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THE EVANSVILLE NEW GENERATION RADAR: 40 YEARS OF S-BAND RADAR DEVELOPMENT

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1. INTRODUCTION

The evolution of the United States National Weather Service (NWS) weather radar systems began soon after World War II. The first system, WSR-1, became operational April 1, 1947 in Wichita, Kansas. A few years later, the WSR-3, an X-band system went online. These systems were World War II surplus radar sets and remained in service until the late-1990's. In the mid-1950's, Congress created a program specifically for the development and deployment of weather radar systems; and the WSR-57 was born. The WSR-74S was developed in the mid-1970's. In the late 1970's and early 1980's, a new weather radar system for the National Weather Service, the NEXt generation RADar (NEXRAD) was designed. Deployment began in the late 1980's and ended in the mid '90's. In 2001, the U.S. National Weather Services requested proposals for the New Generation system installed in Evansville, Indiana. The result was a new species of S-band weather radar using the latest technology derived from 40 years of S-band development. Incorporating modern technology, the New Generation radar represents a quantum leap in performance and reliability in weather radar systems. This paper reviews the history of S-band weather radar development culminating in the New Generation radar.

2. WSR-57 and WSR74

An early S-band weather radar system, the WSR-57 used a conventional magnetron as the high power oscillator with a peak power of 500 kW and an effective range of 463 km. The system utilized a 3.6 m diameter antenna providing a beamwidth of 2^o and a gain of 38 dB.

The WSR-74S (Figure 1) used a coaxial magnetron having a peak power of 500 kW and an effective range of 480 km. This system also utilized an antenna with a 3.6 meter diameter.

The physical differences between a coaxial (WSR74) and conventional (WSR-57) magnetrons are minor, but have a dramatic impact on performance issues. The primary difference is the existence of

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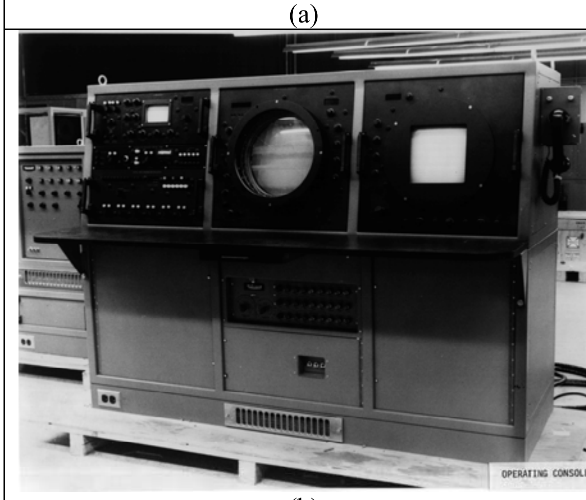

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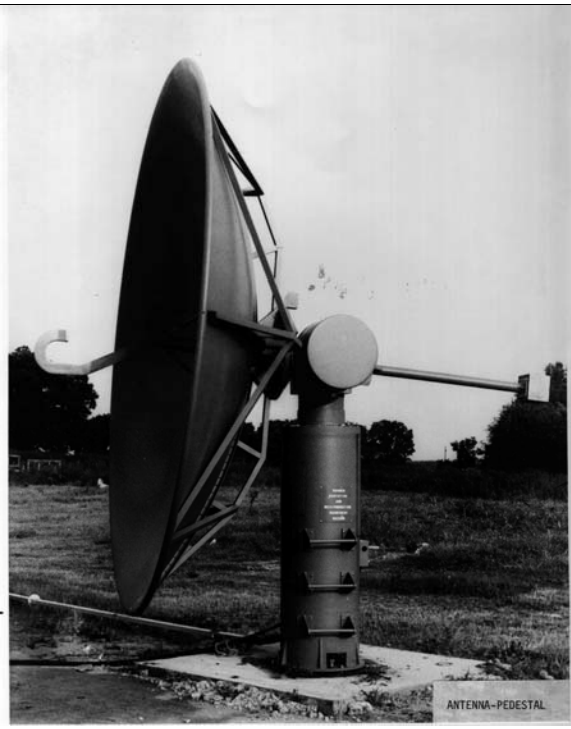

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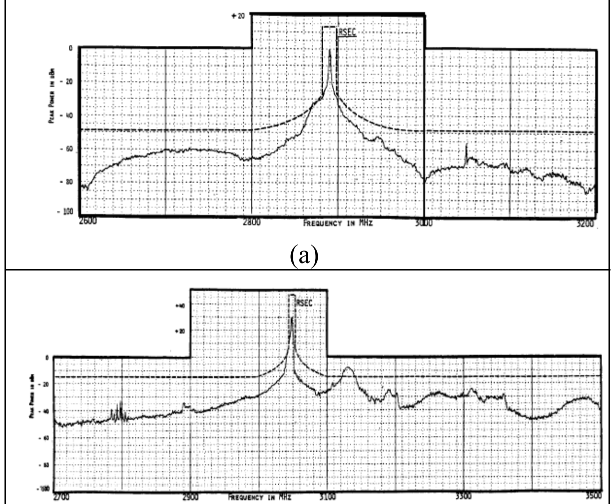
Figure 1 The WSR-74



(a)

(b)

Figure 2 Energy Spectra (a) WSR-57 and (b) WSR-74 (Matheson, 1982).

stabilizing cavities in the coaxial magnetron. These cavities allow more resonating cavities to exist in the magnetron, reducing the necessary electron emission density from the cathode. In addition, bu physically changing the size of the stabilizing cavity (via a noncontacting plunger), the coaxial magnetron can be tuned through a range of frequencies. Conventional magnetrons are not that forgiving. Either inductive pins or capacitive loading had to be introduced into the resonator cavities, changing the shape of the resonators themselves. This resulted in many nonlinear effects and greatly increases arcing in the tube that results in premature destruction. In other words, the tuning of a conventional magnetron is not recommended. In terms of spectral performance, the use of the stabilizing cavity provides a much cleaner energy spectrum as seen in Figure 2. However, there is a resultant hump approximately 100 MHz above the resonant peak. This results from nonlinear modes in the tube.

Approximately 53 sites around the country were outfitted with the WSR-57 and the WSR-74S weather radar systems. In 1981, the manufacterer of the WSR-74S systems, Enterprise Electronics Corporation, developed a Doppler Modification Kit. One of the first systems outfitted with the Doppler kit was the Montgomery, Alabama NWS radar. The modification occurred in 1982. Figure 3 shows a velocity image of a tornado outbreak soon after the upgrade.

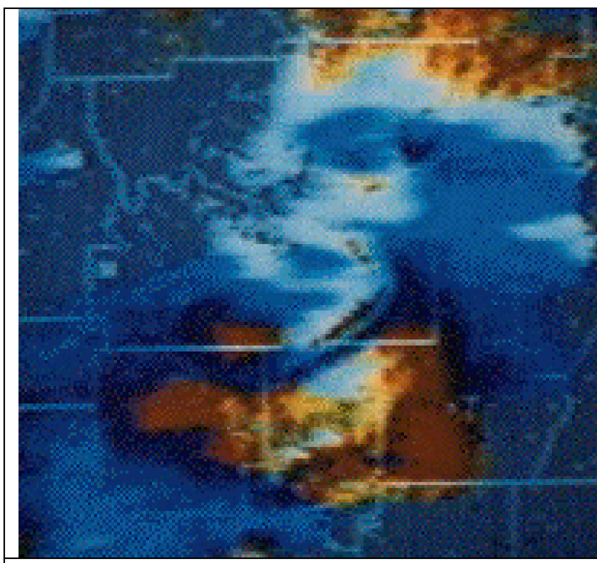


Figure 3. Velocity Image of tornado outbreak from NWS First Doppler WSR-74

3. NEXt generation RADar (NEXRAD)

The NEXRAD radar system was a revolution in weather radar technology designed in the early 1980's and began deployment in the late 1980's. The NEXRAD system is actually a merging of subsystems, the data acquisition system (including the transmitter, antenna, pedestal, and digitization circuits).

The signal processor takes the raw signal data, the *I* (in-phase) and *Q* (quadrature) components of the detected signal and forms them into the base data, and the product generator that takes the base data and produces the radar products. Rather than performing analog operations on the radar signal to produce the radar products, computer algorithms manipulated the data, allowing relatively simple implementation of new algorithms without large hardware expense (at least in theory).

The NEXRAD weather radar system was a great departure away from the low cost magnetron transmitters to high power klystron based transmitters. Whereas a magnetron is a high power RF generator, a klystron is an amplifier. An accelerated electron beam is modulated by the RF signal that requires amplification. The amplification is achieved through the use of resonant cavities sized to match the modulation frequency.

The advantages of the klystron are significant. The engineer has a much greater control of the phase and amplitude of the emitted RF pulse. Thus, every pulse can be at exactly the same phase, or can be coded to optimize the signal detection characteristics. In the same vain, the modulating RF signal that is being amplified can be distorted to optimize the energy spectrum. The result is a very clean energy spectrum that is very versatile.

Current NEXRAD systems transmit with a peak power of 750 kW. The NEXRAD system has a much larger antenna (8.5 m) that the WSR-74, giving a 1^{o} beamwidth and a gain of 45 dB.

The NEXRAD radar system has a solid-state, line-type modulator designed by Westinghouse. The pulse waveform is developed via one of two Pulse Forming Networks (PFN), one for each pulsewidth used (1.5 µs or between 4.5 µs and 5.0 µs). Characteristically, changing pulse widths on a system with a line-type modulator requires a hardware switching action. Each desired pulse width has its own dedicated PFN. Thus, the pulse widths are endemic to the system and are difficult to vary. In addition, PFN's tend to have high failure rates. Current maintenance records show replacement or repair of 108 modulators win the 2002 fiscal year.

Discharge of the pulse energy through the PFN network is controlled by four triggers (eight triggers total to fire the pulse), the transmitter charge trigger, post charge regulator trigger, modulator trigger, and RF trigger. The transmitter charge trigger initiates the charging of the capacitor bank, i.e. the storing of energy for the pulse. The charging of the capacitor bank continues until the Post Charge Regulator Trigger initiates the bleeding off of excess energy until the capacitor bank reaches the stored energy level. The process provides very high tolerances on the energy, allowing for excellent repeatability. The Modulator Trigger initiates the release of energy to the PFN network. Finally, the RF Trigger occurs when the optimal conducting region of the tube is obtained, initiating the formation of the energy pulse is formed and transmitted. Due to the high energy levels and the complexity involved in the triggering of the NEXRAD radar system, the trigger amplifiers have a high failure rate with over 200 failures per year. That averages about 1¼ a system.

The NEXRAD klystron tube is designed for amplification of S-band (2.7 – 2.9 GHz) RF energy and transmits a 750 kW pulse, at the upper level of the modulator design but below the tube's specified minimum transmit level.

The current RDA samples the 57.5491 MHz IF at a rate approximately $1/100^{th}$ the IF frequency. The resultant digitized data is fed into a hardwired signal processor that filters the data and converts it to the base data.

The antenna and pedestal subsystem of the current NEXRAD system uses a specialized antenna produced by Andrew Canada. The pedestal utilizes an oil bath for lubrication and heat transfer of the mechanical components. In the fiscal year 2002, the NEXRAD program replaced 70 motors and 55 encoders.

The reliability of NEXRAD systems have decreased as the systems age. The average MTBF (Mean Time Between Failure) figures for the NEXRAD program are approximately 800 hours. Figure 3 provides a history and trend in NEXRAD maintenance. As expected, as the systems age, more maintenance is required.

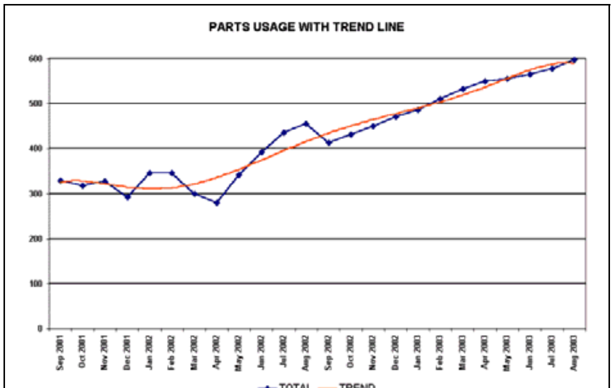


Figure 3 Parts usage trend for NEXRAD

4. New Generation Radar

The NEXRAD radar systems were a revolution in weather radar technology. The New Generation Radar is a dramatic leap forward. Modern power handling technology allows much more efficient management of high power pulse transmission. Modern processor technology provides orders of magnitude better signal processing capability, with extensive reserve for future processing expansion. In addition, modern processors allow the integration of all test functionality, manual control switches, and diagnostic metrics to be performed onsite using a LCD monitor mounted on the radar system, or via remote workstation. The New Generation radar was specified to have at least a 1500 hour MTBF, but actual figures are in the 2400 hour range.

Modulator

The New Generation modulator developed by Enterprise Electronics Corporation (EEC) is an active switch, cathode pulser type modulator. Active switch type modulators allow flexibility with pulse widths and pulse repetition frequencies, allowing a user to vary the pulse width "on the fly". With an active switch modulator, patterns of mixed pulse lengths and/or burst of pulses are available.

The maximum pulse length is determined by the energy storage capability of the capacitor bank. To minimize droop, the capacitor bank must store much more energy than is required for the pulse. For the New Generation modulator, each pulse drains the capacitor bank by 75 V, from a 2000 V potential to a 1925 V potential. The design provides only about 7.5 % of the available energy in the capacitor bank to be used for each pulse resulting in quicker recovery time of the capacitor bank. In addition, the limitation on duty cycle is purely a function of the capacity of the power supply used to charge the capacitor bank.

A unique feature of the New Generation modulator is the number of triggers required to fire the pulse, one. The modulator controls the firing of the beam pulse energy based upon the received trigger, greatly reducing the complexity of the triggering mechanism. The triggers are simply TTL signals, eliminating the high energy / coronal effects endemic to the line type modulators.

EEC designed the New Generation modulator to have a maximum duty cycle of 0.022. Under operational test, the modulator has remained stable running with a 0.027 duty cycle. Figure 3 is initial test data from the New Generation modulator for the 1.6 µs and the 4.6 µs pulses. Thus, pulses of any pulsewidth and PRF may be employed, as long as they do not violate the modulator and tube duty cycles. Safety and tube protection interlocks are built into the modulator allowing quicker response to protect the vital and expensive components of the system. In addition, the New Generation modulator is highly reliable and stable.

The New Generation Modulator was designed and tested to deliver pulse power up to 1.1 MW if desired. The New Generation radar in Evansville is operating on the low end of the Klystron and modulator's operational range, 850 kW (89.3 dBm), a full 100 kW more than the NEXRAD systems.

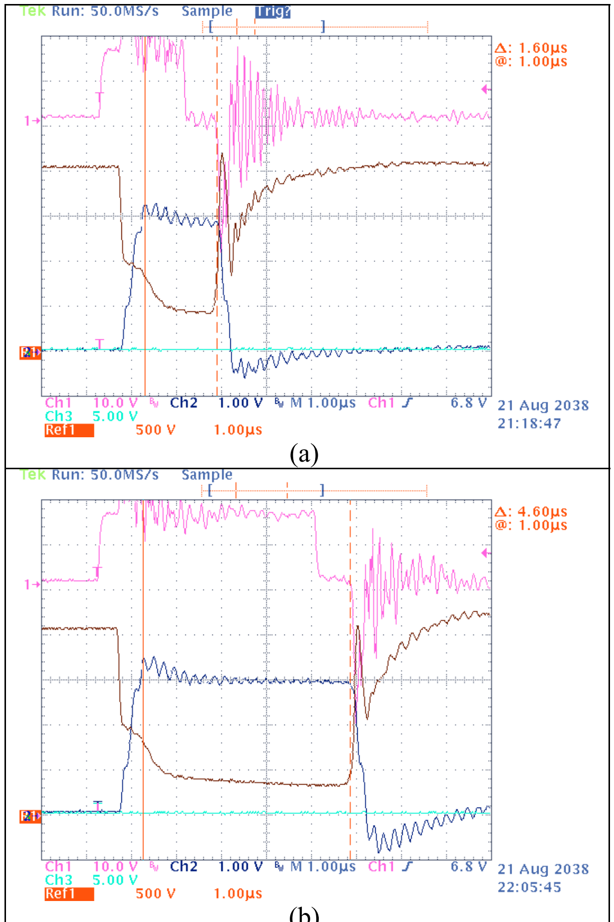


Figure 3. Initial test data from the New Generation Modulator for (a) 1.6 µs and (b) 4.6 µs pulsewidths,

Pedestal

Another leap forward is the antenna pedestal technology. The New Generation pedestal is based upon the field proven F-series pedestal from Enterprise Electronics Corporation. It is a fully integrated pedestal with the servo amplifiers and encoders located within the pedestal itself. The EEC F-series pedestal utilizes two 4.6 horsepower motors (one for azimuth and one for elevation) providing power drive the 8.5 m (28') antenna at a rate of 5 rpm, sustained. The azimuth and elevation drive modules are identical, optimizing spare parts compatibility and minimizing maintenance costs. The New Generation pedestal is environmentally friendly. Rather than a high maintenance oil bath for the lubrication and cooling of the gear heads and bull gear (as with the NEXRAD system), the New Generation pedestal uses standard grease fitting to allow insertion of lubricating grease into the drive modules. In addition, the gearboxes along both axes are no maintenance, grease lubricated planetary gearboxes. Experience has demonstrated these pedestals to be rugged and enduring.

Cabinet

Through the advent of modern computers and networking, the analog meters and switches have been replaced with a centralized computer operated system. The diagnostic information formerly displayed on meters are now displayed on computer screens, and the manual, analog switches are also computer controlled. These diagnostic tools may be accessed via the touchscreen, LCD computer console mounted on the transmitter cabinet. These features may also be accessed remotely over Ethernet connections.

Signal Processor

Another dramatic improvement from the NEXRAD to the New Generation radar is the data handling. In both systems, the detected signal is translated to an intermediate frequency (IF) of about 57.5491 MHz, but that is where the similarity ends.

In the current NEXRAD, IF is mixed with a sample of the burst (at IF) stored in an analog COHO that translates the signal to baseband that is then sampled at a rate of about 600 kHz. The digitized *I* and *Q* data undergoes clutter filtering and is transferred to the hardwired signal processor (HSP) for base data estimation.

The New Generation radar uses the latest in digital receiver and signal processor technology, the EDRP-9 by Enterprise Electronics Corporation. Upon transmission, the burst sample is digitized and signal processing routines determine the frequency, phase and burst power to a high degree of accuracy. The received IF signal is digitized at a rate of 80 MS/s and 14 bit resolution. The digital signal is subsequently translated to baseband, an approach allowing a system to obtain an unprecedented amount of coherency. The digitized baseband signal is then converted into the base data via the standard signal processing algorithms.

The EDRP-9 digital receiver and signal processor is designed for use with wide-band radar signals, with emphasis upon the following features:

- a dynamic range greater than 100 dB
- high linearity (± 0.5 dB)
- 512 Samples of 2048 gates
- a very high channel to channel stability over time and temperature
- 2.9 **GFLOPS** of processing power expandable to 5.7 **GFLOPS**
- fast Ethernet communications
- full BITE capabilities
- simultaneous dual polarization ready

A unique feature of the EDRP-9 is its Arbitrary Waveform Generator (AWG) that can sample and characterize the burst. Then, for subsequent pulses, it can predistort the burst, optimizing the pulse waveform. The AWG also provides the capabilities for advanced signal processing techniques such as phase coding and pulse coding.

The EDRP-9 is designed to meet any future needs of the U.S. National Weather Service and the international meteorological community. As noted, the EDRP-9 is simultaneous dual polarization ready, thus all that is required for such an implementation is the necessary waveguide components and a connection to the second channel of the EDRP-9.

5. New Generation RDA Host

The New Generation RDA Host provides the interface between the EDRP-9 and ORPG. This is a flexible subsystem providing all of the base, Level II radar data, alarm status metadata to the ORPG. The ORPG, in turn, sees the RDA Host as a standard NEXRAD RDA.

An additional benefit of the New Generation RDA Host is the ability to connect to any EEC radar and provide Level II data to an ORPG. This provides an additional level flexibility to the National Weather Service and other users of Level II data.

Other, custom radar control and data formats are equally available to the radar market, allowing any weather radar in the world to become a NEXRAD clone.

The New Generation RDA Host provides the flexibility necessary to meet any future NEXRAD scan strategies and data requirements. This includes the proposed future VCP strategies (Wood, 2000), 0.5 degree data requirement, real-time data multicasting (Saffle, 1999 and Crum, 2002), and simultaneous dual polarization.

6. Conclusion

The New Generation radar system installed in Evansville, Indiana represents a dramatic leap forward in weather radar technology. With its efficient use of modern, high energy/power technology and modular design, the New Generation Radar provides a base for weather radar systems of the future.

The design provides upgrade paths for currently fielded systems of older technology. For example, over 100 current NEXRAD modulators are replaced each year with the same, obsolete, difficult to maintain design. The New Generation modulator represents an easy upgrade option for the current NEXRAD program, providing increased stability, longevity, and flexibility to the NEXRAD systems. The MTBF of the New Generation radar is approximately triple that of NEXRAD systems, with its associated impact on system up-time.

As noted, the New Generation RDA Host allows any weather radar system in the world to become a NEXRAD clone. This has great implications for weather radar in general. Algorithms developed to handle NEXRAD's data, even with its low resolution, can be implemented directly by any radar using the translator package. With the RDA Host, NEXRAD becomes an international meteorological endeavor.

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