 3⟩ shows the block diagram of a two channel radar where each polarization is excited by a separate channel. Depending on the technology, these dual-polarization radars can be of different types, such as dual channel single transmitter/receiver, dual channel dual transmitter /receiver, or dual channel single transmitter and two receivers.Within dual polarization we have radars that can measure full

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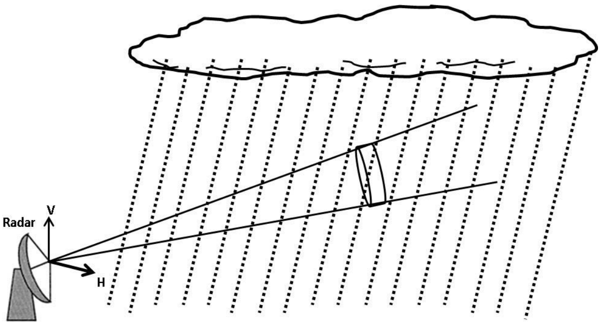
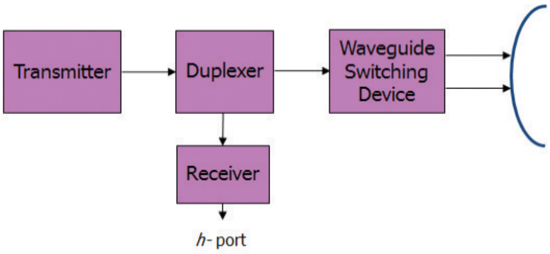
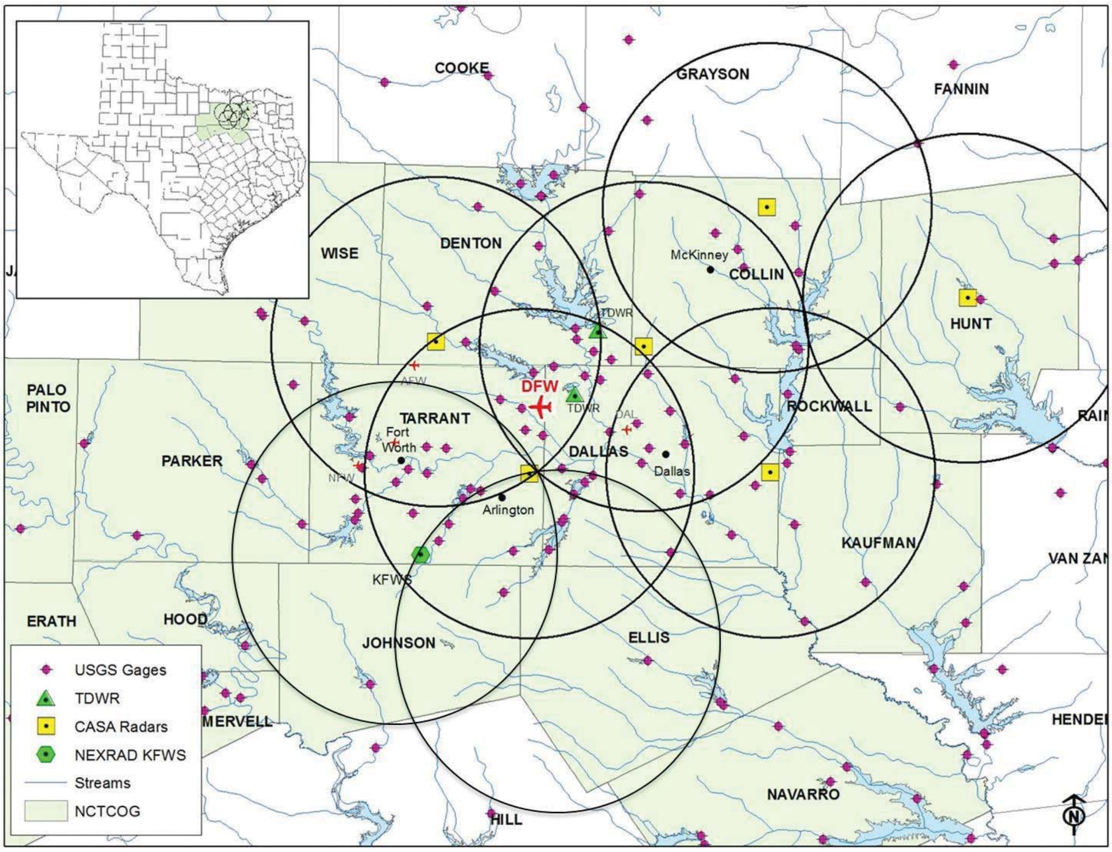


⟨Figure 1⟩ Schematic of radar observation of the prevailing environment. The radar beams must propagate through the environment under observation (such as rain or snow), to observe rain or snow farther away

⟨Figure 2⟩ The picture of the CSU-CHILL radar which is an advanced dual-polarization dual-frequency radar. This picture shows the typical condition that an environmental radar operates in. The big white dome is made of electromagnetically "almost transparent" material so that the radar is protected from the harsh environment such ass now, sleet, hail and heavy rain



⟨Figure 3⟩ A simple block diagram of a dual channel radar, where each channel is used for one polarization



〈Figure 4〉 Radar network deployment to cover the Dallas-Fortworth metropolitan region

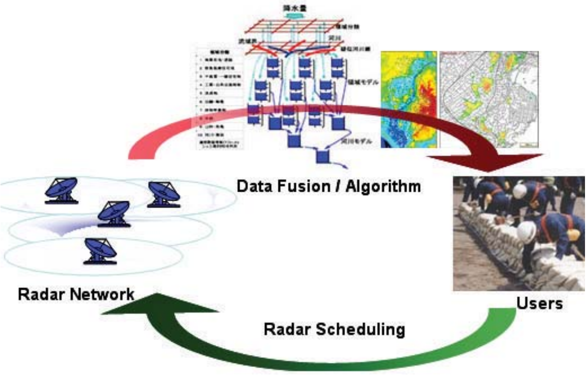
matrix of measurements (all terms of the covariance matrix of the scatters can be measured(Bringi and Chandrasekar, 2001).

Multi frequency radars are of two types. They can use closely spaced frequencies within a band, or multiple frequency bands. CSU-CHILL is a dual-frequency radar operating at S-band and X-band through a dual-wavelength, single-aperture antenna. The NCAR Eldora airborne radar is an example of a radar that radiates multiple carrier frequencies within X-band.

All these classes of radars have been in general characterized as multi-parameter radars. Another important aspect as seen in 〈Fig.2〉 is the radar observed targets are "volume targets" as opposed topoint targets such as aircraft. This has fundamental implications including altering the radar equation. These radars are typically deployed over a large geographical region over which they provide coverage. 〈Figure 4〉 shows a simple example of a network of X band radars that cover short ranges deployed over the Dallas-Fort Worth metropolitan region.

Weather Radar Networks

A dense weather radar network is an emerging concept advanced by the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) (McLaughlin 2012), which has now been demonstrated in a number of test-beds. Some examples of such deployments are the CASA IP1 radar network (Junyent 2010), the Tokyo X-net



〈Figure 5〉 Weather radar network concept

(Maki 2008), and the Puerto Rico Tropical Weather Test-Bed (Galvez 2009), where a coordinated deployment of a small number of X-band radar units allows achieving improved coverage results as described in the related literature (Junyent 2009). 〈Figure 5〉 illustrates the radar network concept: the data from multiple radars operating in the networks are fused and processed at the individual radar and network level; the relevant information is extracted and relayed to the users and used to task the network for the next scanning cycle.

Using multiple short-range radars observing over a common domain allows operating the resulting network adapting the behavior of the individual radars to optimally sample the lower troposphere scene according to user needs. Additionally, the use of short-range radars scanning close to the ground bring a clear improvement of well-known issues of current weather radar surveillance systems based upon the conventional sensing paradigm of widely-separated, stand-alone, long-range radars that operate at wavelengths in 5-10 cm. Such issues include a limited capability to observe close to the surface due to both the Earth’s curvature and blockage from complex terrain, insufficient resolution at far ranges, as well as the operational rigidity and cost of physically large and complex radar systems (NRC 1995). Numerous papers have established that maintaining appropriate low-level coverage in areas of high interest has a great impact on improving the resulting radar data products, and is of key importance for monitoring all lower troposphere weather phenomena including Quantitative Precipitation Estimation (QPE) and severe weather applications. To define the coverage capabilities of radar networks a general framework has been developed and is available in the literature to describe the radar network space, with formulations that can be used for weather radar network characterization and comparison.

In order to develop a radar network for a specific application, following a top-down approach, a number of different aspects have to be considered. At the highest level are the intended coverage capabilities of the network, which are specified to achieve the particular purpose of the network application. Once these are set, a network topology can be determined together with lower level requirements such as the characteristics of the individual radar systems composing the network to achieve that higher-level goal. Radar beam size, minimum beam altitude from ground, and minimum detectable

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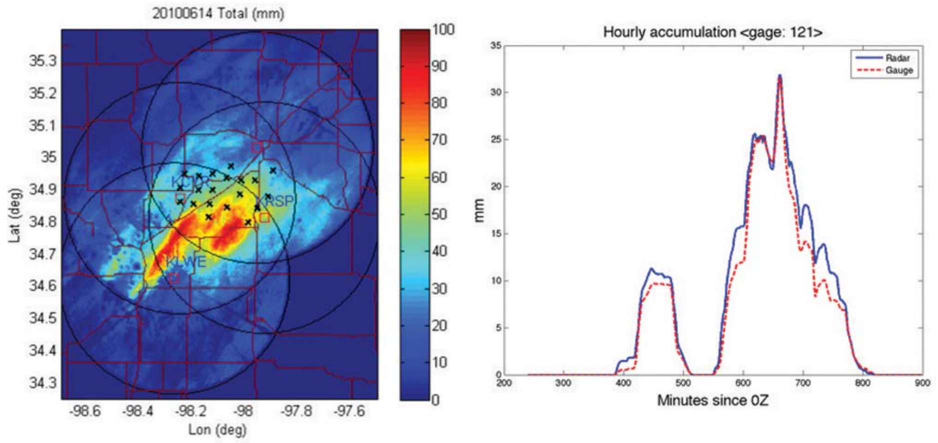
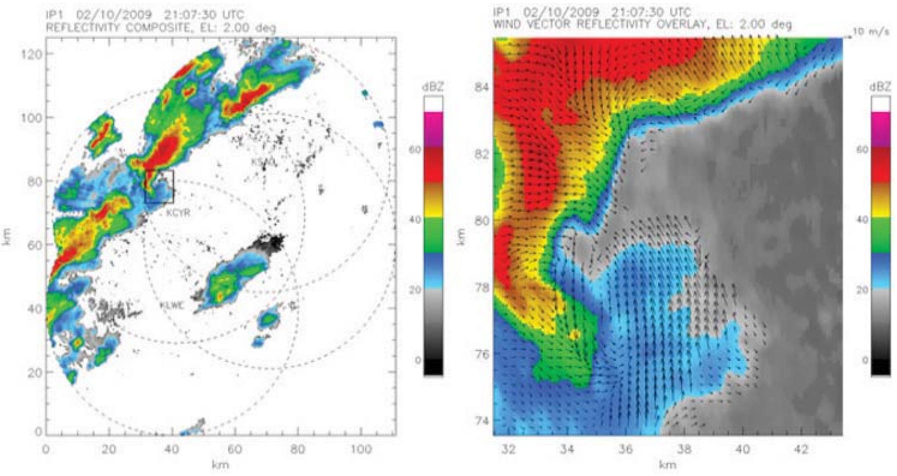


〈Figure 6〉 Radar network results for Quantitative Precipitation Estimation. Left is Storm total accumulation overlaid with GIS information for high resolution flooding evaluation. The x marks indicate rain gage locations, and the circles indicate 40km range rings for networked radars. Time-series profiles show radar and rain gage measurements of hourly rainfall accumulation for flood potential monitoring (Adapted from Wang, 2010)



〈Figure 7〉 Severe weather mapping. Left is network composite reflectivity, right is multiple-Doppler wind vectors overlaid on reflectivity (adapted from Junyent, 2010)

reflectivity are system parameters useful in characterizing a specific weather radar system, as they indicate most of the relevant information concerning a single radar. These system parameters are first established for an individual radar, and then they are extended and generalized over the domain of a radar network composed of multiple radar cells.

Weather radar networks have the potential to make a great impact over localized domains such as densely populated, infrastructure intensive, and/or complex terrain areas of interest. 〈Figures 6 and 7〉 show examples of precipitation estimation and severe weather mapping data products in a weather radar network.

Solid State Transmitters

Rapid strides made in semiconductor technology in the recent past have enabled the development of high-power microwave amplifiers that do not require the use of electron-tube devices such as Klystrons or Travelling Wave Tubes (TWTs) (Meth, 1997). These were available in the late-80s, but only recently has the communications industry made high-power solid-state amplifiers affordable. Individual solid-state amplifiers only produce a few watts of output power, but by power-combining a number of these amplifiers, a reasonably high output power may be achieved.

Solid-state amplifiers generally are not easy to manufacture at high peak power levels associated with typical weather radars. However, they do offer wide pulse widths and high duty cycle operation, and are easily able to generate similar average power as an electron-tube device. Utilizing pulse compression, it is possible to achieve the same sensitivity as an electron-tube transmitter. In addition, the solid-state transmitter offers several advantages:

- Improved MTBF (mean time between failures). Extrapolations from accelerated-life testing have shown 〉 500,000 hour MTBF. An S-band solid-state amplifier, designed as a replacement for a Klystron, has reported a factor-of-four improvement in system MTBF (Hanczor and Kumar, 1993).
- Graceful degradation of system performance when individual modules fail. Well-designed solid-state transmitters even offer hot-swap of failed modules, eliminating down-time.
- No hot cathodes, which eliminates warm-up time. This reduces maintenance down-time.
- Lower operating voltages. Instead of the tens or hundreds of kilovolts required by electron tubes, solid-state amplifiers need only a few volts to operate. Thus, all the advances made in low-voltage power electronics can be leveraged for improved performance, efficiency and reliability.
- Improved clutter rejection capability, due to spectral purity of the transmitter output (Ulanowicz and Hooper, 1998). The RF spectra of existing electron-tube transmitters exhibit strong frequency sidelobes, which restrict the clutter suppression to about 35 dB. With a solid state amplifier, this can be improved to better than 60 dB due to the cleaner spectrum.
- Wideband capability, which is inherent to solid-state amplifiers.

Due to the advantages presented above, solid-state amplifiers are now a viable option for use as a radar transmitter subsystem.

Wide-band Waveform Capabilities

In addition to the operational advantages presented above, Solid-state transmitters offer the ability to transmit wide-band waveforms. The additional degree of freedom offered by wide-band waveforms open up new capabilities to radar systems, such as:

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- Range-velocity ambiguity mitigation, through the use of frequency diversity and coding diversity offer improved performance over current narrow-band techniques
- Faster scanning of a volume, without sacrificing data quality, due to range averaging of the additional independent samples introduced by both frequency diversity as well as pulse compression. Rapid scanning is particularly valuable during studies of electrification and rapidly evolving convective-scale phenomena. An increase in scan speeds is possible if additional independent samples are obtained through frequency diversity.
- Data quality improvement, specifically, reduced variance in estimated parameters, due to range-averaging of the additional independent samples introduced by both Frequency Diversity and Pulse Compression.
- Improved range resolution, without sacrificing sensitivity, due to Pulse Compression. High resolution is important to better study small-scale phenomena such as microbursts.
- Reduced interference between adjacent radar systems using code diversity multiplexing.

Pulse compression radars radiate and receive coded long pulses, and make use of signal processing techniques to recover the range resolution that is lost due to the longer pulse. In modern radars, this processing is done post-digitization. As a result, the peak-to-average power ratio will increase after the analog-to-digital conversion on receiver. Thus, the very high peak-to-average power ratio requirement present in short-pulse radars is mitigated. This results in a reduction of the dynamic range required by the analog subsystems, while maintaining high overall system dynamic range.

Advances in Receiver and Processing Technology

Modern weather radar systems are precision computer-controlled instruments that are capable of performing a variety of measurements tailored to users' needs. As the instrument complexity grows, so does the need for improved signal processing algorithms that can be changed to match the operational requirements of the system. Enhancements in data converter technology, digital logic and computer systems are harnessed to provide greater capabilities to the radar systems.

It has become commonplace to use off-the-shelf computing hardware to perform the signal processing for weather radars. This has the benefit of being inexpensive, and permits rapid upgrades to support new algorithms by simply replacing the computers with upgraded ones. Moore's Law ensures that the cost impact is minimized. Off-the-shelf technologies that are commonplace in data centers, such as Gigabit Ethernet are used to provide an inexpensive, yet reliable communications protocol for high bandwidth digitized radar signals (DRS).

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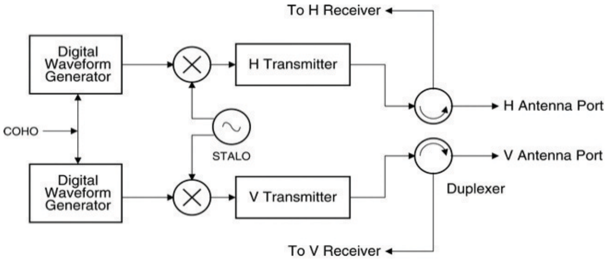
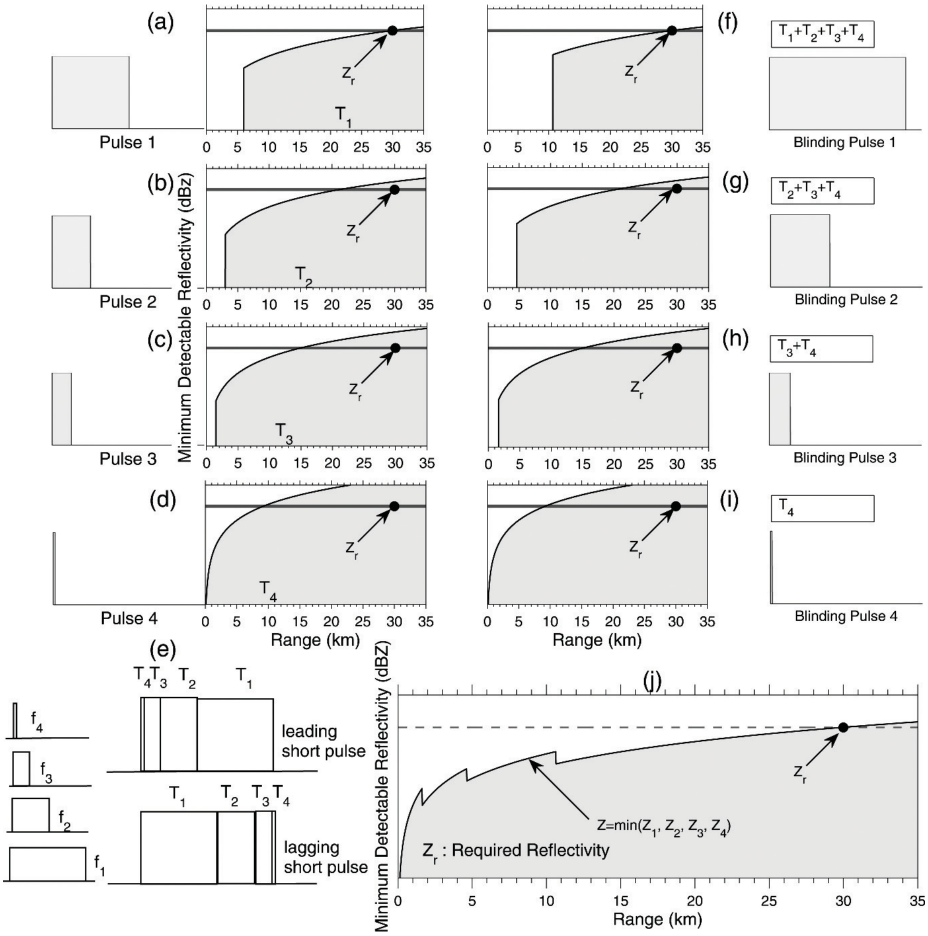
Another application of commercial hardware is in the digital receiver. Data acquisition boards based on Field Programmable Gate

Arrays (FPGAs) provide a cost-effective method of acquiring radar data at very high bandwidths. Initial signal processing, such as mixing to baseband, filtering and pulse compression can be effectively performed within the FPGA device. The FPGA may also be used as a waveform and radar timing generation device. The entire radar digital hardware may, therefore, be implemented on a single commercially available, multi-source PCB.

Signal processing algorithms have seen a steady advance since the early days of weather radar that simply integrated range bins to generate reflectivity maps. Early attempts at digital radar processing algorithms focused on frequency



〈Figure 8〉 Architecture of a dual-polarization dual channel transmit receive system



〈Figure 9〉 Minimum detectable radar reflectivity of a sensitivity-mapped frequency diversity waveform with many sub-pulses. Such waveforms are made possible with agile transmitters (Figure adapted from Bharadwaj and Chandrasekar, 2012) domain approaches, but were limited by available computer technology. Pulse-pair algorithms were a good fit to earlier computer hardware, but have given way to frequency domain techniques such as the Gaussian Model Adaptive Processing (GMAP) that are being used operationally (Bringi and Chandrasekar, 2001). Advanced time-domain parametric modeling methods are being tested on research radar systems that promise performance equivalent to older methods, but with much shorter integration times.

Finally, active phased-array radars promise the ultimate in flexibility and short volume scan times.Adaptively matching the radar scan strategy to the space- and time-variability of the observed weather promises to improve scan times to as short as 14 seconds for a 90 degree volume.

The advantages of agile dual-channel solid-state transmitters can be combined with computational capabilities of advanced digital receiver and signal processors 〈Figure 8〉 to implement versatile algorithms to improve the radar operational capabilities (Bharadwaj and Chandrasekar 2012). 〈Figure 9〉, repeated from Bhardwaj and Chandrasekar (2012) shows some advanced concepts of distributing sensitivity with pulse compression and stacking multiple waveforms at different frequency bands. This takes advantage of the wide-band nature of solid state transmitters and high-speed computation offered by modern digital receivers. 〈Figure 9〉 shows the architectural concepts of advanced waveforms closely linking the transmitter and receiver channels.

Specialized radars

Modern weather radar systems are computer-controlled complex waveform transmitting devices which are capable of performing a variety of measurements adapting to the prevailing environment. This capability has led to implementing architectural and other concepts such as MIMO, or Cognitive radars. As the instrument complexity grows, so does the need for improved signal processing algorithms that can be changed as per the operational requirements of the system. Enhancements in data converter technology, digital logic and computer systems are harnessed to provide greater capabilities to the radar systems. MIMO systems have been written about extensively in the literature and these exploit the multiple input/output capabilities of the antenna. While the MIMO concept itself has not been taken up in environmental applications, multi-function radar concepts are being pursued, to observe weather and track targets at the same time.

Cognitive radars on the other hand utilize extremely flexible transmit and receive waveforms, coupled with extensive embedded computing capabilities that can adaptively adjust to the prevailing environment. The networked CASA system which closes the loop with the users shown in 〈Fig. 4〉 is one implementation of the cognitive concept. It is the time constant of the loop that places demands on the cognitive capability.

Part of the requirement of these radars is to determine the scanning hemisphere where the needs are greatest, and to allocate resources as appropriate. The scan capability gets faster with electronic scan systems. Thus,an electronic scan radar, as part of a network with solid state transmitters, with agile waveform capability will provide a good environment to test cognitive radar capability for environmental applications.

Summary

Modern weather and environmental radar systems have enjoyed revolutionary transformation. This includes scientific advances such as multiple polarization, multiple wavelength and network sensing. Engineering advances include solid state transmitters, advanced signal processors aided by high performance computing, electronic scan antennas, and the ability to close the loop between radar observations and prevailing environment. The rapid advances are being tested and evaluated in several research locations including the CSU-CHILL radar facility. While many of these advances are interesting from a technological point of view, some of these will pass the "cost benefit analysis" tests, and are expected to find place in future operational applications.

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