Received Power Characterization of Terrestrial Cellular Signals on High Altitude Aircraft

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Abstract—The received power of terrestrial cellular 3G code division multiple access (CDMA) and 4G long-term evolution (LTE) signals on a high altitude aircraft is experimentally characterized. The conducted experiments were performed on a Beechcraft C-12 Huron, a fixed-wing U.S. Air Force aircraft. Two types of flight patterns were performed: (i) teardrop-like patterns to characterize the carrier-to-noise ratio ($C/N_0$) versus altitude and (ii) grid-like patterns to characterize $C/N_0$ versus the horizontal distance between the aircraft and cellular towers. Flight campaigns in two regions were conducted: (i) a rural region in Edwards, California, USA, and (ii) an urban region in Riverside, California, USA. It was observed that cellular 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 above ground level (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. In addition, two propagation models were evaluated to describe the behavior of the measured $C/N_0$: (i) free-space path loss model and (ii) two-ray model. It was observed that 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.

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1. Introduction

Global navigation satellite systems (GNSS) are heavily relied upon in today’s aviation communications, navigation, and surveillance (CNS) systems as well as air traffic management [1]. The upsurge in GNSS radio frequency interference (RFI) is jeopardizing safe and efficient aviation operations [2, 3]. RFI sources include repeaters and pseudolites [4, 5], GNSS jammers [6, 7], and systems transmitting outside the GNSS frequency bands [8, 9]. There were 4,364 GNSS outages reported by pilots in 2018, which represents more than a 2,000% increase over the previous year [10]. What is alarming is that RFI is affecting civil aviation at distances of up to 500 km from conflict zones (where GNSS jammers tend to be prevent) and that the majority of RFI (about 81%) affects en-route flights. 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. Moreover, there was a call for supporting multi-disciplinary development of alternative positioning, navigation, and timing (PNT) strategy and solutions to complement the use of GNSS in aviation [11].

Cellular signals have shown tremendous promise as an alternative PNT source [12–23]. This is due to their inherently desirable attributes [24]: (i) they are ubiquitous, (ii) they are transmitted in a wide range of frequencies and in many directions which makes them spectrally and geometrically diverse, (iii) they possess a high received carrier-to-noise ($C/N_0$) ratio (tens of dBs higher than GNSS), and (iv) they are readily available for free as their infrastructure is well established and the signals are broadcasted to billions of users worldwide. Recent results have shown the ability of cellular signals to yield meter-level-accurate navigation on ground vehicles [25–29] in urban environments and submeter-level-accurate navigation on UAVs [30, 31]. Moreover, the robustness and availability of cellular signals have been demonstrated in a GPS-jammed environment [32].

Assessing cellular signals for aerial vehicles has been the subject of several studies recently [33–37]. It was concluded that commercial cellular networks are capable of providing connectivity to aerial vehicles at low altitudes [38, 39]. However, the majority of existing studies considered low altitude aerial vehicles traveling at low speeds and focused on evaluating cellular signals for communication purposes with little attention to evaluating them for PNT [40].

A joint effort between the Autonomous Systems Perception, Intelligence, and Navigation (ASPIN) Laboratory and Edwards Air Force Base, California, USA led to a weeklong flights in March 2020 in a mission called “SNIFFER: Signals of opportunity for Navigation In Frequency-Forbidden EnviRonments.” The flights took place on a Beechcraft C-12 Huron, a fixed-wing U.S. Air Force aircraft, to study the efficacy of terrestrial cellular signals for aircraft navigation. This paper presents findings from these flights to characterize
$C/N_0$ of terrestrial cellular 3G code division multiple access (CDMA) and 4G long-term evolution (LTE) signals. The $C/N_0$ provides a measure of the precision of the navigation observables (pseudorange and carrier phase) [41], which are used to calculate the PNT solution [42, 43]. Two types of flight patterns were performed: (i) teardrop-like patterns to characterize the carrier-to-noise ratio ($C/N_0$) versus altitude and (ii) grid-like patterns to characterize $C/N_0$ versus the horizontal distance between the aircraft and cellular towers. Flight campaigns in two regions were conducted: (i) a rural region in Edwards, California, USA, and (ii) an urban region in Riverside, California, USA. It was observed that cellular 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 above ground level (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. In addition, two propagation models were evaluated to describe the behavior of the measured $C/N_0$: (i) free-space path loss model and (ii) two-ray model. It was observed that 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 to the measured $C/N_0$.

The remainder of the paper is organized as follows. Section 2 overviews (i) hardware and software setup, (ii) flight maneuvers, and (iii) flight regions. Section 3 characterizes the measured $C/N_0$ of 3G and 4G cellular signals as a function of altitude and horizontal distance to the towers in both regions. It also evaluates the free-space path loss model and the two-ray model. Section 4 gives concluding remarks.

2. HIGH-ALTITUDE AIRCRAFT NAVIGATION WITH TERRESTRIAL CELLULAR SIGNALS

This section presents the hardware and software setup with which the aircraft was equipped and flight maneuvers and regions.

Hardware and Software Setup

The C-12 aircraft was equipped with a universal software radio peripheral (USRP) with consumer-grade cellular antennas to sample three cellular bands and store the samples on a desktop computer for off-line processing. The stored samples were post-processed with the 3G and 4G cellular modules of ASPIN Laboratory’s SDR, called MATRIX: Multichannel TRanseiver Information eXtractor [32]. The SDR produces navigation observables: Doppler frequency, carrier phase, and pseudorange, along with the corresponding $C/N_0$. The hardware setup is shown in Figure 1.

Flight Maneuvers

Two types of maneuvers were performed in each region. The first is a teardrop-like pattern while climbing/descending. The pattern has a focal point that is aligned with a geographic point of interest. The measurements used to characterize $C/N_0$ and multipath were taken exactly above the geographic point of interest to maintain the horizontal distance between the aircraft and the cellular base stations. The second type of maneuver is a grid-like pattern with many turns and straight segments. Such patterns were used as a stress test on ASPIN Laboratory’s SDRs to assess the performance of signal acquisition, tracking loops, and navigation solution. The two types of maneuvers are shown in Figure 2.

Flight Regions

Figure 3 shows the regions in which the experiments were performed: (i) Region A, a rural region in Edwards, California, USA, and (ii) Region C, an urban region in Riverside, California, USA.

3. RECEIVED $C/N_0$ CHARACTERIZATION

This section characterizes the $C/N_0$ of received cellular signals in regions A and C. Different channel models are evaluated to find the best model that represents the $C/N_0$ behavior. The precision of navigation observables (pseudorange and carrier phase) is a function of $C/N_0$, which ultimately determines the precision of the navigation solution. As its name suggests, the pseudorange is not quite the range between the transmitter and the receiver, but the sum of the range and the bias due to the difference between the transmitter and receiver’s clocks. Essentially, the pseudorange measurement is constructed by measuring the time-of-arrival (TOA) of the signal. The TOA is obtained by correlating the received cellular signals with known synchronization sequences [24]. The $C/N_0$ can be calculated according to [41]

$$C/N_0 = \frac{C}{N_0} = \frac{C}{\sigma_{\text{noise}}^2 T},$$

where $C$ is the carrier power in Watts (W), $N_0$ is the noise power spectral density in W/Hz, which can be expressed as $N_0 = \sigma_{\text{noise}}^2 T$, where $\sigma_{\text{noise}}^2$ is the discretized noise variance.
and $T$ is the accumulation period, or the period over which correlation is performed. Typically, the $C/N_0$ should be above 35 dB-Hz for reliable acquisition, and above 25 dB-Hz to maintain track \[41\]. High sensitivity receivers can acquire and track at lower values of $C/N_0$ \[44–46\].

### Free-Space Path Loss Model

The free-space path loss (FSPL) model is a simple, yet informative for aerial vehicles’ wireless channels. The FSPL accounts only for the propagation loss between two isotropic radiators in free space and can be expressed as \[47\]

$$\frac{C}{N_0}(h) = \frac{C}{N_0}(R_0) - 10\alpha \log_{10} \sqrt{D} + w,$$

(1)

where $R_0$ is the initial range; $D$ is the line-of-sight given by $D = d^2 + h^2$, where $d$ and $h$ are the horizontal and vertical distances to the tower, respectively; $\alpha$ is the pathloss exponent; and $w$ is a zero-mean random variable. Figure 4 depicts the variables involved in the FSPL model.

The measured $C/N_0$ as a function of altitudes for Region A and both signal types (3G CDMA and 4G LTE) are shown in Figures 5 and 6. Also shown are the FSPL model fit, where the pathloss exponent was assumed to be $\alpha = 2$ (free space). The aircraft-mounted SDR was able to maintain tracking of all acquired cellular signals up to the maximum altitude it reached, namely 23,000 ft AGL.

The $C/N_0$ for six 3G and 4G base stations in Region C are plotted as a function of the horizontal distance in Figure 7. It is worth noting that the aircraft was flying at an altitude of a little above 16,000 ft AGL. At such an altitude, the elevation angles are very high. Since cellular base station antennas are tilted downwards and are directional in the elevation direction, the loss due to the directive radiation pattern of cellular base station antennas dominate the pathloss. This explains why some of the $C/N_0$s in Figure 7 have an increasing trend, especially at shorter horizontal distances where the change in elevation angle is more significant. The big hole between 22 to 38 km in Figure 7 is purely due to the fact that some cellular towers happened to be located either too close or too far with respect to the trajectory traversed by the aircraft. In other words, none of the lines get disconnected in this gap; instead, the $C/N_0$ of the two base stations in the region below the 22 km horizontal distance are different from the four base stations in the region right to the 38 km horizontal distance. The aircraft-mounted SDR was able to maintain tracking of cellular towers as far as 50 km away.

### Two-Ray Model

Next, a more sophisticated model is evaluated, namely the two-ray model. The two-ray model can be expressed as \[47\]

$$\frac{C}{N_0}(D) = \frac{C}{N_0}(D_0) - 20 \log_{10} \left[ r_p \left| \frac{1}{D} + \Gamma(\psi) \frac{e^{-j\Delta\phi}}{D + \Delta D} \right| \right],$$

where $r_p$ is the propagation coefficient, $\Gamma(\psi)$ is the geometric path length, and $\Delta\phi$ is the phase difference between the two rays.
The obtained $C/N_0$ results demonstrate the promise of utilizing cellular signals for aircraft navigation. It was observed that both 3G CDMA and 4G LTE signals exhibited measured $C/N_0$ between 25 and 55 dB-Hz at altitudes of 2,000–23,000 ft AGL. The aircraft-mounted SDRs were able to maintain reliable tracking of acquired cellular signals throughout as the aircraft ascended/descended along the teardrop flight trajectory. In addition, cellular signals were tracked up to a horizontal distance of 50 km, while flying at about 16,000 ft AGL. These unprecedented results are the first of their kind, showing the tremendous potential of cellular signals for aircraft navigation.

**Discussion**

The two-ray propagation model appears to fit the measured $C/N_0$ when flying at an altitude of 16,000 ft AGL, when the cellular transmitter’s horizontal distances ranged between 10 km and about 33 km. For distances lower than 10 km, the mismatch between the measured $C/N_0$ and the two-ray model fit grew. Incorporating the transmitter’s antenna radiation pattern reduced this mismatch, albeit did not remove completely. This could be due to the fact that the exact radiation pattern of the transmitter is not precisely known.

**4. Conclusion**

This paper characterized the received $C/N_0$ of terrestrial cellular 3G and 4G signals on a Beechcraft C-12 Huron, a fixed-wing U.S. Air Force aircraft. Two types of flight patterns were performed in two different regions. It was observed that cellular 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 above ground level (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. In addition, two propagation models were evaluated to describe the behavior of the measured $C/N_0$: (i) free-space path loss model and (ii) two-ray model. It was observed that 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.

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Figure 9. The measured $C/N_0$ of a 4G tower (red dots) and a 3G tower (blue dots) as a function of horizontal distance in Region A. The model fit is obtained by fitting the measured $C/N_0$ using the two-ray model and two-ray + cellular tower antenna radiation pattern.

REFERENCES


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