Agile Weather Observations using a Dual-Polarization X-band Phased Array Radar

1st Pavlos Kollias
Division of Atmospheric Sciences
Stony Brook University
Stony Brook, NY, USA
pavlos.kollias@stonybrook.edu

2nd Edward P. Luke
Environmental and Climate Sciences Department
Brookhaven National Laboratory
Upton, NY, USA
eluke@bnl.gov

3rd Kristofer Tuftedal
Division of Atmospheric Sciences
Stony Brook University
Stony Brook, NY, USA
kristofer.tuftedal@stonybrook.edu

4th Michael Dubois
SKYLER Product Manager
Raytheon Technologies
Marlborough, MA, USA
michael.dubois@raytheon.com

5th Eric J. Knapp
Principal Engineer
Raytheon Technologies
Marlborough, MA, USA
eric.j.knapp@raytheon.com

***Abstract*—Dual-polarization, low-power X-band phased array radars offer an attractive radar technology for short-range weather observations. These systems offer 2-D phase-phase steering, without motors or other moving parts. 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 of cloud physics, water resource management, monitoring of the movement and dispersal of hazardous plumes, and other areas. Over the past three years, the Radar Science group at Stony Brook University in partnership with Raytheon Technologies has been experimenting with novel sampling strategies for weather observations using different generations of the SKYLER dual-polarization X-band phased array radars. Here, examples of weather observations collected by SKYLER are presented along with information on the novel observational strategies based on the Multisensor Agile Adaptive Sampling (MAAS) framework.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

For over 60 years, radars have been at the focal of scientific discoveries in atmospheric science and of irreplaceable value to weather prediction. The same radar returns from natural targets such as clear air turbulence and hydrometeors that were considered a source of interference by the military, have been treasured by the meteorological community. Since then, a large body of theoretical and experimental work has been accomplished and the measurable properties of radar signals—amplitude, phase, polarization, and frequency—can be interpreted in terms of the sizes, shapes, motions, or thermodynamic phase of the precipitation particles. Furthermore, significant advancements in radar technology and digital signal processing have led to the development of sophisticated weather radar systems that provide high quality radar observables.

However, one aspect of meteorological radars that remain unchanged is the mechanical inertia introduced using a large reflector antenna on a positioner. This single aspect exerts considerable influence on a radar's spatiotemporal sampling, the interpretation and quality control of radar observations, and has considerable utilization and maintenance impacts on operational and research radar networks across the world.

Today, phased array radars (PARs) -designed several decades ago for tracking man-made targets- are a mature, established technology, at the cusp of availability to the meteorological community. PARs offer near instantaneous sampling of the atmosphere when and where it is needed without any mechanical inertia limitations, flexible beam forming, multifunctionality and low operational and maintenance costs [1-3]. These PAR features are nearly orthogonal to those offered by our current reflector-based radars; however, the assimilation of PAR technology by atmospheric science will be different in many ways compared to the early days of radar meteorology.

Phased-array radar capabilities such as adaptive scanning and fast revisiting time, especially in a network configuration, could provide the leap in observational power required to address some of the observational shortcomings of the last 50 years. In order to fully capitalize of the PAR features, we propose that a data-driven dynamic sampling framework based on Artificial Intelligence and Machine Learning (AI/ML) methodologies is required. Here, we will present our progress towards achieving this agile, adaptive sampling paradigm.

II. The SKYLER dual-polarization X-band phased array radar

Competition for the frequency spectrum traditionally reserved for long-range radars, physical limitations in observing the low altitude airspace and the spatiotemporal resolution required to handle the dramatic increase of emerging air traffic and the simultaneous need for supporting weather observations in urban and coastal areas motivated R&D investment in two-dimensional X-band PAR's over the past decade.

Raytheon Technologies has developed an active electronically scanned antenna array design 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 [4,5]. The radar system, named Skyler is a low cost, dual-polarization multi-function phased array sensor product, capable of operating as a single radar or networked together to provide long-range gap-free coverage. The software-defined mission capability, coupled with phased array technology, creates a system that can simultaneously provide localized high-resolution weather data, perform aircraft surveillance and precision approach functions, and enable small drone detection and tracking.

Table I
Technical characteristics of the SKYLER I and II systems

Parameter	Range
Operational Frequency Band	9.0-9.6 GHz
Tx Power	< 250 W
Antenna size	~1 m x 1m
Antenna beamwidth	~ 2º x 2º
Maximum Duty Cycle	25%
Pulse Repetition Frequency	Selectable, typical 1.2 – 4.0 kHz
Pulse Width	Selectable, typical 1 – 55 µs
Waveform Pulse Modulation	CW, LFM, NLFM
Tx/Rx Polarization Modes	HH, HV, VV, VH
Angular Coverage	±45°azimuth by ±15°elevation
Instrumented Range	40 km

A. The Stony Brook University X-band phased array radar systems

The Radar Science group at Stony Brook University in collaboration with Raytheon Technologies has been experimenting with the use of SKYLER radars for weather research. In 2019, a SKYLER - I system was integrated onto a mobile platform for weather observations (Fig. 1a). The SBU mobile platform is equipped with a backscatter lidar (0–15-km) that provides cloud base height and boundary layer aerosol backscatter information, and a next generation Micro-Rain Radar (MRR-PRO) that provides time-height information of the vertical structure of precipitation from 0–15 km. The instrumentation includes a Parsivel2 disdrometer, a fisheye and steerable visible camera, a weather station, and a radiosonde (Graw) system. These capabilities provide comprehensive profiling observations of aerosols, clouds and precipitation. The SKYLER-I radar has an antenna beamwidth of 1.98° in azimuth and 2.1° in elevation at boresight. The beam is electronically scanned in the horizontal plane by +/- 45° and in the vertical plane +/- 15° relative to the boresight. The radar transmits H- and V-polarization pulses (alternating) and provides estimates of ΦDP, KDP, ZDR, and ρHV in addition to the standard power and Doppler measurements [6].

During the summer of 2021, Raytheon Technologies provided a second generation system, Skyler-II, which uses a single channel transmit/receive module and a dual polarization antenna operating in alternating transmit, alternating receive mode (ATAR). The software defined transceiver uses long duty cycle pulses and pulse compression to increase sensitivity and can employ phase coding to suppress multi trip echoes. The weather data processor (WDP) utilizes spectrum-based methods for noise estimation and clutter filtering and provides the following polarimetric moments: reflectivity, differential reflectivity, radial velocity, spectrum width, specific differential phase and co-polar correlation coefficient, as well as several quality control parameters.

Fig. 1. (a) SKYLER-I and (b) SKYLER-II on the SBU weather mobile platform

III. Advantages of PAR weather observations

A. Netted operations - Low-level coverage

The current version of the U.S. Weather Surveillance Radars [7], commonly known as Next-Generation Radars (NEXRADs) like a vast majority of weather radars, usually employ a large mechanical scanning parabolic (dish) antenna, and 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 [8,9]. A PAR operational network can offer lower operational and maintenance costs and graceful hardware degradation.

Another important issue is low-level coverage. Only about 30 % of the first 1 km of the CONUS atmosphere is covered by existing ground-based radar systems [10]. Dramatically increased interest in low-level coverage is fueled by the recent growth in affordable Unmanned Aerial Vehicles (UAVs) (also known as drones) for both personal and commercial use. This 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 [11, 12].

Fig. 2 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

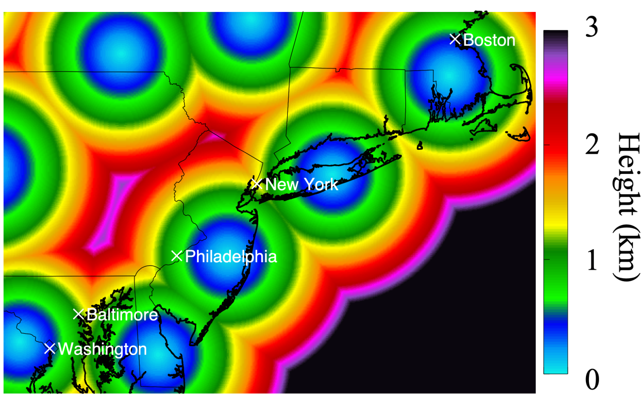

Fig. 2. The NEXRAD network minimum detectable height composite over the Northeastern megalopolis

The National Science Foundation (NSF) Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) introduced 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 [1]. 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. It is important to note that while a dense network of mechanically scanning radars can offer similar low-level coverage, it is the ability of a PAR to perform multi-function operations and simultaneously observe hard (aircraft and drones) and weather targets that provides superior flexibility in addressing the challenge of weather observations in a crowded airspace.

B. Filling the vertical dimension of storms

A great advantage of PAR's is their ability to near-instantaneously position their beam in any direction of interest in the sky. The constant elevation (PPI) and constant azimuth (RHI) scans that traditional mechanically scanning radars perform, provide high resolution horizontal and vertical measurements respectively. Operational weather radars usually accomplish surveillance volume coverage using a sequence of PPI scans at discrete elevation angles and from 0 to 360^o in azimuth. The PPI scans are designed to provide weather surveillance over a large area. Fig. 3a shows an example of a PPI scan from the KHGX NEXRAD radar in Houston, TX.

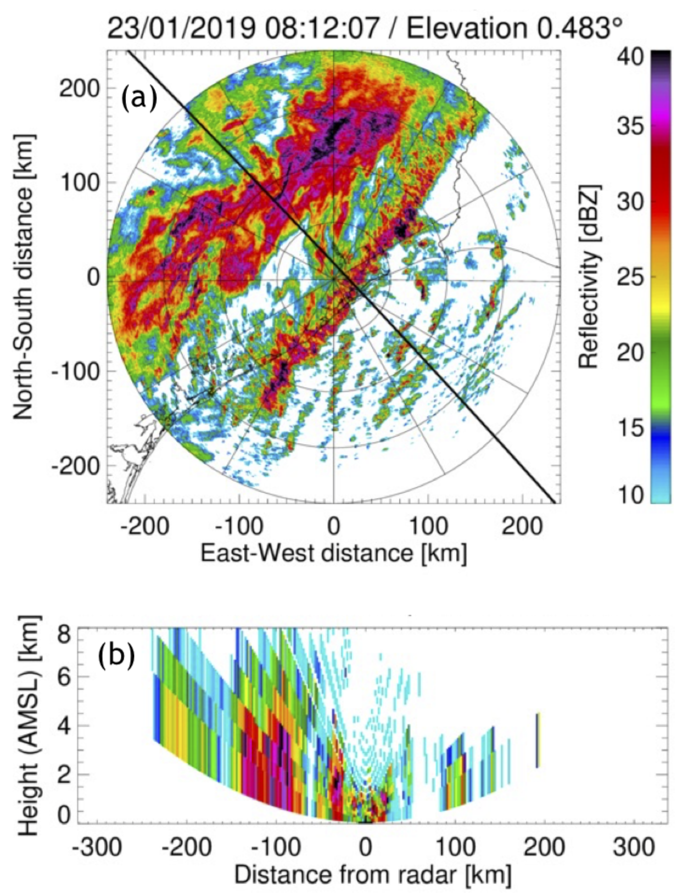

Fig. 3. a) The horizontal view of precipitation from NEXRAD as depicted in the 0.5^o elevation angle and b) the reconstructed vertical view of precipitation from the different PPI's along the black line shown on the PPI image

A vertical cut of the precipitating storms along the black line shown in Fig. 3a can be retrieved by compositing the observations from the different elevations at a particular azimuth angle (Fig. 3b). Several features are noticeable in Fig.

3b. First, the NEXRAD beams' coverage effectively curve upward due to the Earth's curvature, highlighting the low-level sampling challenge mentioned in the previous section. In addition, close to the NEXRAD location, no observations are available (due to the cone of silence). In the area where observations are available, the vertical resolution degrades with distance from the radar due to the broadening of the radar beam and the spacing between the discrete elevation angles where the PPI's are performed. The coarse vertical resolution challenges the interpretation of the vertical storm structure and the estimation of parameters such as the Vertically Integrated Liquid (VIL) that can be useful tools for assessing the severe weather potential of thunderstorms [13]. Furthermore, these images are only available every 4-6 min, a revisiting time that is not suitable for capturing rapidly evolving atmospheric phenomena.

A higher resolution view of the vertical structure of precipitating storms can be generated using an RHI scan. However, accelerating and decelerating the antenna pedestal to accomplish a hybrid PPI/RHI scan strategy results in a considerable time overhead (approximately 1/3 of the time) and is taxing the pedestal hardware. This type of hybrid scan strategy is usually employed by research precipitation radars. These time and hardware considerations are not relevant to PAR's. Fig. 4 shows an example of a PPI and RHI scan from the SBU Skyler-I system. The observations from both views of the precipitating storms were collected within 4s.

The ability of PAR's to obtain near-instantaneous, high-resolution horizontal and vertical views of storms at rapid revisiting time will improve the interpretation of precipitation storms and severe weather nowcasting. The availability of such observations is expected to advance our understanding through the documentation of storm dynamics using multi-Doppler radar techniques. 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 during 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 [14]. However, the development of such targeted PAR observations requires a new operational framework for operational and research applications. Some early work and thoughts on this topic are discussed in the following section.

C. Agile Weather sensing

The vast majority of our observing systems interact with the atmosphere using a predetermined "stare" or "sit and spin" sampling strategy that is not adaptive to the atmospheric conditions. This approach is based on sampling all the sky equally, even clear skies without any atmospheric phenomena of interest. This precludes our ability to revisit more frequently in time and with higher spatial resolution the relevant parts of the sky where a particular phenomenon is occurring.

Here we propose a new PAR scan strategy paradigm in which features of the environment, subject to well-defined observational objectives, are allowed to dynamically steer

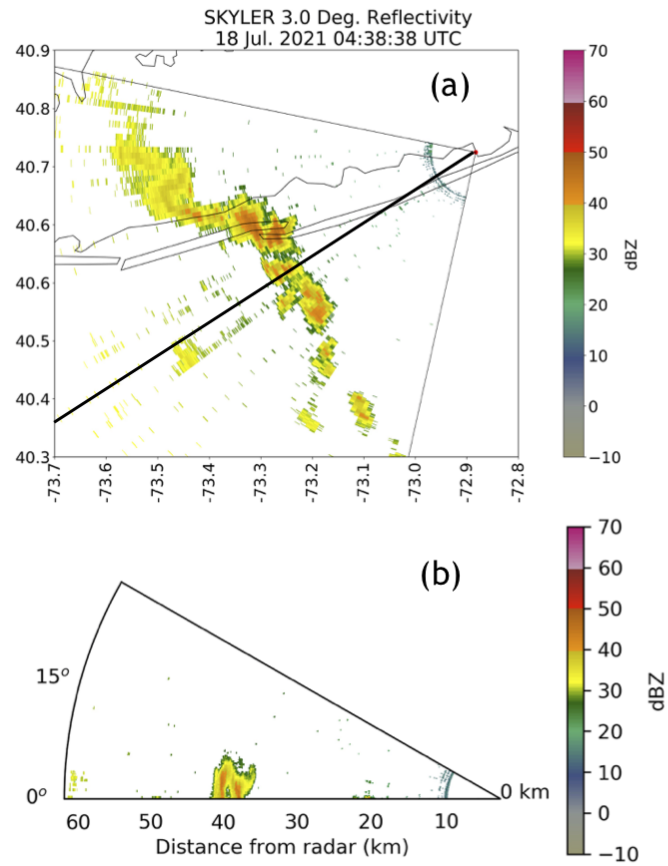

Fig. 4. a) The horizontal view of precipitation from the SBU Skyler-I as depicted in the 0.5^{o} elevation angle and b) the near-instantaneously collected RHI scan along the black line shown on the PPI image

the beam and determine its parameters, such as dwell time and PRF. This is a real-time data-driven approach with the goal of optimizing the effort spent by focusing on gathering information content of greatest interest. To truly capitalize on the benefits of an inertia-free beam requires a break from the sit-and-spin style notions of preplanned PPIs, RHIs, raster scans. By way of analogy, the human visual system offers an example of highly adept, externally driven, dynamic remote sensing. The area of the human retina capable of resolving high-resolution images (the fovea, measuring about 1.5 mm across) is a mere a fraction of the total retinal area. It's very narrow field of view requires there to be a time-sharing scheme in which the eyes' positions shift rapidly (using saccadic motions) between different features of interest, with the features containing more important information getting more revisit time [15]. These "snapshots" are then linked together by the brain to extract meaning. The drivers of these motions are a combination of both automatic and volitional signals.

In a break from traditional sit-and-spin methods, we plan to test a new approach for observing convective weather with similar characteristics, consisting of two parts. The first part consists of a very fast ongoing raster scan that blankets the

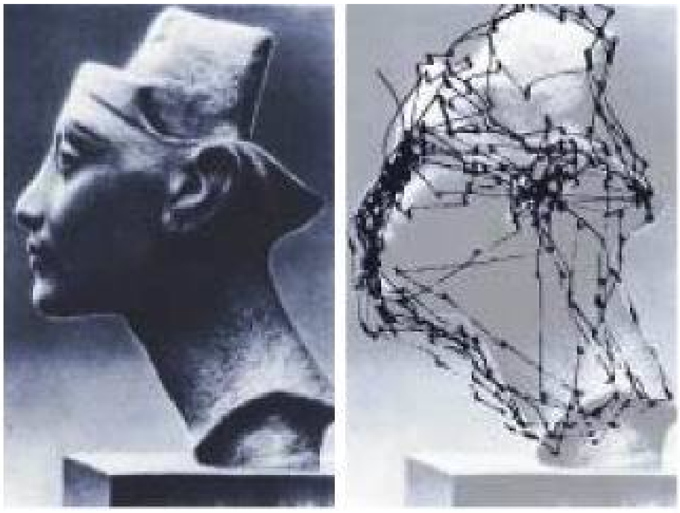

Fig. 5. The eye movements of a subject viewing a picture of Queen Nefertiti. The bust on the left is what the subject saw; the diagram on the right shows the subject's eye movements over a 2-minute viewing period. [15])

full observational sector in azimuth and elevation with a coarse grid of short dwell-time beams. Every few seconds, all data from the grid are periodically sorted in a descending relevance according to a "goodness metric" to identify the most interesting beam directions. Simultaneously, the second part of our approach targets a set of high spatial resolution longer-dwell beams, prioritized by the most interesting directions, until available beam time is exhausted. The budgeting of beam time is split 20%/80% between the first and second parts, allowing high resolution sampling to be continuously targeted towards the most interesting features for the majority of time as they evolve. We term this the Saccadic Phased Array Radar Sampling (SPARS) algorithm. The first part performs a function analogous to the rods in the human visual system covering the bulk of the optical field and providing peripheral vision. The second part is analogous to the high-resolution fovea that resolves the most interesting content. One important difference in our case is that the "fovea" can assume an arbitrary shape and even split into multiple "foveae", as needed.

Projecting this approach further, as phased-array radar becomes integrated with machine learning capabilities, it becomes the input sensor (or eyes, so to speak) of an intelligent atmospheric **computer vision system**.

D. Multisensor Agile Adaptive Sampling (MAAS)

One dynamically driven PAR scan strategy successfully demonstrated by our group uses real-time lightning detections and cloud-top temperature information from the GOES-16 satellite to guide the steering of RHI's toward the azimuths of convective cores to achieve a high revisit rate [16]. In a more recent demonstration, a continuous PAR PPI is used to perform surveillance for the occurrence of convective cores. When a core is detected, an RHI is steered toward it. Once again, a rapid revisit rate is achieved, and the RHI data are used in a feedback loop to track the core. Fig. 6 shows the superposition in space of views of the same precipitating system at four different times acquired from successive RHI's. .

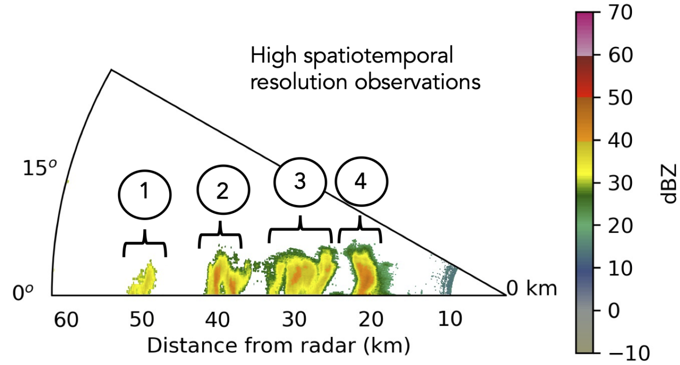

Fig. 6. A composite of 4 RHI's of the same precipitating storm collected during an agile adaptive SKYLER-I scan strategy. The data displayed in the areas 1 to 4 were acquired from adaptive RHI scans with sufficient time spacing to allow us to superimpose them along range in the RHI plot

In addition to the lack of an intelligent, automated observational framework, another limitation of the conventional observational paradigm is the current way in which multi-sensor observations are used. It is common to rely on multiple sensors to observe different parts of the atmosphere, and to gain insights regarding their interactions using multi-sensor retrieval techniques. Traditionally, the value of multi-sensor observations emerges long after their collection, during a post-processing phase. Unfortunately, any knowledge gained at that stage cannot be used to adjust and optimize the observing strategy, often leaving an incomplete picture of the atmosphere

Our group has developed the first iteration of an intelligent agent for weather radars that uses multisensory input for agile adaptive sensing, and we have demonstrated the evolution from an observing system into an intelligent observing protocol system [16]. The intelligent agent, called the Multisensor Agile Adaptive Sampling integrates the ecosystem of existing infrastructure sensing systems (cameras, satellites (GOES), radars (NEXRAD), lidars etc.) into an artificial intelligence system that is able to identify phenomena of interest, allocate resources for their tracking and sampling and creation of the proper warning/response output. MAAS uses best practices for data fusion from low-cost distributed sensors (cameras), operational networks (GOES and NEXRAD) and high-quality research-grade sensors such as Skyler-I and II and a Ka-band scanning polarimetric radar (KASPR) which is part of the Stony Brook University and Brookhaven National Laboratory Radar Observatory (SBRO).

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of this paper. We are also very grateful to Michael Dubois, Eric Knapp, Andrea Terrasi, Chris McCarroll and all of Raytheon Technologies for their efforts in establishing the

SBU-Raytheon partnership, for providing the Skyler I and II systems and for their assistance in the preparation and operation of the radar system.

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