DocuSigned by: Robina Sayed

Travel Authorization Request Form

Must be filled out before travel begins

Name: Bharath Keshavamurthy **ASU ID#:** 1223224041 **Concur Trip ID:** GFKG

Travel Start/End Dates: 01/03/2022 to 01/08/2022 **Destination:** Boulder, CO

Personal Travel during trip (Y/N) N **Start/End Dates of Personal Travel:** _____

Conference/Event Host: Christina Patarino, USNC-URSI NRSM 2022 at UC-Boulder

Workday Acct: Startup **PI Name:** Nicolo Michelusi

PI Authorization Signature (REQUIRED): DocuSigned by: _____

FACULTY ONLY – How/Who is covering your classes? N.A.

- **AIRFARE: $** 300.00 **(Travel request must be fully approved by the ASU Travel Office BEFORE purchasing airfare. All airfare must be purchased through Concur system)**
- **PERSONAL VEHICLE** 0.0 **(Enter mileage to/from travel destination)**
- **LODGING* $** 700.00 **(Conference lodging may be purchased outside of Concur system and reservation must be provided to plans@concur.com and myasutrip@asu.edu prior to travel. NON-CONFERENCE lodging MUST be purchased through Concur system)**
- **HOTEL NAME:** Hilton Garden Inn Boulder

***Non-conference lodging must be within the per diem rate. If not, provide justification/documentation showing that this is the recommended lodging:** _____

- **REGISTRATION: $** 0.00 **(Provide conference website and proof of payment if already purchased)**
- **MEALS: $**_____ **(Concur daily allowance used unless otherwise indicated)**
- **MISC ITEM: $** 160.00 **Specify:** Taxi (Lyft) **MISC ITEM: $**_____ **Specify:** _____
- **RENTAL CAR: ** $** _____ **Completion of Authorized Driver Program is required BEFORE travel.)** https://cfo.asu.edu/what-are-steps-authorized-driver-program. **Provide rental car justification: _____
- **SPONSOR INVITATION: If applicable to this trip, please attach invitation to trip request from sponsor or location site that you have been invited or allowed to participate in an activity**

1. **PROVIDE JUSTIFICATION FOR THIS TRIP AND WHY IT CANNOT BE ACHIEVED ADEQUATELY REMOTELY (E.G. ZOOM)?**

   I will be presenting our research paper titled, "A Robotic Antenna Alignment and Tracking System for Millimeter Wave Propagation Modeling" during this conference (USNC-URSI National Radio Science Meeting 2022) held at the University of Colorado - Boulder. The conference organizers have provided me with a Travel Fellowship which necessitates in-person presentation of our paper. The travel fellowship waives the conference registration fee ($225) and provides a travel reimbursement of $375.

2. **GRANT FUNDED TRAVEL: HOW DOES THE TRAVEL BENEFIT AND RELATE TO THE RESEARCH CONDUCTED ON THE GRANT?**

   This paper presentation allows us to disseminate our research on millimeter-wave propagation modeling -- specifically, the design, operation, and benefits of a fully autonomous antenna alignment & tracking platform employed in our V2X measurement campaign at the NSF POWDER testbed in Salt Lake City, which was one of the objectives of our NSF EARS grant.

3. **PROGRAM/GIFT/DISCRETIONARY FUNDED TRAVEL: HOW DOES THIS TRAVEL BENEFIT ASU?**

   This paper presentation and its subsequent archival in IEEE Xplore will help promote the activities of our research group here at ASU, and emphasize ASU's role as a leader in the field of intelligent wireless networks. In addition to presenting our paper at this conference, I would be attending short courses & tutorials in the radio sciences, plenary talks, and mentoring sessions: these will help augment our research in millimeter-wave propagation modeling, beam-alignment, and MIMO communications.

Welcome to the 2022 USNC-URSI NRSM!

The following information is intended to facilitate your arrival.

LOCATION OF MEETING
All scientific sessions will be held at the **University of Colorado Boulder** campus in the Engineering Center (1111 Engineering Drive). The Plenary will be held in the Mathematics Auditorium (Math 100). http://www.colorado.edu/campusmap/map.html?bldg=EC&x=15&y=8.

ON-SITE REGISTRATION
Conference registration check-in will be available for the following:

Tuesday, January 4, 8:00–15:00 in the Engineering Center main lobby (University of Colorado), and then will move to the Embassy Suites (2601 Canyon Blvd.) from 16:00–21:00.

Wednesday, January 5 in the Engineering Center main lobby (University of Colorado) from 07:30 to 10:30 and will continue during the remainder of the meeting in the Engineering Center (ECCR) Room 135.

OFFICE INFORMATION
USNC-URSI NRSM Office location is in the classroom wing of the Engineering Building Room 135. The hours for this office are below.

Wednesday, January 5:	11:00 - 17:00
Thursday, January 6:	07:30 - 17:00
Friday, January 7:	07:30 - 17:00

A University staff member will be available during these hours to assist you.

INTERNET ACCESS
Access wireless service on campus by selecting UCB Guest Wireless from your available Wi-Fi network options and accepting the terms and conditions upon opening your web browser. You will be prompted to re-accept these terms and conditions periodically. For additional information and needing assistance go to NRSM website: https://www.nrsmboulder.org/logistics.

RECEPTION
A light reception with cash bar (non-hosted bar) will be held in the Byron R. White Club (Folsom Stadium Club) on Wednesday, January 5, from 19:00 - 21:00. Please be prepared to show a government ID/passport and wear conference badge in order to consume alcohol. The legal age to drink in Colorado is 21.

Guests are welcome to attend, but you must indicate on the registration form that you will be bringing a guest. Otherwise, they will not be allowed to attend, due to the alcohol policy of the university. There is no extra cost.

PARKING
Virtual parking permits are available for purchase online. Please follow the instructions below to purchase your permit:

- Go to our Parking Services website: https://cuboulder.pmreserve.com/
- You will be directed to a page with all of our event parking groups. Click on **USNC-URSI National Radio Science Meeting** and follow instructions from there.
- The $19.00 rate offered is good for the week of NRSM.
- The site is much like any online shopping site. Pick your item add it to the cart and proceed to check out.
- Provide the vehicle license plate information to be valid. It is recommended **if renting a vehicle wait to purchase parking permit** until you have the actual license plate information.
- Complete the purchase and print a copy of your permit/receipt. Please display the printed copy on your dashboard as a backup confirmation of your virtual permit.

  This is not required but will help the parking patrol team determine if you accidentally made a typo in your license plate number.
- Please note the specific lot number that you have been assigned to. You must park in the lot assigned to you at the time of purchase. Be sure license plate is viewable from the drive lane.
- **All sales are final**

Please note that **enforcement will be handled through the license plate number**. You will **need to have vehicle make/model/color/plate information at the time of purchase**. You must have this information in order to purchase the virtual permit. Please ensure that all information provided is accurate to avoid a citation. For those renting vehicles, follow the above process once you have secured the vehicle in order to have information needed to complete purchase.

ACCOMODATIONS
Participants must make their own housing arrangements. Blocks of rooms have been set aside at local hotels and special group rates have been arranged.
Visit https://www.nrsmboulder.org/logistics for lodging options.

AIRPORT & LOCAL TRANSPORTATION
Shuttles will not be provided from hotels to the university.

All major airlines have flights into Denver International Airport (Airport code DEN, locally called DIA). A variety of surface transportation is available from DIA to Boulder.
The Regional Transportation District SkyRide (RTD city bus route “AB”) is the least expensive and travels to Boulder via Denver and U.S. 36. Travel time is approximately 90 minutes. Once in Boulder, exit at the Boulder terminal and take a taxi or city bus to your hotel. RTD Bus Schedule.

Green Ride shuttle is a locally owned and operated shuttle service that focuses on resource sustainability and minimizing environmental impact. It is recommended that you make a reservation online via the following website for outgoing service from DIA to Boulder: Green Ride Reservations.

SuperShuttle provides transport from the airport to most local hotels: SuperShuttle Reservations.

Rental cars are available at the airport. We do suggest advance reservations. Boulder is located 26 miles northwest of Denver via U.S. 36. If you decide to take a taxi from the airport, be sure to agree upon the fare with the driver prior to departure from the airport.

Car Rentals:

- eGo CarShare: www.carshare.org
- Zipcar: www.zipcar.com

Boulder Local Buses: https://bouldercolorado.gov/services/bus
Boulder B-Cycle (a community non-profit bike sharing system): www.boulder.bcycle.com/

WEATHER

Boulder's weather in January is notorious for its unpredictability and can range from snow and freezing temperatures to mild, balmy weather with temperatures near 60°F (16°C). Normally, however, the weather is sunny and rather cool (40°F or 4°C) during the month, with little snow. Participants should bring appropriate clothing.

SUSTAINABILITY

CU Boulder is +a leader in climate and energy research, interdisciplinary environmental studies, and in engaging in sustainability and "green" practices on campus. Bring a reusable water bottle and refill free, use the recycling bins across campus, and compost where available. We encourage visitors to consider the purchase of carbon offsets for travel. For more information about CU Boulder's sustainability initiatives and carbon-offset purchases, visit the following websites:

Research, Degrees, Outreach & Operations:	http://www.colorado.edu/sustainability
The Environmental Center:	http://www.colorado.edu/ecenter
Colorado Carbon Fund (carbon offsets):	http://www.coloradocarbonfund.org
Native Energy (carbon offsets):	http://www.nativeenergy.com

HEALTH & SAFETY INFORMATION

- Campus and Off-Campus Emergencies 911
- CU Police Department (On-Campus, Non-Emergency) 303-492-6666
- City of Boulder Police Department (Non-Emergency) 303-441-3333
- Boulder Community Hospital 303-415-7000
  4747 Arapahoe Ave, Boulder, CO 80303

PUBLIC HEALTH RESPONSE

The NRSM will adhere to all University of Colorado Boulder, Boulder County and Colorado state guidelines and recommendations prior to, during and after the conference, to ensure the safety of all participants. As we have learned in this past year, policies currently in place are subject to change based on University of Colorado Boulder, Boulder County and Colorado state and public

health orders. At this time, we cannot speculate what changes may be made to current policies, if any. We will do our best to communicate any updates and appreciate your flexibility. We encourage you to check this site prior to planning your travel to Boulder, and to review the links below for the latest available information.

Related resources:
Public Health Advisory for Boulder County – COVID-19 Surge for Boulder County and Colorado (10/29) **-** Public Health Advisory for Boulder County (govdelivery.com)

The following public health orders remain in effect in Boulder County:

- ***Masks are required for all individuals 2 and older in all public indoor spaces in Boulder County, regardless of vaccination status****, except for approved vaccine verified facilities and events. See Public Health Order 2021-08*

University of Colorado Boulder Current Public Health Measures
Boulder County Public Health Dial
Boulder County Indoor Mask Order
Boulder County COVID-19 Information
Colorado Department of Public Health and Environment's Executive and Public Health Orders

CAMPUS CLOSURES, EXTREME WEATHER, AND OTHER EMERGENCIES

Be in the know. Know what to do.
CU Conference Services is committed to keeping our guests notified with up-to-date and real-time information in the infrequent event of campus closures, extreme weather and other emergencies. CUCS accomplishes this goal by automatically signing up on-site clients and adult attendees to our automated **RAVE Alert System**. All adult's (18 +) e-mail and/or cell phone number provided at registration/check-in are sent to the CU Boulder Alert administrator to be included in the alert database. Individuals are active in the database only for the duration of the event or program on campus. Depending on the contact information provided, alerts are sent straight to either e-mail accounts and/or mobile devices via our text messaging service.

The University of Colorado Boulder is committed to providing timely warnings and/or emergency notifications for situations that represent a serious or continuing threat to the campus community and visiting guests. If warranted, warnings may be followed by a clarification and/or instructional statement from CU Conference Services administration.

How to find additional information in an emergency

- **On your mobile device**—Watch for text or e-mail alerts in the case of a campus closure or if there is a threat to personal safety.
- **On the web**—Visit www.colorado.edu for detailed campus closure and emergency information and updates.
- **On the phone**—Call the campus info line at **303-492-INFO (4636)** for recorded information and updates relating to campus alerts.
- **By e-mail**—Check your e-mail after an emergency for support and resource information.
- **On social media**—Like CU Boulder on Facebook and follow @cuboulder and @cuboulderalerts on Twitter.

SMOKING
The University is a smoke-free environment; smoking is not permitted anywhere on campus. Electronic cigarettes are included in the smoking ban.

ALCOHOL & DRUG POLICY
The University of Colorado Boulder is committed to excellence in all aspects of personal and academic life. We recognize that alcohol abuse and misuse is a significant impediment to achieving this excellence. Therefore, CU-Boulder permits only the responsible, legal consumption of alcohol. The university complies with all federal, state, and local laws concerning alcohol and illegal drugs.

LAW RELATED TO ALCOHOL & DRUG USE
Persons under 21 years of age cannot legally possess or consume alcoholic beverages. The furnishing of alcoholic beverages to underage persons is prohibited. Individuals who are of legal drinking age may possess and consume alcohol only in the privacy of their room with the door closed in their assigned residence hall room or at official conference catered events. Alcohol cannot be consumed or carried in open containers on any street, sidewalk, alley, automobile, or public area on campus. Any participant who consumes or possesses alcohol contrary to the above are subject to request for departing the premises and, upon request, shall leave the premises immediately.

The possession, use, sale, manufacturing, or distribution of Illegal ("Illegal" means unlawful under Colorado state law or federal law) drugs in the residence halls, including marijuana and drug paraphernalia including but not limited to pipes, hookahs, bongs, water pipes, etc. is not permitted. Marijuana remains a controlled substance under the federal Controlled Substance Act and, accordingly, is Illegal. Any participant who involves themselves in the use of possession of Illegal drugs are subject to the campus's request to depart the premises and, upon request, shall leave the premises. A participant may also be subject to legal action.

Possession of firearms, explosives, fireworks, incendiary devices, ammunition, other weapons, or instruments designed to look like any of the above will result in the possible immediate removal from campus.

PRINTING, COPYING, FAXING AND SHIPPING SERVICES
- FedEx Office Print & Ship Center
  2616 Baseline Rd, Boulder, CO 80305 (south end of campus)
  303-494-2622

FURTHER ASSISTANCE
For further assistance, please email Christina Patarino at nrsmboulder@colorado.edu. To make a change in your registration, please email CU Conference Services at conferences@colorado.edu.

For detailed conference information visit the USNC-URSI NRSM web page at http://www.nrsmboulder.org/

We look forward to seeing you in Boulder!

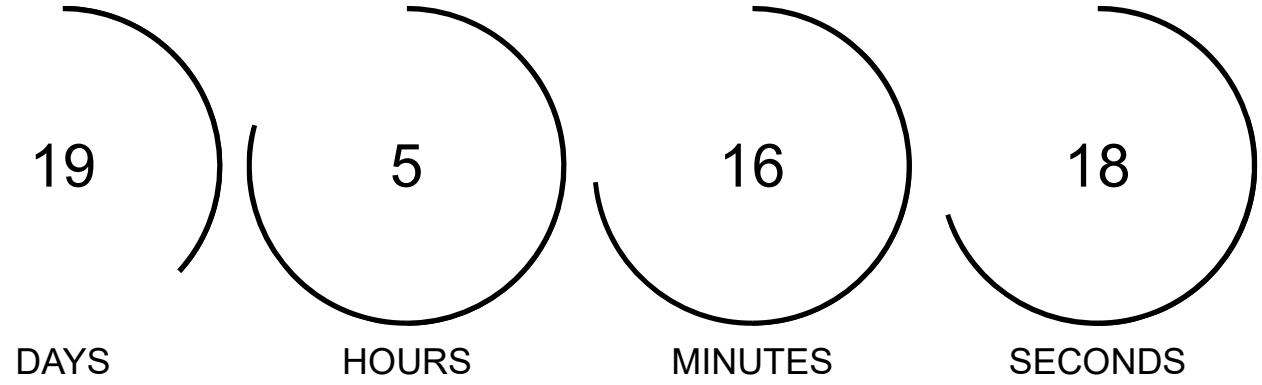
2022 USNC-URSI National Radio Science Meeting

	Time [MST] \ Room	105	150	151	155	200	245	265	1B40	1B51
Tuesday, 4 January	08:30-11:30	**Short Course Joint MIMO-Radar-MIMO-Communications for Autonomous Vehicles (Hybrid)**								
	12:30-14:20	**Tutorial I HFSS Demo (Hybrid)**								
	14:40-16:30	**Tutorial II Near-Field Measurements: Principles & Demo (*In-Person* Only)**								
Wednesday, 5 January	08:00-08:10	**Opening Welcome (Streamed from Math 100)**								
	08:20-12:00	B1 - Antenna Theory, Design, and Measurements	F1* - Advances in GNSS-R and SoOP Systems: Techniques and Applications I	G1* - New Applications of SmallSat Sensors G2 - Meteoroids and Orbital Debris	A1 - Antennas A2 - Materials	B2 - Numerical Methods B4* - 5G and Millimeter Wave Antennas and Applications	H1* - Heliospheric Observations of Waves in Plasmas	J1 - New Telescopes, Techniques and Technologies and Observatory Reports I	B3* - Complex EM and Meta Structures	D1 - Electronics and Photonics
	12:10-13:00	**Women in Radio Science (WIRS) Invited Speaker**								
	13:10-14:50	B5* - Low-Profile Millimeter-Wave / Terahertz Antennas for Mobile and Space Applications	F2* - Advances in GNSS-R and SoOP Systems: Techniques and Applications II		A3* - Multiband Antenna Array Challenges and Solutions	B6 - Electromagnetic Theory annd Techniques	H2* - Active Experiments in Laboratory and Space Plasmas	J2 - New Telescopes, Techniques and Technologies and Observatory Reports II	B7* - Multiscale and Stochastic Modeling in Computational Electromagnetics	D2* - Millimeter-Wave and Terahertz Systems for Space Applications
	15:10-16:50	**Student Paper Competiton (Math 100)**								
	17:00		Commission F		Commission A					
	18:00	Commission C&E						Commission J		
	19:00-20:00	**WIRS Speaker Meet & Greet for all *Virtual* Attendees**								
	19:00-21:00	**Reception for all *In-Person* Attendees at the Folsom Stadium Club**								
Thursday, 6 January	08:20-11:30	**Plenary Session (Math 100) Meeting Highlight Plenary Talks Student Paper Competition Awards Ceremony**								
	11:40-13:10	**Student Mentoring Lucheon (Lunch provided for all students, UNSC-URSI Officers, and Commission Chairs)**								
	13:10-16:50	A4* - Inventive Approaches in Advanced Communications K1* - Dosimetry and Exposure Assessment	F3 - Refractivity Characterization and Numerical Weather Prediction	G3 - Radar and Radio Techniques	C1 - Radar C2 - RF Spectrum	B8 - Analysis and Design of Antennas and RF Components	H3* - Lightning and Plasma Phenomena of the Thermosphere	J3 - New Telescopes, Techniques and Technologies and Observatory Reports III	B9* - Novel Electrically Small Antennas and Matching Networks	D3* - Broadband and Multiband Amplifiers
	17:00			Commission G					Commission B	
	18:00	Commission K					Commission H			Commission D
	19:00	**WIRS Business Meeting (Room 150)**								
	20:00	**WIRS *In-Person* Reception (Location TBA)**								
Friday, 7 January	08:00-08:10	**Closing Day Remarks (Streamed from Math 100)**								
	08:20-12:00	K2 - Human Body Interaction with Antennas and Other Electromagnetic Devices	F4 - Microwave Remote Sensing of the Earth	G4 - Ionospheric Imaging G5 - Ionospheric Modeling and Data Assimilation	C3 - RF Antenna Design and Systems E1 - RF Spectrum and RF Systems in Noise	B10 - Antenna Arrays: Approaches, Realizations, and Applications	J4* - New SETI Technologies	J5* - Imaging Black Holes: the EHT and Beyond I	B11* - Antennas and Systems for Specialized Platforms and Extreme/Harsh Environments	
	12:10-13:00	**Hans Liebe Lecture (Math 100)**								
	13:10-16:50	K3 - Electromagnetic Imaging and Sensing	F5 - Propagation and Remote Sensing in Complex and Random Media			J6* - New Frontiers in Solar Radio Physics†	H4* - Physics of the Radiation Belts	J7* - Imaging Black Holes: the EHT and Beyond II	B12 - Structures and Circuits for RF Sensing, Radar and STAR Applications	

*** Denotes a special session** **†Session J6 will extend to 17:50**

Conference Services
UNIVERSITY OF COLORADO **BOULDER**

You are now registered! See you in...



January 4, 2022—
January 8, 2022

Add to Calendar

Registration Summary

Review your registration information below

Bharath Keshavamurthy

bkeshav1@asu.edu

Address

GWC 325, Arizona State University
650 E. Tyler Mall
Tempe, Arizona 85281
USA

Phone

7657758910

Agenda

Item	Price
Admission Item	
In-Person Full-Time Student Registration	$0.00

Add Another Regisrant

Submit Payment | Modify Registration | Cancel Registration

You will receive a confirmation email with your registration details.

Your Confirmation Number is:

PRNV6MGHZCF

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Fax: 202 334 1990
E-mail: mwelch@nas.edu
www.nationalacademies.org

December 15, 2021

Dear Bharath Keshavamurthy,

Congratulations! We are pleased to inform you that you have been selected for a USNC-URSI 2022 Travel Fellowship (the "Travel Fellowship") to attend the U.S. National Committee for the International Union of Radio Science ("USNC-URSI") National Radio Science Meeting in Boulder, Colorado, January 4 –8, 2022 ("NRSM 2022"), sponsored by the National Academy of Sciences, which includes under its Congressional Charter, the National Academy of Engineering and National Academy of Medicine (collectively "NAS").

The Travel Fellowship is intended to help defray your travel expenses for IN-PERSON ONLY attendance to the NRSM 2022 IN-PERSON ONLY.

USNC-URSI Travel Fellowship Elements:

I. REGISTRATION: Registration Deadline is **December 20, 2021**. Register to participate on the NRSM 2022 Registration website. Click on the REGISTER button and proceed through the entire registration process as normal. When you get to the final page titled "Order Summary", you will see a box where you can enter in the discount code (**STUDENTSUPPORT22**) and apply it to your registration total. After the code has been applied, your balance due will be $0.00 (unless you order any box meals or carbon offsets) and you can then submit your registration to be confirmed. By using the discount code your registration fee of $225.00 will be waived. Everything else will need to be purchased. The discount code can ONLY be used by you as a Travel Fellow, and it is non-transferable.

II. TRAVEL REIMBURSEMENT: NAS will reimburse you for your travel expenses to attend the meeting, not to exceed the following:

Non-Colorado Resident Participants - $375.00
Colorado Resident Participants (minimum 50 mile from Boulder) - $100.00
*Colorado Residents less than 50 miles of Boulder radius are not eligible for travel expense reimbursement.

III. TERMS:

1. You are responsible to make your own travel arrangements. Upon conclusion of NRSM 2022, you will be provided instructions and a link to CONCUR, NAS' online Travel and Expense Management System, for processing your travel reimbursement.
2. You must contact James Manning at jmanning@nas.edu immediately if you are unable to attend NRSM 2022.
3. You are expected to attend the *Student Paper Competition Presentation and Luncheon* on Thursday, January 6, 2022. If you will not be able to meet this requirement, please contact Ana Ferreras, aferreras@nas.edu.
4. You will be asked to complete a survey following the event. If you do not complete and submit the survey your travel reimbursement may be delayed.
5. You will be expected to conform to professional standards of conduct.

If you should have any questions, please contact James Manning, jamanning@nas.edu.

Sincerely yours,

Madeline Welch

Madeline Welch
Contract Administrator
Procurement Services & Subaward Administration

A Robotic Antenna Alignment and Tracking System for Millimeter Wave Propagation Modeling

Bharath Keshavamurthy*, Yaguang Zhang†, Christopher R. Anderson‡,
Nicolò Michelusi*, James V. Krogmeier†, David J. Love†

***Abstract*—In this paper, we discuss the design of a sliding-correlator channel sounder for 28 GHz propagation modeling on the NSF POWDER testbed in Salt Lake City, UT. Beam-alignment is mechanically achieved via a fully autonomous robotic antenna tracking platform, designed using commercial off-the-shelf components. Equipped with an Apache Zookeeper/Kafka managed fault-tolerant publish-subscribe framework, we demonstrate tracking response times of 27.8 ms, in addition to superior scalability over state-of-the-art mechanical beam-steering systems. Enhanced with real-time kinematic correction streams, our geo-positioning subsystem achieves a 3D accuracy of 17 cm, while our principal axes positioning subsystem achieves an average accuracy of 1.1° across yaw and pitch movements. Finally, by facilitating remote orchestration (via managed containers), uninhibited rotation (via encapsulation), and real-time positioning visualization (via Dash/MapBox), we exhibit a proven prototype well-suited for V2X measurements.**

I. Introduction

With the widespread deployment of 5G networks by wireless carriers, primarily leveraging the mid-band spectrum, these service providers have shifted their spectrum procurement focus to the millimeter-wave bands (mmWave: 30–300 GHz) [1], with the long-term vision of providing a significant enhancement in user experience vis-à-vis data rates and latencies in dense urban and suburban environments. Concertedly, academic research into mmWave signal propagation modeling has also gained a renewed emphasis. In this paper, we briefly summarize our efforts in executing a measurement campaign with a 28 GHz sliding-correlator channel sounder and a fully autonomous robotic antenna alignment & tracking platform, on the NSF POWDER testbed at the University of Utah in Salt Lake City, UT [2].

An earlier measurement campaign [3] by our research group centered around a manual antenna alignment & tracking platform in semi-stationary settings for 28 GHz systems in suburban neighborhoods. Similarly, the system detailed in [4] also involves manual alignment and is restricted to indoor environments. On the other hand, the beam-alignment framework outlined here is fully autonomous and capable of operating in V2X mobility scenarios, with remote monitoring and troubleshooting capabilities; furthermore, this measurement campaign on the POWDER testbed is executed on a geographically diverse site encompassing both urban and suburban routes. Although electronic beam-alignment strategies involving phased-arrays offer faster switching times ($\approx$2.5 ms) [5] and greater flexibility (side-lobe & beam-width control) relative to mechanical fixed-beam steering, they constitute computationally expensive signal sampling along multiple directions and their design necessitates complex hardware due to resource-heavy algorithmic models. In the the following section, we briefly summarize the design of our prototype and demonstrate its efficacy through field-tested performance metrics.

Part of this research has been funded by NSF under grant CNS-1642982.
*Electrical, Computer and Energy Engineering, Arizona State University.
†Electrical and Computer Engineering, Purdue University.
‡Electrical Engineering, United States Naval Academy.

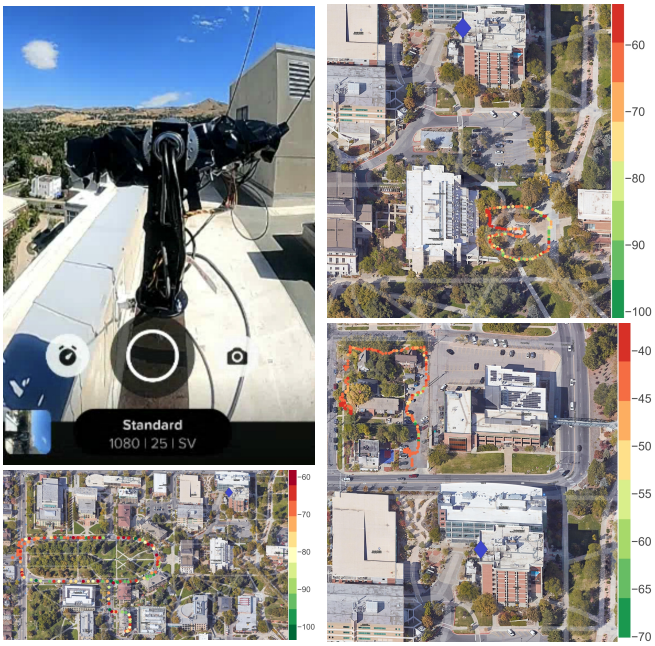

Fig. 1. Clockwise from top-left: our remote monitoring & troubleshooting interface—via an Android Debug Bridge—exhibiting the deployment of our Tx on the roof-top of the William Browning Building; illustrations of the received signal power values superimposed on a Google Hybrid map of the sites under analysis for urban foliage (Rx on cart), suburban neighborhood (Rx on cart), and urban-campus (Rx on minivan), respectively. The dots with heat-map color palette values denote Rx locations as it was driven/pushed around, and the purple diamond denotes the fixed Tx location.

II. Design Description

The prototype deployed for our 28 GHz measurement campaign on the POWDER testbed constitutes three modules: an autonomous *beam-steering controller* replicated at both the transmitter (Tx) and the receiver (Rx), their respective *communication subsystems* consistent with our sounder design, and a *centralized nerve center* for component registration & coordination, timing synchronization, messaging middleware, and data storage with redundancy. Here, the nerve center is deployed on a high-availability cluster of four Dell R740 compute nodes at the Fort Douglas data center; additionally, as depicted in Fig. 1, the Tx is fixed atop the William Browning Building, and the Rx is mounted on a Toyota Sienna minivan or a cart that is driven or pushed around campus.

Channel Sounder: As illustrated in Fig. 2, our prototype consists of a custom-built sliding-correlator channel sounder [3], whose principles have been laid down in [6]. Using highly directional WR-28 horn antennas with +22 dBi gain & 15° half-power beam-width, up/down-converters, and commercial off-the-shelf circuitry, we record the power-

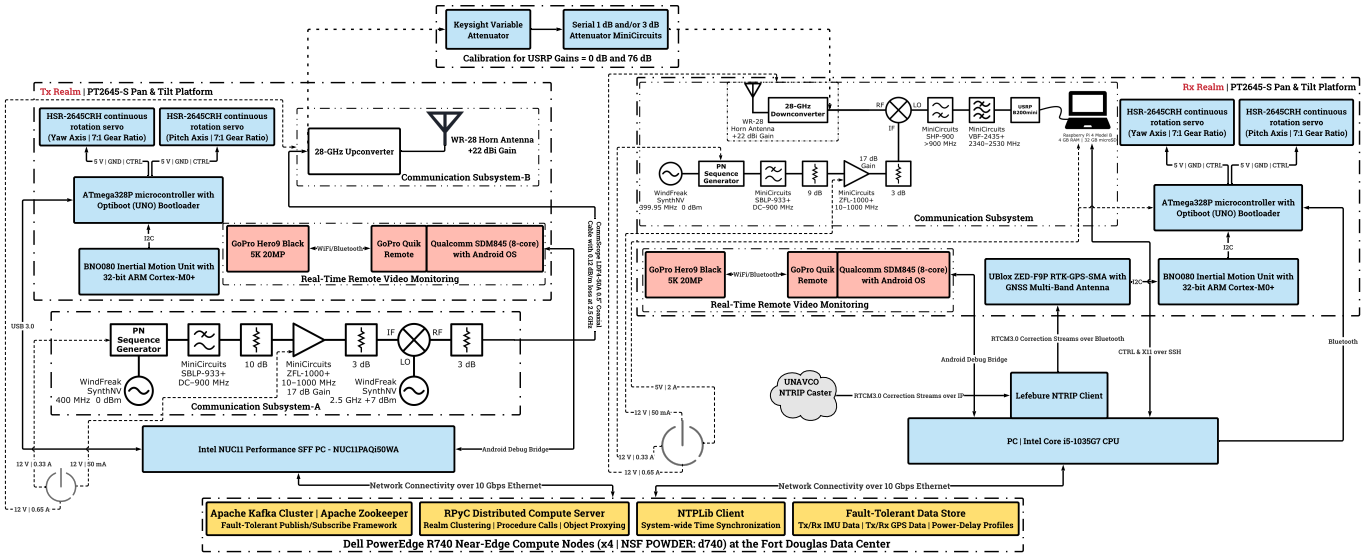

Fig. 2. The system architecture of our fully autonomous robotic antenna alignment & tracking platform with a sliding-correlator channel sounder

delay profiles (as complex-64 I/Q samples) at a Raspberry Pi via a GNURadio sink coupled with a USRP B200mini UHD source (bandwidth=0 Hz, gain=0 or 76 dB, center frequency=2.5 GHz, and sample rate=2 Msps). Furthermore, leveraging QT GUI time sink visualization capabilities of GNURadio (with dynamic trigger levels) over an ad-hoc WLAN with the Pi, this design enables seamless oversight of our recording activities.

Alignment & Tracking: As shown in Fig. 2, our mechanical beam-steering controller (written in C/C++ and Python) is inherited and extended at the Tx and the Rx. Each side interfaces with inertial motion and global positioning breakout boards through an ATMega328P microcontroller over I2C peripherals, gets notified of alignment & location updates from its counterpart in real-time, and orchestrates yaw-/pitch-axis positioning via open-loop servo (HSR-2645CRH) control. The RPyC API handles controller registration & coordination. A Network Time Protocol client-server architecture administers timing synchronization. A Zookeeper-managed cluster of Kafka brokers handles the publish-subscribe middleware operations between the Tx and Rx controllers, with redundant data storage. This fully autonomous architecture allows for an average beam-steering response time of 27.8 ms, evaluated over $12,870$ interactions; moreover, our loosely coupled modular design allows for remote monitoring and troubleshooting of each controller. Corroborated both in-field and on an ad-hoc laser testbed, our principal axes positioning framework achieves an accuracy of 1.1° across all fine- & coarse-grained yaw and pitch movements. Likewise, corroborated both in-field (Plotly Dash/MapBox API) and on a vendor-specific console (uBlox u-Center/Google Maps JavaScript API), our geo-location framework—with real-time kinematic correction streams—achieves a 3D accuracy of 17 cm.

Post-Processing: Upon completion of our data collection activities on the POWDER testbed, for a chosen site, our post-processing scripts parse the metadata associated the recorded power-delay profiles, extract the timestamps corresponding to each recorded data segment (10^6 complex-64 I/Q samples), process the samples in each segment (pre-filtering, temporal truncation, time-windowing, noise elimination), compute the received signal power off of these processed segments (with an initial calibration driven correction), couple these segments with the recorded geo-location & inertial motion logs, and visualize the results on a Google Hybrid map rendered via the Bokeh toolbox: these visualizations for a Rx route around foliage in an urban campus environment, a suburban neighborhood, and President's Circle are shown in Fig. 1.

III. Conclusion

In this summary, we outline the key design details encompassing our mmWave propagation modeling measurement prototype. With several sites successfully analyzed at the University of Utah in Salt Lake City, our system has been proven both in the field and in a laboratory environment to achieve an average alignment accuracy of 1.1°, a 3D geo-location accuracy of 17 cm, and an average beam-alignment response time of 27.8 ms under V2X mobility evaluations. Offering unrestrained rotation and remote orchestration capabilities, in addition to a modular fault-tolerant messaging middleware framework, our fully autonomous beam-steering controller is well-suited to be scaled to increasingly complex mmWave modeling activities.

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