ANALYSIS OF DAILY GNSS POSITION TIME SERIES

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ABSTRACT

Daily GNSS time series are commonly used to study the crustal deformation. The development of large continuous GNSS networks, including hundreds of sites, makes difficult to carefully look at each individual time series and promotes the need of automatic analysis of large data sets. For instance, offsets and transients signal are found in daily position time series, either due to equipment change or real geophysical processes, leading to possible bias in velocity estimates if not properly identified or handled in the analysis.

In this study we present algorithms that allow robust analysis of daily GNSS position time series. The first deals with the optimal reference frame definition of the solutions. We use a robust method of expression results in the current ITRF release, using L1 norm to produce daily time series from loosely constrained solutions. The second is dedicated to the automatic search of the outliers. The method is based on the variations of rms calculated with respect to the local average position through time to identified windows of anomalous behaviour. The last is analysis of time series to determine its parameters.

This paper introduced the calculation method and processing the common problem of GPS position time series in the GPS permanent network, processing the France's RENAG network as an example, in order to determine the velocity field with the highest precision for researching the Alps's geotectonic.

Keywords: *GNSSS position time series, continuous GPS, geodesy for tectonics, Dikin estimation, least square estimation*

1. INTRODUCTION

The geodetic method in Earth's crust displacement research is widely and effectively used in the world. The GNSS (Global Navigation Satellite System) position time series of continuous GNSS station is used to exactly calculate the displacement between continental plates comparede to the Earth center, and the oscillation between continental plates. This is important data for study and for calculating and forecasting the seismic activities such as earthquakes, tsunamis,…

The continuous GNSS observations techniques enable to receive continuous GNSS signal day and night and create the measurement series (GNSS continuous stations). Since then, the coordinates of GNSSS stations will be calculated, allowing to continuously determining the movement of Earth's crust. Currently, GPS and GNSS networks are constantly being developed widely on both network scale and continuous measurement data capacity. Those include Japan's GNSS Earth observation network system (GEONET) with 1300 stations covering over Japan territory; the Plate Bounadary Observation (PBO) with 1100 stations in the West of the United States.

The application of GNSS technique in general and GPS technique in particular for researching Tectonics is very popular in the world (so we can substitute "GNSS" with "GPS"), including (Nocquet, J.-M, Calais, E., 2003), (Shuanggen Jin, Pil-Ho Park, Wenyao Zhu, 2007), (Shui-Beih Yu, Horng-Yue Chen, Long-Chen Kuo, 1997). In Vietnam, this application has been beginning to be deployed. In the period of 2012 – 2015, to study the displacement of crush zones in special regions, the Institute of Geodesy and Cartography developed the Northern geodynamic GPS network, which consists 78 GPS stations covering 11 fault zones in the north of Vietnam; moreover, the Mekong Delta geodynamic GPS network including 17 GPS stations covering 12 fault zones was established at that time. In the period of 2015-2019, the Institute of Geodesy and Cartography is developing a geodynamic GPS network in the Central, the Central Highlands and the South with 64 GNSS stations covering 13 fault zones to study the movement of the fault space in these areas. However, researches of analysis of time series have not been published much; there are few studies having the experiment results compared with the GPS measured data in cycles (Nguyen Anh Duong, Fumiaki Kimata, Tran Dinh To, Nguyen Dinh Xuyen, Pham Dinh Nguyen, Vy Quoc Hai, Duong Chi Cong, 2011).

This paper presents the methods of analysis of continuous GPS position time series for determining of precise velocity vector and other parameters.

2. GNSS POSITION TIME SERIES AND ITS COMMON PROBLEMS

2.1. GNSS position time series

In its most general definition, a time series is a sequence of numerical values representing the evolution of a specific quantity over time. Such value sequences can be expressed mathematically in order to analyze their behavior, usually to understand their past evolution and possibly predict its future behavior.

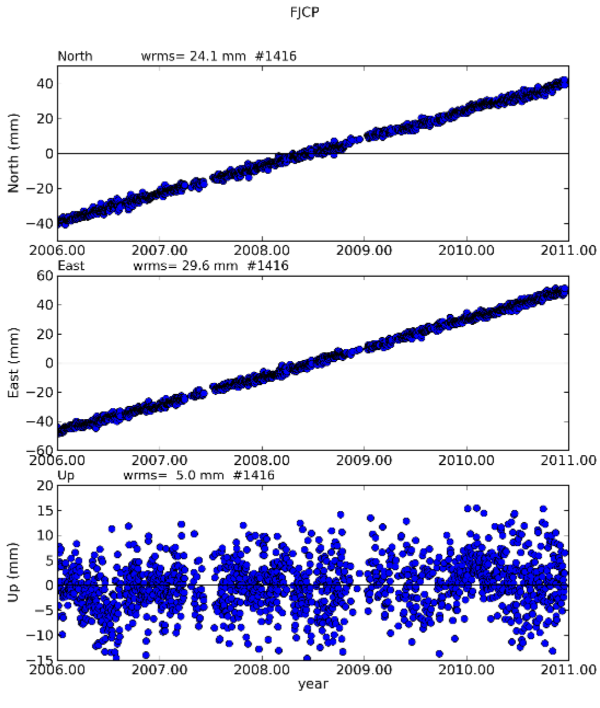


Figure 1. Example of GPS position time series.

The GNSS position time series (in short "GPS time series" or “time series”) are a representation of the temporal evolution of a point in the same three-dimensional space in cartesian geocentric coordinates (x, y, z) or in local coordinates (e, n, u). For example, Figure 2.1 shows the time series of GPS position residuals from the FJCP site (RENAG network) in local coordinates over three components. Thus, this point has three coordinates evolving in time associated manner, that is to say that the movement of the point is reflected on all three coordinates. Now, the Cartesian coordinates (x, y, z) of the points considered at a date t0 come from a complex estimation, generally made by least squares, and the results obtained are data with an associated variance-covariance matrix.

The precision of the time series caracterized by weight root mean square (wrms), an average indicator of the dispersion of the positions [Nocquet, 2011]:

$$wrms = \sqrt{\frac{\sum_{i=1}^{n} \frac{(y_i - \bar{y})^2}{\sigma_i^2}}{(n-1)\sum_{i=1}^{n} \sigma_i^2}} \qquad (1)$$

Where n is the number of positions, $\bar{y}$ is the weight mean of the daily position y_i or the value predicted by the model of the time series, σ_i is the variance of y_i.

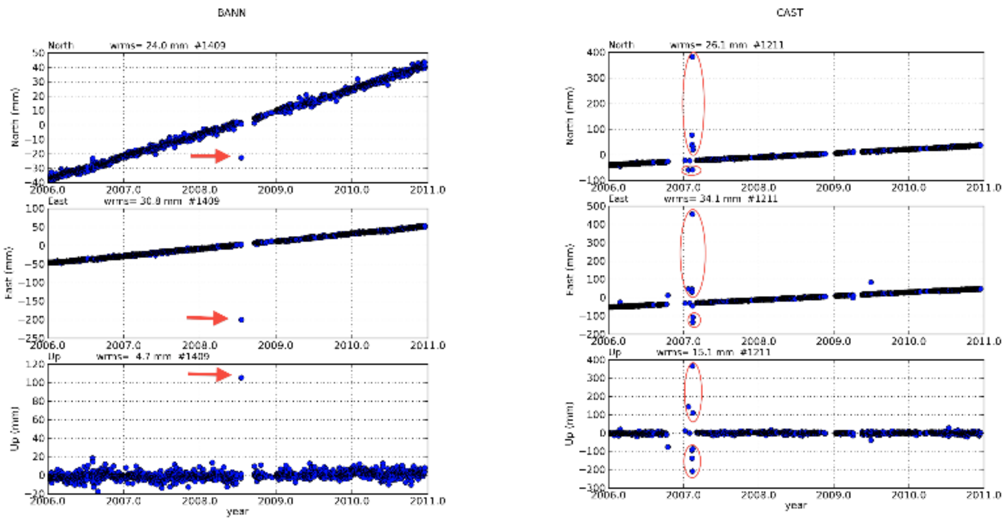
2.2. Common problems in the GNSS position time series

The Continuous GNSS stations are located at locations that clearly reflect tectonic activities such as the margin of faults, the margin of plates, areas near active geophysical phenomena. So its not only reflect the change of surface (changes in groundwater table, tide ...), the displacement of tectonic activities (earthquakes,...), its also reflect the weather changes affecting the station,...

Thus, daily position time series of GNSS station reflect these problems. Identifying the parameters of GNSS position time series is very important, as it is the most accurate data for the geophysical model to study and forecast tectonic activities.

2.3.1 Outlier

Outliers are coordinates, which are very large and unusual, in the coordinate time series. Outliers often exist alone or in a group (figure 2).



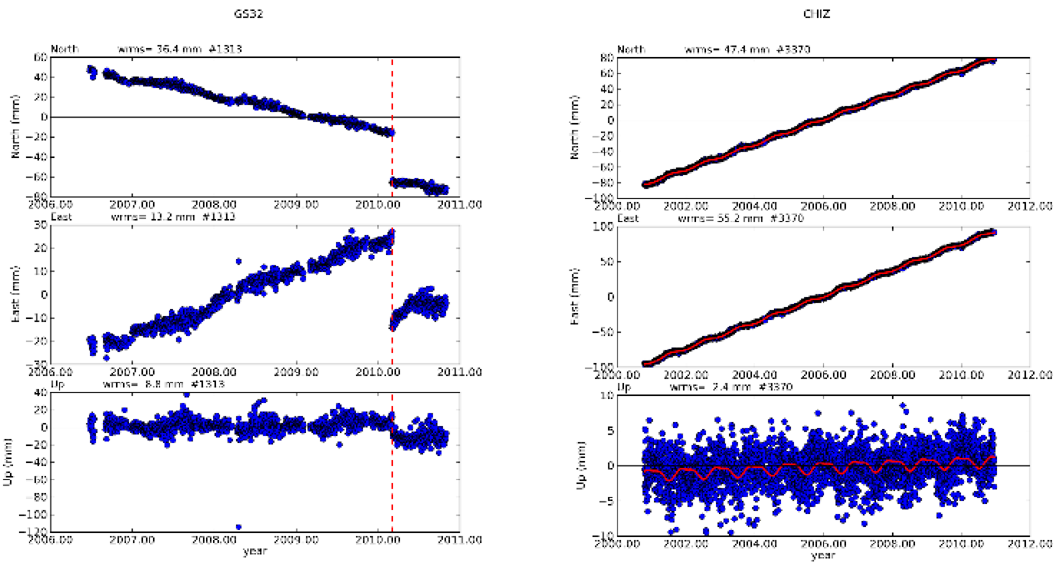
Single outlier Group outliers

Figure 2. Outliers in the daily GNSS position time series.

There are many reasons that cause outliers, in which the popularly causes of the negative signal, missing data, fault calculation by software, processing, weather (due to snow and ice covering antenna) and so on; Outliers must be removed. It is the first step in the processing of the coordinate time series.

2.3.2 Offset

Offsets that appear in the time series are also quite common. A offset can appear one or more in a position time series with diffirent magnitudes (figure 3).



Offset

Seasonal movement

Figure 3. Offset, seasonal movement in the daily GNSS position time series.

Offset are usually caused by material reasons such as change antenna, by phenomena related to the station environment as a shock on the antenna or section of a tree near the antenna, or geophysical processes like the rapid pumping of water or oil into the groundwater and of course the earthquakes. Finally, some offset can be linked to the calculation for example during the modifying the model used (atmosphere), change of algorithm or analysis strategy.

2.2.3 Seasonal movement

Seasonal movement affects the Earth's crust as expressed in the time series, especially the time series of continuous GNSS stations for over a year. This motion varies according to sinusoidal law (Figure 3) with a period of 12 months (annual season) and six months (semi-annual season).

Seasonal signal can be generated by overload effects (continental hydrology for example) or weather phenomena such as snowfall on the antenna.

The amplitude and phase of seasonal movement are also important parameters in the geophysical model, which is used in the plate tectonic research.

The presence of these terms may bias the estimation of velocity when the time series are short. (Blewitt, G., Lavallée, D., 2002) indicate that, for time series beyond 4.5 years, this bias becomes negligible.

3. PROCESSING CONTINUOS GPS DATA

Processing continuous GNSS networks to determine the velocity field vector and other parameters is a complex process; it is implemented on a computer powerful configuration and takes plenty of time. In this processing, we performed over 3 main steps:

(1) Determining the coordinate every 24 hours (daily coordinate) of station in the WGS84 system from its continuous measurements by Gamit software.

(2) Transforming the daily coordinate into the International Terrestrial Reference Frame (ITRF).

(3) Processing coordinate time series: detection and removal outliers; define the geometric model suitable with the coordinate time series; calculated the velocity, seasonal movement, offset and the deformation due to other geotectonic. These parameters are provided for the geophysical model to study and forecast the tectonic activities.

The first step is automatically done by the Gamit software. This paper focus in two next steps.

3.1. Transforming the position time series in ITRF

After processing GPS data by Gamit software in step 1, the (x,y,z) coordinates time series of GPS stations are received in the WGS84 system. In geodynamic research, the International Terrestrial Reference Frame (ITRF) is used popularly that because ITRF benchmarks are more stable, more update and more dense. The ITRF including 500 stations covering the Earth' surface, the coordinate and velocity of ITRF benchmarks are updated every 4 years (Rebischung, P., Griffiths, J., Ray, J., Schmid, R., Collilieux, X., Garayt, B., 2012).

Transferring to the ITRF system is usually performed by Helmert transformation. We met the following difficulties in practice:

- The common benchmarks of ITRF and GNSS networks is unstable during the time: there are many stations (benchmark) that were newly built, but also many other stations lost, or not data for a period of time. It causes the calculated coordinates skewed.
- There are offsets in the time series of common benchmark. It caused systematic errors falsifying the coordinate transfer.
- There exist errors due to unstable operation of GNSS receivers.

To troubleshoot these issues, we used solutions as:

- Selecting common benchmarks that belong to the international GNSS Service (IGS) and GNSS networks to calculate 7 parameters of Helmert model.
- Using Dikin method (Tran Dinh Trong, Dao Duy Toan, Vu Dinh Chieu, 2014) to remove outliers in common benchmarks before estimating 7 parameters of Helmert transformation by the least squares method.

The IGS network (http://www.igs.org/) including 232 hight accyracy stations in the ITRF network only using continuous GPS technology; while the ITRF network is combined 4 technologies that consist Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS) and Very Long Baseline Interferometry (VBLI). We choose the IGS network with advantages: firstly, they are high accuracy stations (the precision of velocity about 0.3mm/year), and stable stations of the ITRF network (Rebischung, P., Griffiths, J., Ray, J., Schmid, R., Collilieux, X., Garayt, B., 2012); secondly, they is calculated and updated every 2 years, which are faster than the ITRF network in every 4 years. Thirdly, the station, which is affected and interrupted by the earthquake or change the antenna and so on, is updated and published on the website (ftp://igs-rf.ign.fr/pub/discontinuities/soln.snx). This information is used to determine offsets and post-earthquake changes in the position time series.

3.2 Processing continuous GPS position time series

3.2.1 Detect and remove outlier

In fact, outliers often exist as the gross error in the time series. They satisfied the calculation results of velocity and other parameters of position time series. Identifying and removing outliers are the first step of analysis of time series. Normally, outliers are detected by manual methods using observed visuals to detect and remove outliers. These methods are easy to apply, but it may identify and remove wrong outliers. In addition, it is not effective for processing of hundreds of position time series in a large network.

We used a method that based on variance value (root mean square - rms). Accordingly, the position time series are divided into small series of the week including 7 juxtaposition (the window). The second window is started from the 2nd coordinate; the third window is started from the 3rd coordinate and so on. This window type is called the sliding window. The rms value of the i^{th} window is calculated as:

$$rms_i = \left(\sqrt{\frac{\sum_{j=1}^{7}(p_j-\overline{p_\iota})^2}{7}}\right)i \qquad (1)$$

Where, p_j is the coordinates of the j^{th} point, $\overline{p\iota}$ is the mean value of the i^{th} window.

The size of windows is equal 7. Because it is large enough to be able to apply statistical calculation and also small enough to outlier value is reflected in rms value (Trong, 2013).

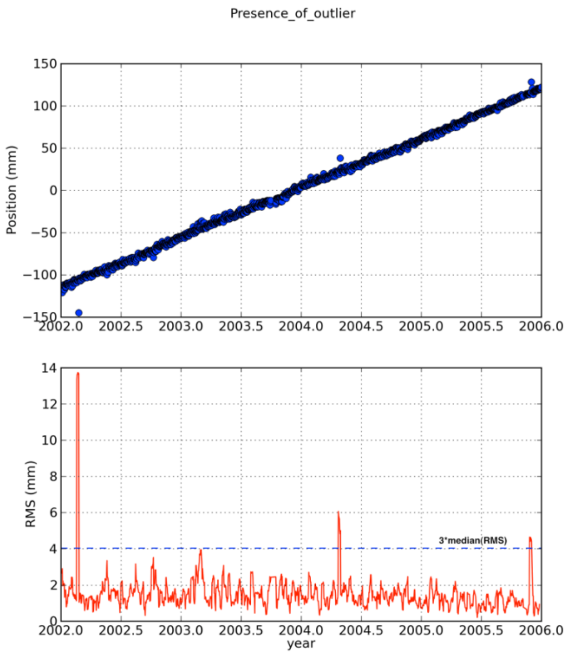


Figure 4. The relationship between the coordinate and their rms.

If a coordinate value is an outlier, the rms value of this window is also an outlier. The threshold is equal 3 times of the median of rms series, which is used to detect outlier, corresponding with the confidence interval is 97%.

There are some advantages of this method including fast calculation, easily programmed to automatically identify and remove outliers. We have used this method to filter out outliers in the time series. After completion of this step, we can receive the new coordinate time series without outliers.

3.2.2 Determining the parameters of the time series

Generally, the mathematical model of daily GNSS position time series including 3 components (Trong, 2013): linear movement, annual and semi-annual seasonal movement and offsets. The equation was represented as (3 components on each []):

$$y(t_i) = [a + bt_i] + [csin(2\pi t_i) + dcos(2\pi t_i) + esin(4\pi t_i) + fcos(4\pi t_i)] + [\sum_{j=1}^{k} g_j H(t_i - T_j)] \quad (2)$$

Where: t_i is the time of the ith coordinate,
a is the position at the reference time; b is the velocity,
(c,d), (e,f) are the parameter of annual and semi-annual seasonal movement,
g_j is the magnitude of offsets at the time of T_j (k is the number of the offset in the position time series),
$H(t_i - T_j)$ is the Heaviside function: $H(t_i - T_j) = 0$ if $t_i \leq T_j$; $H(t_i - T_j) = 0$ if $t_i > T_j$.

However, there is post-seismic relaxation, slow-slip-events and the change of velocity in the coordinate time series complex, which commonly appear in the network located on the complex tectonic area like GEONET (Japan).

Assuming the offset knew until T_j, a linear function of parameters, which described the coordinate time series, is presented as :

$$x = [a\ b\ c\ d\ e\ f\ g_1\ g_2\ ...\ g_k]^T \quad (3)$$

From n number of coordinate time series, we have n equations form (2) writing in matrix form:

$$y = Ax + v \quad (4)$$

The coefficient matrix is:

$$A = \begin{bmatrix} 1 & t_1 & sin(2\pi t_1) & cos(2\pi t_i) & sin(4\pi t_i) & cos(4\pi t_i) & 0 & 0 & ... & 0 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ 1 & t_j & sin(2\pi t_j) & cos(2\pi t_j) & sin(4\pi t_j) & cos(4\pi t_j) & 1 & 1 & ... & 1 \\ ... & ... & ... & ... & ... & ... & ... & ... & ... & ... \\ 1 & t_j & sin(2\pi t_n) & cos(2\pi t_n) & sin(4\pi t_n) & cos(4\pi t_n) & 1 & 1 & ... & 1 \end{bmatrix}_{(n,6+k)} \quad (5)$$

In this case, we assumed that the coordinate time series only were affected by white noise, the variance-covariance matrix is presented in the simple form as follows :

$$C = \begin{bmatrix} \sigma_1^2 & 0 & ... & 0 \\ 0 & \sigma_2^2 & ... & 0 \\ ... & ... & ... & ... \\ 0 & 0 & ... & \sigma_n^2 \end{bmatrix} \quad (6)$$

With σ is the variance of the coordinate.

The movement parameter of the coordinate time series is determined by least squares estimation:

$$x = (A^T C^{-1} A)^{-1} (A^T C^{-1} y) \quad (7)$$

Since which, the velocity of measuring stations and the magnitude of offsets are determined exactly. The parameter amplitude and phase of seasonal movement within year cycle and half-year cycle are calculated from c, d, e, f parameters.

$$A_{ann} = \sqrt{a^2 + b^2};\ \phi_{ann} = \left[\text{atan2}\left(\frac{a}{b}\right)\right]/2\pi \qquad (8)$$

$$A_{semi-ann} = \sqrt{c^2 + d^2};\ A_{semi-ann} = \left[\text{atan2}\left(\frac{c}{d}\right)\right]/4\pi \qquad (9)$$

The model (2) describes basicly the full of phenomena reflected in the time series. It then determines accurately the parameters, especially velocity, based on the least square estimation on the clean time series.

4. CALCULATION EXAMPLE

RENAG (RÉseau National GPS permanent, http://www.renag.fr, figure) is the continuous GPS network in France with several scientific purposes, of which the geophysical research such as dynamic deformation measurement, land surface waves due to earthquakes, etc is noticeable. This network includes 102 continuous GPS stations, with 60 stations in French territory. This network is managed by Institut Géographique National (IGN), and its data-metadata is measured, stored and processed by GeoAzur.

The RENAG network is a part of the RGP network system in Europe, also including 29 points of the IGS network. Until the time we processed the velocity field of the network (2013/03/02), this network was measured continuously since 1996 (each station were measured continuously for 12 years, in average).

The IGS network, which is used to calculate 7 parameters of Helmert transformation, is updated on 08/13/2012 (IGS12P33). The GPS data of RENAG network, which is selected to analyse, is continuously measured data from 1996 to 08/2008. After calculated and adjusted 7 parameters of Helmert transformation based on 29 common stations of IGS08 and RENAG, the coordinate of 102 stations of RENAG network was transformed to the ITRF. The result is 102 GPS position time series of RENAG network.

The quality of GPS coordinate time series is characterized by the standard deviation (wrms). The histogram of wrms of RENAG network is presented:

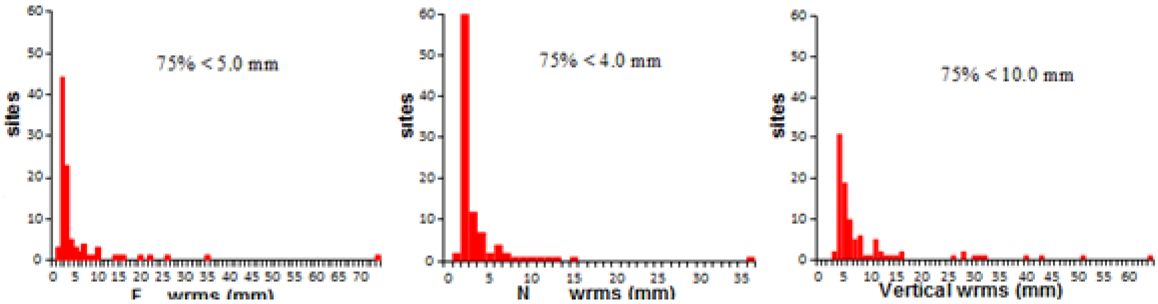


Figure 5. Histogram of wrms of RENAG after transformed to ITRF network.

There are more than 25% of stations that have the standard deviation bigger than 5mm for horizontal and 10 mm for elevation. This number is still too large in processing GPS data with high accuracy.

The main reason is after procession data in step 1, there is still “noise” like outliers, offset, seasonal movement and so on that still exist after transferring the coordinate to the ITRF network. These issues are listed in the figure 3.

Calculate the adjustment for the coordinate time series without outliers to determine the velocity and movement parameters. The accuracy of processing results is presented by statistical standard deviation of every point in the network and showed in figure 6. It demonstrated the calculation result is very good.

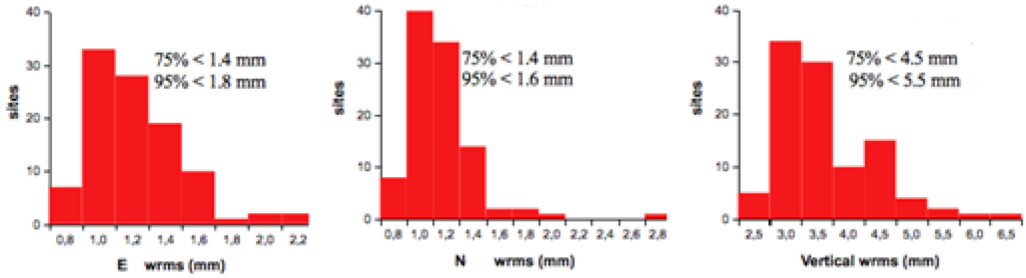


Figure 6. Statistical the variance of position time series after processing.

After processing data, there is about 95% of the points having the standard deviation less than 1.7 mm for horizontal, and 5.5 mm for vertical. The accuracy of results is very high with the average of horizontal standard deviation and vertical standard deviation approximately equal 1.2 and 3.4 mm respectively. In comparison with figure 2, the accuracy has greatly increased. It confirmed that the velocity and other movement parameters of coordinate time series are determined exactly.

There are 102 GPS measuring stations, which were processed, in the RENAG network. In this paper, we illustrated a few typical cases, they are BARK station and WTZR station. There are an outlier and seasonal movement in the coordinate time series of BARK (figure 6) station while the coordinate time series of WTZR station is more complex with a offset (figure 7).

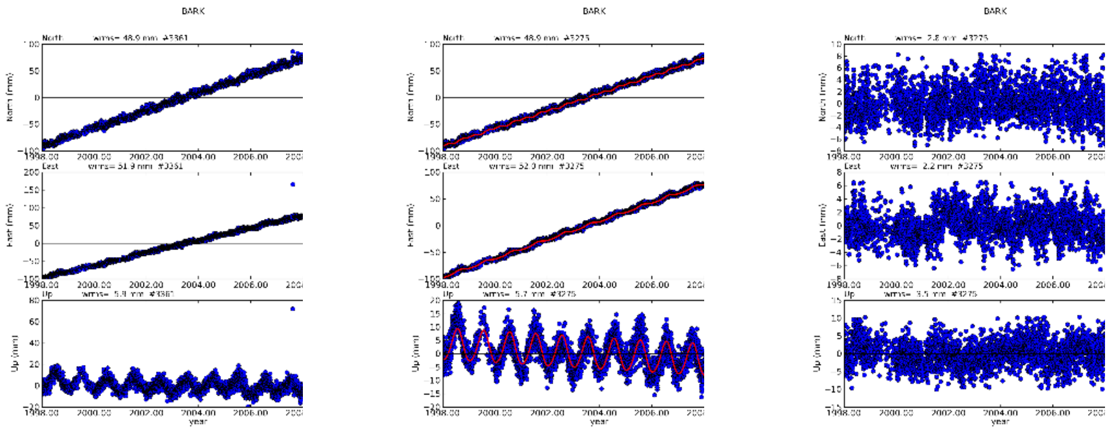


Figure 7. Processing the position time series of BARK station.

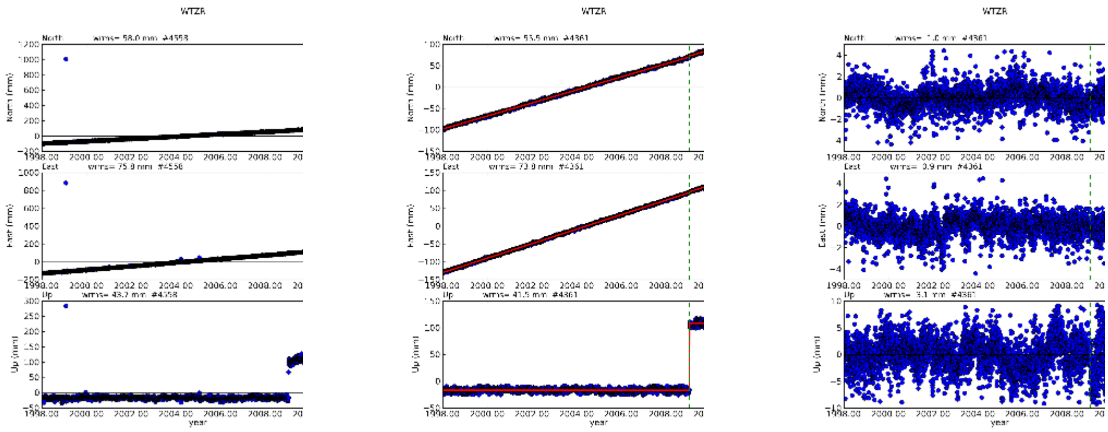


Figure 8. Processing the position time series of WTZK station.

In figure 7 and 8, the time series data in left-hand side is the coordinate time series before processing; the time series data in the middle is the coordinate time series that was removed outliers and calculated adjustment their model (red line); the time series data on the right-hand side is the adjusted series, which was calculated by the formula (4). The accuracy of determining parameters of coordinate time series is higher corresponding the root mean square value of adjusted series is smaller. From two positions time series as an example, we see that the velocity and other parameters were determined exactly.

The velocity of each measuring station is calculated using the velocity component that was determined in the previous step and the velocity field of RENAG network is obtained in the ITRF2008. The average velocity of this network is 16 mm per year in the ITRF2008 with the precision equal 0.4mm. Figure 9 indicated that the network is moving towards the northeast.

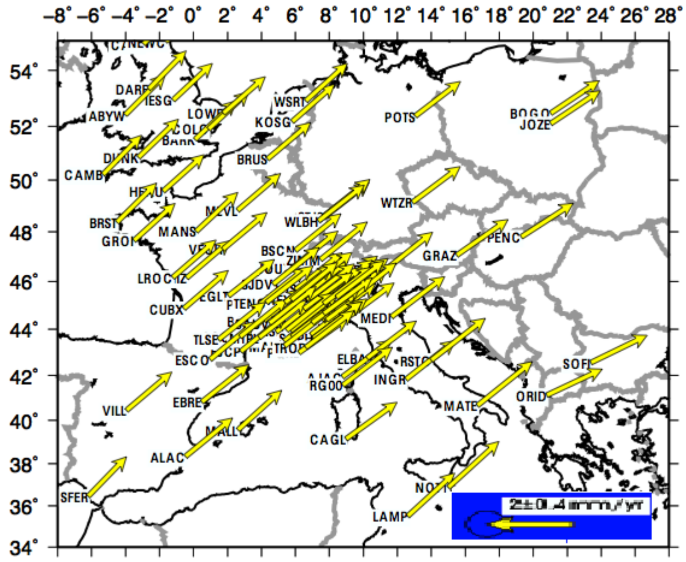


Figure 9. The velocity field of the RENAG network in the ITRF system.

In the comparison with other research as (Nocquet, 2011), the velocity field, which was calculated from our method, is the same with the result of previous studies, but the accuracy achieved higher.

The velocity field that was received in the ITRF is compared to the center of average gravity of the Earth. In the research of geodynamics, they are transferred to a new velocity that is compared with a stable pole of European continental plates to determine the movement local of continentals. In this study, we do not focus on this issue.

Our method not only applied for the geophysical research of regions in France but also be applied effectively to the research in other areas (Nocquet JM, JC. Villegas Lanza, M. Chlieh, PA. Mothes, F. Rolandone, P. Jarrin, D. Cisneros, A. Alvarado, L. Audin, F. Bondoux, X. Martin, Y. Font, M. Rgnier, M. Valle, T. Tran, C. Beauval, JM. Maguina Mendoza, W. Martinez, H. Tavera and H. Yepes, 2014).

4. CONCLUSION

Using the continuous GPS network for the geotectonic research is effective research direction, which is applied very popular in the world. It provides input data that have high reliability for Earth’s surface deformation research, especially forecasts nature disasters such as earthquake and tsunamis.

The coordinate time series of RENAG network are determined exactly, removed maximum of outliers by Dikin adjustment based on the reference station of IGS network. The coordinate time series is removed completely outliers; the mathematical model was applied completely suitable to determine the velocity and other parameters of these coordinate time series. The velocity field of ITRF coordinate system, which is determined from the RENAG network, has average velocity 16 ± 0.4 mm/year. This result is consistent with the transformation of the region that is published before.

The processing method of GPS coordinate time series, which is proposed by us, is programmed into tools and used by geodetic-geophysical experts in the GeoAzur. Based on the results achieved, we proposed and expected to use the method in this study into the project that has been deployed in Vietnam.

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