AFFORDABLE PHASED ARRAY WEATHER RADARS: STARTING TO BECOME A REALITY

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Abstract - Dense placement of short-range (~30 km) radars arranged in collaborating networks achieves improved weather surveillance compared to today's long-range radar technology. Improved safety and security at national-scales can potentially be achieved through widespread deployment of hundreds to thousands of short-range radars. Practical deployment depends on the availability of radars that are inexpensive to acquire, install, and maintain and that are capable of performing accurate weather measurement. 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. Large, high-power phased arrays are a well-developed technology for defense applications but cost makes them too expensive to fit within the budgets typically associated with civil weather surveillance. Small, low-power phased arrays, in contrast, are now being realized with price and performance to support the concept of wide-scale dense radar network deployments. This paper reviews system considerations and key requirements associated with this concept and presents recent research and commercial developments associated with low cost phased array radars.

1. INTRODUCTION

Long-range microwave radars are an important part of the weather and air-surveillance infrastructure used by many nations today. The observing capabilities of these radars have improved considerably over the past 60 years as new technologies such as coherent high-power transmitters, solid state electronics, Doppler and dual-polarization signal processing, digital designs, open software architectures and improved data dissemination and display technologies have been developed and incorporated into the system. Despite significant capability and continual improvement, a fundamental limitation of today's civil radar infrastructure is a lack of comprehensive low-level coverage, as illustrated in Fig. 1 for the case of the United States. Large regions without coverage exist below several thousand feet (several km) altitude owing to earth's curvature blocking the low-altitude part of the radar beam at long ranges. Tornadoes, low-flying aircraft, and other atmospheric and airborne objects are capable of flying-in undetected, under the radar coverage of today's radar infrastructure.

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.

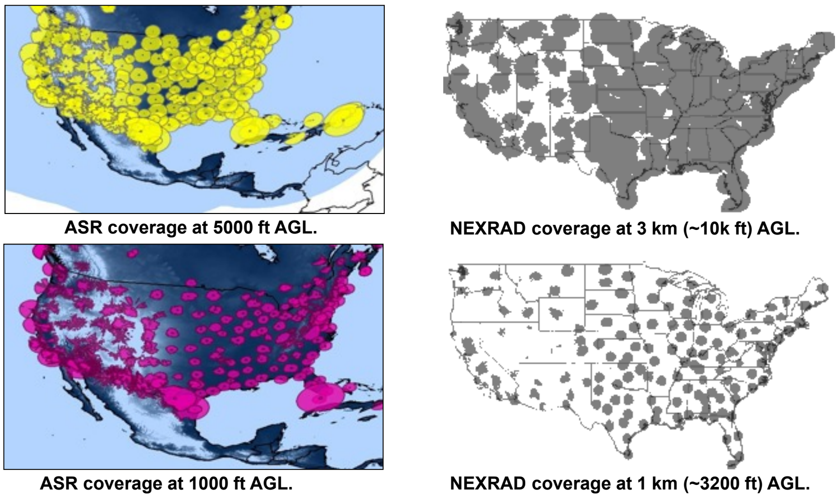

Figure 1 – Present-day radar coverage in the US for commercial air traffic surveillance (l) and weather radar surveillance (r) revealing large expanses of "white space" or gaps in coverage at low altitudes due to earth's curvature blockage.

There is increasing need for improved radar coverage at low altitudes, particularly in the planetary boundary layer, to support numerous applications ranging from improved hazardous weather forecasting and warning, to wind mapping for fire fighting and tracking airborne toxic release, to monitoring bird migration, to enhanced support for roadway weather. Beyond weather, nations are also addressing the need to develop advanced capabilities to improve tracking and identification of low-altitude aircraft and other threats. A variety of concepts are being evaluated for potential expansion, modernization, or replacement of today's civil infrastructure radars. An important consideration for these various concepts is the geometric fact that any network comprised of long-range (hundreds of km) radars is fundamentally incapable of providing comprehensive low-level coverage owing to the curvature of the earth.

The National Science Foundation (NSF) Engineering Research Center (ERC) for Collaborative Adaptive Sensing of the Atmosphere (CASA) is researching a different approach to deploying radars in the civil infrastructure [1]. CASA's concept is to use large numbers of small radars operating at short ranges (i.e., 10's of km) to defeat the earth curvature blockage problem. CASA's concept envisions an observing technology based on low-cost, dense networks of radars that operate at short range, communicate with one another and adjust their sensing strategies in direct response to the evolving weather and to changing user needs. In contrast to the large radars in today's operational networks, such as the US NEXRAD having 9-meter diameter antennas and radar spacing of hundreds of kilometers, the antennas in dense networks are expected to be 1-meter in size with the radars spaced tens of kilometers apart. CASA's idea is that the small size of these radars allows them to be placed on existing infrastructure elements such as communication towers and rooftops as shown in Fig 2.

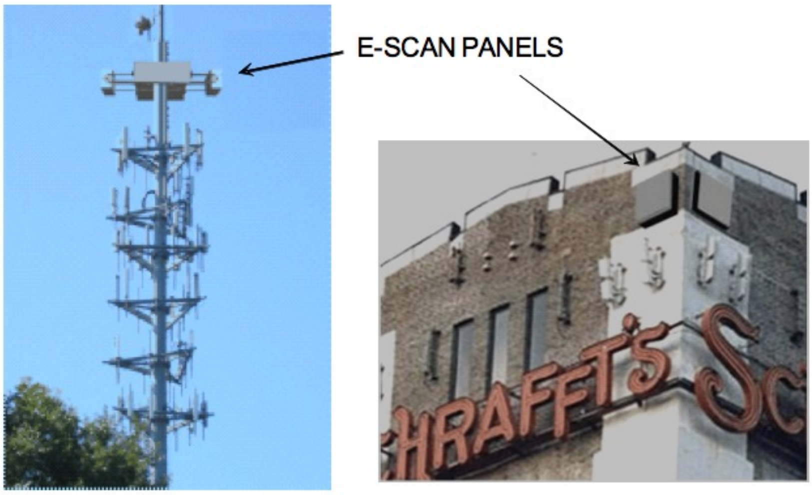

Figure 2 - Artist concept depicting small radar panels deployed on towers and the sides of buildings. Installations such as this, making use of existing infrastructure, are central to CASA's concept of deploying large numbers of small radars within the civil infrastructure.

In addition to enabling comprehensive low-altitude weather observations, such radars offer the potential to observe low-altitude targets flying beneath the views of current radars. A dense network comprising several thousand such radars would be required to blanket the contiguous U.S. at 30 km radar spacing. Such radars would require less than 100 W of average transmitter power, yet they would be capable of < 1 km spatial resolution throughout the entire troposphere – from the critical low troposphere "gap" region up to the tops of storms. Blanket deployment of thousands of small radar nodes across an entire nation or group of nations is but one of several possible future deployment strategies for this technology. Additional strategies would potentially include selective deployment of ~1,000 radars in border regions and more heavily population areas; in geographic regions particularly prone to wind hazards or flash floods; in valleys within mountainous regions; or in specific regions where it is particularly important to improve observation of low-level meteorological phenomena and airborne objects. This paper discusses system-level tradeoffs associated with this new approach to radar network design for the meteorological application and presents recent research and commercialization results indicative of the progress being made in realizing phased array technologies to enable this concept to come to fruition.

2. DEPLOYMENT AND DESIGN CONSIDERATIONS

More comprehensive coverage at lower altitudes (e.g., < 2-3 km AGL) can only be achieved by decreasing the spacing between the radars. Fig 3 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.

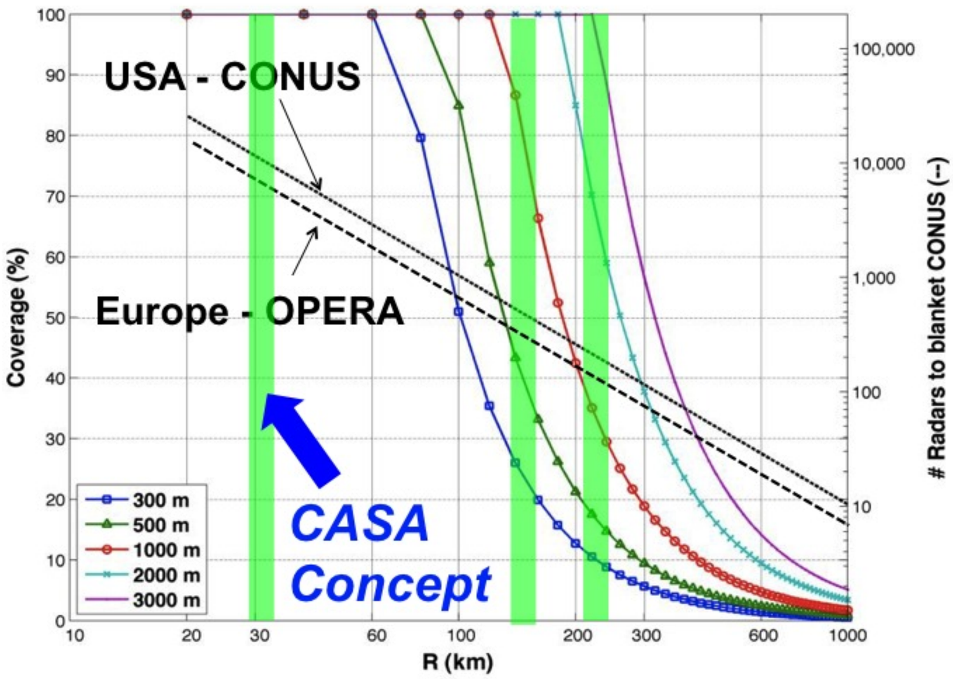

Figure 3 - Percent coverage (solid lines) and number of radars needed for coverage over the continuous USA and European Opera region (dashed lines) vs. radar spacing.

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 [1], 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 four-radar demonstrator test bed network (referred to as "IP1" and installed in "Tornado Alley", in Oklahoma) [1]. 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 as shown in Fig 4.

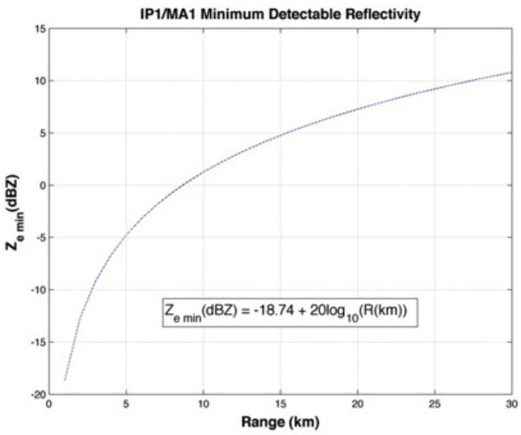

Figure 4 - Sensitivity of the CASA prototype radar design for weather observing revealing that low power radars (~ 10 W average power) can achieve adequate sensitivity for measuring weather radar echoes.

Fig. 5 shows an example of weather data collected by CASA's IP1 network in Oklahoma compared to simultaneous data collected with a much larger NEXRAD radar. In trials conducted with the IP1 network during Oklahoma storms from 2007-2010, the system has been used to demonstrate measurement capabilities that are fundamentally beyond the capability of today's long-range radars. These capabilities include: observations from several hundreds above ground level up to the tops of storms; multiple Doppler coverage for retrieving wind vector fields during rain events; and higher temporal and spatial resolution. These results help to demonstrate the concept that small, low-power radars, arranged in dense networks can probe the full vertical depth of storms without the gaps that limit long-range radars.

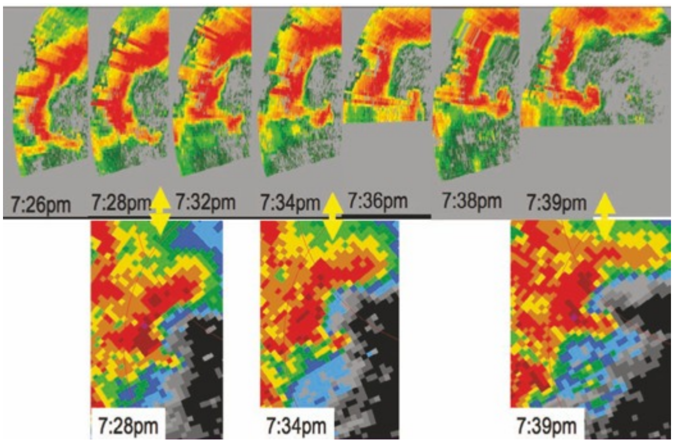

Figure 5. CASA IP1 test bed data (top) compared with NEXRAD radar (below) during a tornadic thunderstorm. Copyright American Meteorological Society.

Going beyond research-oriented trails 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 ~$200k [1]. In addition, the radars that are purchased will need to be easily deployed on existing buildings or towers, soas 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, as shown in Fig. 2, 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 ~$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). Because they require low power, the phased arrays considered here can be developed using different approaches for cooling and handling high voltages than those used to develop the more costly defense-application phased array counterparts. Moreover, they can utilize commercial-type packaging and manufacturing approaches that can help to substantially reduce cost.

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
- 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. An active electronically scanned antenna array design has been described by Raytheon [2,3] that is based on manufacturing processes similar to those for making low-cost computer boards. The realization of such an antenna benefits from leveraging commodity silicon radio frequency semiconductors to achieve T/R functions, in combination with very low-cost packaging, fabrication and assembly techniques. A photograph of prototype sub-array is shown in Figure 6.

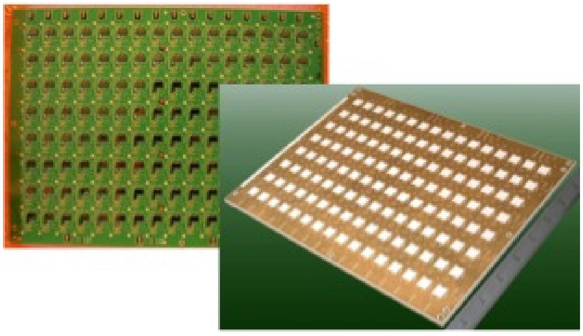

Figure 6. Radiator side (right) and populated active component side (left) of a 128-transmit/receive-channel circuit card assembly sub-array prototype. Source: Raytheon

A key advantage of the circuit card assembly (CCA) phased array described above is that it has no moving parts and lends itself to straightforward installation on the sides of buildings and towers. This technology is still in development.

"Phase-tilt" represents a simpler approach to realizing an antenna array. As shown in Fig. 7, 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.

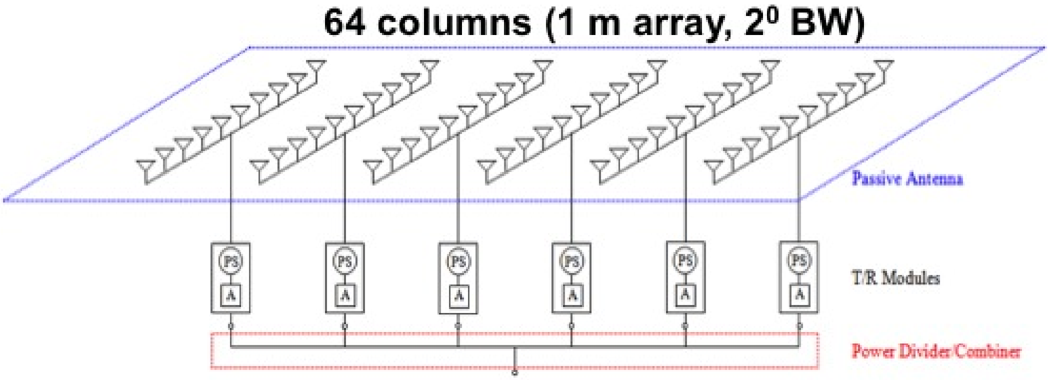

Figure 7. Schematic concept of phase-tilt antenna array.

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.

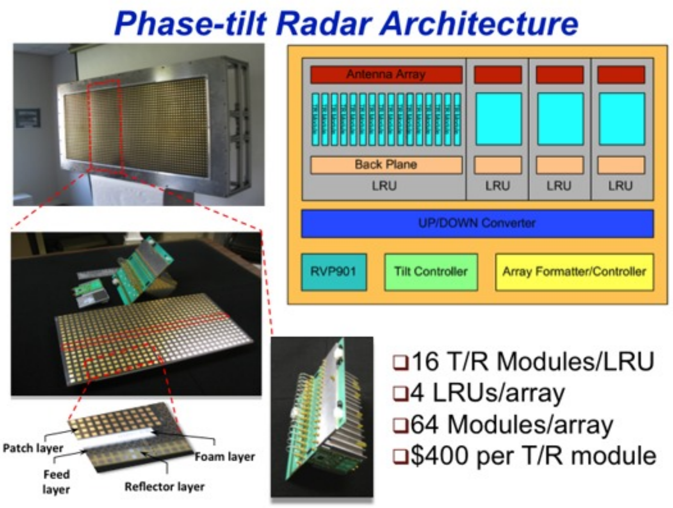

Figure 8. Building block architecture of the UMass Phase-tilt prototype array.

Several publications describing detailed aspects of the antenna radiating patches, T/R module design, and other aspects have been published or will be appearing during the present year [4-7]. Highlights and a summary of performance measurements are given below.

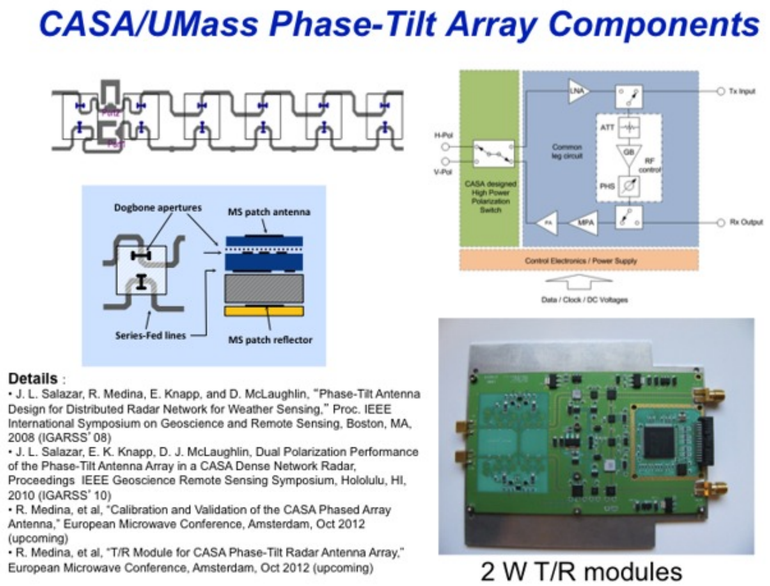

Figure 9. Phase-tilt components: dual-pol radiating patch & serpentine feed line (ul); common-leg T/R module circuit (ur); assembled T/R module (lr); references (ll)

Figure 10 shows antenna radiation patterns for this antenna obtained from a near-field antenna chamber. The key performance requirements for effective observation of weather are to achieve a match better than or equal to 5% in the vertical and horizontal co-polarized radiation patterns and to achieve an integrated cross-polarization isolation of at least 20 dB. These performance requirements are met over the range plus/minus 45 degrees from the bore sight scanning direction as shown.

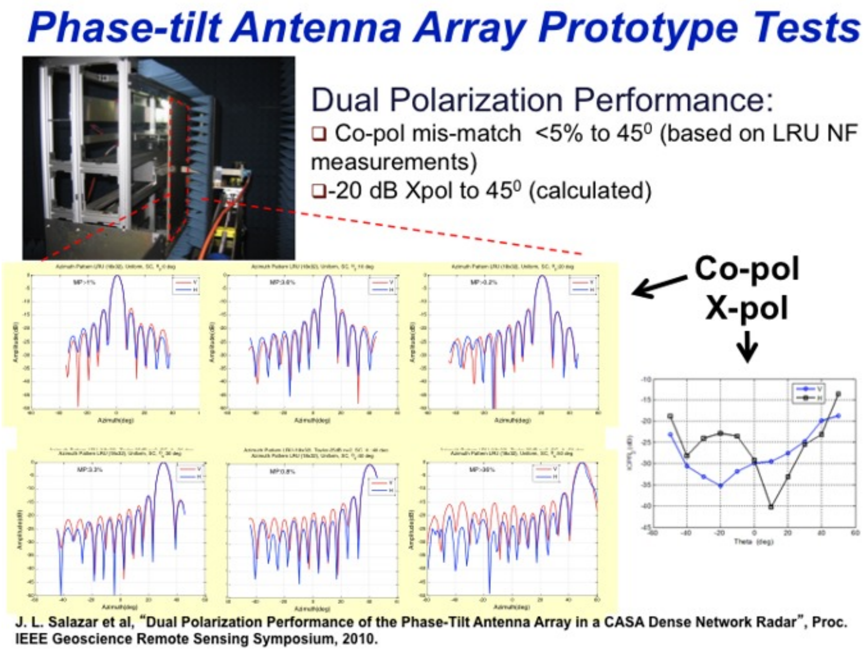

Figure 10. Antenna patterns (6 panels lower left) and cross-polarization isolation measurements (lower right) showing performance of the phase-tilt prototype array.

FirstRF 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. A photograph of this array, which is currently undergoing testing at the University of Massachusetts, is shown in Figure 11.

Figure 11. Commercial FRF-166 Phase Tilt Array from First RF Corp. The array electronically scans plus/minus 45 degrees from broadside in the azimuth direction and mechanically tilts over 90 degrees in elevation enabling beam pointing toward the horizon (right) up to zenith (left).

4. CONCLUSION

Current approaches to operational weather observation are based on the use of physically large, high-power, long-range radars that are blocked from viewing the lower part of the troposphere by the Earth's curvature. This paper describes an alternate approach based on dense networks composed of large numbers of small X-band radars. Spacing these radars tens of kilometers apart defeats the Earth curvature problem and enables the sampling of the full vertical depths of the atmosphere using 1-m antennas and transmitters having only tens of watts of transmitter power. Research prototypes are being developed that support proof-of-concept that low-cost phased arrays can be realized with the needed performance and cost structure. Commercial products are also emerging as well, indicating that this concept is moving closer to reality.

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