CARNATIONS

Center for Assured & Resilient Navigation in Advanced Transportation Systems

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Acknowledgment of Report Authors and Contributors

This report reflects 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 captures leadership direction while highlighting contributions from research teams across the consortium. The report summarizes 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 through three coordinated areas—Research, Education and Workforce Development, and Technology Transfer—led by **Program Manager Aashish Narang,** with support from **Co-PIs Mark Psiaki, Matthew Spenko,** and **Samer Khanafseh**. These efforts are closely integrated to advance research, education, workforce development, and transition 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. In parallel, CARNATIONS emphasizes workforce development through education, outreach, and training initiatives to prepare the next generation of transportation cybersecurity professionals. The program also works with industry partners to develop performance metrics, support standards development, and create open evaluation frameworks, ensuring that research outcomes translate into practical, deployable solutions that enhance transportation safety and reliability.

1.1.1. Research

During the reporting period beginning October 2025, CARNATIONS continued work across thirteen projects involving partner universities. Activities included research execution, data analysis, student engagement, and dissemination through conferences and publications. These efforts contributed to advances in navigation systems, multimodal transportation, and vehicle applications, aligned with U.S. DOT objectives.

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	Old	Moussa Ayyash	ACTIVE	October 01,2024	2024-2026	
11	Development of a Generalized Integrity Monitoring Framework for CAV Applications	UCR	Old	Matthew Barth	ACTIVE	October 01,2024	2024-2026	
12	Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications: Real-World Testing	UCR	Old	Matthew Barth, Hang Qiu	ACTIVE	October 01,2024	2024-2026	
13	Resilient V2X Communication for Cooperative Autonomy	UCR	Old	Hang Qiu	ACTIVE	October 01,2024	2024-2026	
14	Develop and Test Optimal Speed Control Strategies for Connected and Automated Vehicles under GPS Jamming and Spoofing	CSU, VT	New	Moussa Ayyash, Hesham Rakha	ACTIVE	October 01,2025	2025-2026	

This section summarizes each project's objectives, progress, completed activities, key accomplishments, challenges, and impacts for the period October 2025 to March 2026.

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

Project's Objectives:

The project aims to improve GNSS receiver resilience using multi-antenna and distributed receiver approaches for detection, localization, and mitigation of spoofing and jamming across transportation systems.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: At Stanford, distributed non-synchronized receiver techniques were evaluated for spoofing detection and localization using data from Jammertest 2024 and 2025. An ARAIM-based solution separation approach was developed to enable detection using two or more receivers over short and long baselines, with applications across ground, maritime, and aviation domains. Spoofer localization methods were implemented using time-difference measurements to estimate spoofer position through hyperbolic positioning. Additional work analyzed dual polarization antenna (DPA) data from field and controlled tests to study interference mitigation and direction-of-arrival estimation, with focus on resolving ambiguity in signal direction. An application was submitted for participation in Jammertest 2026.

At Virginia Tech, blind multi-antenna techniques were evaluated using simulated datasets and recorded live data. The work focused on nulling strong spoofing signals by steering antenna array nulls toward the interference source, followed by recovery of authentic signals. Extensive analysis was conducted to assess performance under measurement noise and uncertainty. Additional work addressed signal distortions introduced during nulling, including multipath-like correlation patterns and timing offsets across antennas. Methods are under development to separate these components and estimate accurate pseudoranges for authentic signals. The results demonstrate that signal nulling is effective under practical conditions. Ongoing work focuses on improving signal separation and automating the identification of spoofed and authentic signals.

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

Project's Objectives:

The project aims to develop receiver-based methods for GNSS spoofing detection and to improve signal tracking under interference using IMU-aiding.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: A receiver-based spoofing detection method was developed using decomposition of the cross-ambiguity function (CCAF) with full complex (I/Q) measurements to separate authentic and counterfeit signals. The method exploits carrier-phase inconsistencies to detect spoofing, including closely aligned and power-matched attacks, and applies error-decorrelation techniques to improve performance under noise and multipath conditions. Results from multiple satellites are combined using inverse RAIM (iRAIM) to form separate navigation solutions, enabling identification and continued tracking of authentic signals. The approach was validated using simulation and live data, with findings published in IEEE Transactions on Aerospace and Electronic Systems (Ahmed et al., Oct. 2025).

In parallel, work was initiated on IMU-aided GNSS pilot-signal tracking to improve performance under broadband jamming. Initial results show that tracking can be maintained at low signal levels using industrial-grade IMUs, with improved performance expected from higher-grade sensors. Early findings were presented at the ION International Technical Meeting 2026 (Nagai et al., Jan. 2026). Ongoing efforts focus on improving tracking robustness and advancing implementation methods under severe interference conditions.

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

Project's Objectives:

The project aims to detect and mitigate GNSS spoofing and jamming by integrating GNSS with inertial and other onboard sensor data to support reliable positioning.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Multi-sensor methods were developed that integrate GNSS with inertial sensor data to detect spoofing and jamming. An INS-aided spoofing monitor was implemented using temporal patterns in INS/GNSS Kalman filter innovations to identify power-matched attacks that do not follow platform dynamics. The method was evaluated under jamming-then-spoofing scenarios, demonstrating continued detection capability after periods of GNSS denial and degraded IMU performance.

Validation using FAA live-flight spoofing data further demonstrated the detection of deceptive low-magnitude attacks under operational conditions. Additional work evaluated a tightly coupled DME/INS architecture as an alternative positioning approach for aviation applications. Supporting research also examined lidar-based positioning integrity by identifying potential threats and mitigation approaches. Results show that multi-sensor integration improves detection capability. Key challenges remain in managing inertial error growth during GNSS outages and extending integrity methods across diverse sensor types.

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

Project's Objectives

The project aims to develop and evaluate Positioning, Navigation, and Timing (PNT) methods using Signals of Opportunity (SoOP) from Low Earth Orbit (LEO) satellites and to assess their applicability in transportation systems.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on developing navigation methods using carrier Doppler measurements from LEO satellite constellations, including Starlink. A Kalman filter-based approach was implemented to estimate position, velocity, and signal-related biases without requiring prior position knowledge. Simulation models were developed to test filter performance, and results demonstrated that LEO signals can support navigation under dynamic conditions.

Additional work included collection and analysis of live Starlink signal data and identification of repeatable signal features to improve measurement inputs. A nonlinear navigation filter was also developed to improve performance under large initial uncertainties, addressing limitations of standard extended Kalman filters. Results show that LEO-based signals can augment navigation performance. Key challenges include handling measurement variability, mitigating signal biases, and improving filter stability.

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

Project's Objectives:

The project aims to develop reliable and low-latency V2X communication systems using 5G and emerging 6G technologies, with focus on synchronization, interference handling, and sensing-based communication methods.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on two areas: modeling transmission delay jitter in vehicle-to-vehicle communication and evaluating sensing-based communication approaches. A framework was developed to model jitter based on changes in inter-vehicle distance and interference from nearby vehicles. Results show that increasing the number of transmit antennas improves performance under distance effects but may reduce performance under interference conditions. An adaptive power allocation method was implemented and shown to reduce recovery time compared to fixed allocation approaches, supporting stable communication under varying traffic conditions.

In parallel, work was initiated to support integrated sensing and communication (ISAC) using mmWave radar systems. Efforts included evaluation of available hardware and identification of a radar platform for proof-of-concept implementation. A key challenge was limited access to suitable mmWave equipment, which was partially addressed by identifying a Texas Instruments radar system for further testing.

(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:

The project aims to analyze GNSS interference threats in multimodal transportation systems and to define representative jamming and spoofing scenarios for evaluation of system performance.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on evaluating GNSS spoofing threats and developing a classification framework to describe different attack types. ADS-B data was used to study the evolution and characteristics of spoofing events across multiple regions. Additional datasets from Jammertest 2025 were analyzed, including scenarios with multiple spoofers and varied spoofing trajectories. These analyses support the development of a structured taxonomy for spoofing threats applicable to aviation and surface transportation systems.

Further efforts included coordination with Jammertest organizers to define advanced threat scenarios for Jammertest 2026, including multi-directional spoofing cases. A modeling tool was also developed to assess the impact of spoofing on autonomous aircraft with varying levels of GNSS reliance, supporting evaluation of system response under varied threat conditions. Work is ongoing to align the taxonomy with external standards such as RTCA, though this remains challenging due to evolving definitions.

(8) R-PNT Virtual Conflict Simulation

Project's Objectives:

The project aims to examine the impact of spoofing-based cyberattacks on transportation networks by identifying vulnerabilities and analyzing system disruptions under attack scenarios.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on evaluating the impact of spoofing attacks on transportation system performance using the I-66 corridor as a case study. A simulation framework was used to evaluate how falsified navigation data affects routing decisions and traffic flow. Results show that spoofing can introduce perceived congestion and cause rerouting of vehicles, leading to increased travel times and network-wide delays.

A web-based tool is in the development stage to identify candidate road segments for spoofing attacks based on constraints such as segment length and speed limit. Simulations focused on freeway segments of 100–200 meters to meet signal range conditions and evaluate attack feasibility. The results demonstrate that targeted spoofing at selected segments can influence routing behavior and affect overall network performance, providing a basis for further evaluation of system response and mitigation strategies.

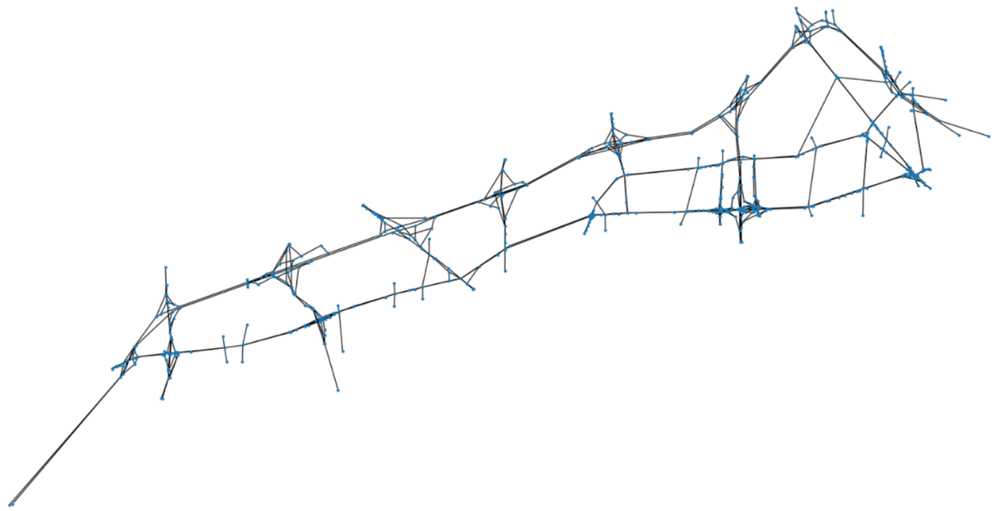

Figure 1. I66 Road Network

Metric	**No-Spoofing**	**Spoofing**			**%**		
Road-Segments (ID)		**298**	**197**	**1335**	**298**	**197**	**1335**
Distance (km)	15.34	15.30	15.34s	15.35	0.22	0.00	-0.10
Avg. Travel Time (seconds)	670.83	674.26	676.75	681.55	-0.51	-0.88	-1.60
Total Delay (seconds)	43.46	44.38	45.19	48.18	-2.10	-4.0	-10.85

Table 1. Effect of spoofing on the performance of the transportation network. Three road segments were chosen for the spoofing attack. The average travel time and total delay are reported.

(9) Comprehensive Testing and Evaluation of Resilient PNT Systems

Project's Objectives:

The project aims to analyze radio frequency interference (RFI) data and evaluate anti-jamming and anti-spoofing methods using experimental and operational data.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Research included the development and deployment of testing capabilities and tools for interference monitoring and prediction using large-scale datasets. A web-based application was updated to support detection of jamming events using data from Continuously Operating Reference Stations (CORS) across more than 900 locations in the United States. Enhancements include improved detection sensitivity, estimation of event duration, and interactive visualization tools to support analysis of RFI activity over time and location. Experimental evaluation was conducted on collaborative multi-sensor PNT systems integrating (1) GNSS with inertial navigation systems (INS), LiDAR, and vehicle-to-vehicle data sharing, and (2) INS, shared motion constraints, and vehicle-to-vehicle scalar or vector cross-links. Results demonstrate that combining multiple sensing modalities supports consistent navigation performance under interference conditions. A major challenge in resilient PNT solution design and development is that broadcasting at GNSS frequencies is illegal. A new testbed is under development with contributions from industry partners, including equipment for simulation and sensing systems. A major outcome of this work is the demonstration of RFI monitoring and validation using actual data of multi-sensor navigation approaches.

(10) Improving GNSS Resiliency Using Edge AI Solutions

Project's Objectives:

The project aims to improve GNSS performance in signal-limited environments using Edge AI, machine learning, and multi-sensor integration.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on developing cloud systems to support GNSS data processing and positioning. A joint GNSS–Distributed Acoustic Sensing (DAS) approach was implemented for signal monitoring and adaptive sensing. Federated learning methods were developed to enable cooperative positioning across distributed nodes, along with decentralized algorithms for task allocation and data consistency. Predictive models were also developed to mitigate non-line-of-sight and multipath effects using environmental features and spatial correlations. In parallel, reinforcement learning was integrated with factor graph optimization to improve positioning in urban environments, and deep learning-based methods were applied for multi-sensor data fusion.

Results show improved positioning availability and continuity under signal-limited conditions. A composite metric was introduced to support to evaluate GNSS resiliency over time. A key outcome is the demonstration of Edge AI-based approaches for real-time positioning support. Further validation is ongoing across diverse operational environments, including tunnels and dense urban areas. Results have been disseminated through conference publications and journal submissions.

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

Project's Objectives:

The project aims to develop and evaluate an integrity monitoring architecture for Connected and Automated Vehicle (CAV) applications by assessing positioning reliability and communication performance in simulated environments.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on developing a co-simulation framework by integrating NS-3 with CARLA to enable exchange of vehicle state and communication data. This setup supports analysis of communication metrics such as latency, packet loss, and throughput. CARLA-based environments were used to generate nominal and altered GNSS trajectories, along with multi-sensor datasets for evaluation. A high-fidelity map of a real-world intersection is also being refined to support accurate simulation of traffic scenarios. Additional efforts included initial development of data-driven methods to introduce controlled variations in sensor data, enabling comparison between reference and modified datasets for integrity evaluation. A key outcome is the establishment of a simulation environment that enables joint analysis of positioning and communication performance. A current limitation is the absence of real-time GNSS measurement generation, as existing tools operate offline. Ongoing work is focused on developing methods to generate GNSS measurements dynamically from simulated vehicle states.

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

Project's Objectives:

This project aims to assess the impact of GNSS spoofing and jamming on CAV systems and to develop detection and mitigation methods using sensor data and vehicle communication.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: Work focused on processing and analyzing a CAV dataset collected under controlled spoofing and jamming conditions. A detection approach was developed that integrates GNSS data, onboard sensors, and Vehicle-to-Vehicle (V2V) communication to identify abnormal positioning behavior. In parallel, development of a factor graph-based tightly coupled inertial navigation system (INS) was initiated to support fault detection and maintain continuous positioning.

A key outcome is the implementation of a detection capability that integrates V2V communication with sensor data, including LiDAR, to support the identification of spoofing and jamming effects and improve system awareness. A current limitation is the availability of field environments for real-time testing. Validation is therefore being conducted through a post-processing approach with simulated spoofing and jamming scenarios, enabling controlled and repeatable evaluation of system performance.

(13) Resilient V2X Communication for Cooperative Autonomy

Project's Objectives:

The project aims to improve communication reliability for autonomous vehicles in limited-visibility and dynamic environments using cooperative and remote driving supported by V2X communication.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact up to September 2025: Work focused on improving timing and communication coordination in V2X networks. A coordination framework (R'CV2X) was developed to support communication between vehicles and roadside units, improving channel utilization and coordinated message exchange. A simulation-based prototype of a flooding-based synchronization protocol was also implemented to support communication continuity in environments without GNSS signals. Results from this work have been prepared for submission to ACM MobiCom 2026.

Additional efforts include development of a standard-compliant C-V2X interface using software-defined radios and the srsRAN platform, enabling flexible implementation and timing control. Work is also ongoing to expand datasets and enable access to a testbed environment. A key outcome is the demonstration of coordination and synchronization methods for V2X communication. A current limitation is the restricted programmability of commercial C-V2X hardware, which is being addressed through open-source implementations.

(14) Develop and Test Optimal Speed Control Strategies for Connected and Automated Vehicles under GPS Jamming and Spoofing

Project's Objectives:

The project aims to develop and evaluate speed control strategies for connected and automated vehicles under GNSS conditions, using resilient positioning and control approaches.

Progress, Completed Activities, Accomplishments, Challenges Encountered, and Impact: This is a new project initiated in late November 2025 following required USDOT approvals, with active work beginning in February 2026. Initial efforts focused on coordination across participating teams to define roles, scope, and research direction. A literature review was conducted to support the development of vehicle control approaches under positioning uncertainty. Initial system concepts are currently under design, with work focusing on defining key components and a unified implementation approach. This phase establishes the foundation for subsequent development and testing activities.

CARNATIONS Collaborative Endeavors

During the reporting period (October 2025 to March 2026), CARNATIONS partner institutions demonstrated strong collaborative engagement across academia, industry, and government. Chicago State University advanced partnerships with the University of North Texas in PNT security and safety through joint proposals, publications, and development of an IEEE technical committee, while also participating in multi-institutional panels with Stanford and the U.S. Department of Transportation. The University of California, Riverside (UCR) strengthened industry engagement through its work with StarNAV, integrating technologies into test vehicles, sharing results for product improvement, and supporting student internships. UCR also engaged regional industry partners and hosted the ITS Forum (October 2025), bringing together stakeholders from academia, industry, and standards organizations, while contributing to workforce development initiatives and programs such as EcoCAR and NSF-supported training.

Virginia Tech expanded its collaborative footprint through partnerships with industry leaders including Xona Space Systems, Inertial Labs, Spirent, and MITRE through NDAs, equipment contributions, and joint research. It also maintained strong cross-university collaboration with Illinois Institute of Technology, Stanford University, Chicago State University, and the University of Texas at Austin, contributing to joint proposals and research efforts. Illinois Institute of Technology further supported collaborative and translational research through partnerships with its Kaplan Center, including joint proposal submissions to NSF STRP and the U.S. DOT ARPA-I challenge, along with active dissemination at conferences. Overall, these efforts reflect a well-integrated CARNATIONS ecosystem advancing resilient PNT and connected and automated vehicle research through coordinated collaboration, technology transfer, and workforce development.

1.1.2. Leadership

During the reporting period (October 2025 to March 2026), CARNATIONS demonstrated leadership in research, technology transfer, and national engagement. A key achievement was the advancement of the Technology Transfer team through Stage 1 of the U.S. Department of Transportation ARPA-I Ideas Challenge, reflecting progress in translating research into practical applications. The center also contributed to research on backup Positioning, Navigation, and Timing (PNT) using Starlink signals, supporting alternative navigation approaches.

CARNATIONS maintained a strong presence at the ION International Technical Meeting 2026, presenting ongoing work in resilient PNT, spoofing detection, and navigation systems. Additional recognition was received at the ION GNSS+ conference, where multiple CARNATIONS papers were awarded Best Presentation honors for contributions to GNSS resilience and interference mitigation.

Center Director Boris Pervan was elected an IEEE Fellow (January 2026) “for contributions to satellite navigation integrity.” This honor is awarded to fewer than 0.1%

of voting members annually. Student achievement was recognized through the U.S. DOT Outstanding Student Award 2026, awarded to Liam Carey for his work on GNSS interference and resilient navigation methods.

Collectively, these efforts reflect strong leadership across research, dissemination, and workforce development.

1.1.3. Education and Workforce Development

During the reporting period (October 2025 to March 2026), the Education and Workforce Development Subcommittee advanced academic instruction, curriculum development, and experiential learning aligned with CARNATIONS objectives. Faculty contributed to core courses in transportation, communications, and navigation, including a specialized GPS course offered at both undergraduate and graduate levels and a graduate-level navigation course accessible to students across partner institutions.

Through the REACH initiative, the project *"Wrong-Way Driving Detection and R-PNT ADAS-Based Navigation System"* was successfully completed, where students developed a resilient R-PNT-enabled ADAS framework to detect hazardous driving behaviors under GPS-challenged conditions. A new REACH project, *"Performance Analysis of CUSUM-Based Anti-Spoofing Algorithms,"* was launched in collaboration with MITRE, focusing on evaluating advanced anti-spoofing techniques using MATLAB-based simulations and performance metrics such as false alarms and missed detections. This REACH project is continuing following a successful Phase 1, further strengthening experiential learning opportunities for students.

The subcommittee also strengthened student engagement, training, and workforce development through regular biweekly research meetings (involving undergraduate and graduate students), internships with industry partners (e.g., StarNAV), and hands-on programs such as EcoCAR. A new educational outreach initiative, the *CARNATIONS Waypoint* podcast, was launched to broaden dissemination of transportation research. The podcast workflow was developed by a dedicated team including Matt Spenko, Boris Pervan, and Aashish Narang, with the teaser already released and the first episode scheduled for May 12, 2026.

Additional outreach included participation in events such as the ITS Forum and the Advanced Sustainable Transportation Workforce Development (ATCIE) workshop, which brought together stakeholders to address workforce needs. Collectively, these efforts build a strong foundation for student success, expand outreach, and advance workforce development in transportation and resilient navigation systems.

1.1.4. Technology Transfer and Collaboration

During the reporting period (October 2025 to March 2026), the Technology Transfer Subcommittee advanced commercialization, industry engagement, and translational research across the CARNATIONS network. The team worked collaboratively across partner institutions and with key industry stakeholders, including TruNav, Xona Space

Systems, Inertial Labs, MITRE, Spirent, and StarNAV, to support the transition of research into practical applications. Efforts included active commercialization initiatives in collaboration with the Kaplan Center, as well as proposal submissions to competitive programs such as NSF STRP and the U.S. Department of Transportation's ARPA-I Challenge, where the team successfully advanced through Stage 1. Additional activities included industry-supported testing, data sharing, equipment contributions, and joint research efforts, along with exploration of new collaborations in PNT security and resilient navigation. These efforts reflect a coordinated, center-wide approach to strengthening industry partnerships and advancing technology readiness.

In parallel, the subcommittee developed digital infrastructure to support CARNATIONS members. A new AI-based internal tool, *CARNATIONS Navigator*, developed by Aashish Narang, was introduced to provide centralized access to CARNATIONS-related information, datasets, and insights on spoofing and jamming incidents; it is now in testing phase. The CARNATIONS website and tools platform were also updated to improve accessibility and usability.

Additionally, a new tool titled "Informed Identification of Road Segments Vulnerable to Spoofing" is currently under development by Hesham Rakha and Mohamed Farag. This tool enables users to load and analyze road network data, visualize network structures, and filter based on parameters such as speed and segment length to identify candidate segments for simulation scenarios using shortest-path analysis. The objective is to support the selection of highway segments where vehicles fall within spoofing ranges, enabling more effective simulation and analysis. Collectively, these efforts highlight a growing technology transfer ecosystem that strengthens collaboration, enhances research impact, and supports practical deployment across the transportation domain.

1.2. What was accomplished under these goals?

1.2.1 Research

Research Performance Metrics	Output March 2026
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.	83

1.2.2 Leadership

Leadership Performance Metrics	Output March 2026
Number of keynote speeches/invited presentations at academic and professional conferences.	9
Number of leadership positions in local, national, and international organizations.	42
Number of CARNATIONS-affiliated students in scholar and professional leadership positions.	10

1.2.3 Education and Workforce Development

Education/Workforce Development Performance Metrics	Output March 2026
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 March 2026
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.	5
Number of Outreach Events	12

1.3 How have the results been disseminated?

CARNATIONS disseminated results through conference participation, publications, industry collaboration, and coordinated research activities. Findings were presented at major conferences such as ION International Technical Meeting 2026 and other technical forums, including work on collaborative CAV localization and integrity monitoring.

Faculty and senior researchers also contributed through leadership roles in conferences and technical panels, including participation in the IEEE World Forum on Safety and program leadership at ION ITM 2026. Collaboration with industry partners further supported dissemination through applied research and data sharing. Activities included integration and testing of technologies with partners such as StarNAV, Inertial Labs, Spirent, and Xona Space Systems.

Dissemination was also supported through internal coordination, including regular research meetings and student engagement across partner institutions. Students contributed through research projects, internships, and training programs. Additional outputs included publications, technical reports, and collaborative research products across institutions, supporting knowledge exchange within the broader research community.

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 continue advancing research, outreach, and coordination activities to support project goals. Planned efforts include launching the *CARNATIONS Waypoint* podcast series and developing a modular YouTube-based course.

The Center will host **CARNATIONS Days 2026** at the University of California, Riverside on July 15–16, 2026, along with a site visit in Riverside, California. CARNATIONS will also participate in national meetings, including the Transportation Cybersecurity Summit in Washington, D.C. on July 21, 2026, and the CUTC Summer Meeting at Auburn University, June 15-17, 2026.

Research dissemination will continue through presentations at conferences such as ION GNSS+ and IEEE venues. Ongoing activities include implementation of the Informed Identification of Road Segments Vulnerable to Spoofing tool and continuation of weekly research discussion meetings to support coordination across projects. These efforts will sustain research progress and strengthen collaboration across the CARNATIONS network.

2 PARTICIPANTS & COLLABORATING ORGANIZATIONS

2.1 What organizations have been involved as partners?

During the reporting period, CARNATIONS strengthened partnerships with leading academic institutions, industry organizations, and government agencies to advance research and innovation in Resilient Positioning, Navigation, and Timing (R-PNT) technologies.

The consortium includes five core academic partners—Illinois Institute of Technology, Virginia Tech, University of California, Riverside, Chicago State University, and Stanford University, which collaborated through coordinated research projects, joint publications, shared courses, student training activities, and regular technical meetings. These partnerships enabled cross-institutional integration of complementary expertise in navigation, communications, and transportation systems, and alignment of research outcomes with CARNATIONS' strategic goals.

CARNATIONS also maintained active engagement with over 40 industry and government partners, including TruNav, StarNAV, Xona Space Systems, Inertial Labs, MITRE, Spirent, and others. These partners contributed through equipment donations, NDAs, data sharing, joint testing and validation, student internships, and participation in advisory and outreach activities. These collaborations enabled testing under spoofing and jamming conditions, informed product development, and supported proposal efforts such as the U.S. Department of Transportation's ARPA-I Ideas Challenge, where CARNATIONS advanced through Stage 1. Overall, these partnerships play a critical role in technology transfer, workforce development, and the practical deployment of resilient PNT solutions in transportation systems.

2.2 Have other collaborators or contacts been involved?

Yes, CARNATIONS engaged with a broad set of collaborators across academia, industry, and government during this reporting period.

Industry collaboration included work with StarNAV on integration and evaluation of CAV technologies, as well as engagement with Inertial Labs and Spirent through equipment support and testing activities. Collaboration with Xona Space Systems was supported through data sharing and technical coordination.

Academic collaboration included engagement with the University of North Texas to explore joint research and proposal development in PNT security. Additional engagement included participation in technical panels and forums involving university researchers, industry partners, and government stakeholders. These activities supported coordination, data exchange, and alignment of research efforts across participating organizations.

3 OUTPUTS

3.1 Publications, Conferences, and Presentations (Oct 2025-March 2026)

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

(1) Blanch, Juan, Lo, Sherman, Chen, Yu-Hsuan, Kriezis, Argyris, and Walter, Todd, "Determining Protection Levels Using Multiple Antennas Under Spoofing Conditions," Published in Proceedings of the IEEE/ION Position Location and Navigation Symposium (PLANS), Salt Lake City, UT, April 2025.

(2) M. Psiaki and A. Frid, "GNSS Spoofing Observed in Israel using Wideband RF Data and Software Radio," Israel Annual Conference on Aerospace Sciences, May 9, 2024, Haifa, Israel.

(3) M. Psiaki, A. Frid, and C. Caravaca, "A GNSS Radio-Frequency Interference Tour of Israel," Proc. ION Joint Navigation Conference, June 2-5, 2025, Covington, KY.

(4) Ahmed, S., Khanafseh, S., and Pervan, B., "Uncovering Subtle GNSS Spoofing by Decomposing the Complex Cross Ambiguity Function," IEEE Transactions on Aerospace and Electronic Systems, Vol 61, No. 5, October 2025.

(5) Nagai, K., Khanafseh, S., and Pervan, B., "GNSS Jamming Mitigation with a Pilot Signal Aided Deep Integration Framework," Proceedings of the 2026 International Technical Meeting of the Institute of Navigation, Anaheim, CA, January 2026.

(6) Rife, J., Khanafseh, S., Pervan, B., and Wassaf, H., “Fundamental Architectures for High-Integrity Georeferenced Lidar Positioning: A Review,” NAVIGATION, Vol. 72, Winter 2025.
(7) Kujur, B., Khanafseh, S., Pervan, B., Vitan, V., Berz, G., and Osechas, O., “Integrated DME/INS Alternative PNT System for RNP 1.0,” Proceedings of ION GNSS+ 2025, Baltimore, MD, September 2025.
(8) Kujur, B., Khanafseh, S., and Pervan, B., “Performance of Optimal INS Monitor Against Jamming Then Spoofing Scenarios,” Proceedings of ION GNSS+ 2025, Baltimore, MD, September 2025.
(9) Nemana, M., Nagai, K., Khanafseh, S., and Pervan, B., “Exploring Lidar Resilience: A Review of Spoofing Threats in Autonomous Driving,” Proceedings of the IEEE/ION Position, Location, and Navigation Symposium (PLANS 2025), Salt Lake City, UT, April 2025.
(10) Kujur, B., Khanafseh, S., and Pervan, B., “Performance of Optimal INS Monitor Against Live Spoofing,” Proceedings of the 2025 International Technical Meeting of the Institute of Navigation, Long Beach, CA, January 2025.
(11) Qin, W., Psiaki, M.L., Bowman, J.R., and Humphreys, T.E., “Pilots and Other Predictable Elements of the Starlink Ku-Band Downlink,” submitted to npj Wireless Technology on 2 Feb. 2026, in review.
(12) T. Shui, W. Saad, and M. Chen, "Sensing Safety Analysis for Vehicular Networks with Integrated Sensing and Communication (ISAC)", in Proc. of IEEE Global Communications Conference (GLOBECOM), Communication & Information Systems Security Track, Taipei, Taiwan, December 2025.
(13) P. Paul, W. Saad, and E. W. Burger, "Resilient Vehicular Communications with Minimal Jitter", in Proc. of 59th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, November 2025.
(14) Lo, Sherman, Liu, Zixi, Ibrahim, Lyla, Chen, Yu Hsuan, Akos, Dennis, and Walter, Todd, “Global Incidents of Aviation Spoofing in 2024-2025 Detected with Automatic Dependent Surveillance Broadcast,” Published in Proceedings of the 2026 International Technical Meeting of The Institute of Navigation, Anaheim, CA, January 2026 (peer reviewed)
(15) Kuwada, S., M. Joerger, and M. Spenko. “Fault-Mode Aware Integrity Monitoring for Collaborative CAV Localization.” Proceedings of the 2026 International Technical Meeting of The Institute of Navigation. Anaheim, California. (2026): 288-301. https://doi.org/10.33012/2026.20494
(16) D. Gandhi, M. Shah, A. Singh and M. Ayyash, "Enhancing GNSS Resiliency Against Spoofing and Jamming Employing Deep Neural Networks," 2025 IEEE World Forum on Public Safety Technology (WF-PST), Orlando, FL, USA, 2025, pp. 212-218, doi: 10.1109/WF-PST65083.2025.00039.
(17) Kaiwei Wang, Ruikang Zhong, Anand Singh, Mona Jaber and Moussa Ayyash, “An Augmented GNSS-DAS Architecture for Continuous and Robust Positioning” accepted for publication in IEEE ICC 2026, Glasgow, UK.
(18) S. P. Nayak and M. Barth, "The Role of Integrity Monitoring in Connected and Automated Vehicles: Current State of Practice and Future Directions," in IEEE Intelligent Transportation Systems Magazine, vol. 17, no. 6, pp. 93-114, Nov.-Dec. 2025

(19) Stas, M., Nguyen, J., Snyder, R. W., Mo, R., & Barth, M. J. (2026). Sensor- and Communication-Based GNSS Spoofing and Jamming Detection Framework for Connected and Automated Vehicle Applications. Proceedings of the 2026 Pacific PNT Conference of the Institute of Navigation (ION Pacific PNT).
(20) Ruoshen Mo, Zhaowei Tan, Hang Qiu, R'CV2X: RSU Coordinated Cooperative Perception via C-V2X Direct Communication, in submission, The 32nd Annual International Conference on Mobile Computing and Networking (MobiCom), Oct 26-30, 2026, Austin, Texas, USA

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

CARNATIONS maintains an active online presence through its website, which serves as a central platform for sharing research progress, events, and key milestones. During this reporting period, the website was enhanced to improve accessibility and user engagement. Previously developed tools, including the Spoofing Incident Tracker and Jamming Detection App, were updated and refined. In addition, an AI-based information tool, CARNATIONS Navigator, was introduced to support user queries and improve access to information. The Center also launched a documentary series highlighting ongoing research activities. A podcast teaser was released on the Center's YouTube channel, with the full episode series scheduled for release in May 2026.

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 produced outcomes across research publications, technology transfer, collaboration, and national engagement. A key research outcome is the collaborative publication on Starlink-based backup PNT, titled *"Pilots and Other Predictable Elements of the Starlink Ku-Band Downlink"* (Qin et al., 2026, under review), co-authored by CARNATIONS researchers Dr. Mark Psiaki and John Bowman. This work identified predictable signal structures in Starlink Ku-band downlink signals, including edge pilots and T-codes, which support improved processing for opportunistic PNT applications. The study reflects collaboration between CARNATIONS and another U.S. DOT University Transportation Center and contributes to ongoing efforts in LEO-based navigation.

Additional research outcomes include numerous peer-reviewed publications and conference papers on GNSS spoofing detection, jamming mitigation, lidar-based positioning, multi-sensor integration, and resilient vehicular communication. These include Ahmed et al. (2025) on cross-ambiguity function-based spoofing detection, Nagai et al. (2026) on pilot-signal aided jamming mitigation, Rife et al. (2025) on lidar positioning architectures, Kujur et al. (2025) on DME/INS systems, and Lo et al. (2026) on global aviation spoofing incidents. Contributions also include work on integrated sensing and communication, deep learning-based GNSS resilience, and integrity monitoring for connected and automated vehicles, reflecting a broad range of research outputs across partner institutions.

In technology transfer, the CARNATIONS partner TruNav advanced through Stage 1 of the U.S. Department of Transportation ARPA-I Ideas Challenge, demonstrating progress in translating research into applied systems. This effort included proposal submission, technical presentation, and engagement with reviewers at the national level. CARNATIONS also maintained strong national engagement in technical forums. At ION International Technical Meeting 2026, Dr. Samer Khanafseh served as Program Chair, and the full CARNATIONS PI team participated in technical sessions, meetings, and collaboration discussions. These activities supported dissemination of research results and engagement with academic, industry, and government stakeholders. Student outcomes include national recognition, with Liam Carey receiving the U.S. DOT Outstanding Student Award 2026 for contributions to GNSS interference research and resilient navigation methods. Collectively, these outcomes demonstrate strong progress in research, collaboration, technology transfer, and workforce development.

5 IMPACTS

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

CARNATIONS research improves transportation system effectiveness by enhancing the reliability of positioning, navigation, and timing under challenging conditions. Advances in multi-sensor integration, LEO-based positioning, and receiver-level detection enable more resilient navigation for vehicles, aircraft, and other transportation platforms. These capabilities support stable operation of systems that rely on GNSS, including routing, traffic management, and automated driving functions.

Research on interference detection, spoofing monitoring, and communication-based coordination supports timely identification of signal disruptions and supports continued operation using alternative data sources. Work on V2X communication and cooperative systems further enhances information exchange between vehicles and infrastructure, improving coordination and traffic flow.

Simulation and testing activities provide insight into system behavior under varied conditions, supporting implementation and operational planning.

Collectively, these efforts contribute to improved continuity, availability, and reliability of positioning and communication functions, strengthening overall transportation system performance.

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?

Technology transfer activities during this reporting period strengthened collaboration with industry and government and supported the application of research outcomes. Partnerships with organizations such as StarNAV, Inertial Labs, Spirent, Xona Space Systems, and the Kaplan Center at Illinois Institute of Technology enabled integration of research into testing platforms, data sharing, and evaluation of navigation technologies. These efforts supported the application of multi-sensor navigation, interference monitoring tools, and resilient PNT methods in operational settings.

A key outcome is the advancement of the CARNATIONS technology transfer partner TruNav through Stage 1 of the U.S. Department of Transportation ARPA-I Ideas Challenge, reflecting significant progress toward commercialization. This included proposal development, technical presentations, and engagement with industry and government reviewers. Additional activities included submission of a non-provisional patent application and proposals for funding to support prototyping and commercialization.

Industry collaboration also enabled system testing through vehicle-based experiments and use of donated equipment for simulation and sensing. Engagement in technical forums, panels, and joint research activities supported alignment with current practices and facilitated adoption of methods for resilient positioning and navigation. Collectively, these efforts demonstrate continued progress in transitioning research to applied use and supporting collaboration across academic, industry, and government.

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

During this reporting period, CARNATIONS advanced the scientific foundation of resilient Positioning, Navigation, and Timing (PNT) through peer-reviewed publications, conference papers, and ongoing research across GNSS interference mitigation, multi-sensor navigation, and transportation systems. Key contributions include Ahmed et al. (2025), which introduced a signal-processing approach for detecting subtle GNSS spoofing using complex cross-ambiguity function decomposition, along with complementary advances in jamming mitigation and monitoring (Nagai et al., 2026; Kujur et al., 2025). Additional work expanded knowledge in multi-sensor and alternative navigation systems, including LiDAR-based positioning (Rife et al., 2025; Nemana et al., 2025) and DME/INS integration for aviation applications (Kujur et al., 2025).

CARNATIONS also contributed to understanding real-world interference through studies such as Sherman Lo et al. (2026) on global aviation spoofing events. Advances in LEO-based navigation were demonstrated in work by Mark Psiaki et al. (*"Pilots and Other Predictable Elements of the Starlink Ku-Band Downlink,"* 2026, under review), identifying predictable signal structures in Starlink transmissions for opportunistic PNT. Further contributions addressed integrity monitoring and connected vehicle systems (Kuwada et al., 2026; Nayak and Barth, 2025; Stas et al., 2026), as well as communication and AI-based methods, including integrated sensing and communication (ISAC), resilient V2X communication, and deep learning approaches to GNSS resilience.

Collectively, these efforts advance the state of the art in spoofing detection, jamming mitigation, multi-sensor integration, LEO-based positioning, and cooperative vehicular systems, providing a strong foundation for continued research in resilient PNT and transportation applications.

5.4 What is the impact on transportation workforce development?

The Education and Workforce Development Subcommittee continues to strengthen the transportation workforce by preparing students with knowledge and experience in Positioning, Navigation, and Timing (PNT) and related transportation systems. Key initiatives include:

- **Student Research Engagement:** Students across partner institutions participate in projects on GNSS resilience, multi-sensor navigation, connected vehicle systems, and communication networks, contributing to system design, data analysis, and testing.
- **Internships and Industry Exposure:** Collaboration with industry partners such as StarNAV and others provides students with opportunities to engage in applied research, system evaluation, and testing environments.
- **Industry-Driven REACH Projects:** The REACH platform connects students, faculty mentors, and industry partners, enabling students to work on defined problem statements and gain experience aligned with industry needs.
- **Workshops and Technical Engagement:** Participation in research meetings, workshops, and technical forums supports knowledge exchange with academic, industry, and government stakeholders.
- **Courses and Training:** Inter-university courses and instruction in navigation, communication, and transportation systems build technical skills, with ongoing expansion of PNT-focused curriculum.
- **Industry Collaboration:** Partnerships with industry and government align research with workforce needs and provide pathways for student involvement in applied projects.
- **Research Dissemination and Participation:** Students contribute to conference papers, presentations, and collaborative research outputs, strengthening communication and research skills.
- **Podcast and Outreach Initiatives:** The *CARNATIONS Waypoint* podcast series provides a platform for students and researchers to engage with experts, understand ongoing work, and connect research with practical applications.
- **Testbeds and Applied Learning:** Access to testbeds and simulation environments, including vehicle-based and communication systems, supports hands-on learning and evaluation of transportation technologies.

Collectively, these efforts prepare students for careers in transportation, navigation, and related technical fields.

6 CHANGES/PROBLEMS

During this reporting period, Aashish Narang was added as Principal Investigator (PI) on Projects 2 and 3 to support coordination of technical activities across teams. In addition to his role as Program Manager, this includes supporting system-level integration, coordinating data activities, tracking progress in algorithm development and testing, and ensuring consistency across simulation, validation, and reporting. This change supports more structured execution of project milestones and improved coordination across partner institutions.

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.