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Real-time cycle slip detection and repair in multi-GNSS, multi-frequency data processing : Part 2

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Introduction

Cycle slip detection and repair are essential quality control steps in recovering the integer ambiguities when loss of tracking signals in GNSS precise positioning occurs. In this contribution, we present an improvement to the previous algorithm [1] for reliable real-time cycle slip detection and repair of the Australian **Analysis Centre Software (ACS)** Pre-processing and Data Editing (PDE) function. First, the traditionally used algorithm based on the quality control theory is used to detect and repair the cycle slips. Then if the cycle slips are detected but not reliably repaired, the information of subsequent epochs are used together to strengthen the model and achieve a higher cycle slip repair success-rate. With such an enhancement, the model becomes more robust to accommodate the measurement noise and the ionosphere disturbance.

Methodology

The original mathematical models for cycle slip detection and repair are [1]:

$$E\{\Delta p_j(i)\} = \Delta\rho + u_i \Delta I \quad (1)$$

$$E\{\Delta\varphi_j(i)\} = \Delta\rho(i) - \mu_j \Delta\iota(i) + \lambda_j \Delta z_j \quad (2)$$

$$E\{\Delta\iota(i)\} = \Delta\varphi_1(i-1) - \Delta\varphi_2(i-1) \quad (3)$$

where p and φ denote the un-differenced code and phase measurements, with noise of σ_p and σ_φ, respectively, Δ being the time-differenced (TD) operator between epoch i and $i-1$, ρ contains all geometric terms together with zenith tropospheric delays, $\Delta\iota$ is the TD ionosphere residual, with the noise of $\sigma_{\Delta\iota}$, μ_j is the ionosphere coefficient, λ_j and Δz_j are the wavelength and TD integer cycle slips on the j frequency. *To detect the cycle slip*, the quality control theory can be used with the null and alternative hypothesis as:

$$E\{l(i)\} = Ax \quad (4)$$

$$E\{l(i)\} = Ax + Bb \quad (5)$$

with $l_i = [\Delta p_j(i) \quad \Delta\varphi_j(i) \quad \Delta\iota(i)]^T$. Vector x consists of TD geometric distance and TD ionosphere residual. B is the wavelength coefficients for the cycle slip vector b. The quadratic form of the least-squares residuals of the null hypothesis is:

$$T = \hat{v}^T P \hat{v} \quad (6)$$

Equation (6) follows chi-square distribution and it is compared with a critical value (e.g. alpha=0.001) to check if cycle slips occurs.

Once cycle slips are detected, the alternative hypothesis (5), together with the Ps-LAMBDA method [2], can be used to *estimate and repair* (resolve) the cycle slips to integers.

The performance of the cycle slip repair step is subjected to the model strength. In case of weak model strength (such as low elevation and high ionospheric disturbance), the success-rate of repair becomes very low. To increase the model strength, the improved algorithm consists from the following steps:

1. if cycle slips are detected from epoch $i-1$ to i but not repaired,
2. then in the $i+1$ epoch, if no cycle slip occurs from epoch i to $i+1$, a TD between epochs $i+1$ and $i-1$ can be formed and used together with the TD information from epochs $i-1$ to i .

The more epochs used, the stronger the model will become.

Results

Previously in [1] the performance of the CS detection and repair algorithms was evaluated with 1Hz data collected from 9 MGEX stations and 1 Australian CORS station. The real-data success-rates from [1] against the elevation are plotted on **Figure 1**.

Then, the improvement of the new method can be theoretically analysed.

In **Figures 2 and 3,** *simulated success-rates* are plotted against the measurement noise and the TD ionosphere residual.

Comparing the left and the right figures, we have:

1) The improved method outperforms the original method by up to 25% increase in the success-rates;
2) Triple-frequency cycle slip repair success-rate is significantly higher than the dual-frequency counterpart, as also demonstrated with real-data from **Figure 1**;
3) Under low elevations or high ionosphere disturbances, cycle slip repair success-rate is poor, particularly for dual-frequency cases.

The improved algorithm is implemented in the ACS PDE and the same data sets and pre-settings from [1] are used. Two satellites, namely **BDS C06** and **Galileo E22**, are selected to showcase the improvement of the new algorithm and the results are given in **Tables 1-4**.

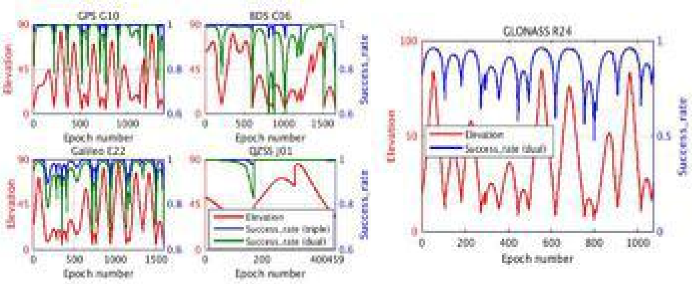

Figure 1: (Left) CDMA based ILS success rates for dual (green) and triple-frequency (blue) and **(Right)** FDMA-based ILS success rate for GLONASS from [1]

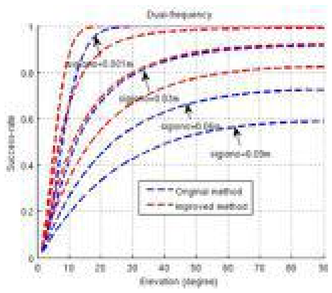

Figure 2: the expected impact of the TD ionosphere residual on the cycle slip repair success-rate for dual-frequency using the original method and the improved method ($\sigma_{\Delta\iota}$ from top to bottom of each colour curve: 0.001m, 0.03m, 0.06m, 0.09m)

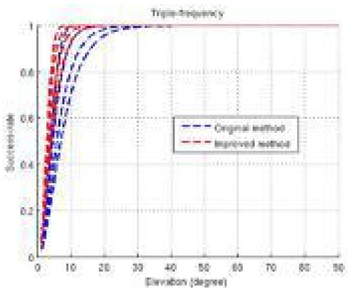

Figure 3: the expected impact of the TD ionosphere residual on the cycle slip repair success-rate for triple-frequency using the original method and the improved method

	Case 1 [1 1]	Case 2 [0 1]	Case 3 [9 7]
Detected	1662	1662	1468
Repaired	1618/1650	1618/1662	1453/1466
Correct fixing	1618/1650	1618/1662	1453/1466
Wrong fixing	0	0	0
Truth	1662	1662	1662

Table 1: cycle slip detection and repair results for satellite C06 using dual-frequency, Red indicates results using the improved algorithm and black those obtained from [1]

	Case 1 [1 1]	Case 2 [0 1]	Case 3 [9 7]
Detected	1662	1662	1627
Repaired	1661/1662	1661/1662	1627
Correct fixing	1661/1662	1661/1662	1627
Wrong fixing	0	0	0
Truth	1662	1662	1662

Table 2: cycle slip detection and repair results for satellite C06 using triple-frequency. Red indicates results using the improved algorithm

	Case 1 [1 1]	Case 2 [0 1]	Case 3 [9 7]
Detected	1589	1589	1585
Repaired	1571/1586	1571/1586	1569/1583
Correct fixing	1571/1586	1571/1586	1569/1583
Wrong fixing	0	0	0
Truth	1589	1589	1589

Table 3: cycle slip detection and repair results for satellite E22 using dual-frequency. Red indicates results using the improved algorithm

	Case 1 [1 1]	Case 2 [0 1]	Case 3 [9 7]
Detected	1589	1589	1589
Repaired	1585/1589	1585/1589	1585/1589
Correct fixing	1585/1589	1585/1589	1585/1589
Wrong fixing	0	0	0
Truth	1589	1589	1589

Table 4: cycle slip detection and repair results for satellite E22 using triple-frequency. Red indicates results using the improved algorithm

Conclusions

The proposed algorithm for cycle slip detection and repair has been verified theoretically and numerically. The results indicate the effectiveness of the algorithm. Using the improved method increases the model's strength even for cases with high ionospheric disturbances. The improvement is larger on the dual-frequency cases, even at low elevations, as expected, than for the triple-frequency cases, where the model is strong already.

[1] Li, T. and Melachroinos, S. (2016), Real-time cycle slip detection and repair for network Multi-GNSS, Multi-frequency data processing, IGNSS2016;
[2] Verhagen, S., Li, B. and Teunissen, P.J.G. (2013), Ps-LAMBDA: ambiguity success rate evaluation software for interferometric applications, Computers & Geosciences, 54: 361-376.

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