Deployment Considerations and Hardware Technologies for Realizing X-Band Radar Networks

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1. Introduction

The operational civil infrastructure radars deployed around the world today are physically large, high-power, mechanically rotating systems. Designed for long-range (hundreds of km) coverage through heavy precipitation, these radars must operate at radar wavelengths not subject to substantial attenuation. This necessitates the use of large antennas to achieve the narrow beam width needed for km-scale spatial resolution throughout the coverage region. The radars use high-power transmitters to meet minimum sensitivity requirements and large mechanically scanned antennas that require dedicated land, towers, and other support infrastructure. The large physical size of these systems combined with potential environmental impacts limits the availability of potential sites. The strategy for deploying national radar networks such as this is to judiciously attempt to site radars where low-altitude coverage is most needed, while simultaneously minimizing the number of radars in the network as a means of controlling the life cycle costs of the overall system. The resulting infrastructure provides good coverage aloft and some coverage close to the ground in specific regions, while leaving large expanses below 2-3 km altitude without radar coverage.

The goal of the Collaborative Adaptive Sensing of the Atmosphere (CASA) National Science Foundation (NSF) Engineering Research Center is to investigate and develop technologies for improving low-altitude weather forecasting. Since its founding, CASA has been the forerunner for advocating the development of a network of small-scale radars to combat this coverage gap issue. In particular, the focus in the past few years has been towards the integration of phased array technology into the small-scale radar network design methodology. Small phased array antennas are a desirable technology for such an application because they permit flexible beam positioning, have lower recurring costs than mechanical antennas, and can be installed on the sides of existing towers and rooftops.

In this paper, we present deployment considerations for realizing radar networks of small scale radars, as well as the design and development of an X-band phased array radar system, known as the Phase-Tilt Weather Radar, which is suited for integration into such a network. This system is a demonstration of the feasibility of realizing X-band radars through the development of a working, low-cost phased array radar system. We will outline the basic components of the system, as well as some initial performance results which demonstrate its effectiveness.

2. Deployment Considerations for X-Band Radar Networks

More comprehensive coverage at lower altitudes (e.g., < 2-3 km AGL) can only be achieved by decreasing the spacing between the radars. Figure 1 plots the percentage of the volume in a thin layer above ground level covered versus radar spacing for different altitudes (solid curves). Also plotted (dashed lines) are the numbers of radars needed for coverage of the contiguous United States (CONUS) versus radar spacing and the numbers of radars needed for coverage of the region that is today covered by the European Opera radar network. The vertical bars in the figure at 120 km and 230 km are the average spacing between radars of the European Opera network and the US NEXRAD network. As shown in the plots, decreasing the spacing between the radars increases the low-altitude coverage (solid lines tending to increase toward 100% with decreasing radar separation). The dashed lines representing the numbers of radars needed in the Opera and CONUS deployments are quadratic functions of radar spacing. Whereas several hundred radars are needed for spacing of ~ several hundred km (today's situation), these curves reveal that several thousand radars are needed in a dense deployment that defeats the Earth's curvature with spacing ~ several 10's km apart. Obviously, deploying dense networks of closely spaced radars such as this represents a significant change from our present concept of sparse, widely spaced radar networks, where we seek to minimize numbers of radars owing to cost and to the "social footprint" of large radar installations. Deployment of a dense network requires that the radars be small enough that they integrate into the background infrastructure, making use of existing towers and rooftops. Cost-effective deployment of such networks requires that the acquisition, deployment, and recurring costs be substantially smaller than the per-radar costs of today's high-power radar designs. Rather than acquiring acre-size land plots and deploying large towers to accommodate megawatt-class transmitters and ~10-m radomes, dense networks will require deployment on small towers having small land footprints or the use of existing infrastructure elements, such as rooftops, sides of buildings, and communication towers. This requires that the radars be physically small and that the radiated power levels be low enough so as not to pose an actual or perceived radiation safety hazard.

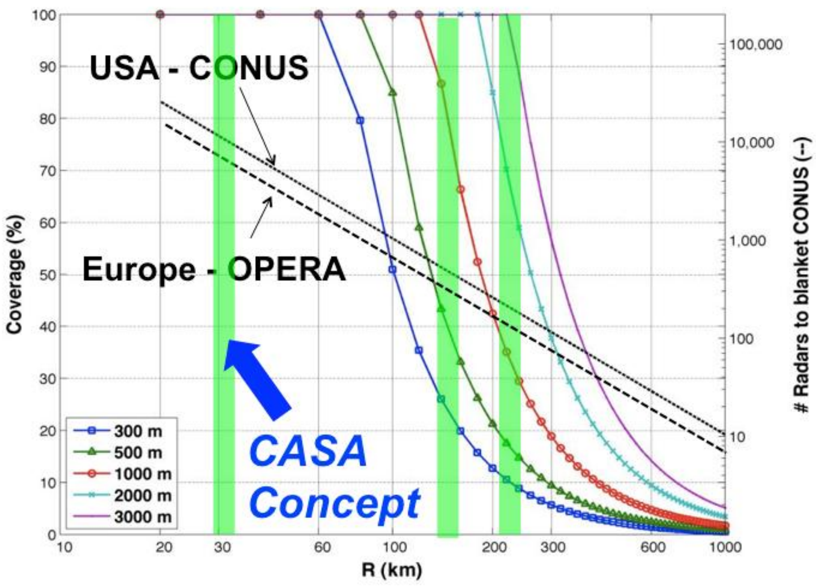


Figure 1: Percent coverage (solid lines) and number of radars needed for coverage over the continuous USA and European Opera region (dashed lines) vs. radar spacing.

A reasonable size for unobtrusive equipment deployment on existing infrastructure (e.g., a communication tower or building) is an antenna aperture of ~1 m. As argued in [4], operating at X-band, versus operating at higher or lower wavelength bands, provides a good compromise between achieving high spatial resolution with a modest amount of attenuation due to propagation through rainfall.

3. Small Radar Technology

To investigate the small radar/dense network concept described here, the participants of the CASA project designed, fabricated, and deployed a four-radar demonstrator test bed network (referred to as "IP1" and installed in "Tornado Alley", in Oklahoma) [4]. The radars in these test beds operate at X-band with dual-polarization and employ 1.2 m parabolic reflector antennas, 10 kW peak power (10 W average power) magnetron transmitters and dual coherent-on-receive receivers. The maximum range at which this class of radar is capable of achieving +10 dBZ sensitivity for weather observation is 30 km.

Going beyond research-oriented trials such as those conducted by CASA will require that meteorological offices or other businesses acquire and deploy networks of small radars; there are many ways to estimate what the costs of such radars needs to be, and the CASA project has produced one estimate that the acquisition cost of these radars should be less than $200,000 [4]. In addition, the radars that are purchased will need to be easily deployed on existing buildings or towers, so as to avoid incurring the costs associated with building infrastructure. Phased arrays are a key enabling technology in many radars produced for defense applications today, and they are a desirable technology for use in dense radar networks because they do not require maintenance of moving parts, they permit flexibility in beam steering without requiring heavy antenna pedestals such as those used in the CASA IP1 design, and they are more robust with respect to component failure. Moreover, phased arrays can potentially be mounted to the sides of towers and buildings, giving flexibility in the selection of suitable radar sites. One estimate of the cost of a modern phased array radar antenna is $1M [US] per square meter of aperture. A particular challenge to realizing cost-effective dense networks composed of thousands of phased-array radars will be to achieve a design that can be volume manufactured for less than $50,000 per 1x1 meter phased-array (this assumes that four such arrays are installed at each radar site and that assuming each array is self-contained with the antenna elements and radar transceivers as well as computers for beam steering, data acquisition, and signal processing, communication interfaces, and power conditioning electronics).

Establishing the specifications for these arrays is currently a work in progress; however several key parameters can be stated as:

- 10W's to 100 W peak power per panel
- ~2° x 2° average beam width
- ~ 1m x 1m array
- Dual linear transmit and receive polarization
- # Array panels per installation: 3 or 4

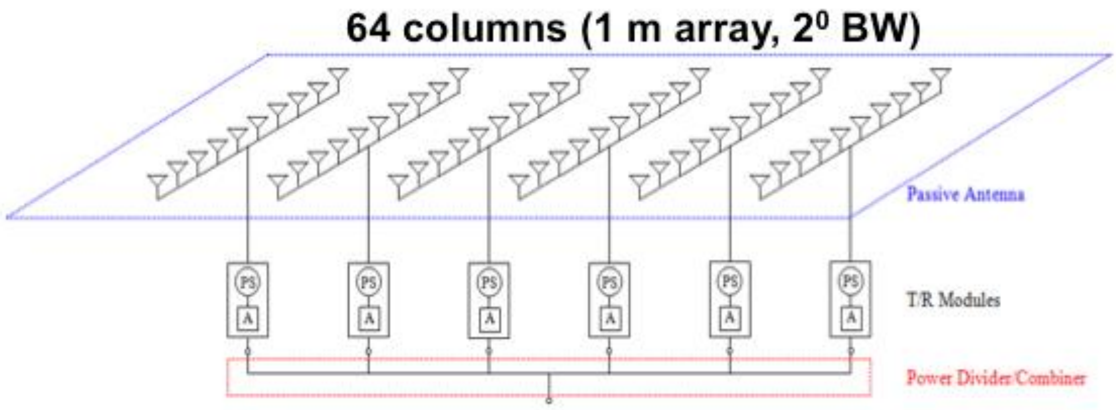


Figure 2: Schematic concept of phase-tilt antenna array.

- Azimuth scan range: $\pm 45^0$ to $\pm 60^0$
- Elevation scan range:
    - $0\text{-}20^0$ (for low level coverage, < 3 km)
    - $0\text{-}56^0$ (for full coverage, to 22 km)

Several thousand radiating elements and transmit/receive (T/R) channels are needed to obtain a phased array capable of electronically steering a 2° beam in two dimensions over the desired scan range without requiring moving parts.

“Phase-tilt” represents a simpler approach to realizing an antenna array. As shown in Figure 2, such an approach performs electronic beam steering in the azimuth direction while mechanically steering (tilting) the antenna in the elevation direction. The array is realized as a series of vertically oriented radiating columns, each fed by a single T/R module. This architecture is substantially less complex than the phase-phase architecture described above because it requires tens, rather than thousands, of T/R channels. The disadvantage of this approach is that it requires mechanical steering (i.e., array tilting) to achieve beam steering in the elevation direction. This complicates the installation and potentially the maintenance of the array, also.

The University of Massachusetts – Amherst within the CASA Engineering Research Center, has developed a research prototype of such an antenna. The array is comprised of 64 1-W T/R modules, each of which is estimated to cost $400-$500 [US] to build. The array is built from 4 LRU’s, each comprised of 16 T/R modules and a segment of passive circuit board.

First RF Corp., of Boulder, CO (http://www.firstrf.com/index.html) has developed a commercial phase-tilt antenna having electrical characteristics and performance similar to the UMass prototype described above. Model FRF-166, described by the company as a Dual-polarized “X-Band Elevation Gimbaled Phased Array,” the antenna is an integrated assembly capable of beam-steering plus/minus 45 degrees from broadside and tilting between horizon and zenith. This phase-tilt antenna has been integrated into a radar system currently in development at the University of Massachusetts – Amherst, known as the Phase-Tilt Weather Radar, as described below.

4. Phase-Tilt Weather Radar Overview

4.1 System Overview

The Phase-Tilt Weather Radar prototype being developed integrates the First RF phase-tilt antenna with a radar backend, which consists of a digital IF transceiver and radar backend software suite. Building upon the performance capabilities of the array, the radar system is designed to provide real-time calculation of raw weather products in a lightweight and simple form factor. There are few major components of the system; the entire radar is comprised of the phase-tilt antenna, the digital IF transceiver, and a host computer. With the backend contained in a few small components, the Phase-Tilt Weather Radar has the capability of being packaged in a standalone unit, requiring only power and a single Ethernet or optical cable for operation. A block diagram of the system is shown in Figure 3. The array subsystem, described below, includes both the phase-tilt antenna and the upconverter and downconverter components. The transceiver connects the host computer to the array subsystem as a standalone unit.

A sequence of reflectivity measurements (moderate to light precipitation) in Amherst, MA (US) on 5/01/2012 over 3 minutes is shown in Figure 5. These measurements were made with a 40usec 3MHz LFM pulse with alternating polarization diversity. This data demonstrates the feasibility of the Phase-Tilt Weather Radar to acquire weather products.

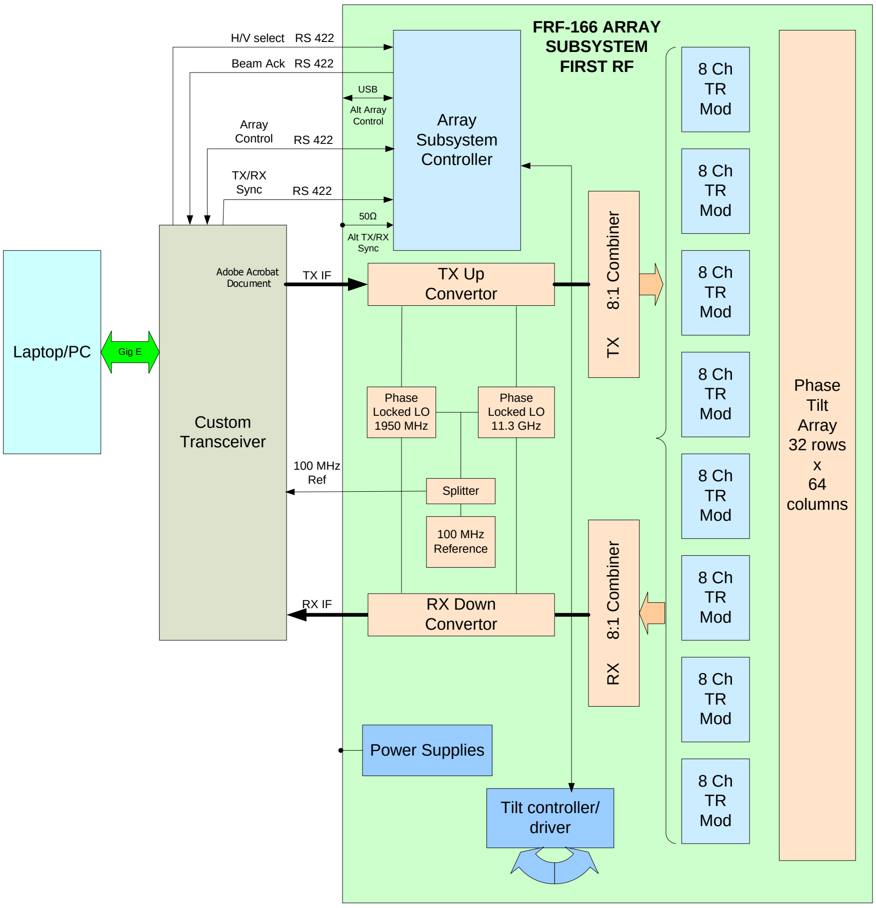
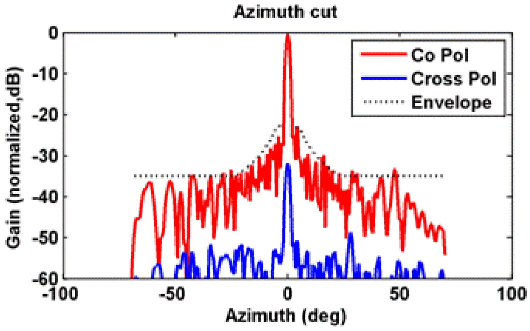


Figure 3: Phase-Tilt Weather Radar system block diagram.

An overview of the radar system parameters is given in Table 1. With a peak transmit power over 70W and pulse compression implemented, the radar system supports a sensitivity of +16dBZ at 30km, as analyzed in [5]. An added benefit of the radar system is the rate at which weather products can be calculated. In the current pulse scanning strategy, dual-polarized weather products can be computed for a full 90° azimuthal sector every on every scan (about 3 seconds with 192 pulses per beam), providing a streaming display of the environment in near real-time (although azimuthal scan time depends on the scan parameters). The weather products are output in a common file format and are fully reconfigurable to link to any custom or commercial software package for display and analysis. Alternatively, the spectral and polarimetric products can be formatted into PPI displays, similarly updated in real-time for rapid data analysis.

Parameter	Units	PTWR
Frequency Range	GHz	9.3 – 9.5
Tx Power (Peak)	W	70
Pulse Length	µS	.6 - 60
Pulse Compression Gain	dB	Up to 20
Duty Cycle (max)		30%
Unambiguous range @ max PRF	km	31
Unambiguous Velocity @ single PRF	m/s	up to 38
Unambiguous Velocity @ Dual PRF	m/s	57 @ (2:3)
Sensitivity @ 30km	dBZ	16
Elevation Beamwidth	deg	2.8
Azimuth Beamwidth	deg	1.8 -2.4
Polarization Mode		Alternating
Integrated Cross Pol Ratio (max)	dB	-20
Power Consumption		600W (avg)

Table 1: Phase-Tilt Weather Radar system parameters.



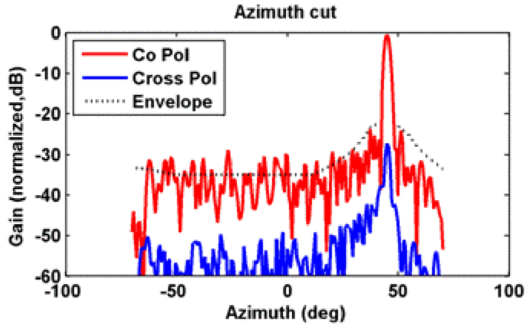


Figure 4: V-polarization azimuth cuts at 0° (left) and 45° (right), showing co- and cross-polarization performance

4.2 Phase-Tilt Antenna

Developed by First RF Corp., the phase-tilt antenna is an application of the phase-tilt concept in a ruggedized package.. Operating at X-band, the array supports switched, dual-linear polarization diversity (i.e. pulse-to-pulse polarization switching). Comprised of 64 center-fed columns of 32 radiating elements each, for a total aperture size of 1.5m^2, the elevation and azimuth beamwidths at boresight are 2.8° and 1.8°, respectively. Each group of 8 columns are fed by a single 8-channel TR card, providing over 1W peak power to each column for a total peak transmit power over 70W at 30% duty cycle. Additionally, the TR and beam switching speed for the phase-tilt antenna is less than 1us, which allows for enhanced scanning speed over traditional mechanically-steered arrays. With low-power operation at 600W average, the array is capable of being powered by standard 48V supplies, common in most utility infrastructures. A Taylor weighting applied along the vertical direction in each column helps to reduce sidelobe interference, which makes the array perfectly suited for near-ground and urban installations.

Figure 4 shows measured V-polarization azimuth cuts with the main lobe of the array pointed towards 0° and 45° (with respect to antenna boresight), respectively. These figures demonstrate a peak cross-polarization performance across all scan angles greater than -25dB. H-polarization results (not shown) demonstrate similar results. These peak cross-polarization measurements verify an Integrated Cross Polarization Ratio (ICPR) of greater than -20dB in both polarizations. Additionally, analysis of near-field results confirm a beam pointing accuracy over all scan angles and polarizations of +/-0.15° and a peak scan loss of 2.5dB at 45°.

4.3 Transceiver Functionality

We developed a custom transceiver to seamlessly integrate with the phase-tilt antenna. The transceiver functions as an arbitrary pulsed waveform generator, synchronously controlling the transmission and receptions of signals to and from the

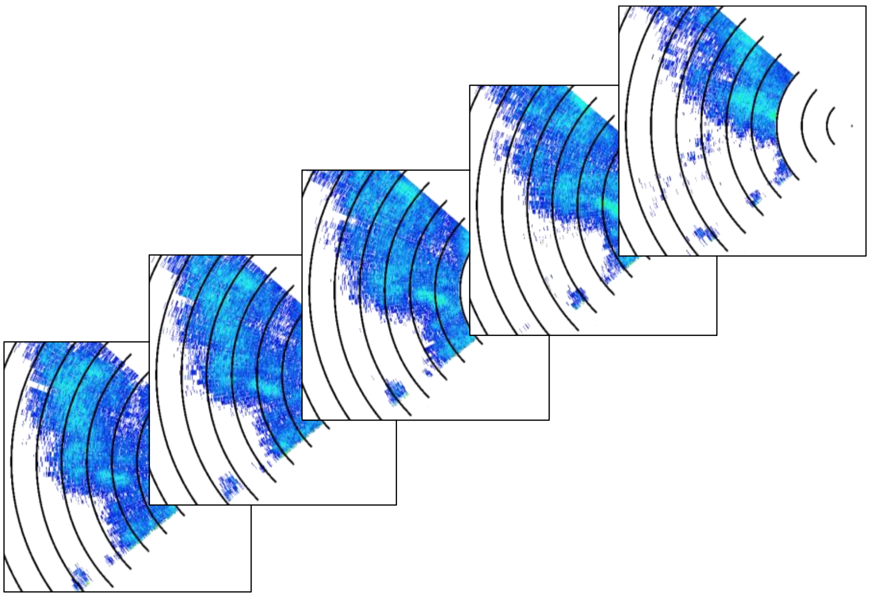


Figure 5: Sequence of reflectivity measurements made on 05/01/2012 over the course of several minutes in Amherst, MA, USA. Black lines denote 2km range separation.

phase-tilt antenna at 60MHz. The host computer communicates with the standalone transceiver via standard gigabit Ethernet. In addition, control signals to the antenna from the host computer are routed through the device, making the transceiver the single interface point between the host computer and the array.

The transceiver is comprised of an on-board FPGA, a dual-channel 16-bit, 400Msps D/A converter, and a dual-channel 14-bit A/D converter. A daughterboard mounted inside the device provides digital attenuation and amplification in both transmit and receive chains. The transceiver provides up to 21dBm peak output power with greater than 50dBc of image rejection within a 15MHz bandwidth around 60MHz. The A/D and D/A converters, along with the FPGA clock, are phase-locked to a 100MHz reference clock provided by the antenna. The phase noise of the transceiver is greater than -90dbc/Hz at 10Hz offset, which corresponds to less than 1ps clock jitter. The transceiver performs real-time pulse compression, and up to four transmit waveforms can be pre-loaded to the device upon startup along with four associated matched filters.

4.4 Radar Backend Software Suite Development

The radar backend software suite, which is the master point of control for both the array and transceiver, performs real-time calculation of weather products, PPI displays, and radar scheduling for the Phase-Tilt Weather Radar system. The signal processing software computes the spectral and polarimetric products: equivalent reflectivity, velocity, spectral width, H/V-propagation phase, differential reflectivity, differential phase, copular correlation coefficient, normalized coherent power, and specific differential phase.

Although the specific signal parameters and processing details are dependent on the environment the radar system will observe, the current software version performs standard time-domain autocovariance processing to compute the raw weather products. Numerous fixed- and dual-polarization scanning strategies are supported, as well as dual-PRT unfolding. To account for azimuth scan loss off boresight in our phased array, we apply an angle-dependent correction to the reflectivity calculation for each beam location. The reflectivity is the only product that requires this correction, since all other products calculated require normalized covariance measurements, which are independent on the received power.

Spectral and polarimetric products output from the software are compatible with commercial analysis software suites, such as IRIS from Vaisala® and Rainbow from Gematronik®. Since these analysis packages typically assume a mechanically-steered antenna, weather products at a particular beam location from a phased array require a conversion into absolute angles. This is due to the fact that the elevation and azimuth location in phased arrays are referenced to array boresight, whereas a rotated mechanically-steered array pointing angles are absolute values in spherical coordinates, referenced to the center of rotation in the system. For the same volume scan in a fixed number of elevation cuts in a mechanical array, the phased array volume scan will require more elevation cuts to observe the same volume. Knowing this, we employ a unique scanning strategy to compensate.

Spectral processing of weather products, along with return trip echo suppression and clutter filtering, is currently being integrated and tested into the software suite. Additionally, the transceiver functionality is being expanded to support random phase-coding on the transmitted and received signals.

5. Conclusions

In this paper, we have presented an overview of deployment considerations for X-band radar networks, as well as a top-level overview of the Phase-Tilt Weather Radar. Though still in development, initial results and descriptions provided herein demonstrate a working X-band radar system, suitable for integration into a radar network due to its simple design, small form factor, and ease of controllability. Live testing with opportunistic weather, in and around the Northeastern United States, will be performed to test and verify system performance.

References

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