INVESTIGATION THE ARABIAN TECTONIC PLATE MOTION USING CONTINUOUSLY OPERATING REFERENCE STATIONS

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ABSTRACT

Due to the continuous movements of the tectonic plates, plenty of studies have been carrying out to estimate the tectonic plate movements and detect earthquake activities. However, these studies have become more precise, easier, and more applicable owing to the advent of the Global Navigation Satellite Systems (GNSS) in addition to the existence of dense networks of Continuously Operating Reference Stations (CORS). What is more, the GNSS raw data, generally, can be processed and analyzed using Double-Difference and Precise Point Positioning (PPP) techniques to hourly, daily, and weekly solutions. These solutions are based for producing accurate and consistent position time series over a long period of time to estimate tectonic plate movement in relation to its seismic activity. What is more, different analysis software has been enormously used to build up position time series, such as GITSA for analyzing and generation GPS time series and computing the velocity vectors. The current study aims to investigate the Arabian tectonic plate motion based on only online web-based GNSS processing software. Consequently, CSRS-PPP is applied, the current study, to process the raw daily observation data of the Iraq CORSs for Erbil city (ISER) city over the period from November 2008 to January 2018 and Najaf city (ISNA) over the period from July of 2009 to January 2018. The produced GPS time series showed that the velocity vector of ISER city is 38mm/yr. in a direction of N 40° 48'E, and the velocity vector of ISNA is 40mm/yr. In a direction of N 45° 06'E. The findings of the current study showed remarkable agreement with the horizontal velocity which was estimated based on the geodetic studies.

Keywords: GNSS, Arabian tectonic plate motion, CORS, GNSS online processing services, CSRS-PPP, GITSA.
Investigation The Arabian Tectonic Plate Motion Using Continuously Operating Reference Stations

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1. INTRODUCTION
The geodesists define the geodesy as the science of determining the shape, size, and the orientation of the Earth and its gravitational field. Additionally, the science of geodesy deals with monitoring the continuous deformation of the Earth's crust which is distributed into a number of tectonic plates. The tectonic plates are a scientific geological theory that was developed in early of the 1960s, to describe how the lithosphere, which is the rigid external shell of the Earth, is divided into tectonic plates. The geologists defined the tectonic plates into eight main plates and many minor plates, which constitute the Earth's lithosphere [1]. The relative motion between any adjacent plates defines the type of the boundary, such as divergent, convergent or transform. Mountain-building, earthquakes, volcanic activity, and oceanic moat formation happen along the plate boundary (or faults). However, the relative plate movement usually varies from 0 to 100 millimeter per year.

With the remarkable advent of the space geodesy, many studies have been performed to give a precise estimation for the velocity and direction of the tectonic plate movement, as well as to detect earthquakes. Furthermore, such of these studies on the Earth's deformation have become more precise, easier, and more applicable in comparison with the studies that based on classical geodetic surveys as a result of the significant development of space geodetic techniques, for instance Very Long Baseline Interferometry (VLBI); Satellite Laser Ranging (SLR); and Global Navigation Satellite Systems (GNSS).

The GNSS indicates into a constellation of satellites emitting navigation signals to the GNSS users for providing positioning and timing services [2, 3, 4]. Gandolfi et al. (2016) [4] stated that the GNSS has been widely used for positioning and particularly for the geodetic and geodynamic application. In addition to the existence of dense networks of Continuously Operating Reference Stations (CORS). The high accuracy of the position of CORS makes it the most suitable tool for precise geodetic applications, for example, long-term monitoring of the land movement. The position time series can be generated effectively using GNSS raw data of CORSs to show seasonal displacements in the vertical and horizontal orientation of the Earth's crust. Consequently, the displacement estimates can be presented precisely regionally and globally for all CORS positions on all continents [5]. Typically, displacement is defined by an annual and semi-annual period and is usually more dominant in the vertical positions than the horizontal positions [6,5,7]. On the other hand, both the Double-Difference (DD) and Precise Point Positioning (PPP) positioning techniques can be efficiently applied for processing the GNSS raw data and producing highly reliable solutions which in turn can be utilized to produce consistency, precise, and homogenous position time series over the whole period of interesting time. What is more, different analysis software has been enormously used to build up position time series, such as GITS A for analyzing and generation GPS time series and computing the velocity vectors.

1.1. The Arabian Tectonic Plate
The Arabian plate is one of three continental plates (the Arabian, African and Indian Plate) that are connected and formed the portion of Gondwana as shown in Figure 1 [8]. It is positioned within western Asia and it is a homeland for countries of the United Arab Emirates, Iraq, Bahrain, Kuwait, Qatar, Saudi Arabia, Yemen, Oman, Syria, and Jordan [9].
Since approximately 25 million years (pre-Miocene), Arabian plate separated from Africa and this separation led to the closure of the subduction Tethys Sea in the northeast [10]. The rifting of Arabia and Africa unlocked the Red Sea as that the Gulf of Aden, bordering the plate on the south-west and southern sides, respectively. The Owen Fracture Zone is bounded to the east, and the spreading half rate of the Red Sea approximately 10mm/yr. The belief prevailed that the Aden Gulf is a propagating rift opening westward at a rate of nearly 3 mm/yr. [11]. Because of the Red Sea is continuously opened up, the Arabian plate finally crashed with Eurasia and this crash zone is delineated by the mountains of Zagros. A limitation rate of mountain chain is 9 ± 3 mm/yr. in the south-east and 5 ± 3 mm/yr. in the north-west [12]. In the west, the Arabian plate is boarded by the Dead Sea transform fault that has experienced about 107 km of left-lateral movement since the mid-Miocene, [11]. The present location of the Arabian plate is shown in Figure 2.

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\text{Figure 1: Pre-Miocene location of the Arabian tectonic plate}
\]

\[
\text{Figure 2: The post-separation site of the Arabic tectonic plates}
\]
1.2. Precise Point Positioning (PPP)

The Global Navigation Satellite System (GNSS) observations have been employed for the purposes of monitoring the land movements over long periods of time [13]. The Precise Point Positioning (PPP) technique is a recent positioning approach which is significantly different from conventional differential GNSS positioning technique. In general, a stand-alone GPS/GNSS receiver can provide an instantaneous position with a low level of precision. Nevertheless, PPP technique with a single receiver can realize accurate positions without the need for simultaneous GNSS observations with other stations or real-time connection to differential corrections, which are computed by regional GNSS reference stations [14]. The theory of PPP comprises determining three-dimensional coordinates of a single receiver utilizing carrier phase and pseudo-range measurements, along, precise satellite orbital information, satellite clock estimates, and atmospheric propagation models received from a global network. As a result, the PPP represents the unique precise positioning technique which is possible to be implemented in isolated areas and remote locations for monitoring the landslides and the crystal's earth deformations due to different natural hazards [15, 16, 17]. In this study, the free online service CSRS-PPP software was implemented to process all the daily raw GNSS observation data. CSRS-PPP software was developed by the Geodetic Survey Division of the Natural Resources Canada (NRCan). It is a web-based application used for single GNSS receiver positioning.

1.3. GPS Interactive Time Series Analysis Software

The position time series is a graphical presentation that shows how the horizontal and vertical positions vary over time, and each dot in the position time series represents the daily position of the GPS site. In geodetic and geodynamic studies, time series analysis has an essential role, particularly when uninterrupted GPS observations are utilized for investigating wide regions with a low percentage of deformation. Therefore, having robust and precise tools for processing the raw GPS/GNSS data and analyzing the position time series is indispensable. For satisfying these requirements, an open-source scientific software package, which is called GPS Interactive Time Series Analysis “GITSA”, was developed utilizing the MATLAB programming language. The Center for Research in Geomatics (CRG), Laval University, developed the GITSA software [18]. GITSA provides a large number of algorithms that have been verified and made ready-to-use for data analysis approaches, such as statistics and quality parameters. Additionally, it has the capability of reading and visualizing various time series forms, detecting and eliminating outliers, interpolating jumps data, creating statistical estimates, and producing quality graphical outputs. Moreover, bivariate statistical analysis (e.g., curvilinear and nonlinear regression, correlation coefficients), spectral analysis and residual analysis set the foremost analysis features of the software.

2. STUDY AREA

The network of Continuously Operating Reference Stations (CORS), which is operated and controlled by the National Geodetic Survey (NGS), provides GNSS observation data continuously. In general, the CORS network is a multi-function cooperative effort comprising government and scientific organizations. The CORS' sites are owned, operated, and maintained by different agencies, which share their raw data with NGS. The CORS data consists of both of code range and carrier phase measurements for supporting 3D positioning, meteorology information, and geophysical applications across the United States in addition to some foreign countries. What is more, the CORS data has become essential for improving the precision of users' positions based on differential positioning technique. Moreover, CORS plays a vital role in enhancing the post-processing approach a centimeter or betters' accuracy.
for both of the horizontal and vertical coordinates relative to the National Spatial Reference System. There are seven CORS stations distributed in different parts of Iraq; these are; ISER, ISBA, ISSD, ISKU, ISNA, ISBS, and ZAXO. These CORSs were established initially for military purposes then offered for general civilian purposes. To achieve the aim of this research, two CORSs were selected, the first one is CORS-ISER, which is located in Erbil city, and the second one is CORS-ISNA, which is located in Al-Najaf city, see Figure 3. The ISER is still operating since 7th of July 2009, where the ISNA was established on 23rd of November 2008, and it is continuously operating till the time of writing this paper. Several reasons are taken into account for selection these two stations. The first reason is that both of ISER and ISNA have almost continuous GNSS raw data in comparison with other CORSs in Iraq over the period from 2009 to the end of 2017. The second reason is related to the differences in the geological situation of these two stations. The geological location of the ISNA, which is located on the stable shelf of Iraq, is considered to be more stable than the location of the ISER station, which is located on the unstable shelf near the thrust zone of Iraq [8]. That is means, the existence of a solid block to the west and southwestern of Iraq within the plateau of the Arabian Peninsula such it resists the ground movements and formation of the mountain chains in the surrounding areas. The presence of a very large sea called the Tethys Sea extends to the north of this mass consists of a layer of rocks less hardness of the first type, which helped to affect the movements of the ground. The divisions of Iraq close to the plateau of the Arabian Peninsula, which was submerged were less affected by the Torsional movements and the extension of the rocks of the plateau solid below it to maintain its spread such as sedimentary plain and desert plateau and adjacent sections of the rippling region or semi-mountainous. The farther away from the plateau, which is located under this sea, the more solid the base is below. The greater the distance from the solid mass is the greater the impact of ground movements on it [19]. Finally, several types of research in the field of geodesy and geodynamic have indicated to the successful application of permanent GPS/GNSS stations for long-term monitoring of the land deformation. The superiority in employing the GPS/GNSS technology for monitoring applications, in general, may be explained by the fact that using GPS/GNSS technique is relatively low-cost and require less effort in comparison with using classical geodetic surveys.

Figure 3 Positions of CORS-ISER and CORS-ISNA Stations in Iraq
3. METHODOLOGY

Four major steps were followed in this research to investigate the tectonic motion of the Arabian plate, see figure 4. Initially, based on CORS data availability, the CORS-ISER and CORS-ISNA were selected, and their daily raw GNSS observation data were downloaded over the period from July 2009 to the end of December 2017 for ISNA and from November 2008 to the end of December 2017 for ISER. The main source for this data is the National Geodetic Survey (NGS) through https://www.ngs.noaa.gov/UFCORS/, where all the CORS GPS data are being archived at 5-second sampling intervals using RINEX format. The second step is the processing scheme, which is performed in this study using an online web-based service. The Canadian Spatial Reference System (CSRS-PPP) tool is used in this study to provide daily PPP solution for each selected CORS. CSRS represent a geodetic tool, which has been provided by Natural Resources Canada’s Canadian Geodetic Survey (CGS) to provide precise horizontal and vertical positions and coordinate transformation. For more information, the reader is referred to Natural Resources Canada website (https://www.nrcan.gc.ca/). It is worth to mention here that CSRS-PPP employs the satellite orbital information and clock correction based on the IGS final products. The daily solution report for each processed GPS raw data, which is received via e-mail, delivers both of accurate point’s coordinates and corresponding standard deviation estimates. The third step involves the processing of generated position time series and presenting the changes in the three-dimensional coordinate using GITSA which has been developed using the MATLAB (V.2013a) programming language with Graphical User Interface (UIG). Additionally, GITSA applies further preliminary analysis and statistical processes in order to strengthen and clarify the produced position time series. Quality analysis was additionally performed for each station separately. Finally, the velocity vector for the Arabian tectonic plate is estimated based on the produced position time series and compared with the results of geodetic studies.

![Workflow of the methodology](image)

4. STATISTICAL ANALYSIS AND DISCUSSION OF RESULTS

Typically, GPS receivers record their position based on satellite communication once a day or so. The geodesists employ two techniques for investigation the tectonic plate motion based on
GPS/GNSS observations: position time series analysis and velocity vector estimates. To achieve the aim of this research, 2629 and 2379 raw GNSS observation daily files where processed for ISNA and ISER stations, respectively. The first GNSS observations of ISNA station covered the period from July 2009 to The first of January of 2018, where the second GNSS observations of ISER station covers the period from November 2008 to the first of January of 2018. All the raw GNSS data were processed using online CSRS-PPP to produce coordinate estimates (daily solution) over the whole periods. Each PPP daily solution contains a number of sub-daily solutions which are corresponding to the sampling intervals of the precise satellite orbital estimates used by CSRS-PPP software. Thus, the standard deviation for each PPP daily solution was computed based on the PPP sub-daily solutions in order to feed GITSA with required parameters. To achieve this transformation process, a Matlab code was built up to create the input data for GITSA in GTS format. Figure 5a shows the position time series for the North, East, and Up components for ISER and ISNA stations.

![Figure 5a Time series for North, East and Up Components](image)

The quality analysis was carried out for the position time series for each station separately. What is more, the trend analysis was also applied to examine the strength of the association between two variables, which are time and observations, by an individual parameter and is normally restricted to a rectilinear trend in bivariate data. The parameter or the "correlation coefficient" is usually employed at the beginning step of a statistical analysis as an earlier examination for linear relationships. Amongst various correlation coefficients in which GITSA calculate, Pearson’s coefficient was used in this study and the results showed that a strong positive relationship as shown in table 1.

<table>
<thead>
<tr>
<th></th>
<th>NORTH</th>
<th>EAST</th>
<th>UP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CORS-ISER</td>
<td>0.996074</td>
<td>0.998963</td>
<td>-0.353634</td>
</tr>
<tr>
<td>CORS-ISNA</td>
<td>0.978469</td>
<td>0.993144</td>
<td>-0.607030</td>
</tr>
</tbody>
</table>

Outlier analysis is performed with GITSA by defining the confidence level parameter. In this study, the confidence level is set to 95%. The identified outliers are fixed and removed in position time series for the north, east and up components. Figure 5b discriminates the
outliers, where figure 5c shows the position time series after removing the outliers. The results for two selected CORS stations are presented in the Table 2.

**Table 2** Detected Outliers and Standard Deviations Of ISER and ISNA Stations by GITS

<table>
<thead>
<tr>
<th>Station</th>
<th>No. of epochs</th>
<th>No. of Outliers</th>
<th>Detected Data As Outliers (%)</th>
<th>Max Standard Dev. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
<td>E</td>
<td>U</td>
</tr>
<tr>
<td>ISER</td>
<td>2629</td>
<td>36</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>ISNA</td>
<td>2379</td>
<td>91</td>
<td>89</td>
<td>32</td>
</tr>
</tbody>
</table>
Additionally, the BLKAVG method was used for detection jumps, however, it was detected that there are no jumps in the produced position time series. GNSS position time series for continuously operating reference stations often suffer from accidental or even uninterrupted missing data, as it could be one of its causes missing the communication link with the data center or malfunctioning of the GPS receiver, antenna, and data. So interpolation is essential to process due to the reason that some data processing approaches require equally spaced data. In this study, the interpolation method of the nearest neighborhood was applied to ISER as shown in Figure 6a and Figure 6b.

On another hand, there is a failure to carry out the interpolation method for ISNA due to the reason that the grid vector is not strictly monotonic increasing and there are huge gaps in the observations for more than two years, which is approximately from mid of 2013 to the mid of 2015. The velocity estimates are calculated for each CORS in the unit of millimeters per year.

5. COMPARISON

The present study was designed to determine the Arabian tectonic velocity estimates based on position time series which were generated for two Iraq CORSs. The results of this study were compared with A. O. Alothman and S. Schillak (2013) [20] and Muhamad Al Rajhi et al. (2014) [21] results which based on two different space geodetic techniques, SLR and GNSS, respectively. A. O. Alothman and S. Schillak (2013) [20] showed the findings of Riyadh SLR station solutions for more than fourteen years of activity and gave the absolute shift of the middle part of the Arabian tectonic plate. In 1995, the Saudi Arabia Laser Ranging Observatory (SALRO-7832) was established and set in the Arabian tectonic plate. To estimate Riyadh SLR stations coordinates and velocity estimates, Laser ranging observations of approximately twenty SLR stations, which are distributed globally, to two Laser Geodynamics Satellite (LAGEOS-1 and LAGEOS-2) over the period from 1996 to 2009 were gathered and processed. The NASA Goddard’s GEODYN-II orbital software was employed to accomplish orbit determination for these two satellites. The results obtained from the preliminary analysis of Riyadh SLR station are 31.6 ± 0.2 mm/yr, 29.1 ± 0.2 mm/yr, and 1.9 ± 0.3 mm/yr in the East, North, and Up components, respectively. Additionally, the resultant for the horizontal velocity was 42.9 ± 0.2 mm/yr. with an azimuth of 47.4 ± 0.8 arc degrees. Regarding the GNSS results, Muhamad Al Rajhi et al. (2014) [22] investigated the tectonic movement in Saudi Arabia and discussed different scientific applications such as the results of the velocity of the Arabian plate. Their research was partially accomplished based on the
outcomes of the precise positions for 13 Geodetic Fiducial Network (GFN-CORS) by studying the results of GPS/GNSS data which are archived for ten years period. The result pointed to a shift of 40.6 cm in the northeastern direction with a velocity of 41 mm/yr. Table 3 summarizes the comparison between the results of the current study and previous studies.

**Table 3**

<table>
<thead>
<tr>
<th>Geodetic Technique</th>
<th>Data Processing Method</th>
<th>Velocity</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSR</td>
<td>The NASA Goddard’s GEODYN-II orbital software</td>
<td>42.9 ± 0.2 mm/yr.</td>
<td>N40° 36’ E</td>
</tr>
<tr>
<td>GNSS</td>
<td>Geo++ GPS software</td>
<td>40.1 mm/yr.</td>
<td>N47° 24’ E</td>
</tr>
<tr>
<td>GNSS</td>
<td>online web-based GNSS processing softwareCSRS-PPP</td>
<td>39 mm/yr.</td>
<td>N43° 12’ E</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS

Using the GNSS processing services, which have been enabled as open source software, can be effectively applied in many surveying applications including high-precision studies without a need for comprehensive knowledge in GNSS processing software. In addition, the GPS Interactive Time Series Analysis (GITSA) represents an effective tool for generating precise position time series, analyzing the results using sophisticated statistical approaches, and provides instant visualization. Besides, a position time series analysis is very useful for detecting and identifying different errors and visualizing position variation during time flow. The results of this study showed a significant agreement with the results of other research related to investigating the velocity and direction of the Arabian tectonic plate motion using different geodetic studies. What is more, this study found that the horizontal velocity estimate of 39 mm/yr. in the direction of N43° 12’ E. In comparison with other studies which based on SLR and GNSS, there is a significant agreement of about a few millimeters. Finally, the findings reported here shed new light on long-term monitoring of CORS stations distributed in different parts of Iraq to produce precise position time series to give comprehensive explanations for the causes and effects of the recent earthquake activities which have been happened in the eastern border of Iraq.

REFERENCES


