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Evaluation of the Performance of Online GPS/GNSS Data Processing Services for Monitoring the Land Deformations and Movements

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ABSTRACT

In recent years, the Global Navigation Satellite Services (GNSS) technology has been frequently employed for monitoring the Earth crust deformation and movement. Such applications necessitate high positional accuracy that can be achieved through processing GPS/GNSS data with scientific software such as BERENSE, GAMIT, and GIPSY-OSIS. Nevertheless, these scientific softwares are sophisticated and have not been published as free open source software. Therefore, this study has been conducted to evaluate an alternative solution, GNSS online processing services, which may obtain this privilege freely. In this study, eight years of GNSS raw data for TEHN station, which located in Iran, have been downloaded from UNAVCO website on a daily basis. Furthermore, TEHN GNSS observations are processed with CSRS-PPP, which is based on Precise Point Positioning (PPP) algorithm, and OPUS, which is based on double difference (DD) algorithm, to compare between these two techniques in terms of station velocity estimation and Earth deformation. On the other hand, TEHN station solutions that produce via scientific software, GIPSY-OSIS, are obtained from Nevada Geodetic Laboratory (NGL) website for data validation. Eventually, the results show that both GNSS online processing services (CSRS-PPP and OPUS) are credibly efficient to estimate station velocities, while CSRS-PPP trustworthy service for monitoring the Earth deformation.

Keywords: Global Navigation Satellite System (GNSS), GNSS online processing services, Station velocity, Earth deformation, CSRS-PPP, OPUS.

تقيم أداء خدمات معالجة الارصادات الملاحية للأقمار الصناعية على الشبكة العنكبوتية في مراقبة تشوهات وتحركات القشرة الارضية

الخلاصة

في السنوات الاخيرة، تقنيات نظم الملاحة العالمية وظفت لمراقبة تشوهات وتحركات القشرة الارضية حيث انها تتطلب دقة مكانية عالية. يمكن الحصول على دقة عالية لهكذا اغراض من خلال توظيف البرامج الذكية مثل (BERENSE, GAMIT, GIPSY) في معالجة بيانات منظومات (GPS/GNSS) لكن هذه البرامجيات الذكية معقدة الاستخدام وغير متاحة مجاناً. تهدف هذا الدراسة الى تقييم الحلول البديلة لتلك البرامجيات و التي توفر دقة عالية ايضا وبشكل مجاني. تم استخدام ارصدات المستلمات الارضية للاقمار الصناعية لمدة ثمان سنوات لمحطة الرصد الموجوده في طهران (TEHN) و التي تم الحصول عليها من موقع (UNAVCO) بشكل ملفات رصد يومية. بالاضافة الى معالجة بيانات تلك المحطات بخدمة المعالجة

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(CSRS-PPP) و المستندة على خوازمية (PPP) للمعالجة الدقيقة و خدمة (OPUS) المعتمدة على خوازمية المعالجة التفاضلية (DD). ان الغاية من المعالجة بالطرقيتين المذكورتين سلفا هي للمقارنة بين كفائة كل تقنية قي مجال تحديد سرعة حركة المحطة الرصدية الناتجة عن حركة الصفائح التكتونية و مراقبة تشوهات القشرة الارضية. من جهة اخرى، استخدمت حلول البرنامج الذكي (GIPSY) المتوفرة على موقع مختبر نيفادا الجيودسي (NGL) لاغراض التحقق من النتائج. جاءت النتائج لتظهر ان كل من خدمات المعالجة على الشبكة العنكبوتية (CSRS, OPUS) كفوءة بامتياز في تقدير سرع المحطات الرصدية. بالاضافة لذلك فان (CSRS) ذو دقة عالية في مراقبة تشوهات القشرة الارضية.
الكلمات الرئيسية : نظم الملاحة العالمية بواسطة الاقمار الصناعية، خدمات المعالجة على الشبكة العنكبوتية، سرعة حركة المحطة الرصدية، التشوهات القشرة الارضية, CSRS-PPP, OPUS.

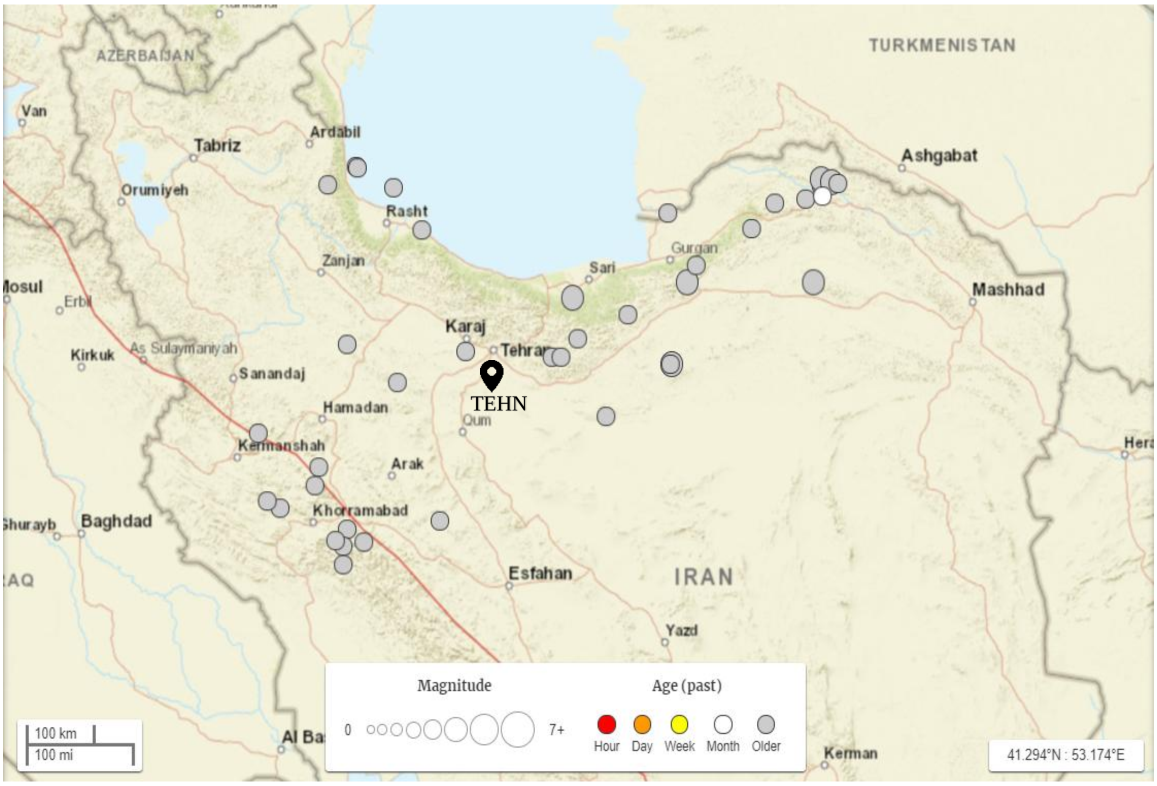
1. INTRODUCTION

Over the past few decades, lights have been shed on the employing of Global Navigation Satellite System (GNSS) for developing broad research in the field of Earth time variable, such as earthquakes, Earth surface deformation, changes in the global and regional mean sea level, tides, and tectonic plate movements. In other words, the dynamic characteristics of the Earth have been analyzed based on GPS satellite observations. However, the success of these applications depends entirely on the availability of precise position time series for GNSS stations' positions over a particular period. These time series can deliver enriched information concerning the positions and magnitude of these geophysical phenomena. It is worth to mention here that **Bossier, 1983** initially introduced the possibility of using GNSS for measuring the tectonic plate motion. He declared that it is no longer necessary to deal with the networks as a static system since the GPS presented. Additionally, this study stated that the crustal movements could be precisely detected and tracked using GPS technique efficiently. Consequently, the 1980s witnessed the first experiment of measuring the Earth crustal movement using GPS. **Hurst** and **Beavan, 1987** conducted the early investigation of the geophysical phenomena based on GPS in Southern California. Furthermore, **Dixon, 1993** assessed the relative motion of the Cocos-Caribbean plate's based on GIPSY software. Also, **Gill, et al., 2015** investigated the tectonic plate motion of Malaysia utilizing the Malaysian Real time Kinematic GNSS Network (MyRTKnet) and Malaysia Active GPS permanent Stations (MASS) using GPS/GNSS data over the period from 2001 to 2013. GPS/GNSS data were analyzed in **Gill, et al., 2015** study using Bernese GPS version 5.0. Furthermore, **Holden, et al., 2016** evaluated a campaign GNSS velocity field, which was derived based on an online Precise Point Positioning (PPP) service. Their study showed that the quality of the velocity estimates based on online service solutions could be used to measure the deformation, which is related to a variety of geophysical processes.
Consistent, accurate, and homogeneous positional time series can be produced very efficiently using GNSS scientific processing software, such as Bernese GPS software **Dach, et al., 2015** and GIPSY-OASIS **Zumberge, et al., 1997**. However, these sophisticated GPS/GNSS processing software have not been published and shared in the public domain as open-source software as they were built up for academic and scientific purposes. Nevertheless, there is an alternative solution to obtain this privilege for free, which is online processing services, for instance, CSRS-PPP **Mireault, et al., 2008** and OPUS **Mader, et al., 2003** and **Kashani, et al., 2008**. Thus, a comparison is needed to be drawn between these two services to figure out whether the online processing services are as effective as scientific software or not. The performance of CSRS-PPP and OPUS services are evaluated in this study via comparing their daily solutions with GIPSY-OASIS everyday solutions to reveal which positioning technique (PPP or DD) is reliable for geophysical applications in such remote region (non-CORS intensive).

2. CASE STUDY

This study is carried out based on the GPS/GNSS raw data of IGS station TEHN (**Nankali, 2016**). The station is mainly selected in this study due to two reasons. Firstly, the position of this station is nearby fault zone. Additionally, data availability. On the other hand, the second selected station ISKU have been neglected because of the lack of its data, which leads to forming gaps in the position time series and improper data representation.

TEHN station is located in Tehran, Iran, with geographic coordinates of lat. 35° 41′ 50.21″ N and



long. 51° 20′ 02.73″ E. Furthermore, TEHN station is located on the Iranian plate and departs from a fault zone (North Tehran Fault) by 11 km. The station TEHN was installed on the 1st of October, 1999, however, the online archiving for observations was started on the 1st of September, 2010.

Figure 1. Earthquakes activity in the study area. Credit: **pubs.usgs.gov**.

3. A BRIEF REVIEW OF ONLINE GPS/GNSS PROCESSING SERVICES

Online GPS/GNSS processing services are defined as web-based services that offer unlimited hourly/daily position solutions and freely available to users using two GPS/GNSS positioning techniques, PPP and Double Difference (DD). In general, there are many organizations and analysis centers, such as the Geodetic Survey Division (GSD) in Canada, Geohazards Division of Geoscience Australia, Scripps Orbit and Permanent Array Center (SOPAC) at the University of California, National Geodetic Survey (NGS), and the Jet Propulsion Laboratory (JPL) at National Aeronautics and Space Administration (NASA), which offer open-source services e.g. CSRS-PPP, APPS, MagicGNSS, OUPS and AUSPOS. Most of these services support Receiver Independent Exchange Format (RINEX) format. In addition to that, these services are freely available for unlimited usage.

It is worth to mention here that there are many studies which have discussed in details the concept of GPS/GNSS online processing services and their effective performance for producing precise positions. For instance, **Ghoddousi-Fard** and **Dare, 2006** presented an initial study regarding GNSS online processing services. What is more, **Tsakiri, 2008** conducted a study concerning GNSS observation processing based on GNSS online services in terms of horizontal and vertical accuracies and adequate occupation time for achieving a certain level of accuracy. Moreover, a detailed comparison of online processing services was drawn in this study.

4. METHODOLOGY

Initially, the daily GNSS observations of TEHN IGS station are gained using University NAVSTAR Consortium (UNAVCO) based on a graphical user interface which is known as Data Archive Interface (DAIv2). DAIv2 allows users to browse and download GPS/GNSS metadata and data. The TEHN GNSS observation data were processed twice using two different GPS/GNSS positioning techniques. The first processing technique is Precise Point Positioning (PPP), which is implemented in the Canadian Spatial Reference System-Precise point positioning (CSRS-PPP). The second processing technique is Double-Difference (DD) relative positioning, which is implemented in Online positioning user services (OPUS).

The algorithm of PPP was initially formed by **Zumberge, et al., 1997**. It implements an undifferenced pseudo-range and carrier phase observations of a single GPS/GNSS receiver. The PPP algorithm has been enormously applied to process the GPS/GNSS observations for different precise applications which necessitate a high level of accuracy. PPP has been considered as an alternative to DD technique due to reasons that it is simpler, very efficient in terms of the time of processing and cost and more accurate differenced observations

However, the precise application of the PPP algorithm requires specific satellite orbital information, Earth orientation parameters, and satellite clock correction estimates due to the reason that PPP implement of undifferenced observations. Consequently, the PPP technique has been considered by IGS and IGS analysis centers to evaluate the consistency and the homogeneity of their products periodically. Additionally, PPP has been made accessible for several years now using the Bernese GPS software, and the GNSS-Inferred Positioning System and Orbit Analysis Simulation Software (GIPSY-OASIS) developed at the Astronomical Institute of the University of Bern and the Jet Propulsion Laboratory (JPL), correspondingly.

In this paper, the terms 'TEHN _PPP' and 'TEHN_DD' are used interchangeably to mean the PPP solution for TEHN daily observations using CSRS-PPP service and the DD solution for TEHN daily observations using OPUS service, respectively.

However, the approach of processing GPS/GNSS observations based on web-based services suffers from some serious limitations. Generally, one major drawback of this approach is that these services deal with only single observations file (hourly or daily file), and the results are sent back to the users via email. Therefore, the users cannot process several sequential observations file to build up a position time series over a long period. Another problem with this approach is that it does not allow the users to fix the precise satellite orbital information and clock correction estimates to perform the processing scheme. This significantly affects the accuracy and the homogeneity of the position time series due to the inconsistency in the IGS products which have been generated since 1994 and till the present time. This inconsistency in the IGS products comes from different reasons. First of all, the IGS has produced such remarkable quality products in support of GPS for Earth science applications. What is more and valuable, since the end of 2006, there have been major developments in these by the improvement of models for absolute satellite and receiver antenna phase centers and the forming of atmospheric path delays. Secondly, periodic and regular modifications in the definition of the global geodetic reference frame have yielded to deterioration in the homogeneity and the consistency of the IGS products over time. Thus, the IGS ACs started in 2008 their first reprocessing campaign, which is called repro1, to reanalyze the fully IGS raw data, which have

been archived since 2994, utilizing the most recent models and methodologies. In 2013, the IGS ACs carried out the second reprocessing campaign (repro2), for further information, the authors guide readers to see IGS website www.igs.com.
After finishing the processing schemes, the TEHN _PPP and TEHN_DD solutions were reformulated to make them applicable to apply GPS Interactive Time Series Analysis (GITSA) where it only supports its native format (GTS) (Goudarzi et al., 2013). Therefore, a Matlab code, called POS2GTS, is developed by the authors and used to transform the TEHN _PPP solution into GTS format, whereas the TEHN_DD solution was converted to GTS format using Microsoft Excel. At the same time, GIPSY-OASIS solutions were downloaded from Nevada Geodetic Laboratory (NGL) and converted into GTS format to compare them with in-house solutions .

The generated position time series, the results are analyzed statistically to provide a comprehensive understanding concerning the homogeneity of the generated position time series.

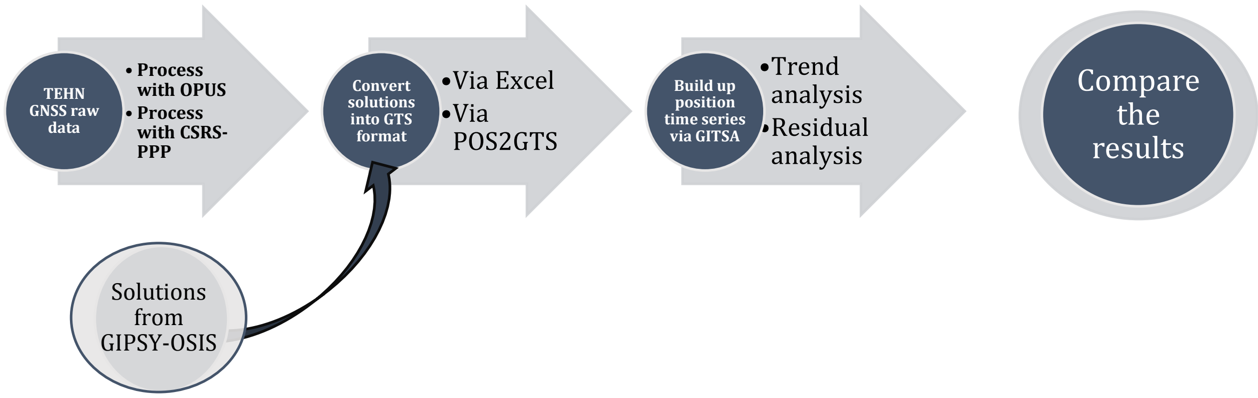


Figure 2. The workflow of the research paper.

Eventually, the position time series originated from GNSS online processing services (both CSRS-PPP and OPUS) are compared to the ones derived from scientific software (GIPSY-OASIS) solutions accordingly to station velocities and earthquake detection capability. **Fig. 2** demonstrates the workflow of the research paper.

5. POSITIONAL TIME SERIES ANALYSIS

Various statistical processes are performed in this study to enhance and clarify the position time series. Moreover, trend analysis is applied to these in-house position time series to examine the homogeneity of sequential daily solutions.
To clarify the position time series plots, outliers are detected and removed. It is essential to remove outliers before estimating linear velocities **Goudarzi et al., 2013**. Data interpolation is necessitated in this research because some data analysis processing approaches necessitate equally spaced data. Therefore, an interpolation method, which is the nearest neighborhood, was applied to generate the position time series.
Furthermore, a correlation coefficient (Person's coefficient) is assessed along with its P-values for all produced time series. Person's coefficient states the relationship strength between the position time series, i.e., describes the consistency in the daily solution accuracy. Person's coefficient P-values test the hypothesis of no correlation against the alternative that there is a correlation in position estimations. It is necessary to remove the trend from the time series before estimate the correlation coefficient.

Eventually, the residual analyses are performed to position time series to reveal its ability for detecting the seismic activity and the change of station equipment (receiver and antenna). The residual analysis presents the distribution of the solution residuals, which could conform with Gaussian distribution. This analysis employs Chi2 ($\chi 2$) to test the hypothesis of matching the residuals with the Gaussian distribution against the alternative hypothesis that states there is no matching between the distributions. Hence, the alternative hypothesis is delivered because of the uncertainty of solutions, the trend in time series data, and the effect of seismic activity. After removing outliers and trend from position time series, the alternative hypothesis represents that the Earth deformation will be detectable in the time series.

6. RESULTS

The position time series are estimated for TEHN IGS station using GNSS online processing services and GIPSY-OASIS scientific software. **Fig. 3** shows the coordinate time series of TEHN IGS station built up based on CSRS-PPP solutions. The time series plot reflects the tectonic plate movement in each direction. Hence, easting and northing components indicate the horizontal motion, and the up component gives an impression of the rate of the region subsidence. Moreover, the dashed line represents an earthquake or station hardware change. **Fig. 4** displays TEHN coordinate time series built up using OPUS solutions. Whereas, **Fig. 5** shows TEHN time series derived from GIPSY-OASIS software solutions. Additionally, **Table 1** demonstrates thethree-dimensional velocities of TEHN station from each positioning technique.

Table 1. TEHN station velocities estimated from each position technique

	Northing (MM/y)	**Easting (MM/y)**	**Up (MM/y)**
Based on OPUS solutions	20.429	25.083	-5.143
Based on CSRS-PPP solutions	21.429	25.832	-5.071
Based on GIPSY solutions	20.000	24.572	-3.815

Furthermore, the residual analysis for the position time series shows that the distribution of the residual from OPUS solutions conforms with Gaussian distribution and the $\chi 2$ value for each component do not exceed the critical value as shown in **Table 2**. Whereas the residual distribution of CSRS-PPP solutions do not match the Gaussian distribution and $\chi 2$ for each component exceed the critical value as demonstrated in **Table 2**. On the other hand, GIPSY-OASIS solution residuals distribute in a manner not similar to Gaussian distribution and $\chi 2$ values for each component exceed the critical value as shown in **Table 2**.

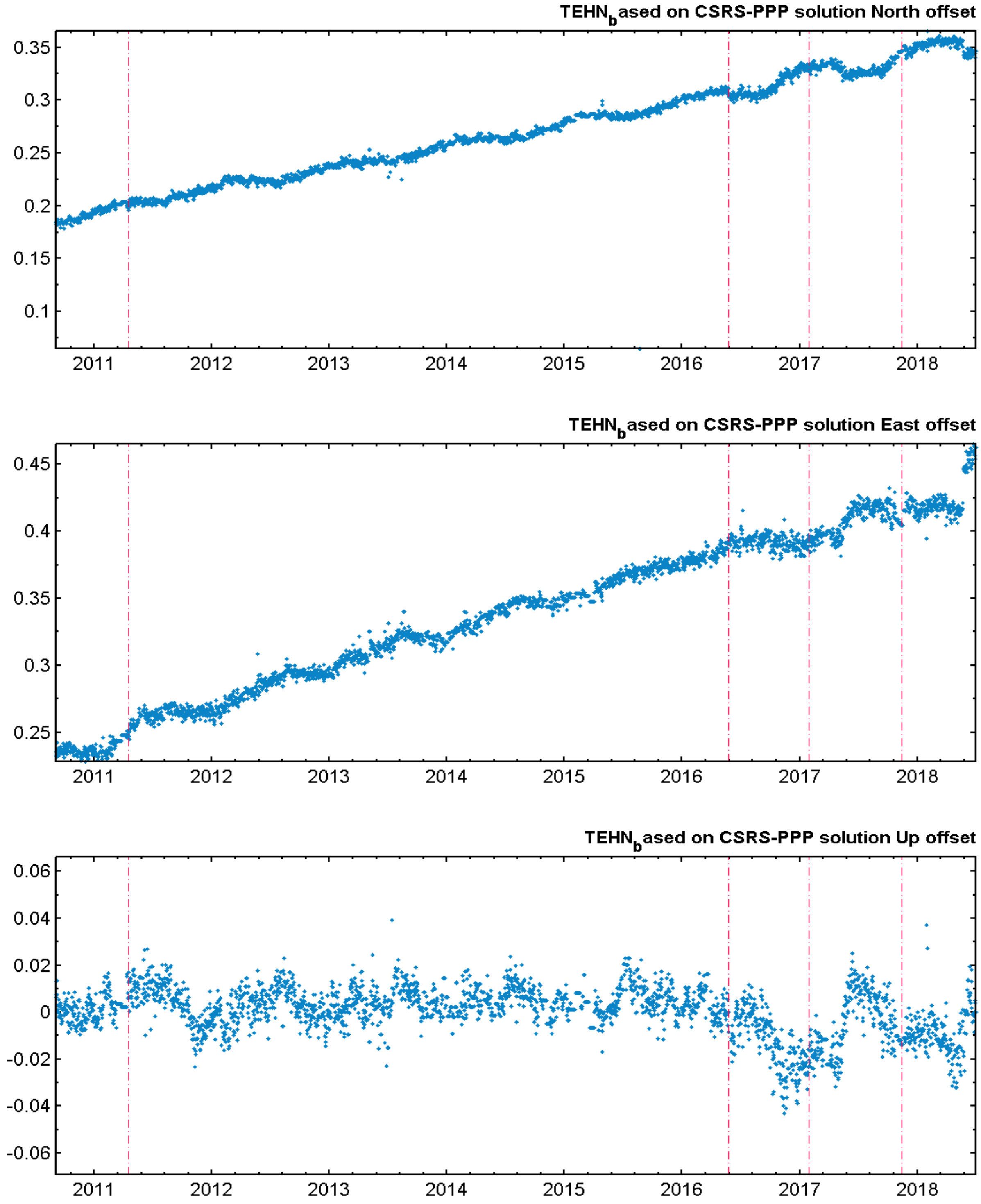


Figure 3. TEHN time series based on CSRS-PPP solutions

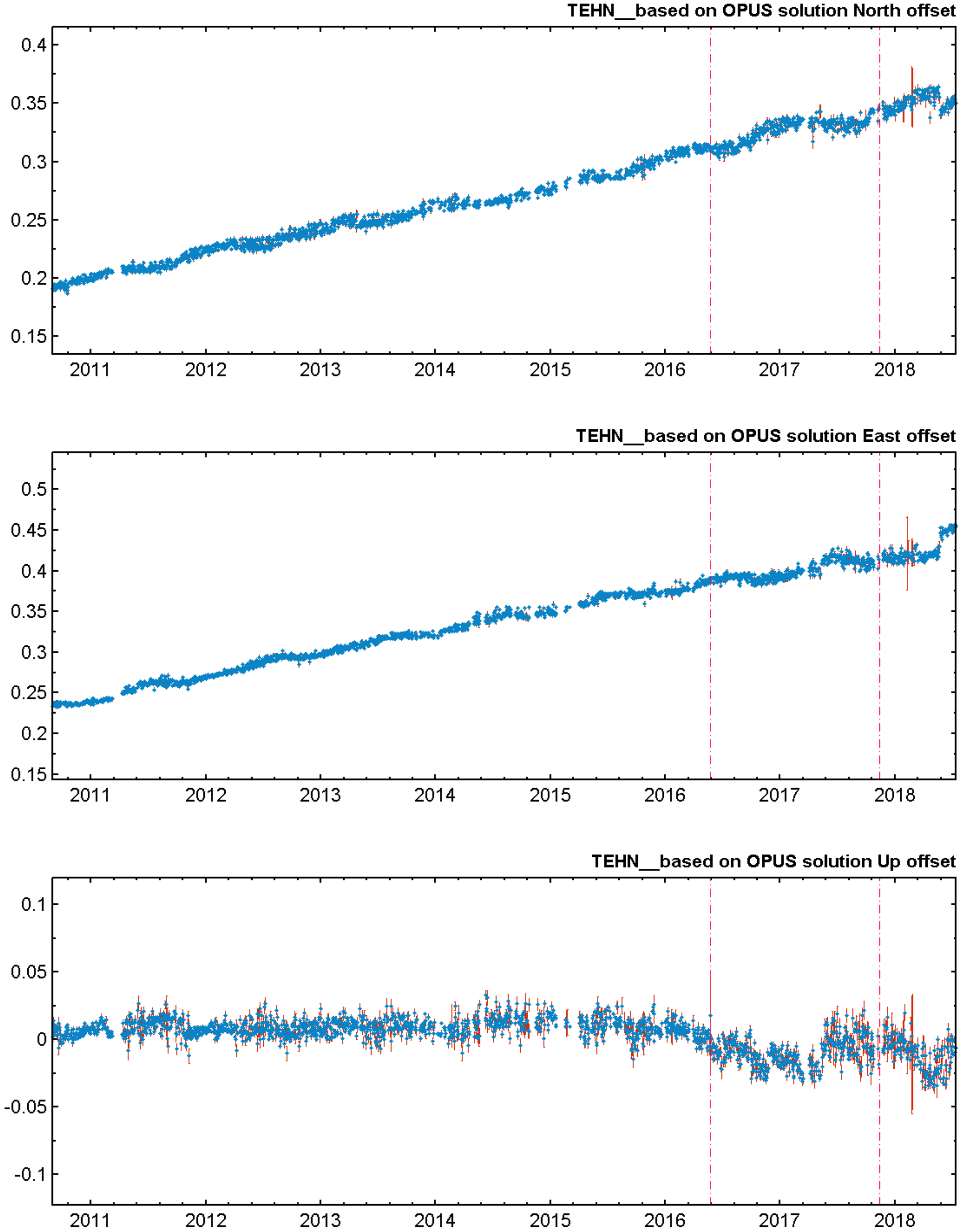


Figure 4. TEHN time series based on OPUS solutions.

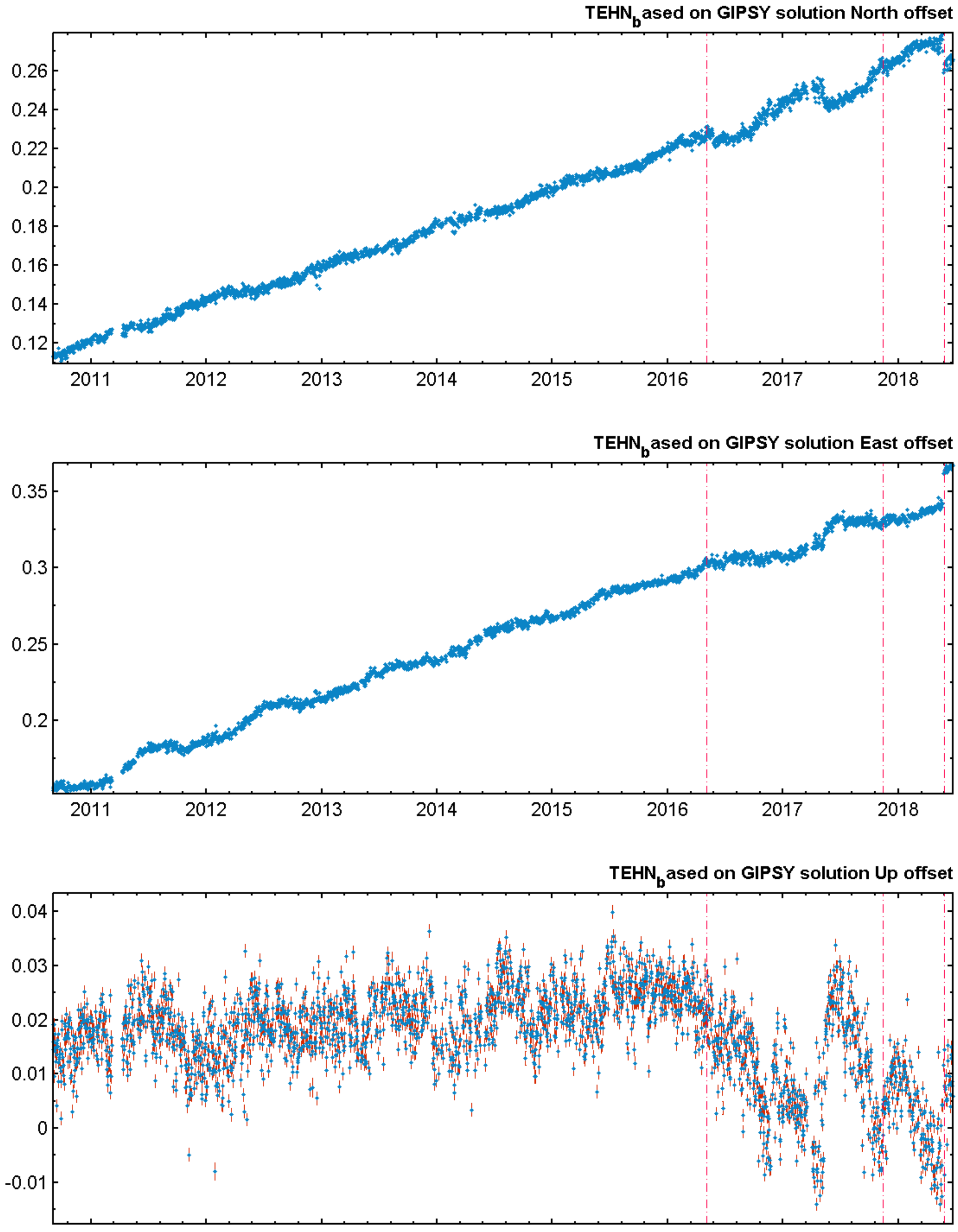


Figure 5. TEHN time series based on GIPSY solutions

Table 2. $\chi2$ for each solution residuals compared to its critical value

	χ^2 for northing	χ^2 for easting	χ^2 for up	Critical value
residuals OPUS solution	138.757566	163.294694	221.928764	248.334961
CSRS-PPP solution residuals	4.24319562	316.780039	9.05720825	257.878821
GIPSY solution residuals	289.770711	401.727605	290.305381	280.107749

Moreover, the solution residuals distribution from OPUS, CSRS-PPP, and GIPSY-OASIS techniques aredemonstrated in **Fig. (6, 7, and 8)**.

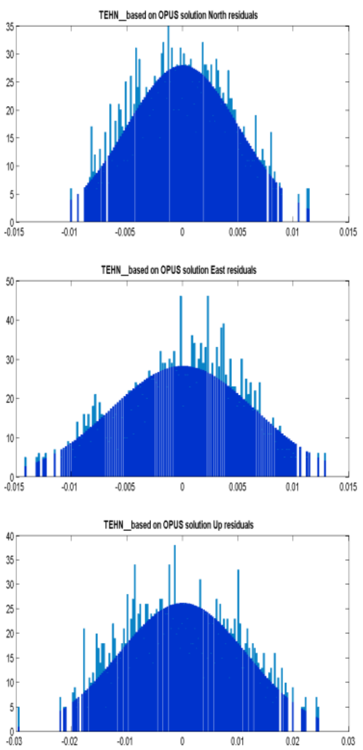


Figure 6. OPUS solution residuals distribution

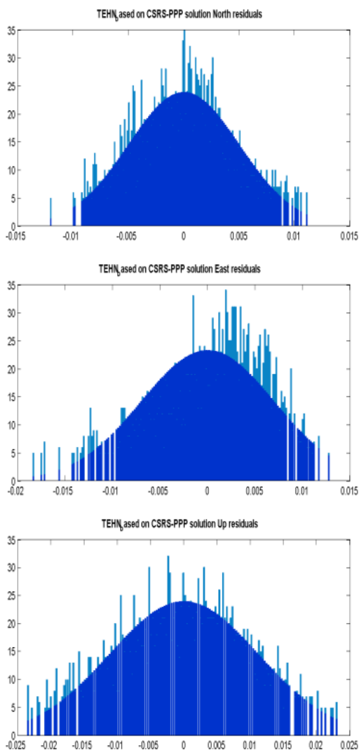


Figure 7. CSRS-PPP solution residuals distribution

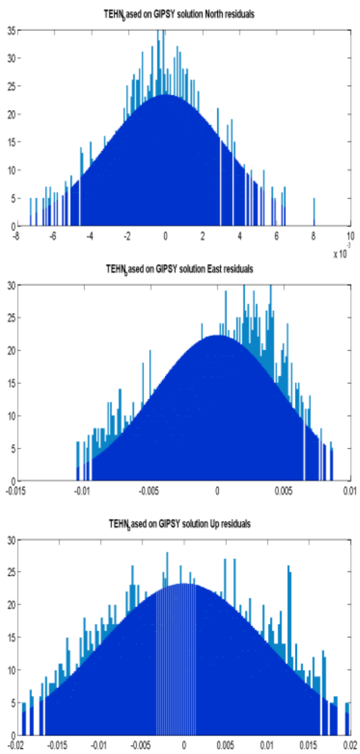


Figure 8. GIPSY solution residuals distribution

7. RESULT COMPARISON

Fig. 1 shows that the time series produced from all positioning technique solutions can detect station hardware change and earth changes at a specific range of distance and magnitude. However, the residual analysis results indicate that the least potential of detecting earthquakes or station hardware change is the time series that built up using OPUS solutions. On the other hand, time series produced based on CSRS-PPP solutions deliver a good potential of detecting changes in the earth crust and station hardware. Nevertheless, the latter is less potent than the time series built up based on the scientific software, GIPSY-OASIS, solutions.

On the other hand, the velocity of TEHN station estimated based on OPUS solutions are more accurate than that delivered based on CSRS-PPP solutions. However, there is an only slight difference in the estimated velocities based on each technique. Therefore, CSRS-PPP and OPUS can be considered as an effective technique in estimating station velocity.

8. DISCUSSION AND CONCLUSION

The results show that the OPUS solutions are not effective like CSRS-PPP and GIPSY-OASIS solutions in earth deformation studies. There are two reasons behind that deficiency. Firstly, TEHN IGS station is located in a non-CORS intensive region that makes it necessitate baseline observations of length exceeding thousands of kilometers, which degrade the quality of the results achieved based on DD. Secondly, OPUS does not provide the standard deviation within the daily solution report, the matter that necessitates the manual computation of standard deviation. Each three successive daily solutions have been involved in executing standard deviation values. This is likely to eliminate the effect of slight deformations of the Earth crust.

Moreover, the solutions of GIPSY-OASIS, which is scientifically indicated as high accurate GNSS processing software, have been compared to GNSS online processing services (CSRS-PPP and OPUS) in term of station velocity estimation and the results show there is no significant difference as demonstrated in **Table 2**.

Lastly, both GNSS online processing services (CSRS-PPP and OPUS) are credibility efficient to estimate station velocities, while CSRS-PPP worth trust service for monitoring the Earth deformation.

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