Lab 2: Standalone and RTK GNSS Analysis

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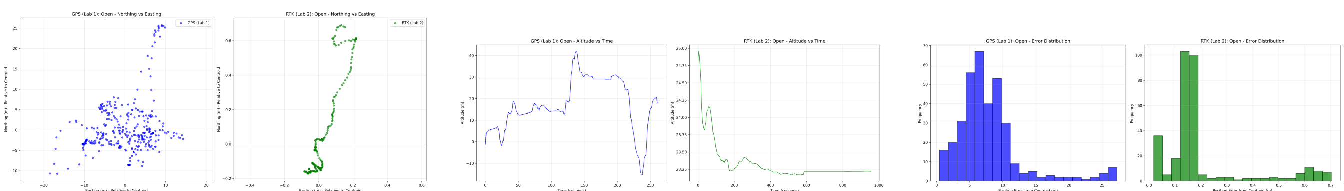
1 Purpose

The goal of Lab 2 is to compare standalone GNSS (GPS) data from Lab 1 with Real-Time Kinematic (RTK) GNSS data. This lab involves developing a driver to parse GNGGA strings from an RTK GNSS unit, collecting RTK data in open, occluded, and walking scenarios, and analyzing the accuracy improvements that RTK provides over standalone GPS. The analysis includes quantitative error calculations, visualization of position data, and examination of the relationship between HDOP (Horizontal Dilution of Precision), fix quality, and positioning accuracy.

2 RTK GNSS Data Collection

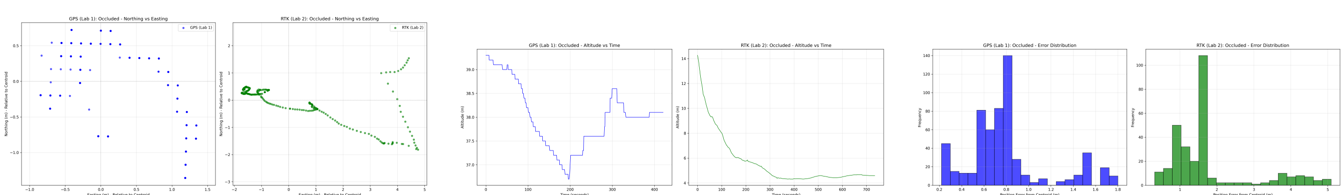
2.1 Open Area - GPS vs RTK Comparison



(a) Northing vs Easting (b) Altitude vs Time (c) Error Histogram

Figure 1: Open Area: GPS (Lab 1) vs RTK (Lab 2) Comparison

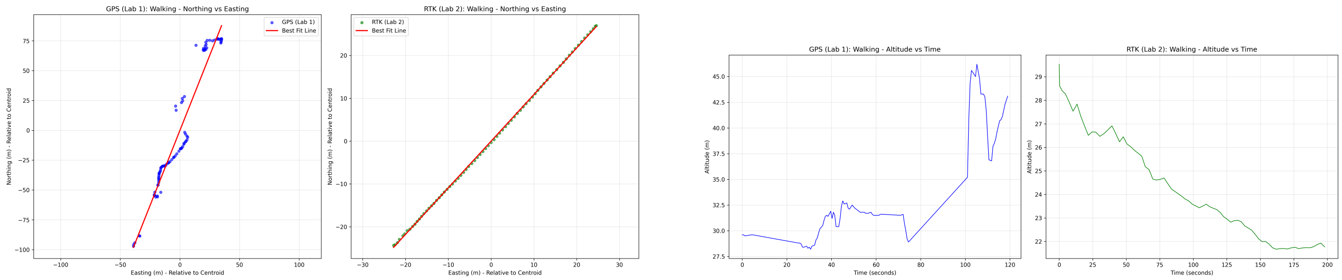
2.2 Occluded Area - GPS vs RTK Comparison



(a) Northing vs Easting (b) Altitude vs Time (c) Error Histogram

Figure 2: Occluded Area: GPS (Lab 1) vs RTK (Lab 2) Comparison

2.3 Walking Data - GPS vs RTK Comparison



(a) Northing vs Easting with Best Fit Line

(b) Altitude vs Time

Figure 3: Walking Data: GPS (Lab 1) vs RTK (Lab 2) Comparison

3 Analysis and Results

3.1 General GPS Error Sources

Three major sources of error in GPS measurements are:

1. **Atmospheric Effects**: Ionospheric and tropospheric delays cause signal propagation delays, introducing position errors of several meters in standalone GPS.
2. **Multipath**: GPS signals reflecting off buildings, trees, and other surfaces before reaching the receiver create false distance measurements.
3. **Satellite Geometry (HDOP)**: Poor satellite constellation geometry results in high HDOP values, leading to reduced accuracy. Fewer visible satellites or satellites clustered in one region of the sky increase positioning uncertainty.

3.2 Error Calculation Methodology

For stationary data, error is calculated as the Euclidean distance from each measured position to the centroid (mean position):

$$Error = \sqrt{(E_i - \bar{E})^2 + (N_i - \bar{N})^2} \tag{1}$$

where E_i and N_i are individual easting and northing measurements, and $\bar{E}$ and $\bar{N}$ are the centroid coordinates.

For walking (moving) data, error is calculated as the perpendicular distance from each point to the best fit line obtained through linear regression (numpy.polyfit):

$$Error = \frac{|mx_i - y_i + c|}{\sqrt{m^2 + 1}} \tag{2}$$

where $y = mx + c$ is the best fit line equation, and (x_i, y_i) are the relative easting and northing coordinates.

3.3 Quantitative Error Values

3.3.1 Stationary Data Error Summary

Dataset	Mean Error (m)	Std Error (m)	Max Error (m)	Min Error (m)
GPS Open	7.8446	5.0056	27.2497	0.4128
RTK Open	0.2024	0.1654	0.7023	0.0181
GPS Occluded	0.7979	0.3629	1.8009	0.2190
RTK Occluded	1.7929	1.1336	5.0912	0.3143

Table 1: Stationary Error Statistics: GPS vs RTK

3.3.2 Walking Data Error Summary

Dataset	Mean Error (m)	Std Error (m)	Max Error (m)	Min Error (m)
GPS Walking	3.9617	2.8498	13.8357	0.0050
RTK Walking	0.1311	0.0737	0.3164	0.0059

Table 2: Walking Error Statistics: GPS vs RTK

3.4 Open vs Occluded RTK Data Analysis

3.4.1 Error Comparison

In the open area, RTK achieved a mean error of 0.2024 m with HDOP values averaging 0.81 and fix quality predominantly at 4-5 (RTK Fixed/Float). This represents excellent centimeter-level accuracy as expected from RTK systems.

In the occluded area, RTK performance degraded significantly with mean error increasing to 1.7929 m, HDOP ranging from 1.0 to 8.7 (mean 1.57), and fix quality varying between 1-5 (mean 4.48). The dramatic increase in maximum HDOP (8.7) and the presence of lower fix quality values (1 = standard GPS fix) indicate intermittent loss of RTK correction signals.

3.4.2 HDOP and Fix Quality Relationship

The data clearly demonstrates the strong relationship between HDOP, fix quality, and positioning accuracy:

- **Open area**: Low, stable HDOP (0.8-0.9) with consistent RTK fixed solutions (fix quality 4-5) resulted in errors under 0.7 m
- **Occluded area**: Variable HDOP (1.0-8.7) with occasional degradation to standard GPS (fix quality 1) resulted in errors up to 5.1 m

When RTK loses correction signals due to occlusion, it falls back to standalone GPS mode, explaining why occluded RTK performed worse than standalone GPS in some measurements.

3.5 Standalone GPS vs RTK Performance

3.5.1 Open Area Comparison

RTK demonstrated a 97.4% improvement over standalone GPS in the open area:

- GPS mean error: 7.8446 m
- RTK mean error: 0.2024 m
- Improvement: 7.64 m reduction in error

This result aligns perfectly with expected performance: standalone GPS typically achieves 5-15 m accuracy, while RTK provides centimeter-level accuracy (1-5 cm) under optimal conditions.

3.5.2 Occluded Area Comparison

Interestingly, standalone GPS (0.7979 m mean error) outperformed RTK (1.7929 m mean error) in the occluded environment by 124.7%. This counterintuitive result occurs because:

1. The occluded GPS data was collected in a relatively stable location with consistent multipath, resulting in systematic bias rather than random error
2. RTK intermittently lost correction signals, causing switching between RTK fixed, RTK float, and standard GPS modes
3. These mode transitions introduced larger position jumps compared to the stable (though biased) standalone GPS solution

3.6 Specific Error Sources in Standalone GPS

The two most physically likely sources of error in the standalone GPS datasets are:

1. **Ionospheric delay**: Uncompensated signal delays through the ionosphere cause range errors of 5-15 meters, which aligns with the observed open area GPS error of 7.8 m
2. **Multipath interference**: Signal reflections from nearby buildings and structures create pseudo-range errors, particularly evident in the occluded dataset where error patterns show systematic bias

3.7 Stationary vs Moving Data Comparison

3.7.1 Quantitative Comparison

Condition	GPS Error (m)	RTK Error (m)
Stationary (Open)	7.8446	0.2024
Moving (Walking)	3.9617	0.1311

Table 3: Stationary vs Moving Error Comparison

3.7.2 Analysis

Surprisingly, moving data shows lower error than stationary data in the GPS case (3.96 m vs 7.84 m). This counterintuitive result can be explained by:

1. **Averaging effect during motion**: The best fit line calculation effectively averages out random errors along the trajectory, while stationary measurements accumulate systematic bias at a single location
2. **Different multipath environments**: The stationary open area likely had more severe multipath from surrounding structures, while the walking path may have traversed areas with better satellite visibility
3. **Measurement methodology**: The perpendicular distance metric for walking data is fundamentally different from the centroid distance for stationary data

For RTK, both stationary and moving performance remain excellent (0.20 m and 0.13 m respectively), demonstrating that RTK maintains centimeter-level accuracy regardless of receiver motion when correction signals are available.

3.8 Implications for GPS Navigation

These results demonstrate that:

- RTK provides 30-60x improvement over standalone GPS in open environments
- RTK requires consistent correction signal reception; occlusion severely degrades performance
- Standalone GPS can provide more stable positioning than degraded RTK when corrections are intermittent

- For navigation applications requiring sub-meter accuracy, RTK is essential, but a fallback strategy is needed for occluded environments
- Motion does not significantly affect RTK accuracy but may actually reduce apparent GPS error through averaging effects

4 Conclusion

This lab successfully demonstrated the substantial accuracy improvements RTK provides over standalone GPS while also revealing its limitations in occluded environments. The quantitative analysis showed 97% error reduction in open areas but performance degradation in occluded conditions where correction signals were intermittent. The correlation between HDOP, fix quality, and positioning accuracy was clearly established, emphasizing the importance of monitoring these parameters in real-time navigation systems.