BQC：A New Multi-GNSS Data Quality Checking Toolkit

Huicui Liu[1], Geshi Tang[1], Davide Imparato[2], Hongzheng Cui[1], Baiyan Song[1],Chirs Rizos[3],

1. Science and Technology on Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center, China, hcliu_bacc@163.com
2. Geoscience and Remote Sensing, TU Delft, Netherlands, D.imparato@tudelft.nl
3. School of Civil & Environmental Engineering, University of New South Wales, Australia, c.rizos@unsw.edu.au

Abstract: Multi-GNSS networks, for example M-GEX and iGMAS, are set up and grow quickly with the development of new navigation systems and multi-GNSS receivers. It is unavoidable that GNSS signals are deteriorated by several error sources. Thus GNSS network operators, data users and receiver designers all require data quality checking (QC). However, few GNSS data QC software can process data of new navigation systems even modernized GPS signals. This paper introduces BQC, a multi-GNSS data QC toolkit which can process data of GPS/GLONASS/Galileo/Beidou recorded in RINEX version 2 or 3. Various QC outputs are written in QC report files as well as graphically displayed. Also in this paper, the cycle slip detection processing of BQC is emphasized as a key algorithm and compared with that of TEQC, the most widely-used GNSS data QC toolkit. The numerical results show that BQC reduces miss probability in cycle slip detection and repairs cycle slip effects on multipath sequences more reliable compared to TEQC.

BIOGRAPHIES

Huicui Liu, PhD, is an engineer of the Science and Technology on Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center. Her current research is in GNSS data quality checking and GNSS application in deep space exploring.

Geshi Tang, PhD, is the leader of the Science and Technology on Aerospace Flight Dynamics Laboratory. His current research is in orbit determination and GNSS data analysis.

Davide Imparato, is a PhD student at Delft University of Technology, The Netherlands, at the Department of Geoscience and Remote Sensing. He holds a M. Sc. Degree from the faculty of aerospace engineering of the University of Pisa, Italy. His research focuses on Aircraft Navigation Integrity, statistical hypothesis testing for RAIM algorithms and future GNSS integrity concepts.

Hongzheng Cui, PhD, is a post PhD of the Science and Technology on Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center. His current research is in GNSS data analysis.

Baiyan Song, is an engineer of the Science and Technology on Aerospace Flight Dynamics Laboratory, Beijing Aerospace Control Center. His current research is in GNSS data analysis.

Chris Rizos is a professor of School of Civil & Environmental Engineering, University of New South Wales, Australia. Chris has been researching the technology and high precision applications of GPS since 1985, and has published over 600 journal and conference papers. Chris established the Satellite Navigation and Positioning Group at UNSW in the early 1990s - Australia's premier academic R&D group for GNSS and wireless positioning technology and applications, now a combined lab with the School of Electrical Eng & Telecommunications. Chris is a member of a number of national and international committees, a Fellow of the Australian Institute of Navigation, a Fellow of the U.S. Institute of Navigation, a Fellow of the International Association of Geodesy (IAG), an honorary professor of Wuhan University (P.R. China), and is currently President of the IAG (2011-2015). He is a member of the International GNSS Service (IGS) Governing Board and a member of its Executive. He is also co-chair of the Steering Committee of Multi-GNSS Asia.

1 INTRODUCTION

Beidou Navigation Satellite System was declared a regional navigation service for the Asia-Pacific region with 14 functioning satellites at the end of 2012. Additional Galileo satellites are to be launched in the next year or so, so as to reach Final Operational Capability by 2018. Meanwhile GPS and GLONASS are being modernised, with new signals being added in order to improve user navigation and timing performance. As a result we have entered an era of "multi-GNSS" with capable receivers and antennas now available. To prepare for the analysis of different GNSS measurements, to support the development of new products and services the International GNSS Service (IGS) has established the multi-GNSS Global Experiment (M-GEX) and associated ground receiver network (ftp://igscb.jpl.gov/pub/resource/pubs/IGS_2010_Newcastle_Workshop_Recommendations.pdf) and issued a Call For Participation worldwide in the summer of 2011 (Hugentobler & Neilan 2011). By September 2013 the M-GEX network had more than 90 receiver stations (ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/, http://mgex.igs-ip.net/, http://igs.org/mgex) supporting at least one of the new navigation systems, including Galileo, Beidou, and Japan's Quasi-Zenith Satellite System (QZSS), besides GPS, GLONASS, and satellites broadcasting Satellite Based Augmentation System (SBAS) signals (Langley 2013). The China Satellite Navigation Office has proposed the establishment of a parallel global network of multi-GNSS stations as part of the "international GNSS Monitoring and Assessment System" (iGMAS) comprising about 30 tracking stations (9 in China and 21 in other countries).

All GNSS signals (and measurements) are degraded by several error sources, such as ionospheric delay, tropospheric delay, multipath, and others. Furthermore the impact on derived products and services varies among systems even in the case of the same multi-GNSS receiving antenna/receiver since the satellite orbits, carrier frequencies and modulation types are different. Thus multi-GNSS networks such as M-GEX and iGMAS would benefit from data quality checking (QC) tools.

The TEQC software, developed by UNAVCO is the most widely used GNSS data pre-processing software for file format translation, file edition and QC (Estey & Meerterns 1999). However its QC function is limited in the case of multi-GNSS applications for two reasons. The first is that TEQC QC only handles RINEX file versions up to version 2.11 (see, e.g., http://igs.org/igscb/data/format/rinex2.11.txt), but multi-GNSS networks such as M-GEX and iGMAS use RINEX version 3 (see, e.g., http://igs.org/igscb/data/format/rinex3.00.txt). The second one is that TEQC QC can only scan GPS or GLONASS measurements. Most widely-used GNSS data processing toolkits, such as GpsTools (Takasu & Kasai 2005) also have the above drawbacks. The German Federal Agency for Cartography and Geodesy (BKG) has developed the BKG Ntrip Client (BNC) whose QC function is compatible with RINEX version 3. However BNC only outputs QC results for one navigation system at a time. Moreover, QC results of GLONASS, Beidou and Galileo do not provide information on the multipath effect – an important data quality index.

China's Science and Technology on Aerospace Flight Dynamics Laboratory (AFDL) has developed "BQC", which can scan all GPS/GLONASS/Beidou/Galileo measurements recorded in RINEX version 2 or 3. This paper presents a brief introduction and describes the primary BQC algorithms. A set of multi-GNSS observation data from M-GEX and iGMAS stations has been analysed to validate BQC's processing capability.

2 BQC AND ITS PRIMARY OUTPUTS

BQC provides the users an easy operating experience with a friendly GUI interfacing shown in Figure 1, which are divided into two ribbons: the QC ribbon and the QC product view ribbon. With the QC product view ribbon, the user can view the various QC results generated by previous QC analysis.

In the QC ribbon, there are two optional processing modes: in single-file QC mode, one RINEX observation file is analyzed at a time to compute the following QC results using combinations of carrier phase and pseudorange measurements, as well as ephemeris data in the RINEX navigation file:

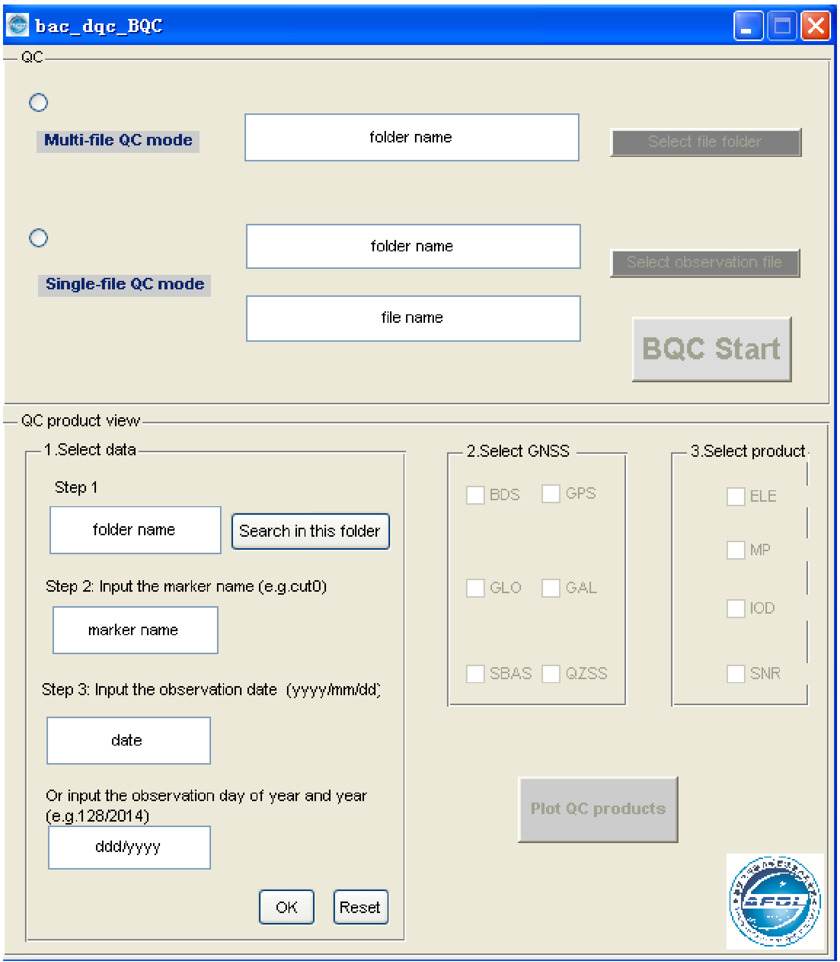

Figure 1. The interface of BQC

- satellite position including elevation (ELE) and azimuth
- signal-to-noise ratio (SNR)
- ionospheric delay and it's rate of change (IOD)
- pseudorange multipath effects (MP)

Various statistical data, such as cycle slips, moving average of the MP sequence, mean SNRare recorded system by system, satellite by satellite and item by item (shown in Figure 2 and Figure 3) in a summary file similar to TEQC's S-file, as well as observation information (shown in Figure 4).

```
-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*GPS summary
Band choise : L1->1 L2->2 L5->5

##SNR summary
      G01    G02    G03    G04    G05    G06    G07    G08    G09    G10    G11    G12    (
S1    -   40.6    -   25.7    25.8    -    -    -   41.9    -    -   28.8    -    -
S2    -   40.8    -   25.7    25.5    -    -    -   42.1    -    -   28.9    -    -

##Slip_detection summary
            total    G01    G02    G03    G04    G05    G06    G07    G08    G09    G10
L1L2            5    -      0    -      0      0    -    -    -      0    -    -      0   -
IODL1-L2       13      0      1      0      2      1      0      0      0      0      0
MPC1-L2         1    -      1    -    -    -    -    -    -      0    -    -    -    -    -
MPP2-L1         1    -      0    -      0      0    -    -    -      0    -    -    -    -
MPP1-L2         1    -      0    -      0      0    -    -    -      0    -    -    -    -

##Multipath summary
            total    G01    G02    G03    G04    G05    G06    G07    G08    G09    G10
MPC1-L2     0.50     -   0.28     -    -    -    -    -    -   0.23    -    -    -    -
MPP2-L1     0.38     -   0.14     -    -    -    -    -    -   0.12    -    -    -    -
MPP1-L2     0.36     -   0.15     -   0.52    0.37    -    -    -   0.11    -    -
```

Figure 2. The data header section (GPS system) of BQC summary file in single-file QC mode (for observation files in RINEX 2)

```
-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*GPS summary
Band choise : L1->1 L2->2 L5->5

##SNR summary
      G01    G02    G03    G04    G05    G06    G07    G08    G09    G10    G11    G12    (
S1C   -   43.2    38.7    -   41.7    41.4    -    -    -    -    -   46.5    -    3
S2W   -   27.3    20.3    -   26.0    25.3    -    -    -    -    -   33.8    -    1
S2X   -    -    -    -   39.7    -    -    -    -    -    -   43.5    -    -   37.3    -
S5X   -    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -

##Slip_detection summary
            total    G01    G02    G03    G04    G05    G06    G07    G08    G09    G10
1C2W           18    -      1      1    -      1      1    -    -    -    -    -      1    -
1C2X            8    -    -    -    -      1    -    -    -    -    -    -      1    -    -
1C5X            4    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -
IOD1C-2W       47      0      0      0      0      0      2      0      0      0      0
IOD2X-1C       28      0      0      0      0      0      0      0      0      0      0
IOD5X-1C        1      0      0      0      0      0      0      0      0      0      0
MP1C-2W         6    -      0      0    -      0      0    -    -    -    -    -      0    -
MP2W-1C         0    -      0      0    -      0      0    -    -    -    -    -      0    -
MP2X-1C         1    -    -    -    -      0    -    -    -    -    -    -      0    -    -
MP5X-1C         0    -    -    -    -    -    -    -    -    -    -    -    -    -    -    -

##Multipath summary
            total    G01    G02    G03    G04    G05    G06    G07    G08    G09    G10
MP1C-2W     0.62     -   0.82    0.72     -   0.83    0.66     -    -    -    -    -
MP2W-1C     0.41     -   0.45    0.54     -   0.50    0.38     -    -    -    -    -
MP2X-1C     0.44     -    -    -    -   0.59     -    -    -    -    -    -   0.45     -
MP5X-1C     0.38     -    -    -    -    -    -    -    -    -    -    -    -    -    -    -
```

Figure 3. The data header section (GPS system) of BQC summary file in single-file QC mode (for observation files in RINEX 3)

```
Version BQC 1.3
-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*QC Report*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
Marker name : ADIS
Marker number : 31502M001
Receiver type : JPS LEGACY          (# = MT300102915          Vers = 2.6.1 JAN,10,2008    )
Antenna type  : TRM29659.00      NONE(# = 0220173805           )
Approximate marker XYZ(ITRS)  :   4913652.8072  3945922.6351   995383.2858
Observation interval  :     30.000 seconds
Time of the first observation :   2013      1      1      0      0     0.000000
Time of the first observation : 13  1  1  0  0  0.0000000
Epochs w/ observations  : 240
Epochs / expected epochs  : 1.000

Total satellites  : 23
Total Beidou satellites : 0
Total GPS satellites  : 14  02  04  05  08  09  10  12  15  17  21  24  25  26  29
Total GLONASS satellites: 9 06  09  10  11  16  19  20  21  22
Total Galileo satellites: 0
Total SBAS satellites : 0
Total QZSS satellites : 0
```

Figure 4. The header section of BQC summary file in single-file QC mode

One should note that multi-signal measurements of the four GNSSs are defined and recorded in RINEX version 3 as listed in Table 1, which can all be compatible in BQC. In Addition, BQC scans all the recorded observation types for pseudorange/carrier phase/Doppler/SNR and provides separate QC results because different types of observation are attributed by different tracking mode or channel and may behave different quality characteristics.

Table 1. The compatible frequencies of BQC

Frequency / System	f_1	f_2	f_3	f_4	f_5
Beidou	L1	L2	L5	\	\
GPS	G1	G2	\	\	\
GLONASS	B1	B2	B3	\	\
Galileo	E1	E5a	E6	E5b	E5a+b
SBAS	L1	\	L5	\	\
QZSS	L1	L2	L5	LEX	\

Choosing the multi-file QC mode can QC all the observation files stored in one folder and generates a summary listing the key results of every observation file besides the QC products mentioned above so that the user can have an overall browse.

3 CYCLE SLIP DETECTION ALGORITHMS

3.1 LINEAR CNBINATIONS FOR CYCLE SLIP DETECTION

The use of GNSS carrier phase measurements can deliver highly accurate positioning solutions as long as the cycle slips are detected and repaired correctly. Cycle slip detection is a key processing of any GNSS data QC software. Several dual-frequency linear combinations are used to do the cycle slip detection and each is effective to different situations.

IOD and MP are the only two applied in TEQC. As derived in Estey & Meerterns (1999), the IOD of epoch t_k for f_2 can be estimated using:

$$\begin{aligned} I_2OD_k &= \frac{\alpha}{\alpha - 1} \cdot \frac{(L_{1,k} - L_{2,k}) - (L_{1,k-1} - L_{2,k-1})}{t_k - t_{k-1}} \\ &= \frac{(I_{2,k} - I_{2,k-1})}{(t_k - t_{k-1})} + \frac{\alpha}{\alpha - 1} \cdot \frac{\lambda_1 \Delta N_{1,k} - \lambda_2 \Delta N_{2,k}}{t_k - t_{k-1}} \end{aligned} \quad (1)$$

where $\alpha = \left(\frac{f_1}{f_2}\right)^2$, and $I_{i,k}$ and $\Delta N_{i,k}$ represent the ionospheric delay and cycle slips at epoch t_k for frequency f_i ($i = 1,2$) respectively. According to equation (1), cycle slips only show up in the IOD sequence if $\lambda_1 \Delta N_{1,k} \neq \lambda_2 \Delta N_{2,k}$. Then IOD is not effective for certain receivers which do not have truly independent GPS L1 and L2 tracking. MP can be estimated using the following linear measurement combinations (Rizos, 1996):

$$\begin{aligned} MP1 &= C_1 - \left(1 + \frac{2}{\alpha - 1}\right) L_1 + \frac{2}{\alpha - 1} L_2 \\ &= M_1 + g_1(N_1\lambda_1, N_2\lambda_2) + g_1(m_1, m_2) \end{aligned} \quad (2)$$

$$\begin{aligned} MP2 &= C_2 - \frac{2\alpha}{\alpha - 1} L_1 + \left(\frac{2\alpha}{\alpha - 1} - 1\right) L_2 \\ &= M_2 + g_2(N_1\lambda_1, N_2\lambda_2) + g_2(m_1, m_2) \end{aligned} \quad (3)$$

where $g_1(x, y) = -\left(1 + \frac{2}{\alpha - 1}\right) x + \frac{2}{\alpha - 1} y$, $g_2(x, y) = -\frac{2\alpha}{\alpha - 1} x + \left(\frac{2\alpha}{\alpha - 1} - 1\right) y$, and m_i and M_i are the phase multipath error and pseudorange multipath error for frequency f_i respectively. The multipath error in carrier phase is relatively small, with a maximum of 1/4 cycles (Kaplan and Hegarty, 2006), and can largely be ignored. Hence the MP sequence obtained using the above equation is predominately affected by integer ambiguities. The MP sequence shows step offsets when a cycle slip has occurred, and can be used for cycle slip detection either by a 1st-order forward difference or by a moving RMS comparison. This detection approach is effective for most cases of $\lambda_1 \Delta N_{1,k} = \lambda_2 \Delta N_{2,k}$ as mentioned before. And the detection efficiency is secured by the using of MP1 and MP2 both combined using L_1 and L_2 but with different weights. However the MP sequence is not stable especially when the satellite elevation is low, consequently they are less sensitive to small cycle slips.

The widely used Melbourne-Wübbena linear combination (Melbourne, 1985, and Wübbena, 1985) is added in BQC to enhance detection efficiency, which is written as:

$$\begin{aligned} L_{MW} &= \frac{1}{f_1 - f_2}(f_1 L_1 - f_2 L_2) - \frac{1}{f_1 + f_2}(f_1 P_1 + f_2 P_2) \\ &= \frac{c}{f_1 - f_2}(N_1 - N_2) \end{aligned} \quad (4)$$

where *c* is the light speed. This combination removes the effects from the atmosphere (both ionosphere and troposphere), the geometry, and the satellite and receiver clocks L_{MW} and MP are combination of both pseudorange measurements and carrier phase measurements, while IOD combines only the latter one. It is clear according to equation (4) that L_{MW} will not signify the occurrence of cycle slips when the cycle slips on L_1 and L_2 are the same. Slips is suspected if

$L_{MW} > 6\sigma_{LMW}$, where σ_{LMW} is the standard deviation of previous M (M is set to be 50 by default) points of the L_{MW} sequence.

Besides an additional linear combination in cycle slip detection, BQC does several improvement compared to TEQC, which are presented in the following two sections.

3.2 IOD SEQUENCES AND CYCLE SLIP DETECTION

The slip-free IOD is expected to be small if the ionosphere is stable and the observation interval is short enough. TEQC employs this method and assumes by default that cycle slips are detected if the IOD>400cm/min considering signal path changes in the ionosphere, time variation of the ionospheric delay, motion of the satellite and possible motion of the antenna itself. This threshold is a widely used empirical value for GPS and can be modified by users according to the tracking scenario.

However, this cycle slip detection algorithm has drawbacks. False identification occurs when $\frac{\alpha}{\alpha-1}\cdot\frac{\lambda_1\Delta N_{1,k}-\lambda_2\Delta N_{2,k}}{t_k-t_{k-1}} \leq$ 400cm/min according to equation (1). As an example, the observation data collected at the IGS 'aira' station on the 180th day of 2013 were processed. The I_2OD sequences of seven GPS satellites calculated by TEQC are shown in Figure 5 (a). Every detected slip-deteriorated I_2OD value has been replaced by the one of the previous slip-free epoch, hence the jumping points in Figure 5 (a) correspond to cycle slip epochs missed because the I_2OD value was less than the standard threshold value. Thirdly, in multi-GNSS applications the characteristics of IOD varies with different satellite orbits, signal frequencies, observation stations and so on, thus it is not always possible for users to define the threshold values with any certainty.

Instead of setting an arbitrary threshold, one cycle slip is declared by BQC when the IOD value of one epoch is larger than 6σ, where σ is the standard deviation of previous M (M is set to be 50 by default) points of the IOD sequence. Then the detected IOD value is corrected in the same way as by TEQC. The I_2OD sequence of the same set of 'aira' data output by BQC is shown in Figure 5 (b). Note fewer false identifications of cycle slips compared with Figure 5(a).

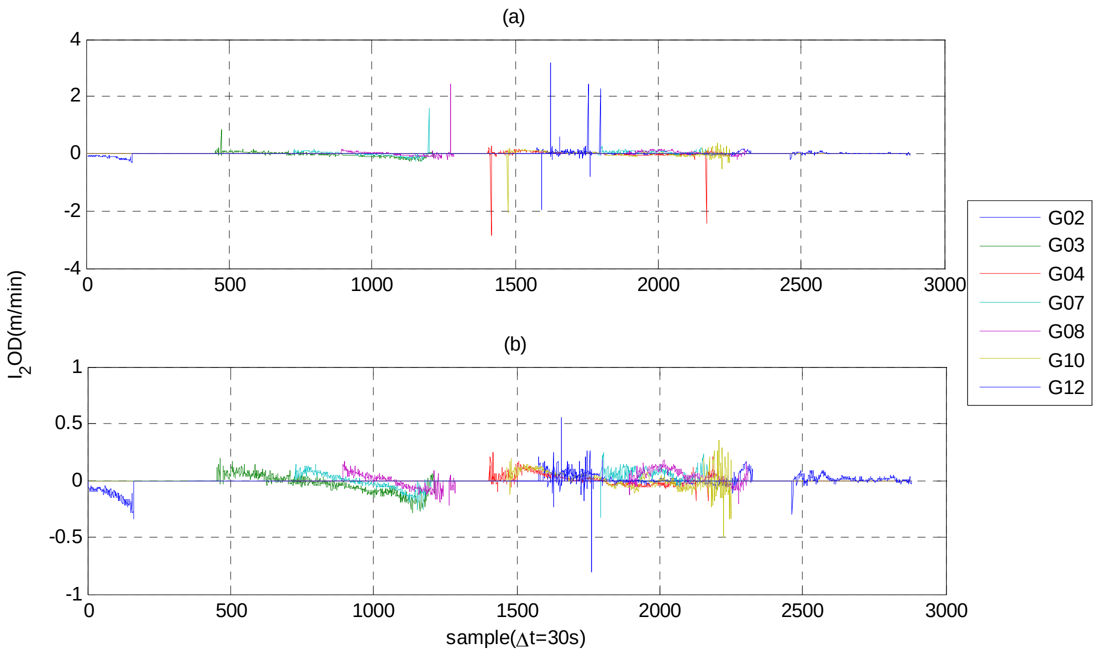

Figure 5. The I2OD sequences calculated by TEQC and BQC for IGS station 'aira'

3.3 THE REPAIR CYCLE SLIP EFFECTS ON MP SEQUENCES

MP, correlated with pseudorange code rate, antenna pattern, satellite-antenna-reflector location, etc, cause positioning bias of up to several metres (Braasch, 1994), and should therefore be monitored carefully. Thus cycle slips in MP should be repaired as well as detected.

The MP sequence is assumed to be random, similar to zero-mean noise. Thus BQC does the repair in the following way: the unknown ambiguity can be assumed to be a constant and be subtracted directly if there is no cycle slip during the observation period. If cycle slips do occur, the MP sequence should be repaired section-by-section, as defined by cycle slip epochs. Although how TEQC does the repair is not clear yet, its corresponding QC results can be shown compared with BQC. Figure 6 shows the MP1 sequence of GPS satellite G09 on the 180th day of 2013 from IGS 'aira' station. Note the cycle slip at the 1024^{th} epoch, and the difference between the two repaired sequences, although they coincide with each other after the 1072^{th} epoch. The MP1 sequence near the cycle slip epoch has been changed after processed by TEQC, which leads to larger MP standard derivation. However BQC preserves the original characteristics of the MP sequence and the corresponding statistics is more reliable.

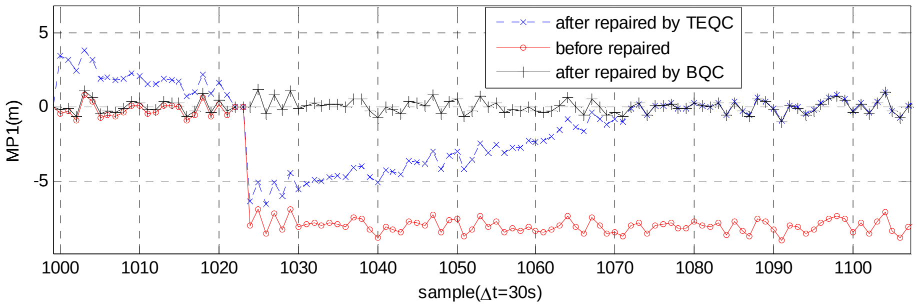

Figure 6. The repairing to MP sequence with cycle slips

4 CONCLUSION

BQC, as introduced in this paper, is a useful multi-GNSS data QC toolkit designed with a friendly and easy operating GUI interfacing. BQC is compatible with all the frequencies and observation types of GPS / GLONASS / Beidou / Galileo / SBAS / QZSS defined in RINEX 2 and 3. Compared with TEQC, BQC detects cycle slips in carrier phase measurements with relatively diverse methods, and provides fewer false identifications and more reliable repair of cycle slip effects on MP. BQC is already used routinely as a QC tool for iGMAS and MGEX data in BACC. The users can access the relative QC results as well as the toolkit for free after the website of AFDL is established in the near future.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Lou Estey of UNAVCO for his help in understanding TEQC. This work is funded by China's iGMAS and the data used in this paper are provided by M-GEX and iGMAS tracking stations.

REFERENCES

Hugentobler U. and Neilan R. (2011). [IGSMAIL-6459] IGS Multi-GNSS Global Experiment, Call for Participation .

Langley R. (2013). Getting a Grip on Multi-GNSS: The International GNSS Service MGEX Campaign. GPS World, 2013 July, pp. 44-49.

Estey L. and Meerterns C. (1999). TEQC: The Multi-purpose Toolkit for GPS/GLONASS Data*, GPS Solutions*, vol. 3, no. 1, pp. 42-49.

Takasu T. and Kasai S. (2005). Evaluation of GPS Precise Point Positioning (PPP) Accuracy, IEIC Technical Report, vol. 105, no. 208, pp. 40-45.

Rizos C. (1996). Principles and practice of GPS surveying (Monograph 17), Sydney, Australia: The University of New South Wales, School of Geomatic Engineering,.

Kaplan E.D. and Hegarty C.J. (2006). Understanding GPS: Principles and Applications, 2nd edition, Artech House.

Braasch M. (1994). Optimum Antenna Design for DGNSS Ground Reference Stations, Proceedings of the 7th International Technical Meeting of the Satellite Division of the Institute of Navigation, pp. 1291-1297.

Melbourne WG. (1995). The case for ranging in GPS based geodetic system, in Proceedings of the 1st international symposium on precise positioning with the global positioning system, Rockville, Marylan, pp 373-386

Wübbena G. (1985). Software developments for geodetic positioning with GPS using TI 4100 code and carrier measurements, Proceedings of the 1st international symposium on precise positioning with the global positioning system, Rockville, Marylan, pp 403-412