Waveform Diversity Experimentation System (WaDES)         5a. CONTRACT NUMBER       5b. GRANT NUMBER         N00014-19-1-2666       5c. PROGRAM ELEMENT NUMBER         5d. PROJECT NUMBER       5e. TASK NUMBER       5f. WORK UNIT NUMBER			REPORT DOCUMENTA	TION PAGI				
20220301     Final     START DATE 20190801     END EATE 20190801       S. TILE AND SUBTITLE Waveform Diversity Experimentation System (WaDES)     Se. PROGRAM ELEMENT NUMBER N00014-19-1-2666     Se. PROGRAM ELEMENT NUMBER N00014-19-1-2666     Se. PROGRAM ELEMENT NUMBER N00014-19-1-2666     Se. PROGRAM ELEMENT NUMBER N00014-19-1-2666       S. AUTHOR(6)     Se. ATASK NUMBER     Sr. MORK UNIT NUMBER N00014-19-1-2666     Sr. WORK UNIT NUMBER       S. AUTHOR(6)     Se. AUTHOR(6)     Sr. WORK UNIT NUMBER N00014-19-1-2666     Sr. WORK UNIT NUMBER       S. AUTHOR(6)     Se. AUTHOR(6)     Sr. MORK UNIT NUMBER N00014-19-1-2066     Sr. WORK UNIT NUMBER       S. AUTHOR(6)     Se. AUTHOR(6)     Sr. MORK UNIT NUMBER N00014-19-1-1000     Sr. MORK UNIT NUMBER       J. PERFORMING ORGANIZATION NAME(6) AND ADDRESS(ES) UNITED STATES OF AMERICA     II. SPONSORMONITOR'S ACRONYM(8) ONR     II. SPONSORMONITOR'S ACRONYM(8) ONR    <	1. REPORT DATE	2. REPORT TYPE		3. D/	3. DATES COVERED			
Waveform Diversity Experimentation System (WaDES)       b. GRANT NUMBER       Sc. PROGRAM ELEMENT NUMBER         Sa. CONTRACT NUMBER       b. GRANT NUMBER       Sc. PROGRAM ELEMENT NUMBER         Sd. PROJECT NUMBER       b. TASK NUMBER       Sf. WORK UNIT NUMBER         Sa. UTHOR(S)       Blunt, Shannon; Allen, Christopher; Stiles, James; DePardo, Dan; Ravenscroft, Brandon.       St. WORK UNIT NUMBER         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       RePORT NUMBER       St. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)         2353 RVNOK HILL RD       LAWRENCE KS. 66043-7552       Namobility Strett       ACRONYM(S)         7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       N. Randopilis Brett       ACRONYM(S)       11. SPONSORMONITOR'S         8. PONSORINGMONITORIOL AGENCY NAME(S) AND ADDRESS(ES)       ONR       N. Randopilis Brett       Arrington VA 22203-1995       11. SPONSORMONITOR'S       11. SPONSORMONITOR'S       11. SPONSORMONITOR'S       11. SPONSORMONITOR'S       11. SPONSORMONITOR'S       12. SUPPLEMENTARY NOTES         13. SUPPLEMENTARY NOTES       This Estable will angord a variety of emerging radar modes that refer on multiple-output waveform diversity, such are metaded diversity reliable waveform diversity, Such are wordorm diversity of Kansas (KU).       13. NUMEER OF PAGES         14. SUBJECT TERMS       SAREPORT       C. THIS PAGE								
Sa. CONTRACT NUMBER       Sb. GRANT NUMBER N00014-19-1-2666       Sc. PROGRAM ELEMENT NUMBER         Sa. PROJECT NUMBER       Se. TASK NUMBER       Sf. WORK UNIT NUMBER         Sa. AUTHOR(S)       St. MICK UNIT NUMBER       Sf. WORK UNIT NUMBER         Blunt, Shamon; Allen, Christopher; Stiles, James; DePardo, Dan; Ravenscroft, Brandon       PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)         ZSS RWING HILL RD       ENTROPENDE KS 66045-7552       Image: Control of Cont	4. TITLE AND SUBTITLE							
a. OUNTOKET NUMBER       District of the second of the secon	Waveform Diversity Ex	perimentation System	(WaDES)					
56. PROJECT NUMBER     50. TASK NUMBER     51. WORK UNIT NUMBER       56. AUTHOR(S)     Blunt, Shannon; Allen, Christopher; Stiles, James; DePardo, Dan; Ravenscroft, Brandon       7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)     8. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)       2285 IRVING HILL RD     8. PONSORINGMONITORING AGENCY NAME(S) AND ADDRESS(ES)       2385 IRVING HILL RD     10. SPONSORMONITORING AGENCY NAME(S) AND ADDRESS(ES)       2385 IRVING HILL RD     11. SPONSORMONITORING AGENCY NAME(S) AND ADDRESS(ES)       ONR - LIEC SENSORS & NETWORKS RESEARCH DIV     ACRONYM(S)       75. N. Randolph Street     Aclington VA. 22203-1995       12. DISTRIBUTIONAVAILABILITY STATEMENT     DISTRIBUTION A. Approved for public release: distribution is unlimited.       13. SUPPLEMENTARY NOTES     14. ABSTRACT       14. ABSTRACT     This DURL's mode spatial modulation, wideband MIMO for imaging, joint MIMO / waveform altivering radar modes that rely on multiple-input multiple-output (MIMO) transmit and receive configurations to incorporate spatial degrees of feedom into other forms of waveform diversity. Such new modes inclued spatial modulation, wideband MIMO for imaging, joint MIMO / waveform altivering radar modeded 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 Kanas (KLI).       16. SECURITY CLASSIFICATION OF:     17. LIMITATION OF ABSTRACT     18. NUMBER OF PAGES       16. SECU	5a. CONTRACT NUMBER	2	5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER			ENT NUMBER		
BAUTHOR(S)         Blunt, Shamon; Allen, Christopher, Stiles, James; DePardo, Dan; Ravenscroft, Brandon         7, PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)         DINIVIERSTITY OF KANSAS CENTER FOR RES         283 IRVINO HILL RD         1.AWRENCE KS 6045-7532         UNITED STATES OF AMERICA         a. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         ONR         10. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         ONR         2. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         ONR         2. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES)         ONR         2. DISTRIBUTION/AVALABILITY STATEMENT         DISTRIBUTION/AVALABILITY STATEMENT         DISTRIBUTION/AVALABILITY STATEMENT         DISTRIBUTION A. Approved for public release: distribution is unlimited.         13. SUPPLEMENTARY NOTES         14. ABSTRACT         This DURP supported the design and development of the WaDES testbed for the purpose of experimental investigation into new multi- dimensional / multi- 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, widebam MIMO for imaging, joint MIMO / waveform agility, radar-embedded communications, joint polarization and spatial modulation, widebam MIMO for imaging, joint MIMO / waveform agility real- multiple- multiple- multiple- multiple- multiple- multiple- multiple re			N00014-19-1-2666					
Blunt, Shannon; Allen, Christopher; Stiles, James; DePardo, Dan; Ravensorôft, Brandon 7, PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF KANSAS CENTER FOR RES 285 IRVING HIL J. RD LAWRENCE KS 66045-7552 UNITED STATES OF AMERICA 9. sPONSORIMGMONTORING AGENCY NAME(S) AND ADDRESS(ES) ONR - ELEC SENSORS & NETWORKS RESEARCH DIV 875 N. Randolph Street Arlington VA 22203-1995 12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION/AVAILABILITY STATEMENT 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 rader modes that rely on multiple- implicitly. Such new modes include spatial modulation, and numerous others. These new modes har rely on multiple- diversity. Such new modes include spatial modulation, and numerous others. These new modes har ely on multiple- multiple-output environ-diverse radar emissions, much of which has been performed and experimentally demosstrated at the University of Kansas (KU). 14. SUBJECT TERMS  16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 14. ABSTRACT 14. NUMBER OF PAGES 14. ABSTRACT 14. NUMBER OF PAGES 15. SECURITY CLASSIFICATION OF: 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 14. ABSTRACT 14. MUBER OF PAGES 15. SUBJECT TERMS	5d. PROJECT NUMBER		5e. TASK NUMBER		5f. WORK UNIT NUMBER		BER	
7. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) UNIVERSITY OF KANSAS CENTER FOR RES 2385 IRVING HILL RD LAWRENCE KS 66045-7552 UNITED STATES OF AMERICA       8. PERFORMING ORGANIZATION REPORT NUMBER         9. SPONSORIMGNONTORING AGENCY NAME(\$) AND ADDRESS(E\$) ONR - ELEC SENSORS & NETWORKS RESEARCH DIV 875 N. Randolph Street Arington VA 22203-1995       10. SPONSORIMONITOR'S ACRONYM(\$) ONR       11. SPONSORIMONITOR'S ACRONYM(\$) ONR       12. SPONSORIMONITOR'S ACRONYM(\$) ONR	6. AUTHOR(S)							
1. BUPPORTING OF CONTROLOGY OF DESCRIPTION FOR EACH OF DESCRIPTION	Blunt, Shannon; Allen,	Christopher; Stiles, Ja	ames; DePardo, Dan; Ravenscroft,	Brandon				
LAWRENCE KS 66045-7552 UNITED STATES OF AMERICA a. sponsoring/monitoring a deency name(s) and address(es) ONR - ELEC SENSOR'S & NETWORK'S RESEARCH DIV 875 N. Randolph Street Arlington VA 22203-1995 12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION A. Approved for public release: distribution is unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This DURR' 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 frecom magility, radar-embedded 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). 18. SUBJECT TERMS 16. SECURITY CLASSIFICATION OF: U LABSTRACT LU LIMITATION OF ABSTRACT LIMITATION OF ABSTRACT LU LIMITATION OF ABSTRACT LIMITATION OF ABS	UNIVERSITY OF KA	NSAS CENTER FOR	D ADDRESS(ES) RES					
UNITED STATES OF AMERICA								
S. BORSORUS ELECTION OF LECTION OF:       I. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES         16. SECURITY CLASSIFICATION OF:       I. ABSTRACT       II. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES         16. SECURITY CLASSIFICATION OF:       II. SUBJECT TERMS       II. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES								
S. BORSORUS ELECTION OF LECTION OF:       I. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES         16. SECURITY CLASSIFICATION OF:       I. ABSTRACT       II. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES         16. SECURITY CLASSIFICATION OF:       II. SUBJECT TERMS       II. LIMITATION OF ABSTRACT       II. NUMBER OF PAGES				1.0.4			44 SPONSOR/HONITOR'S	
875 N. Randolph Street       ONR         12. DISTRIBUTION/AVAILABILITY STATEMENT       DISTRIBUTION/AVAILABILITY STATEMENT         DISTRIBUTION/AVAILABILITY STATEMENT       DISTRIBUTION/AVAILABILITY STATEMENT         DISTRIBUTION/AVAILABILITY STATEMENT       DISTRIBUTION/AVAILABILITY STATEMENT         DISTRIBUTION/AVAILABILITY STATEMENT       DISTRIBUTION/AVAILABILITY STATEMENT         13. SUPPLEMENTARY NOTES       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).         15. SUBJECT TERMS       17. LIMITATION OF ABSTRACT       18. NUMBER OF PAGES         14.       14       14	9. SPONSORING/MONIT ONR - ELEC SENSO	ORING AGENCY NAME	(S) AND ADDRESS(ES) ESEARCH DIV			NITOR'S		
Ardington VA 22203-1995       10.000         12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION A. Approved for public release: distribution is unlimited.         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, 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).         16. SECURITY CLASSIFICATION OF: U       17. LIMITATION OF ABSTRACT U       18. NUMBER OF PAGES 14	875 N. Randolph Stree	t			ONR			
DISTRIBUTION A. Approved for public release: distribution is unlimited.         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).       11. LIMITATION OF ABSTRACT UU       18. NUMBER OF PAGES         16. SECURITY CLASSIFICATION OF: U       C. THIS PAGE U       11. LIMITATION of ABSTRACT I 14	Arlington VA 22203-1	995			onik			
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).         16. SECURITY CLASSIFICATION OF:       In LIMITATION OF ABSTRACT a. REPORT U       In LIMITATION of ABSTRACT SAR       I. LIMITATION of ABSTRACT U       18. NUMBER OF PAGES 14								
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).         16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF PAGES         a. REPORT       b. ABSTRACT       C. THIS PAGE       UU       14	13. SUPPLEMENTARY N	NOTES						
16. SECURITY CLASSIFICATION OF:       17. LIMITATION OF ABSTRACT       18. NUMBER OF PAGES         a. REPORT       b. ABSTRACT       C. THIS PAGE       UU       14         U       U       U       14	This DURIP supported dimensional / multi-fu multiple-output (MIM diversity. Such new m communications, joint physically realizable v	nction sensing approace O) transmit and receive odes include spatial m polarization and spati vaveform-diverse rada	ches. This testbed will support a va re configurations to incorporate spa odulation, wideband MIMO for in al modulation, and numerous othe	ariety of emerg atial degrees of naging, joint M rs. These new 1	ing radar moo freedom into IIMO / wavef modes levera	des that r o other fo form agili ge recent	ely on multiple-input rms of waveform ity, radar-embedded work on the design of	
b. ABSTRACT     C. THIS PAGE     UU     14       U     SAR     U     14	15. SUBJECT TERMS							
U SAR U U	16. SECURITY CLASSI	FICATION OF:		17. LIMITATIO	ON OF ABSTR	ACT	18. NUMBER OF PAGES	
	a. REPORT	b. ABSTRACT			UU		14	

#### 19a. NAME OF RESPONSIBLE PERSON

Dr. Shannon Blunt

785-864-7326

### **INSTRUCTIONS FOR COMPLETING SF 298**

### 1. REPORT DATE.

Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

### 2. REPORT TYPE.

State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

### 3. DATES COVERED.

Indicate the time during which the work was performed and the report was written.

#### 4. TITLE.

Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

#### 5a. CONTRACT NUMBER.

Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

#### 5b. GRANT NUMBER.

Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

#### 5c. PROGRAM ELEMENT NUMBER.

Enter all program element numbers as they appear in the report, e.g. 61101A.

#### 5d. PROJECT NUMBER.

Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

#### 5f. WORK UNIT NUMBER.

Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/ FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

# Waveform Diversity Experimentation System (WaDES) Final Report 1 MAR 2022

University of Kansas Dr. Shannon Blunt Dr. Christopher Allen Dr. James Stiles Dan DePardo Brandon Ravenscroft



Office of Naval Research 875 N. Randolph Street Suite 1425 Arlington VA 22203-1995

DISTRIBUTION A. Approved for public release: distribution unlimited.

### **TABLE OF CONTENTS**

Se	ection		Page
1	Sumr	mary	1
2	WaD	ES Design Overview	1
	2.1	16-Channel Transmitter System	2
	2.2	16-Channel Receiver System	6
3	Ante	nnas	9
	3.1	Antenna Development	10
4	Unive	ersity of Kansas Infrastructure Investment	12
5	Parti	cipants	12
6	Publi	cations	12

### **LIST OF FIGURES**

### Figure

### Page

1.	Transmitter & Receiver Rack Connections	. 2
2.	Baseband to X-Band Upconverter; 1 of 16	. 2
3.	8-Channel Baseband to X-Band Upconverter 19" Chassis Layout; 1 of 2	. 3
4.	8-Channel X-Band RF Power Amplifier 19" Chassis Layout; 1 of 2	. 4
5.	16-Channel Transmitter Rack	. 5
6.	Transmitter Rack Component Test Fit	. 6
7.	X-Band to Baseband Downconverter; 1 of 16	. 7
8.	8-Channel X-Band to Baseband Downconverter; 1 of 2	. 7
9.	16-Channel Receiver Rack	. 8
10.	Receive Rack Component Configuration and Test Fit	. 9
11.	2-11 GHz Planar Log-periodic antennas	10
12.	20 Element 8.75 GHz Planar ULA ANSYS 3D Model	11
13.	20 Element 8.75 GHz Planar ULA ANSYS HFSS Simulation	11
14.	WaDES KUIP Phase III Supporting Infrastructure	12

# 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 radarembedded 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.

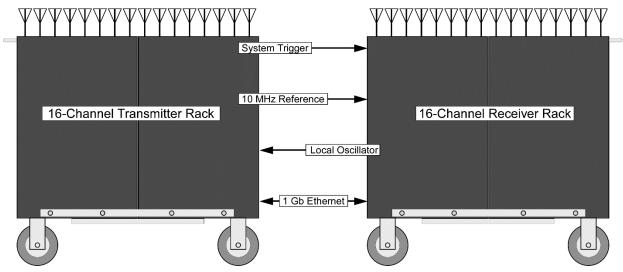
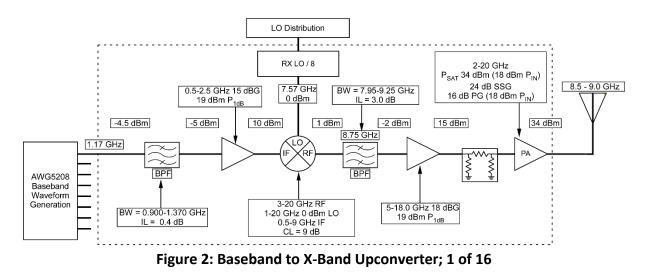


Figure 1: Transmitter & Receiver Rack Connections

### 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.



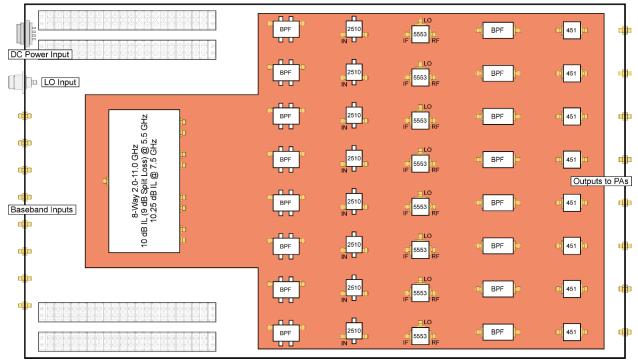


Figure 3: 8-Channel Baseband to X-Band Upconverter 19" Chassis Layout; 1 of 2

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.

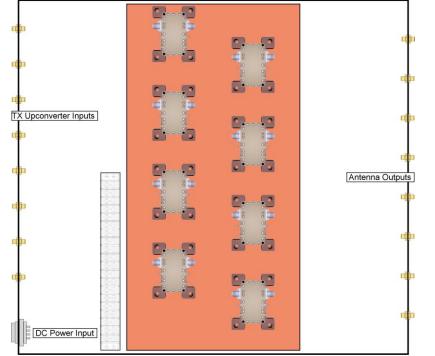


Figure 4: 8-Channel X-Band RF Power Amplifier 19" Chassis Layout; 1 of 2

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.

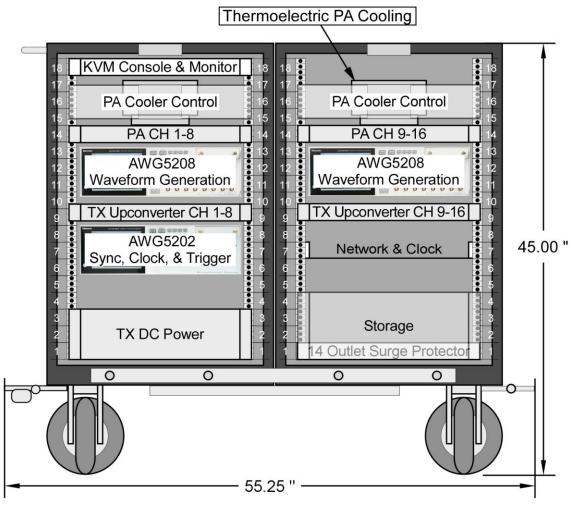


Figure 5: 16-Channel Transmitter Rack

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.

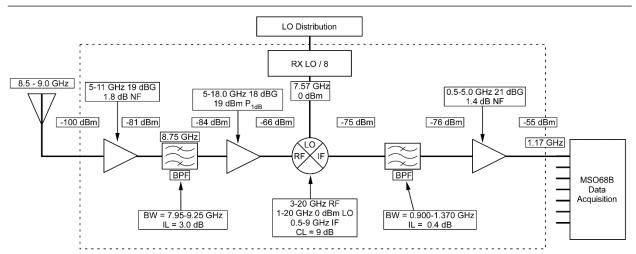


Figure 7: X-Band to Baseband Downconverter; 1 of 16

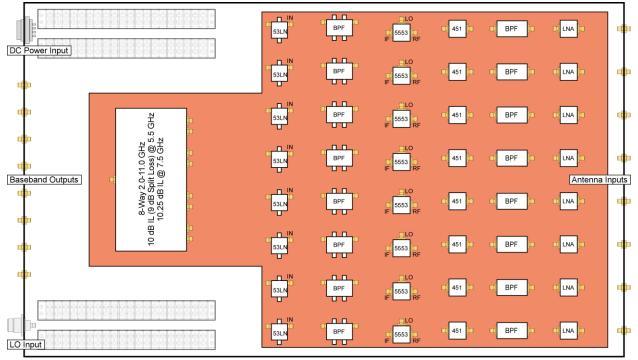
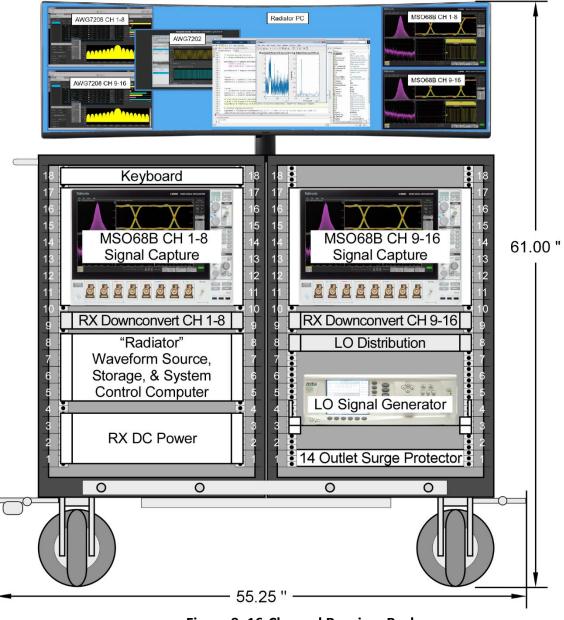


Figure 8: 8-Channel X-Band to Baseband Downconverter; 1 of 2

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 PCI e 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.





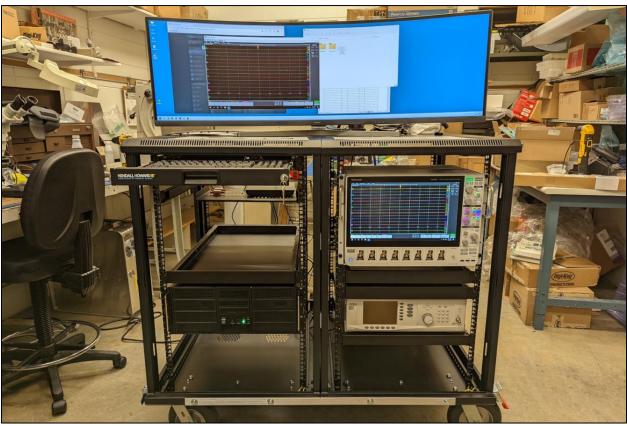


Figure 10: Receive Rack Component Configuration and Test Fit

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.

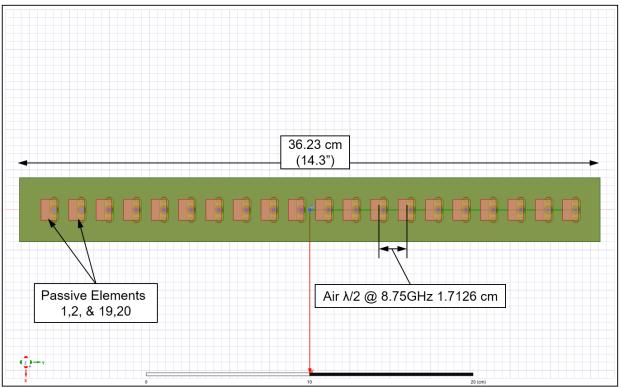


Figure 12: 20 Element 8.75 GHz Microstrip Patch ULA ANSYS 3D Model



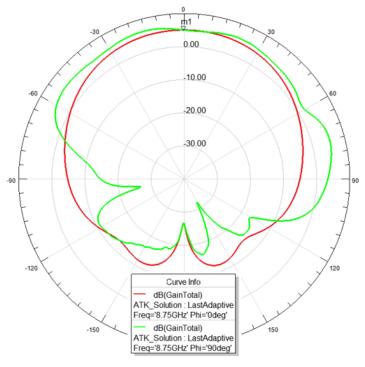


Figure 13: 20 Element 8.75 GHz Microstrip Patch ULA ANSYS HFSS Simulation

# 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.

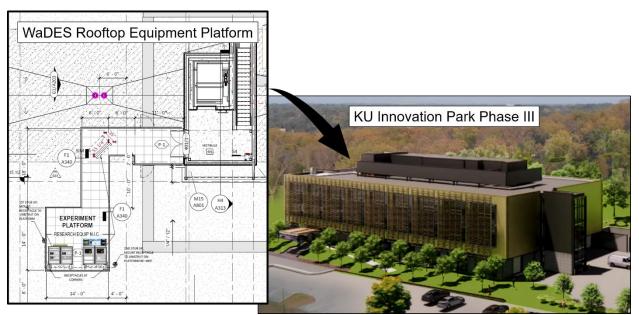


Figure 14: WaDES KUIP Phase III Supporting Infrastructure

# **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*.