Manuscript accepted for **International Association of Geodesy Symposia No. 143**

G-Nut/Anubis – open-source tool for multi-GNSS data monitoring with a multipath detection for new signals, frequencies and constellations

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Received: date / Accepted: date

Abstract The GNSS software library G-Nut has been developed at the Research Institute of Geodesy, Topography and Cartography since 2011. Along with the PPP applications for positioning and troposphere monitoring, the third tool recently built using the new library is called Anubis. Its initial purpose is to provides quantity and quality monitoring for multi-GNSS data stored in RINEX 2.xx (≤ 2.11) and 3.0x (≤ 3.02) formats. Editing, cutting and splicing modes will be supported after implementing RINEX encoder in future. The Anubis is capable to handle all new emerging signals from all global navigation satellite systems and their augmentations (GPS, GLONASS, Galileo, BeiDou, SBAS and QZSS). Additionally, Anubis supports GPS, GLONASS and Galileo broadcast navigation messages, while others will be implemented soon. Supported with relevant navigation messages, Anubis performs single point positioning and provides GNSS data characteristics in elevation and azimuth dependences. The pre-processing mode is used for the reconstructing observations affected by cycle slips or receiver clock jumps. A new algorithm was developed for code multipath detection supporting all signals, frequency bands and GNSS constellations. Being an open-source tool, Anubis is suitable for GNSS data providers as well as data and analysis centres for the quality and content monitoring prior to the data archiving, dissemination or a final GNSS analysis. The Anubis first version was released in the mid of 2013 under the GNU General Public Licence, version 3.

Keywords Multi-GNSS · MGEX · quality checking · pre-processing · code multipath · experimental data

1 Introduction

The Geodetic Observatory Pecný (GOP) acts as analysis centre for precise GNSS data processing of various networks for coordinate and velocity estimation, troposphere monitoring and GNSS orbit determination. Data from national, European and global sites stemming from various sources are used for all these applications. Data are disseminated in the standard RINEX (Receiver Independent Exchange) format [6], but usually without information on the data quality and content. Any corrupted file may cause unexpected behaviour in analyses requiring specific manual interventions.

Data quality monitoring provides information not only for data processing activities, but also for a high-quality data collection and archiving by individual providers or by scientific services such as the International GNSS Service (IGS) [1]. New challenges arose with emerging many new GNSS signals, frequencies and constellations over past years. The RINEX 3.0x format has been standardized for including all new data. Several programs for data quality checking exist, such as TEQC [4] and BKG Ntrip Client [5], but only the latter is open-source and supports the new RINEX 3.0x format. Experimental data, e.g. provided by the IGS MGEX campaign [8] including a maximum of GNSS signals available in space, need to be properly monitored and tested prior to their use in operational analyses. This was the main motivation to develop a new open-source tool which we call Anubis.

The Anubis application is derived from the G-Nut software library [3] being developed at GOP of the Research Institute of Geodesy, Topography and Cartography. The library is designed for developing various GNSS end-user ap-

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plications, e.g. for positioning, troposphere monitoring and others. It is written in C++ applying object-oriented programming approach for a high adaptability in future utilizations. Although it is designed for a command-line operation with a single input configuration file, a graphical user interface can be added in future.

The main purpose of the Anubis tool is currently the quantity and quality monitoring of all available GNSS data, i.e. signals, frequencies and satellite constellations. Editing, cutting and splicing modes will be supported after implementing RINEX encoder which is planned in future. Proper attention was paid recently to support RINEX 2.xx (≤ 2.11) and RINEX 3.0x (≤ 3.02) input formats. While the G-Nut library is not publicly distributed, the Anubis and other end-user applications are released under the GNU Public License v3 and the source code can be downloaded from the web http://www.pecny.cz/. The compilation and execution can be tested using the example data and configurations provided in an additional support area (see the web page). The software is designed as a multi-platform application with no extra need for specific developing libraries or programming frameworks. Although Anubis was successfully compiled on Windows and OS X, we currently support only Linux operating systems due to the presence of a few critical points for an easy compilation on other systems. However, this is expected to be resolved for any future release.

This paper aims for describing basic functionalities and algorithms of the first release of Anubis in August, 2013. The program configuration structure and setting options are described in the second section. Extraction output format including quantitative and qualitative statistics is discussed in the third section. Algorithms used for data quality monitoring, i.e. pre-processing and code multipath estimation, is described in the fourth and fifth section, respectively. In particular, the fifth section provides a new formula developed for the multi-signal, multi-frequency and multi-constellation code multipath detection. Summary and future Anubis developments are concluded in the last section.

2 User configuration

Anubis can be executed from a command line with a single parameter defining the configuration file name in the Extensible Markup Language (XML) format or, alternatively, by reading XML configuration from the standard input (or via Linux pipe):

Anubis -x config.xml *(Anubis < config.xml).*

The XML format has been chosen because of its flexibility, extensibility and the support by many end-user editors. The format is applied for all end-user applications derived from the G-Nut library while different elements correspond to the specific application functionalities. The configuration file starts with sections common to all G-Nut's applications concerning the input, output and general settings. Additional XML elements are used by individual applications, such as $< qc >$ used by Anubis only. The example of a configuration is given below for a brief discussion:

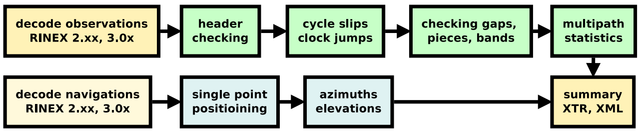

Fig. 1 Basic block diagram of Anubis operation

```
<?xml version=”1.0” encoding=”UTF−8” standalone=”yes” ?>
<!DOCTYPE config>
<config>

 <gen>
   <beg> ”2013−02−09 00:00:00” </beg>
   <end> ”2013−02−09 23:59:30” </end>
   <sys> GPS GLO GAL BDS SBS QZS </sys>
   <int> 30 </int>
   <rec> BRUX GOPE MATE </rec>
 </gen>

 <inputs>
   <rinexo> RINEX/mate0400.13o </rinexo>
   <rinexo> RINEX/gope0400.13o </rinexo>
   <rinexo> RINEX/brux0400.13o </rinexo>
   <rinexn> RINEX/brux0400.13n </rinexn>
   <rinexn> RINEX/brux0400.13g </rinexn>
   <rinexn> RINEX/brux0400.13l </rinexn>
 </inputs>

 <qc sec_sum=”1”
     sec_hdr=”1”
     sec_est=”1”
     sec_obs=”1”
     sec_gap=”1”
     sec_bnd=”2”
     sec_pre=”1”
     sec_ele=”1”
     sec_mpx=”2”
     int_stp=”1200”
     int_gap=”600”
     int_pcs=”1800”
     mpx_nep=”15”
     mpx_lim=”3.0” />

 <outputs verb=”1” >
   <xtr> $(rec)_130400.xtr </xtr>
   <xml> $(rec)_130400.xml </xml>
   <log> /dev/stdout       </log>
 </outputs>
</config>
```

The section $< gen >$ defines general information, such as the beginning and the end epoch of data to be dealt with (*beg*, *end*), list of requested satellite systems (*sys*), sampling interval (*int*) and the list of marker names included in the processing (*rec*). The section $< inputs >$ defines all input files in specific formats, such as observation (*rinexo*) and navigation (*rinexn*) data. If navigation files are defined, extracted quantities are supported with azimuths and elevations.

The section $< qc >$ contains the level of verbosity settings for individual Anubis functions as shown in Fig. 1:

– summary information (*sec_sum*),
– meta data in header and from user requests (*sec_hdr*),
– overall observation statistics (*sec_obs*),

- data gaps and small data pieces (*sec_gap*),
- band counting from available observations (*sec_bnd*),
- cycle slip and clock jump detection (*sec_pre*),
- azimuth and elevation information (*sec_ele*),
- multipath estimation (*sec_mpx*).

Additional attributes concern specific procedure settings, such as a) interval step in seconds for all time-specific characteristics (*int_stp*), b) intervals in seconds for detecting gaps and small data pieces (*int_gap*, *int_pcs*) and c) settings for the multipath estimation – the number of epochs used for the multipath calculation (*mpx_nep*) and the factor for sigma multiplication for internal cycle slip detection (*mpx_lim*). It should be noted, that this factor does not relate to the pre-processing part. In case of missing any specific setting, the default values are used.

The last section $< outputs >$ defines requested output files, which can be done uniquely for all processed sites (receivers) via applying a specific variable (*rec*). Along with the general log file (in our example the standard output), Anubis output can be stored in two extraction files (*xtr*) and (*xml*). While the former is an original Anubis format described in the next section, the latter is the XML format developed at the Center for Orbit Determination in Europe (CODE) [9]. As shown in the setting example, Anubis can be configured to process more RINEX files at once, e.g. all data stored in a directory.

3 Anubis summary file

Results of the Anubis data quality and quantity analysis are summarized in the extraction file. Its format has been defined as a plain text divided into multiple sections containing similar structure and supporting easy information searching via defined keywords. The format also support epoch-wise and satellite-specific characteristics suitable for plotting; the former is organized in lines, the latter in a fixed column format. Table 1 shows three example segments of the extraction – a) summary part, b) observation quantitative statistics and c) elevation and azimuth angles. Users decide how detailed information they require via the verbosity setting in the configuration file.

The observation section contains a list of available systems, satellites and signals. The summary contains two lists – the one reported in the header (e.g. *GPSHDR* keyword in Tab. 1) and the second from collecting real data (*GPSOBS* keyword). From such comparison the user can identify empty data records which is often the case in the EUREF and IGS experimental campaigns. The elevation and azimuth section is supported only if broadcast ephemerides are available.

For a brief user overview, the most important is the summary section which is explained in detail. Each line represents one GNSS or augmentation system and its relevant data summary quantification. The first first three values provide an overview of the number of epochs – expected within a period and sampling (*ExpEp*), observed (*HavEp*) and usable (*UseEp*). The usable epoch is introduced if four or more satellites are observed with the minimum of two frequencies. The criterion of four satellites is applied only to global constellations, i.e. not the augmentation systems like SBAS or QZSS.

The next two values (*xCoEp* and *xPhEp*) count the amount of excluded measurements due to the presence of single-frequency code or carrier phase observations. Additional details are given in the *xCoSv* and *xPhSv* values summarizing the total number of satellites with only a single-band code and carrier phase observation, respectively. If the level of verbosity for the pre-processing is set to two or more, numbers of detected cycle slips and clock jumps are printed in *nSlp* and *nJmp* columns, while further event details are printed in the pre-processing section, see Tab. 2. The presence of data gaps and short data pieces, both defined by criteria in the settings, are summed up in the *nGap* and *nPcs*, respectively. The last columns (*mpx*) show mean values of multipath for individual frequencies over all signals.

4 Data pre-processing algorithm

Data pre-processing, i.e. searching and repairing clock jumps and phase cycle slips, is very important part of any software dealing with GNSS carrier phase data analysis. For high-accurate applications, only periods with uninterrupted satellite tracking can be used efficiently due to a single initial ambiguity set up for each satellite and frequency. If the continuity is broken for a particular satellite and a relevant cycle slip cannot be estimated, a specific ambiguity must be added to the solution implying additional estimated parameters.

Anubis exploits various time differenced linear combinations that are compared with predefined thresholds. The cycle slip detection algorithm is based on Melbourne-Wuebbena [2] and geometry-free linear combinations due to their useful properties. The latter is usually denoted as L_4 and defined by the equation

$$\begin{aligned} L_4 = L_1 - L_2 &= \lambda_1 N_1 - \lambda_2 N_2 - I_1 + I_2 \\ &= \lambda_1 N_1 - \lambda_2 N_2 - I_1 \left(1 - \frac{f_1^2}{f_2^2}\right), \end{aligned} \tag{1}$$

where subscripts 1 and 2 stand for band numbers, L is the carrier frequency in meters, λ denotes wavelength, N initial ambiguity, I ionospheric delay and f frequency. The L_4 is independent of receiver clock errors and geometry (satellite/receiver position) and it contains only ionospheric delays and initial ambiguities for both frequencies. All other frequency-independent terms are neglected. The first two terms on the right site of Eq. 1 are constant in time meaning

Table 1 Selected segments of the Anubis extraction from RINEX 3.01 observation and navigation data for GOP7 station, April 15, 2013

```
# gNut-Anubis [1.0.1] compiled: Nov  1 2013 09:52:48 ($Rev: 615 $)

#====== Summary (v.1)
#GNSSUM 2013-04-15 00:00:00  ExpEp  HavEp  UseEp  xCoEp  xPhEp  xCoSv  xPhSv   nSlp   nJmp   nGap   nPcs    mp1    mp2    mp5    mp6    mp7    mp8
=GPSSUM 2013-04-15 00:00:00   2880   2880   2880      0      0    430    424    219      0      0      0   47.7   53.5   23.5      -      -      -
=GALSUM 2013-04-15 00:00:00   2880    974      0    974    974      2      2      0      0      0      0   43.3      -   16.1      -      -      -
=GLOSUM 2013-04-15 00:00:00   2880   2880   2880      0      0    162    156      0      0      0      0   53.3   64.2      -      -      -      -
=QZSSUM 2013-04-15 00:00:00   2880     96     96      0      0      0      0      0      0      0      0      -      -      -      -      -      -
=SBSSUM 2013-04-15 00:00:00   2880   2880   2880      0      0  10226  10226      0      0      0      0      -      -      -      -      -      -

#====== Observations (v.1)
=GNSSYS 2013-04-15 00:00:00        5 GPS GAL GLO QZS SBS
=GPSSAT 2013-04-15 00:00:00       32 G01 G02 G03 G04 G05 G06 G07 G08 G09 G10 G11 G12 G13 G14 G15 G16 G17 G18 G19 G20 G21 G22 G23 G24
=GALSAT 2013-04-15 00:00:00        2   -   -   -   -   -   -   -   -   -   - E11 E12   -   -   -   -   -   -   -   -   -   -   -   -
=GLOSAT 2013-04-15 00:00:00       24 R01 R02 R03 R04 R05 R06 R07 R08 R09 R10 R11 R12 R13 R14 R15 R16 R17 R18 R19 R20 R21 R22 R23 R24
=QZSSAT 2013-04-15 00:00:00        1 J01   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -
=SBSSAT 2013-04-15 00:00:00        4   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - S20   -   -   - S24
=GALHDR 2013-04-15 00:00:00        6 C1X L1X S1X C5X L5X S5X
=GPSHDR 2013-04-15 00:00:00       15 C1C L1C S1C C1W L1W S1W C2X L2X S2X C2W L2W S2W C5X L5X S5X
=QZSHDR 2013-04-15 00:00:00        9 C1C L1C S1C C2X L2X S2X C5X L5X S5X
=GLOHDR 2013-04-15 00:00:00       12 C1C L1C S1C C1P L1P S1P C2C L2C S2C C2P L2P S2P
=SBSHDR 2013-04-15 00:00:00        3 C1C L1C S1C
=GPSOBS 2013-04-15 00:00:00       15 C1C C1W C2W C2X C5X L1C L1W L2W L2X L5X S1C S1W S2W S2X S5X
=GALOBS 2013-04-15 00:00:00        6 C1X C5X L1X L5X S1X S5X
=GLOOBS 2013-04-15 00:00:00       12 C1C C1P C2C C2P L1C L1P L2C L2P S1C S1P S2C S2P
=QZSOBS 2013-04-15 00:00:00        9 C1C C2X C5X L1C L2X L5X S1C S2X S5X
=SBSOBS 2013-04-15 00:00:00        3 C1C L1C S1C

#====== Elevation & Azimuth (v.1)
#GNSELE 2013-04-15 00:00:00      Mean  x01  x02  x03  x04  x05  x06  x07  x08  x09  x10  x11  x12  x13  x14  x15  x16  x17  x18  x19  x20  x21  x22  x23  x24
 GPSELE 2013-04-15 00:00:00        36    -    -   46    -    -   67   11    -    -    -    -    -    -    -   10   61    -   51   24    -   56   34    -    -
 GPSELE 2013-04-15 00:15:00        40    -    -   53    -    -   74   11    -    -    -    -    -    -    -   12   57    -   55   30    -   49   41    -    -
 GPSELE 2013-04-15 00:30:00        40    -    -   60    -    -   80   11    -    -    -    -    -    -    -   13   51    -   56   36    -   43   48    -    -
 GPSELE 2013-04-15 00:45:00        35    -    -   67    -    -   85    9    9    -    -    3    -    -    -   14   44    -   56   43    -   37   54    -    -
 GPSELE 2013-04-15 01:00:00        34    -    -   73    -    -   81    7    9    -    -    9    -    -    -   13   38    -   54   49    -   31   60    -    -
 GPSELE 2013-04-15 01:15:00        35    -    -   77    -    -   74    4    8    -    -   14    -    -    -   11   31    -   50   56    -   25   64    -    -
 GPSELE 2013-04-15 01:30:00        34    4    -   76    -    -   67    0    7    -    -   20    -    -   10    -   24    -   46   63    -   20   67    -    -
 GPSELE 2013-04-15 01:45:00        36    9    -   72    -    -   60    -    5    -    -   26    -    -   15    -   18    -   41   69    -   14   67    -    -
 GPSELE 2013-04-15 02:00:00        32   15    -   65    -    -   53    -    2    -    -   32    -    -   21    -   11    -   35   75    -    9   64    -    -
 GPSELE 2013-04-15 02:15:00        32   20    -   58    -    -   46    -    -    -    -   38    -    -   26    -    5    -   29   78    -    3   60    -    -
 GPSELE 2013-04-15 02:30:00        38   26    -   51    -    -   39    -    -    -    -   45    -    -   32    -    -    -   23   77    -    -   54    -    -
 GPSELE 2013-04-15 02:45:00        34   32    -   44    -    -   32    -    -    -    -   51    -    -   36    -    -    -   18   71    1    -   48    -    -
```

that any unexpected jump in L_4 must be caused by a cycle slip. The detection is based on the following criterion

$$L_4(t_2) - L_4(t_1) > k \cdot \sigma_{L4} + \Delta I_{max}. \tag{2}$$

The maximal ionospheric delay I_{max} is implicitly defined as 0.4 m/hour in Anubis and the factor k is set to 4. The advantage of such approach is that it is based on carrier phase data only. On the other hand, it should be noted that in case of a positive test, we do not know whether any of L_1, L_2 or both are corrupted.

If dual-frequency carrier phase L and pseudorange P are available, the Melbourne-Wubbena linear combination (L_6) can be formed mixing wide-lane phase (L_W) and narrow-lane pseudorange (P_N) measurements

$$\begin{aligned} L_6 = L_W - P_N &= \frac{1}{f_1 - f_2}(f_1 L_1 - f_2 L_2) \\ &- \frac{1}{f_1 + f_2}(f_1 P_1 + f_2 P_2) \\ = \lambda_W N_W &= \frac{c}{f_1 - f_2}(N_1 - N_2) \end{aligned} \tag{3}$$

where λ_W and N_W are called wide-lane wavelength and ambiguity, respectively.

The advantage of using the L_6 combination is due to the elimination of ionosphere, troposphere, geometry (satellite and receiver positions) and satellite and receiver clocks. The wavelength of this combination is approximately 86 cm. On the other hand, the inclusion of pseudorange observations increase the noise of the linear combination. Comparing L_6 for epochs t_1 and t_2 provides the information whether a slip occurs or not. It should be noted that slips on L_1 or L_2 cannot be checked directly, but their difference only. Due to a constant property of the right term in Eq. 3 we can check a presence of a cycle slip through the temporal differencing of L_6 observations. The detection is based on the criteria

$$L_6(t_2) - L_6(t_1) > k \cdot \sigma_{L6} \tag{4}$$

where the coefficient k is set to 4 and σ_{L_6} is the sigma of the L_6 observation. The coefficient k is introduced with assumption of normally distributed measurement linear combinations. Almost 99.9 cycle slips should be detected with k set up to 4. Sigmas for L_4 and L_6 are calculated according to the law of variance propagation from used observation sigmas. Since a cycle slip on any specific frequency cannot be detected, but only on $L_1 - L_2$ linear combination, any cycle slip common to L_1 and L_2 becomes undetectable. An improvement of the technique resides in the differencing L_6 from a single epoch and a mean value over all previous epochs

Table 2 Pre-processing sample output for station KUNZ (December 26, 2010)

```
#======  Preprocessing (v.3)
#PREPRO  2010-12-26 00:00:00  TotSlp[GPS]  TotSlp[GLO]   TotJmp
=SUMPRP  2010-12-26 00:00:00            1            0      121

#GPSSLP  2010-12-26 00:00:00   PRN   SlipL1   SlipL2
 GPSSLP  2010-12-26 05:15:30   G10     -106    24694

#CLKJMP  2010-12-26 00:00:00   [ms]
 CLKJMP  2010-12-26 00:07:30    1
 CLKJMP  2010-12-26 00:19:30    2
 CLKJMP  2010-12-26 00:31:00    3
 CLKJMP  2010-12-26 00:42:30    4
 CLKJMP  2010-12-26 00:54:30    5
 CLKJMP  2010-12-26 01:06:00    6
  ...
```

since the last occurring cycle slip. This approach is planned for the next release.

The second purpose of the pre-processing consists of detecting and correcting for receiver clock jumps. Due to a low quality of some receiver oscillators, clocks are shifted by one or a few milliseconds when the clock bias becomes too large. Observations at a particular epoch as well as observations in all subsequent epochs are affected in the same way and must be corrected for. Otherwise ambiguity re-initialization and a new convergence interval would appear regularly. The principle of our algorithm resides in the pseudorange compensations of the clock jumps, while carrier phases for each satellite could still contain the same cycle slip [7]. Fortunately, we know that the slip is exactly a millisecond or a few milliseconds, therefore, we can repair it precisely. Anubis can be thus used for recovering the coherency between range and phase data. One section of Anubis extraction provides results from the cycle slip and receiver clock jump detection, in which all values estimated and relevant epochs are reported. Values of cycle slips and clock jumps as well as epochs at which these occur are reported.

Table 2 shows an example of extracted results from the pre-processing. It starts with a summary of the number of detected cycle slips and clock jumps (*TotSlp* and *TotJmp*) followed by estimated values of slip cycles for each frequency and milliseconds of a clock jump in a particular epoch. As long as the cycle slip can not be calculated reliably, the 'n/a' flag is reported.

5 Code multipath algorithm

The multipath affects both basic GNSS observations pseudoranges and carrier phases, however, the former is much larger and variable among receiver types. The multipath error has a substantial contribution to the accuracy of observed pseudoranges, which are mainly used in a single point positioning technique (navigation, precise point positioning etc.). The knowledge of the multipath effect and pseudorange noise can be useful for a proper observation weighting. Such information can also provide specific characteristics of the receiver or about the station environment.

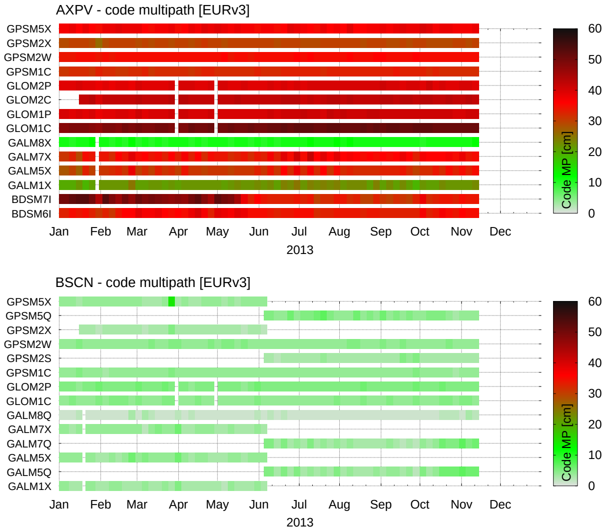

Fig. 2 Pseudorange multipath estimated for all GNSS signals observed at the EUREF station AXPV (top) and BSCN (bottom) during January-November, 2013

When dual-frequency data are available, pseudorange multipath is estimated from the linear combination eliminating the satellite-receiver geometry and all atmospheric effects. However, this combination does not eliminate ambiguities and any differential biases. While the latter is almost constant over time, this assumption is not always true for ambiguities due to a presence of cycle slips. The pre-processing (and optionally a cycle slip repair) is thus important for the multipath estimation. A simple cycle slip detection is already included in our algorithm independently of the Anubis's standard pre-processing algorithm (see above section) that does not still support all these signals.

We have developed a new general formula for Anubis supporting linear combination (*MP*) for pseudorange multipath estimates for all frequencies, available signals and GNSS constellations providing dual-frequency observations at least

$$MP_k = P_k - L_i - \beta(L_i - L_j) = P_k + \alpha L_i + \beta L_j, \tag{5}$$

with

$$\alpha = -\frac{(f_j^2 + f_k^2)}{(f_i^2 - f_j^2)}\frac{f_i^2}{f_k^2} \qquad \beta = \frac{(f_i^2 + f_k^2)}{(f_i^2 - f_j^2)}\frac{f_j^2}{f_k^2}, \tag{6}$$

where k, i and j are frequency (band) indexes. In the case of $k = i = 1$ and $j = 2$, the well-known equation for the code multipath at the first frequency can be obtained [4]

$$MP_1 = P_1 - L_1 - \frac{2f_2^2}{(f_1^2 - f_2^2)}(L_1 - L_2). \tag{7}$$

Similarly for $k = i = 2$ and $j = 1$ the code multipath for the second frequency is

$$MP_2 = P_2 - L_2 - \frac{2f_1^2}{(f_2^2 - f_1^2)}(L_2 - L_1). \tag{8}$$

Finally, for $k = 5$, $i = 1$ and $j = 2$ or any other frequency the code multipath can be expressed as follows

$$MP_5 = P_5 - L_1 - \frac{(f_1^2 + f_5^2)}{(f_1^2 - f_2^2)}\frac{f_2^2}{f_5^2}(L_1 - L_2). \tag{9}$$

The multipath statistics are then estimated as a standard deviation over a sequence of consecutive epochs (usually 15-30; *mpx_int* setting option) where the calculated mean represents all remaining biases. We do not require any specific pre-processing for all involved GNSS constellations because a simple cycle slip detection algorithm was implemented as a part of the statistics estimation based on multipath linear combinations only.

In the case of dual-frequency data, the multipath statistics are calculated applying the same formulas as used in other software, e.g. teqc and BNC. However, the results may differ due to tuning the estimation procedure which concerns of the cycle slip detection, observation window or others. The main advantage of the approach applied in Anubis relies in a flexible extension to all signals while keeping two carrier phase observations common to all multipath observables. Applying Eq. 5, we need to check two carrier phases for cycle slips only, which is used to speed up the algorithm.

Figure 2 shows the example of pseudorange multipath estimation calculated for two EUREF stations – AXPV (top) and BSCN (bottom). All GNSS signals for all available frequency bands are plotted for the period of January-November 2013. First, we can notice a stable multipath estimation during the whole interval, however, interesting is a progressive improvement for the BeiDou C7I signal[1]. Second, the lowest multipath effect can be observed for Galileo C8I signal (which was expected due to the AltBOC modulation), while the most worse performance shows the GLONASS C1C signal (visible at AXPV, but also typical for other stations). Two receivers, TRIMBLE NETR9 (AXPV) and LEICA GR25 (BSNC), show different quality of pseudorange observations in general. We can also notice the switch between X and Q tracking modes[2] at BSCN station for most of the GPS and Galileo signals. This is commonly observed at many other stations in the EUREF and IGS MGEX experimental campaigns. Finally, occasional interruptions of tracking GLONASS and Galileo satellites can be identified too.

Table 3 Multipath detection summary in the first verbose mode (example station GOP7)

```
#====== Code multipath (v.1)
#GNSMxx 2013−04−15 00:00:00    mean x01 x02 x03 x04 x05 x06 ...
=GPSM1C 2013−04−15 00:00:00   48.06  42  47  58  43  45  41 ...
=GPSM1W 2013−04−15 00:00:00   58.44  49  59  85  66  52  43 ...
=GPSM2W 2013−04−15 00:00:00   61.08  57  58 100  66  56  51 ...
=GPSM2X 2013−04−15 00:00:00   62.15  48   −   −   −  62   − ...
=GPSM5X 2013−04−15 00:00:00   27.55  15   −   −   −   −   − ...
=GALM1X 2013−04−15 00:00:00   45.33   −   −   −   −   −   − ...
=GALM5X 2013−04−15 00:00:00   18.58   −   −   −   −   −   − ...
=GLOM1C 2013−04−15 00:00:00   76.39  65  62  77  88  68  63 ...
=GLOM1P 2013−04−15 00:00:00   38.45  48  28  33  39  37  32 ...
=GLOM2C 2013−04−15 00:00:00  106.41 125 149  77  92  90  89 ...
=GLOM2P 2013−04−15 00:00:00   33.86  40  41  25  32  32  35 ...
```

Table 3 demonstrates multipath estimates for the undetailed verbose mode. Each line represents a single GNSS signal together with code multipath values for all available satellites as well as the mean over all of them.

6 Outlook and conclusion

We have described initial functionality of the open-source tool Anubis for a qualitative and quantitative monitoring of new GNSS signals. The Anubis has been developed at GOP in particular for the monitoring of experimental GNSS data collected within the IGS MGEX and EUREF RINEX3 campaigns. A new development was demonstrated for the code multipath estimation based on a fully multi-signal, multi-frequency and multi-constellation approach. The software was released in August 2013 and updated in November, 2013. Some functionalities foreseen for near future implementations are presented below.

While data are retrieved from RINEX files, we started to implement RTCM decoder that will support input data from real-time streams too. On the other hand, after implementing RINEX encoder, users will be able to edit, cut or splice GNSS data as well as modify header records. Combining two above features, users will be able to read data from real-time streams and store them in RINEX files. As shown in examples in this paper, most of the functions already supports multi-GNSS operation. The exceptions remains in three functionalities: navigation message processing, single point positioning and azimuth/elevation calculation. Not all the satellite systems are fully operational, therefore Anubis is restricted to GPS-only and GLONASS-only single point positioning at the moment. The station position quantities relating to other constellation have to be calculated with support of GPS or GLONASS. Future development will thus aim to support also navigation messages from BeiDou, SBAS and QZSS along with currently supported GPS, GLONASS and Galileo. A real challenge then concerns developing new pre-processing algorithms in order to provide a general cycle slip detection, i.e. not only

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[1] For systems providing wide-band tracking (e.g. for Galileo E5a, E5b and E5a+E5b), the band/frequency number (n) in RINEX3 format is assigned by its definition and not necessarily agrees with the official frequency, e.g. for Galileo, n=7 for E5b, n=8 for E5a+E5b (AltBOC).

[2] While I, Q (and others) represents two individual tracking modes, the X designates a dual-channel tracking mode and Z designates a triple-channel tracking mode.

for additional GNSS constellations, but also for all available signals and bands. A significant rise of the computing time (from seconds to tens of seconds) was observed when processing large RINEX3 multi-GNSS data files. In this context, we will work on improving the efficiency of the source code to reduce the execution time for all new constellations, frequencies and signals. The station parallel processing will also help to support efficient control of many stations at a single place. Last, but not least, Anubis will be ready to support also users of Windows, OS X or other platforms in future.

Acknowledgements The development of the G-Nut software library was supported by the Czech Scientific Foundation (P209/12/2207). The data from two stations, GOP7 and KUNZ, used for the testing of Anubis were provided with support of the project CzechGeo (No. LM2010008). We thank three anonymous reviewers for their valuable remarks. We also thank to EUREF and IGS for supporting experimental data dissemination and to all individual contributors providing data in RINEX 3.0x format within the IGS MGEX and EUREF RINEX3 campaigns.

References

1. Dow, J., Neilan, R., Rizos, C.: The International GNSS Service in a Changing Landscape of Global Navigation Satellite Systems. J Geod 83(3-4), 191198 (2009)
2. Wuebbena, G.: Software development for geodetic positioning with GPS using TI 4100 code and carrier measurements. In: Proceedings 1st international symposium on precise positioning with the global positioning system, pp. 4034012. Rockwille, Maryland (1985)
3. Vaclavovic, P., Dousa, J., Gyori, G.: G-Nut software library - state of development and first results. Acta Geodyn Geomater 10(4), 431436 (2013)
4. Estey, L., Meertens, C.: TEQC: The Multi-Purpose Toolkit for GPS/GLONASS Data. GPS Solut 3(1), 4249 (1999)
5. Weber, G., Mervart, L.: The BKG Ntrip Client (BNC). In: Report on EUREF Symposium 2007 in London, vol. 42. Mitteilungen des Bundesamtes fuer Kartographie und Geodaesie (2009)
6. Gurtner, W., Estey, L.: Receiver Independent Exchange Format. Tech. rep., Astronomical Institute, University of Bern (2009). Http://igscb.jpl.nasa.gov/igscb/data/format/rinex301.pdf
7. Guo, F., Zhang, X.: Real-time clock jump compensation for precise point positioning. GPS Solut (2013)
8. Montenbruck, O., Rizos, C., Weber, R., Weber, G., Neilan, R., Hugentobler, U.: The International GNSS Service MGEX Campaign. GPS world (2013)
9. Lutz, S., Arnold, D., Schaer, S., Dach, R., Jaeggi, A.: New RINEX file monitoring at CODE. Presented at EUREF Symposium 2013, Budapest, Hungary, May 29-31, 2013