REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 26-07-2018	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 20-Apr-2016 - 17-Aug-2017

4. TITLE AND SUBTITLE Final Report: Equipment to support prototyping for millimeter wave communication and radar	5a. CONTRACT NUMBER W911NF-16-1-0219
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611103
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Texas at Austin 101 East 27th Street Suite 5.300 Austin, TX 78712 -1532	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 68526-NS-RIP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Heath, Jr.
UU	UU	UU	UU		19b. TELEPHONE NUMBER 512-232-2014

RPPR Final Report
as of 14-Aug-2018

Agency Code:

Proposal Number: 68526NSRIP **Agreement Number: W911NF-16-1-0219**

INVESTIGATOR(S):

Name: PhD Robert W. Heath, Jr.
Email: rheath@utexas.edu
Phone Number: 5122322014
Principal: Y

Organization: **University of Texas at Austin**
Address: 101 East 27th Street, Austin, TX 787121532
Country: USA
DUNS Number: 170230239 EIN: 746000203
Report Date: 17-Nov-2017 Date Received: 26-Jul-2018
Final Report for Period Beginning 20-Apr-2016 and Ending 17-Aug-2017
Title: Equipment to support prototyping for millimeter wave communication and radar
Begin Performance Period: 20-Apr-2016 **End Performance Period:** 17-Aug-2017
Report Term: 0-Other
Submitted By: PhD Robert Heath, Jr. Email: rheath@utexas.edu
Phone: (512) 232-2014
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 2

Major Goals: The warfighter of the future will require reliable, easily deployable, decentralized high-speed wireless communication networks for high quality video, imagery, voice, and position data to ensure an information advantage in combat. To meet these demands, mobile ad hoc networks (MANETs) have the potential to support the high bandwidths available at millimeter wave (mmWave) frequencies. Unfortunately, validating many ideas in mmWave systems has remained a challenge. In this equipment grant, our major goal was to improve our ability to prototype mmWave communication and radar systems. Through the grant, we purchased key pieces of mmWave communication and radar equipment. This equipment is allowing us to advance the state-of-the-art in communication and radar research. Ongoing research has been using that equipment to test new ideas in joint communication and radar, as well as to develop new algorithms for radar sensor fusion.

Accomplishments: A PDF document has been uploaded with a detailed technical report that describes everything we accomplished.

Training Opportunities: The project provided several opportunities for training graduate students. This was an equipment grant with no direct support for graduate students. Nonetheless, several graduate students were involved with the equipment acquisition and initial experiments.

Results Dissemination: This equipment is currently being used in several research studies, whose results will be submitted for publication in the coming year.

Honors and Awards: 2017 Fellow of the National Academy of Inventors

2017 European Association for Signal Processing (EURASIP) Technical Achievement Award

2017 IEEE ICC Best paper Award for the Signal Processing for Communications Symposium (with Wenqian Shen, Linglong DAi, Guan Gui, Zhaochen Wang, and Fumiyuki Adachi)

2017 IEEE Marconi Prize Paper Award in Wireless Communications (with Omar El Ayach, Sridhar Rajagopal, Shadi Abu-surra, and Zhouyue (Jerry) Pi)

IEEE GLOBECOM 2016 Most Attended Industry Panel Award (with Tom Marzetta)

Co-author of paper receiving the 2016 SPS Young Author Best Paper Award (given to my students Ahmed Alkhateeb and Omar El Ayach)

Named a Highly Cited Researcher 2015-2017 by Clarivate Analytics in Computer Science.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Robert Wendell Heath Jr.
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Preeti Kumari
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Khurram Mazher
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 14-Aug-2018

Equipment to support prototyping for millimeter wave communication and radar

Robert W. Heath Jr., Principal Investigator (PI)

Wireless Networking and Communications Group
The University of Texas at Austin

1. Introduction

The warfighter of the future will require reliable, easily deployable, decentralized high-speed wireless communication networks for high quality video, imagery, voice, and position data to ensure an information advantage in combat. To meet these demands, mobile ad hoc networks (MANETs) are now leveraging a suite of technologies for high spectral efficiency including multiple-input multiple-output (MIMO) communication, high-order modulation, orthogonal frequency division multiple access (OFDMA), and interference alignment. Bandwidth at lower frequencies, however, is limited which fundamentally limits the capacity of wireless networks at UHF frequencies. Wireless LAN devices employ channels as large as 160MHz in the 5GHz band; cellular technologies use advanced channel bonding techniques to stitch channels together from sparse channels available at lower frequencies. The potential to expand further in the UHF band is limited by a lack of space and incumbent users. The bandwidth available at mmWave, however, is massive in comparison.

Prototyping mmWave systems has remained a challenge. The reason is that equipment for processing mmWave signals is not widely available at low cost. In this equipment grant, we purchased key equipment to enhance our ability to prototype mmWave communication systems. We purchased important pieces that enhanced our ability to prototype mmWave communication and radar systems. This equipment is allowing us to advance the state-of-the-art in communication and radar research. In the duration of this report, we describe the current equipment and how the DURIP grant has expanded our capabilities.

2. National instruments joint communication and radar prototype, and antennas

Millimeter wave communication is used for many applications in communications (5G cellular, wireless local area networks) as well as automotive radar applications. Our group has developed pioneering work in the use of wireless local area network standards at millimeter wave simultaneously for both communication and radar [1]. To enhance our ability to test joint communication and radar, we purchased equipment from National Instruments to support phased array communication. This enhanced the capabilities of the existing prototype, which was acquired through donations and other funds.

An overview of the current system is provided in Figure 1.

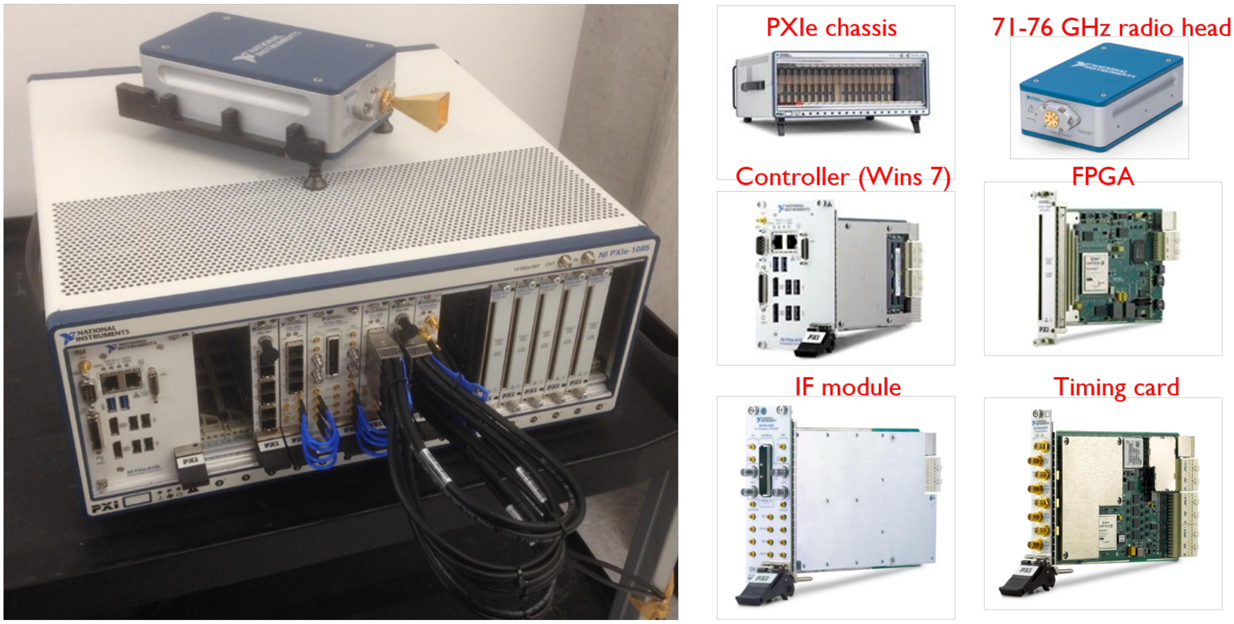


Fig. 1: An overview of the mmWave transceiver system. The system provides a flexible hardware platform that can be configured for different purposes such as joint communication and radar system or channel sounder system. On the right are components that could be used which include the controller, the FPGA, DAC, ADC, IF module, timing card, and radio head. (Photos of components are from http://www.ni.com)

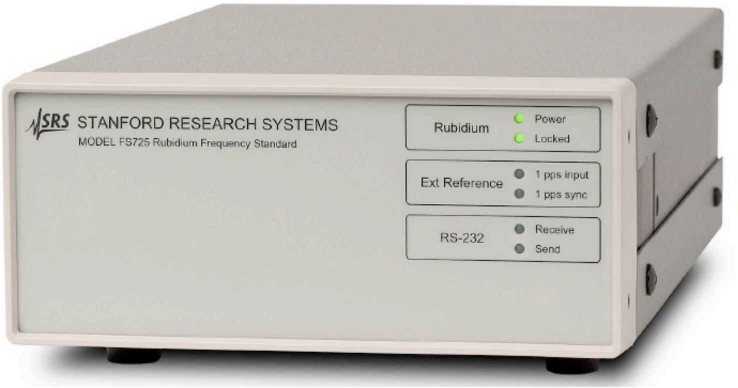


Fig. 2: Rubidium frequency standard from Stanford Research Systems. This clock is used to provide accurate 10 MHz reference clock to the chassis. It can also be used for synchronizing chassis together. It is used when precise reference clock is required or when tight synchronization between chassis is needed.

Fig. 3: AZ/EL turntable allowing mechanical steering of the radio head. The current system uses horn antennas, and thus mechanical steering is required to control the direction of transmission/reception. The turntable can be controlled using LabVIEW, which is the language used for implementing the signal processing part, and thus can be integrated into one application.

We have configured the system as a channel sounder system to conduct a car reflection measurement campaign as shown in Fig. 4. A screen shot of the graphical interface of the channel sounder is shown in Fig. 5. We used two separate chassis in this setup. For channel sounding, it is required that the transmitter and the receiver are synchronized, so that the signals are captured at the right timing. For this purpose, we used the Rubidium clock shown in Fig. 2 and shared the 10 MHz reference and the PPS (pulse-per-second) signals. The PPS is used as the trigger. As shown in Fig. 4, both the transmitter and the receiver were mounted on tripods, which allows us to change the antenna heights. In the campaign, we used three different heights: 0.5 m (bumper), 1.0 m (side mirror), and 1.5 m (roof). Using these three heights, we measured a total of 12 different transmit and receive antenna heights combinations. In this measurement campaign, horn antennas were used. Since horn antennas are directional, it is necessary that we conduct the measurements at different pointing directions. We used the turntable for mechanical steering.

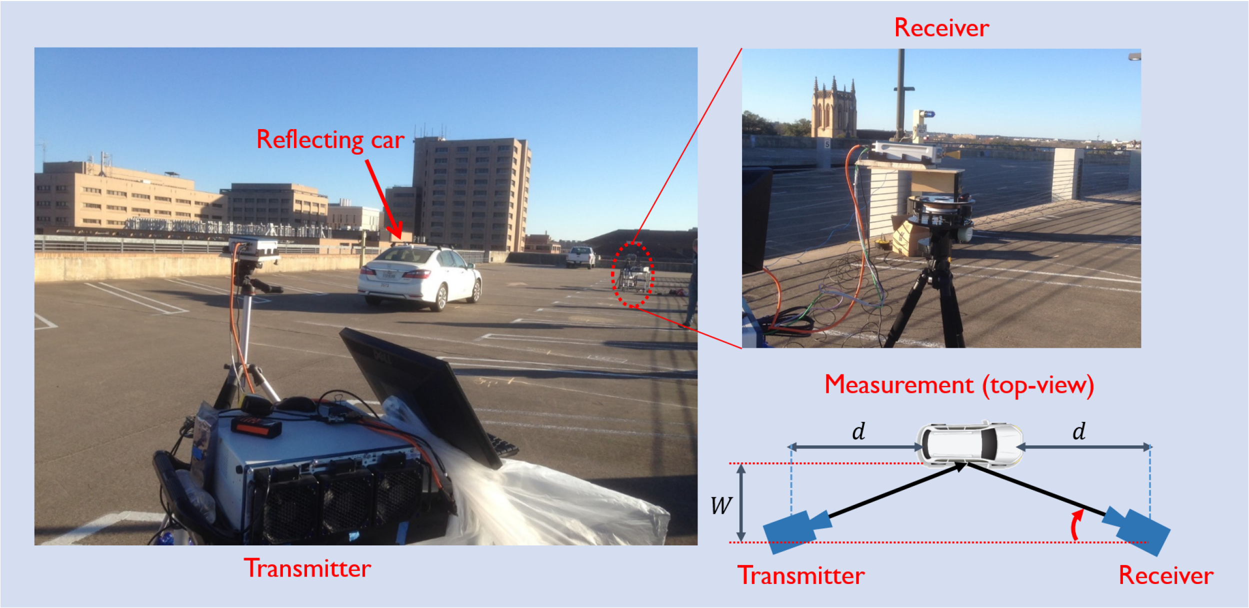


Fig. 4: Car reflection measurement.

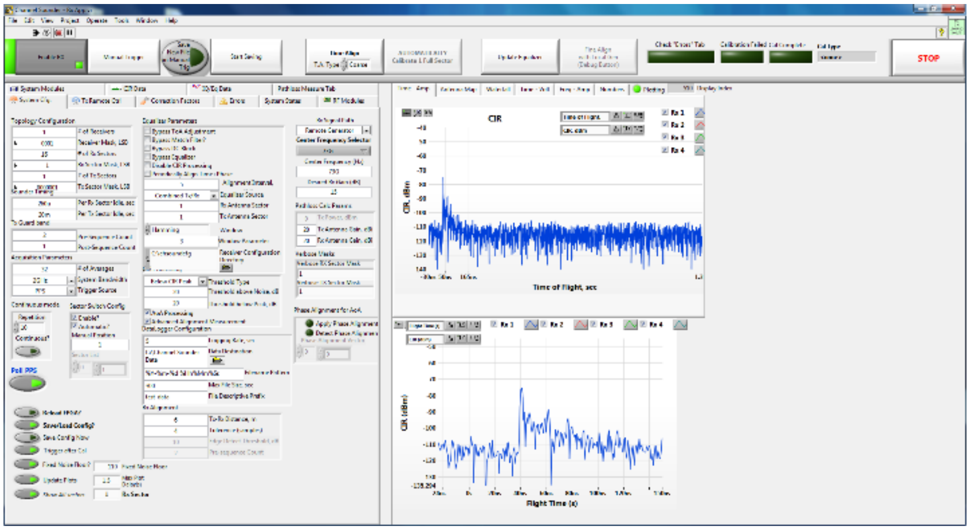


Fig. 5: Screen shot of the channel sounder graphical interface.

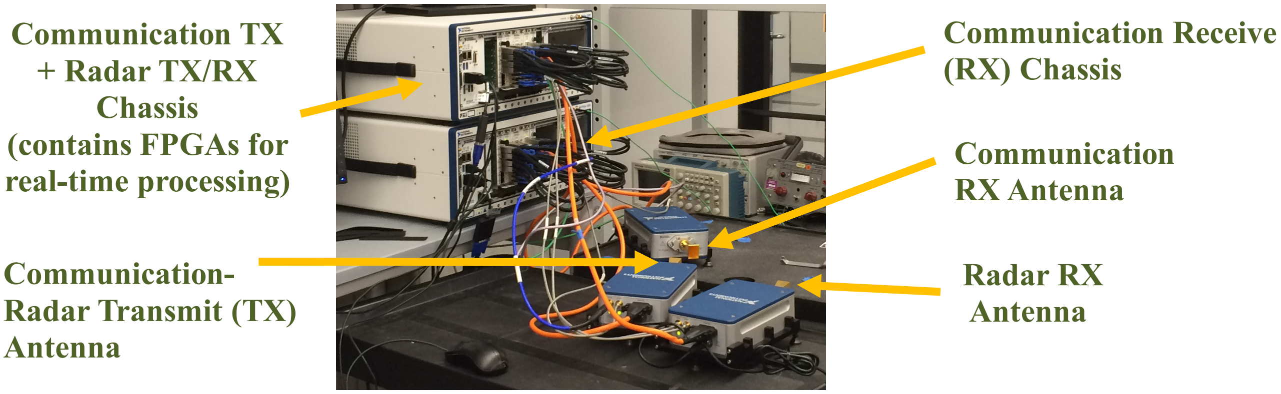


Figure 6: Joint radar-communication testbed with horn antennas

We have also set-up the NI mmWave testbed with horn antennas for a single-input-single-output (SISO) joint communication-radar configuration, as shown in Figure 6. The mmWave testbed supports 2 GHz bandwidth in the 71-76 GHz band. This band has less attenuation due to the atmospheric oxygen at 60 GHz unlicensed band. The mmWave testbed consists of two chassis, which houses NI PXIe 7902 for baseband transmit (TX)/ receive (RX) processing, NI PXIe 3630 (IF and LO unit) with 10.5-12 GHz IF frequency, ADC/DAC adapter modules, NI PXIe 3610 (14 bit DAC) and 3630 (12-bit ADC) with sample rate 3.072 GS/s and 2 GHz bandwidth, as shown in Fig. 1. Each chassis is connected to mmWave transceiver RF front-ends and horn antennas. The chassis can be connected using Rubidium clock shown in Fig. 2 for time and frequency synchronization of the joint communication-radar system. The horn antennas can be mounted on the rotator shown in Fig. 3 for sensing and communication in different directions.

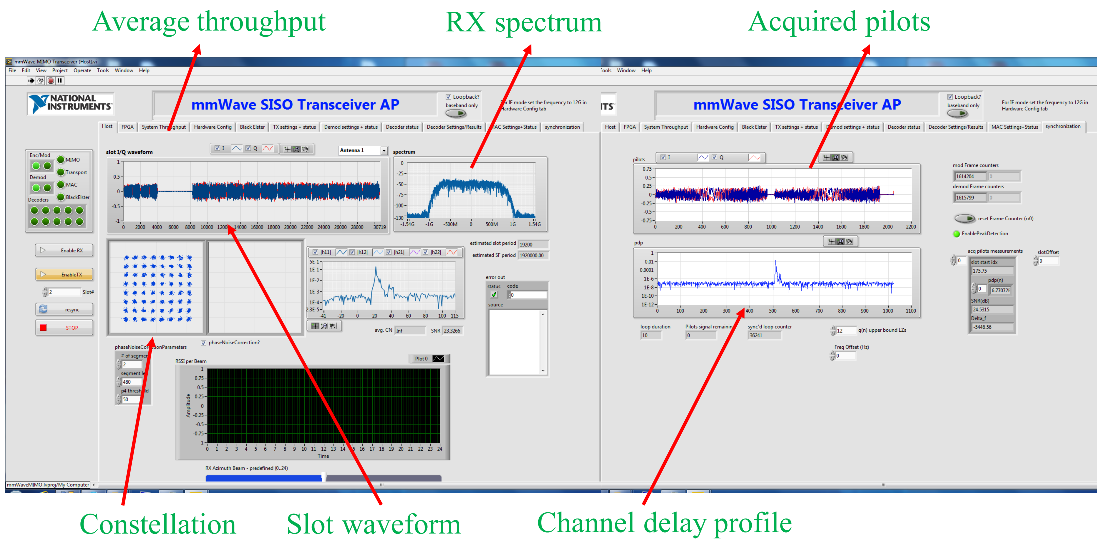


Figure 7: Screenshot of the mmWave datalink code

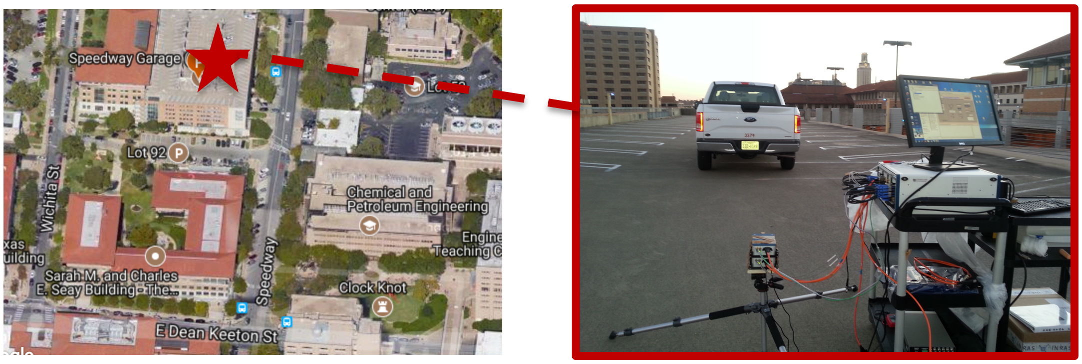


Figure 8: Radar channel measurement using channel sounder set-up at Speedway Garage

The joint communication-radar set-up supports two testing modes. In the first mode, a real-time joint communication-radar testing is enabled for short distances using mmWave datalink code that supports 5G proof-of-concept NI experimental cellular system. The datalink code is based on LabVIEW FPGA, whose front panel is shown in Figure 7. In the second mode, a joint communication-radar channel sounding is facilitated by adapting the communication channel sounding set-up for simultaneous two-way radar and one-way radar sounding. A screenshot of the channel sounder graphical user interface is shown in Figure 5 and the measurement campaign for outdoor radar sounding using the mmWave channel sounder set-up is shown in Figure 8.

3. INRAS radar

We also used the DURIP funds to expand our ability to evaluate develop and evaluate radar signal processing algorithms. Our existing radars come from commercially sourced automotive radars from Delphi. Unfortunately, we do not have access to the internal workings of the radars. We purchased several RadarLog and RadarBooks from INRAS. These programmable radar evaluation boards provide a much higher level of customization and flexibility in trying different radar waveforms. Multiple units are requested to explore different MIMO radar configurations and also to explore the possibility of joint communication and radar.

Initial measurements with the INRAS hardware are summarized in Figure 9 and Figure 10. From these figures, we see that the radar is able to generate useful signal processing data. This hardware will allow us to further develop ideas in collaborative sensing with multiple radar units. Such work will be important for broadening our ongoing research activities.

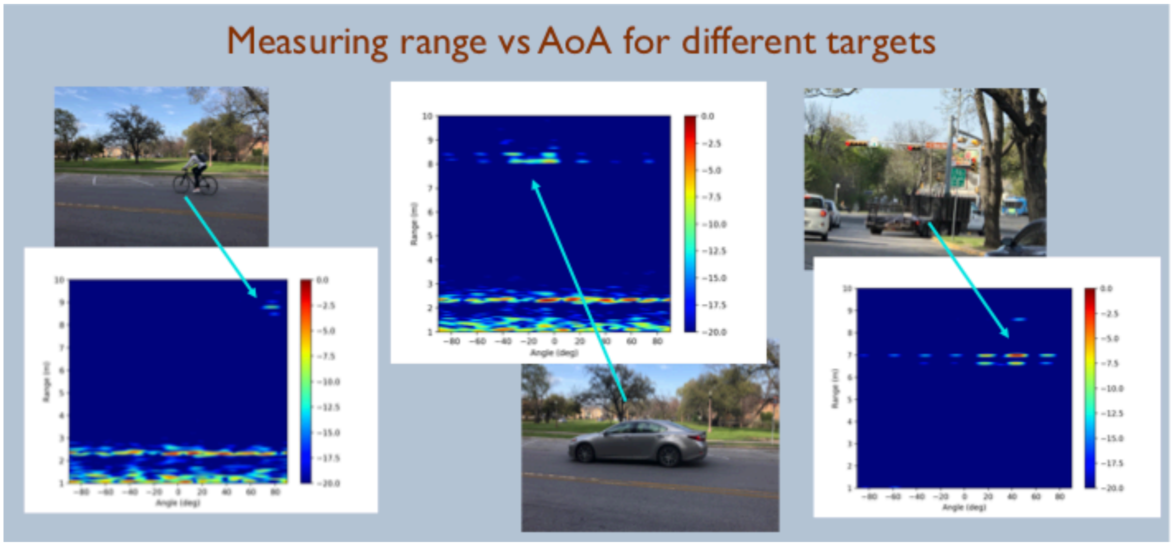
Radarbook aligned with street lane

- 4 TX antennas and 8 RX antennas
- 28 and 77 GHz possible

WLAN interface via USB port

Laptop running radar control code

Figure 9: RadarBook setup as used for initial outdoor measurements.



Measuring range vs AoA for different targets

Figure 10: Results from initial tests of the RadarBook using some of the software algorithms provided by INRAS. From the range / angle plots we can distinguish different types of targets. More elaboration is needed to refine the algorithms for detection and tracking.

4. References

[1] P. Kumari, Junil Choi, N. González Prelcic and R. W. Heath, Jr., `` IEEE 802.11ad-based Radar: An Approach to Joint Vehicular Communication-Radar System," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 3012-3027, April 2018.