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**LAB-2 REPORT**

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*NOTE: For the X-axis representing GPS-Time in the graphs in this report, the value of the first epoch is ‘239460’ seconds, but the X-axis has been offset or deducted by ‘239460’ seconds and set to ‘0’ for better readability.*

# Task 1: Implement the phase rate method for cycle slip detection on L1

For the Phase Rate Method, the threshold value chosen to adjudge whether cycle-slip has occurred or not is the wavelength of GPS L1 frequency = 0.190293 meters.

## Subtask A: Plot any cycle slips as a function of time.

Figures 1, 2, 3 are the cycle-slip plots for between-receiver-single differenced (Remote & Base Station) observations for GPS satellite PRN 18, 11, and 8. These three plots adequately summarize the different types of cycle-slip plots possible. Since PRN 11 remains blunder free throughout the duration of the whole dataset, it will be taken as the reference/base satellite.  
  
*NOTE: Following is the definition of the values on Y-axis in the Figures 1, 2, 3 -****0 : Signal Lost , 1 : Cycle Slip/ Phase Lock Lost and 2 : Phase Locked/Constant Ambiguity***

Chart

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Figure : Cycle Slip plot for PRN 18

Table

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Figure : Cycle Slip plot for PRN 11

Graphical user interface

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Figure : Cycle Slip for PRN 8

## Subtask B: Identify Error-Free Data Subset

Out of several possible error-free data subsets, I reckon the following two are the most significant

Table : Possible Subsets

|  |  |
| --- | --- |
| Subset 1 | Subset 2 |
| Time Range : (0 – 2200) seconds | Time Range : (0 – 3400) seconds |
| Eight Satellites included (PRN : 7, 8, 15, 17, 19, 24, 26, 27) | Six Satellites included (PRN : 7, 15, 17, 24, 26, 27) |
| Advantage: Better Geometry | Advantage: More epochs present, means more time for convergence |
| Disadvantage: Lesser epochs are present, therefore negatively impacting the convergence of unknown parameters( Not enough convergence time) | Disadvantage: Fewer satellites present are present, poorer geometry will adversely impact the parameter estimation |

I have chosen to work with subset 2 for this lab, as I believe a larger convergence time will be more crucial for parameter estimation compared to better geometry.

# Task 2: Perform RTK-Float POSITION Estimation

I have performed RTK-Float based positioning on the whole dataset(3600 epochs + All visible satellites) and the selected Data Subset (Subset 2 in Table 1) using Kalman Filter.

Table : Dataset for which RTK-Float estimation is performed

|  |  |
| --- | --- |
| 1. Whole Dataset | 1. Data Subset |
| Epoch count = 3600 | Epoch count = 3400 |
| Satellite count = 13 (Not visible for the whole duration) | Satellite count = 6 (visible throughout the whole duration, 3400 seconds) |
| Blunders and Cycle Slips are present | No blunders or cycle-slips present |

Table : Kalman Filter Dynamics

|  |  |
| --- | --- |
| Prediction | Measurement Update |
| The transition matrix(F) is the Identity matrix and the process-noise matrix(Q) is null. Effectively state remains the same.  This step is only used when the cycle slip occurs for a satellite and the corresponding ambiguity estimate and its apriori estimate covariance are re-initialized. | Following is the measurement equation:  The measurement noise(R) for Pseudorange( is taken as and for Carrier Phase() is taken as or depending on the type of dataset. Former value for data subset 2 and latter for whole dataset. |

In this section, results and graphs for RTK-Float based positioning for **Whole Dataset** is shown, and in the later sections, RTK-float solution for **Data Subset** will also be presented.

## Results, Graphs and COMPARISON (SUBTASK A, B and C)

Table : Positional Error/Accuracy comparison between different positioning algorithms

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Method | Weighted Least Squares(RMSE(m)) | Between-Receiver-Single-Differenced(RMSE(m)) | RTK-Float(RMSE(m)) | RTK-Float(absolute of the converged value at the end or last epoch) |
| Easting | 1.3470 | 0.4130 | 0.1576 | 0.0358 |
| Northing | 0.5192 | 0.5617 | 0.1016 | 0.1107 |
| Up | 7.2910 | 1.077 | 0.0961 | 0.1130 |
| 3d Error | 7.4326 | 1.2835 | 0.2107 | 0.1622 |
| 2d Error | 1.4437 | 0.6972 | 0.1875 | 0.1164 |
| Note: | Single Receiver/Undifferenced observations/Only Pseudorange based | Two Receivers/Single differenced observations/Only Pseudorange based | Two Receiver/Double-Differenced observations/Carrier Phase+ Pseudorange based | |
| **Positional Accuracy: RTK-Float > BRSD > WLS** | | | | |

*NOTE: Following are the legend description for the below graphs –*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **BRSD:** Between Receiver Single Differenced | **WLS** : Weighted Least Squares | **RTK-Float:** floating ambiguity based RTK | **+SD** : Positive Standard deviation value | **-SD** : Negative Standard deviation value |

Chart, line chart

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Figure : RTK-Float East Error(in m)

Chart, line chart

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Figure : RTK-Float North Error(in m)

Chart, line chart

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Figure : RTK-Float Up Error(in m)

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Figure : RTK-Float 2D Error(in m)

Chart, line chart

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Figure : RTK-Float 3D RMSE(in m)

**Chart, scatter chart

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Figure : RTK-Float vs WLS vs BRSD 2D Error(in m)

**A picture containing chart

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Figure : RTK-Float vs WLS vs BRSD 3D RMSE(in m)

RTK-Float positional accuracy is superior to WLS or BRSD, which can be inferred from Table 4 and Figure 9 and 10. From Table 4, it can be observed that RTK-Float position solution compared to BRSD in East and North component is five times more accurate and in Up/Vertical direction is ten times more accurate. Figure 9 shows the stark difference between the preciseness of the position algorithms. The RTK-float 2D solution is tightly clustered around a mean of (0,0). In contrast, BRSD 2D solution is scattered around although still centered around the origin compared to WLS, which is better clustered than BRSD but has an apparent bias from origin. 3D error plot (Figure 10) clearly demonstrate the outstanding accuracy of RTK-float in vertical direction compared to BRSD and WLS.

## Subtask C: Discuss the differences between the true and estimated accuracy.

The estimated accuracy is derived from the state-estimate covariance matrix(P) used in Kalman Filter. It enables us to define a theoretical envelope around the estimates, based on which one can figure out the probability of it being bounded by it. For e.g. in our case a bound of1 sigma or std. deviation is defined around a true value of a parameter, which means that the estimates will be computed within that bound from true value ~68 % of time. The true accuracy on the other hand is derived based on the actual difference between the estimated value and true value and is quantified using metrics like RMSE, DRMS, CEP, etc. The estimated accuracy in my Kalman filter algorithm is influenced based on the values set for the measurement noise covariance matrix(R) and initial state-estimate covariance matrix().

# Task 3: Perform Integer Ambiguity Resolution

I have performed ambiguity resolution(AR) using two different methods

1. **Search Method**: Brute Force Search method based on Sum of Squares method and Ratio-Test
2. **Rounding-Off Method**: Rounding converged floating ambiguities obtained at the end of sequential filtering to estimate integer ambiguities. And then again performing sequential filtering, this time only utilizing carrier phases from which estimated integer-ambiguities are removed.

For this case of Integer-Ambiguity resolution, I have utilized the selected **Data Subset** devoid of any blunders and cycles slips, hence making the estimation process easier.

## Subtask A: List the estimated integer values of the ambiguities

### Search Method

* Searching commenced at epoch/time( = 800th second
* Standard deviation() of the ambiguities are well below 0.3 L1 cycle at this epoch, making search space of or ~ L1 cycle have success rate of finding correct integer ambiguity greater than 99.7% .
* Sum of Squared Residual Formula:

=

* Ratio-Test threshold has been set as 3.

> threshold, where is the second smallest total sum of squared residual and

is the smallest

Table : Estimated Integer Ambiguity and corresponding ratio test value

|  |  |
| --- | --- |
| At t = 858th second the ratio test passed, with = 3.003917 | |
| PRN | Integer Ambiguity |
| 7 | 0 |
| 15 | -10 |
| 17 | -11 |
| 24 | -12 |
| 26 | 9 |
| 27 | -2 |

Following Figures 11 and 12 shows, the timeseries of ambiguity fixing process of GPS satellites PRN 7 and 27. The same happens for other satellites.

Chart, line chart

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Figure : Ambiguity Fixing for PRN 7

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Figure : Ambiguity Fixing for PRN 27

### Rounding-Off method

This ambiguity-resolution(AR) method performs sequential filtering twice. The first filtering process calculates the floating ambiguities. It then rounds-off the converged floating ambiguities obtained at the end of the 1st filtering process to estimate the integer ambiguities. The 2nd sequential filter only utilizes carrier-phases, from which estimated integer-ambiguities have been deducted. I have performed this AR method based on one primary assumption, which is

floating ambiguities at the end of 1st sequential filtering have converged around the true integer ambiguity value, and since the standard deviation will be minimal( less than 0.1 GPS L1 cycle, observed for the chosen *dataset*) rounding-off the floating value to estimate the integer ambiguity is an adequate technique in this instance.

Table : Estimated Integer-Ambiguity after rounding off the converged float ambiguities obtained at the end of 1st Filtering process

|  |  |
| --- | --- |
| PRN | Integer Ambiguity |
| 7 | -1.0 |
| 15 | -11 |
| 17 | -13 |
| 24 | -13 |
| 26 | 8 |
| 27 | -4 |

## Subtask B: list the search space used for the ambiguity search

Since at the time of initiating the fixing process and searching for candidate integer values, the standard deviation associated with estimated ambiguities was well below 0.3 GPS L1 cycles, I have chosen the following search-space based on AR method used

1. **Search Method**: L1 cycle, with a success rate of finding correct integer ambiguity within this range being more 99.7 %
2. **Rounding-Off Method:** As converged floating ambiguities at the end of 1st filtering have been observed to have less than 0.1 GPS L1 cycle standard deviation for the given dataset, rounding-off is assumed to be an adequate method.

## Subtask C: Plot the fixed ambiguities on top of the float ambiguities

*NOTE: There are total of 6 satellites( + 1 reference satellite) being used in the estimation, but to demonstrate the nature of the float and fixed ambiguities. Plots for only three satellites are shown below.*

Chart, line chart

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Figure : Float vs Fixed Ambiguity for PRN 24

Chart, line chart

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Figure : Float vs Fixed Ambiguity for PRN 15

Graphical user interface, chart, line chart

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Figure : Float vs Fixed Ambiguity for PRN 26

Figures 13, 14, and 15 show the progression of floating ambiguity related to integer ambiguity. During the initial filtering period, floating ambiguity is still converging to its true state and therefore appears to disagree with integer ambiguity.

# task 4: PERFORM RTK-FIX Position Estimation

Position solution determined using the Rounding-Off AR method will be presented below. The positional accuracy/error shown in this section (Table 7-8 and Figures 16-24) is for the **Data Subset**.

## Subtask A

Table : RMSE(in m) for WLS vs BRSD vs RTK-Float vs RTK-Fixed

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Method/RMSE(m) | Weighted Least Squares | Between-Receiver-Single-Differenced | RTK-Float | RTK-Fixed |
| Easting | 1.3625 | 0.4115 | 0.1212 | 0.1026 |
| Northing | 0.5158 | 0.5174 | 0.2082 | 0.0729 |
| Up | 7.2218 | 0.9347 | 0.3180 | 0.4857 |
| 3d Error | 7.3673 | 1.1449 | 0.3990 | 0.5017 |
| 2d Error | 1.4569 | 0.6611 | 0.2409 | 0.1259 |
| **Positional Accuracy:   3D :** RTK-Float >RTK-Fixed > BRSD > WLS  **2D :** RTK-Fixed > RTK -Float>BRSD>WLS | | | | |

Table : Error comparison of Converged position estimate obtained at the end of Sequential Filtering

|  |  |  |
| --- | --- | --- |
| Method - > | RTK-Float | RTK-Fixed |
| Easting | 0.1154 | 0.094 |
| Northing | 0.0134 | 0.0013 |
| Up | 0.1870 | 0.1439 |
| 3d Error | 0.2202 | 0.1724 |
| 2d Error | 0.1162 | 0.0950 |
| **Positional Accuracy:** RTK-Fixed >RTK-Float | | |

Graphical user interface, application, table

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Figure : RTK-Fix East Error(in m)

Chart, line chart

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Figure : RTK-Fix North Error(in m)

Chart, line chart

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Figure : RTK-Fix Up Error(in m)

Chart, line chart

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Figure : RTK-Fix 2D Error(in m)

Chart, line chart

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Figure : RTK-Fix 3D RMSE(in m)

Graphical user interface, chart

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Figure : RTK-Fix vs RTK-Float 2D Error(in m)

Chart, line chart

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Figure : RTK-Fix vs RTK-Float 3D RMSE(in m)

Chart

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Figure : RTK-Fix vs RTK-Float vs BRSD vs WLS 2D Error(in m)

Chart, histogram

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Figure : RTK-Fix vs RTK-Float vs BRSD vs WLS 3D RMSE(in m)

## Subtask B

According to my results(refer to Table 7), RTK-Fix RMSE error in 3D is worse compared to RTK-Float by around 10 cm, but on the other hand, RTK-Fix 2D RMSE error is better than RTK-Float by 10 cm. The converged position estimated at the end of the filtering process is better for RTK-Fix than RTK-float(refer Table 8). The most significant advantage of RTK-fix over RTK-float is the preciseness of position estimates, especially in 2D or horizontal components (refer Figure 21 and Figure 23). Also, observing RTK-Fix ENU graphs 16, 17 and 18, it can be inferred that error in position estimates seem to be converging to zero.

# Task 5: Choose one of the ambiguities at random, and add exactly one cycle to its fixed value.

I chose GPS Satellite PRN 27 and added 1 cycle to it.

## Subtask A

Chart

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Figure : PRN 27 Correct and Incorrect Ambiguity Fix

Graphical user interface, chart, line chart

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Figure : RTK-Fix East Error(in m)

Chart

Description automatically generated

Figure : RTK-Fix North Error(in m)

Chart, line chart

Description automatically generated

Figure : RTK-Fix East Error(in m)

Chart

Description automatically generated

Figure : RTK-Fix 2D Error(in m)

Chart, line chart

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Figure : RTK-Fix 3D Rmse (in m)

Table : Correct vs Incorrect RTK-Fix

|  |  |  |
| --- | --- | --- |
| Method/RMSE(m) | Correct RTK-Fix | Incorrect RTK-Fix |
| Easting | 0.1026 | 0.1351 |
| Northing | 0.0729 | 0.0879 |
| Up | 0.4857 | 0.6671 |
| 3d Error | 0.5017 | 0.6863 |
| 2d Error | 0.1259 | 0.1612 |

## Subtask C

It is apparent from observing the figures 26-30, that positional accuracy has been degraded for the incorrect RTK-fix compared to correct RTK-fix. Especially in vertical direction additional error of ~20 cm has been introduced. Figure 29 shows that for incorrect RTK-fix a bias gets introduced in the horizontal positional components. Methods similar to Data Snooping can be employed to monitor the innovation sequence divergence. Phase residuals or Innovation sequence will continue to grow in presence of an incorrect ambiguity fix.

***NOTE:*** *The source code for this Java based project can also be found on the github – (link:* [*naman4u13/ENGO625 (github.com)*](https://github.com/naman4u13/ENGO625)*). User only needs to modify the output file path, before compiling the code to output the solution. Graphs and Output file concerning estimation accuracy and errors can be found in ‘ENGO625 -> result’ folder in the home directory. Code is present inside ‘ENGO625 -> engo625\_lab’ folder.*