INTRODUCTION TO MULTI-CHANNEL RECEIVER DEVELOPMENT FOR THE REALIZATION MULTI-MISSION CAPABILITIES AT THE NATIONAL WEATHER RADAR TESTBED

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Abstract

This paper describes the beginning states of a new project that will digitize radar signals coming from eight channels on the phased array antenna at the National Weather Radar Testbed (NWRT) in Norman, Oklahoma. At the current time, a single-channel digital receiver is operational to mimic the current WSR-88D capability. The multi-channel digital data will foster a new generation of adaptive/fast scanning techniques and space-antenna/interferometry measurements, which will then be used for improved weather forecasting via data assimilation. Differing from the conventional rotating radar, the phased array is suited for multi-mission capabilities so that a variety of targets may be observed simultaneously with a high degree of fidelity. The development of a multi-channel receiver will be the catalyst and an enabling tool for research in this area for the next decade. This collaborative project, which involves scientists and engineers from the University of Oklahoma and the National Severe Storms Laboratory in Norman, is the result of a recently funded a grant from the National Science Foundation (as described in the Acknowledgement section of this paper).

Instrumentation of the phased array radar system with a multi-channel receiver suite will bring the full creativity of researchers using advanced techniques for maximizing the information from radar observations, and optimally using them in numerical models to improve weather prediction. The multi-channel receiver will collect signals from the sum, azimuth-difference, elevation-difference, and five broad-beamed auxiliary channels. One of the major advantages of the NWRT is the capability to adaptively scan weather phenomena at higher temporal resolution than is possible by the WSR-88D. Hemispherical coverage in 1 min or less vs. 4 min, can be accomplished without comprising data accuracy. The multi-channel receiver will allow direct implementation of inteferometry techniques to measure cross-beam wind, shear and turbulence within a radar resolution volume. Access to the auxiliary channels will enable clutter mitigation and advanced array processing for high data quality with short dwell times. Potential benefits of high quality and high resolution data together with cross-beam wind, shear and turbulence include better understanding of storm dynamics and convective initiation, better detection of small-scale phenomena including tornado and microburst, ultimately leading to increased lead time for warnings, and improved weather prediction.

1. INTRODUCTION AND MOTIVATING FACTORS

The current configuration of the single-channel digital receiver is designed to mimic the current WSR-88D capability. The full power of adaptive sensing, resolution enhancement, quality improvement, and measuring new meteorological parameters can be explored by developing a suite of digital receivers to access signals from existing multiple channels on the antenna that are not yet instrumented. The impact of the additional crossbeam wind/shear/turbulence measurements, and the higher data rates, achieved through adaptive and optimal scans, and their improved data quality on three-dimensional retrieval of the wind, thermodynamic and microphysical state of the atmosphere will be systematically evaluated within several existing and future projects. Figure 1 summarizes all the research components and their feedback into the receiver design and operation.

A digital receiver suite is being built which will enable researchers using the National Weather Radar Testbed (NWRT) access to all the functionalities normally found on multi-function radars. This receiver suite will replace the current single channel (sum-beam) receiver

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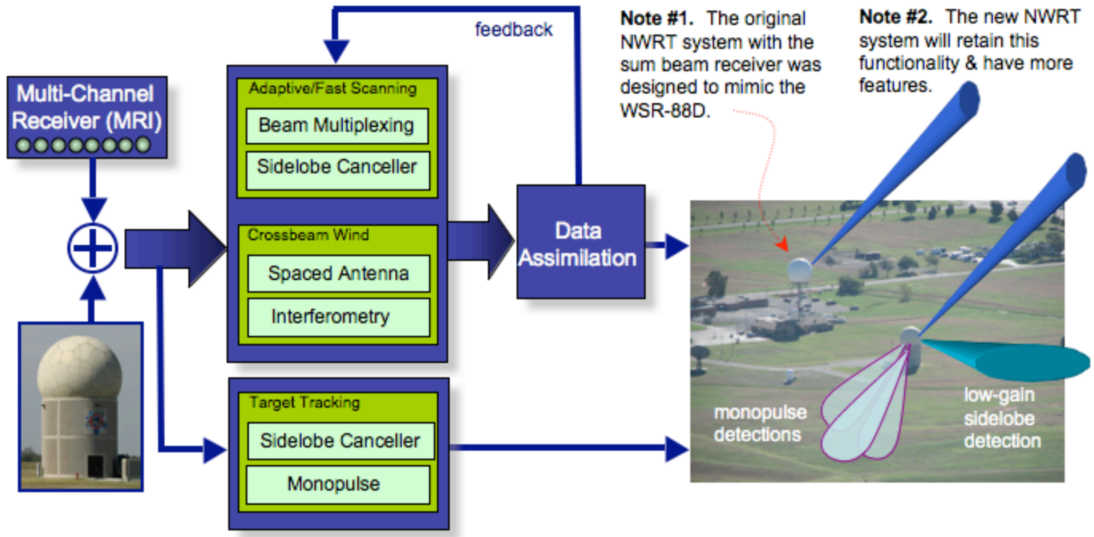

Figure 1: *The current National Weather Radar Testbed plus the proposed multi-channel receiver yields a system that supports multi-mission capabilities.*

system with an eight-channel suite to receive, digitize and record sum, azimuth difference, elevation difference and a combination of five auxiliary channels. All of these channels are available with no modification to the SPY-1 Phased Array antenna at the site. The receiver suite will be made "drop-in" compatible with the current antenna and processor system, and will include a separate recording system to accommodate the nearly 320MB/sec data rate generated by these additional channels. The current NWRT system was developed by a team consisting of Lockheed Martin, National Severe Storms Labs and the University of Oklahoma. The OU team will continue to work closely with the National Severe Storms Lab to assure the design can interface with the current system, and the operation of the integrated system will include all the functionality of the current system in addition to the multi-function hardware made possible by this MRI development. Details about the current system can be found in [Forsyth et al., 2007]. As in the current system, access to the multi-mode functionality will be available for remote operation from the National Weather Center operations center. The addition of the multi-channel receiver system will allow the NWRT to be configured as a multi-function radar. Multi-function radar modes will not be developed as a part of this MRI activity, but all the hardware required for experimentalists to gather contemporary data from each channel so that multi-function algorithms can be tested off line with self-consistent data sets.

1.1. Beam Multi-Plexing

Rapid scanning is one of the primary motivating factors. Faster data updates are often required for fast-evolving convective storms [e.g., Carbone et al., 1985]. In addition, [Shapiro et al., 2003] and [Qiu and Xu, 1996] have shown that single Doppler wind retrieval can be improved using data with rapid updates on the order of 1 min, and [Xue et al., 2006] and [Xu et al., 2007] have shown that the thunderstorm analysis can be significantly improved by using 1 minute volume scans when assimilated using the ensemble Kalman filter method. Recent results from mobile radars have shown that the dynamics and structure of tornadoes can vary significantly over a few minutes [e.g., Alexander and Wurman, 2005; Bluestein et al., 2003]. Therefore, rapid scanning is needed not only to increase the warning lead time but also to advance the understanding of fast-evolving weather systems. However, for mechanically rotating antenna, fast update of volumetric weather data is achieved at the expense of degradation in data quality because fewer independent samples are obtained and used in the spectral moment estimation. On the other hand, a phased array radar can directly collect independent samples by revisiting the region of interest through flexible beam steering to optimized the data quality. During the revisit period, the radar can managed to perform other tasks such as surveil other regions or airplane tracking to maximize the use of radar resources. This scanning scheme is termed beam multiplexing (BMX) with a minimum number of two pulses transmitted in each beam direction each visit in order to estimate all three spectral moments using the autocovariance method [Doviak and Zrnić, 1993]. Next, [Yu et al., 2007] have shown that BMX can improve the data update time by an average factor of 2-3.8 at the NWRT.

Radar returns sometimes are contained unwanted signals such as interference and clutters. For the WSR-88D, a notch filter with variable width was developed to mitigate ground clutter. The filter is implemented on a number of samples from uniform prt and can be considered of time-domain filter. Ice et al. [2004] have shown that Gaussian model adaptive processing (GMAP) for clutter filtering in the spectral domain can provide better moment estimation. At least several samples (approximately 16) are required to obtain a representative spectrum of both signal and clutter. For a phased array radar operating in a BMX mode, although accurate data with fast update time can be obtained, effective clutter mitigation is limited due to only two samples are available. *Therefore, clutter filtering using signals from sidelobe cancellers (SLC) becomes essential to optimize radar performance*.

1.2. Generalized Sidelobe Canceller

The next motivating factor is the ability to implement spatial filtering, which is not possible with the conventional WSR-88D. The present discussion relates to improvements in signal-processing systems and more particularly to improved techniques for eliminating interference introduced into the mainlobe of an antenna from an interference source. Signal-processing equipment in general is designed with a goal of receiving only particular information for evaluation. However, as is often the case, desired information is not isolated by itself but may be found in the presence of unwanted signals. Antenna systems in particular have characteristics that include a mainlobe for receiving desired information and a plurality of sidelobes at various angles relative to the mainlobe. Due to the nature of an antenna, information received in a sidelobe is indistinguishable from information received in the mainlobe and thus renders the equipment highly susceptible to interference from unwanted signals or information. This problem is particularly acute in radar systems where the presence of sidelobes makes it possible for a single interference source to degrade a radar from any angle of azimuth.

Sidelobe cancellation is a fundamental approach to eliminating interference in received signals and has been used relatively successfully to eliminate the interference and ground clutter. Generally, to provide successful cancellation, the sidelobe canceller employs auxiliary omni-directional antennas, receiving channels and adaptive cancellation loops to remove interference signals which enter the sidelobe response of a radar system. The adaptive loops function by adjusting the phase and magnitude of the received auxiliary signals such that they subtract out the interference present in the main radar channel. The gains of the auxiliary channels are nominally made much less than the mainlobe gain of the radar system in order to prevent cancellation of legitimate target-return signals. This relative gain difference prohibits the sidelobe canceller from effectively cancelling direct-path interference received by the radar mainlobe.

Based on the array configuration of the phased array radar, there is a high-gain main array and six sidelobe canceling (SLC) low-gain elements. (Five of these or five externally mounted micro-strip antennas will be used here.) The availability of the additional six SLC elements allows for the implementation of a general sidelobe canceller (GSC) spatial filter [Applebaum, 1976; Griffiths and Jim, 1982; Kamio et al., 2004] which can be viewed as a special case of an adaptive array [Palmer et al., 1998]. The purpose of the GSC is to adaptively introduce nulls toward regions of high interference. For the weather radar case, stationary ground clutter is a major concern. Given the advantages of beam multiplexing, it is likely that only a few pulses will be used for each pointing direction over the coherence time of the signal. Therefore, traditional clutter mitigation schemes, implemented with *temporal* filters, will be problematic. *We propose to use the SLC elements to implement an adaptive ground clutter spatial filter to attenuate the ground clutter signal resulting from the sidelobes*.

1.3. Crossbeam Wind Measurements

Another motivation is to acheive spaced antenna interferometry to estimate crossbeam wind, shear and turbulence. The vector wind, shear and turbulence are needed to fully understand, quantify and forecast weather. Wind field is measured either by Doppler or interferometric techniques [Doviak and Zrnić, 1993; Doviak et al., 1996]. Weather radars such as WSR-88Ds measure the Doppler velocity (i.e., the radial component of the scatterers' velocity) and its associated distribution (i.e., the spectrum width). But a Spaced Antenna Interferometer (SAI) such as NCAR's Multiple Antenna Profiler Radar (MAPR) [Cohn et al., 2001] can, if wind is uniform, also measure the crossbeam wind, as well as the along-beam wind component within the radar's resolution volume. The NWRT offers an opportunity to explore SAI techniques for the measurements of crossbeam wind, shear and turbulence along selected directions using electronically scanned beams [Zhang and Doviak, 2007]. At the current time, the SAI performance has been verified, but is extremely limited – although the difference channels can be accessed along with the sum channels using one receiver switched between the sum and difference channels. *It would be ideal to access the sum and differences simultaneously with a multi-channel receiver, which would provide lag measurements up to three times more often*.

1.4. Data Assimilation

The final and most comprehensive motivating factor is the ability to improve the existing data assimilation techniques by offering new state variables to gain a fuller description of the state of the atmosphere and to initialize NWP models. The fully instrumented phased array radar is in a unique position to offer more versatility over the WSR-88D, since it can return data at a faster rate and other new parameters (such as crossbeam wind estimates). As such, an important and yet very challenging research goal of the NWRT is to optimally design and utilize the electronically controlled agile beam scans for meteorological applications, such as assimilating phased-array radar observations to improve numerical analysis and prediction of severe storms and other hazardous weather conditions. Here, we explore this direction with particular attentions to the following important issues: (i) how to design phased-array scan strategies to enhance radar observation information content for data assimilation; (ii) how to take the advantages of phased-array rapid and flexible scan capabilities to improve error covariance estimation for radar data assimilation. These issues will be addressed theoretically, and some practical solutions will be proposed and demonstrated by numerical experiments. This concludes the guiding multi-factor genesis of the project, and the new hardware that makes it possible, for the first time, is discussed next.

2. MULTICHANNEL RECEIVER

The SPY-1A antenna array was designed to provide robust monopulse and sidelobe cancellation capabilities. The functionality is facilitated by existing azimuth and elevation difference channels and additional sidelobe channels in addition to the primary sum channel. Currently only the sum channel is instrumented in the NWRT. Utility of the additional channels has received much attention among researchers. The difference channels, for example, can be used to measure transverse wind fields and sidelobe channels can be useful in reducing obscuration of weather by stationary targets. The MCR features 8 high-speed digital receivers to acquire and process eight signals simultaneously from the antenna array in real-time. Figure 2 shows a simplified block diagram of the MCR. RF signals from the low-noise amplifiers (LNAs) and super low-noise amplifiers (S-LNAs) that are mounted on the array will be supplied to the analog receiver subassembly. After filtering and down-conversion the analog receivers provide intermediate frequency (IF) signals to the digital receiver chassis which produces the digital time-series data suitable for ingest by processing and recording engines. The aggregate output rate from the MCR can be as high as 640 MB/sec (million bytes per second). Such high data rates require special routing and transport mechanisms for reliable delivery of data to the users.

A critical component in development of the multi-channel receiver system that makes use of all ports available on the NWRT antenna is a computer-controlled, waveguide switch that can manage the distribution of the antenna sum beam signal between these receivers. The desired modes include switching the main beam signal between the in-place receiver and a new, sum-beam, receiver in a multi-channel receiver suite (diplex mode); or allowing the sum-beam return from the antenna to be shared between these two receivers: each receiver getting 50% (duplexed mode) of the energy from each radar return signal. The new receiver estimates of the target azimuth and elevation angles depend on phase and amplitude comparisons of the sum return to two other, identical path-length antenna ports known as the elevation azimuth and elevation difference ports.

2.1. Analog Receiver Subassembly

The RF signals from the antenna are initially amplified by LNA devices that are mounted on the back side of the array. The outputs from these amplifiers are introduced to the analog receiver subsystem for filtering and down-conversion. For each channel, coherent conversion to IF is accomplished by two mixer stages using two local oscillator signals from the existing exciter chassis. In addition, a coherent reference signal and a trigger pulse from the existing real-time controller (RTC) are buffered and conditioned for the digital receiver modules. The first mixer stage converts the 3200 MHz input signal to 750 MHz using a 3950 MHz local oscillator signal (LO1) from the exciter. The bandpass filter selects the lower sideband at 750 MHz and attenuates the remaining mixer artifacts. The second mixer converts the 750 MHz sig-

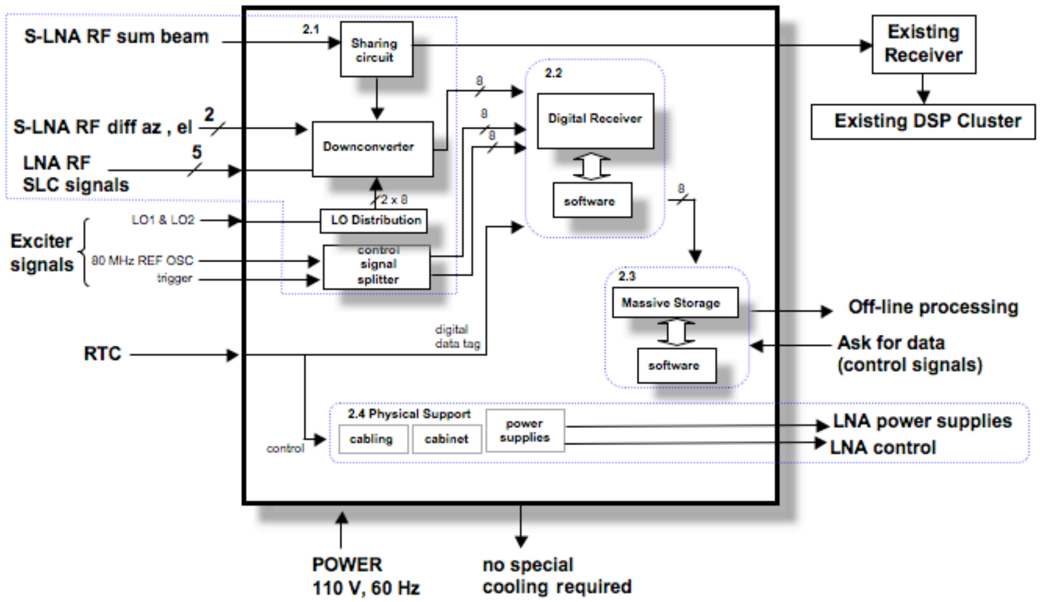

Figure 2: *The block diagram of the multi-channel receiver project. In a teamwork approach, the project is broken down into four main areas. The nominclature that defines this is: 2.1 Downconverter, 2.2 Digital Receiver, 2.3 Massive Storage, and 2.4 Physical Support.*

nal to 50 MHz using a 700 MHz local oscillator signal (LO2) supplied by the exciter. Another bandpass filtering stage is needed to pass only the lower sideband. The resulting IF signals are buffered and supplied to the digital receiver chassis for processing. The digital receivers also require a coherent reference clock and a trigger pulse for synchronization. These two signals are available from the exciter and the real-time controller (RTC). They are split and conditioned for the next stage. Since the configuration is based on four 2-channel digital receiver modules, four copies of the clock signal and trigger pulses are produced for the digital receivers.

2.2. Digital Receiver Subassembly

The digital receiver chassis contains all of the equipment necessary to ingest the eight analog IF signals and produce a multi-channel digital data stream suitable for processing and/or recording by user equipment. The digital receiver modules convert the IF signals to discrete samples using 14-bit analog to digital converters (ADCs). Although these converters are capable of sampling in excess of 100 MHz, they are clocked at 80 MHz. Raw discrete samples are converted to in-phase and quadrature (I & Q) components and then filtered by programmable filtering stages. Filtering and decimation operations result in a maximum data rate of 10 MHz for each channel which corresponds to a 15 meter range resolution. The output data are usually in 24-bit fixed-point format which are subsequently converted to an appropriate floating-point format. The resulting high data rates are not suitable for many conventional buses. Therefore, a very high-speed serial transport fabric will be used to reliably transfer all data to their required destinations.

The output data from the digital receivers must be encapsulated and tagged with acquisition parameters to clearly identify each radar pulse. Thus all data from the digital receivers are dumped into bulk memory where they are encapsulated and tagged by the host computer prior to transfer to external user ports. Acquisition parameters are extracted by the RTC from user-supplied stimulus (STIM) files which control the overall operation of the radar system. The host computer in the digital receiver chassis can obtain this information directly from the RTC or the original STIM files using the local area network (LAN). Trigger pulses synchronize operation of the digital receivers and facilitate encapsulation of the data.

In order to reliably transfer large amount of data to user equipment special input/output modules are required. These devices have special embedded processors and have access to the bulk memory through the transport fabric. Upon command from the host computer the direct memory access (DMA) controllers on these modules transfer data pulse by pulse from memory to user equipment.

To implement the digital receiver assembly, an Echotek receiver system from Mercury will be implemented in the next few months. The EchotekTM Series ECV4-2 family of wideband digital receivers from Mercury Computer Systems implements a flexible field-programmable gate array (FPGA) based architecture in a space-efficient PMC/XMC form factor. The flexibility and power of the VirtexTM-4 FPGAs allow the family to deliver unique capabilities, such as multi-board coherency, while addressing a range of analog signal requirements. Figure 4 depicts the receiver's functional block diagram, while Figure 3 depicts its signal flow graph.

The ECV4-2 is designed to support a broad range of digital receiver applications. The receiver channel synchronization allows all important receiver functions to be synchronized across all receiver channels in a multi-board configuration using front-panel sync input and sync output connectors. This capability makes the ECV4-2 especially well-suited for beamforming and direction-finding as required by radar, SIGINT, ELINT, medical imaging, and communications. The ECV4-2 product family supports two FPGAs. One Xilinx Virtex- 4 FX, SX, or LX FPGA functions as the primary data processor. This FPGA allows the user to run custom algorithms such as digital down/up conversion (wideband or narrow-band), fast Fourier transforms (FFT), and filtering directly on the board. The default board verification IP will be available

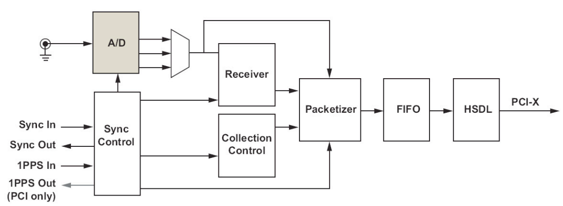

Figure 3: *The functional block diagram of one channel of the digital receiver that is employed in the design.*

from Mercury to implement its own IP, and the verification IP includes the basic functionality required to verify the operation of the hardware. Included in this IP package is a PCI/PCI-X interface with AutoDMA capability, as well as various Mercury designed cores. This IP package includes a local control bus (LCB) interface, a DDR SDRAM interface, a dual-port SRAM interface, a high-speed data link (HSDL) interface for inter-FPGA data flow, plus A/D and D/A interfaces with collection control logic. Sophisticated off-chip interfaces such as DDR and source-synchronous LVDS are also included. The team can develop its own application IP and can gain access to the previous functionality via a local user interface. This allows the end-user to focus on developing application-specific functionality and simplifies the integration of that IP. The team will develop its own unique application IP using standard FPGA development tools such the Xilinx ISE. Then, the team can easily integrate the IP into the board by downloading the end-user images into the field-upgradeable flash memory over a simple memory map PCI/PCI-X interface. The ECV4-2 supports up to 16 MB of flash memory that is used to program both FPGAs, which can be reconfigured from the flash at any time. The flash itself can also be reprogrammed at any time.

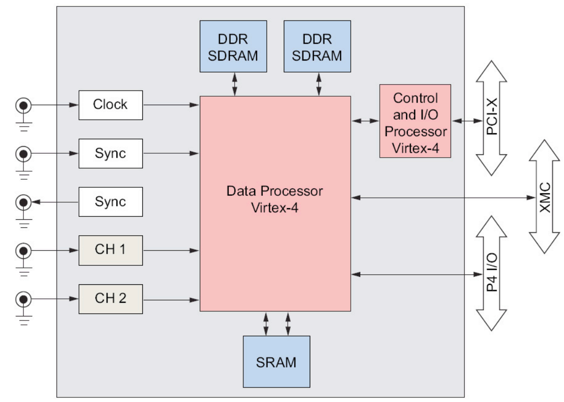

Figure 4: *The component block diagram of one of four 2-channel digital receivers that are employed in the design.*

For completeness, a few of the manufacturer's details about the receiver are noted below. The ECV4-2-2R130-SL-PMCX front panel has 2 SSMC coax input connectors labeled Analog Channel 1-2. Each analog input is single ended. The input is terminated into 50 Ohms. A zero dB attenuator is standard, but other values can be populated when it is necessary to change the analog input range to a larger value (standard is +5.9dBm equals full scale). After the attenuator, the sin- gle-ended input is transformer coupled to the 130 MSPS 16 bit A/D converter. This creates the differential input into the A/D converter, sets the full-scale input to be +5.9dBm, and sets the 1dB bandwidth to be up to 350 MHz. The output of the A/D converter is routed into the User FPGA for digital processing. The local interface is implemented in a Xilinx VirtexTM-4 XC4VLX25 FPGA. A Xilinx core is used for the basic PCI-X interface. A local bus interface and a high speed full-duplex LVDS inter- face to user FPGA connect the PCI-X core to these data busses for data flow. There are 2 DMA controllers: one for input, and one for output. There are several DMA interrupts that are standard, and are passed to 1 PCI interrupt. The local bus is similar in signaling and protocol to the PCI bus. Lastly, the local bus operates at 50MHz.

3. CONCLUSION

The project is a collaborative effort between university and federal scientists. Assembly and test of the instrument will be accomplished in Atmospheric Radar Research Center (ARRC)'s Radar Innovation Laboratory (RIL) prior to integration into the NWRT. Scientists from the National Severe Storms Lab (NSSL) will take an active role in the integration of this instrument. As examples of future projects, a few are mentioned: monopulse tracking & subbeam resolution, interested agencies – DoD, FAA, and NSF; sidelobe cancelling for ground clutter mitigation, interested agencies – ONR, FAA, and government labs; advanced modeling and forecasting, interested groups – NSF, NOAA, FAA, and DoD; validation of Observing System Simulation Experiments (OSSEs), interested groups – NOAA, NSF, and NASA. More importantly, the digital data will open to the general research community.

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