Accuracy and Robustness Analysis of Raw GNSS Data in Diversified Scenarios

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1 GOALS OF THE LABORATORY

This lab investigates the capabilities of collecting GNSS measurements using Android smartphones and evaluates their reliability and accuracy through analysis and visualization in MATLAB. By acquiring pseudoranges and quality parameters such as C/N_0 and HDOP, we aim to study the behavior of commercial GNSS receivers in various environments.

GNSS data were collected in a variety of environmental scenarios. By comparing the resulting plots and key values derived from them, it is possible to perform a comprehensive analysis and identify potential sources of signal interference.

2 SETUP

The scenarios were designed to be as diverse and insightful as possible, we conducted the experiments by logging data over a fixed 5-minute window. Initially, we focused on gathering high-quality reference data by collecting GNSS signals in an open field, where there were no interferences and the sky was clear, providing optimal conditions. This dataset served as the baseline reference for evaluating the impact of spoofing techniques on the signal parameters and their detection. The second scenario aimed to evaluate how a small difference in position could influence the quality of GNSS measurements. This scenario involved comparing data collected indoors with that collected just a meter away, on a balcony, allowing for a direct comparison with the reference case. Finally, in the third scenario, we investigated the effects of signal degradation on GNSS data quality by wrapping the device in layers of aluminum foil to block or attenuate the signals.

3 TOOLS

In this section we briefly see the tools used to perform the tests.

3.1 GNSS Logger

GNSS Logger is an Android app that captures raw satellite data to assess real-time positioning. It records measurements every second during user-defined sessions, collecting pseudorange data from GPS, GLONASS, Galileo, and BeiDou. The recorded data are exported in TXT format for further analysis in MATLAB.

3.2 MATLAB

The `ProcessGnssMeasScript.m` script takes as input the raw GNSS Logger file in TXT format and produces several figures useful for the analysis of the measurements made by GNSS Logger. Below are analyzed the graphs that were used for this report.

- **diff(raw pr)/diff(time) and reported prr** In the plot, the continuous line represents the satellite-reported pseudorange rate, indicating the relative velocity between each satellite and the receiver. The more irregular, oscillating line corresponds to the computed velocity, obtained as the time derivative of the raw pseudorange (i.e., distance over time). The comparison between the two helps evaluate consistency and detect anomalies in the signal.
- **HDOP (Horizontal Dilution of Precision)** Shows the HDOP value over time, is used to quantify the effect of satellite geometry on the estimated position.
- **WLS: Position states offset from medians** Plot the variation of the position (latitude, longitude, altitude) from the median value.
- **C/N_0 in db*Hz** Displays signal strength for each satellite.
- **Raw Pseudoranges, Weighted Least Square solution** This graph displays the dispersion of the measured positions. The final estimate of the position is indicated by the median coordinates. The radius of the circle, called CEP50 (Circular Error Probable at 50%), defines the area around the estimated position that contains 50% of the measurements taken. The CEP50 expresses the precision of the estimate, that is, how closely the measurements are grouped together.

3.3 Devices

Data collection was performed using two commercially available Android smartphones, each equipped with a GNSS chipset capable of logging raw satellite measurements via the GNSS Logger app. The selected devices are described below:

- **Samsung Galaxy S10 Lite** (used for outdoor measurements)
  - SoC: Qualcomm Snapdragon 855
  - GNSS: Dual-frequency (L1 & L5)
  - Constellations: GPS, A-GPS, GLONASS, Galileo, BeiDou, BDS
- **Samsung Galaxy A33 5G** (used for indoor/balcony/alluminium case measurements)
  - SoC: Samsung Exynos 1280
  - GNSS: Dual-frequency (L1 & L5)
  - Constellations: GPS, A-GPS, GLONASS, Galileo, BeiDou

All devices were configured with identical logging parameters (Location ON, GNSS Location ON, Measurements ON, Fused Location ON, Network Location ON, GnssStatus ON, Logs of 5 minutes), to ensure a consistent comparison of positioning performance.

4 SCENARIOS AND RESULTS

This section provides a detailed analysis of three scenarios and their corresponding results. To perform the tests, we used the ProcessGnssMeasScript.m script.

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2025.

4.1 GNSS: Data Analysis and Spoofing Simulation

In the first scenario, we compare an ideal open-field condition (no spoofing) with the same condition in which, after a certain period, spoofing is introduced. We will highlight the impact of spoofing on the recorded measurements, emphasizing the differences between the two cases.

4.1.1 Open field measurements with no spoof. This scenario represents ideal GNSS operating conditions: data were collected in an open field, free from nearby interference and with favorable satellite geometry. The figure (1) shows the cloud of samples taken during the measurement. The final estimate corresponds to the median value of the coordinates [39.631305,15.852830], which effectively represents the physical location from which the measurements were taken. Over 50% of the position fixes fall within a 5-meter radius (CEP50), highlighting a high level of precision. This is further confirmed by the figure, where few significant outliers are visible. This compact distribution of values, together with the correctness of the estimated position, confirms both the absence of interference and the fact that the measurements were conducted under ideal open-sky conditions.

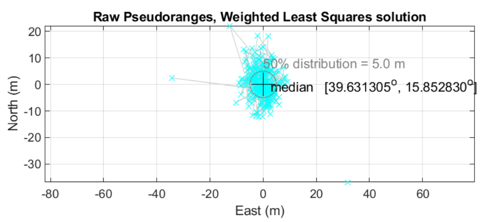

Figure 1: Open Field: Median & CEP50

The precision and reliability of the measurements are further confirmed by the additional plots in Figures (2) and (3). The HDOP remains consistently low, between 0.8 and 1.4, indicating excellent satellite geometry during the acquisition. At the same time, the number of satellites involved ranges from 6 to 9, and most signals show high carrier-to-noise ratios (C/N_0), confirming strong, undisturbed signal reception.

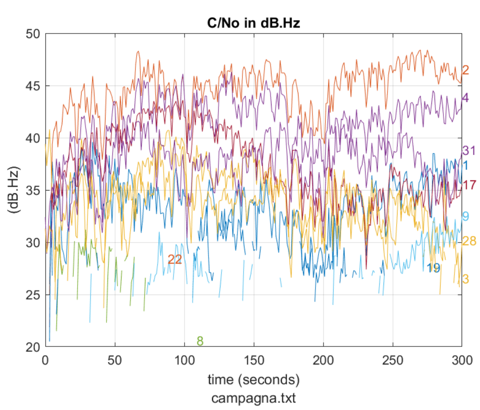

Figure 2: Open Field: Signal Strength

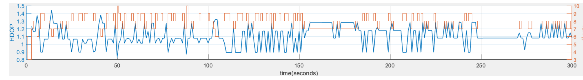

Figure 3: Open Field: HDOP & Number Of Satellites

4.1.2 Open field measurements with spoofing. This scenario was conducted under the same conditions as the previous one (4.1.1), except that a spoofing attack was introduced after 180 seconds of data acquisition. By comparing the two cases, it is possible to observe the effects of the attack. In Figure (4), the outcome differs significantly from the non-spoofed case: some measurements are recorded up to 150 meters further north than the true position. Moreover, the radius of the circle containing 50% of the recorded positions (CEP50) increases to 10.2 meters, which is more than double the value observed in the spoof-free scenario. This increase in CEP50 reflects a higher dispersion of the position fixes. Another element that supports the theory of the presence of spoofing is the plot itself, where two distinct and concentrated clusters of positional values appear clearly separated, making the spoofing even more evident.

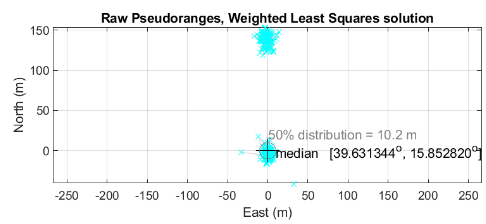

Figure 4: Open Field Spoofed: Median & CEP50

In Figure (5) significant variations in altitude and latitude are observed after the attack is introduced. Such abrupt, unexplained changes in position are typical indicators of a spoofing attack, as they deviate from the continuity and stability that is expected from GPS signals under normal conditions. The presence of these anomalies supports the diagnosis and detection of a potential spoofing attempt.

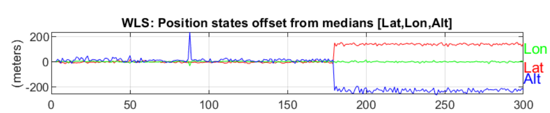

Figure 5: Open Field Spoofed: Position States

In Figure (6), we observe a sudden spike in all the satellite's speeds. This occurs because the receiver compares the newly received spoofed satellite positions with the legitimate ones from before. The large discrepancy between the actual and spoofed positions leads the receiver to wrongly interpret these as rapid movements of the satellite, resulting in an artificially high velocity. Such a spike is a clear sign of spoofing, as satellites do not move in this manner under normal conditions.

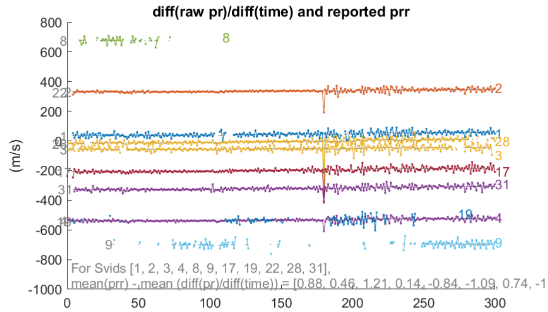

Figure 6: Open Field Spoofed: Satellite Velocity

4.2 GNSS: Balcony to Indoors

For this scenario, we evaluated the effect of moving the receiver from a balcony to just one meter indoors. Measurements were taken on the first-floor balcony of a five-story building in central Turin, and then repeated inside, where walls and structures obstruct GNSS signals. We will first compare balcony data with open-field reference measurements to assess the impact of an urban semi-open environment, then contrast the balcony and indoor results to quantify the additional degradation caused by indoor obstructions.

4.2.1 Out-Door. This configuration represents a semi-open environment, where GNSS performance is expected to degrade compared to ideal open-sky conditions. The presence of surrounding buildings leads to multipath effects, signal attenuation, and partial sky obstructions, all of which compromise the accuracy of the measurements. In addition, nearby electronic devices, such as WiFi routers and mobile phones, can emit electromagnetic interference. Since some of these technologies operate on frequencies close to those used by GNSS signals (around 1.5 GHz), overlapping spectral ranges can lead to unintentional interference, further degrading the quality and reliability of GNSS reception. As shown in Figure (7), the point cloud is significantly more dispersed than in the open countryside case. The median of the coordinates deviates slightly from the true position, while the radius of the CEP50 circle is equal to 14.5 meters, indicating a greater dispersion than in the open sky case.

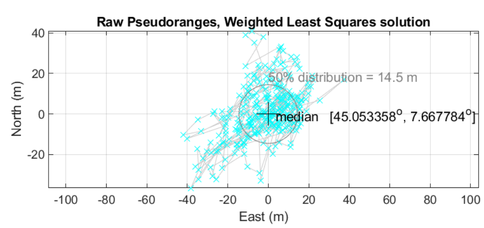

Figure 7: Out-Door: Median & CEP50

However, the degradation is not attributable to the number of satellites or to the satellite geometry. As can be seen from Figure (9), the HDOP remains low, generally lower than 1.5, and the number of detected satellites remains high, with an average of about 8-9 satellites. The main problem lies in the quality of the received signal: as reported in Figure (8), only two satellites show a high level of signal strength (C/N_0), while the others are attenuated, probably due to reflections on the walls or partial obstructions.

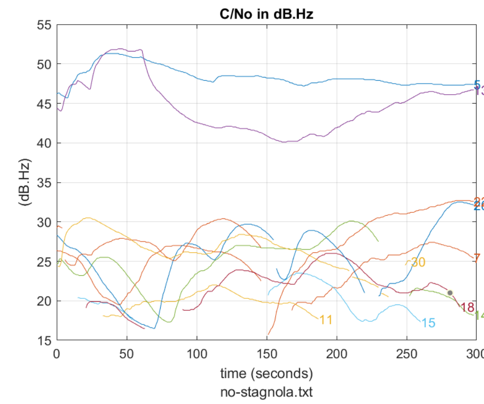

Figure 8: Out-Door: Signal Strength

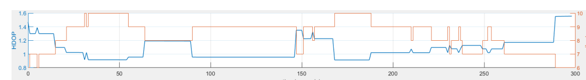

Figure 9: Out-Door: HDOP & Number Of Satellites

4.2.2 In-Door. In this case, the measurements were taken just one meter away from the previous ones, but inside the building. As shown in Figure 10, the measurements are even less precise than the two previous cases. The radius of the CEP50 circle widens further, reaching 39.5 meters, indicating a much greater dispersion of the fixes. In the graph, some outliers (anomalous values) are visible that highlight the problems in receiving a precise signal, probably caused by strong attenuations or internal reflections, which distort the data and introduce uncertainties in the measurements.

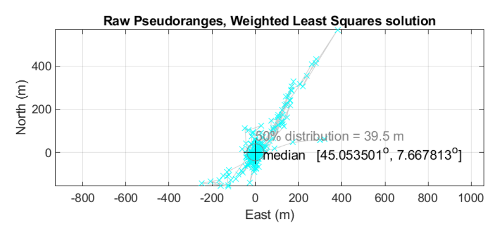

Figure 10: In-Door: Median & CEP50

From Figure 11 it can be seen that the number of detected satellites is significantly reduced compared to the previous cases, with an average of only 4 satellites. The HDOP present higher values, always higher than 2 and even reaching peaks of 16. This reflects a less favorable satellite geometry, caused by the reduced visibility of the sky.

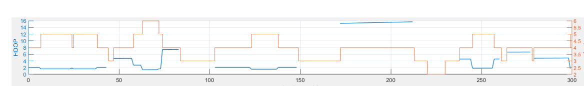

Figure 11: In-Door: HDOP & Number Of Satellites

Finally, from Figure 12 it can be seen that only the signal of one satellite arrives with continuity and high power, while the other signals are weaker (between 20 and 25 dB*Hz) and are detected with discontinuity. This situation of poor coverage and signal quality further confirms the difficulties in obtaining precise measurements in closed environments, where the presence of physical obstacles, together with the reduced visibility of the satellites, compromises the reliability and precision of the GNSS data.

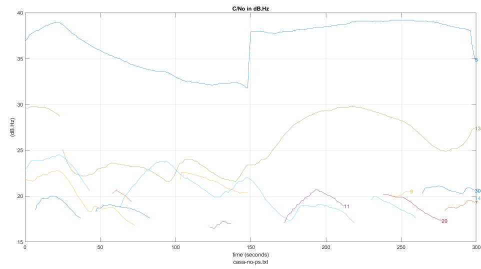

Figure 12: In-Door: Signal Strength

4.3 GNSS: Signal Attenuation with Aluminium Foil

For this scenario, we wrapped our Android device in aluminum foil to observe the effects of this experiment on our measurements.

4.3.1 Measurements with aluminium foil. In this scenario, the GNSS measurements were conducted from the same balcony location used in the previous case (see Section 4.2.1), but with a crucial variation: the receiver was wrapped in a layer of aluminum foil. This configuration was intended to simulate a shielding effect, potentially introducing signal attenuation or reflective interference.
Figure 13 illustrates the distribution of position fixes, as anticipated, the shielding severely degraded GNSS signal quality and measurement accuracy. The resulting dispersion of positional fixes was notably worse than in both the semi-open (balcony) and indoor cases. The circle containing 50% of the position estimates (CEP50) expanded its radius dramatically to 69.8 meters, a clear indicator of significant signal degradation and high uncertainty in position estimation.

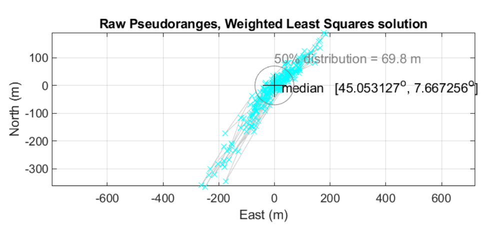

Figure 13: Alluminium Case: Median & CEP50

The HDOP values, shown in Figure 14, vary considerably during the five-minute acquisition period. While some periods show relatively stable geometry with HDOP values as low as 2, other moments display highly unfavorable conditions, with peaks reaching 15. The number of tracked satellites fluctuates between 4 and 5, further confirming the impact of the source of interference.
Figure 15 displays the signal power levels from the satellites. Only two satellites are received with continuity and moderate signal strength, averaging around 35 dB·Hz. The rest are either detected sporadically or exhibit very low signal power—often below 20 dB·Hz. This poor signal quality, together with the reduced number of usable satellites, results in an overall degradation that surpasses even the fully indoor scenario discussed earlier.

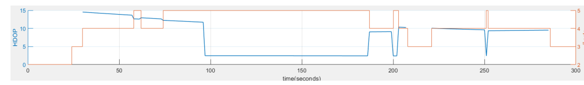

Figure 14: Alluminium Case: HDOP & Number Of Satellites

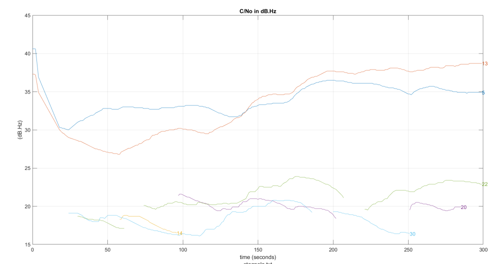

Figure 15: Alluminium Case: Signal Strength

5 CONCLUSION

From the experiments that we have conducted we obtained interesting results to be analyzed:

- The comparison between open-field GNSS measurements with and without spoofing clearly shows the difference between genuine and manipulated data. In the spoof-free case, fixes are precise, with over 50% within a 5-meter radius. With spoofing, dispersion increases (CEP50 of 10.2 m), and two clusters appear—clear evidence of manipulation. While standard indicators (HDOP, satellite count, signal power, etc.) remain stable, sudden changes in position and velocity reveal the attack, emphasizing the need for spatial-temporal analysis in detection.
- The three test scenarios show how environmental conditions affect GNSS measurement quality. Open-field data is accurate due to full sky visibility. On the balcony, surrounding structures introduce multipath and signal loss, lowering precision. Indoors, walls and ceilings block signals more severely, increasing dispersion. Even small environmental changes can significantly impact GNSS reliability.
- The aluminum foil experiment shows how external shielding can severely degrade GNSS performance, even in semi-open environments. The rise in CEP50, fluctuating HDOP, and signal weakening confirm aluminum as a strong barrier.