CARNATIONS

Center for Assured & Resilient Navigation in Advanced Transportation Systems

ILLINOIS INSTITUTE OF TECHNOLOGY · CHICAGO STATE UNIVERSITY · UC RIVERSIDE · Stanford · VIRGINIA TECH

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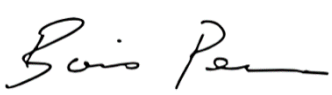
Signature:	

Acknowledgment of Report Authors and Contributors

This report showcases the collective efforts of the CARNATIONS community, faculty, researchers, students, and partners in advancing resilient transportation systems. Authored by **Center Director Boris Pervan, Associate Director Mathieu Joerger, and Program Manager Aashish Narang**, it reflects our leadership and expertise while highlighting contributions from all research teams across the consortium. It summarizes the key objectives, activities, and progress in developing Resilient Positioning, Navigation, and Timing (R-PNT) technologies for multimodal transportation.

Introduction

The Center for Assured and Resilient Navigation in Advanced Transportation Systems (CARNATIONS), a Tier-1 University Transportation Center, addresses the U.S. Department of Transportation's priority of reducing cybersecurity risks in transportation. Focusing on Resilient Positioning, Navigation, and Timing (R-PNT) and secure Vehicle-to-Everything (V2X) communications, CARNATIONS strengthens PNT resilience across multimodal networks. CARNATIONS operates three subcommittees—Research, Education and Workforce Development, and Technology Transfer—led by **Program Manager Aashish Narang,** and **Co-PIs Mark Psiaki, Matthew Spenko,** and **Samer Khanafseh**. These teams collaborate closely to advance research, education, workforce development, and the transfer of new technologies from academia to industry

1 ACCOMPLISHMENTS

1.1. What are the major goals of the program?

CARNATIONS aims to advance the resilience and cybersecurity of Positioning, Navigation, and Timing (PNT) systems in alignment with U.S. DOT strategic goals. The program focuses on identifying and mitigating vulnerabilities such as jamming and spoofing, advancing R-PNT technologies to ensure reliable and secure transportation infrastructure. Alongside research, CARNATIONS emphasizes workforce development through education, outreach, and training initiatives to prepare future professionals in transportation cybersecurity. The program also collaborates with industry partners to develop performance metrics, establish standards, and create open evaluation frameworks, ensuring that research outcomes translate into practical, deployable solutions that enhance transportation safety and reliability.

1.1.1. Research

Over the past six months, CARNATIONS has achieved notable progress across its twelve core projects through active collaboration among partner universities. This period marked steady advancement in research execution, data analysis, student engagement, and dissemination at professional conferences. Collective efforts by Principal Investigators (PIs) and students have enhanced outcomes in resilient navigation,

multimodal systems, and advanced vehicle applications, aligning with U.S. DOT objectives. The projects and their respective PIs are listed below:

No.	Ongoing Projects	University Partners	Age	PIs	Status	Start Year	Duration	End Year
1	GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation	Stanford, VT	Old	Sherman Lo, Mark Psiaki	ACTIVE	October 01,2023	2023-2026	
2	Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks	IIT	Old	Boris Pervan, Samer Khanafseh	ACTIVE	October 01,2023	2023-2026	
3	Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration	IIT	Old	Boris Pervan, Samer Khanafseh	ACTIVE	October 01,2023	2023-2026	
4	Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks	VT	Old	Mathieu Joerger, Mark Psiaki	ACTIVE	October 01,2023	2023-2026	
5	Towards Resilient V2X Communications over 5G/6G Networks: Sensing and Cooperative Perception	VT	Old	Walid Saad, Hang Qiu	ACTIVE	October 01,2023	2023-2026	
6	Multi-Vehicle/Infrastructure Jammer/Spoofer Detection and Localization	VT, UCR	Old	Jay Farrell, Matthew Barth, Mathieu Joerger	COMPLETED	October 01,2023	2023-2024	September 30, 2024
7	Threat Models and Use Cases for Multimodal Transportation	Stanford	Old	Todd Walter, Sherman Lo	ACTIVE	October 01,2023	2023-2029	
8	R-PNT Virtual Conflict Simulation	VT	Old	Hesham Rakha, Mark Psiaki	ACTIVE	October 01,2023	2023-2029	
9	Comprehensive Testing and Evaluation of Resilient PNT Systems	IIT, VT	Old	Mathieu Joerger, Matthew Spenko	ACTIVE	October 01,2023	2023-2029	
10	Improving GNSS Resiliency Using Edge AI Solutions	CSU	New	Moussa Ayyash	ACTIVE	October 01,2024	2024-2026	
11	Development of a Generalized Integrity Monitoring Framework for CAV Applications	UCR	New	Matthew Barth	ACTIVE	October 01,2024	2024-2026	
12	Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications: Real-World Testing	UCR	New	Matthew Barth, Hang Qiu	ACTIVE	October 01,2024	2024-2026	
13	Resilient V2X Communication for Cooperative Autonomy	UCR	New	Hang Qiu	ACTIVE	October 01,2024	2024-2026	

This section provides a summary of each project's objectives, progress, completed activities, accomplishments, challenges encountered, and impact up to September 2025.

(1) GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation

Project's Objectives:

The project aims to enhance GNSS receiver resilience in transportation systems through multi-element antenna architectures—Controlled Reception Pattern Antennas (CRPAs), Dual Polarization Antennas (DPAs), and distributed patch antennas—developing detection and mitigation methods for jamming and spoofing using both simulated and live interference data.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025

Progress includes successful DPA integration with commercial receivers (Trimble BX992 and Novatel PwrPk7D), improved CRPA development using low-cost KrakenSDR arrays, and validation of spoofing detection methods through tests at Jammertest 2025 and Virginia Tech's blind multi-antenna analyses. Completed activities encompass DPA and CRPA testing, spoofing detection evaluations, and refinement of detection thresholds for distributed antennas. Key accomplishments involve demonstrating practical DPA use with commercial systems and advancing scalable spoofing detection methods. Challenges include limited CRPA sensitivity, phase inconsistencies in DPA results, and intermittent data dropouts. Overall, the project has established a foundation for effective, low-cost GNSS interference detection and mitigation, strengthening navigation reliability across transportation platforms.

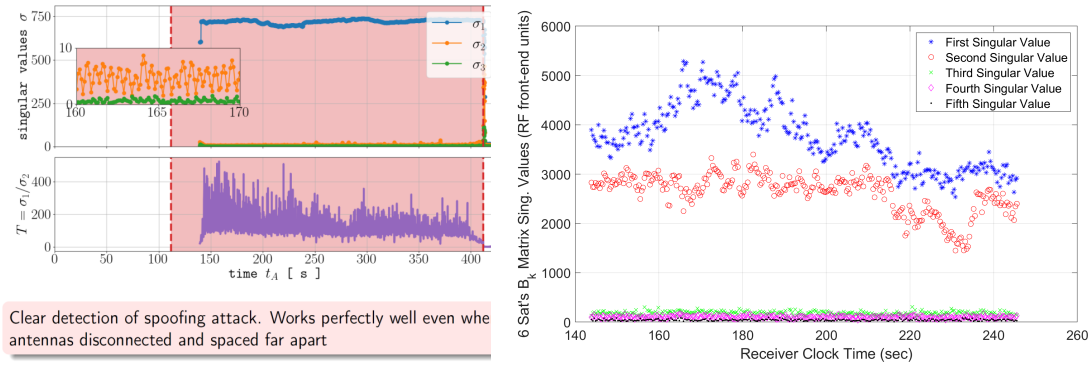


Figure 1. Blind spoofing test statistics indicate spoofing attacks in September 2024 Norway data (left-hand panel) and in July 2024 Israel data that features 2 spoofers (right-hand panel)

(2) Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks

Project's Objectives:

This project aims to enhance GNSS receiver resilience against spoofing and jamming through two complementary approaches. The first develops advanced signal autocorrelation monitoring methods to separate authentic, spoofed, and multipath signals, enabling detection even when spoofed signals are closely aligned in code delay and Doppler. The second employs Kalman filter–based carrier tracking to maintain phase lock during broadband interference. A new spoofing detection method using the Complex Cross Ambiguity Function (CCAF) further strengthens detection by exploiting carrier-phase differences that spoofers cannot replicate, advancing the security and reliability of GNSS systems for transportation and other critical applications.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Significant progress was made in refining the CCAF-based spoofing detection technique and validating it through both simulated and live RF experiments. The method demonstrated strength against multipath and closely aligned spoofers, aided by the introduction of a CCAF error-decorrelation process that mitigates thermal noise. Integration of the inverse RAIM (iRAIM) framework enabled the separation and independent tracking of authentic and counterfeit signal sets. Results were presented at PLANS 2025 (April), included in Ahmed's Ph.D. defense (May), and accepted for publication in IEEE Transactions on Aerospace and Electronic Systems (June 2025). In parallel, Kalman filter–based pilot tracking on GPS L1C and L5, supported by IMU data, showed promising performance—sustaining tracking through broadband jamming down to 4 dB-Hz with an industrial-grade IMU and to 0 dB-Hz with a tactical-grade unit. While early in development, this work represents an important step toward next-generation GNSS receivers capable of maintaining reliable positioning in contested and complex signal environments.

(3) Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration

Project's Objectives:

This project aims to enhance the integrity and resilience of navigation systems by developing detection and mitigation strategies for sophisticated spoofing scenarios and by assessing vulnerabilities in alternative sensing technologies such as LiDAR. The goal is to ensure reliable positioning and situational awareness in complex and contested environments where both GNSS and supporting sensors may be exposed to interference or deception.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Progress includes the development of an INS-aided monitor capable of detecting advanced spoofing attacks where counterfeit signals closely replicate authentic GNSS signals. An optimal detector was derived to exploit temporal structures in the innovations, with initial experimental results showing promising yet improvable performance. Identified challenges include conservative GNSS error modeling and vibration effects coupling into the IMU. These findings were presented at ION GNSS+ 2025 (September). In parallel, the team conducted a comprehensive assessment of LiDAR spoofing threats, focusing on integrity risks from laser-injection attacks and physical scene tampering that compromise feature-based localization. Preliminary results were presented at PLANS 2025 (April). Together, these efforts advance the understanding of multi-sensor vulnerabilities and support the development of more resilient, cross-referenced navigation architectures.

(4) Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks

Project's Objectives

This project focuses on developing and evaluating complementary Positioning, Navigation, and Timing (PNT) algorithms using Signals of Opportunity (SoOP) from Low Earth Orbit (LEO) satellites not originally designed for navigation, with applications in safety-critical transportation systems. It also aims to assess the performance of dedicated LEO satellite PNT systems and strengthen collaboration between CARNATIONS and industrial partners, Xona Space Systems and Iridium. The approach includes designing vehicle position and velocity estimation methods using time-sequenced Doppler measurements and Gauss-Markov models for motion and clock dynamics, eliminating the need for prior position knowledge in dynamic environments.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Significant progress was made in developing LEO satellite–based resilient PNT algorithms and evaluating them through simulations for air and ground transportation applications. In collaboration with Xona Space Systems, the team developed recursive integrity evaluation methods integrating GNSS and Xona "Pulsar" satellites, created new time-correlated measurement error models, and identified navigation performance requirements for uncrewed air vehicles and automated ground systems. They analyzed the worldwide accuracy, integrity, and availability of GNSS-only, Xona-only, and combined systems. In parallel, Doppler-only SoOP filters were designed to process fewer than eight LEO signals efficiently, supported by new geometric dilution of precision (GDOP) analysis for accuracy evaluation. The team also reverse-engineered repeatable components of Starlink Ku-band signals to enable precise Doppler shift measurements. Key accomplishments include defining integrity requirements for Xona's constellation,

improving industry collaboration, and advancing Doppler-based SoOP navigation methods. Challenges include experimental validation of LEO PNT algorithms and refinement of signal models, which will be the focus of the upcoming year. The project supported three Ph.D. students (one of whom graduated) and a postdoctoral researcher, resulting in multiple publications and fostering collaboration and knowledge exchange with industry experts.

(5) Towards Resilient V2X Communications over 5G/6G Networks: Sensing and Cooperative Perception

Project's Objectives:

This project aims to advance 5G and emerging 6G technologies to build secure, resilient, and low-latency vehicular networks. It focuses on improving reliability, synchronization, and threat mitigation in Vehicle-to-Everything (V2X) communications while exploring integrated sensing and communications (ISAC) and semantic communication for enhanced resilience.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Key progress includes developing a two-phase resilience framework for cellular V2X networks under imperfect channel state information (CSI), achieving up to 56% delay reduction and 16% throughput improvement. The team also demonstrated and mitigated new security threats in 6G ISAC systems using a neuro-symbolic AI detection approach, improving attack identification accuracy by over 50%. Additionally, a semantic communication microservice was created to preserve message meaning during degraded connectivity. The project identified key vulnerabilities in 6G sensing, proposed AI-based defenses, and advanced cooperative perception research. It supported one Ph.D. student, one M.S. student, and a VT-funded postdoctoral researcher, resulting in a completed thesis and multiple publications.

(6) Multi-vehicle/Infrastructure Jammer/Spoofer Detection and Localization

Completed September 30, 2024.

(7) Threat Models and Use Cases for Multimodal Transportation

Project's Objectives:

This project aims to extend aviation-based radio frequency interference (RFI) research to surface and multimodal transportation systems by analyzing cyber-physical threats such as jamming and spoofing. The objectives are to: (1) apply the aviation RFI knowledge base to identify and assess threats affecting connected and automated vehicle (CAV) and port operations, and (2) define representative jamming and spoofing

scenarios—including “closed-loop spoofing”—to evaluate the operational benefits of enhanced receiver under various attack conditions.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Between March and September 2025, the project achieved substantial progress in identifying, analyzing, and modeling GNSS interference events across multimodal transportation environments. Using the Stanford GPS Laboratory’s Automatic Dependent Surveillance–Broadcast (ADS-B)-based RFI localizer and low-cost GNSS RFI monitors (LCMs), the team improved algorithms and visualization tools on *rfi.stanford.edu* to map and assess global spoofing and jamming incidents. Analysis revealed trends toward multi-frequency and tiered attacks, where jamming and spoofing occur concurrently, and varying spoofing patterns that appear to target different types of users. Receiver testing at Jammertest 2024 and in Stanford laboratories demonstrated that commercial off-the-shelf (COTS) receivers, such as the ublox F9 series, employ cross-signal and cross-frequency aiding that influences how RFI manifest themselves—highlighting the need for more advanced, realistic threat models. To address this, the team proposed a modular framework for generating test scenarios that combine genuine and spoofed signals across multiple frequencies to flexibly simulate diverse attack conditions.

Figure 2. Map of identified spoof events and ADS-B locations (before spoofing) relevant to the RFI from rfi.stanford.edu

(8) R-PNT Virtual Conflict Simulation

Project's Objectives:

This project aims to simulate and analyze the effects of cyberattacks on transportation networks through *virtual conflict simulations* that integrate both offensive ("red-team") and defensive ("blue-team") strategies. The primary objective is to assess the resilience of transportation systems under spoofing-based cyberattacks by studying how routing algorithms respond to falsified traffic information and how such disruptions propagate across road networks.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Between March and September 2025, the project examined the impact of spoofing attacks on the QNET corridor road network under varying traffic demand levels. The attack was designed to manipulate routing data, diverting vehicles from the freeway to parallel arterials, which increased congestion and degraded network performance. Simulations revealed that the spoofing attack disrupted not only the directly targeted origin-destination (OD) trip but also multiple arterial-based trips, demonstrating cascading congestion effects. Analysis of 46 OD trips across 10 network zones showed that rerouted traffic caused persistent travel-time increases, with percentage changes ranging from -35.7% to +6.9% at low demand and up to +20% at full demand levels. Notably, while most trips experienced degradation, some benefited due to redistributed freeway traffic. These results highlight how localized spoofing can produce systemwide disruptions, emphasizing the importance of developing adaptive routing and cyber-defense mechanisms for resilient transportation systems.

(9) Comprehensive Testing and Evaluation of Resilient PNT Systems

Project's Objectives:

This project focuses on analyzing data from actual radio frequency interference (RFI) events and experimentally evaluating anti-jamming and anti-spoofing technologies developed by CARNATIONS. Due to legal restrictions on open-sky GNSS signal broadcasting, testing is limited to controlled environments such as anechoic chambers where the impacts of vehicle dynamics on RFI-detection cannot be evaluated. To overcome these limitations, the project utilizes crowd-sourced data from connected vehicles, aircraft receivers, and mobile devices to monitor RFI activity across the United States and internationally, supporting the development of practical mitigation solutions for transportation systems.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Key progress includes expanding crowd-sourced RFI monitoring, developing new online tools for interference prediction, and testing CARNATIONS' multi-sensor, multi-vehicle navigation systems. The team automated a live jamming prediction method using data from 900 U.S. Continuously Operating Reference Stations (CORS) and redeployed an alert web application, now hosted on OracleWS and available at *https://rfi.aoe.vt.edu/*. Field tests in collaboration with Inertial Lab demonstrated that GNSS can be effectively augmented with inertial navigation systems (INS), LiDAR, and vehicle-to-vehicle motion sharing. Plans are also underway to establish an anti-RFI testbed at Virginia Tech's Smart Roads, offering a safe environment for controlled RF testing. The project supports graduate students at Virginia Tech and Illinois Tech and has strengthened industry partnerships with TUALCOM and Spirent, who contributed a GSS 9000 simulator as a cost-share to CARNATIONS. Despite restrictions on open-air RF testing, the project continues to advance safe, data-driven approaches for analyzing and mitigating RFI impacts on transportation navigation systems.

(10) Improving GNSS Resiliency Using Edge AI Solutions

Project's Objectives:

This project aims to enhance Global Navigation Satellite System (GNSS) performance in environments where signals are weak or disrupted, such as urban canyons and indoor areas, through the integration of Edge Artificial Intelligence (Edge AI). By deploying low-power, compact edge devices capable of local processing, the project seeks to minimize latency, improve decision-making, and strengthen navigation resilience. Research areas include the use of Machine Learning (ML) and Deep Learning (DL) models to mitigate multipath interference and signal degradation, as well as multi-sensor fusion and hybrid positioning methods that combine GNSS with Wi-Fi, Bluetooth, LiDAR, and 5G technologies.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

From March to September 2025, the project achieved several milestones toward developing AI-driven hybrid GNSS frameworks. An advanced resiliency framework combining Reinforcement Learning (RL) and Factor Graph Optimization (FGO) was proposed for urban canyon environments, demonstrating improved mitigation of multipath and non-line-of-sight disruptions. A Deep Neural Network (DNN) model was also developed for GNSS resilience against spoofing and jamming, with results presented at the 2025 IEEE World Forum on Public Safety Technology. Additionally, the team began exploring Distributed Acoustic Sensing (DAS) for signal integrity assessment. The project established a foundational baseline for integrating Edge AI in cooperative, multi-modal GNSS systems. The main challenge remains identifying a

reliable simulation tool to validate the proposed Edge AI framework before large-scale implementation.

(11) Development of a Generalized Integrity Monitoring Framework for CAV Applications

Project's Objectives:

This project aims to develop and evaluate a Generalized Integrity Monitoring Framework for Connected and Automated Vehicle (CAV) applications by assessing the reliability of vehicle positioning under real conditions. It focuses on creating a SUMO–CARLA co-simulation platform featuring a digital twin of a smart intersection in Riverside, California, to test safety-critical scenarios such as illegal pedestrian crossings and occluded vehicle movements. The project also seeks to establish a unified integrity metric for evaluating the usability, reliability, and timeliness of information exchanged through Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, supporting safer and more dependable transportation operations.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

Between March and September 2025, the project successfully designed a digital twin of the Iowa–University Avenue intersection in Riverside, incorporating accurate lane geometry and calibration to map virtual coordinates to geodetic positions. The CARLA simulator was integrated with the NS3 network simulator to establish a Vehicle-to-Everything (V2X) communication framework, enabling foundational CAV functionality testing. The team completed the initial release of *CAV TESTS V1.0*, integrating SUMO, CARLA, and NS3 for comprehensive co-simulation. While key goals were achieved, challenges remain in managing the complexity of multi-platform synchronization and refining the digital twin with photorealistic, metrically accurate landmarks. Ongoing work focuses on improving simulation fidelity and expanding testing to mixed-traffic environments involving automated and connected vehicles.

(12) Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications: Real-World Testing

Project's Objectives:

This project aims to address cybersecurity vulnerabilities in Connected and Automated Vehicle (CAV) systems by investigating the effects of GNSS spoofing and jamming attacks and developing mitigation strategies. The goal is to understand how such attacks affect not only the targeted vehicle but also surrounding vehicles and critical subsystems such as sensors and communication modules. The project further seeks to enhance vehicle positioning integrity and communication resilience by utilizing Basic Safety Message (BSM) data for spoofing detection and cooperative defense.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

During the reporting period, the team modified its MK6 Vehicle-to-Vehicle (V2V) communication hardware to sustain operations under GNSS-denied conditions. A custom BSM Part 2 structure was developed to improve V2X resilience during spoofing and jamming events, including indicators for GNSS time loss, last valid timestamps, and inconsistent vehicle data. This system was successfully field-tested at the APEX25 experiment at White Sands Missile Range, where live jamming and spoofing conditions were evaluated over five nights. Data analysis showed reliable communication performance via C-V2X sidelink and effective clock drift estimation under interference. Challenges included limited access to spoofing environments and extended review timelines for Department of Defense (DoD) data release. Future efforts will focus on developing LiDAR-assisted V2V integrity monitoring, refining time synchronization protocols, and incorporating anomaly detection within BSM data to automatically flag inconsistent sensor or communication reports.

(13) Resilient V2X Communication for Cooperative Autonomy

Project's Objectives:

This project investigates the challenges faced by autonomous vehicles (AVs) in corner-case scenarios involving limited visibility or unpredictable conditions. It focuses on cooperative driving—where vehicles share sensor data—and remote driving, which allows human intervention when needed. Both applications rely on secure, low-latency, and high-bandwidth Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications via Cellular Vehicle-to-Everything (C-V2X). The objective is to strengthen the reliability and resilience of communication channels that support these advanced driving functions.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025:

From March to September 2025, the project achieved major milestones by collecting and publicly releasing the world's first C-V2X direct communication dataset, detailing real throughput, latency, and channel performance. The team expanded this work into *CooperScene*, a multi-agent, multi-modal CAV dataset with integrated C-V2X communication, targeted for submission to a top-tier conference in late 2025. Collaboration was also established with Virginia Tech to explore semantic communication for enhancing PNT resilience in cooperative and remote driving. Challenges included synchronization and calibration issues, as GNSS-based timing limited strength. To address this, the team began exploring GNSS-free synchronization using the Flooding Time Synchronization Protocol (FTSP). Additionally, a new calibration method, *BEVCalib*, was developed and published at CoRL (Conference on Robot

Learning) in September 2025, improving multi-modal sensor alignment and setting the stage for future research in GNSS-denied environments.

CARNATIONS Collaborative Endeavors

Between March 2025 and September 2026, CARNATIONS continued to strengthen collaboration across all levels of the Center, emphasizing both academic and industry engagement. Bi-monthly coordination calls were held, during which Principal Investigators and students presented updates on their respective projects, shared progress, and discussed cross-institutional synergies. These structured discussions facilitated a deeper exchange of ideas and ensured alignment with the Center's strategic objectives.

CARNATIONS demonstrated strong collaborative participation at several high-impact national and international conferences. Students and Principal Investigators presented their research at **ION PLANS 2025**, **CARNATIONS Days 2025**, **ION GNSS+ 2025**, **Association for Computing Machinery (ACM) 2025**, **Conference on Robot Learning (CoRL 2025)**, **IEEE World Forum on Public Safety Technology (WF-PST 2025)**, and the **International Conference on Robotics and Automation (ICRA 2025)**. The **CARNATIONS Days 2025** event particularly highlighted the Center's collective leadership, where teams showcased ongoing research and development to audiences from academia, industry, and government. Continuous meetings between subcommittees and industry partners further enhanced collaboration by encouraging feedback, exploring innovative concepts, and aligning research with everyday needs.

1.1.2. Leadership

During this reporting period, CARNATIONS continued to demonstrate leadership in Resilient Positioning, Navigation, and Timing (R-PNT) through its active participation in prominent conferences and strategic outreach. The collective efforts of students, Principal Investigators, and leadership at multiple conferences underscored the Center's visibility and thought leadership within the transportation research community.

At **CARNATIONS Days 2025**, the leadership team, faculty, and students collectively demonstrated the Center's growing influence by presenting their research outcomes and innovations to a diverse audience of academic experts, industry representatives, and government officials. The event exemplified CARNATIONS' ability to convene thought leaders and promote dialogue on the future of secure and resilient transportation systems. In parallel, the Executive Committee initiated an internal documentation campaign beginning in May 2025 to film and archive key project milestones. This effort aims to visually capture the scope and impact of CARNATIONS' research, enhance public understanding, and support technology transfer. Additionally, the Center maintained structured subcommittee meetings with industry partners and Advisory Board members, idea exchange, aligning goals, and ensuring that leadership decisions remain adaptive and forward-looking. Through these initiatives, CARNATIONS has

continued to solidify its reputation as a national leader advancing the resilience, safety, and innovation of transportation technologies.

1.1.3. Education and Workforce Development

During this reporting period, the Education and Workforce Development Subcommittee advanced CARNATIONS' academic and training initiatives by emphasizing experiential learning, inter-university collaboration, and active industry engagement. The subcommittee rebranded the ERT (Engineering Research Toolkit) as the REACH – Research Engagement and Collaboration Hub, which now serves as a central platform for applied R-PNT research. Through REACH, five projects have been launched to date, with four successfully completed and seven students engaged in research and implementation. A new project titled "Wrong-Way Driving and R-PNT ADAS-Based Navigation System," initiated in collaboration with the new industry partner SAINAV, was launched in September 2025, with two students beginning work in October 2025.

Building on the success of the Inter-University Course Initiative, the subcommittee reopened MMAE-555: Introduction to Navigation Systems for Fall 2025, enrolling 13 in-person and 2 online students, reflecting sustained academic interest across partner institutions. Under the leadership of Professor Matt Spenko, the subcommittee continued progress on a student competition first proposed in the previous reporting cycle, now being developed with industry support to offer students exposure to R-PNT challenges. Collectively, these efforts demonstrate measurable progress in expanding educational opportunities, strengthening academic–industry partnerships, and preparing a capable and innovative workforce for the future of resilient transportation systems.

1.1.4. Technology Transfer and Collaboration

The Technology Transfer Subcommittee has played a key role in advancing CARNATIONS' research outcomes through purposeful collaboration with industry and government stakeholders. Through its initiatives, the subcommittee has strengthened partnerships, expanded CARNATIONS' visibility within the PNT community, and accelerated the transition of research outcomes into practical applications. A major highlight of this reporting period was the successful organization of CARNATIONS Days 2025 at Virginia Tech, which brought together 55 participants in person and 12 participants online, representing academia, industry, government, and students. The event featured research presentations, interactive discussions, and project showcases, highlighting CARNATIONS' leadership in resilient transportation technologies. Dr. Andrew Hansen from the U.S. Department of Transportation served as the keynote speaker, providing valuable insights on advancing navigation resilience and innovation within the transportation sector. As part of this event, members of the subcommittee also conducted a site visit to the Virginia Tech Smart Roads testing facility, introducing participants to the concept and development plan for an anti-RFI testbed designed to support resilient navigation research. The Center also welcomed SAINAV as a new industry partner during this period, broadening its network of collaborators and expanding applied research capacity.

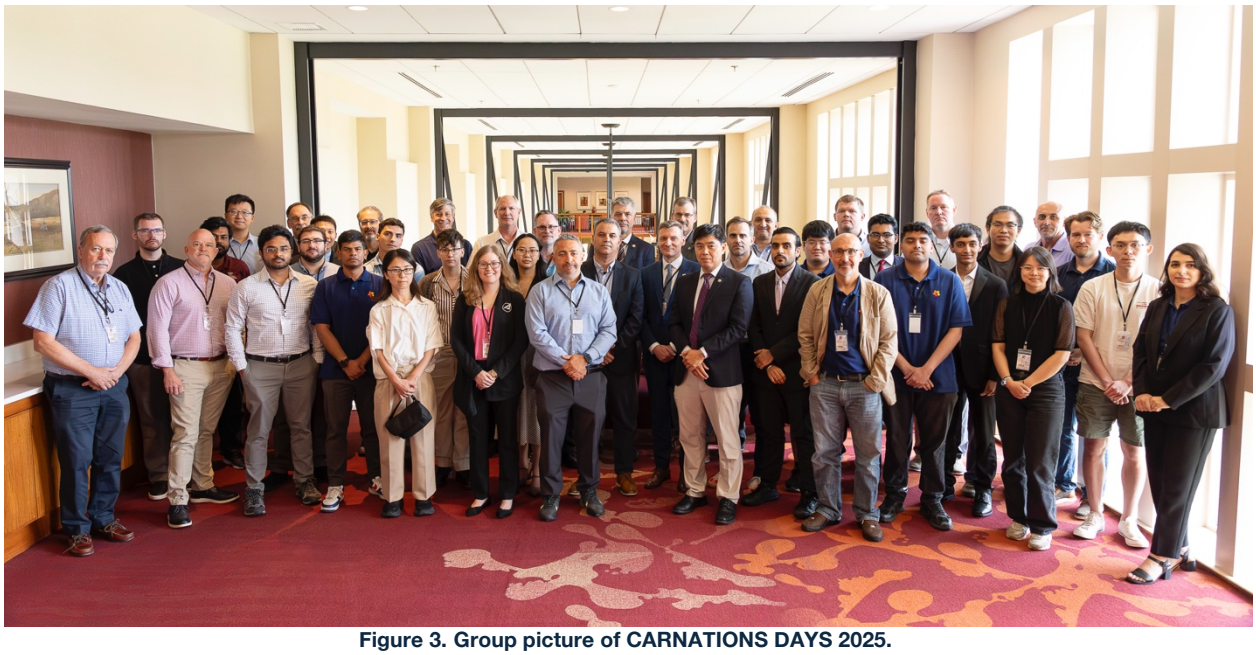


Figure 3. Group picture of CARNATIONS DAYS 2025.

In addition, the subcommittee facilitated individual meetings between the Technology Transfer Lead and industry partners during ION GNSS+ 2025, offering a focused forum to discuss ongoing collaborations, technology transition strategies, and future partnership opportunities. Other key achievements included the launch of the CARNATIONS Annual Magazine, documenting the Center's research accomplishments, and a comprehensive redesign of the CARNATIONS website to improve accessibility and engagement. CARNATIONS teams also participated in major experimental demonstrations, including APEX 2025 at White Sands, where the UCR team tested anti-jamming and anti-spoofing systems alongside government and industry participants, and Jammertest 2025 in Norway, where the Stanford team evaluated GNSS interference mitigation methods. The subcommittee is also developing outreach videos showcasing key projects and submitted a proposal titled "NavSentinel: A Resilient and Unspoofable GNSS Receiver" to ARPA-I, further demonstrating CARNATIONS' leadership in resilient PNT research and technology transition.

1.2. What was accomplished under these goals?

1.2.1 Research

Research Performance Metrics	Output September 2025
Number of new technologies, procedures/policies, and standards/design practices influenced by the research and adopted by organizations.	6
Number of research projects funded by sources other than UTC and matching fund sources.	8
Number of research articles presented in conferences and published in peer-reviewed journals.	64

1.2.2 Leadership

Leadership Performance Metrics	Output September 2025
Number of keynote speeches/invited presentations at academic and professional conferences.	9
Number of leadership positions in local, national, and international organizations.	40
Number of CARNATIONS-affiliated students in scholar and professional leadership positions.	8

1.2.3 Education and Workforce Development

Education/Workforce Development Performance Metrics	Output September 2025
Student enrollment numbers and grades in CARNATIONS courses.	87
Number of Webinars Organized	5
Number of Courses taught by CARNATIONS	4

1.2.4 Technology Transfer and Collaboration

Technology Transfer and Collaboration Performance Metrics	Output September 2025
Number of CARNATIONS research efforts successfully transferred to partners and stakeholders.	0
Number of new collaborative efforts between institutions formed because of CARNATIONS.	26
Number of CARNATIONS-affiliated patents.	1
Number of CARNATIONS-related students joining partners or collaborators.	3
Number of Outreach Events	10

1.3 How have the results been disseminated?

CARNATIONS continues to advance research dissemination through academic, technical, and stakeholder-driven initiatives, ensuring meaningful contributions to Resilient PNT innovation and workforce development.

Conference Presentations and Recognition

CARNATIONS researchers and students presented at leading venues during March-September 2025, including ION GNSS+, ION PLANS, IEEE GLOBECOM, IEEE ICC,

ICRA, IEEE WF-PST, Nordic Navigation Forum, ACM SenSys, and CoRL, advancing national discussions on resilient navigation, sensing, and transportation cybersecurity. In recognition of excellence, Ph.D. students Hasan Kinatas and Liam Carey received Best Presentation Awards at the Institute of Navigation's GNSS+ Conference for their research on spoofing detection and collaborative navigation. Both are advised by Dr. Mathieu Joerger.

- Carey, L., and M. Joerger. "CUSUM-Based Innovations Monitoring Against Spoofing Threats."
- Kinatas, H., and M. Joerger. "Experimental Evaluation of Collaborative Navigation Through Shared Motion Constraints During GNSS Interference."

Additionally, Liam Carey (Virginia Tech) was selected as the CARNATIONS Student of the Year, recognizing his outstanding contributions to resilient navigation research and leadership within the Center.

Internal Engagement

CARNATIONS continues to emphasize strong internal coordination and collaboration. Regular twice-a-month research meetings bring together principal investigators, graduate students, and staff to share progress, discuss challenges, and align on strategic objectives. These meetings serve as vital checkpoints for progress tracking and foster an environment of continuous innovation and problem-solving across partner institutions.

Education and Workforce

The reopening of previously offered inter-university courses reflects the program's success and growing interest in PNT education. *MMAE-555: Introduction to Navigation Systems* was reopened for Fall 2025 with strong enrollment, marking the continued demand for CARNATIONS-led academic programs. Additionally, the **CARNATIONS** Educational Webinar Series will resume in November 2025, serving as a platform for technical outreach and knowledge exchange among academia, industry, and government stakeholders. The REACH (Research Engagement and Collaboration Hub) has also expanded, with more industry-linked projects and student participation, offering research experience and fostering innovation across multiple partner institutions.

Outreach and Communications

To enhance visibility and stakeholder communication, CARNATIONS continues publishing its Quarterly Newsletter, a key medium highlighting research outcomes, student milestones, and field activities. The next issue is scheduled for December 2025, following two successful editions earlier this year. In addition, the CARNATIONS Annual Magazine 2025 was launched, showcasing the Center's achievements, ongoing projects, and collaborative partnerships. These publications, alongside expanded digital outreach and upcoming educational content, reinforce CARNATIONS' commitment to transparency, innovation, and leadership in resilient navigation and transportation research. As part of ongoing applied research, testing activities for Projects 12 and 13 were initiated at the Riverside Smart Intersection Test Site. These projects focus on

developing and validating integrity monitoring frameworks and cooperative communication strategies for Connected and Automated Vehicles (CAVs). The initiation of field testing marks a key step in translating research outcomes into performance validation. Together with continued outreach through publications, webinars, and educational materials, these initiatives reinforce CARNATIONS' commitment to innovation, transparency, and national leadership in resilient navigation and transportation research.

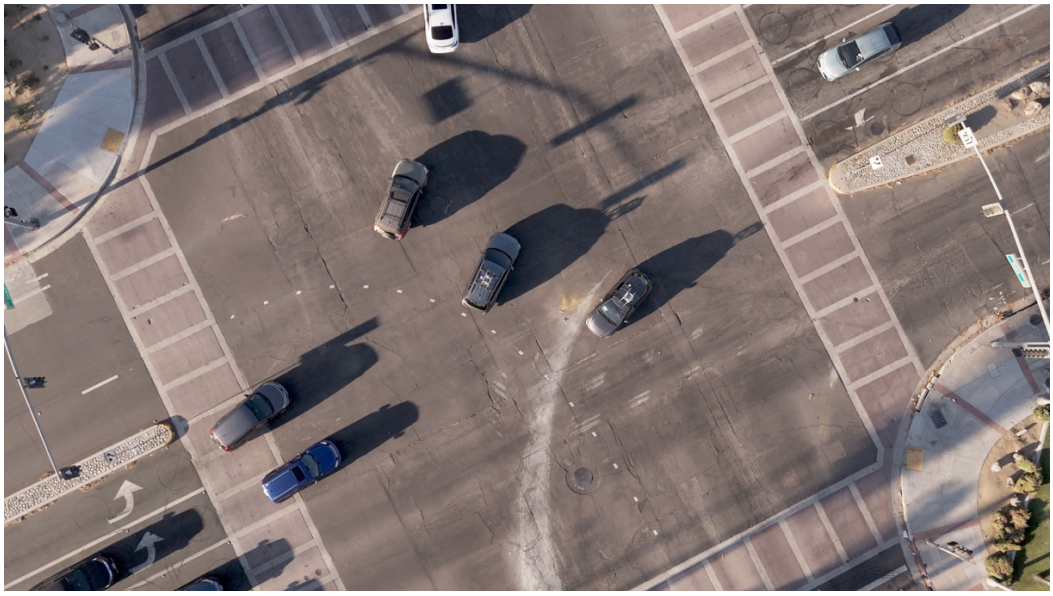


Figure 4. UCR Testing site where two cars are equipped with hardware on roof and communicating

1.3.1 What do you plan to do during the next reporting period to accomplish the goals?

During the next reporting period, CARNATIONS will focus on strengthening industry engagement, expanding field testing, and advancing the transition of research into applications. Efforts will include developing new relationships with industry partners, launching Newsletter Issue 3, and delivering presentations at major upcoming events, including the UTC Directors' Meeting in Washington, D.C. (January 2026) and ION ITM 2026, IEEE, etc. The Center also plans to initiate field testing at the UCR Smart Intersection, expanding ongoing work on Projects 12 and 13, while extending testing capabilities at Virginia Tech's Smart Roads. A key goal is to open these testing sites to external collaborators, allowing broader participation from government, academia, and industry to accelerate innovation and technology validation.

Additionally, CARNATIONS will begin a new project titled "Develop and Test Optimal Speed Control Strategies for Connected and Automated Vehicles under GPS Jamming and Spoofing." This initiative aims to strengthen system resilience in degraded navigation areas. CARNATIONS also plans, subject to USDOT approval, to co-host a joint panel with CARMEN+ at ION ITM 2026 (January 2026). Both UTCs fall under the

cybersecurity theme, and the symposium will provide a collaborative platform to showcase ongoing research, share insights, and explore future partnership opportunities. The IIT team also plans to represent the Center at NavFest 2026 (February–March 2026), a government-organized event that provides a unique platform for testing technologies under live jamming and spoofing conditions. Collectively, these activities will expand CARNATIONS' operational reach, enhance collaboration, and advance the Center's leadership in resilient positioning, navigation, and timing research.

2 PARTICIPANTS & COLLABORATING ORGANIZATIONS

2.1 What organizations have been involved as partners?

CARNATIONS has established strong partnerships with leading universities, industry organizations, and government agencies to advance research and innovation in Resilient Positioning, Navigation, and Timing (R-PNT) technologies. These collaborations provide vital technical expertise, data resources, and testing support, ensuring the practical application and transition of research outcomes to systems. The consortium includes five academic institutions — Illinois Institute of Technology (Boris Pervan, Samer Khanafseh, and Matthew Spenko), Virginia Tech (Mathieu Joerger, Mark Psiaki, Hesham Rakha, and Walid Saad), University of California, Riverside (Matthew Barth and Hang Qiu), Chicago State University (Mousa Ayyash), and Stanford University (Todd Walter, Sherman Lo, and Sam Pullen).

CARNATIONS also maintains active engagement with 42 industry and government partners, including TuSimple, UrsaNav, TORC, DOT, Xona Space, Spirent, Bosch, Trimble, MITRE, SAE, Hexagon, Satelles, Aeva, IS4S, VOLPE (DOT), CA DOT, Port of Long Beach, Qualcomm, The Aerospace Corporation, ILAV Association, Motional, FAA, Qunav, Oroliads, Seoul National University, DLR, Aero, StarNav, Collins Aerospace (RTX), VectorNav, Corvus Labs, TruNav, the International Telecommunication Union, and the newest partner SaiNav. These alliances play a pivotal role in supporting CARNATIONS' mission to develop and deploy resilient PNT solutions that strengthen national transportation systems and ensure secure, and efficient navigation across all modes.

2.2 Have other collaborators or contacts been involved?

CARNATIONS strengthened collaboration across academia, industry, and government through conferences, meetings, and technical exchanges. A total of 67 participants joined CARNATIONS Days 2025, promoting active engagement and research exchange. Technology transfer meetings during ION GNSS+ 2025 and follow-up calls advanced project discussions and future collaborations. Additionally, one new member joined the network during CARNATIONS Days, expanding the Center's collaborative reach.

3 OUTPUTS

3.1 Publications, Conferences, and Presentations

Journal Papers, ***Conference Papers, Presentations, and Submissions***

(1) Ahmed, S., Khanafseh, S., & Pervan, B. GNSS spoofing detection and exclusion by decomposition of the complex cross ambiguity function with INS aiding. In Proceedings of ION GNSS+, Denver, CO. September 2023. Federal support acknowledged.
(2) Joerger, M., Jada, S., Yan, C., Psiaki, M., & Bowman, J. Resilient PNT for safe transportation. AUVSI Symposium, Blacksburg, VA. October 2023. Federal support acknowledged.
(3) Hu, W., Uwineza, J.-B., & Farrell, J. A. Outlier accommodation for multi-GNSS precise point positioning using risk-averse performance-specified approach. Accepted to American Control Conference (ACC), January 2024.
(4) Nagai, K., Ahmed, S., & Pervan, B. Integrity with LiDAR incorrect extraction faults in adverse weather conditions. In Proceedings of the 2024 International Technical Meeting of the Institute of Navigation, Long Beach, CA. January 2024. Federal support acknowledged.
(5) Saswat, P. Infrastructure-assisted cooperative state estimation via augmentation of asynchronous kinematic measurements. ION ITM, Long Beach, CA. January 2024.
(6) Saswat, P. Feasibility studies on CAV applications with state uncertainties: A survey. IEEE FISTS. February 2024.
(7) Nagai, K., Spenko, M., Henderson, R., & Pervan, B. Fault-free integrity and continuity for driverless urban vehicle navigation with multi-sensor integration: A case study in downtown Chicago. NAVIGATION, 71(1), March 2024. Federal support acknowledged.
(8) Kujur, B., Khanafseh, S., & Pervan, B. Optimal INS monitor for GNSS spoofer tracking error detection. NAVIGATION, 71(1), March 2024. Federal support acknowledged.
(9) Ayyash, M. Jamming-resilient mirror element allocation scheme for OIRS-aided UAV-based FS networks. IEEE Transactions on Intelligent Vehicles, March 2024. https://doi.org/10.1109/TIV.2024.3450191
(10) Joerger, M., & Jada, S. Impacts of GNSS interference on CAVs. ERASMO, UTC France. March 2024. Federal support acknowledged.
(11) Hu, W., Mohsenian-Rad, H., & Farrell, J. A. Optimization-based outlier accommodation for CAV state estimation. Submitted to IEEE Transactions on Vehicular Technology. March 2024.
(12) Hu, W., Jiang, Z., Mohsenian-Rad, H., & Farrell, J. A. Convex reformulation of risk-averse state estimation with binary variables. Submitted to the CDC. March 2024.
(13) Andrei, V., Djuhera, A., Li, X., Monich, U., Boche, H., & Saad, W. Resilient, federated large language models over wireless networks: Why the PHY matters. Submitted to IEEE GLOBECOM. April 2024.
(14) Nagai, K. Fault-free integrity of urban driverless vehicle navigation with multi-sensor integration: A case study in downtown Chicago. ION Webinar. April 2024. Federal support acknowledged.

(15) Zixi, L. An automated pipeline for detection and localization of GNSS interference sources. Aerospace UPP Conference. April 2024.
(16) Anargyros, K. Low-cost GNSS monitors for RFI detection. Aerospace UPP Conference. April 2024.
(17) Ayyash, M. Jamming attacks on FSO networks: Challenges, opportunities, and a public safety use-case. IEEE WF-PST. May 2024.
(18) Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., Boche, H., & Saad, W. Resilient, federated large language models over wireless networks: Why the PHY matters. In Proceedings of IEEE ICC Workshop, Denver, CO. June 2024.
(19) Rife, J., Wassaf, H., Khanafseh, S., & Pervan, B. Fundamental architectures for high-integrity georeferenced LiDAR positioning. In Proceedings of ION GNSS+, Baltimore, MD. September 2024. Federal support acknowledged.
(20) Stas, M. Optimization-based outlier accommodation for tightly coupled RTK-aided inertial navigation systems in urban environments. IEEE ITSC, Edmonton, Canada. September 2024.
(21) Becker, J., & Joerger, M. Uncertainty quantification for radar/inertial pose estimation in GNSS-denied areas. ION GNSS+, Baltimore, MD. September 2024. Federal support acknowledged.
(22) Joerger, M., & Hassani, A. Wrong association risk bounding using innovation-projections for landmark-based LiDAR localization. ION GNSS+, Baltimore, MD. September 2024.
(23) Nagai, K., & Pervan, B. Integrity with LiDAR positioning: Case studies in automatic feature extraction. ION GNSS+, Baltimore, MD. September 2024. Federal support acknowledged.
(24) Nagai, K., & Pervan, B. Enhanced integrity of LiDAR localization: A study on feature extraction techniques. ION GNSS+, Baltimore, MD. September 2024. Federal support acknowledged.
(25) Moore, M. O., Psiaki, M. L., & Buehrer, R. M. Time-diverse Doppler-only LEO PNT: Initial solution. ION GNSS+, Baltimore, MD. September 2024.
(26) Shui, T., & Saad, W. Design and analysis of resilient vehicular platoon systems over wireless networks. In Proceedings of IEEE GLOBECOM. December 2024.
(27) Shelim, R., Saad, W., & Ramakrishnan, N. Fast geometric learning of MIMO signal detection over Grassmannian manifolds. In Proceedings of IEEE GLOBECOM. December 2024.
(28) Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., Saad, W., & Boche, H. Resilient, federated large language models over wireless networks: Why the PHY matters. In Proceedings of IEEE GLOBECOM. December 2024.
(29) Ahmed, S., Khanafseh, S., & Pervan, B. Uncovering subtle GNSS spoofing via cross ambiguity decomposition. IEEE Transactions on AES. December 2024. Federal support acknowledged.
(30) Chen, Y. H., Liu, Z., Kriezis, A., Lo, S., & Walter, T. Combining ADS-B, LCM, and DPA for GNSS jammer detection. ION ITM, Long Beach, CA. January 2025.
(31) Kujur, B., Khanafseh, S., & Pervan, B. Performance of optimal INS monitor against live spoofing. ION ITM, Long Beach, CA. January 2025. Federal support acknowledged.

(32) Chen, Y. H., Liu, Z., Kriezis, A., Lo, S., & Walter, T. Interference detection in massive GNSS jammer test. ION ITM, Long Beach, CA. January 2025.
(33) Lo, S., Liu, Z., Ibrahim, L., Chen, Y. H., & Walter, T. Observations of GNSS spoofing in Russia, 2023–2024. ION ITM, Long Beach, CA. January 2025.
(34) Kriezis, A., Chen, Y. H., Akos, D., Lo, S., & Walter, T. Real-world spoofing detection with low-cost receivers. ION ITM, Long Beach, CA. January 2025.
(35) Kriezis, A., Chen, Y. H., Lo, S., Walter, T., Pullen, S., & Akos, D. Low-cost receiver RF interference analysis. Inside GNSS. March 2025.
(36) Lo, S. Jammertest 2024 Results & Lessons Learned. Findings from Jammertest 2024 at General Assembly of the Nordic Navigation Forum, April 2025.
(37) Ahmed, S., Khanafseh, S., & Pervan, B. Experimental validation for GNSS spoofing detection by decomposition of the complex cross ambiguity function. Proceedings of IEEE/ION PLANS 2025, Salt Lake City, UT, April 2025.
(38) Nemana, M., Nagai, K., Khanafseh, S., & Pervan, B. Exploring LiDAR resilience: A review of spoofing threats in autonomous driving. Proceedings of IEEE/ION PLANS 2025, Salt Lake City, UT, April 2025.
(39) Moore, M. O., Psiaki, M. L., & Buehrer, R. Analysis of Time-Diverse Doppler-Only LEO PNT. IEEE/ION PLANS 2025, Salt Lake City, UT, April 2025.
(40) Kuwada, S., Joerger, M., & Spenko, M. Fault detector sensitivity in centralized collaborative localization. IEEE/ION PLANS 2025, Salt Lake City, UT, April 2025.
(41) Ahmed, S. GNSS Spoofing Detection and Exclusion Using Decomposition of the Complex Cross Ambiguity Function (CCAF). Ph.D. Oral Defense, May 2025.
(42) Mo, R., Wu, B., & Qiu, H. SEE-V2X: C-V2X Direct Communication Dataset – An Application-Centric Approach. ACM SenSys, May 2025.
(43) Kuwada, S., Joerger, M., & Spenko, M. Integrity Monitoring for Centralized Connected Autonomous Vehicles Localization. International Conference on Robotics and Automation (ICRA 2025), Atlanta, GA.
(44) Ahmed, S., Khanafseh, S., & Pervan, B. Uncovering Subtle GNSS Spoofing by Decomposing the Complex Cross Ambiguity Function. IEEE Transactions on Aerospace and Electronic Systems, accepted June 2025.
(45) Joerger, M., Hassani, A., Spenko, M., & Becker, J. Data Association Using Innovation-Projections for Landmark-Based LiDAR Localization. NAVIGATION: Journal of the Institute of Navigation, 2025.
(46) Hassani, A., & Joerger, M. Spherical Grid-Based IMU/LiDAR Localization and Uncertainty Evaluation Using Signal Quantization. NAVIGATION: Journal of the Institute of Navigation, 2025.
(47) Racelis, D. Advanced Receiver Autonomous Integrity Monitoring for Multi-Constellation GNSS and LEO-Augmented GNSS. Ph.D. Dissertation, Virginia Tech, July 2025.
(48) QoS-Enabled Wireless Split Federated Learning: A Reinforcement Learning and Optimization Approach. IEEE Transactions on Consumer Electronics, July 2025. DOI: 10.1109/TCE.2025.3587176
(49) Multi-Stage Enhanced Zero Trust Intrusion Detection System for Unknown Attack Detection in Internet of Things and Traditional Networks. ACM Transactions on Privacy and Security, August 2025. https://doi.org/10.1145/3725216

(50) Babcock-Chi, J., Lo, S., Chen, Y.-H., Blanch, J., & Walter, T. TDOA-Based Spoofing Source Localization Using Multi-Constellation Unsynchronized Receivers. Proceedings of ION GNSS+ 2025, Baltimore, MD, September 2025. https://doi.org/10.33012/2025.20369
(51) Beatty, D., & Psiaki, M. L. Blind Multi-Vehicle GNSS Spoofing Detection with Extended Baselines. Proceedings of ION GNSS+ 2025, Baltimore, MD, September 2025. https://doi.org/10.33012/2025.20287
(52) Kujur, B., Khanafseh, S., & Pervan, B. Performance of Optimal INS Monitor Against Jamming-Then-Spoofing Scenarios. Proceedings of ION GNSS+ 2025, Baltimore, MD, September 2025.
(53) Wang, S., Racelis, D., & Joerger, M. Integrity Analysis of GNSS/LEO Positioning Using Range and Doppler Measurements. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(54) Psiaki, M. L. The Why & the How of Research into LEO-Based Signals of Opportunity. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(55) Psiaki, M. L. A Generalized GDOP Analysis for PNT that Requires Sequential Filtering. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(56) Carey, L., Langel, S., & Joerger, M. CUSUM-Based Innovations Monitoring Against Spoofing Threats. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(57) Kinatas, H., & Joerger, M. Experimental Evaluation of Collaborative Navigation Through Shared Motion Constraints During GNSS Interference. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(58) Marti, M., & Joerger, M. Kalman Filter Integrity Monitoring Over Finite Time Intervals. Proceedings of ION GNSS+ 2025, Baltimore, MD, 2025.
(59) Enhancing GNSS Resiliency Against Spoofing and Jamming Employing Deep Neural Networks. IEEE World Forum on Public Safety Technology (WF-PST 2025), September 2025.
(60) Nayak, S. P., & Barth, M. The Role of Integrity Monitoring in Connected and Automated Vehicles: Current State of Practice and Future Directions. IEEE Intelligent Transportation Systems Magazine, 2025. https://doi.org/10.1109/MITS.2025.3589632
(61) DeRieux, J.-L. Artificial Intelligence (AI)-Based Semantic Communications with Multimodal Data: Framework and Implementation. M.S. Thesis, Virginia Tech, 2025.
(62) Shui, T., Saad, W., & Chen, M. Sensing Safety Analysis for Vehicular Networks with Integrated Sensing and Communication (ISAC). IEEE Global Communications Conference (GLOBECOM), 2025.
(63) Yuan, W., Li, J., Yue, J., Shah, D., & Qiu, H. BEVCALIB: LiDAR-Camera Calibration via Geometry-Guided Bird's-Eye View Representations. Conference on Robot Learning (CoRL), September 2025.

3.2 Website(s) or other Internet site(s)

CARNATIONS maintains an active online presence through its updated website, which

shares research progress, events, and milestones. During this period, the site was refreshed to enhance accessibility and engagement. The Center launched its 2025 Annual Magazine, showcasing major achievements and collaborations, and began producing a documentary series highlighting key research milestones, to be released on its YouTube channel after approval.

3.3 Technologies or techniques

Nothing to report.

3.4 Inventions, patent applications, and/or licenses

Nothing to report.

4 OUTCOMES

During this reporting period, CARNATIONS achieved measurable progress in advancing resilient Positioning, Navigation, and Timing (R-PNT) research, education, and technology transfer. Key outcomes include: CARNATIONS introduced and initiated testing at two testing sites: the Virginia Tech Smart Roads testing facility and the University of California, Riverside (UCR) Smart Intersection. These sites represent critical milestones in transitioning from simulation-based validation to experimentation, supporting testing of anti-RFI systems, spoofing and jamming resilience, and connected vehicle integrity frameworks.

The Center strengthened collaboration across 42 industry and government partners, expanding joint applied research, data collection, and field deployment opportunities. Research outcomes continued to align with CARNATIONS' three-pillar strategy of Toughen, Augment, and Protect, delivering validated simulation tools, spoofing detection algorithms, and early-stage field results. Workforce development also advanced significantly, with new students joining applied projects through the REACH (Research Engagement and Collaboration Hub) platform, the reopening of the inter-university course: *Introduction to Navigation Systems* for Fall 2025, and national recognition of student excellence. Outreach activities expanded through the launch of the CARNATIONS Annual Magazine 2025, the website redesign, and the initiation of a documentary project showcasing key milestones, further amplifying the Center's visibility and national leadership in resilient navigation and transportation research.

5 IMPACTS

5.1 What is the impact on the effectiveness of the transportation system?

The research, testing, and outreach activities conducted by CARNATIONS during this reporting period (March 2025 to September 2025) have substantially advanced the effectiveness of the transportation system. By developing and validating Resilient Positioning, Navigation, and Timing (R-PNT) technologies, the Center continues to enhance transportation safety, reliability, and efficiency—particularly for connected and

automated vehicles (CAVs). New testing initiatives at the Virginia Tech Smart Roads and UC Riverside Smart Intersection sites have marked a transition from simulation to validation, allowing researchers to analyze how spoofing, jamming, and signal degradation affect vehicle coordination and navigation integrity. These advancements directly contribute to improving transportation system resilience against interference and cyber threats.

CARNATIONS' active collaboration with industry and government organizations such as DOT, SAE, and Spirent has strengthened the practical application of research findings. The integration of multi-sensor fusion, cooperative positioning, and AI-based detection frameworks is improving communication stability and navigation safety across connected systems. The dissemination of findings through national conferences, educational initiatives, and professional training—along with tools developed under the REACH program—ensures that students, engineers, and decision-makers gain access to the latest advancements in resilient PNT technologies. Collectively, these efforts are paving the way for safer, smarter, and more secure transportation networks nationwide.

5.2 What is the impact of technology transfer on industry and government entities, on the adoption of new practices, or on research outcomes that have led to initiating a start-up company?

The impact of technology transfer on industry, government entities, and the adoption of new practices has been significant during this reporting period. Through the Technology Transfer Subcommittee and the CARNATIONS Advisory Board (CAB).

(1) **Advancing Applied Collaboration:** Strong engagement with partners such as Spirent, Trimble, Satelles, SAE, DOT, Volpe, and SaiNav has driven the adoption of resilient navigation and anti-spoofing practices. One-on-one sessions during ION GNSS+ 2025 and CARNATIONS Days helped industry teams refine testing and system integration.

(2) **Practical Testing and Validation:** Demonstrations at the Virginia Tech Smart Roads and UC Riverside Smart Intersection sites enabled validation of anti-jamming and spoofing technologies, connecting academic innovation with operational testing.

(3) **Standardization and Best Practices:** CARNATIONS continued efforts toward developing harmonized threat models and frameworks that promote interoperability and R-PNT standardization across sectors.

(4) **Expanding Industry Engagement:** The addition of SaiNav through the REACH platform created new opportunities for students and strengthened collaborative, industry-driven research.

Overall, these initiatives demonstrate CARNATIONS' growing impact in translating research into applications, enhancing national transportation safety.

5.3 What is the impact on the body of scientific knowledge?

Over the 2025 reporting period (March–September 2025), CARNATIONS-supported research has made significant contributions to the fields of resilient navigation,

positioning, intelligent transportation systems, and wireless communications. The publications and presentations during this period collectively enhance safety, integrity, and resilience in Positioning, Navigation, and Timing (PNT) systems, while also demonstrating strong interdisciplinary collaboration and application impact.

5.3.1. Enhancing Safety and Integrity in Navigation Systems

Recent studies advanced methodologies to ensure continuity and reliability in autonomous and connected navigation.

- Beatty, D., & Psiaki, M. L. (2025). *Blind Multi-Vehicle GNSS Spoofing Detection with Extended Baselines. ION GNSS+ 2025*, Baltimore, MD. https://doi.org/10.33012/2025.20287. Introduces a cooperative multi-vehicle spoofing detection framework for enhanced situational awareness.
- Babcock-Chi, J., Lo, S., Chen, Y.-H., Blanch, J., & Walter, T. (2025). *TDOA-Based Spoofing Source Localization Using Multi-Constellation Unsynchronized Receivers. ION GNSS+ 2025*, Baltimore, MD. https://doi.org/10.33012/2025.20369. Proposes a localization technique improving detection accuracy across GNSS constellations.
- Kujur, B., Khanafseh, S., & Pervan, B. (2025). *Performance of Optimal INS Monitor Against Jamming-Then-Spoofing Scenarios. ION GNSS+ 2025*, Baltimore, MD. Federal support acknowledged. Enhances integrity monitoring for hybrid navigation systems.
- Ahmed, S., Khanafseh, S., & Pervan, B. (2025). *Uncovering Subtle GNSS Spoofing by Decomposing the Complex Cross Ambiguity Function. IEEE Transactions on Aerospace and Electronic Systems*, accepted June 2025. Introduces detection for low-level spoofing threats.
- Nayak, S. P., & Barth, M. (2025). *The Role of Integrity Monitoring in Connected and Automated Vehicles: Current State of Practice and Future Directions. IEEE Intelligent Transportation Systems Magazine.* https://doi.org/10.1109/MITS.2025.3589632. Discusses integrity assurance frameworks for autonomous vehicle safety.

Together, these publications strengthen the theoretical and applied basis for reliable, interference-resilient navigation.

5.3.2. Innovative Detection and Resilience Techniques

Research introduced new algorithms and experimental methods to detect, localize, and mitigate interference.

- Lo, S. (2025). *Jammertest 2024 Results & Lessons Learned. Nordic Navigation Forum General Assembly*, April 2025. Provides insights into large-scale jamming test environments.
- Ahmed, S., Khanafseh, S., & Pervan, B. (2025). *Experimental Validation for GNSS Spoofing Detection by Decomposition of the Complex Cross Ambiguity Function. IEEE/ION PLANS 2025*, Salt Lake City, UT, April 2025. Federal support

acknowledged. Validates the performance of cross-ambiguity-based spoofing detection.

- Nemana, M., Nagai, K., Khanafseh, S., & Pervan, B. (2025). *Exploring LiDAR Resilience: A Review of Spoofing Threats in Autonomous Driving. IEEE/ION PLANS 2025*, Salt Lake City, UT. Summarizes spoofing vulnerabilities in autonomous vehicle LiDAR systems.
- Moore, M. O., Psiaki, M. L., & Buehrer, R. (2025). *Analysis of Time-Diverse Doppler-Only LEO PNT. IEEE/ION PLANS 2025*, Salt Lake City, UT. pp. 782–787. Explores LEO-based Doppler signals for improved PNT strength.
- Kinatas, H., & Joerger, M. (2025). *Experimental Evaluation of Collaborative Navigation Through Shared Motion Constraints During GNSS Interference. ION GNSS+ 2025*, Baltimore, MD. Demonstrates cooperative navigation resilience.
- Marti, M., & Joerger, M. (2025). *Kalman Filter Integrity Monitoring Over Finite Time Intervals. ION GNSS+ 2025*, Baltimore, MD. Improves short-duration state estimation for integrity assurance.

These results expand the state of knowledge in current interference detection and network-based PNT resilience.

5.3.3. Real-World Applications and Case Studies

Several studies validated CARNATIONS-developed methods in field and simulation-based environments.

- Kriezis, A., Chen, Y. H., Lo, S., Walter, T., Pullen, S., & Akos, D. (2025). *Low-Cost Receiver RF Interference Analysis. Inside GNSS*, March 2025. Assesses interference mitigation performance in commercial receivers.
- Kujur, B., Khanafseh, S., & Pervan, B. (2025). *Performance of Optimal INS Monitor Against Live Spoofing. ION ITM 2025*, Long Beach, CA. Federal support acknowledged. Evaluates spoofing resilience using integrated navigation.
- Ahmed, S. (2025). *GNSS Spoofing Detection and Exclusion Using Decomposition of the Complex Cross Ambiguity Function (CCAF). Ph.D. Oral Defense*, May 2025. Presents an experimentally validated spoofing detection architecture.
- Racelis, D. (2025). *Advanced Receiver Autonomous Integrity Monitoring for Multi-Constellation GNSS and LEO-Augmented GNSS. Ph.D. Dissertation*, Virginia Tech, July 2025. Develops advanced RAIM frameworks for multi-sensor systems.
- Lo, S., Liu, Z., Ibrahim, L., Chen, Y. H., & Walter, T. (2025). *Observations of GNSS Spoofing in Russia, 2023–2024. ION ITM 2025*, Long Beach, CA. Documents spoofing occurrences to inform future mitigation.

These works demonstrate operational readiness and empirical validation of CARNATIONS-developed PNT technologies.

5.3.4. Cross-Disciplinary Research and Collaboration

Integrating navigation, AI, and wireless networks, several works expanded collaboration between communications and navigation communities.

- Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., & Saad, W. (2025). *Resilient, Federated Large Language Models over Wireless Networks: Why the PHY Matters. IEEE GLOBECOM 2025.* Examines wireless layer effects on distributed AI resilience.
- *QoS-Enabled Wireless Split Federated Learning: A Reinforcement Learning and Optimization Approach. IEEE Transactions on Consumer Electronics*, July 2025. DOI: 10.1109/TCE.2025.3587176. Integrates learning-based optimization in federated networks.
- *Multi-Stage Enhanced Zero Trust Intrusion Detection System for Unknown Attack Detection in IoT and Traditional Networks. ACM Transactions on Privacy and Security*, August 2025. https://doi.org/10.1145/3725216. Improves detection of zero-day network intrusions.
- DeRieux, J.-L. (2025). *AI-Based Semantic Communications with Multimodal Data: Framework and Implementation. M.S. Thesis*, Virginia Tech. Proposes semantic-aware communication for connected vehicles.

These studies bridge communications, AI, and transportation research, promoting cross-sector innovation.

5.3.5. Informing Policy and Standards

Research outcomes guided evolving navigation standards and safety frameworks.

- Ayyash, M. (2025). *Enhancing GNSS Resiliency Against Spoofing and Jamming Employing Deep Neural Networks. IEEE World Forum on Public Safety Technology (WF-PST 2025).* September 2025. Introduces AI-based interference mitigation supporting safety standards.
- Nayak, S. P., & Barth, M. (2025). *The Role of Integrity Monitoring in Connected and Automated Vehicles. IEEE Intelligent Transportation Systems Magazine.* Offers policy-aligned insights for vehicle monitoring frameworks.

These studies influence technical standards for transportation safety, public safety communications, and PNT resilience.

5.3.6. Foundation for Future Research

CARNATIONS research provides a foundation for next-generation resilient and AI-integrated navigation systems.

- Psiaki, M. L. (2025). *The Why & the How of Research into LEO-Based Signals of Opportunity. ION GNSS+ 2025*, Baltimore, MD. Defines opportunities for LEO-based navigation.
- Wang, S., Racelis, D., & Joerger, M. (2025). *Integrity Analysis of GNSS/LEO Positioning Using Range and Doppler Measurements. ION GNSS+ 2025*, Baltimore, MD. Explores multi-orbit integration for resilient positioning.
- Yuan, W., Li, J., Yue, J., Shah, D., & Qiu, H. (2025). *BEVCALIB: LiDAR-Camera Calibration via Geometry-Guided Bird's-Eye View Representations. Conference on Robot Learning (CoRL 2025).* Advances sensor calibration in autonomous systems.

- Mo, R., Wu, B., & Qiu, H. (2025). *SEE-V2X: C-V2X Direct Communication Dataset – An Application-Centric Approach. ACM SenSys 2025.* Provides benchmark data for vehicle communication studies.

These works outline the trajectory of future resilient PNT research integrating AI, LEO, and sensor fusion.

5.4 What is the impact on transportation workforce development?

The Education and Workforce Development Subcommittee continues to strengthen the transportation workforce by cultivating skilled professionals equipped to advance Positioning, Navigation, and Timing (PNT) technologies. Key initiatives include:

- **Internships and Employment Opportunities:** The CARNATIONS job portal connects students with industry positions, bridging academic learning and practical experience.
- **Workshops and Seminars:** Joint events with industry and government partners foster knowledge exchange and exposure to emerging technologies.
- **Industry-Driven REACH Projects:** Students engage with challenges, gaining experience that enhances their problem-solving and readiness for industry roles.
- **Expanded Courses and Training:** Specialized PNT courses ensure students develop advanced technical and analytical skills.
- **Industry Collaboration:** Strengthened partnerships promote technology transfer, research collaboration, and workforce innovation.
- **Newsletter and Annual Magazine:** These platforms sustain engagement by sharing research highlights, opportunities, and updates with the broader transportation community.
- **Student Competitions:** Center-level competitions encourage creativity, innovation, and teamwork through practical applications.

6 CHANGES/PROBLEMS

During this reporting period, several updates were implemented to better align project titles and tools with ongoing research objectives. The *Engineering Research Toolkit (ERT)* was officially renamed to REACH (Research Engagement and Collaboration Hub) to reflect its expanded role in facilitating student–industry collaboration. Additionally, project titles were refined to emphasize technical scope and clarity: Project 5 was updated to Towards Resilient V2X Communications over 5G/6G Networks: Sensing and Cooperative Perception; Project 12 to Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications: Real-World Testing; and Project 13 to Resilient V2X Communication for Cooperative Autonomy.

6.1 Changes in approach and reasons for change

Nothing to report.

6.2 Actual or anticipated problems or delays and actions or plans to resolve them.

Nothing to report.

6.3 Changes that have a significant impact on expenditures

Nothing to report.

6.4 Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards

Nothing to report.

6.5 Change of primary performance site location from that originally proposed

Nothing to report.

7 SPECIAL REPORTING REQUIREMENTS

Nothing to Report.