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

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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 reliable 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 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 where 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 SINFFER, 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 eNodB'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 B[1], 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 eNodeBs[2], 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 3G[3] 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.

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

[2] At 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.

[3] This 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.

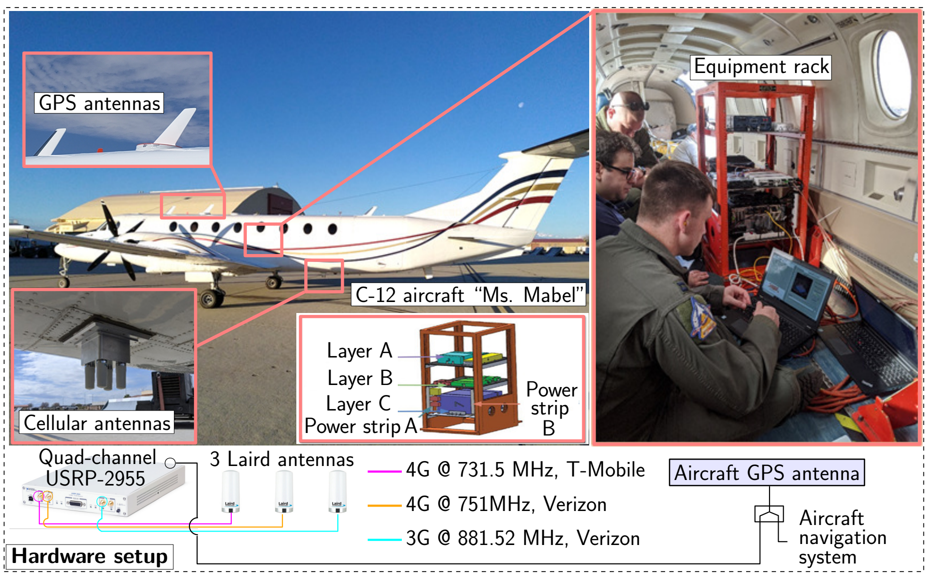

Figure 2: Hardware setup with which the C-12 aircraft was equipped.

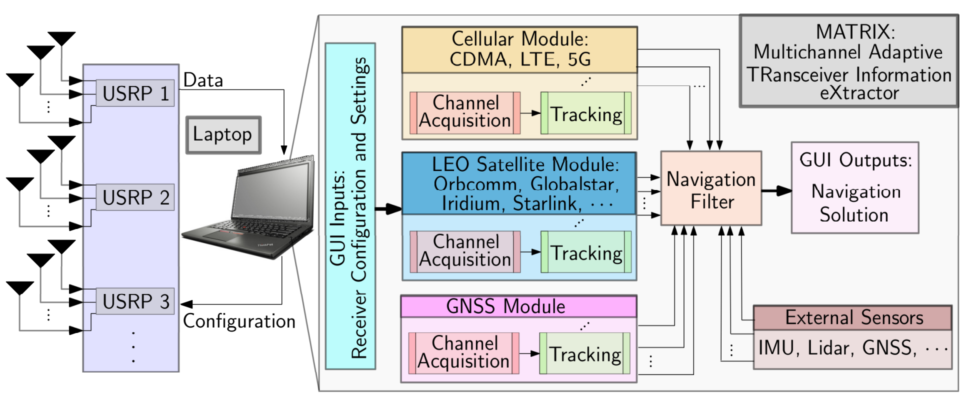

Figure 3: Software setup used for cellular SOP signal collection.

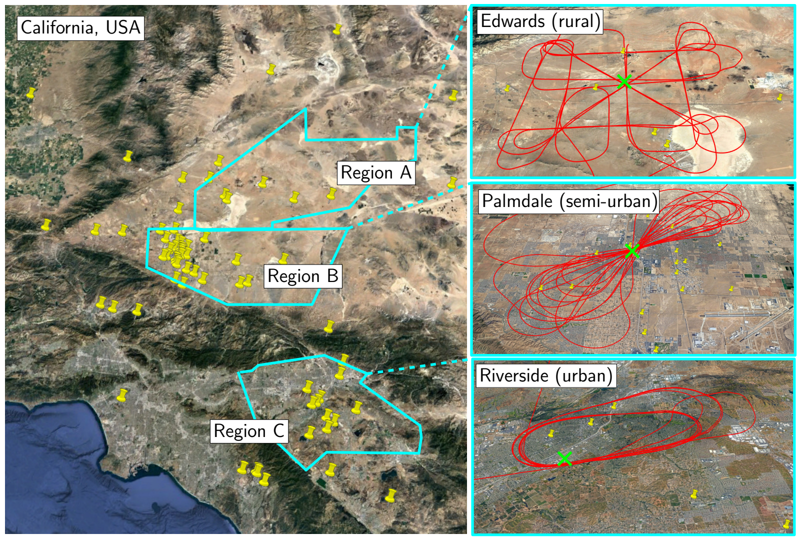

Figure 4: Regions A, B, and C in which the flight campaigns took place. The yellow pins represent 3G and 4G cellular towers that were mapped and analyzed in this study. The right figures show the aircraft trajectory in all regions (shown in red).

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	731.5
	751	751
	739	
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

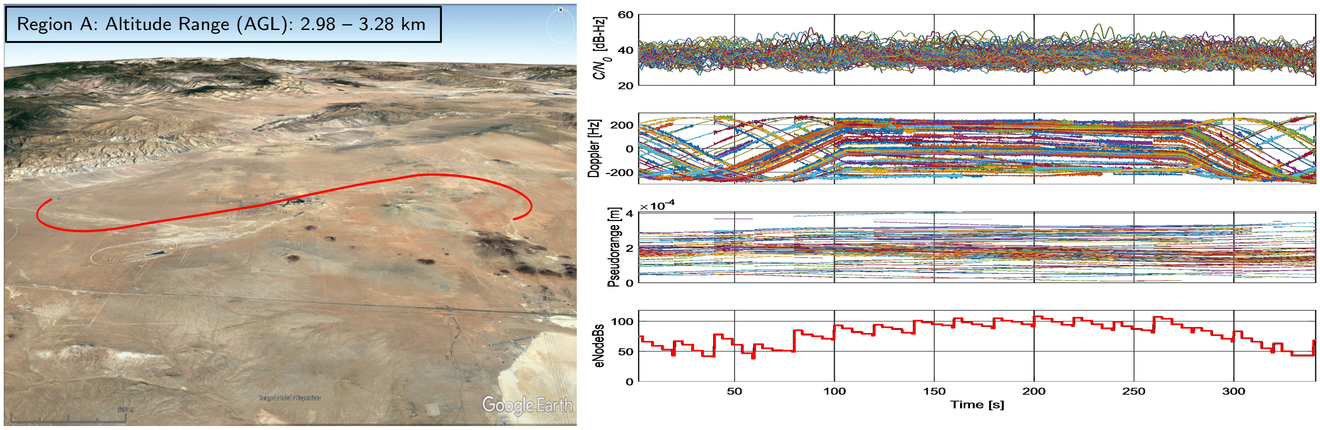

Figure 5: Left: climbing teardrop aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

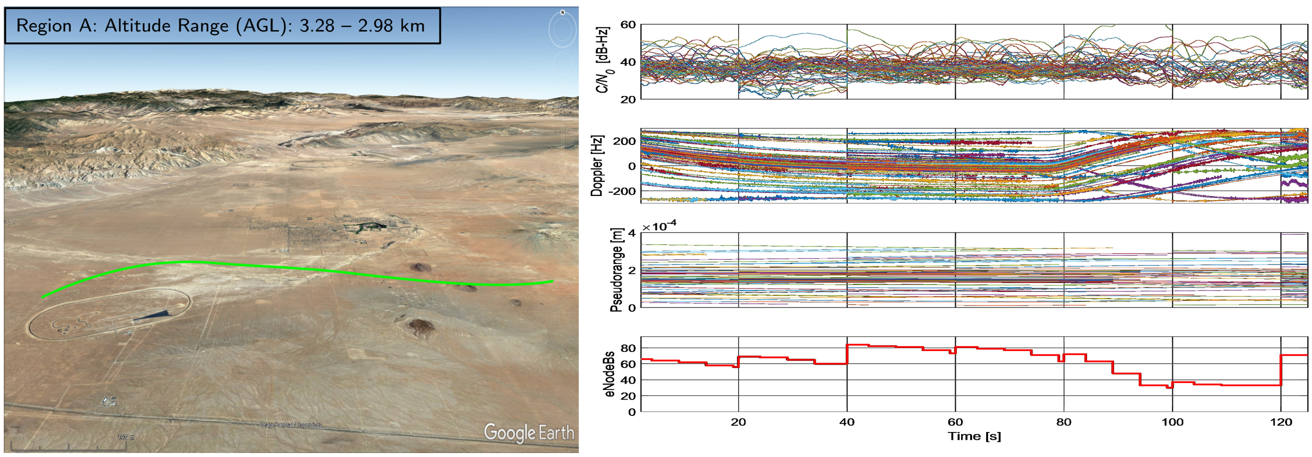

Figure 6: Left: descending teardrop aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

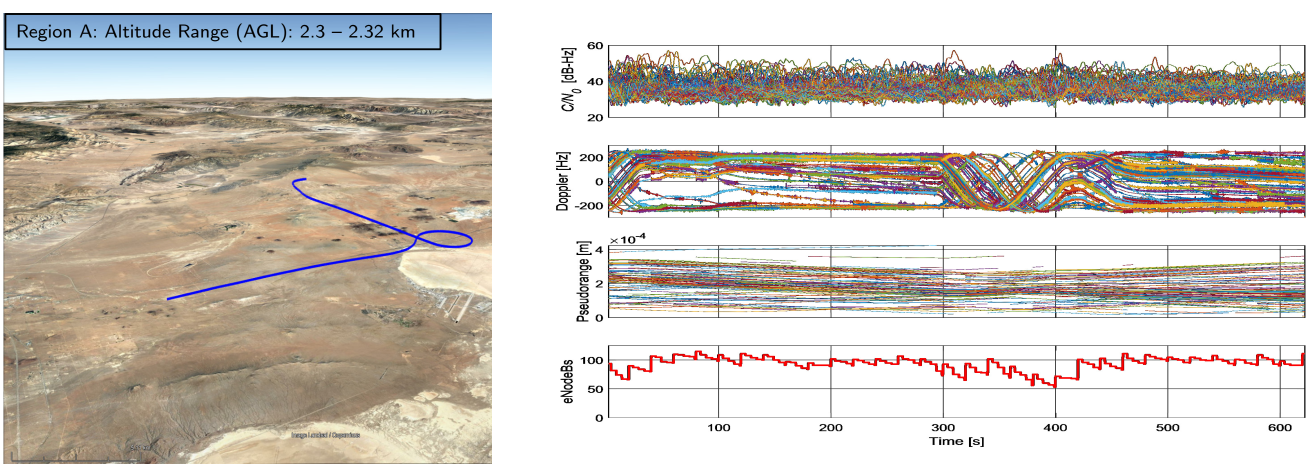

Figure 7: Left: grid aircraft trajectory in Region A. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

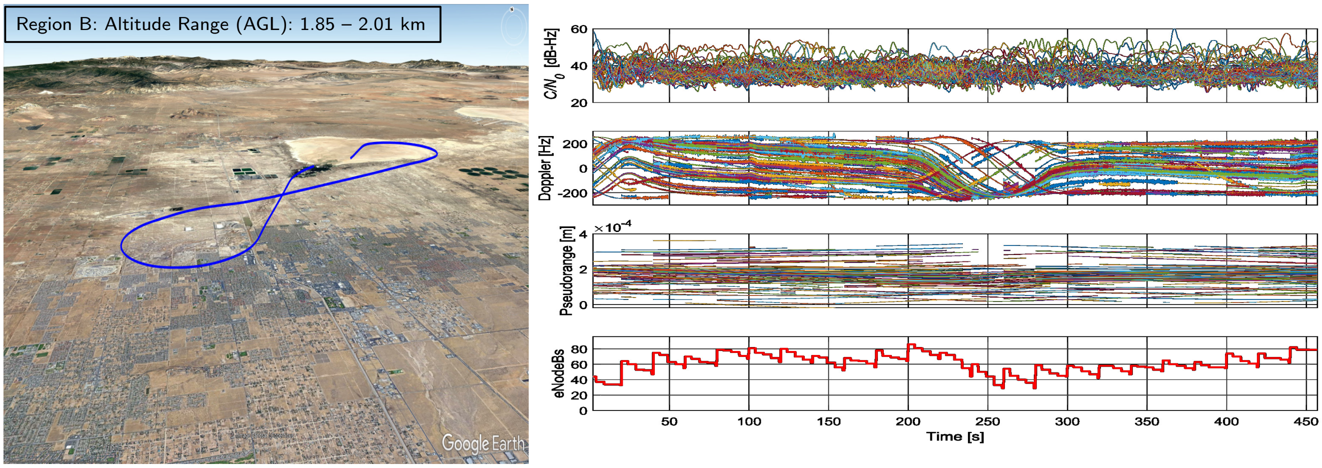

Figure 8: Left: climbing teardrop aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

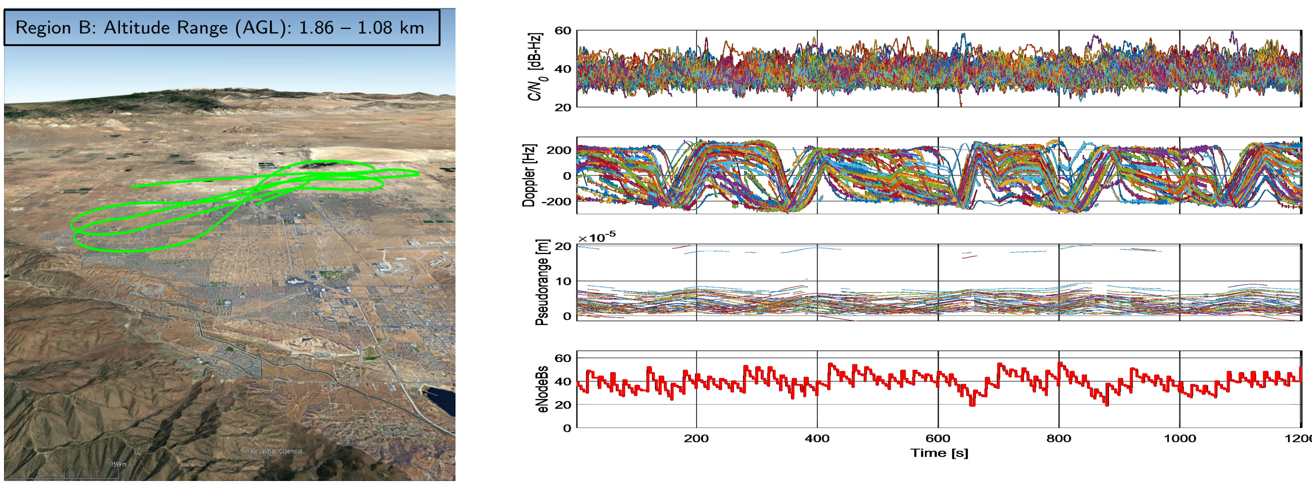

Figure 9: Left: descending teardrop aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

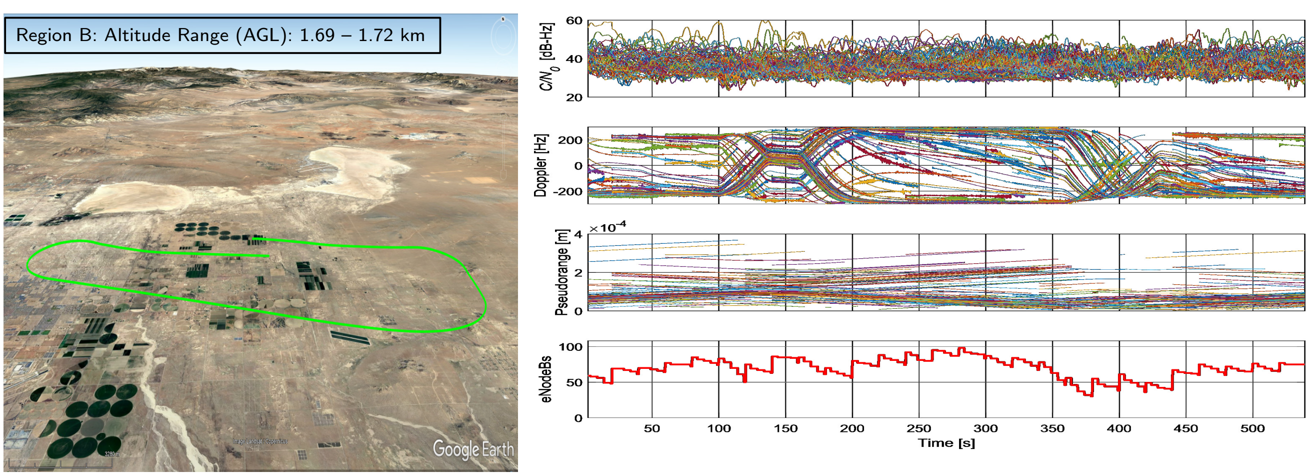

Figure 10: Left: grid aircraft trajectory in Region B. Right: receiver's pseudorange and Doppler tracking results from cellular LTE eNodeBs during this trajectory along with the C/N_0 and number of tracked eNodeBs.

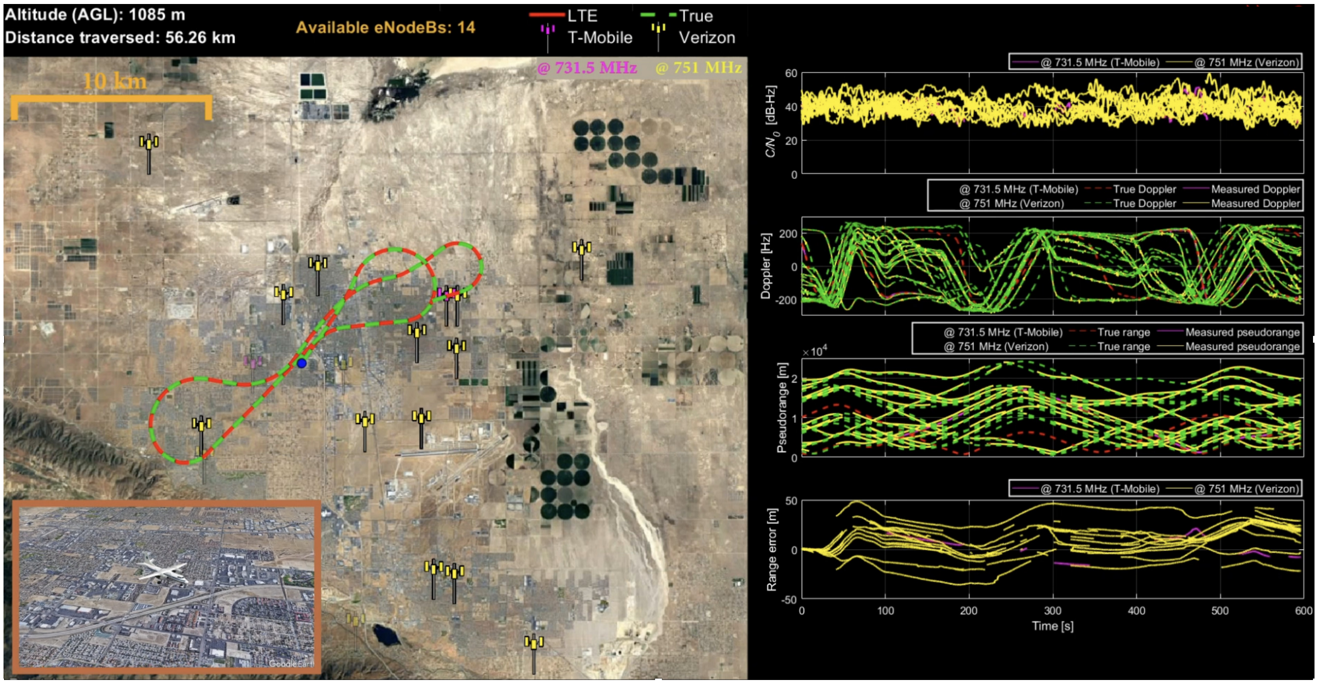

Figure 11: Left: Region A environment layout showing the cellular eNodeBs' locations and aircraft's true and estimated trajectories (from LTE signals). Right: LTE pseudorange and Doppler tracking during this trajectory along with C/N_0 and number of tracked LTE eNodeBs.

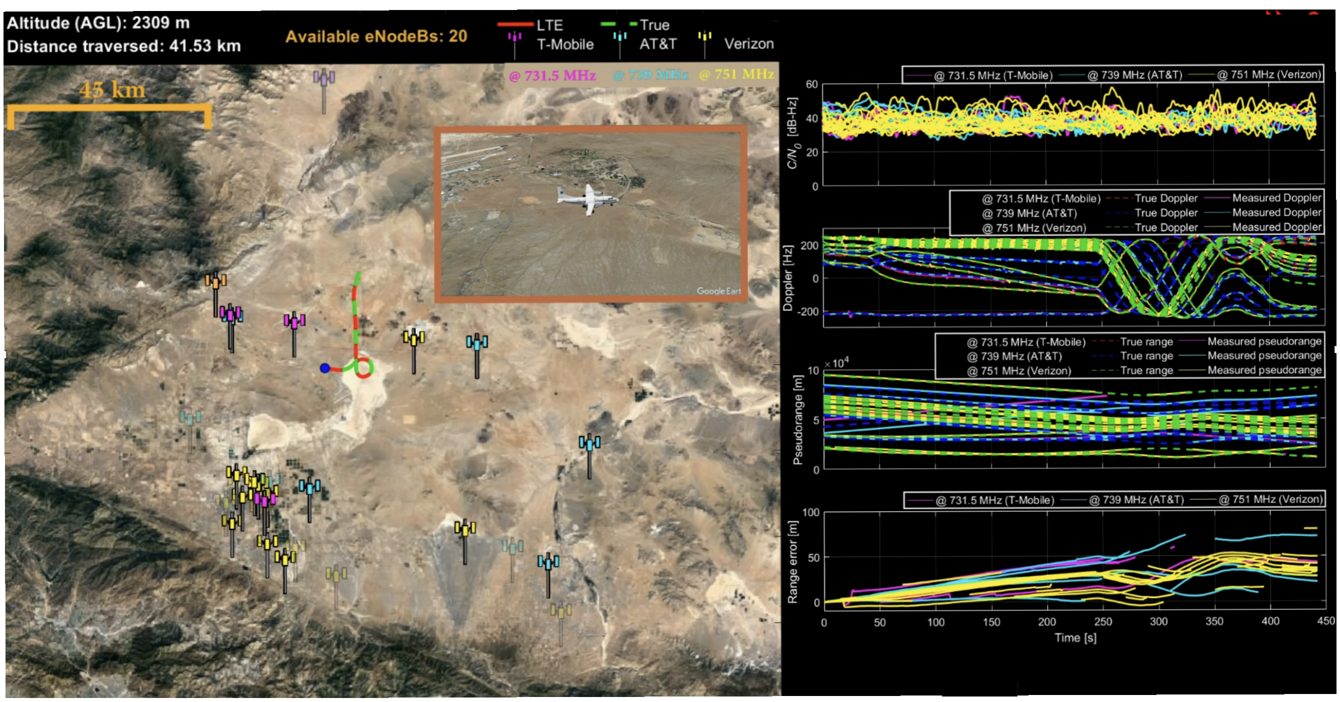

Figure 12: Left: Region B environment layout showing the cellular eNodeBs' locations and aircraft's true and estimated trajectories (from LTE signals). Right: LTE pseudorange and Doppler tracking during this trajectory along with C/N_0 and number of tracked LTE eNodeBs.

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

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