EECE 5554 Lab 2: Standalone and RTK GNSS Analysis

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1 Introduction

This report presents the analysis of Global Navigation Satellite System (GNSS) data collected under two receiver configurations: a standalone consumer-grade GPS puck (BU-353S4) and an RTK-corrected GNSS receiver (Emlid Reach with MaCORS corrections). Data were recorded in three scenarios for each configuration—stationary in an open-sky environment, stationary in a satellite-occluded environment, and while walking along a roughly straight path. The objectives are to quantify positioning error for each scenario, compare standalone and RTK performance, and discuss the physical error sources that explain the observed differences.

2 Equipment and Setup

Standalone GPS (Lab 1): GlobalSat BU-353S4 USB GPS puck, outputting NMEA-0183 at 4800 baud, publishing `GPGGA` / `GNGGA` sentences at 1 Hz.

RTK GNSS (Lab 2): Emlid Reach receiver with real-time kinematic corrections streamed from the Massachusetts Continuously Operating Reference Station (MaCORS) network. The receiver outputs multi-constellation `GNGGA` sentences at 1 Hz. RTK data were provided as text files (`openRTK.txt`, `occludedRTK.txt`, `walkingRTK.txt`) and streamed through the sensor emulator to the ROS 2 driver.

All RTK datasets were collected on 2 February 2024 under cloudy conditions.

3 RTK Driver Modifications

The standalone driver from Lab 1 was copied to `rtk_driver.py` and modified as follows:

- The parser accepts `GNGGA` sentences (multi-constellation).
- A new custom message `Customrtk.msg` adds two fields beyond the Lab 1 message: `fix_quality` (int32) and `hdop` (float64).
- The launch file `rtk_driver_launch.py` mirrors the Lab 1 launch structure with updated node and executable names.
- The driver publishes on the `/gps` topic and accepts an arbitrary serial port as a launch argument.

4 RTK Data Analysis

For every dataset the analysis pipeline is identical: (1) parse all `GNGGA` sentences with a valid fix (`fix_quality` ≥ 1), (2) convert latitude and longitude from NMEA `ddmm.mmmmm` format to decimal degrees, (3) project to UTM (zone 19T) using the `utm` Python library, and (4) compute the statistics described below.

4.1 RTK Stationary Data—Open Sky

The open-sky stationary dataset (`openRTK.txt`) contains approximately 321 epochs (5 min 21 s). Fix quality is predominantly 5 (RTK float) with intermittent fix 4 (RTK fixed). The mean HDOP is 0.84 with 17–20 tracked satellites across GPS, GLONASS, and Galileo constellations.

figures/rtk_open_ne_scatter.png

Figure 1: RTK open-sky stationary data: northing vs. easting scatter plot with centroid subtracted. The cluster is tight, with the majority of points within 0.3 m of the centroid. Total offset from centroid shown on axes.

figures/rtk_open_alt.png

Figure 2: RTK open-sky stationary data: altitude vs. time. Altitude converges from approximately 24.7 m to 23.2 m as the RTK float solution stabilises.

4.2 RTK Stationary Data—Occluded

The occluded stationary dataset (`occludedRTK.txt`) contains approximately 312 epochs (5 min 11 s). Fix quality varies among 1 (standalone), 4 (RTK fixed), and 5 (RTK float). Mean HDOP is 1.67 but ranges as high as 8.7 when only 2–3 satellites are tracked. Satellite count ranges from 2 to 11—far fewer than the open-sky case.

figures/rtk_occluded_ne_scatter.png

Figure 3: RTK occluded stationary data: northing vs. easting scatter plot (centroid subtracted). The scatter is visibly larger than the open-sky case, reflecting degraded satellite geometry.

figures/rtk_occluded_alt.png

Figure 4: RTK occluded stationary altitude vs. time. Altitude drifts from approximately 16 m down to 4.6 m, far more variation than the open-sky case.

4.3 Stationary RTK Histogram Plots

For each stationary dataset, the Euclidean distance from each point to its respective centroid was computed in the horizontal plane:

$$d_i = \sqrt{(\Delta E_i)^2 + (\Delta N_i)^2} \tag{1}$$

where ΔE_i and ΔN_i are the easting and northing offsets from the centroid. Figure 5 shows the resulting 1-D histograms.

figures/rtk_open_hist.png

(a) Open sky

figures/rtk_occluded_hist.png

(b) Occluded

Figure 5: Histograms of Euclidean distance from centroid for RTK stationary data. The open-sky distribution is sharply peaked near zero, while the occluded distribution is broader and right-skewed.

4.4 RTK Walking Data

The walking dataset (`walkingRTK.txt`) spans 75 seconds. The receiver maintained RTK float (fix 5) for most of the walk, with 10–17 satellites and HDOP 0.9–1.3. The path is approximately 70 m long on a northeast heading ($\sim 41°$ from north).

figures/rtk_walking_ne.png

Figure 6: RTK walking data: northing vs. easting scatter plot with a first-order polynomial line of best fit (red). The path is nearly straight, consistent with walking along a sidewalk.

figures/rtk_walking_alt.png

Figure 7: RTK walking altitude vs. time. Altitude decreases from approximately 31 m to 22 m over the walk, reflecting a gentle downhill grade and solution convergence.

5 Standalone GPS Data (Lab 1)

The following figures are reproduced from Lab 1 for comparison. All were collected with the BU-353S4 standalone GPS receiver (fix quality 1, no differential corrections).

figures/standalone_open_ne.png

(a) Open sky N vs. E

figures/standalone_occluded_ne.png

(b) Occluded N vs. E

figures/standalone_open_alt.png

(c) Open sky altitude vs. time

figures/standalone_occluded_alt.png

(d) Occluded altitude vs. time

figures/standalone_walking_ne.png

figures/standalone_walking_alt.png

6 Error Calculation Methodology

Two error metrics are used throughout this report.

6.1 Stationary RMSE from Centroid

For a stationary dataset of N positions, the centroid is computed as

$$\bar{E} = \frac{1}{N}\sum_{i=1}^{N} E_i, \qquad \bar{N} = \frac{1}{N}\sum_{i=1}^{N} N_i \tag{2}$$

where E_i and N_i are UTM easting and northing. The Euclidean distance of each point from the centroid is given by Eq. (1), and the root-mean-square error is

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} d_i^2} \tag{3}$$

This yields a single scalar error value (in metres) that captures the 2-D horizontal positioning precision, ignoring altitude.

6.2 Walking RMSE from Line of Best Fit

For walking data, a first-order polynomial is fit to the easting–northing data using `numpy.polyfit`:

$$N = m \cdot E + b \tag{4}$$

The perpendicular distance from each point to this line is

$$d_i = \frac{|m \cdot E_i - N_i + b|}{\sqrt{m^2 + 1}} \tag{5}$$

and the RMSE is again computed via Eq. (3).

7 Quantitative Error Results

Table 1 summarises the computed RMSE values for all datasets.

Table 1: Horizontal RMSE (metres) for each dataset and receiver configuration.

Scenario	**Metric**	**Standalone GPS**	**RTK GNSS**
Open stationary	RMSE from centroid	2.85	0.24
Occluded stationary	RMSE from centroid	7.42	2.07
Walking	RMSE from line of best fit	3.18	0.52

The RTK receiver reduces horizontal error by roughly an order of magnitude in the open-sky stationary case and by approximately 3.6× in the occluded case.

8 Discussion

8.1 Three Major Sources of Error in GPS Measurements

1. **Atmospheric delays.** The ionosphere and troposphere refract and slow GNSS signals, introducing range errors on the order of metres. Dual-frequency receivers and RTK corrections mitigate ionospheric delay; tropospheric models reduce—but do not eliminate—the remaining error.

2. **Multipath.** Signals reflecting off buildings, terrain, or other surfaces arrive at the antenna with additional path length, biasing the pseudorange measurement. Multipath errors are environment-dependent and particularly severe in urban canyons or near tall structures.

3. **Satellite geometry (dilution of precision).** When visible satellites are clustered in a small portion of the sky, the geometric dilution of precision (GDOP/HDOP) is large, amplifying range errors into position errors. Obstructions that block large portions of the sky worsen DOP.

8.2 Open vs. Occluded Error for RTK and Relationship to Fix Quality

The open-sky RTK RMSE (0.24 m) is nearly an order of magnitude smaller than the occluded RMSE (2.07 m). Several factors explain this difference:

- **HDOP.** The open-sky mean HDOP is 0.84, whereas the occluded mean HDOP reaches 1.67 and spikes above 8 during periods with only 2–3 visible satellites. Higher HDOP directly amplifies range errors into position errors.

- **Fix quality.** The open-sky data maintains RTK float (fix 5) or fixed (fix 4) for the entire session. In contrast, the occluded data frequently falls back to standalone (fix 1) when too few satellites are available for ambiguity resolution. A standalone fix lacks the centimetre-level carrier-phase corrections that RTK provides, so those epochs contribute metre-level errors.

- **Satellite count.** The open-sky session tracks 17–20 satellites; the occluded session tracks only 2–11. Fewer satellites degrade both geometry and the ability to detect and exclude erroneous measurements.

8.3 Standalone vs. RTK Error—Stationary Data

The four computed RMSE values for stationary data are:

	Standalone	**RTK**
Open	2.85 m	0.24 m
Occluded	7.42 m	2.07 m

RTK reduces the open-sky error by a factor of $\sim$12 and the occluded error by a factor of $\sim$3.6. These results align with published specifications: standalone GPS accuracy is typically 2 m to 5 m CEP in open sky and degrades to 5 m to 15 m under obstructions, while RTK float solutions achieve sub-metre accuracy in favourable conditions.

The improvement is smaller in the occluded case because RTK corrections can only be applied when the receiver maintains a carrier-phase lock on enough satellites to resolve integer ambiguities. When the fix reverts to standalone, the RTK infrastructure offers no benefit, and those epochs contribute standalone-level errors to the overall RMSE.

8.4 Top Two Error Sources in Standalone GPS Data

1. **Ionospheric delay.** The BU-353S4 is a single-frequency (L1-only) receiver and therefore cannot form ionosphere-free combinations. Residual ionospheric delay after broadcast model correction is typically 1 m to 5 m, making it the dominant standalone error source.

2. **Multipath.** The puck antenna has no ground plane or choke ring, so it is particularly susceptible to multipath, especially in the occluded environment where nearby structures create strong reflected signals. Multipath typically contributes 0.5 m to 3 m of additional error.

8.5 Stationary vs. Moving Error Comparison

Table 2 compares stationary and moving RMSE values.

Table 2: Stationary (open) vs. moving RMSE comparison.

Configuration	**Stationary (open)**	**Moving**
Standalone GPS	2.85 m	3.18 m
RTK GNSS	0.24 m	0.52 m

For both receiver types the moving RMSE is moderately larger than the stationary open-sky RMSE. For standalone GPS, the increase is modest (+12%), while for RTK the moving error is approximately 2.2× the stationary error.

Several factors explain why moving data yields higher error:

- **Solution convergence.** RTK float solutions require time to converge. While walking, the constellation geometry changes continuously, preventing the filter from reaching its steady-state accuracy.

- **Dynamic multipath.** The walking path traverses varying multipath environments, introducing transient range errors that a stationary receiver would average out over time.

- **Human path deviation.** The "line of best fit" metric assumes perfectly straight walking, but small lateral deviations in the actual walked path inflate the computed RMSE. This is a measurement artefact rather than a receiver error, but it is inseparable from the data without an independent ground-truth trajectory.

- **Receiver dynamics.** While the standalone receiver uses a position filter that smooths stationary data effectively, the filter must track actual motion when walking, reducing the amount of temporal averaging available.

These results suggest that for navigation applications with our receivers, stationary averaging significantly improves accuracy. When moving, RTK still delivers sub-metre accuracy and remains far superior to standalone GPS, but the advantage is somewhat reduced compared to the stationary case.

9 Conclusion

This lab demonstrated the substantial accuracy improvement that RTK corrections provide over standalone GPS. In open-sky stationary conditions, RTK reduced RMSE by roughly $12\times$ (0.24 m vs. 2.85 m). Under satellite occlusion, the improvement was approximately $3.6\times$ (2.07 m vs. 7.42 m), limited by the receiver's inability to maintain a float or fixed RTK solution with few visible satellites. Walking data showed sub-metre RTK accuracy (0.52 m) compared to $\sim$3.2 m for standalone GPS. The dominant standalone error sources are ionospheric delay and multipath, both of which are substantially mitigated by RTK carrier-phase corrections and the higher-quality RTK antenna. Satellite geometry, quantified by HDOP, is the primary factor distinguishing open-sky from occluded performance for both receiver types.