Advances and Applications in Low-power Phased Array X-band Weather Radars

P. Kollias[*,†], D. J. McLaughlin[‡], S. Frasier[‡], M. Oue[*], E. Luke[†] and A. Sneddon[*]
Email: {pavlos.kollias, mariko.oue, alexander.sneddon}@stonybrook.edu, {dmclaugh, frasier}@umass.edu, {eluke}@bnl.gov
[*] School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY
[†] Center for Multiscale Applied Sensing, Brookhaven National Laboratory, Upton NY
[‡]Department of Electrical and Computer Engineering, University of Massachusetts, Amherst MA

Abstract— **Low-cost, low-power X-band phased array radar (LPAR) is an enabling technology for future deployment of distributed short-range radar networks. Such networks offer the potential for superior and lower altitude surveillance of atmospheric and airborne events compared with today's larger, long range national radar networks. Two dimensionally steered (phase-phase steering, without motors or other moving parts) phased array radars are complex systems comprising multiple subsystems including several thousand transmit/receive (T/R) channels, beam steering computers, thermal management. Owing to this complexity and the associated cost, phased array technology has not historically been used in weather and air traffic control radars. Competition for the frequency spectrum traditionally reserved for long-range radars is motivating the search for new approaches to national air surveillance; this has motivated R&D investment in two-dimensional X-band LPAR over the past decade, to the point where prototype systems are now emerging in several application settings including, for the first time, the university research setting. Two-dimensional high-speed (inertia-less) beam steering combined with dual polarization, programmable/adaptive waveforms, and the ability to combine multiple radars into networks is leading to new atmospheric science research opportunities related to hazardous storm forecasting and response, understanding cloud physics, water resource management, monitoring the movement and dispersal of hazardous plumes, and other areas.**

Keywords—phased-array radars; weather; X-band; network

I. Introduction

For over half a century, radars operating in a wide range of frequencies have been the primary source of observational insights of clouds and precipitation microphysics and dynamics and contributed to numerous significant advancements in the field of weather research, forecasting and precipitation estimation. The development of multi-wavelength and polarization diversity techniques has further improved the quality of radar-based microphysical and dynamical retrievals and has assisted in overcoming some of the limitations imposed by scattering physics. Some of these advancements (e.g. polarization) have been incorporated in the current version of the U.S. Weather Surveillance Radars [1], commonly known as Next-Generation Radars (NEXRADs). NEXRADs, like a vast majority of weather radars, usually employ a large mechanical scanning parabolic (dish) antenna as such, their ability to point to and subsequently revisit specific volumes within the atmosphere is limited by inertia. Furthermore, these systems are expensive, require significant infrastructure and are prone to pedestal and high-power amplifier failures. In contrast, electronically scanning (e-scan) phased array radars, are based on low voltage solid-state technology which eliminates the use of high power amplifiers that are prone to failure. In addition, e-scan radars are inertia-less enabling rapid spatial sampling of the atmosphere, and have no moving parts, thus offering an attractive low maintenance, low operational cost, multi-functional alternative for the sampling of the atmosphere for air surveillance and weather applications. These arguments along with the benefits of consolidating existing radar networks (NEXRAD's, the Terminal Doppler Weather Radar (TDWR's) and Air Surveillance Radars (ASR's)) led to the concept of high-power S-band multifunction phased array radar (MPAR) systems and the development of the National Weather Radar Testbed [3]. The NOAA National Severe Storms Laboratory (NSSL), the Advance Radar Research Center (ARRC) and the MIT Lincoln Laboratory are leading most of the research and development in the concept design, signal processing (i.e. beam multiplexing, improved clutter rejection, cross beam wind estimation, adaptive sensing) and weather applications (i.e. tornadic storm studies).

In parallel with the MPAR research and development activities, several mobile X-band phased-array systems have been developed and used in severe weather research. Examples of such systems include: i) the rapid Doppler-on-Wheels single polarization X-band with frequency scan in elevation which is based on an array of slotted waveguide antennas and mechanical in azimuth [4], ii) the MWR-05XP X-band, re-purposed military radar with phase scan in elevation and mechanical in azimuth [5], iii) the Atmospheric Imaging Radar X-band active electronic scanning array radar with digital beamforming [6] and the Toshiba corporation X-band Active Phased Array Weather Radar (PAWR) with digital beamforming [7].

While the MPAR system offers some exiting potential for rapid inertia-less surveillance, that system, like all long-range C- and S-band weather radars, suffers from an inability to observe the lower troposphere due to earth curvature [8]. The National Science Foundation (NSF) Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) introduce the notion of distributed networks of small, short-range (~ 30 km) X-band radars to address the low-level atmosphere coverage gap imposed by the Earth's curvature and the typical spacing between NEXRAD nodes [8,9]. The CASA project has advanced the idea of deploying several thousand small, low-power X-band phased arrays as an alternative to today's use of large C- and S-band systems to provide gap-free coverage.

The first proof-of-concept CASA small network of X-band radars known as the Integrated Project-1 (IP1) was based on fast scanning, magnetron-based mechanical scanning radars and the low-level meteorological target of interest was tornados [10]. The goal of the IP-1 testbed was to evaluate the concept of Distributed Collaborative Adaptive Sensing (DCAS). The IP-1 radar network is now part of a long-term deployment of an 8-radar node in the Dallas Fort-Worth area [11]. In parallel to the IP1 network development, CASA developed a partially electronically-scanned phased array radar. Known as the phase-tilt architecture, the radar antenna electronically scans in the azimuthal direction and mechanically tilts in elevation [12,13]. Raytheon company subsequently developed a two-dimensional (azimuth and elevation) electronically steered radar, thus achieving the goal of a low-power X-band radar without moving parts [14,15].

The phase-tilt technology, and variations of this design that perform electronic beam steering in one direction but rely on mechanical scanning on the other direction, are becoming somewhat commonplace now; several universities have assembled them, and commercial units are available. Phase-phase radars, on the other hand are significantly more complex; they are expensive to develop and require engineering facilities not typically associated with university labs. To illustrate the complexity, ~ 60 transmit/receive (T/R) modules are needed to realize electronic beam steering in a phase-tilt system whereas several thousand (~ 60 x 60) T/R modules are needed to realize two-dimensional beam-steering with a phase-phase system (Fig. 1). Raytheon Company recently established partnerships with two academic institutions in the Northeast to advance the understanding of phase-phase radar technology applied to atmospheric and airborne sensing.] One partnership is with the Microwave Remote Sensing Laboratory (MIRSL, http://mirsl.ecs.umass.edu/) at the Department of Electrical and Computer Engineering at the Univ. of Massachusetts (UMass) at Amherst and the second with the Radar Science group (https://you.stonybrook.edu/radar/) at the School of Marine and Atmospheric Sciences at Stony Brook University (SBU). As part of their research partnership with Raytheon, each academic institution received a version 1 Low-Power Phased Array Radar (LPAR v1) system, which is further described in section 2.

Fig. 1: Small X-Band radar technology evolution

The ongoing and planned research activities at SBU and UMass using the LPAR v1 systems (and newer versions of these systems in the future) aim to: i) tackle some of the broader challenges regarding the use of phased-array radar (e.g., calibration, polarization bias) evaluate the capabilities, performance, and added value of inertia-free radars (as single node or as network) in several areas of weather research where low-level coverage and rapid volume imaging are expected to advance our understanding of weather processes. One area of active research in the Northeastern United States is urban and coastal meteorological measurements from street-level to the mesoscale to improve our ability to predict hazardous weather (e.g., flooding, winds) and climate conditions (e.g. heat waves) in urban and coastal areas. Other areas of research include the winter snowstorms and deep convective dynamics. In addition, the recent growth in affordable Unmanned Aerial Vehicles (UAVs) (also known as drones) for both personal and commercial use has led to a re-evaluation of the scope and extent of the national airspace. While current regulations limit UAVs to altitudes below 500 ft and prevent Beyond Line-Of-Sight (BLOS) operation, many companies are pushing for widespread deployment for a variety of applications from package delivery to emergency and hydrologic monitoring [16, 17].

II. Low Power X-Band Phased Array Radar Technology

Deployment of a dense network envisioned by CASA requires that the radars be small enough that they integrate into the background infrastructure, making use of existing towers and rooftops. 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. 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 [8], 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. Phased arrays are the desirable technology for this application since they lack moving parts and offer high reliability compared to mechanical scanners and since they offer the ability to rapidly scan different regions of the atmosphere where threats exist. Participants in the CASA project established a working set of specifications for these arrays [8] which is summarized in Table 1.

Table 1: Summary of LPAR specifications

Peak power	100 W
Antenna beamwidth	2 x 2 degrees
Antenna Size	~ 1m x 1m
Polarization	Dual Linear (V, H)
Azimuth Scan Range	+/- 45 deg
Elevation Scan Range	+/- 30 deg

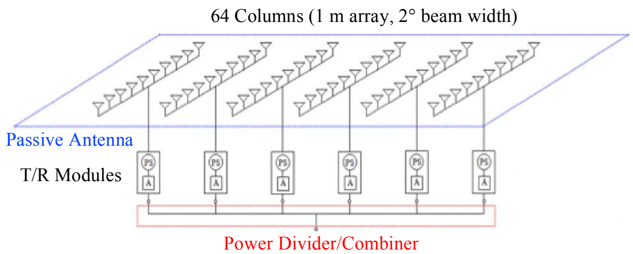

Fig. 2: Schematic showing a phase-tilt array realized as a series of vertically oriented radiating columns, each fed by a single T/R module. The University of Massachusetts – Amherst developed a research prototype of such an antenna comprised of 64 1-W T/R modules. The array is based around 4 Line Replaceable Units (LRU's) each comprised of 16 T/R modules and a segment of passive circuit board shown in Figure 4. Publications describing detailed aspects of the antenna are given in [12-13].

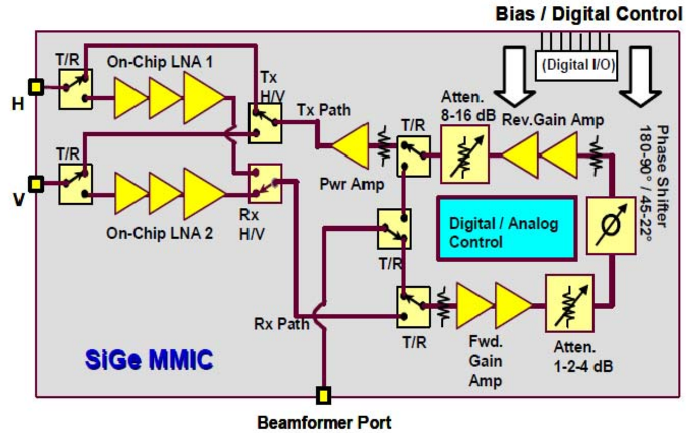

Fig. 4: Custom SiGe MMIC developed for T/R Function [14]

Phase-tilt is a relatively simple approach to realizing an antenna array that performs electronic beam steering in the azimuth direction while mechanically steering (tilting) the antenna in the elevation direction (Fig. 2). 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 (Fig. 3). 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.

An active electronically scanned antenna array design has been developed by Raytheon 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. Key parameters of are listed in Table 2 [14,15]. The radar is comprised of 2560 transmit/receive channels each transmitting less than 50 mW of power. The channels are realized using a Silicon Germanium (SiGe) custom application-specific integrated circuit (ASIC) shown schematically in Fig. 4 [14].

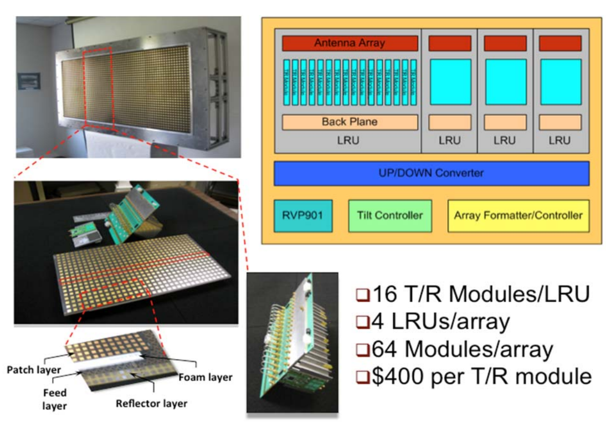

Fig. 3: Prototype Phase-Tilt Radar architecture

The main building block of the radar is a multi-layer circuit card assembly (CCA) comprising 128 T/R ASICS coupled via PIN diode switches to dual-polarized radiating elements [18]. Twenty of these building blocks are assembled to realize the complete radar as shown in Fig. 5.

III. Future Research and Educational Activities

In the last 10 years, electronically scanning radars of varying technological complexity and capabilities have been developed and present an attractive alternative for the operational and research community. Inertial-less beam steering, flexible waveforms, low operational and maintenance cost and low infrastructure requirements all offer new potential to an atmospheric sensing research community that has heretofore been limited a slow-update "sit and spin" view of the atmosphere and an associated "low tech" operational context. This new technology offers the potential to explore the rapid evolution of weather phenomena, fill the low-level gaps in mountainous and urban areas, and observe phenomena from multiple radars at the same time. It is fair to state that the research community has much to do in order to understand and unlock the potential of *phased-array radars*. Here we will briefly describe the on-going and planned future research and educational activities at the University of Massachusetts and at Stony Brook University using the LPAR v1 systems.

Table 2 LPAR Characteristics

Frequency	9.0 - 9.6 GHz
Peak Power	125.4W
Average Power	23W
PRFs	3317HZ
Pulse Widths	6-55 uS
Bandwidth	2 & 6 MHz
Horizontal Pol BW	2.12 EL, 1.85 Az
Vertical Pol BW	2.14 EL, 1.88 AZ
Sidelobe level	< -25 dB typ
Antenna Gain	37 dB
Cross Pol Isolation	~ -35 dB Boresight
Range	30 km
Az Coverage	+/- 45 deg
El Coverage	+/- 15 deg

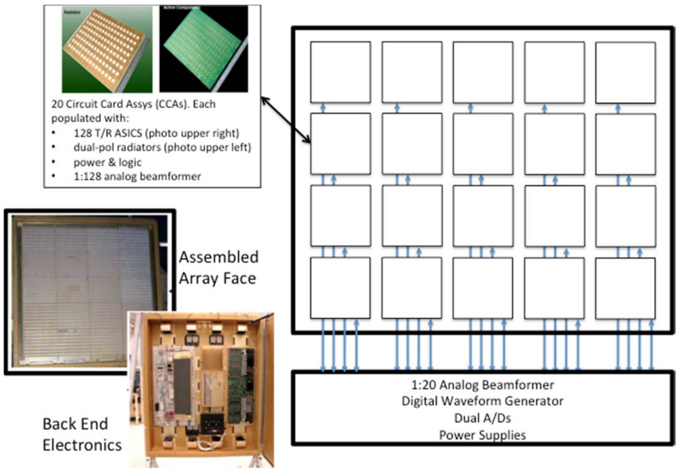

Fig. 5: Phase-Phase LPAR architecture [18]

At the University of Massachusetts, MIRSL was a core partner of the CASA ERC and a well-known engineering-focused laboratory and plans to use the LPAR v1 phase-phase radar to study the engineering characteristics and performance of the dual-polarization phased array radar. MIRSL's research with the LPAR v1 includes topics such as: i) the characterization of the performance of the dual-pol phased array radar using lab testing and comparisons with a co-sighted parabolic reflector X-band radar, ii) the development of signal processing techniques for calibrating and mitigating the polarization distortion inherent in planar phased-array radars and iii) the development of particular scan strategies and modes for weather observations.

At Stony Brook University, the Radar Science group is part of the Institute for Terrestrial and Planetary Atmospheres with expertise in radar applications in weather and climate, regional weather prediction, data assimilation, microphysics and climate modeling. Whereas other atmospheric science research groups are in possession of 1D X-band scanned phased arrays, this is the first time, to our knowledge, that such a group is taking possession of a fully electronic dual-polarization phase-phase radar that scans the atmosphere without moving parts. The incorporation of an LPAR v1 system by an atmospheric science group with strong ties to weather applications is therefore, novel. At the same time this represents a daunting challenge and a great opportunity for research and teaching. Advancements in the field of radar meteorology have often been made by individuals and research groups that understood hardware and signal processing well enough to harness the radar's capabilities to advance their applications while at the same time were able to articulate future concepts and systems to fill remaining gaps in our remote sensing capabilities. Thus, incorporating the LPAR v1 technology into the research and education programs represents an important strategic direction at Stony Brook. Currently (spring of 2018), the radar system is undergoing extensive testing of its sub-components. An Ettus Research Universal Software Radio Peripheral model #N210 [19] is repurposed in collaboration with MIRSL to generate pulse transmission (Digital to Analog Converter) and reception (Analog to Digital Converter) of arbitrary waveforms. Eventually, the radar will be fitted on a new flatbed truck for mobile observations in urban and coastal locations. The careful testing and evaluation of the hardware and software functionality of the LPAR v1 at Stony Brook will help us to understand and evaluate its performance and to educate our radar applications researchers and students on the current and future capabilities of phased-array radars. In addition, the Radar Science group, MIRSL and Raytheon intend to jointly develop a new web-seminar course on single-radar and networked LPAR technology and applications. The course will cover topics including: system hardware and software architecture; sensor network laydown geometry; information extraction algorithms; beam scheduling; scattering physics; and projects centered around student-defined applications ("apps") using the technology.

IV. CONCLUSIONS

Looking forward, *moving away from the inertia-limited view of the weather processes with the introduction of networks of low-power X-band phased array radars could provide the leap in observational power required to address some of the observational shortcomings of the last 50 years.* There are several other areas of weather research where inertia-free radars with ability to provide rapid volume imaging are expected to advance our understanding of weather processes. Two such areas of active research are the documentation of storm dynamics using multi-Doppler radar techniques and the study of the rapid evolution of winter storms in order to assess the microphysical-dynamical interactions. Two of the most important limiting factors in multi-Doppler radar retrievals of vertical velocity are the horizontal and vertical advection of the convective cloud while the 5-6 min required to complete the volume coverage pattern and the limited number of radar observations at the upper part of the convective clouds [20]. An example of the expected improvement in vertical velocity retrievals is shown in Fig. 6 where high-resolution model output from the Weather Research Forecasting (WRF) model (500 m horizontal resolution, 20 sec output) is use as input to the Cloud Resolving Model Radar SIMulator (CR-SIM, [21]) to simulate radar reflectivity and Doppler velocity from scanning radars. The simulated reflectivity and Doppler velocity are used to estimate 3D wind field using a 3DVAR multi-Doppler radar wind retrieval algorithm [22].

Winter storms in areas such as the Northeastern United States is another area of active weather research that will benefit from low-power X-band phased array radars. Winter storms have fine-scale, transient structure where turbulence gravity waves and boundary layer circulations contribute to ice particle mass growth [23]. Understanding these microphysical-dynamical interactions at short temporal and spatial scales requires rapid updates and a small network of LPAR systems can provide valuable insights. X-band radars are ideal for winter weather studies due to their higher sensitivity to dual polarization measurements and the negligible hydrometeor attenuation in snow.

Another area of growing interest are urban and coastal areas. The Northeastern megalopolis, stretching from Boston to Washington, is home to more than 50 million people and the region represents 20 percent of the country's gross domestic product. Critically, our ability to predict and monitor extreme

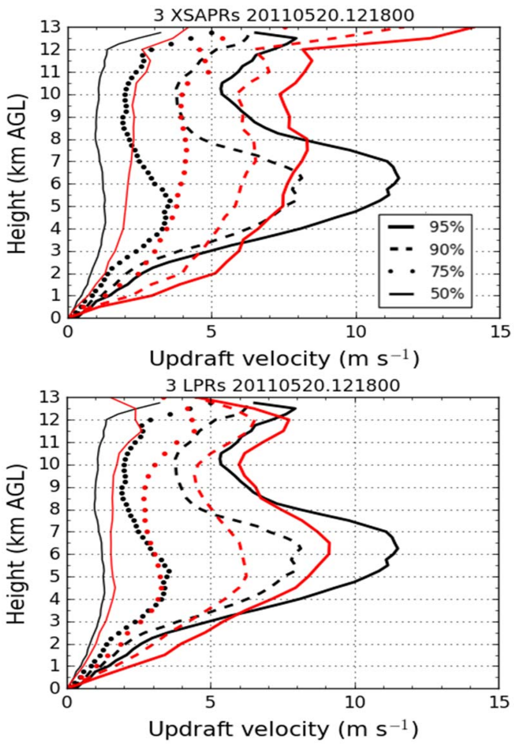

Fig. 6: Vertical profiles of percentiles of updraft in a region with reflectivity > 10 dBZ. The top panel shows the multi-time PPI X-band wind retrieval (3 radars) with a 5-min VCP, beamwidth 1° and maximum elevation 50°. The bottom panel shows snapshot X-band Phased Array Radar wind retrieval (3 radars) with 20-sec VCP, beamwidth 2° and maximum elevation 60°. Black lines indicate the WRF model output and the red lines the 3DVAR output. The phased-array radar configuration captures better the WRF updraft statistics especially near the convective cloud tops.

and hazardous weather events and address national security needs in atmospheric transport and dispersion is limited. Developed urban and coastal areas are characterized by highly heterogeneous energy sources and landscapes. Thus, boundary layer schemes developed over flat homogeneous surfaces are not suitable for coupling the urban system and the mesoscale flow and do not consider urban feedbacks to weather [24].

One of the factors that contribute to our limited understanding of the weather and climate processes occurring around urbanized areas are the temporal-spatial limitations of existing weather monitoring networks. Fig. 7 shows the minimum detectable height of today's NEXRAD operational radar network over the Northeastern urban corridor. Low-altitude observations (depicted as blue and green regions) are only possible in the regions in close proximity to the NEXRAD stations. A significant fraction of this region is without any radar coverage whatsoever below 1 km altitude.

A network of LPAR's around urban cities along with measurements from Doppler lidars [25] and other hyperspectral sensors [26] can provide valuable information to fill the gap in measurements from the street level flow to the mesoscale (www.bnl.gov/CMAS). Additional research is needed to identify the scattering source at X-band especially during the summer months. NEXRAD's observe often clear air echoes in their vicinity (within 50 km range) arising from a combination of coherent (Bragg) scattering from refractive index inhomogeneity's and incoherent (Non-Rayleigh) scattering from insects [27]. The density of insect/birds echoes around the Upton, NY NEXRAD system (KOKX) for the month of July 2017 is shown in Fig. 8. The current spacing of the NEXRAD systems does not allow a gap-free mapping of low-level winds using insects, however a dense network of LPARs could provide a spatially continuous low-level winds coverage using insects.

In addition, the potential for bistatic probing of clear-air winds using LPARs will be investigated [28, 29].

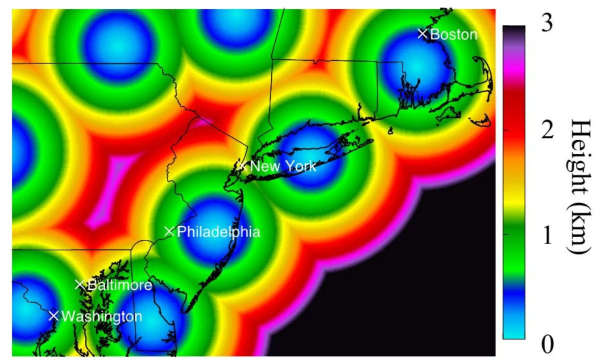

Fig. 7: The NEXRAD network minimum detectable height composite over the Northeastern megalopolis.

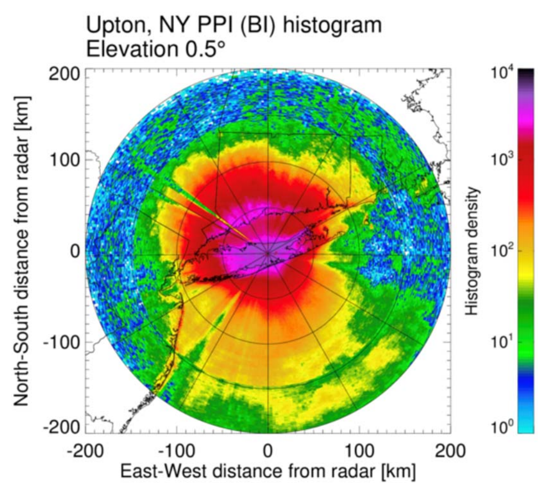

Fig. 8 Density of biological targets around the KOKX for the month of July 2017

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