A Dual-Doppler Ka-band Mobile Radar Architecture With Rapid-Scanning Volumetric Imaging for Earth Systems Science

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***Abstract*—This paper describes a new radar architecture for a dual-polarized Ka-band mobile rapid-scanning volumetric imaging radar (KaRVIR) system, the first ground-based millimeter-wavelength phased array radar (PAR) for Earth systems science. KaRVIR's concept enables unprecedented four-dimensional measurements including high-temporal resolution and full volumetric imaging at Ka-band. It will enable transformative studies of clouds, precipitation, and boundary layer processes, and unleash innovative applied environmental research to study fires plumes, and insect migration. In this paper, we discuss the design trade-offs of this cost-effective PAR architecture that will provide high-fidelity radar data at Ka-band, enabling impactful studies throughout the scientific community. It is designed to observe cloud and precipitation processes and other environmental phenomena requiring mm-wavelength observations at high spatial resolution and radar sensitivity.**

***Index Terms*—Cloud radar, dual-polarization, imaging radar, rapid-scanning, phased array radar, mmWave, weather radar.**

I. Introduction

Millimeter (mm)-wavelength radar technology has contributed immensely to scientific understanding of cloud and precipitation processes, dynamics, and turbulence. Compared to longer wavelength radars used primarily for precipitation measurements (S-, C-, and X-bands), existing mm-wavelength radars that rely on parabolic reflector antennas have enhanced sensitivity to small particles such as cloud droplets and ice crystals [1]. Analyses of dual-polarization and Doppler spectral data have enabled better discrimination of ice hydrometeor types in the precipitation frequency bands [2], while vertically pointing, mm-wavelength radars have only been used to obtain distributions of vertical velocities and turbulence in convective and stratiform clouds [3, 4] and the convective boundary layer [5]. Networks of ground-based mm-wavelength radars have been deployed as a part of the Department of Energy (DoE) Atmospheric Radiation Measurement (ARM) program [1], enabling climatological studies of cloud microphysics and dynamics in different regions. These mm-wavelength radars include both vertically pointing and scanning radars with dual-polarization capability. Airborne mm-wavelength radars have also been developed to couple radar measurements with in-situ observations of clouds and precipitation [6, 7]. Current mm-wavelength radars are not able to provide rapid three-dimensional scans of clouds and precipitation processes because volume scans require ∼10-15 min and clouds can evolve substantially during that period [8]. The combination of sensitivity requirements and narrow beamwidths make it impossible to scan more quickly with mechanically rotating antennas. Instead, scanning strategies are adopted to perform 1-D or 2-D scans (e.g., vertical stares, PPIs, RHIs), but these scanning strategies cannot observe the 3-D evolution of clouds and precipitation. Likewise, airborne and spaceborne radar observations are frequently limited to 2-D observations along their respective flight/orbital paths. For these reasons, past studies [1, 8, 9] have encouraged the development of new technologies that can provide 3-D cloud radar measurements. Phased array radar (PAR) technology is being adopted by the atmospheric science community for precipitation studies at S-, C-, and X-bands, however, it has not yet been used at mm-wavelengths for ground-based remote sensing. Developing a mm-wavelength PAR would provide the higher temporal resolution needed for 3-D scanning of clouds and other small scatterers poorly observed at longer wavelengths. This paper puts emphasis on a cost-effective radar architecture that could enable the first high sensitivity radar with unprecedented four-dimensional views including high-temporal resolution and volumetric imaging at Ka-band. It will enable transformative studies of clouds, boundary layer processes, and unleash innovative applied environmental research to study fires plumes, and insect migration. The paper is organized in three sections. Section II, presents KaRVIR system description and design trade-offs for a cost-effective radar architecture. Section III presents a simulation study of the KaRVIR architecture, in comparison to the mechanically steered ARM Ka-SCAR radar. Section IV summarizes the benefits of the KaRVIR architecture.

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II. Description of Proposed Radar Systems

A. High-Level System Description

KaRVIR will be composed of two, co-located, polarimetric mobile ground-based Ka-band rapid-scan volumetric imaging radar systems that will enable unprecedented research in atmospheric observation. The combination of unique radar

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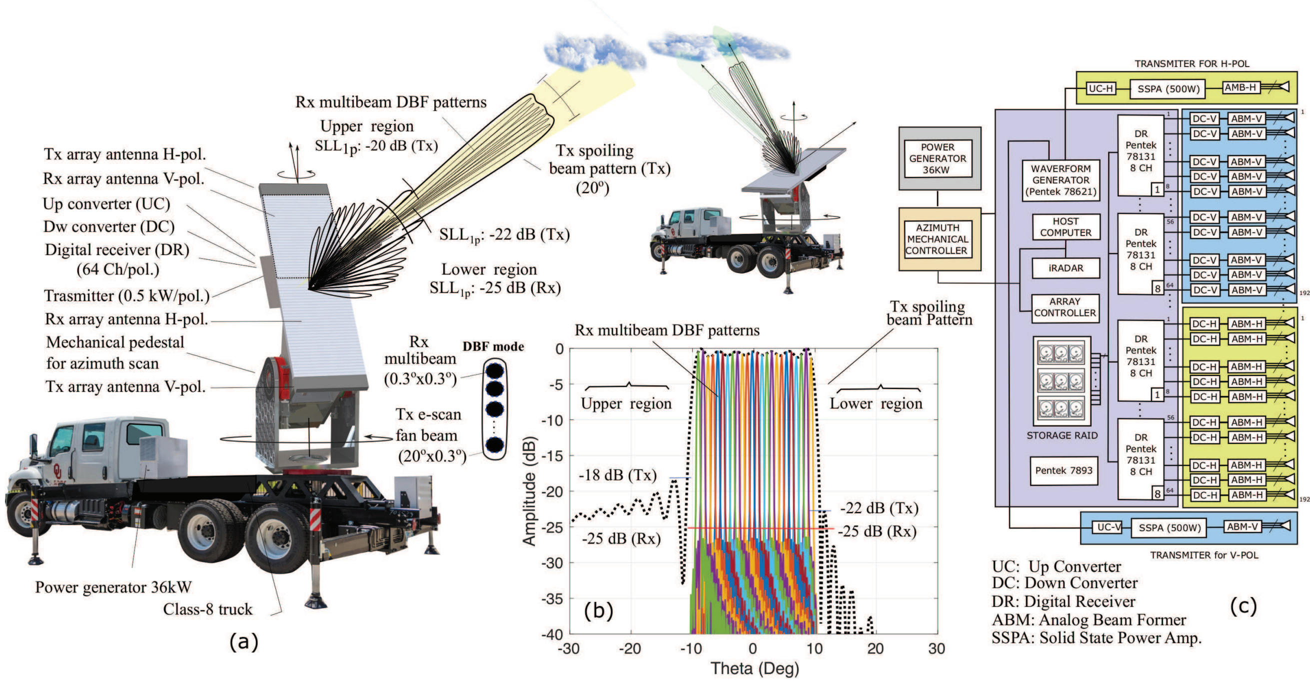

Fig. 1. (a) Renderings of two-mobile KaRVIR radars, (b) Simulated two-way antenna radiation patterns, and (c) High-level system block diagram of proposed KaRVIR radars.

architecture, using mature Ka-band phased array antenna technology with digital beamforming on reception, makes this proposed radar system feasible and cost-effective to provide a state-of-the-art radar for the scientific research community. The proposed system allows multiple simultaneous beams in elevation with mechanical scanning in azimuth that will provide excellent temporal resolution (<20 sec), spatial resolution (24 m at 5 km), and radar sensitivity (-26 dBz at 5 km) due to the continuous-wave (CW) transmitter design. High-quality polarimetric radar products can be guaranteed since electronic scanning is maintained on the vertical principal plane, where very low cross-polarization levels can be achieved. Leveraging the expertise of the team in the design and calibration of high isolation array antennas, unprecedented cross-polarization isolation (better than 50 dB) can be obtained using slotted waveguide antenna arrays and high isolation (better than -90 dB) between transmit and receive sub-systems [10, 11]. Different phase centers of the separated arrays in transmit (Tx), receive (Rx), and polarizations will be properly corrected during the radar calibration process [12]. As illustrated in Fig. 1(a-b), each radar will have a 0.3° beamwidth in azimuth and a fixed 20° beamwidth in elevation on transmission. On reception, every three rows of 268 elements will be arranged to perform as a sub-array (3×268 elements). Each sub-array will be integrated with an independent down-converter (DC) and digital receiver (DR) to produce in-phase and quadrature (I/Q) signals. In total, 64 digital receivers per polarization will be used. An advanced cluster computing system will be employed to aggregate and process the dual-polarization I/Q data from the 64 sub-arrays. After digital beamforming, a flexible number of receive beams can be formed with a regular beamwidth of $0.3^\circ \times 0.3^\circ$ in azimuth and elevation. A simplified block diagram of the proposed radar is illustrated in Fig. 1(c).

B. Technical Description of Sub-Systems

1) Antenna Arrays: To maximize the power efficiency and polarization purity, the KaRVIR antenna is composed of four separated apertures using a slotted waveguide array technology. On transmit, two independent arrays of 3×268 elements for H- and V-polarization will be used to synthesize a fan beam with a 20° fixed elevation beamwidth. In the elevation plane, the antenna can be mechanically adjusted to obtain a larger field of view. On receive mode, two independent antenna arrays, each composed of 192 rows of 268 elements per row will be used to form simultaneous pencil beams of $0.3^\circ \times 0.3^\circ$. Grating lobes at $\pm 90^\circ$ in elevation, produced by the element spacing of 1λ, will be mitigated with the nulls of the synthesized transmit fan beam. As illustrated in Fig. 1(b), two-way patterns with side-lobes better than -25 dB are expected for each polarization. The separate transmit/receive arrays provide the added benefit of allowing simultaneous reception *during* transmission, which eliminates any blind range while using high-duty-cycle transmission for higher sensitivity. An alternative approach that will make the antenna aperture smaller, consist of using a novel dual-polarized slotted waveguide array antenna that shares one single aperture for transmit and receive [11]. This new antenna is illustrated in the Fig 2., where each slotted row is a dual-polarized series-fed slotted waveguide array antenna with 268 elements. For both polarizations, the antenna element spacings

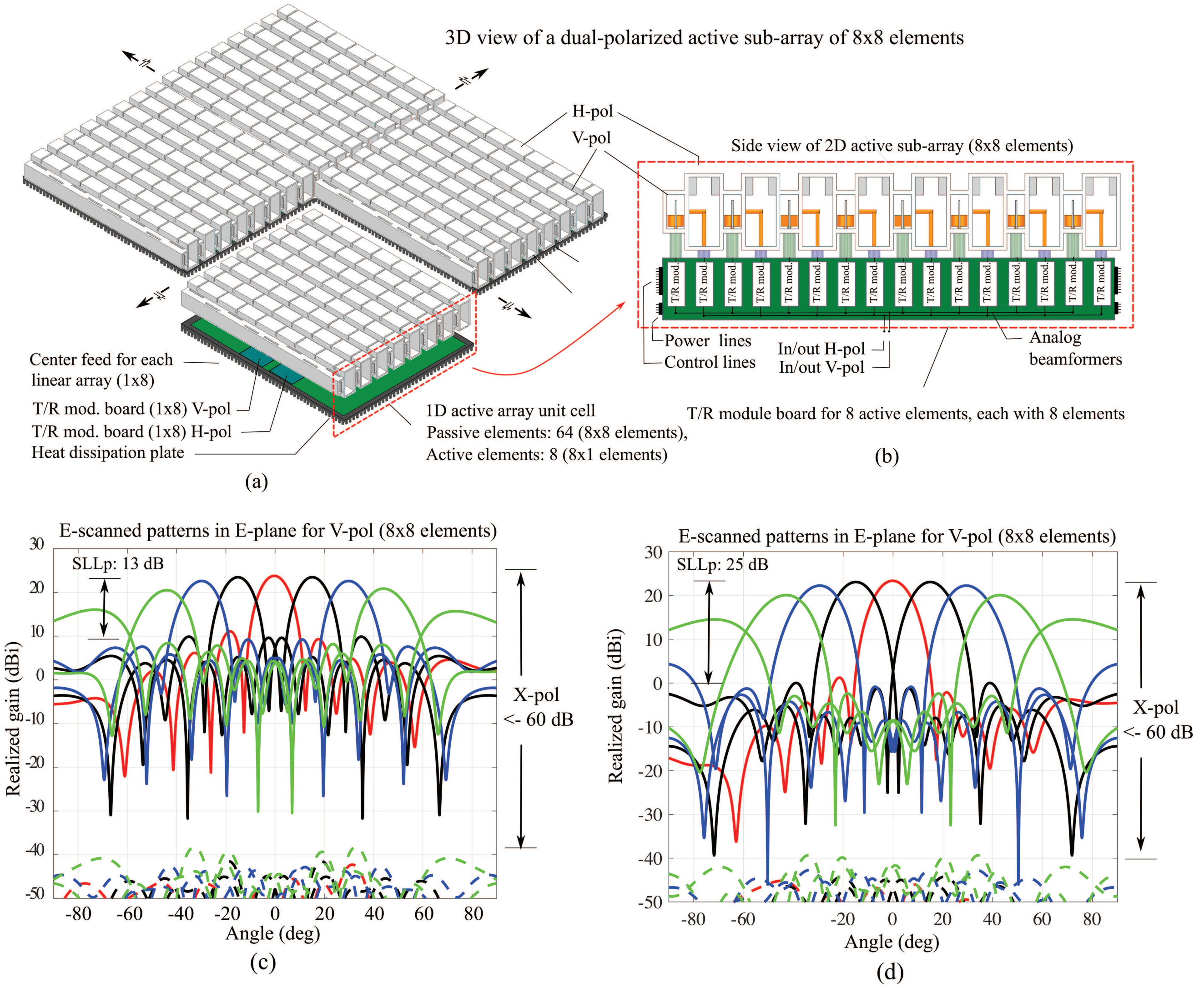

Fig. 2. Antenna concept and predicted sub-array scanned radiation patterns performance. (a) 3D view of antenna array assembly for KaRVIR image radar. (b) Side view of the of the array highlighting TR modules. (c) Co-polar and cross-polar radiation patterns of sub-array of 8x8 elements for uniform illumination. (d) Co-polar and cross-polar radiation patterns of sub-array of 8x8 elements for Taylor -25 dB taper illumination.

are 0.62λ. Conventional slotted waveguide array antennas are ideal for this proposed radar since it support high power and is the best antenna to reduce feed losses and to maximize the overall radiation efficiency in the array. One limitation of using conventional slotted waveguide antenna arrays is due to the spacing between slots. Having two slotted linear arrays (side-to side) for H- and V- polarization requires a space of 1-1.2 λ. This sub-array separation will creates grating lobes that will drastically reduce antenna efficiency to 30% and will not allow the antenna array to scan in the elevation plane. Figure 3 (a) illustrates the cut section of linear dual polarized array with conventional waveguide WR-28 (for H- and V-polarization), where the overall dual-polarized unit cell dimensions is 1.2 λ. Figure 3. shows the grating lobe diagram for the array using the conventional waveguides. In this case 100% overlap between the antenna visible region and grating lobe regions, indicates this array have grating lobes even when the array is not scanning. Alternatively, using the proposed novel antenna architecture, the dual-polarized unit cell (0.6 λ) prevents the presence of grating lobes and enables scanning of 84° (± 42°) in elevation. Unit-cell of antenna geometry with 0.6 λ spacing and grating lobe diagram analysis shows the proposed arrays enables a scanning range of ±42° in elevation without grating lobes beams are illustrated in Fig. 3c-d.

2) Transmitter: The transmitter will use solid state power amplifier (SSPA) technology that enables 500 Watts in continuous wave (CW) mode for each polarization. SSPA is a mature technology developed for SATCOM and 5G applications. Innovative GaN-on-SiC enables significant improvements in efficiency and operational bandwidth. Currently, SSPAs can deliver high power density, providing up to 500 Watts along with reduced size, excellent gain, high reliability, and process maturity with volume production dating back to 2000 [13].

Separate aperture arrays for Tx, Rx, and H- and V-

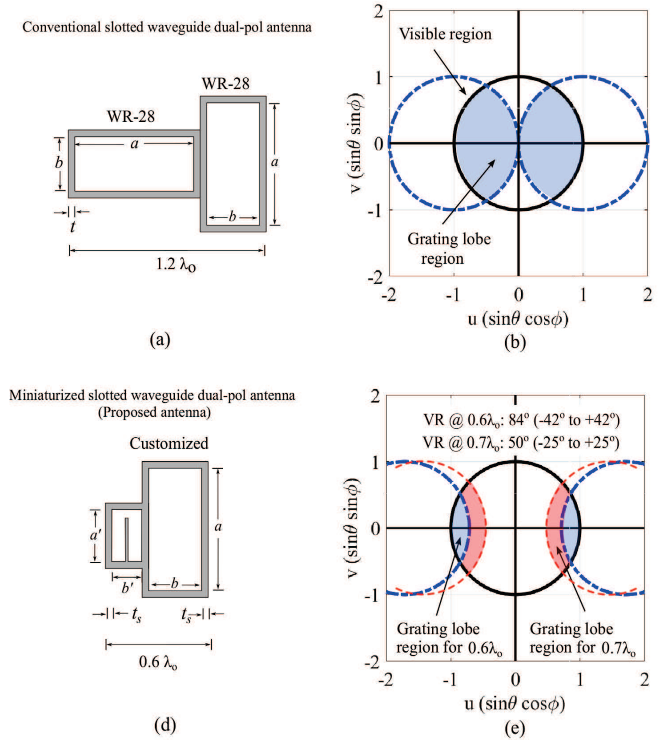

Fig. 3. Grating lobe diagram using a conventional and proposed compact waveguide unit cell for dual-polarized array antenna. In (a-b), grating lobe analysis for a dual-polarized unit cell based on convectional WR-28 standard waveguides, in this case unit cell spacing is $1.2\lambda_{\circ}$. In (d-e), grating lobe analysis for a dual-polarized unit cell based on proposed machined compact waveguides using a proposed array for V-pol and H-pol where element spacing is $0.6\lambda_{\circ}$ that enables a scanning range of $\pm 42^{\circ}$ in elevation without grating lobes.

polarizations, enable high isolation (better than -90 dB) between Tx and Rx, and high cross-polarization isolation (better than -50 dB) between H and V. This is ideal for a polarimetric atmospheric radar that operates in a high-duty-cycle transmit mode with simultaneous polarizations.

3) Up/Down Converter and Digital Receiver: The team will leverage its many years of software-defined-radio experience [14–18] to provide a highly flexible and reliable multi-channel digital receiver and waveform generator assembly. On reception, every 3 rows of sub-arrays will be integrated into an RF down-converter (DC) and digital receiver (DR), as seen in Fig. 1(c). Eight Pentek commercial digital receivers, consisting of 8-channels each, will be employed for each polarization (each channel is abundantly sampled with 16 bits). These off-the-shelf receivers are based on field-programmable gate arrays that can be easily reconfigured. The Pentek receiver boards (model 78131) will be directly connected to the host computer using the peripheral component interconnect (PCI) bus slots. The team's receiver solution enables row-level waveform digitization of the 64 channels. Hence, digital baseband I/Q data will be provided for each row. In the transmission mode, two-stage up-converters (UC) will be designed using commercial RF components; thus, a UC will be provided for each of the H- and V- polarizations. Each UC is driven by one

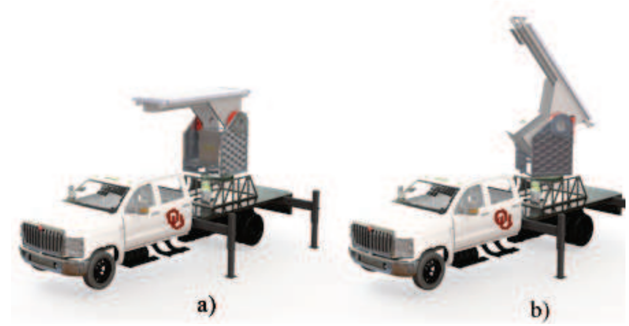

Fig. 4. Rendering of the KarVIR trucks for field deployment. a) Vertical pointing and transportation mode. b) Scanning operation mode.

software-defined waveform generator (2-channel transmit card, Pentek model 78621). Finally, maintaining coherency between the transmit channels and all of the receive channels is the most important aspect of the entire digital portion of the radar; therefore, a specific clock distribution card (Pentek model 7893) will be used to synchronize multi-channel sampling, gating, and triggering functions.

4) Radar Back-end and Signal Processing: Based on our experience with the Atmospheric Imaging Radar (AIR) [19], the PX-1000 [20] radar, and the all-digital S-band Horus PAR [21], a modern computer node can handle eight channels of raw I/Q data storage and transport without any complications. The KaRVIR team envisions that the data storage will be distributed, since each node will be responsible for storing the raw I/Q data locally on a self-connected storage device that is integrated with the Pentek receiver cards. Digital data transport, storage, and real-time computing for the KaRVIR is one of the most significant challenges for the system. While we do not anticipate that all of the data will be available for real-time beamforming and visualization, the software can be designed so that the command center node can selectively request regularly spaced sets of the data for beamforming, radar product derivation, and visualization during field campaigns [20].

5) Mechanical Considerations and Radar Platform: The proposed KaRVIR systems will be mounted on a medium-truck-size platform (US class-8) that will facilitate the use of both radars in a wide variety of locations, terrain, and theater of operations. The entire system is designed to support the safe, reliable, and fast deployment of a tactically mobile radar in all types of operational conditions, including birdbath modes for polarimetric calibration and (near-) vertical profiling (see Fig.4a). The system provides a versatile and stable line of sight for the array while offering comfort and advanced operational capability for the crew. The radar system and its support equipment are designed for a minimum service life of 10 year, given periodic maintenance.

III. PREDICTED KARVIR RADAR PERFORMANCE

Designing affordable radar systems capable of providing certain functionality involves evaluating complex engineering

Comparison of KaRVIR with the ARM/Ka-SACR

Parameter	Ka-SACR (ARM/DoE)[1]	KaRVIR (ARRC/OU)
Radar type Technology	Dish Mechanical	Imaging Phased array
Radar scan mode	Pencil beam. 2D Mech.	1D DBF in elev. 1D Mech.in azim.
Frequency	35.29 GHz	35 GHz
Trasmitter type	TWT(EIKA)	SSPA(1)
Tx peak power	2.2 kW/Pol.	0.5 kW/Pol.
Polarization	Dual linear	Dual linear
X-pol isolation	-27 dB	-50 dB(2)
Tx/Rx isolation	-	-90 dB
Tx ant. beamwidth	0.33° x 0.33°	0.3° x 20°
Rx ant. beamwidth	0.33° x 0.33°	0.3° x 0.3°
Tx gain	53.5 dB	38 dB
Rx gain	53.5 dB	56 dB
Tx # elements	–	3 x 268
Rx # elements	–	192 x 268
Scan rate	36° /sec.	up 120° /sec.
Bandwidth	3 MHz.	up to 10 MHz.
Pulse width	13 μs	1 μs to CW
Volume scan(3)	17 min.	<20 sec.
Spatial resolution	29 m @ 5 km	24 m @ 5 km
Tx Sidelobe level	-	-18 to -20 dB
Rx Sidelobe level	-	-25 to -27 dB (Tx)
Sensitivity (N=1)	-21 dBZ @5 km	-22 dBZ @5 km
Sensitivity (N=100)	-	-26 dBZ @5 km

(1) SSPA: Solid State Power Amplifier.
(2) Minimum cross-polarization isolation across radar field of view of 20° x 360° .
(3) Volume scan 20° x 360° .

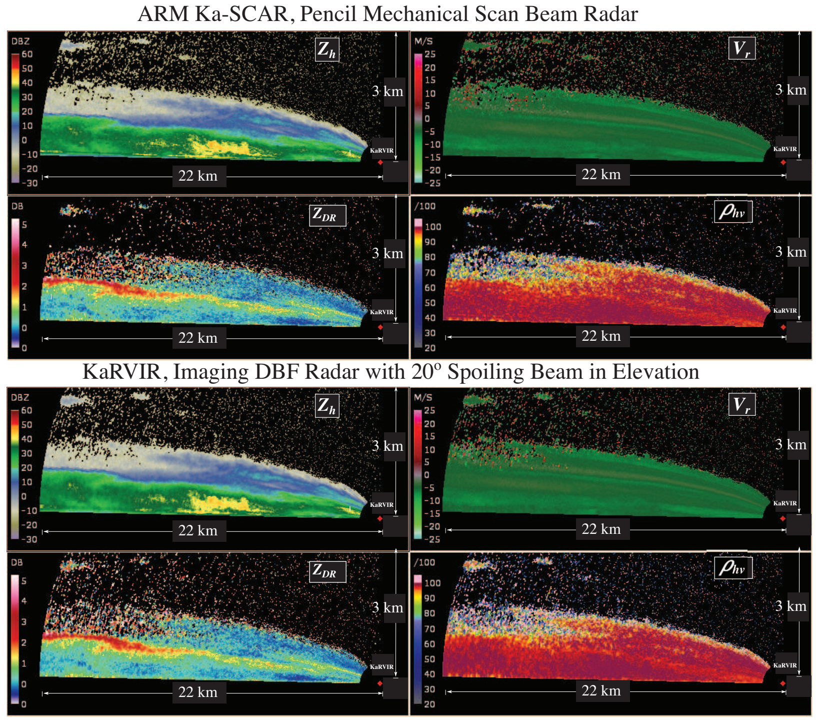

Fig. 5. Specifications comparison between proposed KaRVIR and ARM/DoE Ka-SACR radars (left). Polarimetric products of ARM/Ka-SACR radar (top-right). Simulated polarimetric products with spoiling beam of 20° in elevation, using data collected with ARM/Ka-SACR radar (bottom-right).

trade-offs that may impact the quality of meteorological observations. The quality of meteorological data (i.e., bias and standard deviation of radar-variable estimates) is determined by the the scanning strategies and the signal processing techniques used to produce fields of radar-variable estimates, which is tightly coupled with the radar architecture. In this section, we use the Signal Processing And Radar Characteristics (SPARC) [22] simulator to evaluate the predicted performance of the KaRVIR system.

The SPARC simulator is a flexible weather-radar time-series scenario simulator able to ingest archived dual-polarization base radar data and produce time-series data as it would be observed by a modeled radar system. In contrast with other simulators, the SPARC simulator allows for an end-to-end system-level emulation that considers the interactions between radar sub-systems (e.g., antenna, exciter), the scanning strategy (e.g., PRT, number of samples), and the signal processing techniques. For the modeled radar configuration (characterized by parameters such as antenna pattern, transmit waveforms, etc.), simulated returns from “scattering centers” within each resolution volume are weighted and coherently summed to emulate the time-series signals received by the modeled radar. Simulated data are processed using the modeled radar’s signal processing methods to produce a high-fidelity simulation of its output.

Archived dual-polarization data from the DoE atmospheric radiation measurement (ARM) mm-wave radars [23, 24], are ingested by the SPARC simulator to evaluate KaRVIR. The specifications of the ARM Ka-band scanning radar (Ka-SACR), considered the benchmark system due to its widespread use for cloud studies, are shown in the table below for comparison [1, 3].

The Ka-SACR provides better radar sensitivity (-21 dBZ at 5 km) and a finer beamwidth (0.3° $\times$ 0.3°) compared to cm-wavelength radars, and includes dual-polarization capability [1]. The Ka-SACR operates at diverse scanning modes including sequences of plan-position indicator (PPI) or range-height indicator scans, and it also uses pulse compression to improve sensitivity. Although the Ka-SACR radar system provides exceptional data quality, its mechanical scanning with narrow beamwidth results in long volume scan times (17 min) that limits full 3-D observations. The proposed KaRVIR system addresses the need for high-temporal and spatial resolution in 3-D volume scanning by providing scan times of less than 20 s. A summary of KaRVIR specifications is also provided in the table above, including a sensitivity comparison with the Ka-SACR. KaRVIR will provide better sensitivity than the ARM Ka-SACR; therefore, KaRVIR should also provide similar detection capabilities as clouds observed by the ARM Ka-SACR (including cumulus and cirrus clouds). It will provide the narrowest beamwidth of all existing cloud radars, producing the fine spatial resolution (cross-beam distance of 24 m at 5 km) with the fastest temporal resolution (<20 s).

Fig. 5 shows the ARM Ka-Band data used to simulate KaRVIR using a transmit beam spoiled by 20° in elevation. Results show that using a transmit beam spoiled by 20°, the scan time can be reduced by a factor of about 30, while a small loss in spatial resolution is observed, there is no apparent impact from higher sidelobe levels (i.e., gradients are not very sharp in clouds) or impact on the quality of polarimetric data. KaRVIR could produce the finest spatial resolution of all existent cloud radars.

IV. Conclusion

In this work, the architecture for two co-located Ka-band mobile imaging radars that enable high spatial and temporal resolution measurements for cloud radar research is presented. The radar system description and design trade-offs of the radar front-end are discussed. Polarimetric and rapid-scanning volumetric capabilities enable four-dimensional measurements capturing fine cloud processes and their evolution into precipitation systems. KaRVIR will enable impactful studies throughout the scientific community. KarVIR new radar capabilities are unique and it will offer better understanding of clouds and precipitation processes and other environmental challenges.

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