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**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
This DURIP supported the design and development of the WaDES testbed for the purpose of experimental investigation into new multi-dimensional / multi-function sensing approaches. This testbed will support a variety of emerging radar modes that rely on multiple-input multiple-output (MIMO) transmit and receive configurations to incorporate spatial degrees of freedom into other forms of waveform diversity. Such new modes include spatial modulation, wideband MIMO for imaging, joint MIMO / waveform agility, radar-embedded communications, joint polarization and spatial modulation, and numerous others. These new modes leverage recent work on the design of physically realizable waveform-diverse radar emissions, much of which has been performed and experimentally demonstrated at the University of Kansas (KU).

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**19a. NAME OF RESPONSIBLE PERSON**
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# Waveform Diversity Experimentation System (WaDES)

**Final Report**
**1 MAR 2022**

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# 1 Summary

The growing demand for spectrum combined with requirements for enhanced sensitivity, robust interference protection, higher fidelity, and lower implementation cost has driven innovation in advanced radar waveform design and multi-function system capabilities. This DURIP grant supported the design and construction of the Waveform Diversity Experimentation System (WaDES) radar testbed that will greatly enhance the innovation process by supporting investigation into new multi-dimensional / multi-function sensing approaches, and providing experimental feedback to differentiate between useful and unrealistic assumptions.

WaDES adds crucial experimental capabilities to the investigation of a variety of emerging radar modes that rely on multiple-input multiple-output (MIMO) transmit and receive configurations to incorporate spatial degrees of freedom into other forms of waveform diversity. These new modes of operation include spatial modulation, wideband MIMO for imaging, joint MIMO / waveform agility, radar-embedded communications, and joint polarization and spatial modulation. All of these topics involve ongoing University of Kansas (KU) research undertaken by KU faculty and graduate students under current and continuing DoD-funded projects.

# 2 WaDES Design Overview

The Waveform Diversity Experimentation System design consists of 16 separate X-Band transmit channels with independent baseband arbitrary waveform generation capability, and 16 separate X-Band receive channels with independent baseband channel digitization. Hardware components are housed in two mobile equipment racks to facilitate outdoor range testing. One rack primarily contains transmitter components while the second rack is populated with receiver components and support hardware such as a shared local oscillator (LO) and “Radiator”, which is a high-performance waveform source, storage, and system control rack-mounted computer. The racks are connected by a custom 15’ multi-cable snake containing a CAT6 ethernet cable and LO, a 10 MHz reference, and trigger signal coaxial cables, as indicated in Figure 1.

WaDES has been designed to support an assorted set of antenna configurations and polarization formats, along with bistatic / multistatic arrangements and antenna schemes for radar-embedded communications. In short, we have focused on maximizing capability and flexibility of usage to enable experimental evaluation of as many different MIMO and related approaches as possible.

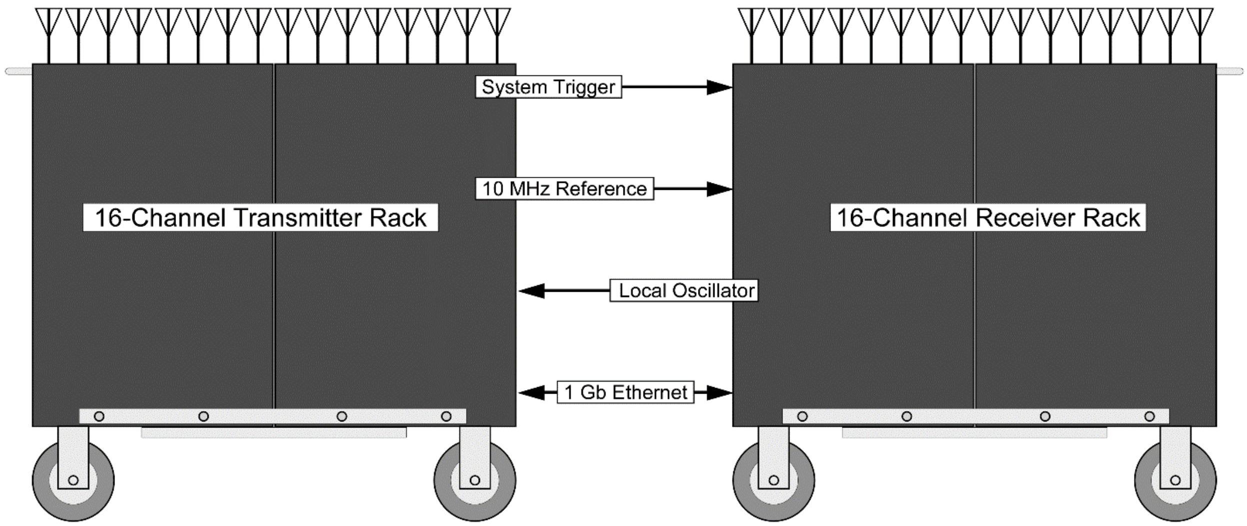


**Figure 1: Transmitter & Receiver Rack Connections**

## 2.1 16-Channel Transmitter System

Baseband transmit signals are generated using two synchronized Tektronix AWG5208 8-channel Arbitrary Waveform Generators (AWGs), then up-converted to a nominal 8.75 GHz X-Band transmit center frequency via 16 upconverter signal chains housed in two 19" rack enclosures. A single upconverter signal chain block diagram is shown in Figure 2 and the signal chain module layout for each 8-channel upconverter rack enclosure is illustrated in Figure 3.

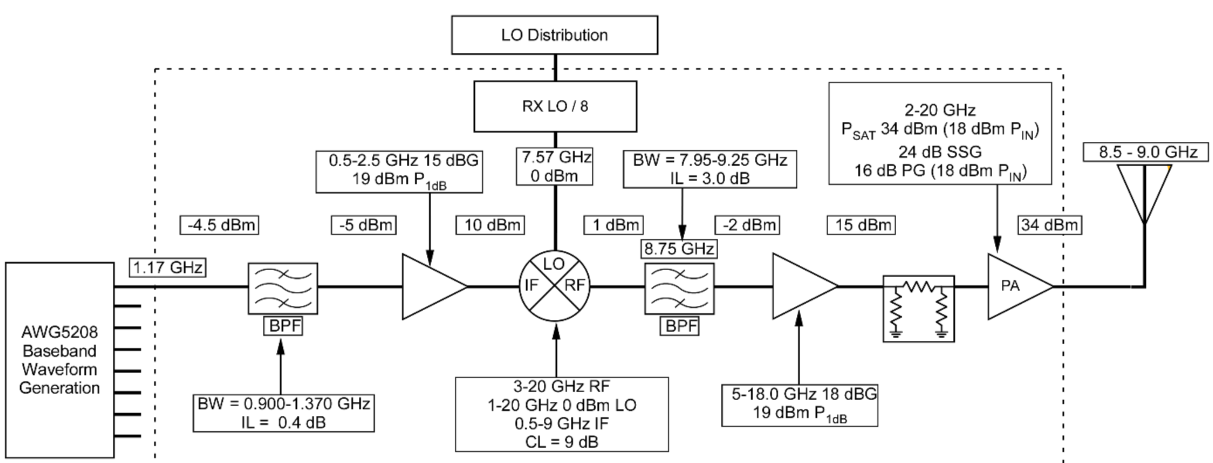


**Figure 2: Baseband to X-Band Upconverter; 1 of 16**

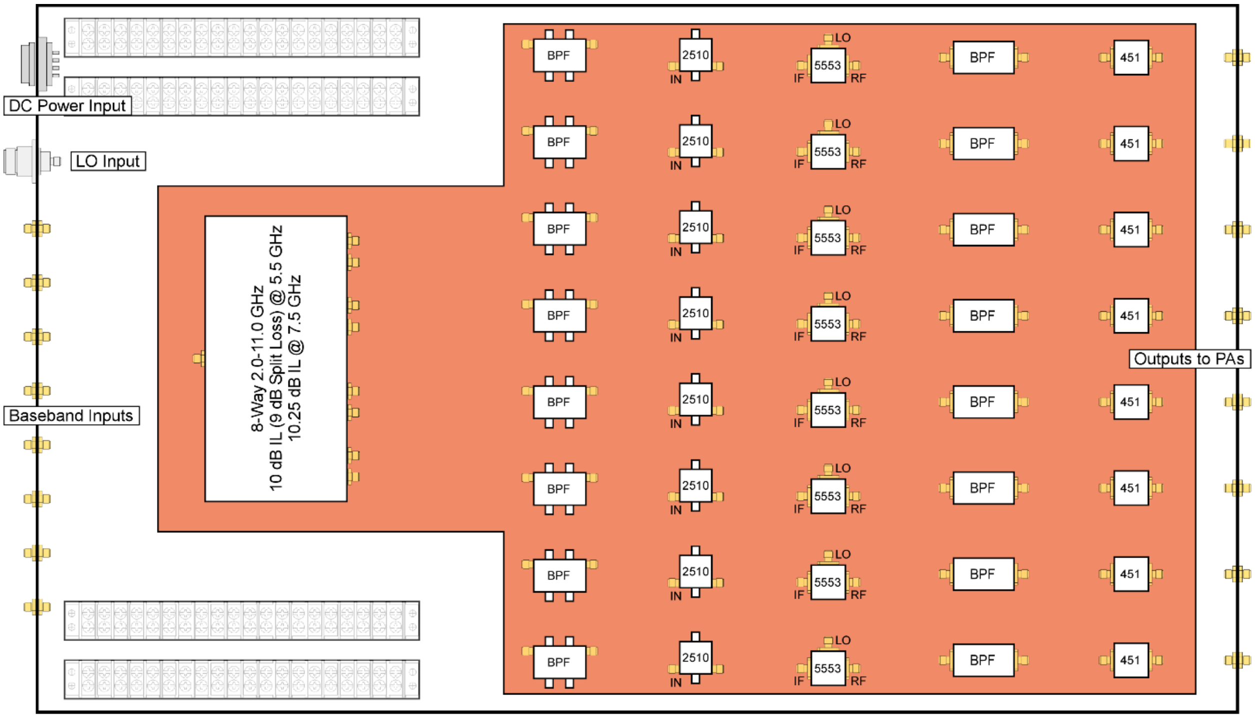


**Figure 3: 8-Channel Baseband to X-Band Upconverter 19" Chassis Layout; 1 of 2**

The outputs of the 16 upconverter channels are fed to 16 power amplifiers (PA) housed in two additional rack enclosures. The separate PA enclosures facilitate the use of active thermoelectric cooling to combat high ambient outdoor test range temperatures. The power amplifier layout inside each 19" PA rack enclosure is illustrated in Figure 4.

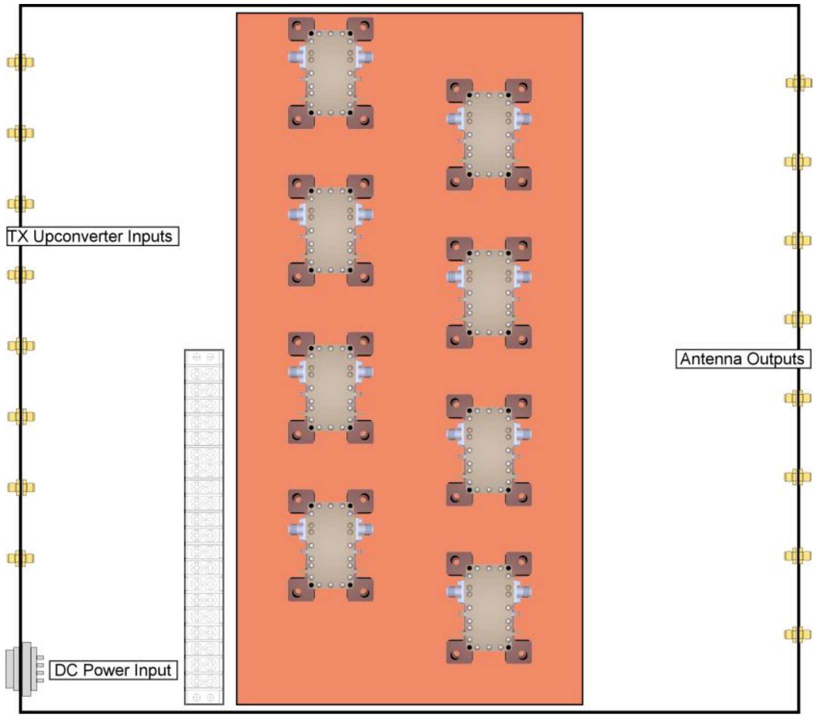


**Figure 4: 8-Channel X-Band RF Power Amplifier 19" Chassis Layout; 1 of 2**

The transmit output frequency range is 8.5-9.0 GHz, with 2.5 watts of RF power available at each antenna port, resulting in up to 10 watts of effective radiated power (ERP) per channel using a basic planar uniform linear array (ULA) antenna with a nominal 6 dBi of gain per active element. RF modules housed in the upconverter and PA rack enclosures will be mounted to 99.99% copper content super-conductive copper sheet to maximize RF grounding and module thermal dissipation. The PA modules will be mounted to the bottom of custom top covers fabricated for the two PA 19" rack enclosures, to provide the shortest thermal path to the 126-watt Peltier-based thermoelectric coolers mounted on top of each rack enclosure cover. The thermoelectric PA coolers are instrumented with separate programmable controllers.

The transmitter rack physical configuration is illustrated in Figure 5. Transmitter components such as the AWG5208 waveform generators are loaded and controlled using virtual network computing (VNC) via 1 Gb ethernet connections from "Radiator"; a custom-built, high-performance computer located in the receiver rack.

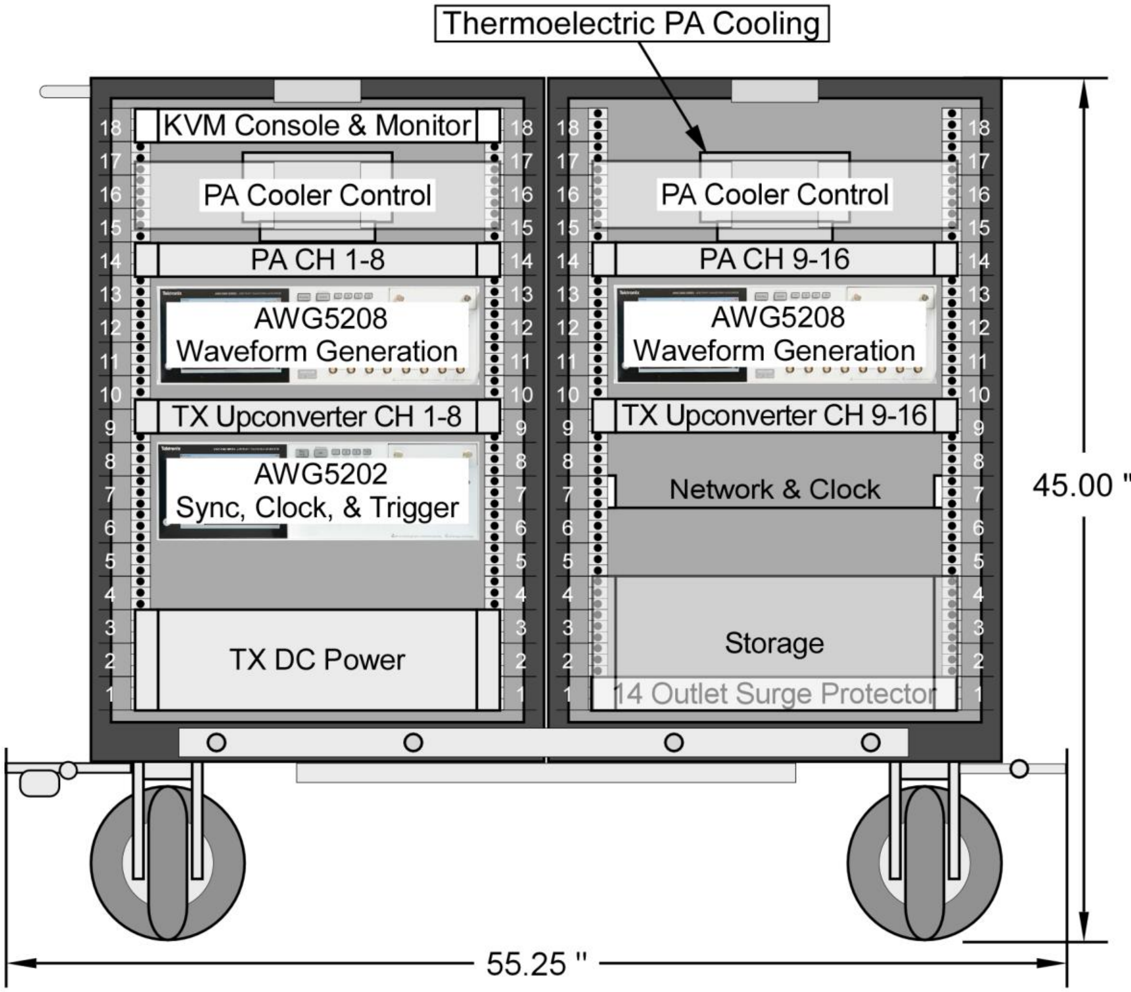


**Figure 5: 16-Channel Transmitter Rack**

The AWG5202 2-channel AWG located in the transmitter rack provides a synchronization clock for the pair of AWG5208 8-channel AWGs, in addition to supplying a 10 MHz reference clock and triggering signals to the receiver rack. Assembly of the transmitter rack is in progress (component acquisition was repeatedly delayed due to supply chain issues). Figure 6 shows a test fit of transmitter components into the customized “doublewide” 32U 19” mobile rack enclosure.


**Figure 6: Transmitter Rack Component Test Fit**

## 2.2 16-Channel Receiver System

The receiver system input frequency range is 8.5-9.0 GHz and consists of 16 X-Band to baseband downconverter signal chains, comprised of components selected to provide high spurious-free dynamic range, housed in two 19” rack enclosures. A single downconverter signal chain block diagram is shown in Figure 7 and the signal chain module layout for each 8-channel downconverter rack enclosure is illustrated in Figure 8.

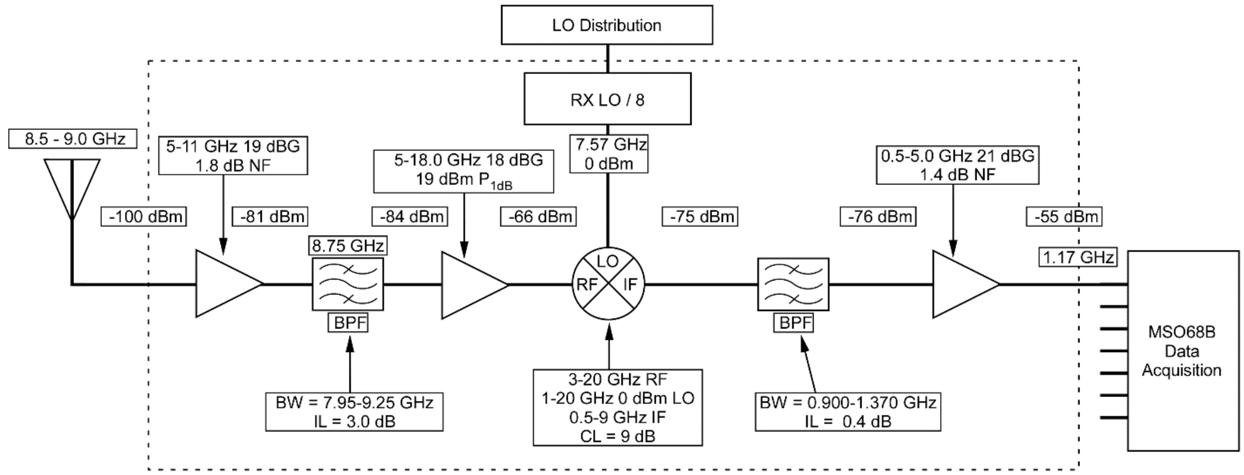


Figure 7: X-Band to Baseband Downconverter; 1 of 16

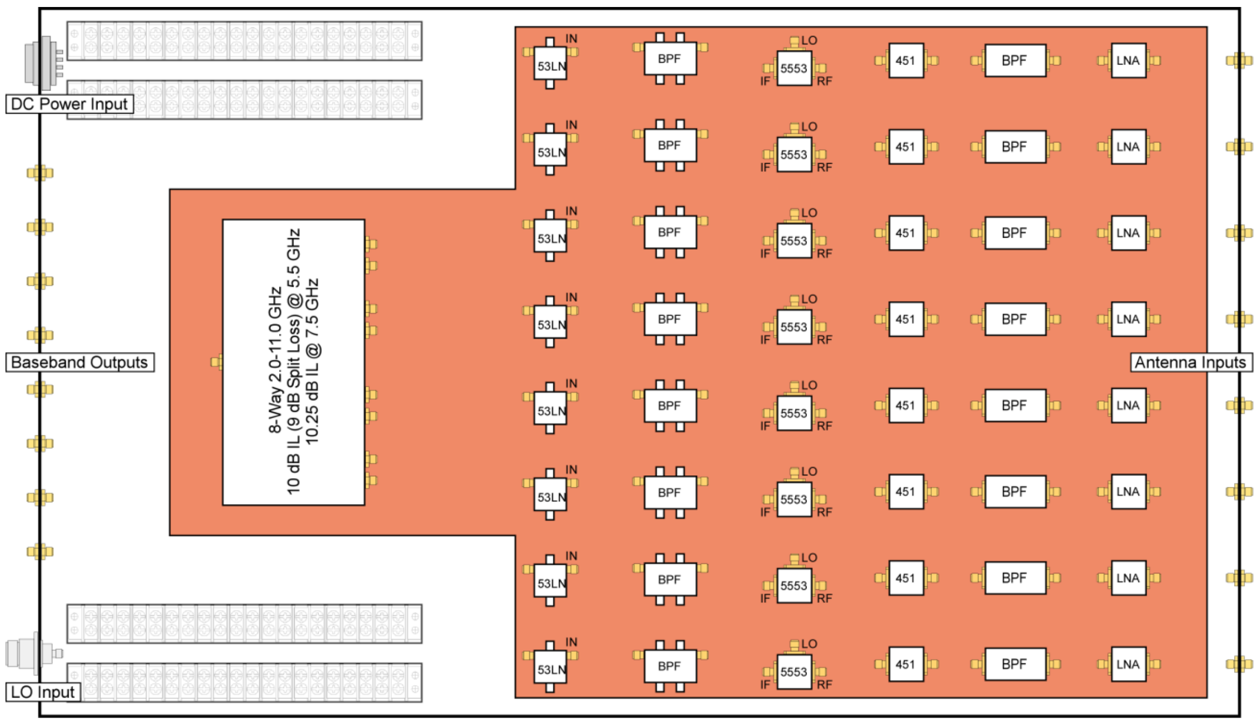


Figure 8: 8-Channel X-Band to Baseband Downconverter; 1 of 2

Down-converted baseband signals are captured by two synchronized 8-Channel MSO68B 12.5 GS/s oscilloscopes with data sets stored by "Radiator", the waveform source, storage and system control computer located in the receiver rack. The receiver rack physical configuration is illustrated in Figure 9. As is the case for the transmitter, receiver components such as the MSO68B oscilloscopes are configured and controlled by Radiator using VNC via 1 Gb ethernet connections. Radiator hardware components include an Intel Core i7-12700K 12-core CPU overclocked to 5.2 GHz, 128 GB PC4-28800 DDR4 3600 RAM, a 2.0 Trusted Platform Module (TPM), and two 2 TB M.2 PCI Express (PCIe) 4.0 solid state drives (SSD). The M.2 PCIe drives are

12 times faster than Serial ATA (SATA) SSDs. One 2 TB M.2 SSD is installed on the motherboard, while the second 2 TB SSD is intended to support future Controlled Unclassified Information (CUI) work and is removable via a rear panel accessible carrier. Radiator can boot from either M.2 SSD, since both drives are currently loaded with Windows 11 operating system images configured to support a CUI environment. Each drive is separately encrypted with a unique key stored in the TPM to prevent inadvertent intermixing or exchanging of data. A test fit of receiver components into the custom "doublewide" 32U 19" mobile rack enclosure is shown in Figure 10.

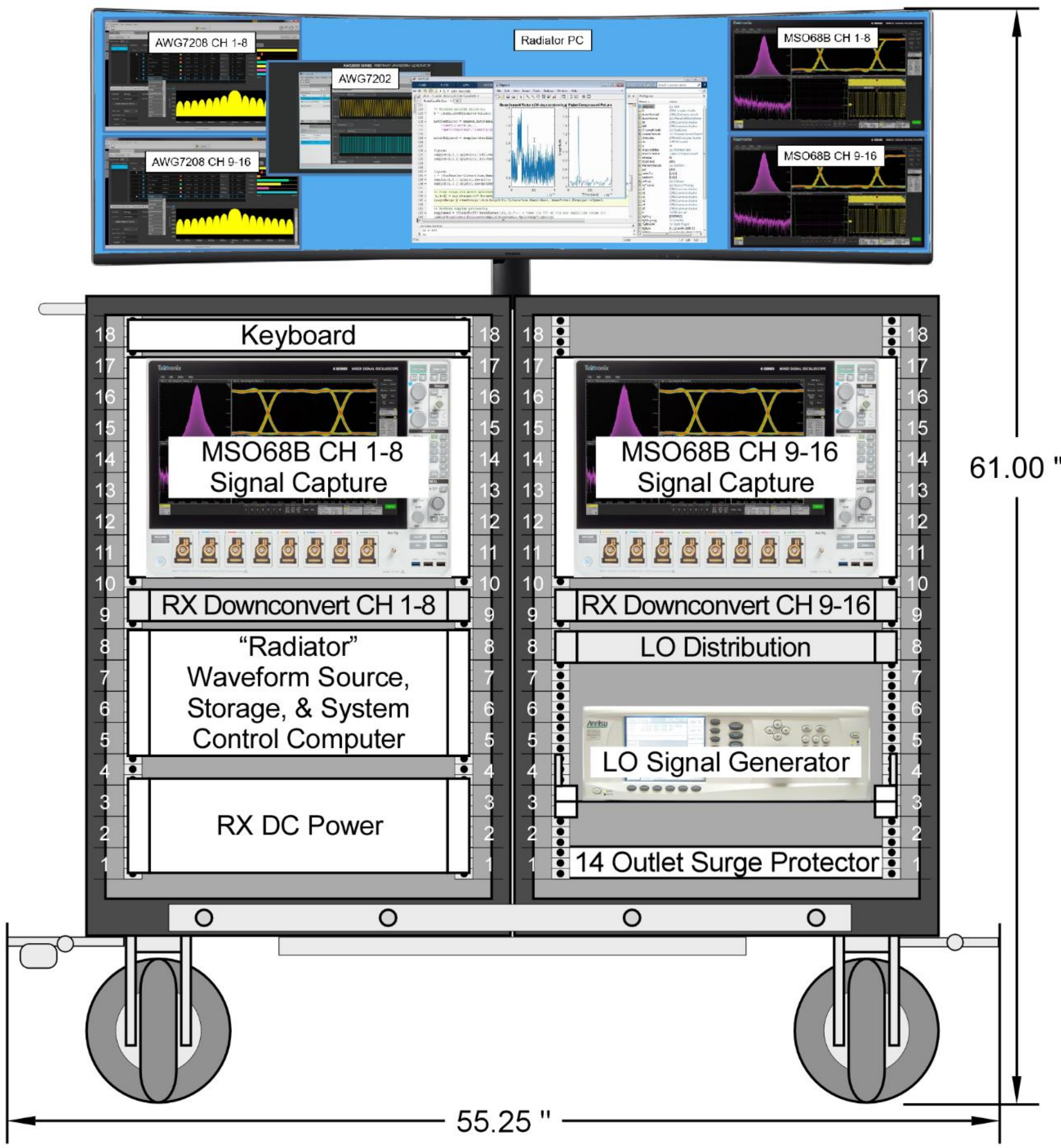


**Figure 9: 16-Channel Receiver Rack**

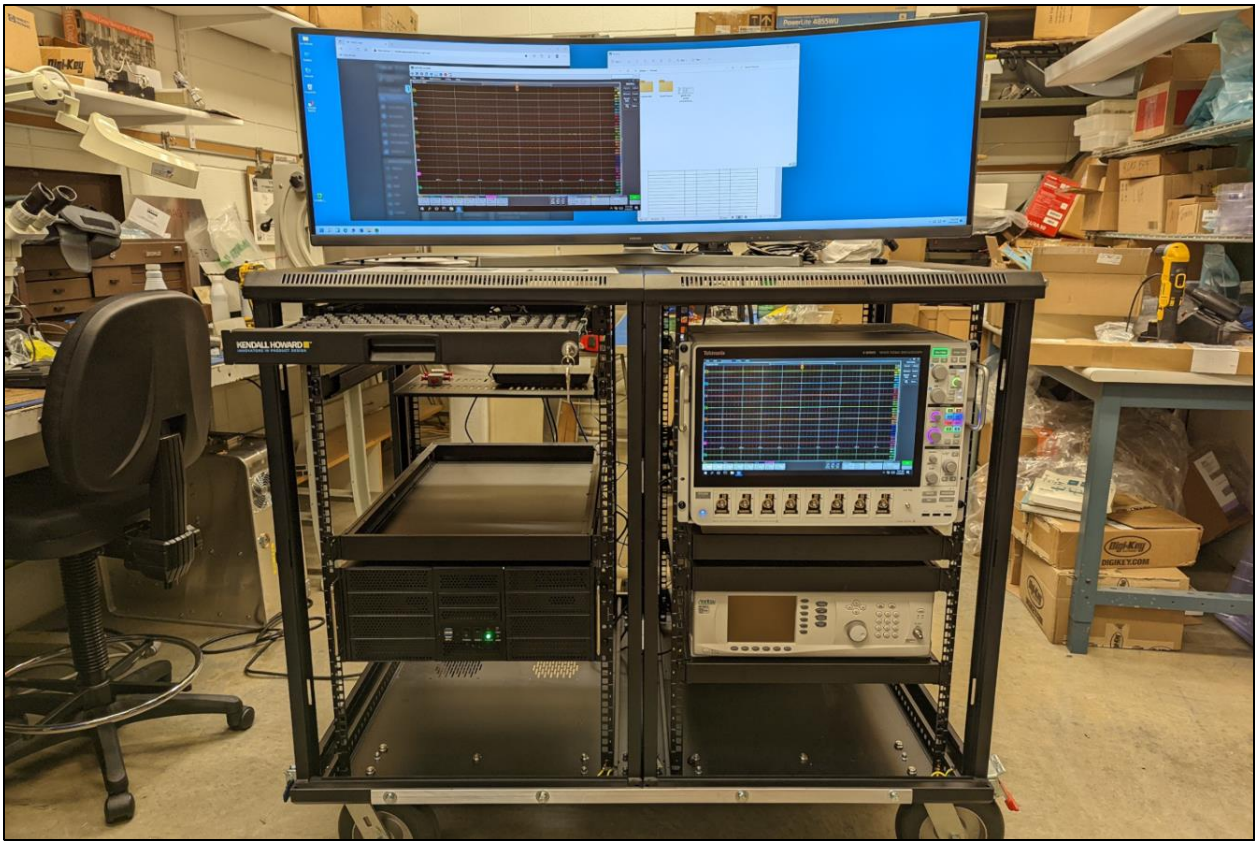


**Figure 10: Receive Rack Component Configuration and Test Fit**

All system components have been purchased and assembly is well underway. However, due to manufacturer supply chain delays and vendor back-order issues, some items have not yet been received.

# 3 Antennas

Custom WaDES antennas are currently in the design and simulation phase. To support interim testing, 32 commercial 2-11 GHz planar log-periodic antennas were acquired for use in a variety of transmit and receive antenna array configurations.


**Figure 11: 2-11 GHz Planar Log-periodic antennas**

### 3.1 Antenna Development

A 20-element microstrip patch uniform linear array (ULA) with 16 active and 4 passive probe-fed microstrip elements is the first antenna specifically designed for WaDES research efforts. An ANSYS 3D electromagnetic (EM) simulation model of the array is shown in Figure 12 and a simulated 2D antenna pattern can be found in Figure 13.

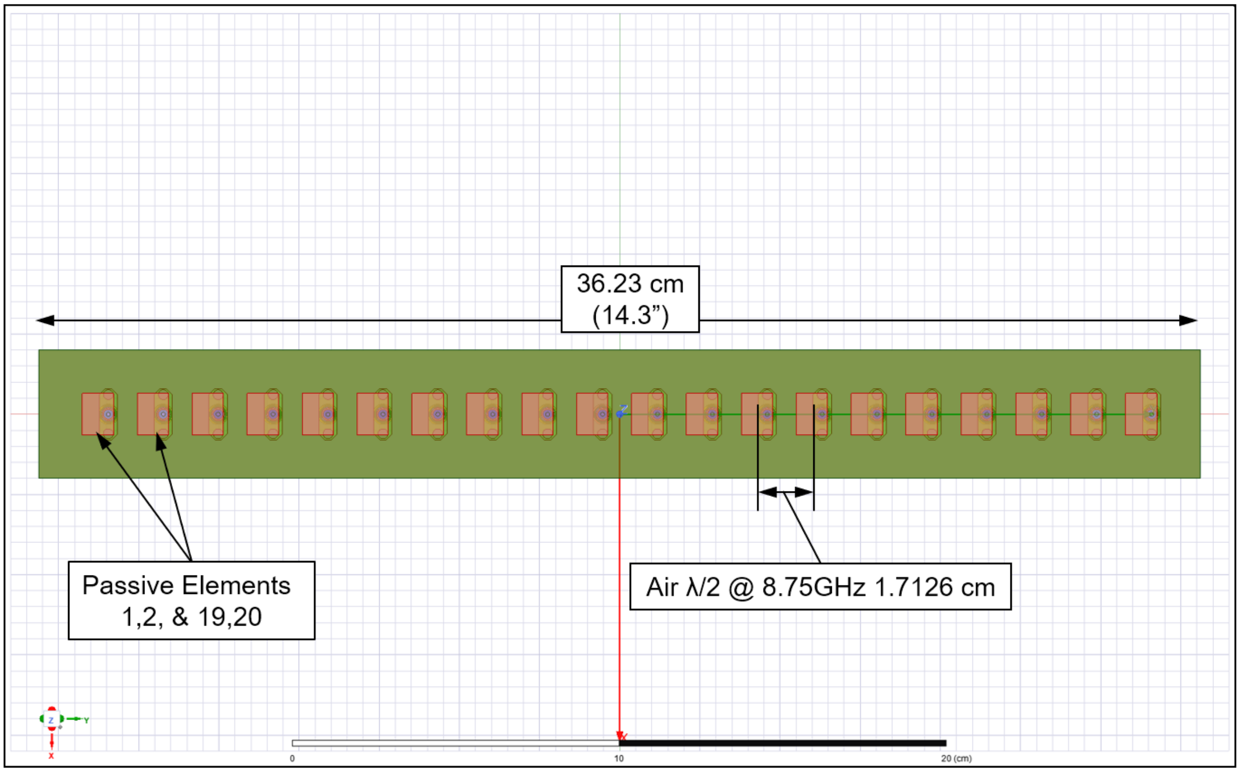


**Figure 12: 20 Element 8.75 GHz Microstrip Patch ULA ANSYS 3D Model**

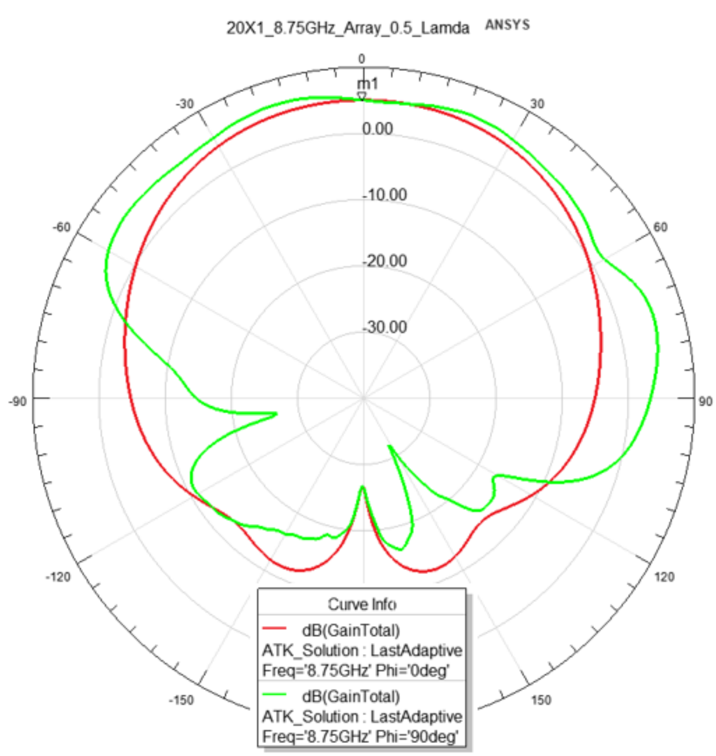


**Figure 13: 20 Element 8.75 GHz Microstrip Patch ULA ANSYS HFSS Simulation**

## 4 University of Kansas Infrastructure Investment

The WaDES testbed will primarily be operated at facilities located within the KU Innovation Park (KUIP) on KU's west campus. KUIP Phase III is a 66,000 square foot laboratory and office building currently under construction, which will offer specific accommodations for WaDES research efforts, such as elevator access to the building roof, and a rooftop equipment platform designed to support transmitter and receiver equipment rack operation, illustrated in Figure 14.

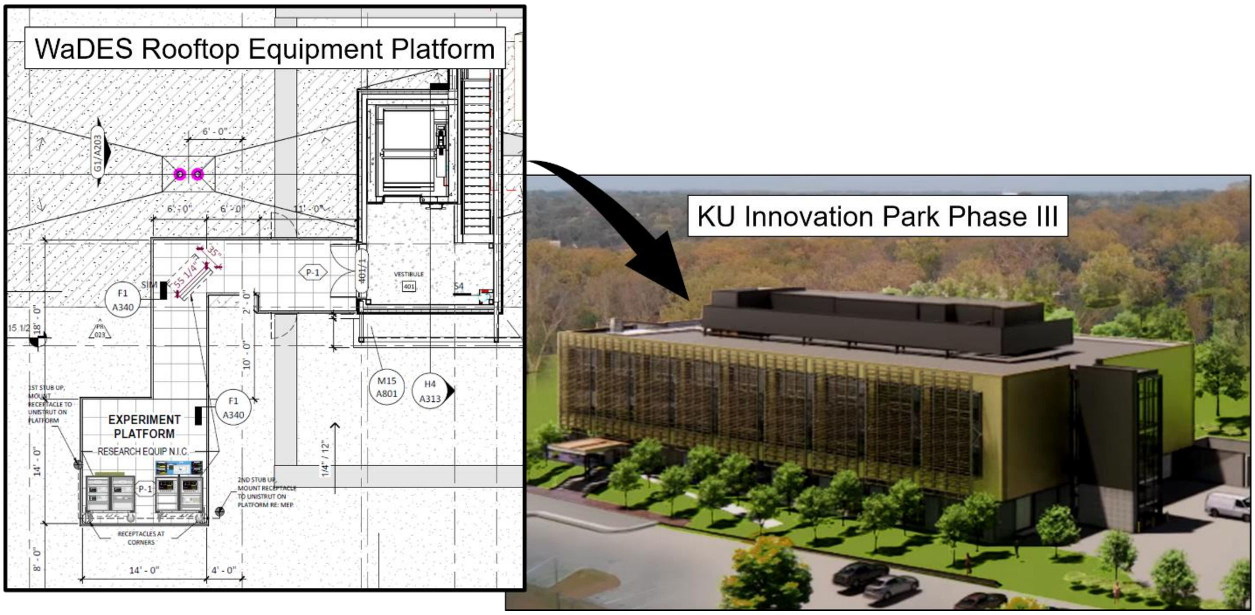


**Figure 14: WaDES KUIP Phase III Supporting Infrastructure**

## 5 Participants

Number of undergraduate and graduate STEM participants: 2
Number of participants that received a STEM degree: 1

## 6 Publications

[1] Z. Gannon, B. Ravenscroft, D. DePardo, C.T. Allen, S.D. Blunt, J.M. Stiles, "Development and initial testing of an X-band MIMO radar testbed," in preparation for *IEEE Aerospace & Electronic Systems Magazine*.