Benefit of Triple-Frequency on Cycle-Slip Detection

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Key words: triple-frequency, cycle slip

SUMMARY

At the time of writing, all the Global Navigation Satellite Systems (GNSS) support or are designed to support triple- or multi- frequency, which is expected to have advantages over single- and dual- frequency. This paper will conduct research on how triple-frequency can benefit the cycle-slip detection process. Correctly detecting and repairing cycle slips can help extend the latency of the fixed ambiguities, estimate the ionospheric delay, reduce the measurement noise and finally improve the positioning precision of the carrier phase. This paper will firstly review the widely used cycle-slip detection methods, including high-order phase differencing, Doppler integration and the ionospheric residual. For applying triple-frequency in cycle-slip detection, we will modify the Hatch-Melbourne-Wübbena combination to eliminate the effect of the ionospheric bias and reduce the measurement noise on the detection value. The triple-frequency method can detect and correct cycle slips instantaneously. All the mentioned methods will be tested using triple-frequency Galileo data observed in static condition. The results show that the performance of the triple-frequency method has a higher success rate and a lower missed detection compared to those using single-frequency, especially in detecting small cycle slips in observation with large intervals. Although the ionospehric residual provides higher success rates at low elevation angles, the triple-frequency method is more advanced than the ionospheric residual, which cannot decide the magnitude of the cycle slips easily.

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1. INTRODUCTION

Cycle slips can derogate the precision of carrier phases in positioning, such as the real-time kinematic and precise point positioning (PPP). Correctly detected and fixed cycle slips are able to extend the efficacy of ambiguities and shorten the convergence time of PPP (Zhao et al. 2017). Currently, multi GNSS systems, such as GPS, BDS, Galileo, and GLONASS, support triple frequencies, which are supposed to benefit the cycle-slip detection by forming more combinations less affected by ionospheric bias and measurement noise (Feng 2008, Zhao et al. 2016). In order to evaluate the advantage of the triple-frequency, this paper will review and assess several cycle-slip detection methods using single-, dual- and triple-frequency. For single-frequency, high-order phase differencing, Doppler integration are selected, while the ionospheric residual is for dual-frequency. For triple-frequency, we select and extend the newly proposed method by Zhao et al (2017).

2. METHODS REVIEW

2.1 High-order phase differencing

The detection value of high-order phase differencing is the 3-order differencing phase measurements, which can eliminate the geometry term, and reduce the effect of the ionospheric bias, tropospheric bias, satellite orbit error, satellite and receiver clock errors, based on the assumption that these errors vary smoothly with time. Thus, this method can only be applied in static and low dynamic scenarios. A cycle slip may break this assumption, making the detection value unfit the polynomial derived from the former 10 epochs. The detection value is less affected by multipath, but clock jumps, due to only employing phase measurements. Therefore, clock jumps have to be fixed before applying high-order differencing.

2.2 Doppler integration

The variation rate of the carrier phase decides Doppler measurements, which is only affected by rates of biases, such as ionospheric bias. The detection value is the agreement between the Doppler measurement and the time-differenced phase measurement. Part of the bias is eliminated in the calculation; thus this detection value will be more precise than that only employing phase data. As Doppler data is cycle-slip free, a cycle-slip may break this agreement. However, Doppler data is not available by some receivers. Besides that, this method is also limited by the interval, as the Doppler data is generated with a high-rate frequency, while the RINEX observations are sampled with a lower frequency (Dai 2012).

2.3 Ionospheric residual

When GNSS signals pass through the ionosphere, a systematic error will be added into the observation, known as the ionopheric bias or the ionospheric residual, which will vary slowly with the moving of satellites under normal conditions. Thus, the ionospheirc residual can be used as the detection value, as a cycle slip could bring a sudden jump in the ionospheric residual. The ionospheric residual can be estimated using a dual-frequency combination, however, it is not easy to decide which frequency the cycle slip occurs and the magnitude. Although Roberts (2017) tried to decide the magnitude of the cycle slip using the ionospheric residual refinement integer values, it is still not an easy job to determine the magnitude as his method is limited by the search range, to say 10 cycles. A coarse detection technique has to be adopted to bring the cycle slip value to this small range. Besides that, the ionospheric residual can also be disturbed by some ionosphere phenomenon, such as ionospheric scintillation (Romano et al., 2013a, Romano et al., 2013b, Sreeja et al., 2011).

2.4 Triple-frequency cycle-slip detection

When employing triple-frequency, the cycle slip can be detected and fixed instantaneously and precisely. One of the commonly used methods is called Hatch-Melbourne-Wübbena (HMW) combination (Hatch 1982; Melbourne 1985; Wübbena 1985), which can eliminate both the geometry term and the non-dispersive errors, such as ionospheric bias. However, the traditional HMW combination is not sensitive to small cycle slips, due to only adopting the latency signals, L1 and L2. The wavelength of this combination is not big enough on account of the noise of the code measurement. This problem can be solved by introducing the triple-frequency using the method proposed by Zhao et al (2017). This method was originally proposed to detect cycle slips for GPS observations under ionospheric scintillation, but unable to fix, as only one combination was selected. In this paper, we tested this method using Galileo triple-frequency data by the newly proposed two combinations, making it be able to detect and correct cycle slips at the same time.

This method firstly employs the extra-wide-lane (EWL) HMW combination $\Phi_{(0,1,-1)}$ to detect cycle slips and provide a cycle-slip free combined signal $\breve{\Phi}_{(0,1,-1)}$ to work with another two combined signals in the following two steps. Same as the traditional HMW combination, time-differenced ambiguities of the combined signals are selected as the detection value, shown as follows,

$$\Delta N_{(i,j,k)} = \frac{1}{\lambda_{(i,j,k)}}\left(a\Delta P_1 + b\Delta P_2 + c\Delta P_3 + d\Delta\breve{\Phi}_{(0,1,-1)} - \Delta\Phi_{(i,j,k)}\right) \qquad (1)$$

where Δ denotes the time-differenced operation between two consecutive epochs; N is the ambiguity; the subscripts 1, 2 and 3 denote for Galileo E1, E5b and E5a respectively; i, j and k are coefficients of the selected combined signals; P denotes the code measurement. The optimal combined signals are those which can eliminate the ionospheric bias and minimize the noise of the code measurement with the constraint that the sum of the coefficients a, b, c, and d should be 1, which is for maintaining the geometry-free property. Based on our study, the two selected combined signals are (1,-6,5) and (4,-5,0). Due to the integer properties of the time-differenced ambiguities and cycle slips, the magnitude of the cycle slips on the original signals can be corrected simply by multiplying the inverse of the coefficient matrix of the of the combined signals to the matrix of the cycle slips detected by the three combined signals.

3. NUMERICAL TESTS

Static triple-frequency Galileo data was observed on 29th July, 2017 from Station CUT0, which is belonged to the Curtin GNSS Research Center. The types of receiver and antenna are JAVAD TRE_G3TH_8 and TRM59800.00 SCIS respectively. In order to compare the applicable of the four cycle-slip detection methods on different intervals, the original 1s observations are decimated into intervals up to 30s. As the triple-frequency cycle-slip method employs code measurements, the multipath effect needs to be taken into account. Thus these data samples are divided based on satellite elevation angles, such as 5°~20°, 20°~40°, 40°~60° and >60°. Artificial cycle slips with magnitude from 1 to 20 are added into all these samples.

In order to study the benefit of the triple-frequency on cycle-slip detection, we adopt three criteria, including the standard deviation (STD) of the detection value, the missed detection rate (MR) and the success rate (SR). All the former detection methods are based on the precision of the detection value, so a smaller STD means a more reliable detection. The missed detection rate refers to the ratio of the false alarms to the number of the total epochs using the data samples without artificial cycle slips, while the success rate is defined as the ratio of the correctly detected to the totally added cycle slips. A lower missed detection rate means the detection value is less affected by the measurement noise and the ionospheric bias. A higher success rate denotes a stronger ability to detect such kind of cycle slips.

Figure 1 shows the variation of the STD of the detection value with the increase of intervals. Optimally, the STD should be smaller than 0.1581 cycle in order to provide a reliable detection based on our study. The two methods using only one frequency can only meet this condition when the interval is no larger than 2s. With the increase of intervals, the STD of the Doppler integration does not grow as quickly as that of the high-order phase differencing, due to the elimination of the ionospheric bias by employing the Doppler data. The STDs of ionospheric residual and the triple-frequency method can always be lower than 0.1581 cycle regardless intervals. The four panels in Figure 1 from top to bottom also show a decrease of the STD of the triple-frequency method with the increase of satellite elevation angles, while those of the other three methods maintains nearly the same. This is because the code measurements employed in the triple-frequency method are affected by the multipath brought by low satellite elevation angles, while for the others, only phase observations are adopted. On account of the magnitude of STDs, the triple-frequency method can provide a competitive performance compared to the ionospheric residual, but a much more reliable cycle-slip detection compared to ones using single-frequency,

Figure 2 illustrates the variation of the MR with the increase of intervals. The MRs of the ionospheric residual and the triple-frequency method are more stable and lower than those using one frequency, because the detection value of which are more easily to get noisy. With the changes of intervals, all the MRs have some fluctuations, due to the mismatch of the detection boundaries and the changes of the detection values for some intervals. Figure 2 also shows that with the increase of satellite elevation angles, the triple-frequency provides a lower MR for middle-low elevation angles, while ionospheric residual performs better for high elevation angles. However, on account of the amount of MRs, it is reasonable to say both the triple-frequency method and the ionospheric residual can provide acceptable MRs for cycle-slip detection.

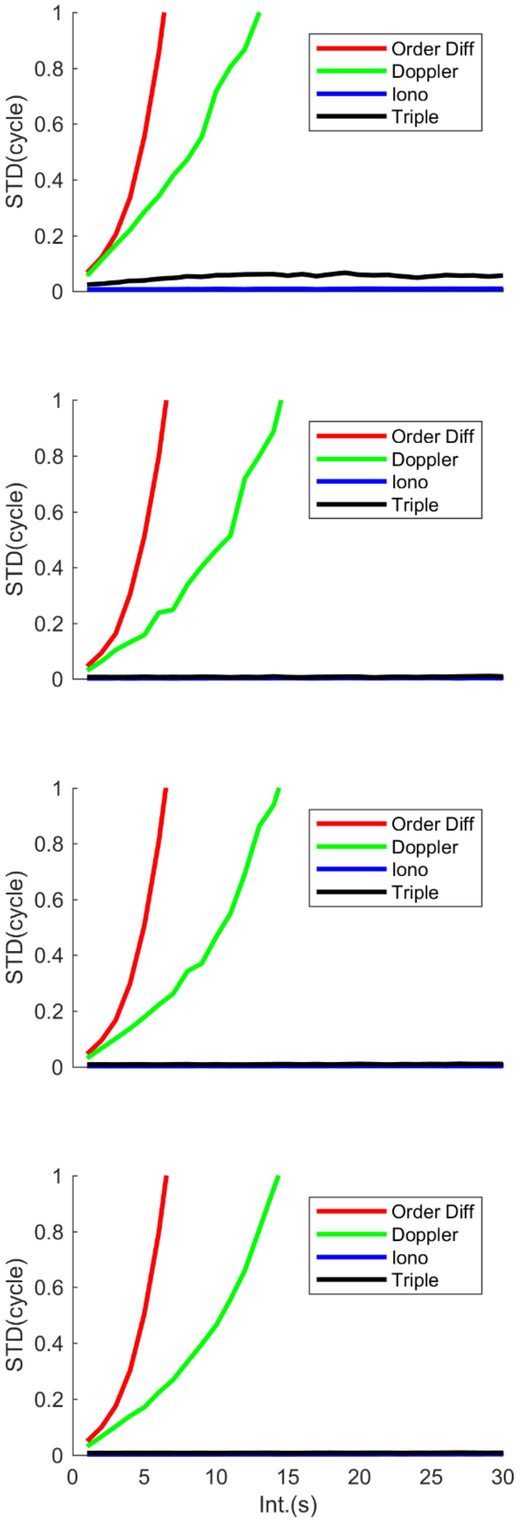

Figure 1. The standard deviation of the detection values. Panels from top to the bottom are obtained from the data with elevation angles 5°~20°, 20°~40°, 40°~60° and >60° respectively. “Int.” denotes interval.

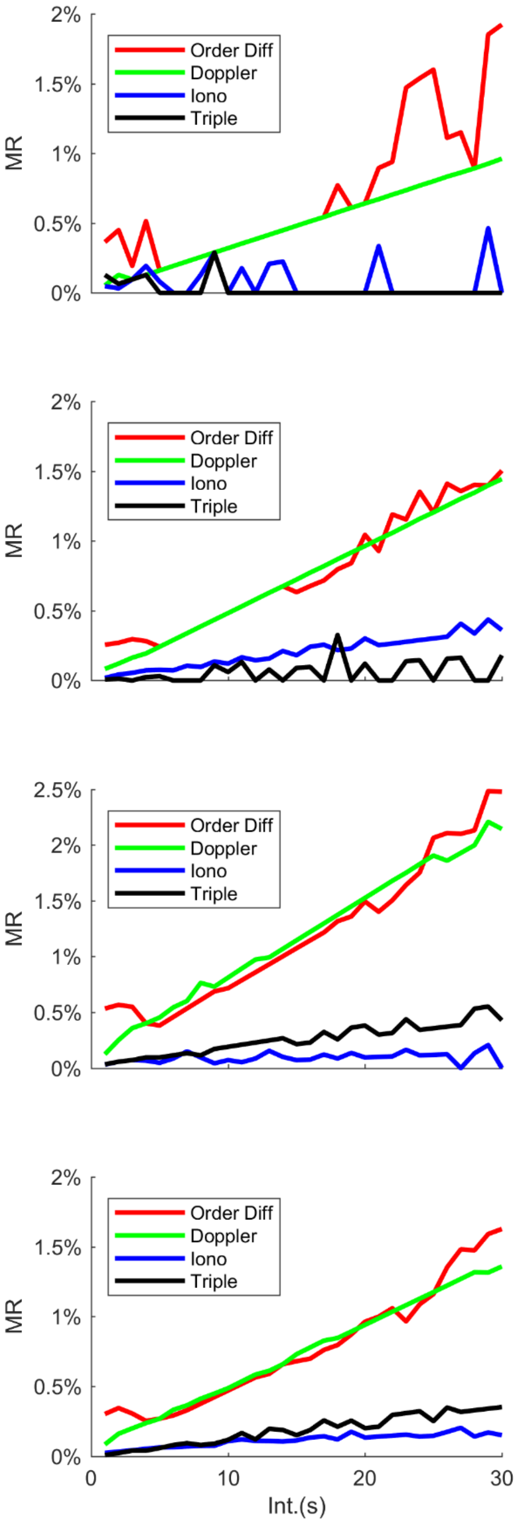

Figure 2. The missed detection rate. Panels from top to the bottom are obtained from the data with elevation angles 5°~20°, 20°~40°, 40°~60° and >60° respectively.

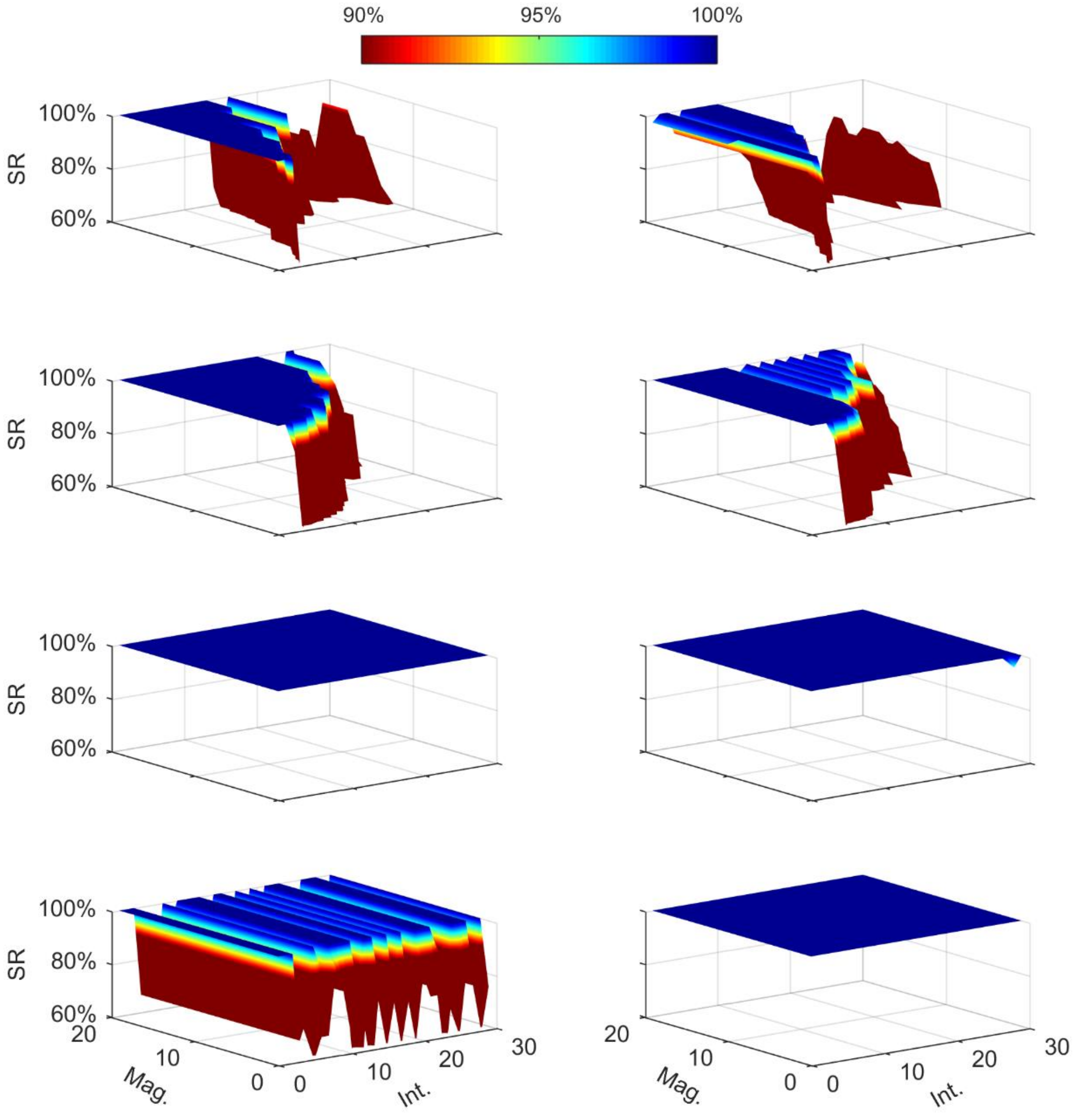

Figure 3. The success rate. The left panels are obtained from data with satellite elevation angle 5°~20°, while the right panels are for 20°~40°. The panels from top to bottom are for high-order phase differencing, Doppler integration, ionospheric residual and the triple-frequency method respectively. “Mag.” stands for magnitude in the unit of cycle.

Figure 3 and Figure 4 illustrate the SRs to different magnitudes of cycle slips and intervals. The top four panels show the high-order phase differencing can only detect small cycle slips, we say 1 or 2 cycles, when the interval is 1s or 2s and fail to detect cycle slips when the interval is larger than 10s. This meets with the STDs shown in Figure 1, where the STD value will be larger than 1 cycle when the interval exceeds 10s. Similarly, the Doppler integration cannot be used to detect cycle slips in large interval data. When the satellite elevation angle is larger than 20°, both the ionospheric residual and the triple-frequency method can obtain a full success rate, while the ionospheric residual performs better during low elevation angles. One reason can be the multipath brought by the low elevation code measurements in the triple-frequency method. Another reason can be that for the ionospheric residual, a cycle slip is regard as success when a slip is detected at the epoch artificial added, while for triple-frequency method, the magnitude should be also met, as the magnitude cannot be easily obtained from ionospheric residual.

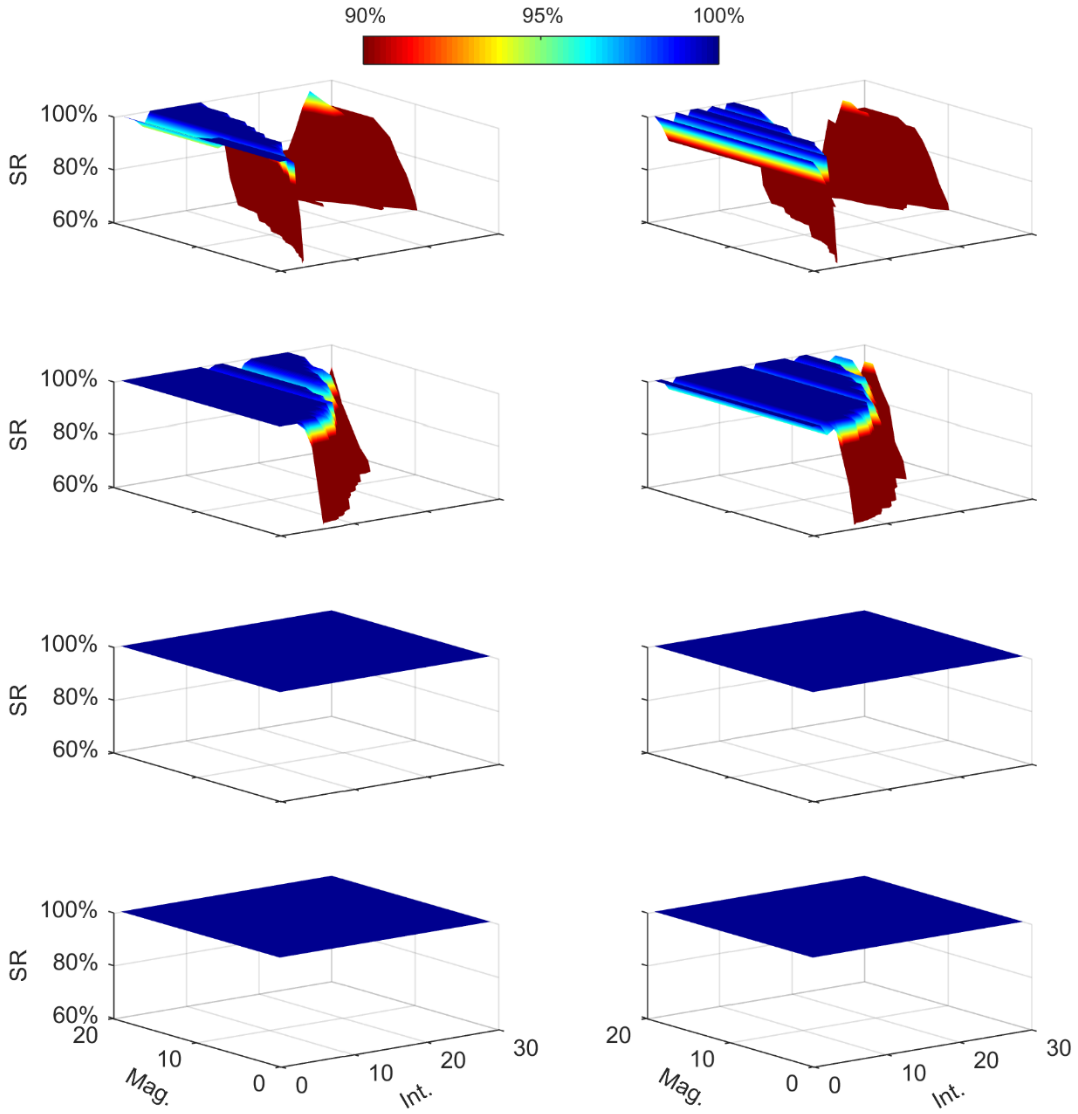

Figure 4. The success rate. The left panels are obtained from data with satellite elevation angle 40°~60°, while the right panels are for >60°. The panels from top to bottom are for high-order

phase differencing, Doppler integration, ionospheric residual and the triple-frequency method respectively.

4. CONCLUSIONS

Compared to the high-order phase differencing and the Doppler integration, the proposed triple-frequency cycle-slip detection method can provide a more reliable performance, especially in detecting small cycle slips in the observations with large intervals. The triple-frequency method can detect and correct all kinds of cycle slips instantaneously regardless the interval when the satellite elevation angle is larger than 20°. For observations with low elevation angles, not all the cycle slips can be detected by the triple-frequency method. In such cases, the ionospheric residual could help, although it cannot fix the slips in real time. Therefore, the future work will investigate how to obtain the cycle slips using these ionospheric residuals.

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BIOGRAPHICAL NOTES

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