

Protecting the Skies: GNSS-less Aircraft Navigation with Terrestrial Cellular Signals of Opportunity

Zaher M. Kassas

The Ohio State University

Ali Abdallah

University of California, Irvine

Chiawei Lee, Juan Jurado, Steven Wachtel, Jacob Duede, Zachary Hoeffner, Thomas Hulsey, and Rachel Quirarte

United States Air Force

RunXuan Tay

Republic of Singapore Air Force

BIOGRAPHY

Zaher (Zak) M. Kassas is a Professor at The Ohio State University and director of the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory. He is also director of the U.S. Department of Transportation Center: CARMEN (Center for Automated Vehicle Research with Multimodal Assured Navigation), focusing on navigation resiliency and security of highly automated transportation systems. He received a B.E. in Electrical Engineering from the Lebanese American University, an M.S. in Electrical and Computer Engineering from The Ohio State University, and an M.S.E. in Aerospace Engineering and a Ph.D. in Electrical and Computer Engineering from The University of Texas at Austin. He is a recipient of the 2018 National Science Foundation (NSF) CAREER award, 2019 Office of Naval Research (ONR) Young Investigator Program (YIP) award, 2022 Air Force Office of Scientific Research (AFOSR) YIP award, 2018 IEEE Walter Fried Award, 2018 Institute of Navigation (ION) Samuel Burka Award, and 2019 ION Col. Thomas Thurlow Award. He is a Senior Editor of the IEEE Transactions on Intelligent Vehicles and an Associate Editor of the IEEE Transactions on Aerospace and Electronic Systems and the IEEE Transactions on Intelligent Transportation Systems. His research interests include cyber-physical systems, navigation systems, autonomous vehicles, and intelligent transportation systems.

Ali Abdallah received his M.S. degree in Electrical Engineering and Computer Science (EECS) from University of California at Irvine and was a member of the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory. He is currently a research intern at Google. He is a recipient of the 2020 IEEE/ION Position, Location, and Navigation Symposium (PLANS) Best Student Paper Award and the 2020 IEEE Signal Processing Society video contest for beamforming research (5-MICC) Grand Prize.

Chiawei Lee is an Assistant Professor and Instructor Flight Test Engineer at the U.S. Air Force Test Pilot School. He serves as the Test Management Program Director where he oversees about a dozen student and staff led flight test projects each year. In addition, he is the Chief Test Safety Officer responsible for the safe execution of curriculum and flight test project safety packages. He received a B.S. in Aerospace Engineering from University of California, Los Angeles and a M.S. in Aero/Astro Engineering from Stanford University.

Juan Jurado is a U.S. Air Force Lieutenant Colonel and the Director of Education at the U.S. Air Force Test Pilot School. He holds a B.S. from Texas A&M University, an M.S. from the Air Force Test Pilot School, and M.S. and Ph.D. from the Air Force Institute of Technology. Previously, he served as Director of Engineering for the 413th Flight Test Squadron and oversaw various C-130, V-22, and H-1 flight test programs. His research interests include aircraft performance modeling, online sensor calibration, image processing, visual-inertial navigation, and statistical sensor management for multi-sensor navigation problems.

Steven Wachtel is a U.S. Air Force Captian and a Flight Test Engineer, assigned to the 780th Test Squadron, Eglin Air Force Base, FL. He received a B.S. in Mechanical Engineering from The Ohio State University, an M.S. in Flight Test Engineering from the U.S. Air Force Test Pilot School, and an M.S. in Systems Engineering from the Air Force Institute of Technology.

Jacob Duede is a Major in the U.S. Air Force. He was trained as a Communication/Navigation/Mission Systems apprentice on C-17 Globemaster II aircraft and stationed at McChord Air Force Base, WA. He graduated from the U.S. Air Force Academy as a commissioned officer with a B.S. in Mechanical Engineering. He attended the Undergraduate Pilot Training at Columbus

Air Force Base, MS. In 2020, he graduated from the U.S. Air Force Test Pilot School at Edwards Air Force Base, CA. He is a Senior Pilot with over 2,000 hours and holds an M.S. in Engineering from the University of Arkansas and an M.S. in Flight Test Engineering from Air University.

Zachary Hoeffner is a flight test engineer at the U.S. Air Force. He received a B.S. in Nuclear Engineering from the U.S. Air Force Academy, an M.S. in Flight Test Engineering from the U.S. Air Force Test Pilot School, an M.S. in Engineering Physics and Applied Physics from the Air Force Institute of Technology, and an M.S. in Nuclear Engineering from the Air Force Institute of Technology.

Thomas Hulsey is a U.S. Air Force Flight Commander of Operations Engineering. He received a B.S. in Aerospace Engineering from Missouri University of Science and Technology, an M.S. in Aeronautical Engineering from the Air Force Institute of Technology, and an M.S. in Experimental Flight Test Engineering from the United States Air Force Test Pilot School.

Rachel Quirarte is a KC-46 and KC-135 programmatic flight commander and test pilot in the 418th Flight Test Squadron in the U.S. Air Force. She received a B.S. in Aeronautical Engineering from the U.S. Air Force Academy, an M.S. in Flight Test Engineering from the U.S. Air Force Test Pilot School, and an M.S. in Mechanical Engineering from Rice University.

RunXuan Tay received a B.S. degree in Electrical Engineering from the University California, San Diego and an M.S. degree in Flight Test Engineering from the U.S. Air Force Test Pilot School. He is currently a test pilot at Air Warfare Center, Republic of Singapore Air Force, where he works on fixed wing test programs.

ABSTRACT

This paper shows how to protect our skies from harmful radio frequency interference (RFI) to global navigation satellite system (GNSS) signals, by offering terrestrial cellular signals of opportunity (SOPs) as a viable aircraft navigation system backup. An extensive flight campaign was conducted by the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory in collaboration with the United States Air Force (USAF) to study the potential of cellular SOPs for high-altitude aircraft navigation. A multitude of flight trajectories and altitudes were exercised in the flight campaign in two different regions in Southern California, USA: (i) rural and (ii) semi-urban. Samples of the ambient downlink cellular SOPs were recorded, which were fed to ASPIN Laboratory's MATRIX (Multichannel Adaptive TRansceiver Information eXtractor) software-defined receiver (SDR), which produced carrier phase measurements from these samples. These measurements were fused with altimeter data via an extended Kalman filter (EKF) to estimate the aircraft's trajectory. This paper shows for the first time that at altitudes as high as about 11,000 ft above ground level (AGL), more than 100 cellular long-term evolution (LTE) eNodeBs can be reliably tracked, many of which were more than 100 km away, with carrier-to-noise ratio (C/N_0) exceeding 40 dB-Hz. The paper shows pseudorange and Doppler tracking results from cellular eNodeBs along with the C/N_0 and number of tracked eNodeBs over the two regions, while performing ascending, descending, and grid maneuvers. In addition, the paper shows navigation results in the semi-urban and rural regions, showing a position root mean-squared error of 9.86 m and 10.37, respectively, over trajectories of 42.23 km and 56.56 km, respectively, while exploiting an average of about 19 and 10 eNodeBs, respectively.

I. INTRODUCTION

A quick search of the phrase "global positioning system (GPS)" on the aviation safety reporting system (ASRS) returns 579 navigation-related incidents since January 2000. Out of these incidents, 508 were reported to be due to a malfunction or failure in GPS and other satellite navigation components. Among these, 100 are suspected to be due to GPS jamming and interference leading to the loss of the main and auxiliary GPS units in some cases.

Over the past few years, global navigation satellite system (GNSS) radio frequency interference (RFI) incidents skyrocketed, jeopardizing safe and efficient aviation operations. RFI sources include repeaters and pseudolites, GNSS jammers, and systems transmitting outside the GNSS frequency bands (Blasch et al., 2019). According to EUROCONTROL, a pan-European, civil-military organization dedicated to supporting European aviation, there were 4,364 GNSS outages reported by pilots in 2018, which represents more than a 2,000% increase over the previous year (EUROCONTROL, Aviation Intelligence Unit, 2021). What is alarming is that while the majority of RFI hotspots appear to be due to conflict zones, they affected civil aviation at distances of up to 300 km from these zones. The majority of RFI (about 81%) affected en-route flights, even though this is where RFI should be at its lowest, as the aircraft is faraway from a ground-based interferer. In 2019, the International Civil Aviation Organization (ICAO) issued a Working Paper titled "An Urgent Need to Address Harmful Interferences to GNSS," where it concluded that harmful RFI to GNSS would prevent the full continuation of safety and efficiency benefits of GNSS-based services (International Civil Aviation Organization (ICAO), 2019). ICAO followed this by an "Action Required" letter for "Strengthening of Communications, Navigation, and Surveillance (CNS) Systems Resilience and Mitigation of Interference to Global Navigation Satellite System (GNSS)" (International Civil Aviation Organization (ICAO), 2020).

In 2021, the National Institute of Standards and Technology (NIST) issued a report on "Foundational PNT Profile: Applying

the Cybersecurity Framework for the Responsible Use of PNT Services,” where it identified signals of opportunity (SOPs) and terrestrial RF sources (e.g., cellular) as a mitigation category that apply to the PNT profile (Bartock et al., 2021). Indeed, SOPs (Leng et al., 2016; Casado et al., 2018; Mortier et al., 2020; Kassas et al., 2020; Zhu et al., 2021; Psiaki and Slosman, 2022), particularly from cellular infrastructure, have shown tremendous promise over the past decade as an alternative PNT source (del Peral-Rosado et al., 2017; Ikhtiari, 2019; Souli et al., 2020; Gante et al., 2020; Kassas, 2021; Souli et al., 2021a; Xhafa et al., 2021; Ivanov et al., 2023).

Among various cellular generations, the forth-generation (4G) long-term evolution (LTE), which adopts orthogonal frequency division multiplexing (OFDM) as a modulation technique, possesses desirable attributes for navigation purposes:

- **Abundance:** LTE transmitters (also known as evolved Node Bs or eNodeBs) are abundant in many locales of interest.
- **Geometric diversity:** eNodeBs possess favorable geometric configurations by construction of the cellular infrastructure.
- **Frequency diversity:** eNodeBs transmit in a wide range of frequencies.
- **High received power:** LTE’s received carrier-to-noise (C/N_0) ratio is tens of dBs higher than that of GNSS signals, even indoors (Abdallah et al., 2021).
- **High bandwidth:** LTE’s bandwidth can be up to 20 MHz, which allows for more accurate time-of-arrival estimation (Shamaei et al., 2017).
- **Free to use:** The LTE infrastructure is already operational; thus, with specialized receivers, navigation observables can be extracted from LTE’s “always on” transmitted signals.

Cellular LTE signals have shown high ranging and localization accuracy (del Peral-Rosado et al., 2018; Kang et al., 2019; Gadka et al., 2019; Han et al., 2019; Shamaei and Kassas, 2021; Souli et al., 2021b; Kazaz et al., 2022; Yang et al., 2022; Wang and Morton, 2022), even in urban and indoor environments experiencing severe multipath (Wang and Morton, 2020; Dun et al., 2020; Wang and Morton, 2020; Abdallah and Kassas, 2021; Strandjord et al., 2021; Wang et al., 2022; Whiton et al., 2022; Jao et al., 2022; Pan et al., 2022) and environments under intentional GPS jamming (Kassas et al., 2022b). Experimental navigation results with LTE signals demonstrated meter-level positioning accuracy on ground vehicles (Shamaei et al., 2019; del Peral-Rosado et al., 2019; Yang et al., 2020; Soderini et al., 2020; Hong et al., 2021; Maaref and Kassas, 2022; Lapin et al., 2022) and sub-meter-level positioning accuracy on unmanned aerial (UAVs) (Khalife and Kassas, 2022b,a).

However, the potential of cellular LTE signals for high-altitude aircraft navigation has been largely unstudied (Kim and Shin, 2019; Stevens and Younis, 2021). To the authors’ knowledge, the first such studies appeared in (Kassas et al., 2022a,c). The results therein were achieved from a collaboration between the United States Air Force (USAF) at Edwards Air Force Base (AFB), California and the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory through a week-long flight campaign called “SNIFFER: Signals of opportunity for Navigation In Frequency-Forbidden EnviRonments.” In SNIFFER, ASPIN Laboratory’s Multichannel Adaptive TRansceiver Information eXtractor (MATRIX) specialized software-defined receiver (SDR) was flown on a Beechcraft C-12 Huron, a fixed-wing USAF aircraft, to collect ambient cellular LTE signals. The collected data consisted of combinations of flight runs performed over three regions: (A) Edwards: rural; (B) Palmdale: semi-urban; (C) Riverside: urban. The flights spanned different altitudes (up to 23,000 ft above ground level (AGL)) and a multitude of trajectories including straight segments, banking turns, benign and aggressive maneuvers, and ascending and descending teardrops with a descent rate ranging between 0 to 1500 ft/min. The flights were performed by members of the USAF Test Pilot School (TPS). Terabytes of LTE data was collected over the three regions under various conditions.

The main conclusions from the studies in (Kassas et al., 2022a,c) were:

- Cellular LTE signals are surprisingly powerful at both (i) high altitudes, exhibiting C/N_0 of 25–55 dB-Hz at altitudes of 2,000–23,000 ft AGL and (ii) faraway horizontal distances, exhibiting C/N_0 of about 30 dB-Hz for towers as far as 50 km, while flying at about 16,000 ft AGL.
- The two-ray model fits the measured C/N_0 sufficiently well for towers more than 10 km away, while flying at an altitude of 16,000 ft AGL. For towers closer than 10 km, the antenna radiation pattern should be incorporated into the two-ray model to improve model fitting.
- With carrier phase navigation observables produced by the MATRIX SDR from 5 4G LTE eNodeBs and 6 3G code-division multiple-access (CDMA) base transceiver stations (BTSs), fused with altimeter measurements via an extended Kalman filter (EKF), a three-dimensional (3-D) position root mean-squared error (RMSE) of 10.5 m was achieved over a 51-km trajectory traversed in 9 minutes.

Upon improving the MATRIX SDR design to exploit an eNodeB’s multiple antenna ports and the time-orthogonality of OFDM signals, the number of acquirable and trackable LTE eNodeBs grew monumentally, from less than a dozen as reported in (Kassas et al., 2022a,c) to more than 100. This paper presents these findings. In particular, for three different maneuvers (climbing

teardrop, descending teardrop, and grid) in Regions A and B¹, the results were consistent: the number of tracked eNodeBs at altitudes as high as 11,000 ft AGL can be higher than 100, with C/N_0 over 40 dB-Hz. In addition, upon fusing the carrier phase observables with altimeter data via an EKF, a sustained accurate and robust navigation solution was achieved. In particular, over trajectories of 42.23 km and 56.56 km in regions B and A, respectively, traversed in 450 s and 600 s, respectively, a 3-D position RMSE of 9.86 m and 10.37, respectively, was achieved by exploiting an average of about 19 and 10 eNodeBs², respectively.

The rest of the paper is organized as follows: Section II overviews the hardware and software setup with which the aircraft was equipped and overviews the environments in which the flight campaigns took place. Section III presents experimental characterization of tracked cellular LTE signals as a function of their C/N_0 and total number over different aircraft maneuvers. Section IV summarizes the cellular LTE navigation results. Section V gives concluding remarks.

II. EXPERIMENTAL SETUP AND FLIGHT REGIONS

This section overviews the hardware and software setup used for data collection and processing. It also describes the flight regions and aircraft maneuvers.

1. Hardware and Software Setup

For this study, the C-12 aircraft, called Ms. Mabel, was equipped with

- A quad-channel universal software radio peripheral (USRP)-2955.
- Three consumer-grade 800/1900 MHz Laird cellular antennas.
- A peripheral component interconnect express (PCIe) cable.
- A desktop computer equipped with a solid-state drive for data storage.
- A laptop computer running ASPIN Laboratory's MATRIX SDR for real-time monitoring of the signals, which was operated during the flight by a flight engineer to determine when, where, and what cellular signals were available to tune the USRP accordingly.
- A GPS antenna to (i) feed GPS measurements for the aircraft navigation system and (ii) discipline the USRP's onboard GPS-disciplined oscillator (GPSDO).

Figure 1 shows the C-12 aircraft and the USAF pilots and ASPIN researchers. The equipment was assembled at the ASPIN Laboratory on a special rack provided by the USAF and was shipped to be mounted on the C-12 aircraft. The three Laird antennas were connected to the USRP to capture impinging 4G LTE signals, and the USRP was tuned to listen to three carrier frequencies corresponding to two 4G U.S. cellular providers and one 3G³ U.S. cellular provider as shown in Figure 2. Terabytes of in-phase and quadrature samples were collected throughout the experiment with a sampling rate of 10 MSps per channel. The 4G cellular module of the MATRIX SDR (Kassas et al., 2020) was then used to post-process the stored samples to produce navigation observables: Doppler frequency, carrier phase, and pseudorange, along with corresponding C/N_0 's. The hardware and software setup are shown in Figures 2–3, respectively.

2. Flight Regions and Aircraft Maneuvers

The campaign took place in three regions: (i) Region A: a rural region in Edwards AFB, California, (ii) Region B: a semi-urban region in Palmdale, California, and (iii) Region C: an urban region in Riverside, California. Different maneuvers were planned over the three regions to test several aspects of aircraft navigation with cellular SOPs.

Figure 4 shows the regions in which the experiments were performed. More than 70 3G BTSs and 4G eNodeBs were mapped throughout the experiment via the method described in (Morales and Kassas, 2018). The mapped towers were cross-checked via Google Earth and online databases and are shown in Figure 4. This paper investigates the potential of cellular SOPs for navigation; therefore, mapping the SOPs will not be discussed.

Two main types of maneuvers were performed in each region (see Figure 4). The first was a teardrop-like pattern while climbing/descending. The patterns have a focal point that is aligned with a geographic points of interest (see the green “×” in Figure 4). The measurements used to characterize the C/N_0 were taken exactly above the geographic point of interest to maintain the horizontal distance between the aircraft and the cellular base stations. The second was a grid-like pattern with many turns and straight segments. Such patterns were used as stress-test for the navigation receivers to assess their ability to track cellular synchronization signals in a robust and accurate fashion as well as to evaluate the navigation solution.

¹At the time of writing of this paper, the data collected in Region C has not been processed with the improved MATRIX SDR yet.

²At the time of writing of this paper, not all 100+ eNodeBs in the environment were mapped yet. Only eNodeBs whose positions were mapped were used in the EKF.

³This paper focuses on the 4G LTE signals only. Results for 3G signals were published in (Kassas et al., 2022c).



Figure 1: USAF Pilots and ASPIN researchers with the C-12 aircraft.

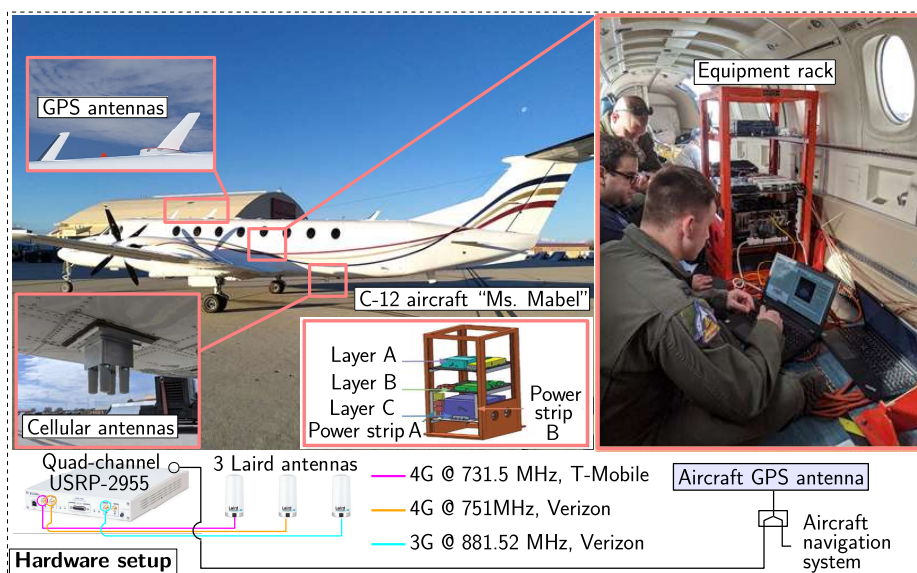


Figure 2: Hardware setup with which the C-12 aircraft was equipped.

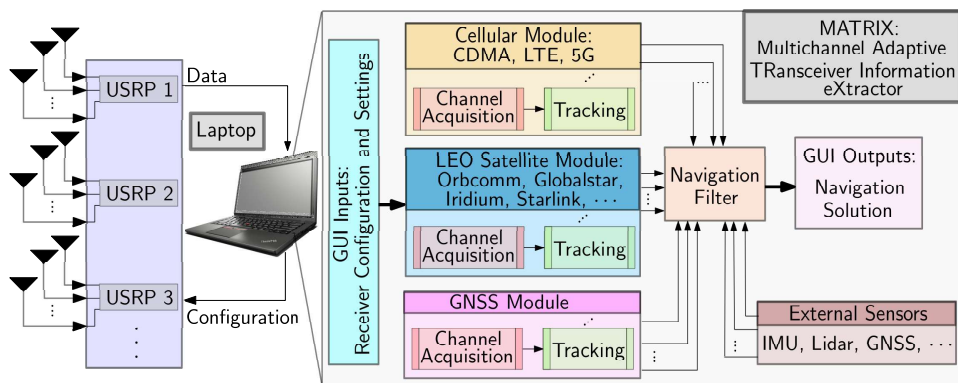


Figure 3: Software setup used for cellular SOP signal collection.

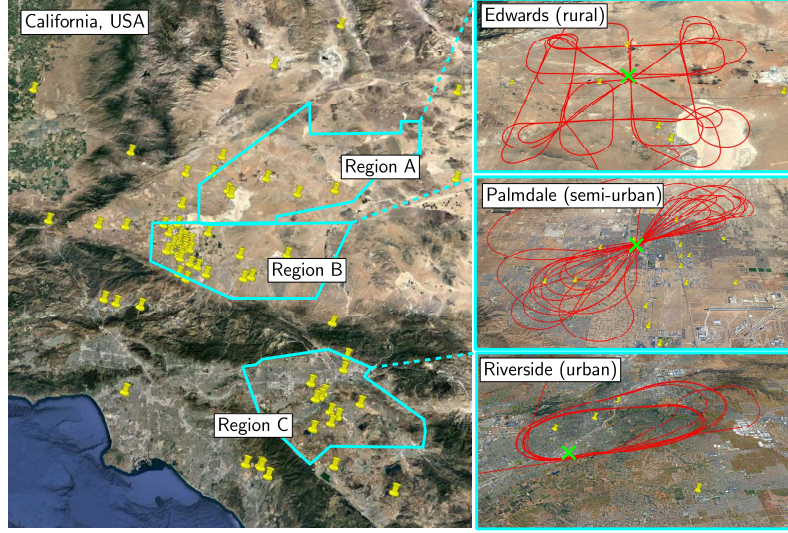


Figure 4: Regions A, B, and C in which the flight campaigns took place. The yellow pins represent 3G and 4G cellular towers that were mapped and analyzed in this study. The right figures show the aircraft trajectory in all regions (shown in red).

III. CELLULAR LTE AVAILABILITY AND C/N_0 CHARACTERIZATION

This section presents experimental results evaluating cellular LTE availability in Regions A and B with the improved MATIX SDR. To this end, Figures 5 – 10 show the outputs of the navigation observables produced by the receiver (pseudorange and Doppler) along with the C/N_0 and number of tracked LTE eNodeBs during various flight trajectories.

The following conclusions can be made from these results. First, while the results presented in (Kassas et al., 2022c,a) revealed tremendous potential for tracking cellular LTE signals at high-altitude aircraft, there is more room for improvement from a receiver design perspective. In particular, the improved receiver design increased the sensitivity of the receiver, enabling it to track much weaker signals from further away eNodeBs. Second, in rural and semi-urban regions, the aircraft could track more than 100 eNodeBs simultaneously, some of which were more than 100 km away. No matter the aircraft maneuvers, tens of eNodeBs were trackable. A significant factor behind the change in the number of tracked eNodeBs is attributed to the aircraft's body and wings causing signal blockage and severe attenuation during banking.

IV. CELLULAR LTE NAVIGATION RESULTS

The navigation carrier phase observables produced by the improved MATRIX SDR were fused with altimeter data through the EKF navigation filter as described in (Kassas et al., 2022c). Note that the EKF employed herein employed a continuous Wiener process acceleration model for the aircraft's dynamics, in place of the nearly constant velocity dynamical model adopted in (Kassas et al., 2022c). The navigation performance in all three Regions is summarized in Table 1. It is worth emphasizing that the reported performance is expected to improve significantly if an inertial navigation system (INS) is coupled with the LTE navigation observables (e.g., via a tightly-coupled SOP-aided INS (Morales and Kassas, 2021)) and/or all the tracked eNodeBs (see Figures 5 – 10) are exploited in the EKF.

Table 1: Navigation Performance with Cellular LTE Signals

Metric	Region B	Region A
Number of cellular towers used	11 – 28	5 – 16
Cellular frequencies (MHz)	731.5 751 739	731.5 751
Flight duration (sec)	450	600
Flight length (km)	42.23	56.56
Altitude AGL (m)	2,295 – 2,316	1,079 – 1,394
Position RMSE (m)	9.86	10.37
Standard deviation (m)	5.92	4.39
Maximum position error (m)	35.26	24.42

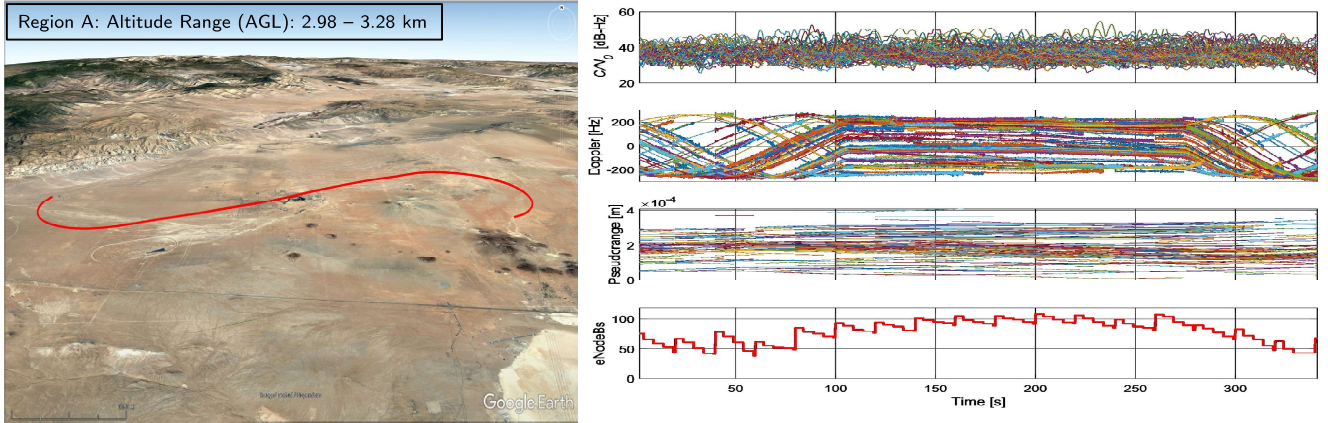


Figure 5: Left: climbing teardrop aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

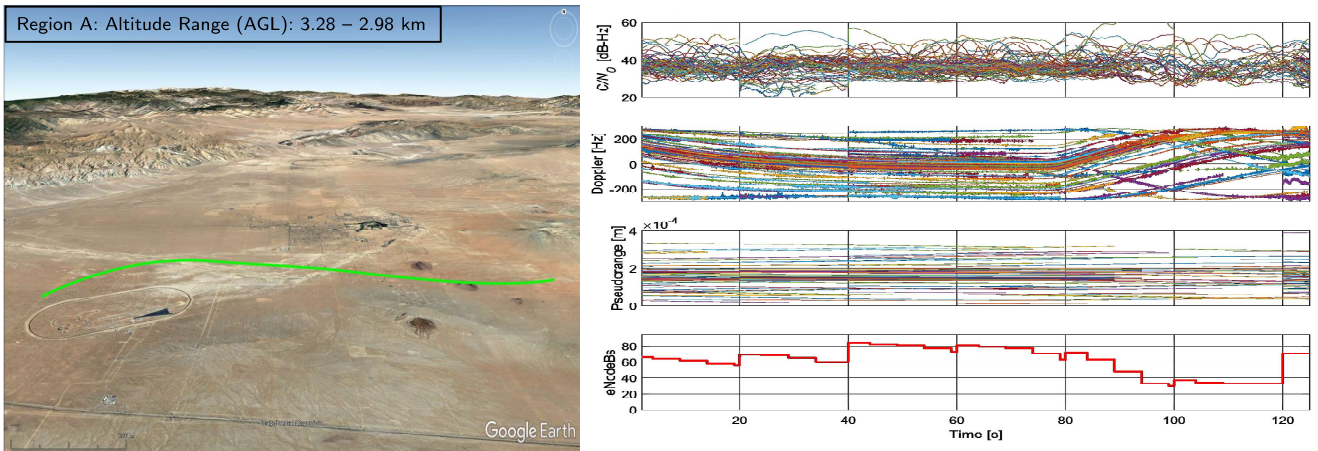


Figure 6: Left: descending teardrop aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

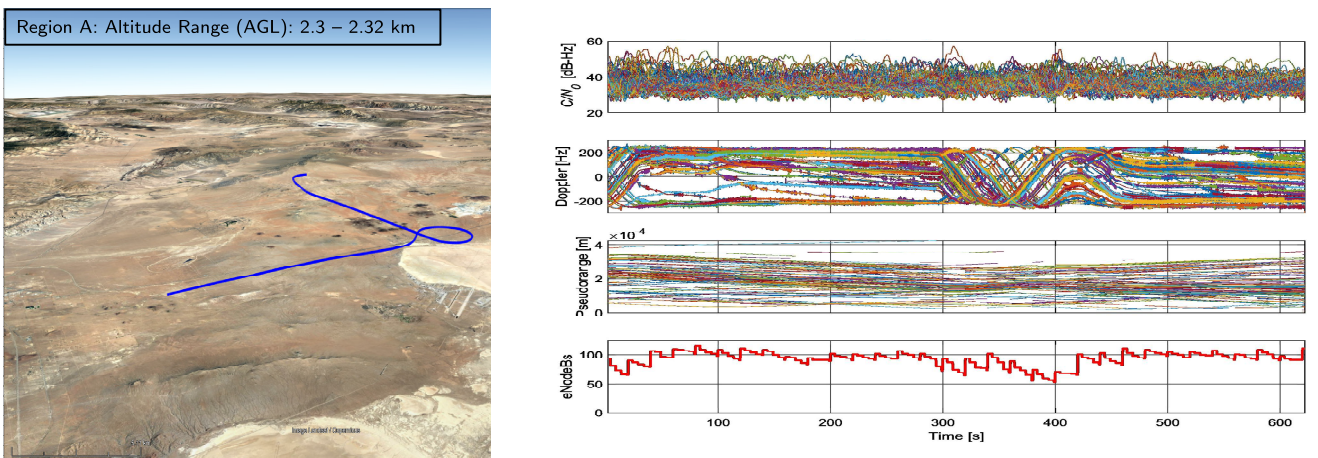


Figure 7: Left: grid aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

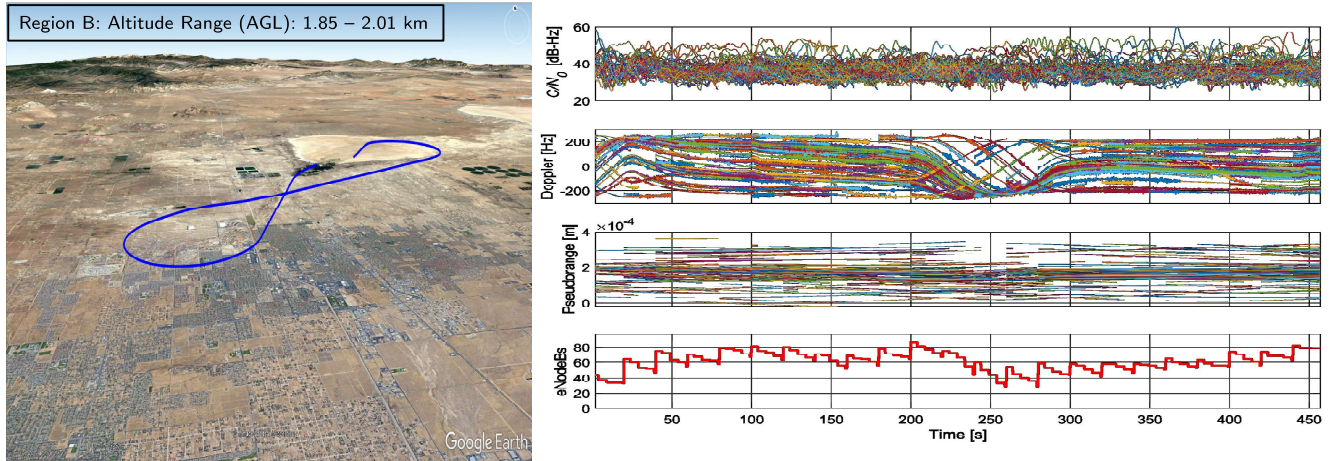


Figure 8: Left: climbing teardrop aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

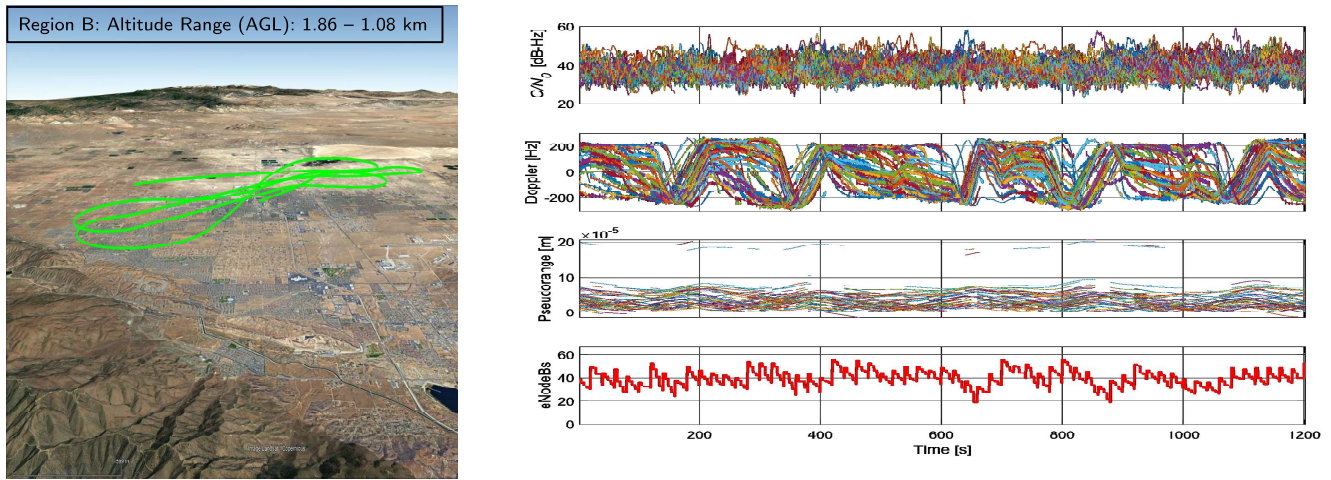


Figure 9: Left: descending teardrop aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

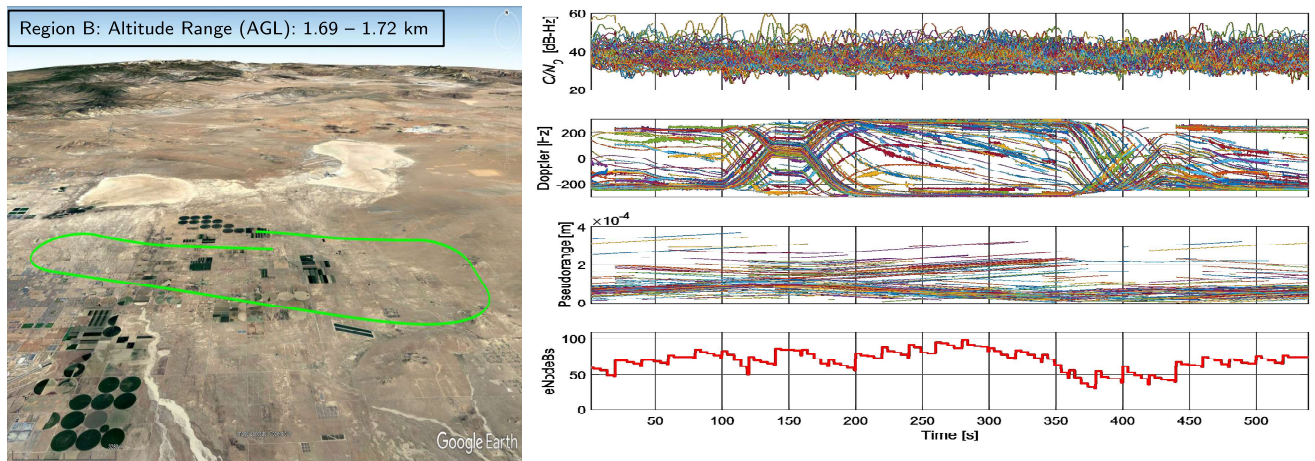


Figure 10: Left: grid aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

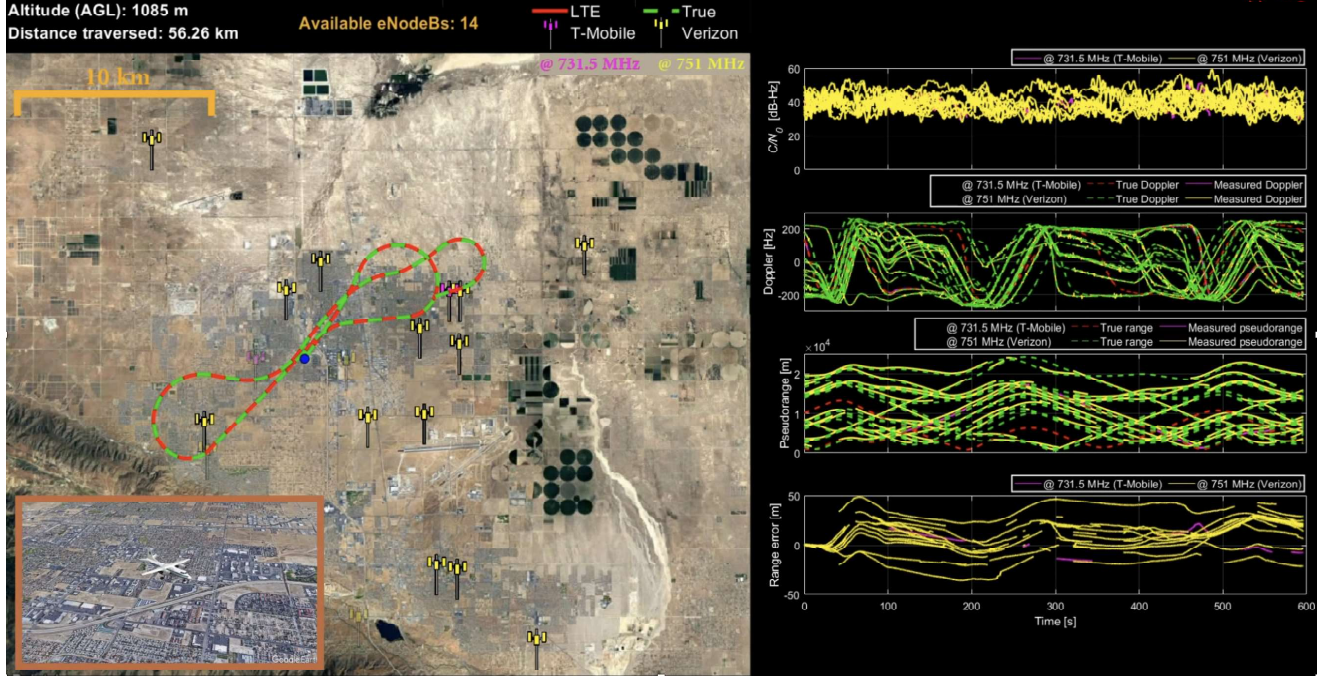


Figure 11: Left: Region A environment layout showing the cellular eNodeBs' locations and aircraft's true and estimated trajectories (from LTE signals). Right: LTE pseudorange and Doppler tracking during this trajectory along with C/N_0 and number of tracked LTE eNodeBs.

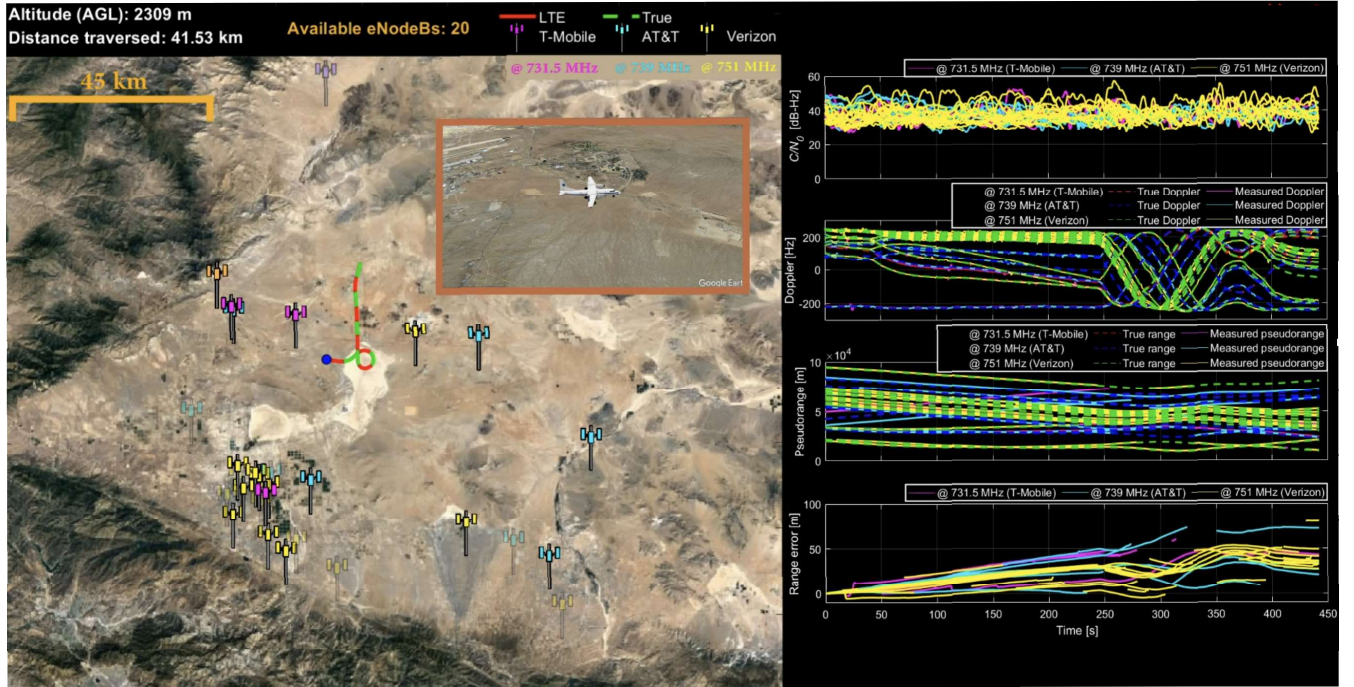


Figure 12: Left: Region B environment layout showing the cellular eNodeBs' locations and aircraft's true and estimated trajectories (from LTE signals). Right: LTE pseudorange and Doppler tracking during this trajectory along with C/N_0 and number of tracked LTE eNodeBs.

V. CONCLUSION

This paper unveiled the tremendous potential of cellular SOPs as a viable aircraft navigation system backup. SNIFFER flight campaign data were re-processed with an improved LTE receiver design, enabling the tracking of more than 100 eNodeBs simultaneously, many of which were more than 100 km away, with C/N_0 exceeding 40 dB-Hz. In addition, the paper showed navigation results in rural and semi-urban regions, showing a position root mean-squared error of 9.86 m and 10.37, respectively,

over trajectories of 42.23 km and 56.56 km, respectively, while exploiting an average of about 19 and 10 eNodeBs, respectively.

ACKNOWLEDGEMENTS

The authors would like to thank Edwards AFB and Holloman AFB for inviting the ASPIN Laboratory to conduct experiments on Air Force aircraft in the “SNIFFER: Signals of opportunity for Navigation In Frequency-Forbidden EnviRonments” flight campaign. The authors would like to thank Joshua Morales, Kimia Shamaei, Mahdi Maaref, Kyle Semelka, MyLinh Nguyen, and Trier Mortlock for their help with preparing for data collection. DISTRIBUTION STATEMENT A. Approved for public release; Distribution is unlimited. 412TW-PA-20146.

This work was supported in part by the Office of Naval Research (ONR) under Grant N00014-19-1-2511 and Grant N00014-19-1-2613, in part by the National Science Foundation (NSF) under Grant 2240512, in part by the U.S. Department of Transportation (USDOT) under Grant 69A3552047138 for the CARMEN University Transportation Center (UTC), and in part by the Air Force Office of Scientific Research (AFOSR) under Grant FA9550-22-1-0476. This work was also supported in part by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. SAND2022-13901 C

REFERENCES

- Abdallah, A. and Kassas, Z. (2021). Multipath mitigation via synthetic aperture beamforming for indoor and deep urban navigation. *IEEE Transactions on Vehicular Technology*, 70(9):8838–8853.
- Abdallah, A., Khalife, J., and Kassas, Z. (2021). Experimental characterization of received 5G signals carrier-to-noise ratio in indoor and urban environments. In *Proceedings of IEEE Vehicular Technology Conference*, pages 1–5.
- Bartock, M., Brule, J., Li-Baboud, Y., Lightman, S., McCarthy, J., Reczek, K., Northrip, D., Scholz, A., and Suloway, T. (2021). Foundational PNT profile: Applying the cybersecurity framework for the responsible use of positioning, navigation, and timing (PNT) services. *National Institute of Standards and Technology (NIST)*, (NISTIR 8323).
- Blasch, E., Sabatini, R., Roy, A., Kramer, K., Andrew, G., Schmidt, G., Insaurralde, C., and Fasano, G. (2019). Cyber awareness trends in avionics. In *Proceedings of IEEE/AIAA Digital Avionics Systems Conference*, pages 1–8.
- Casado, A., Krauthammer, A., Olsen, S., and Valles, E. (2018). Environment-RF-based positioning using machine learning. In *Proceedings of ION GNSS+ Conference*, pages 3327–3334.
- del Peral-Rosado, J., Estatué-Castillo, R., Lopez-Salcedo, J., Seco-Granados, G., Chaloupka, Z., Ries, L., and Garcoa-Molina, J. (2017). Evaluation of hybrid positioning scenarios for autonomous vehicle applications. In *Proceedings of ION International Technical Meeting Conference*, pages 2541–2553.
- del Peral-Rosado, J., López-Salcedo, J., Zanier, F., and Seco-Granados, G. (2018). Position accuracy of joint time-delay and channel estimators in LTE networks. *IEEE Access*, 6:25185–25199.
- del Peral-Rosado, J., Renaudin, O., Gentner, C., Raulefs, R., Dominguez-Tijero, E., Fernandez-Cabezas, A., Blazquez-Luengo, F., Cueto-Felgueroso, G., Chassaing, A., Bartlett, D., Grec, F., Ries, L., Prieto-Cerdeira, R., Lopez-Salcedo, J., and Seco-Granados, G. (2019). Physical-layer abstraction for hybrid GNSS and 5G positioning evaluations. In *Proceedings of IEEE Vehicular Technology Conference*, pages 1–6.
- Dun, H., Tiberius, C., and Janssen, G. (2020). Positioning in a multipath channel using OFDM signals with carrier phase tracking. *IEEE Access*, 8:13011–13028.
- EUROCONTROL, Aviation Intelligence Unit (2021). Does radio frequency interference to satellite navigation pose an increasing threat to network efficiency, cost-effectiveness and ultimately safety? Technical report.
- Gadka, P., Sadowski, J., and Stefanski, J. (2019). Detection of the first component of the received LTE signal in the OTDoA method. *Wireless Communications and Mobile Computing*, pages 1–12.
- Gante, J., Sousa, L., and Falcao, G. (2020). Dethroning GPS: Low-power accurate 5G positioning systems using machine learning. *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, 10(2):240–252.
- Han, S., Kang, T., and Seo, J. (2019). Smartphone application to estimate distances from LTE base stations based on received signal strength measurements. In *International Technical Conference on Circuits/Systems, Computers and Communications*, pages 1–3.

- Hong, T., Sun, J., Jin, T., Yi, Y., and Qu, J. (2021). Hybrid positioning with DTMB and LTE signals. In *Proceedings of International Wireless Communications and Mobile Computing*, pages 303–307.
- Ikhtiari, N. (2019). Navigation in GNSS denied environments using software defined radios and LTE signals of opportunities. Master's thesis, University of Canterbury, Christchurch, New Zealand.
- International Civil Aviation Organization (ICAO) (2019). An urgent need to address harmful interferences to GNSS. Technical report.
- International Civil Aviation Organization (ICAO) (2020). Strengthening of communications, navigation, and surveillance (CNS) systems resilience and mitigation of interference to global navigation satellite system (GNSS). Technical report.
- Ivanov, A., Koshncharova, D., Tonchev, K., and Poulkov, V. (2023). Localization in cellular and heterogeneous networks for 5G and beyond: A review. *Journal of Mobile Multimedia*, pages 47–72.
- Jao, C., Abdallah, A., Chen, C., Seo, M., Kia, S., Kassas, Z., and Shkel, A. (2022). Sub-meter accurate pedestrian indoor navigation system with dual ZUPT-aided INS, machine learning-aided LTE, and UWB signals. In *Proceedings of ION GNSS+ Conference*. accepted.
- Kang, T., Lee, H., and Seo, J. (2019). Analysis of the maximum correlation peak value and RSRQ in LTE signals according to frequency bands and sampling frequencies. In *International Conference on Control, Automation and Systems*, pages 1182–1186.
- Kassas, Z. (2021). Position, navigation, and timing technologies in the 21st century. volume 2, chapter 38: Navigation with Cellular Signals of Opportunity, pages 1171–1223. Wiley-IEEE.
- Kassas, Z., Abdallah, A., Khalife, J., Lee, C., Jurado, J., Duede, J., Hoeffner, Z., Hulsey, T., Quirarte, R., Wachtel, S., and Tay, R. (2022a). Received power characterization of terrestrial cellular signals on high altitude aircraft. In *Proceedings of IEEE Aerospace Conference*, pages 1–8.
- Kassas, Z., Khalife, J., Abdallah, A., and Lee, C. (2020). I am not afraid of the jammer: navigating with signals of opportunity in GPS-denied environments. In *Proceedings of ION GNSS Conference*, pages 1566–1585.
- Kassas, Z., Khalife, J., Abdallah, A., and Lee, C. (2022b). I am not afraid of the GPS jammer: resilient navigation via signals of opportunity in GPS-denied environments. *IEEE Aerospace and Electronic Systems Magazine*, 37(7):4–19.
- Kassas, Z., Khalife, J., Abdallah, A., Lee, C., Jurado, J., Wachtel, S., Duede, J., Hoeffner, Z., Hulsey, T., Quirarte, R., and Tay, R. (2022c). Assessment of cellular signals of opportunity for high altitude aircraft navigation. *IEEE Aerospace and Electronic Systems Magazine*, 37(10):4–19.
- Kazaz, T., Janssen, G., Romme, J., and Van der Veen, A. (2022). Delay estimation for ranging and localization using multiband channel state information. *IEEE Transactions on Wireless Communications*, 21(4):2591–2607.
- Khalife, J. and Kassas, Z. (2022a). Differential framework for submeter-accurate vehicular navigation with cellular signals. *IEEE Transactions on Intelligent Vehicles*. accepted.
- Khalife, J. and Kassas, Z. (2022b). On the achievability of submeter-accurate UAV navigation with cellular signals exploiting loose network synchronization. *IEEE Transactions on Aerospace and Electronic Systems*. accepted.
- Kim, E. and Shin, Y. (2019). Feasibility analysis of LTE-based UAS navigation in deep urban areas and DSRC augmentation. *Sensors*, 19(9):4192–4207.
- Lapin, I., Granados, G., Samson, J., Renaudin, O., Zanier, F., and Ries, L. (2022). STARE: Real-time software receiver for LTE and 5G NR positioning and signal monitoring. In *Proceedings of Workshop on Satellite Navigation Technology*, pages 1–11.
- Leng, M., Quitin, F., Tay, W., Cheng, C., Razul, S., and See, C. (2016). Anchor-aided joint localization and synchronization using SOOP: Theory and experiments. *IEEE Transactions on Wireless Communications*, 15(11):7670–7685.
- Maaref, M. and Kassas, Z. (2022). Autonomous integrity monitoring for vehicular navigation with cellular signals of opportunity and an IMU. *IEEE Transactions on Intelligent Transportation Systems*, 23(6):5586–5601.
- Morales, J. and Kassas, Z. (2018). Optimal collaborative mapping of terrestrial transmitters: receiver placement and performance characterization. *IEEE Transactions on Aerospace and Electronic Systems*, 54(2):992–1007.
- Morales, J. and Kassas, Z. (2021). Tightly-coupled inertial navigation system with signals of opportunity aiding. *IEEE Transactions on Aerospace and Electronic Systems*, 57(3):1930–1948.

- Mortier, J., Pages, G., and Vila-Valls, J. (2020). Robust TOA-based UAS navigation under model mismatch in GNSS-denied harsh environments. *Remote Sensing*, 12(18):2928–2947.
- Pan, M., Liu, P., Liu, S., Qi, W., Huang, Y., You, X., Jia, X., and Li, X. (2022). Efficient joint DOA and TOA estimation for indoor positioning with 5G picocell base stations. *IEEE Transactions on Instrumentation and Measurement*, 71:1–19.
- Psiaki, M. and Slosman, B. (2022). Tracking digital FM OFDM signals for the determination of navigation observables. *NAVIGATION, Journal of the Institute of Navigation*, 69(2).
- Shamaei, K. and Kassas, Z. (2021). A joint TOA and DOA acquisition and tracking approach for positioning with LTE signals. *IEEE Transactions on Signal Processing*, pages 2689–2705.
- Shamaei, K., Khalife, J., and Kassas, Z. (2017). Comparative results for positioning with secondary synchronization signal versus cell specific reference signal in LTE systems. In *Proceedings of ION International Technical Meeting Conference*, pages 1256–1268.
- Shamaei, K., Morales, J., and Kassas, Z. (2019). A framework for navigation with LTE time-correlated pseudorange errors in multipath environments. In *Proceedings of IEEE Vehicular Technology Conference*, pages 1–6.
- Soderini, A., Thevenon, P., Macabiau, C., Borgagni, L., and Fischer, J. (2020). Pseudorange measurements with LTE physical channels. In *Proceedings of ION International Technical Meeting*, pages 817–829.
- Souli, N., Kolios, P., and Ellinas, G. (2020). Relative positioning of autonomous systems using signals of opportunity. In *Proceedings of IEEE Vehicular Technology Conference*, pages 1–6.
- Souli, N., Kolios, P., and Ellinas, G. (2021a). Online relative positioning of autonomous vehicles using signals of opportunity. *IEEE Transactions on Intelligent Vehicles*, pages 1–1.
- Souli, N., Makrigiorgis, R., Kolios, P., and Ellinas, G. (2021b). Real-time relative positioning system implementation employing signals of opportunity, inertial, and optical flow modalities. In *Proceedings of International Conference on Unmanned Aircraft Systems*, pages 229–236.
- Stevens, B. and Younis, M. (2021). Detection algorithm for cellular synchronization signals in airborne applications. *IEEE Access*, 9:55555–55566.
- Strandjord, K., Morton, Y., and Wang, P. (2021). Evaluating the urban signal environment for GNSS and LTE signals. In *Proceedings of ION GNSS+ Conference*, pages 2166–2182.
- Wang, P. and Morton, Y. (2020). Multipath estimating delay lock loop for LTE signal TOA estimation in indoor and urban environments. *IEEE Transactions on Wireless Communications*, 19(8):5518–5530.
- Wang, P. and Morton, Y. (2020). Performance comparison of time-of-arrival estimation techniques for LTE signals in realistic multipath propagation channels. *NAVIGATION, Journal of the Institute of Navigation*, 67(4):691–712.
- Wang, P. and Morton, Y. (2022). Impact analysis of inter-cell interference in cellular networks for navigation applications. *IEEE Transactions on Aerospace and Electronic Systems*. accepted.
- Wang, P., Wang, Y., and Morton, J. (2022). Signal tracking algorithm with adaptive multipath mitigation and experimental results for LTE positioning receivers in urban environments. *IEEE Transactions on Aerospace and Electronic Systems*, 58(4):2779–2795.
- Whiton, R., Chen, J., Johansson, T., and Tufvesson, F. (2022). Urban navigation with LTE using a large antenna array and machine learning. In *Proceedings of IEEE Vehicular Technology Conference*, pages 1–5.
- Khafa, A., del Peral-Rosado, J., López-Salcedo, J., and Seco-Granados, G. (2021). Evaluation of 5G positioning performance based on UTDa, AoA and base-station selective exclusion. *Sensors*, 22(1):101–118.
- Yang, C., Arizabaleta-Diez, M., Weitkemper, P., and Pany, T. (2022). An experimental analysis of cyclic and reference signals of 4g LTE for TOA estimation and positioning in mobile fading environments. *IEEE Aerospace and Electronic Systems Magazine*, 37(9):16–41.
- Yang, C., Pany, T., and Weitkemper, P. (2020). Effect of antenna ports on TOA estimation with 4G LTE signals in urban mobile environments. In *Proceedings of ION International Technical Meeting*, pages 2166–2181.
- Zhu, H., Xu, W., Sang, Y., Yao, Z., Liu, L., and Okonkw, M. (2021). Mobile communication signal selection algorithm for signal of opportunity navigation. In *Proceedings of International Conference on Advanced Communication Technology*, pages 166–171.