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To cite this article: N G Trong *et al* 2021 *J. Phys.: Conf. Ser.* **1809** 012038

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240th ECS Meeting ORLANDO, FL

Orange County Convention Center Oct 10-14, 2021



Abstract submission due: April 9

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Designing GNSS HUMGAdj software package for surveying and mapping

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Abstract. GNSS technology has made great contributions to the development of surveying and mapping in Vietnam. Many useful GNSS processing software packages have been created and widely used all over the world. However, since these software programs only have input and output, the new users without expert theoretical knowledge (especially new students) can not understand the principle or interfere with the process to obtain explicit results at each step. Therefore, the research team has built the GNSS-HUMGAdj software package to visually illustrate GNSS data processing steps for students to use. In the design stage, the group has learnt the experience in programming GNSS processing software, inheriting published GNSS data processing algorithms. In addition, some algorithms such as converted GNSS baseline in resolving the relative positioning problem, adjusting the receiver antenna height, and the effect caused by the change of distance over time were developed in the software.

1. Introduction

GNSS technology has been applied since the 1990s and has created a new revolution in surveying and mapping in Vietnam. Based on it, a 2D traditional geodetic network was modernized, and unified on Vietnam's territory; thus, successfully establishing the VN-2000 reference system [1]. In addition, GNSS technology is also widely applied in other fields such as environmental resource monitoring, disaster warning and observing. However, in Vietnam, the application of GNSS technology monitoring still uses instruments, software packages, and technology solutions by foreign corporations such as Trimble, Leica, Topcon,... There have been some significant researches on manufacturing GNSS receivers and software packages like the product of Navis center – Hanoi University of Science and Technology [2], the short baseline GNSS processing software using GPS/GLONASS mixture data [3].

GNSS processing software can be divided into the following groups:

- a. The software group installed in the receiver (The Software-Defined Receiver (SDR)): It is used for controlling the hardware of the receiver, namely GNSS-SDR [4], ipexSR [5], NAMURU [6],...
- b. The commercial software group designed by GNSS manufacturers such as Trimble Business



Center made by Trimble [7], Topcon tool [8], HGO [9], Compass post-process [10]: This group is often used for processing short baseline with medium accuracy requirements.

- c. The group of scientific software: It is applied for processing long baseline for the purposes of geodynamic research, atmospheric studies,... Some typical examples are Bernese [11], Gamit/Globk [12], Gipsy-Oasis [13],...
- d. The online processing software group: This group provides the GNSS processing service based on continuously operating reference stations (CORS) like [14, 15],...
- e. The open-source software group including some software packages as follows:
 - RTKLib [16] programmed by C++ language for processing GNSS data for RTK and PPP problems using signals from all GNSS data.
 - LAMBDA [17] for determining the integer ambiguity with many versions. It is built on different programming languages based on the theory of searching integer ambiguity [18] that include both paid and free versions.
 - Raw GNSS measurements [1] with some solutions for receiving the raw data from some types of mobile phones...

Among these aforementioned software, there are many solutions and software packages created by some institutes and universities such as: GNSS-SDR [4], ipexSR [5], NAMURU [6], Bernese [11], LAMBDA [17]... Some of them are being widely used by scientists all over the world like Bernese or effectively utilized in researches on processing GNSS data such as LAMBDA,... Furthermore, there is some software built for teaching about satellite positioning as BaselineByCode [19].

Vietnamese users are also divided in two groups as: (1) surveyors at surveying - mapping companies who are using commercial software packages such as TBC, Leica Spider, Topcon Tool, etc..., (2) researchers at institutes and universities who are applying both the commercial and scientific software packages (mainly Bernese and Gamit/Globk), online software and open source software.

These above-mentioned software packages (except the open source software) such as black box only have input and output; therefore, the users (especially new students who have just studied Satellite Positioning) can not understand the principle or interfere with the process to obtain explicit results at each step. In the case of using open source software, the users must have expert theoretical knowledge to interfere with existing programs or build advance modules. Based on these issues, in order to improve education quality, the research team has built the GNSS-HUMGAdj software package to visually illustrate GNSS data processing steps for students to use. In the design stage, the group has learnt the experience in programming GNSS processing software, inheriting published GNSS data processing algorithms. In addition, some algorithms such as converted GNSS baseline in resolving the relative positioning problem, adjusting the receiver antenna height, and the effect caused by the change of distance over time were developed in the software. These self – developed algorithms will be introduced later.

2. Theoretical basis

2.1. GNSS data format

Data types that are used in processing GNSS observation includes the following formats:

- RINEX includes Observation data (*.OBS or *.yyO) which contain the code pseudo-range, phase measurements...., the broadcast file (*.NAV or *.yyN, *.yyG) and meteorological data (*.MET) [20].
- ANTEX comprises receiver antenna and satellite antenna information [21], used to adjust the satellite antenna and receiver antenna errors.
 - Precise ephemeris (*.SP3).
 - Difference Code Bias (DCB).
 - Other data like the coefficients to correct the effect of ocean load (*.BLQ) [22],...

2.2. Computation of the satellite position over time

The principle of satellite positioning problem is intersection baseline in space problems in which

satellite coordinates serve as original data. Depending on the computing method, the coordinates can be determined by using broadcast ephemeris or precise ephemeris. In case of processing short baseline with medium accuracy, the satellite positions are calculated from broadcast ephemeris. When solving the long baseline processing problems or the high accuracy problems (such as studying the geodynamic, establishing the reference system), the satellite coordinates are computed by using precise ephemeris [23]. The formula for calculating satellite positions using precise ephemeris is:

$$l_j(t) = \frac{(t-t_0)(t-t_1)\dots(t-t_{j-1})(t-t_{j+1})\dots(t-t_n)}{(t_j-t_0)(t_j-t_1)\dots(t_j-t_{j-1})(t_j-t_{j+1})\dots(t_j-t_n)} \quad (1)$$

$$X(t) = \sum_{j=0}^n X(t_j)l_j(t) \quad (2)$$

$$Y(t) = \sum_{j=0}^n Y(t_j)l_j(t) \quad (3)$$

$$Z(t) = \sum_{j=0}^n Z(t_j)l_j(t) \quad (4)$$

$$dT(t) = \sum_{j=0}^n dT(t_j)l_j(t) \quad (5)$$

It should be noted that the antenna phase center and geometric center of some satellite do not overlap, thus we need to adjust this deviation (the eccentricity of the transmitter satellite signals) when computing the satellite position over time [14].

2.3. Adjusted effects of some error sources to GNSS observations

GNSS observations are influenced by many error sources which can be divided into 3 groups:

a. The satellite errors:

- Satellite's clock error: For relative positioning, this error can be removed by the single difference. For single point positioning, this error is minimized by using the clock parameters in the ANTEX file or precise ephemeris [24].

- The delay time caused by satellite hardware.
- The eccentricity of satellite transmitter signal.

b. The receiver errors:

- The receiver's clock error: When eliminated, this error is treated as a unknown number in the satellite positioning problem;

- The delay caused by receiver's hardware: there are two methods to remove this error: (1) downloading and adjusting the parameters to observation if they are estimated for receiver [25]; (2) determining these parameters in the preprocessing data stage before resolving the positioning problem.

- The eccentricity of antenna phase center: the parameters are used in ANTEX file to adjust these errors [23, 26].

c. The transmission medium errors:

- The ionosphere error: The electron particles along the wave propagation direction from satellite to receiver have different effects on phase observation and code pseudo-range [23, 25]. The linear combination of GNSS observations and Global (or regional) Ionosphere Map can be used to minimize this error.

- The troposphere refraction: Due to the variation of refractive index coefficient, the signal propagation from satellite to receiver is refracted so the transmission time is delayed. This error affects both phase observation and code pseudo-range [23, 25]. The troposphere models such as Hopfield, Saataainen, Neil... are often used to adjust this error.

- The multi-path error: This is a common error to GNSS observation, there are some methods to adjust this error [27].

2.4. Ambiguity resolution problem

Phase measurement is used in all high precise positioning problems. It's characteristic is the undetermined integer of wavelength (Integer ambiguity). This value is computed simultaneously with other parameters when the positioning problem is resolved. The accuracy of integer ambiguity is the deciding factor to solve the positioning problem using phase

measurements. There are many methods to determine integer ambiguity like FAST, IR, IB, LAMBDA The GNSS_HUMGAdj resolves integer ambiguity by IR, IB, LAMBDA.

2.5. Single point positioning problem

Absolute positioning is one of the two basic problems in satellite positioning problem. According to statistic results [14], the application of single point positioning accounts for more than 90% of GNSS applications. Absolute positioning is divided into two problems: Standard Point Positioning – SPP and Precise Point Positioning – PPP.

SPP problems is solved by the following procedure [24]: From the code measurements R_j for $n \geq 4$ satellites

$$R^j = \rho^j + c(\delta t - \delta t^j) + Tr^j + \hat{a}_1 I^j + TGD^j + M^j + \varepsilon^j, \tag{6}$$

$j = 1, \dots, n$

After adjusting some error sources to the observation, we linearize equation (6):

$$R^j - \rho_0^j - D^j = \frac{x_0 - x^j}{\rho_0^j} dx + \frac{y_0 - y^j}{\rho_0^j} dy + \frac{z_0 - z^j}{\rho_0^j} dz + c\delta t, \tag{7}$$

$j = 1, \dots, n$

where $D^j = -c\delta t^j + Tr^j + \hat{a}_1 I^j + TGD^j$.

The previous system for the navigation equation is written in a matrix notation as:

$$\begin{pmatrix} R^1 - \rho_0^1 - D^1 \\ \dots \\ R^n - \rho_0^n - D^n \end{pmatrix} = \begin{pmatrix} \frac{x_0 - x^1}{\rho_0^1} & \frac{y_0 - y^1}{\rho_0^1} & \frac{z_0 - z^1}{\rho_0^1} & 1 \\ \dots & \dots & \dots & \dots \\ \frac{x_0 - x^n}{\rho_0^n} & \frac{y_0 - y^n}{\rho_0^n} & \frac{z_0 - z^n}{\rho_0^n} & 1 \end{pmatrix} \begin{pmatrix} dx \\ dy \\ dz \\ c\delta t \end{pmatrix} \tag{8}$$

After solving Equation 8, the estimated coordinates of the receiver is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} + \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix} \tag{9}$$

The issue of resolving SPP problem is computing satellite coordinate using broadcast ephemeris, thus the accuracy of point location in this case is m.

Different to SPP, PPP problem uses some special solutions to achieve accuracy from cm to dm, namely, using linear combination of both code pseudo-range and phase measurement; determining satellite position using precise ephemeris; adjusting the effects of ionosphere layer using Global and regional ionosphere map; correcting the effects of some errors such as the earth pole movement, the ocean loading, the earth tide... [14, 24]. Equation 8 in this case will be:

$$y = Gx \tag{10}$$

while

$$y = \begin{pmatrix} R_C^1 - \rho_0^1 + c\delta t^1 - Tr_0^1 \\ \Phi_C^1 - \rho_0^1 + c\delta t^1 - Tr_0^1 - \lambda_N W^1 \\ \dots \\ R_C^n - \rho_0^n + c\delta t^n - Tr_0^n \\ \Phi_C^n - \rho_0^n + c\delta t^n - Tr_0^n - \lambda_N W^n \end{pmatrix} \tag{11}$$

$$G = \begin{pmatrix} \frac{x_0 - x^1}{\rho_0^1} & \frac{y_0 - y^1}{\rho_0^1} & \frac{z_0 - z^1}{\rho_0^1} & 1 & M_{wet}^1 & 0 & \dots & 0 & \dots & 0 \\ \frac{x_0 - x^1}{\rho_0^1} & \frac{y_0 - y^1}{\rho_0^1} & \frac{z_0 - z^1}{\rho_0^1} & 1 & M_{wet}^1 & 1 & \dots & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{x_0 - x^k}{\rho_0^k} & \frac{y_0 - y^k}{\rho_0^k} & \frac{z_0 - z^k}{\rho_0^k} & 1 & M_{wet}^k & 0 & \dots & 0 & \dots & 0 \\ \frac{x_0 - x^k}{\rho_0^k} & \frac{y_0 - y^k}{\rho_0^k} & \frac{z_0 - z^k}{\rho_0^k} & 1 & M_{wet}^k & 0 & \dots & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \frac{x_0 - x^n}{\rho_0^n} & \frac{y_0 - y^n}{\rho_0^n} & \frac{z_0 - z^n}{\rho_0^n} & 1 & M_{wet}^n & 0 & \dots & 0 & \dots & 0 \\ \frac{x_0 - x^n}{\rho_0^n} & \frac{y_0 - y^n}{\rho_0^n} & \frac{z_0 - z^n}{\rho_0^n} & 1 & M_{wet}^n & 0 & \dots & 0 & \dots & 1 \end{pmatrix} \quad (12)$$

$$x = (dx \quad dy \quad dz \quad c\delta t_R \quad \Delta Tr_{z,wet} \quad B_C^1 \quad \dots \quad B_C^k \quad \dots \quad B_C^n)^T \quad (13)$$

Instead of using the least-square principle, the Kalman filter is often used to solve the absolute positioning [28].

2.6. Resolving the relative problem

Relative positioning achieves the accuracy from mm to cm, depending on the measurement time, and the algorithm applied to solve the problem. Relative positioning includes static problem and kinematic problem. The procedure of solving this problem can be described as the following steps:

- Input and manage data;
- Preprocess;
- Choose the referent satellite;
- Compute the effects of error sources to observation;
- Resolve the real resolution;
- Estimate the variance for observation;
- Resolve integer ambiguity;
- Fix the solution.

2.7. Developing solutions for processing GNSS data

Apart from using the GNSS process algorithms which are developed by scientists all over the world, the research team also developed some algorithms such as adjusting the receiver antenna height in relative positioning, the algorithms for correcting the change of distance over time [26]. In this article, the authors will introduce the algorithm for adjusting the distance over time to observation.

In the absolute positioning problem using code pseudo-range, the derivative of the distance over time ($\dot{\rho}(t)$) must be considered as the varied coefficient and adjusted to pseudo-range due to the asynchronous time as below:

$$\Delta\rho(t) = \dot{\rho}(t) \cdot \Delta t \quad (14)$$

While $\dot{\rho}(t) = (d\rho/dt)$ and Δt is the propagation time from satellite to receiver.

From the relation:

$$\rho^2 = R^2 + r^2 - 2Rr \cos \psi \quad (15)$$

We have:

$$\left(\frac{d\rho}{dt}\right)_{VT} = \frac{r-R \cos \psi}{\rho} \cdot \frac{dr}{dt} + \frac{R \cdot r}{\rho} \sin \psi \frac{d\psi}{dt} \quad (16)$$

There is a relationship between the radius and the major axis of the orbital motion of the satellite:

$$r = \frac{a(1-e^2)}{1+e \cos v} \quad (17)$$

The derivative of radius over time is computed as follows:

$$\frac{dr}{dt} = \frac{a \cdot e(1-e^2) \sin v}{(1+e \cdot \cos v)^2} \cdot \frac{dv}{dt} \quad (18)$$

Through some transformation steps, we have:

$$\left(\frac{d\rho}{dt}\right)_{VT} = \left\{ \frac{a.e.(1-e^2) \sin v(r-R \cos \psi)}{\rho(1+e \cos v)^2} + \frac{R.r}{\rho} [A_1 \sin(\omega + v) - B_1 \cos(\omega + v)] \right\} \frac{dv}{dt} \quad (19)$$

$$\frac{dv}{dt} \approx \frac{dE}{dt} = \frac{n_0}{(1-e \cos E)} \approx \frac{n_0}{(1-e \cos v)} \quad (20)$$

Formula (19) will be rewritten as below:

$$\left(\frac{d\rho}{dt}\right)_{VT} = \left\{ \frac{a.e.(1-e^2) \sin v(r-R \cos \psi)}{\rho(1+e \cos v)^2(1-e \cos v)} + \frac{R.r [A_1 \sin(\omega+v) - B_1 \cos(\omega+v)]}{\rho(1-e \cos v)} \right\} n_0 \quad (21)$$

When proving formula (21), only the movement of satellite on its orbit is considered, the Earth is regarded as motionless. In fact, the Earth is constantly orbiting, so this movement must be computed into the derivative $d\rho/dt$:

$$\left(\frac{d\rho}{dt}\right)_{td} = \omega_E R \cos B_M \cos E \cdot \sin A \quad (22)$$

Thus, the total effect of satellite movement and Earth movement in derivative $\dot{\rho}$ is

$$\dot{\rho}(t) = \left(\frac{d\rho}{dt}\right)_{VT} - \left(\frac{d\rho}{dt}\right)_{td} \quad (23)$$

It can be seen that after adjusting the effect of the Earth movement, the value of $\left(\frac{d\rho}{dt}\right)_{td} \cdot \Delta t$ is removed due to the opposite sign.

3. GNSS-HUMGAdj

With the target of developing a GNSS processing software package for teaching and researching at Hanoi University of Mining and Geology, this program must ensure that the language in the interface is Vietnamese.

GNSS-HUMGAdj is built by Visual Studio language with the interface in Figure 1.

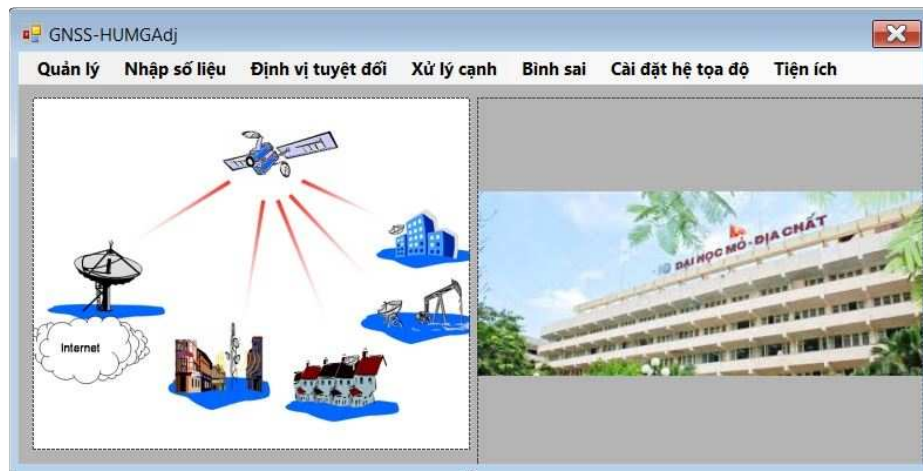


Figure 1. The main interface of GNSS-HUMGAdj

Some major features of this software are listed as follows:

- Management: This function can create new folder, the object where the data input is stored, intermediate calculation data and final result.

- Input data: The program can input some data types such as all RINEX versions (include both observation data, broadcast ephemeris), precise ephemeris, IONEX, ANTEX, Ocean loading data, data of the the Earth pole movement... The input data function of the software is illustrated in Figure 2.

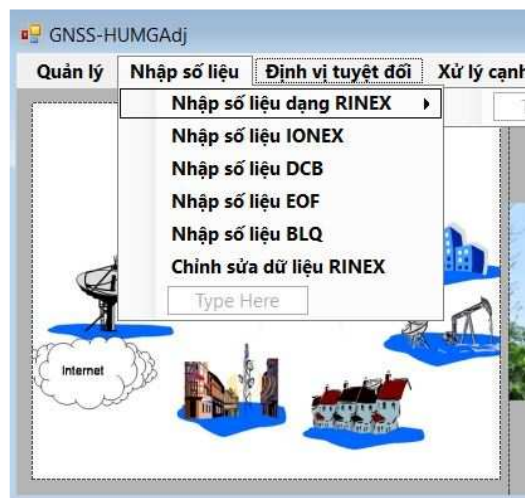


Figure 2. Input data interface

- Single point positioning: This feature permits users to choose SPP or PPP problems with different setting options as shown in Figure 3.

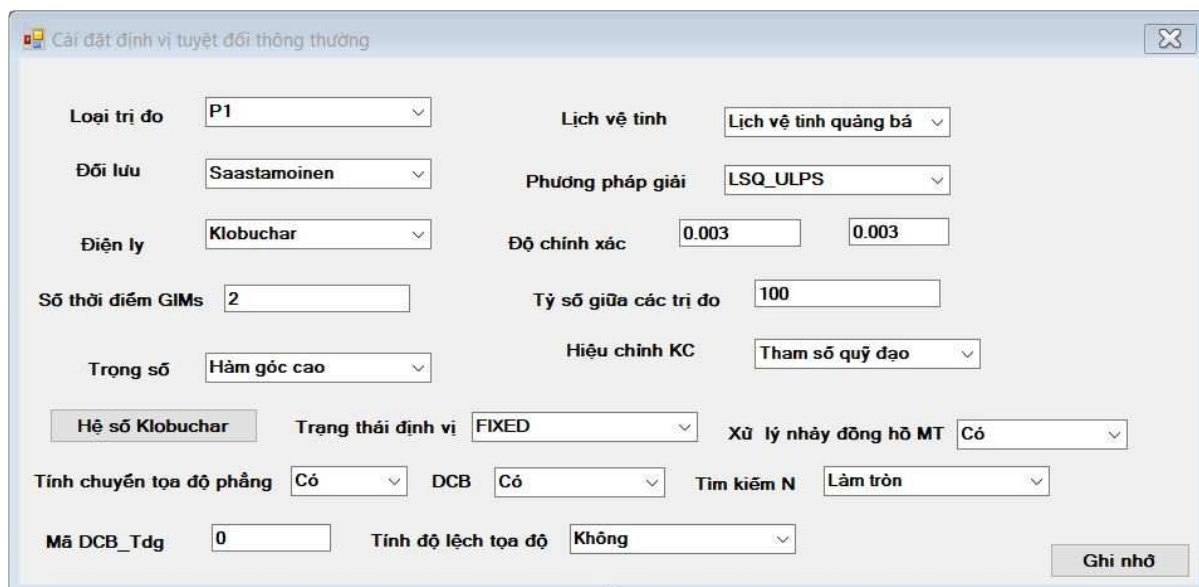


Figure 3. Setting some parameters for single point positioning

Users can choose and change many setting options, for example, types of observation, ephemeris types, methods to adjust the effects of troposphere, ionosphere; methods to correct the change of distance, methods of computing weighting numbers, transference to horizontal coordinate...

- Baseline Processing: Similar to single point positioning, this section also allows users to set various related parameters to solve positioning problems as presented in Figure 4. In addition, the authors also offer many setting options to illustrate clearly and visually how to resolve the satellite positioning.

- Coordinate system setting: GNSS positioning results are the coordinates perpendicular to the geocentric space (XYZ) and usually in the WGS-84 coordinate system. This module allows converting coordinates from BLH to XYZ and vice versa, from the WGS-84 coordinate system to the VN-2000 coordinate system and vice versa, from geodetic coordinate BL to the planar orthogonal coordinate system xy and vice versa.

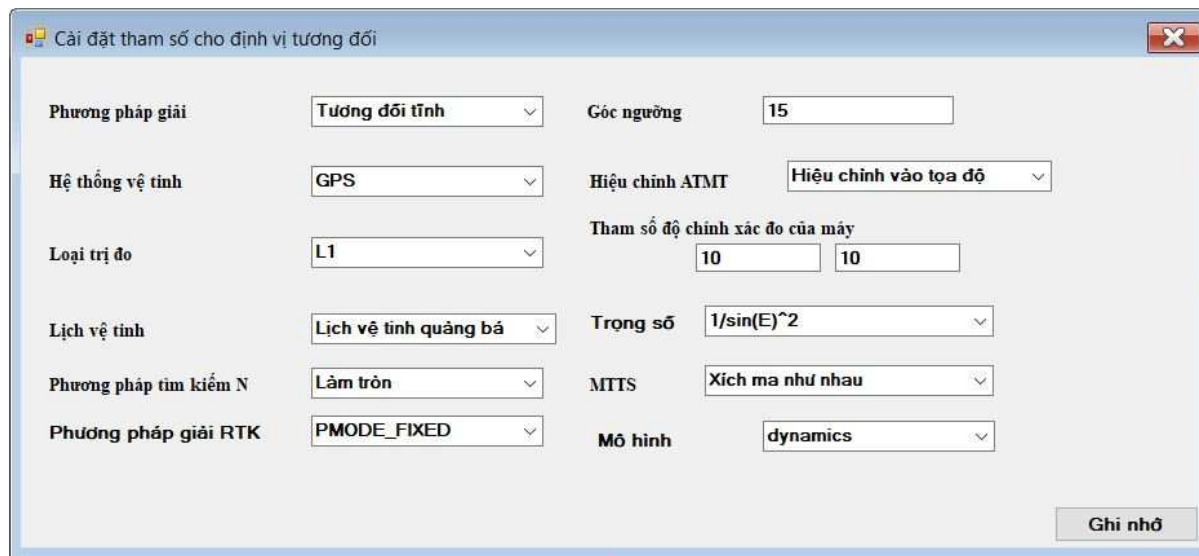


Figure 4. Setting some parameters to resolve relative positioning problems

Utility module: This function provides some options for users.

When positioning problems are resolved, all values of all calculation steps are printed in separate files for users to follow and refer to.

4. Empirical calculations

This section illustrated the results of empirical calculations in searching integer ambiguity and solving absolute point positioning problems (SPP and PPP).

4.1 Results of integer ambiguities

a. Input data

Integer ambiguities in real number format [29] are:

$$\hat{a} = \begin{pmatrix} 5.45 \\ 3.10 \\ 2.97 \end{pmatrix}$$

The corresponding co-variance matrix of the integer ambiguities in real number format is:

$$Q_{\hat{a}} = \begin{pmatrix} 6.290 & 5.978 & 0.544 \\ 5.978 & 6.292 & 2.340 \\ 0.544 & 2.340 & 6.288 \end{pmatrix}$$

b. Results of integer ambiguities

- The ambiguity computed by the integer rounding method is: $\check{a}_R = \begin{pmatrix} 5 \\ 3 \\ 3 \end{pmatrix}$

- The ambiguity obtained from the integer bootstrapping method is:

$$\check{a}_B = (Z^T)^{-1}\check{z} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & -1 \\ 0 & 1 & -3 \end{pmatrix} \begin{pmatrix} -5 \\ 10 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 \\ 3 \\ 4 \end{pmatrix}$$

- The integer ambiguity computed by the LAMBDA method is:

$$\check{a}_B = (Z^T)^{-1}\check{z} = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & -1 \\ 0 & 1 & -3 \end{pmatrix} \begin{pmatrix} -5 \\ 10 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 \\ 3 \\ 4 \end{pmatrix}$$

It can be seen the resultant integer ambiguities calculated by the authors are completely similar to

the results in the announced documents.

4.2 Results of absolute point positioning problems

a. Empirical data

Empirical data used in resolving absolute point positioning problems are data of points measured in Hanoi as clearly mentioned in Table 1.

Table 1. Information about data of points in absolute positioning problems

No.	Point name	Receiver type	Antenna type	Interval (second)
1	DANP	GB-1000	TPSPG_A1	30

In order to have data for comparison, Bernese software was used to process the above-mentioned data obtained from IGS stations surrounding Vietnam. The results are shown in Table 2.

Table 2. The obtained coordinate based on Bernese software

No.	Point name	coordinate components (m)		
		X (m)	Y (m)	Z (m)
1	DANP	-1611206.0777	5731022.2975	2281407.9258

b. Results of empirical calculations

GNSS-HUMGAdj software is used to solve SPP and PPP problems with experimental data to archive the coordinate of points in both WGS-84 and VN-2000 coordinate reference. After that, this achieved coordinate was compared to the obtained coordinate based on Bernese software and RTKPOST.exe module of RTKLib 2.4.2 software.

b.1 Comparison of results by GNSS-HUMGAdj and Bernese software

The values of deviations of coordinate components when resolving SPP and PPP problems in UTM projection at epochs are presented in Figure 5 and Figure 6, respectively.

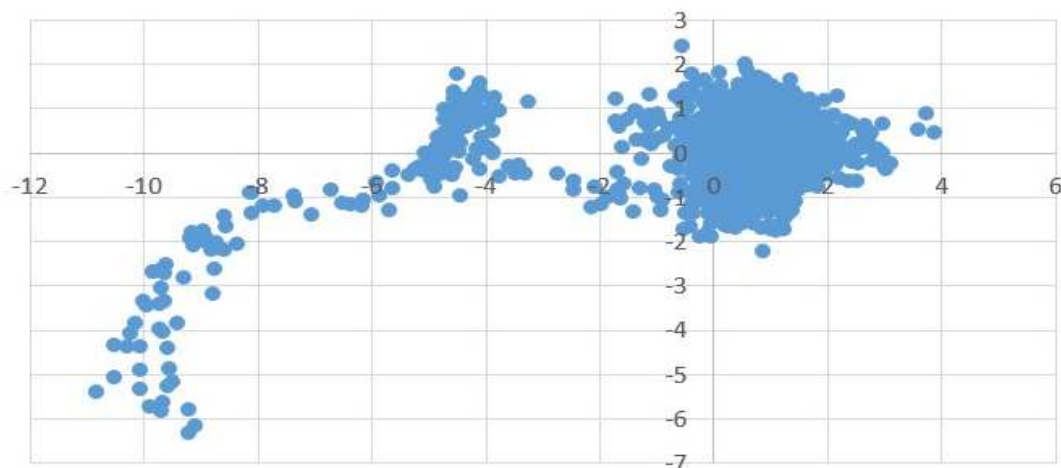


Figure 5. The deviations of coordinate components archived when solving SPP problem

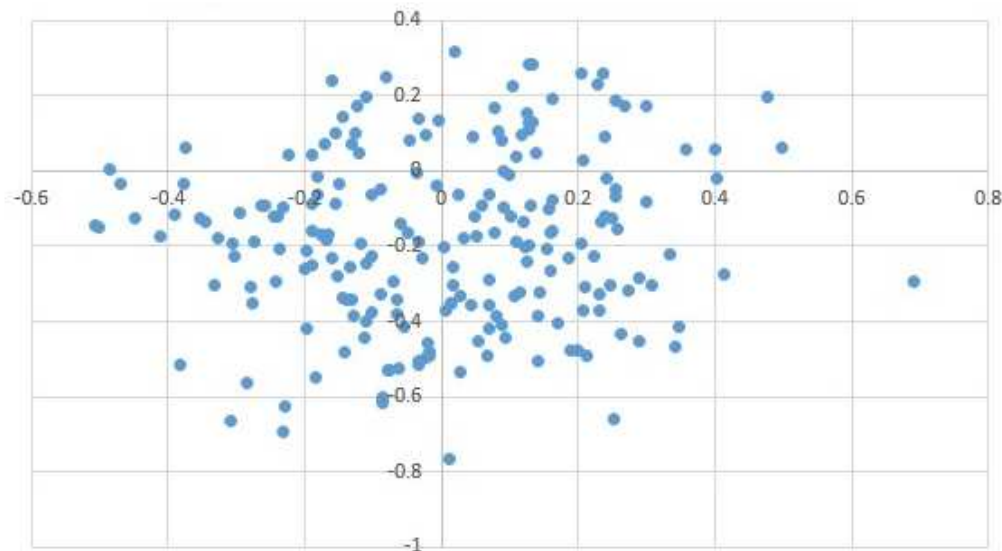


Figure 6. The deviations of coordinate components archived when solving PPP problem

In Figure 6, the first 205 epochs' coordinate components were compared.

Besides, the deviations of 3D coordinate components in WGS-84 coordinate reference was also determined as shown in Figure 7 below.

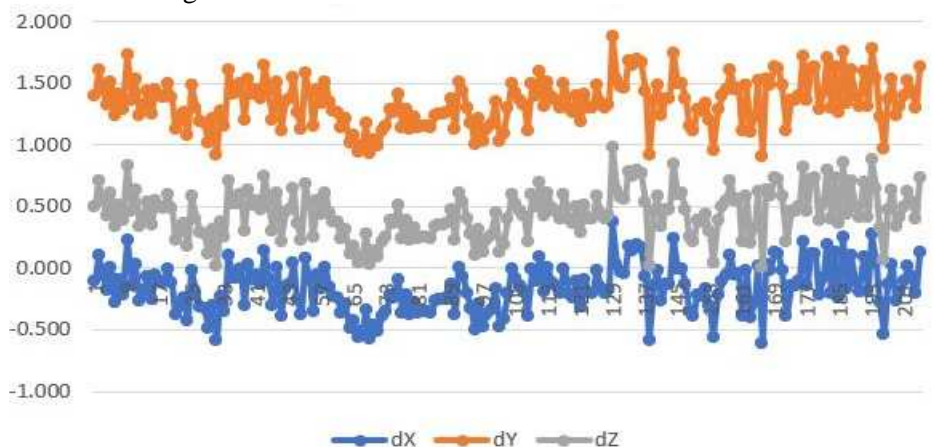


Figure 7. The deviations of 3D coordinate components in WGS-84 coordinate reference

From figure 7, it can be seen that there are still some systematic errors in the results processed by GNSS-HUMGAdj because of deviations of coordinates with the same sign at epochs.

b.2 Comparison of results by GNSS-HUMGAdj and RTKPOST.exe

The authors directly used the program running in .exe format without interfering with the program's source code in order to investigate the accuracy when using an existing program.

The used RTKPOST.exe module comprises such parameters as: Using IONEX to determine correction of ionospheric, Saastamoinen model to determine correction of tropospheric, Precise ephemeris (SP3) to calculate satellites's coordinate; ngs_abs.pcv and igs05.atx to determine correction of satellites and receiver phase center. All the parameter options are shown in figure 8 a, b and c, respectively.

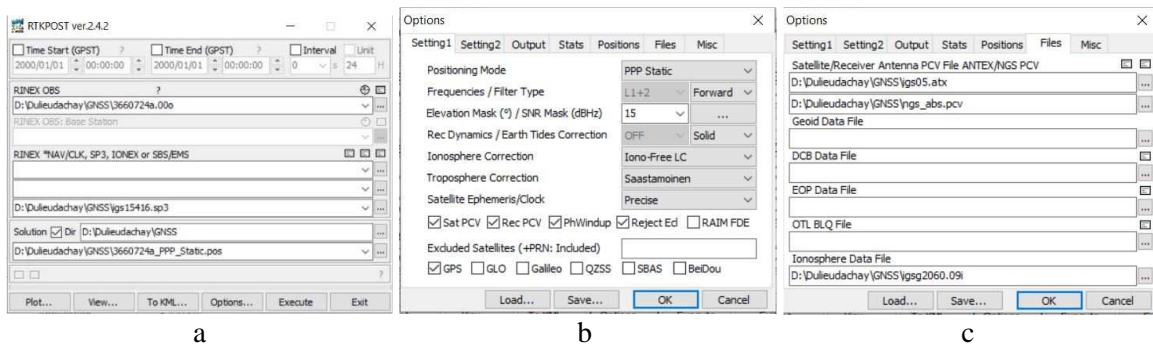


Figure 8. Parameters when processing data by RTKPOST.exe module

The deviations of coordinate components in WGS-84 coordinate reference when using RTKLib, GNSS-HUMGAdj and Bernese software to solve PPP problem in static and kinematic modes are shown in the following figures.

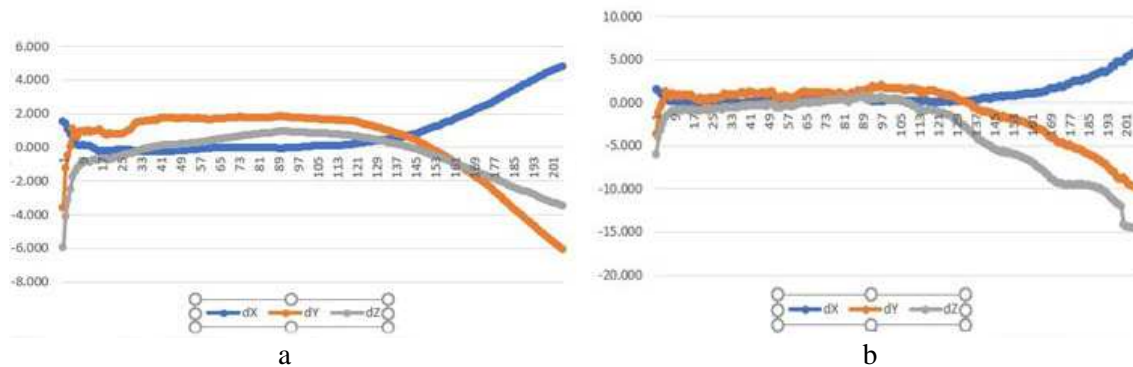


Figure 9. The deviations of coordinate components processed by RTKLib and Bernese software

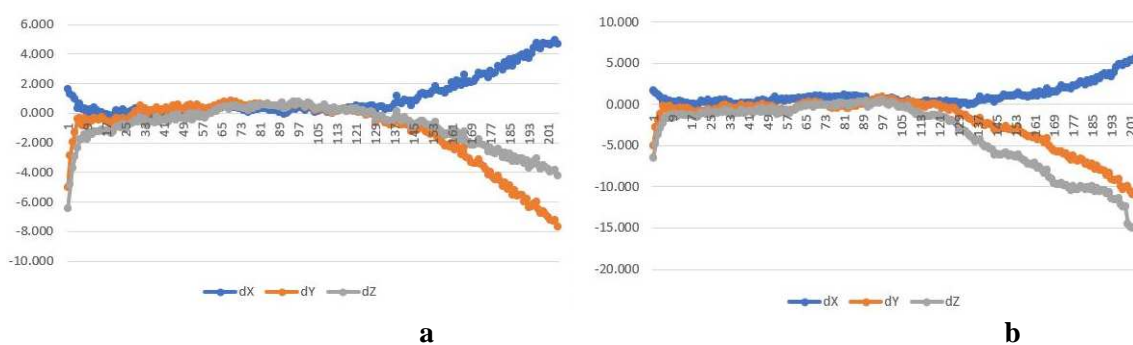


Figure 10. The deviations of coordinate components processed by RTKLib and GNSS-HUMGAdj software

While Figure 9a and Figure 10a illustrate the results in static mode, Figures 9b and 10b present the results in kinematic mode when processing PPP problem by RTKPOST.exe module of RTKLib software.

5. Conclusion

It can be concluded that the GNSS-HUMGAdj software package for surveying and mapping was successfully built by the authors. This software visually illustrates GNSS data processing steps for new students even without experience to easily solve point positioning problems. Beside inherited GNSS

data processing algorithms, some algorithms such as converted GNSS baseline in resolving the relative positioning problems, adjusting the receiver antenna height, and the effect caused by the change of distance over time were also developed the GNSS-HUMG Adj.

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