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DEVELOPMENT TOWARDS ADVANCED GNSS DATA QUALITY MONITORING

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Abstract

Global Navigation Satellite Systems (GNSS) has been developing rapidly. Besides full constellation systems, such as GPS and GLONASS, Chinese system BeiDou and European Galileo has become significant. Together with GNSS, there are also regional augmentations, such as Japanese QZSS or Indian IRNSS. In addition, new modernized satellites observe more than two frequencies. International GNSS service (IGS) initiated global campaign MGEX (multi-GNSS experiment) which is focused on collecting and distributing multi-GNSS data. Quality control of such data within this campaign is very important. This paper presents the software called Anubis developed for multi-GNSS and multi-frequency data quality monitoring at the Geodetic Observatory Pecny. Its initial purpose is to provide data quantity and quality monitoring stored in RINEX 2.xx and 3.xx formats. Supported with relevant navigation messages, Anubis can performs single point positioning and provides GNSS data characteristics in elevation and azimuth dependences. The pre-processing mode is used for re-constructing observations affected by cycle slips or receiver clock jumps. A new algorithm was developed for a code multipath detection supporting all signals, frequency bands and GNSS constellations. The software is distributed under the GNU General Public Licence V3.

[1]   Introduction

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 within scientific services, such as the International GNSS Service (IGS) or EUREF Permanent Network (EPN). New challenges arose with emerging new GNSS signals, frequencies and constellations over past years. The RINEX 3.0x format has been standardized for including all such data. Several programs for the data quality checking exist, such as TEQC [1] and BKG Ntrip Client [2], 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 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 also the main motivation in developing a new open-source tool which we call Anubis.

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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 has been designed for developing various GNSS end-user applications, e.g. for positioning, troposphere monitoring and others. The library has been written in C++ language, using object-oriented programming approach for a high adaptability in future utilizations and aiming at command-line utilization primarily.

The main purpose of the Anubis tool is the quantity and quality monitoring of all available GNSS data, i.e. signals, frequencies and satellite constellations. The G-Nut/Anubis is released under the GNU Public License V3, and the source code, example data, and configuration are available at http://www.pecny.cz/.

This paper describes functionalities and algorithms of the Anubis development. The program configuration 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 section. Conclusion is provided in the last section.

[2]   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 as follows:

anubis -x config.xml

The configuration file consists of several elements with particular number of attributes. The general element <gen> is common to all G-Nut applications. Example is as follows

```
<gen>
   <beg> "2000-12-26 00:00:00" </beg>
   <end> "2049-01-01 00:00:00" </end>
   <sys> GPS GLO GAL BDS SBS QZS </sys>
   <int> 30 </int>
   <rec> WROC ZECK KUNZ </rec>
</gen>
```

This setting is considered as the input data filtering, e.g. input data are considered only those within the period specified with the first <beg> and the last <end> epochs. User may also request only specific satellite systems, sampling interval, and the list of marker names included in the processing, i.e. <sys>, <int>, and <rec> respectively.

The section <inputs> defines all input files in specific formats. While <rinexo> defines input observation files, <rinexn> defines user navigation file both in the RINEX format. If navigation files are defined, extracted quantities are supported with satellite azimuths and elevations information. Moreover, the navigation file is necessary for GLONASS constellation because providing satellite channel numbers. The example is given below

```
<inputs>
   <rinexo>  file://../data/obs/wroc2010.14o   </rinexo>
   <rinexo>  file://../data/obs/zeck2010.14o    </rinexo>
   <rinexo>  file://../data/obs/kunz2010.10o    </rinexo>
   <rinexn>  file://../data/brdc/brdm2010.14p  </rinexn>
</inputs>
```

The section <outputs> defines requested output files which can be provided uniquely for all processed sites (receivers) via applying a specific variable *$(rec)* automatically set from the general section described above. Along with the general log file (in our example the standard output), Anubis output can be stored in two extraction files <xtr> and <xml>. The former is the original Anubis format described in the next paragraph, and the latter is the XML format developed at the Centre for Orbit Determination in Europe (CODE).

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

The section <qc> contains settings for the level of verbosity for all individual Anubis functions defined by these attributes:

- 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. Standard example of settings can be following

```
<qc
  sec_sum="9" sec_hdr="3" sec_est="2" sec_obs="2" sec_gap="2" sec_bnd="2" sec_pre="2" sec_ele="2" sec_mpx="2"
  int_stp="30" int_gap="600" int_pcs="1800" mpx_nep="20" mpx_lim="3.0"
/>
```

[3]   Output extraction 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 and containing similar structure in order to support the easy information searching via known keywords. The format also supports epoch-wise and satellite-specific characteristics suitable for the 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) coordinates calculation and c) pre-processing part. A user decides how detailed information they require via the verbosity setting in the configuration file.

```
#====== Summary (v.9)
#GNSSUM 2014-07-20 00:00:00 ExpEp HavEp UseEp xCoEp xPhEp xCoSv xPhSv  nSlp  nJmp  nGap  nPcs  mp1  mp2  mp3 ...
=GPSSUM 2014-07-20 00:00:00  2088  2088  2088     0     0    52    52   136     0     0     0    -    -    - ...
=GALSUM 2014-07-20 00:00:00  2088   376     0   376   376     3     3    31     0     0     0    -    -    - ...
=GLOSUM 2014-07-20 00:00:00  2088  2088  2088     0     0   270   270   140     0     0     0    -    -    - ...
=BDSSUM 2014-07-20 00:00:00  2088  2088  1971   117   117    26    26   530     0     0     0    -    -    - ...
=QZSSUM 2014-07-20 00:00:00  2088   629   629     0     0   629   629     0     0     0     0    -    -    - ...
=SBSSUM 2014-07-20 00:00:00  2088  2088  2088     0     0  4176  4176     0     0     0     0    -    -    - ...
#====== Estimated (v.1)
=PERIOD 2014-07-20 00:00:00 2014-07-20 00:00:00    2014-07-20 17:23:30
=XYZGPS 2014-07-20 00:00:00    3835751.6880   1177250.2388    4941605.6810       2.1    1.0    2.0   70    0
=XYZGLO 2014-07-20 00:00:00    3835753.0702   1177250.6749    4941606.9772       3.7    2.7    7.2   69    0
=XYZBDS 2014-07-20 00:00:00    3835766.8069   1177251.3853    4941618.2010       1.9    0.9    1.3    2    0
=BLHGPS 2014-07-20 00:00:00      51.113260233    17.062042390        181.4344     1.7    1.6    2.4   70    0
=BLHGLO 2014-07-20 00:00:00      51.113257407    17.062042553        183.3533     4.4    3.6    7.0   69    0
=BLHBDS 2014-07-20 00:00:00      51.113227403    17.061994697        200.4647     0.8    0.5    2.4    2    0
#====== Preprocessing (v.1)
#PREPRO 2014-07-20 00:00:00    TotSlp[GPS]    TotSlp[GLO]    TotSlp[GAL]    TotSlp[BDS]    TotSlp[QZS]   TotJmp
=SUMPRP 2014-07-20 00:00:00            136            140             31            530              0        0
```
Table 1: Selected segments of the Anubis extraction from RINEX 3.02 observation and navigation data for WROC station, July 20, 2014

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 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 observations, respectively. 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.

The second section gives averaged coordinates from single point positioning. The average is determined on the basis of estimation results from every epoch referring to predefined sampling interval. The geocentric XYZ and ellipsoidal BLH coordinates are calculated independently from each constellation supported by navigation data. The receiver position is estimated by GPS-only, GLONASS-only, and BeiDou-only in the example above. The coordinates are provided together with their standard deviations, number of results for the average, and number of rejected results due to outliers.

The last section of the extraction file summarizes pre-processing results, such as number of cycle slips for each GNSS (TotSlp) and number of receiver clock jumps (TotJmp). In case the verbosity level is equal or greater than 2, detected and estimated cycle slips is listed for each signals too.

[4]   Used algorithms

This paragraph is focused on giving fundamental principle of multipath monitoring and cycle slips detection and estimation. Both algorithms support multi-constellation and multi-frequency observations.

4.1   Code Multipath algorithm

The multipath affects both basic GNSS observations pseudoranges and carrier phases; however, the former is much larger and varies among receiver types. The multipath error has a substantial contribution to the accuracy of observed pseudoranges, which are mainly used in single point positioning methods such as navigation and precise point positioning. 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 potential 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 standard Anubis pre-processing algorithm.

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

$$MP_k = P_k - L_i - \beta(L_i - L_j) = P_k + \alpha L_i + \beta L_j$$

with

$$\alpha = -\frac{f_j^2 + f_k^2}{f_i^2 - f_j^2}\frac{f_i^2}{f_k^2}, \quad \beta = -\frac{f_i^2 + f_k^2}{f_i^2 - f_j^2}\frac{f_j^2}{f_k^2}$$

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 [1].

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

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

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

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

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

The multipath statistics are then estimated as the standard deviation over a sequence of consecutive epochs (usually 15-30; mpx_int setting option) where the calculated mean represents all remaining biases. This does 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.

4.2   Cycle slips detection and repair

For cycle slips detection and repair, we follow the approach published in [4]. The original observations can be used only for the detection of large slips due to their noise; therefore, wide-lane combinations with longer wavelength and narrow-lane combination with shorter wavelength can be conveniently exploited. As a result, slip up to one cycle can be estimated. In case of GPS triple frequency carrier phase observations ($\emptyset_1, \emptyset_2, \emptyset_5$), we can form extra-wide-lane, wide-lane, and narrow-lane combinations as:

$\emptyset_{ewl} = \emptyset_2 - \emptyset_5 \quad\quad (\lambda = 5.861 \text{ m})$

$\emptyset_{wl} = \emptyset_1 - \emptyset_5 \quad\quad (\lambda = 0.751 \text{ m})$

$\emptyset_{nl} = 2\emptyset_1 - \emptyset_2 \quad\quad (\lambda = 0.156 \text{ m})$

The procedure consists of three steps:

1) Forming the Melbourne-Wuebbena combination with coefficients for extra-wide-lane and making difference between two consecutive epochs. If the difference is greater than 0.5, the slip is detected. The most important advantage of Melbourne-Wuebbena combination is direct access to the extra-wide-lane cycle slip ΔN_{ewl}.

2) Differencing the wide-lane and the extra-wide-lane combination. The result is again differenced between two consecutive epochs. We can exploit the estimated slip from the first step. If the difference is greater than 0.5, the wide-lane slip ΔN_{wl} is detected. The ionospheric delay can be ignored in the first as well as in the second step because it is small enough relative to the wavelengths.

3) In the last step, the narrow-lane combination is subtracted from the wide-lane and epoch difference is made as in the previous step. The threshold for slip detection is

still 0.5. The narrow-lane wavelength is significantly shorter, i.e. 0.156 m; therefore, a ionospheric delay has to be considered.

After these steps, we have three different slips: $\Delta N_{ewl}, \Delta N_{wl}, \Delta N_{nl}$. They can be transformed into cycle slips on the original observations ($\Delta N_1, \Delta N_2, \Delta N_5$) by solving following equation

$$\begin{bmatrix} 0 & 1 & -1 \\ 1 & 0 & -1 \\ 2 & -1 & 0 \end{bmatrix} \begin{bmatrix} \Delta N_1 \\ \Delta N_2 \\ \Delta N_5 \end{bmatrix} = \begin{bmatrix} \Delta N_{ewl} \\ \Delta N_{wl} \\ \Delta N_{nl} \end{bmatrix}$$

Detailed information can be found in [4]. The aforementioned technique is designed for triple-frequency data, but we have improved it for all multi-GNSS data with more than one frequency. In addition, Anubis is capable to repair all signals observed at every frequency.

[5] Závěr

We have described current functionalities of the open-source tool G-Nut/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. The development was demonstrated for the code multipath estimation and new pre-processing based on a fully multi-signal, multi-frequency and multi-constellation approach. The first release of the software was out in August 2013 (available at www.pecny.cz), the version 1.2 was ready in July 2014 and next released is planned in Spring 2015.

Literatura

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