Predicting Displacement Effects of Tectonic Movements on the Kenyan Geodetic Reference Frame Network (KENREF)

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Key Words: AFREF, KENREF, GNSS, plate tectonics, geodetic reference frame

SUMMARY

The East African Rift System (EARS) is a developing divergent plate boundary and Kenya lies on two tectonic plates: the Nubian plate to the west and the Somalian plate to the east. Studies show that the Somalian plate is pulling away from the rest of the continent that comprises the Nubian plate. Tectonic movements have an effect on a geodetic reference frame depending on the station velocities.

This research set out to investigate the current magnitude and rate of horizontal and vertical movements between the two blocks separated by the Kenyan Rift Valley by carrying out GNSS static measurements at selected Kenyan Geodetic Reference Frame (KENREF) stations. The GNSS data was then processed to determine the KENREF station velocities and the magnitude of tectonic movements and therefore deduce the effect of the tectonic movements on the accuracy of coordinates of the control network and in turn the survey measurements done based on these control stations. The results of this research will contribute to the definition of KENREF and African Geodetic Reference Frame (AFREF).

For this research the Zero Order KENREF Network station coordinates, although not published yet, were adopted as the reference for the study. The KENREF Network was observed and computed in December 2012, (a total of eighteen stations were observed in three sessions and each station was observed for at least five days)

A second epoch of observations was carried out in October 2019 using integrated geodetic grade commercial multi-constellation and multifrequency GNSS receivers. A total of five KENREF stations were selected for this research and observations were made for 24 hours at each of the five stations concurrently. Data analysis was done using Bernese version 5.2 and GipsyX software and the results obtained show that all the KENREF stations have an average horizontal displacement of 35mm/year. These results are consistent with IGS station velocities as computed by JPL. Two more epochs of observations will be taken at the same stations to validate the consistency of these results.

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1. INTRODUCTION

Plate tectonics, meaning "plate structure", is the theory that the Earth's outer layer is made up of plates, which have moved throughout Earth's history. This concept was formulated in the 1960s (Wolfgang et al., (2011)).

Plate tectonics theory deals with the dynamics of Earth's outer shell—the lithosphere (Earth's crust and upper mantle). It provides a uniform context for understanding mountain-building processes, volcanoes, and earthquakes as well as the evolution of Earth's surface and reconstructing its past continents and oceans (Wolfgang et al., (2011)).

Plate movement is caused by the convection (heat transfer resulting from the movement of a heated fluid) of magma in Earth's interior. The heat source is thought to be the decay of radioactive elements. Upwelling magma at spreading centres pushes the plates, whereas the weight of a portion of a subducting plate (one that is forced beneath another) may pull the rest of the plate along.

Plate tectonic movement can be estimated from two lines of evidence; **geologic and geodetic** (Wolfgang et al., (2011)).

Geologic Plate Motion; Three different geologic methods help determine the trajectories of plates: paleomagnetic, geometric and seismic. Paleomagnetic method is based on the earth's magnetic field. The ocean floors are a key piece to the puzzle. Because the ocean-floor magnetic striping records the flip-flops in the Earth's magnetic field, scientists, knowing the timings of magnetic reversals, can calculate the average rate of plate movement over time spans of several million years.

Plate tectonics was born from the sea, and the magnetic "barcode" remained the unique geological watch to measure plate velocities for decades until the advance of space geodesy.

Geodetic Plate Motion; Geodesy allows the measurement of plate motion directly using GNSS technology. The longer the GNSS observation period, the more accurate it is to estimate plate motion.

Because plate motions are global in scale, they are best measured by satellite-based methods. By repeatedly measuring distances between specific points, it is possible to determine the movement along faults or between plates. Space-geodetic data have already confirmed that the rates and directions of plate movements, averaged over several years, compare well with rates and directions of plate movements averaged over millions of years. GNSS can also be used to measure within plate motion.

The Great Rift Valley is part of an intra-continental ridge system that runs from Ethiopia in the north to Mozambique in the south and continues to the Antarctica plate (Chorowicz, J., (2005)). In the middle, it is divided into two branches; the Western branch that passes through Uganda

(Lake Albert) and Tanzania (Lake Tanganyika) and the Eastern branch also known as the Gregory Rift, which cuts across Kenya from Lake Turkana in the north to Lake Magadi in the Southeast, and then crosses over into Tanzania (Chorowicz, J., (2005)).
The East African Rift System (EARS) is still active as evidenced by an increase in volcanic activities in the Eastern Africa region and the Afar Triple Junction in Ethiopia (Kendall et al., (2016)).
National geodetic datums that span tectonic plate boundaries and deforming zones are subject to distortion which increases in magnitude over time. KENREF is not an exception because its network stations fall on two tectonic plates (Nubia and Somalia, separated by the Rift Valley). Attempts have been made to quantify the annual spread of the Kenyan Rift Valley (Waithaka, H.E. (2004)).
Five KENREF zero order network stations were selected for this study (see figure 2 and 3), because these stations are monumented as a concrete pillar in a concrete block on bedrock or soil and are stable. The legacy network stations (triangulation pillars) were not used since most of them have been destroyed and the few that exist were observed and computed as separate networks and therefore their accuracy cannot be guaranteed.

2. RESEARCH PROBLEM

Studies show that the African continent is made up of two major tectonic plates; that is the Nubian and Somalian plates (Saria et al., (2012)). The two plates are separated by the East African Rift System (EARS), a divergent plate boundary splitting the African continent in a north-south direction from Ethiopia to Mozambique.
Geodetic reference frames are defined based on plate boundaries in order to overcome the challenge of frequently computing new coordinates for the network stations as a result of plate motion. Coordinates of locations on plate fixed datums do not change because as the tectonic plates move the datum moves as well. The European Geodetic Reference Frame (EUREF) is defined based on stations that are fixed on the Eurasian plate, the African Geodetic Reference Frame (AFREF) was computed based on GNSS data logged at stations located on the rigid Nubia plate (Combrinck, L., (2020)).
In Kenya, the new Kenya Geodetic Reference Frame (KENREF) consists of stations that are both on the Nubia and Somalia plates as well as on the floor of the Rift Valley. See Figure 2.
This study hypothesizes that since the Nubia and Somalia plates are moving apart and as a consequence Kenya's geodetic network stations will experience a spatial displacement. Studies done in Israel as reported by Hagi et al., (2017) and Taiwan (Ching et al., (2015)) emphasize the importance of defining a semi-dynamic geodetic datum for countries that lie on more than one tectonic plate. A semi-dynamic datum is one in which the station coordinates always refer to a specific epoch and do not change until the datum is updated.
To understand the effect of tectonic movements on KENREF, a study was carried out using GNSS observations recorded at five KENREF stations. This study endeavours to fill the highlighted knowledge gap by answering the following research questions.
(a) What is the current magnitude of horizontal and vertical tectonic movements in the Kenyan Rift Valley?
(b) What is the displacement effect of tectonic movements on the stability and spatial accuracy of geodetic network stations?

3. RATIONALE

The Survey of Kenya is currently working on the establishment of a new geodetic reference frame (KENREF) aligned to the International Terrestrial Reference Frame (ITRF). It is important to understand the dynamics of the Zero Order Network stations to be able to attain an optimal implementation of KENREF. GNSS measurements across the Rift Valley will help in detecting any tectonic movements and therefore aid in quantifying the net effect of the tectonic movements on KENREF.

The current land laws in Kenya; that is the Land Act 2012, the Land Registration Act 2012 and the Community Land Act 2016, require that all land being registered must be georeferenced. There have been efforts to georeference cadastral plans and maps but with little success because of the numerous and disjointed reference frames used in in the country. Once the integrity of KENREF is ascertained it will catapult the process of georeferencing of cadastral maps and plans because itis a uniform reference frame covering the entire country, similarly this will aid in operationalizing the digital/electronic land transactions.

In the recent past there have been instances where roads were closed down because a section of the road is sinking as a result of tectonic activities in the Rift Valley. A case in point is the Mai Mahiu – Narok highway, which was rendered impassable near Suswa because of subsidence, (Ombati, C., (2018)). This study intends to characterize an optimal deformation monitoring network in the Rift Valley that if implemented will support disaster preparedness whereby the monitoring network will act as an early warning system that can detect such activities in advance.

4. METHOD

4.1 GNSS in Measuring Plate Motion

The Global Positioning System (GPS) has been the most useful space geodetic technique for studying the Earth's crustal movements (Rodger et al., (2015)). By repeatedly measuring distances between specific points, one can determine the movement along faults or between tectonic plates. Space-geodetic data have confirmed that the rates and directions of plate movements averaged over several years, are in agreement with rates and directions of plate movements averaged over millions of years. To study plate motions, GNSS receivers are anchored firmly in bedrock and they record observations that are processed to estimate the rate of motion of the tectonic plates.

As the tectonic plates move the positions of GNSS stations on these plates move as well. Using GNSS observations, station coordinates are computed and consequently time series plots for the stations can be generated. Time series plots for each GNSS station can be broken down into three vector/directional components North - South, East – West and Up – Down (Height/Vertical movement) (https://sideshow.jpl.nasa.gov/post/series.html).

In the time series plots, the X-axis represents time in years, while the Y-axis represents the distance in millimeters that the GNSS station has moved. Time series plots show the change of position of the GNSS monument over time relative to ITRF. The time series plots are interpreted as follows:

- A positive slope for the north, east and vertical plots implies that the station is moving to the north, east and up respectively.
- A negative slope for the north, east and vertical plots means the station is moving south, west and down respectively.
- If the slope is zero for the north, east and vertical plots then the station is neither moving to the north, east nor up respectively, (the station is not moving at all).

In most instances, time series plots are interpreted as vectors, because they have magnitude and direction. For GNSS monuments, the vector's magnitude is the speed at which the station moves. The vector's tail is the starting location of the GNSS monument, the direction in which the vector points is the direction the GNSS station is moving while the length of the vector indicates how fast the GNSS station is moving. Equation 2.1 and 2.2 demonstrate how station speed and velocity are computed respectively.

$$\textit{Annual Station Speed in N/E/Up} = \frac{Change\ in\ Position\ in\ N/E/Up\ (mm)}{Time\ Difference\ (Years)}$$

Equation 2.1: Annual Station Speed

$$Annual\ Station\ Velocity = \sqrt{}(Annual\ \text{Change}\ in\ N/S)^2 + (Annual\ Change\ in\ E/W)^2$$

Equation 2.2: Annual Station Velocity

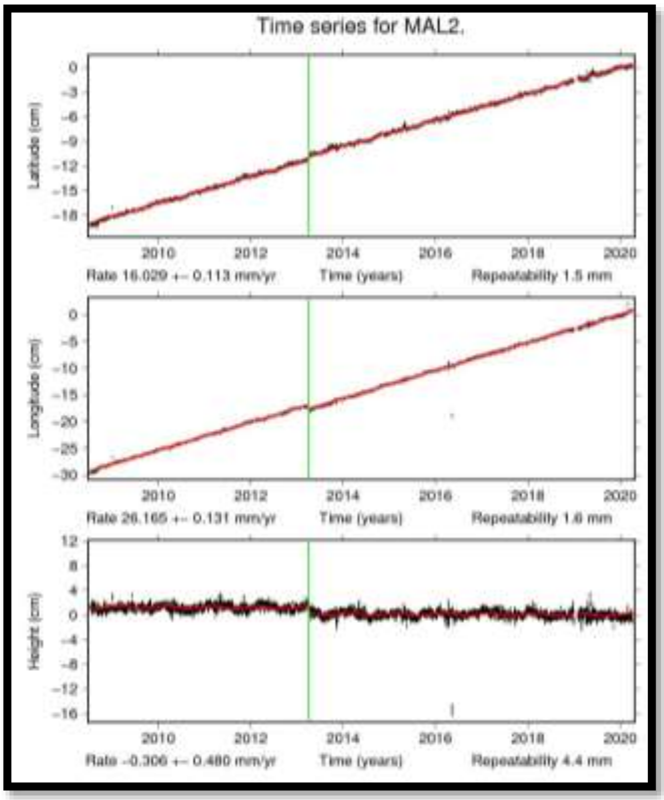

Figure 1: Time Series Plot for MAL2, Station in Malindi – Kenya
(https://sideshow.jpl.nasa.gov/post/series.html)

From the time series plots in Figure 1 the annual speed of MAL2 to the North = 16.029 mm/year, to the East = 26.165 mm/year while in the Height = - 0.306mm/year. This results in an annual station velocity of 30.684 mm/year in the North-East direction. See table 3 for computed IGS Station velocities for the past twelve years.

There are mainly two approaches proposed for collecting GNSS data for plate motion estimation;

1. Campaign or Epoch GNSS mode or
2. Continuous GNSS mode (Fernandes et al., (2004)

In campaign GNSS mode, the plate motion monitoring observation network is determined and the station markers established. GNSS measurements are made periodically at these stations after a pre – defined time interval also known as epoch to determine the stations' positions. During each visit portable GNSS receivers are installed on the station markers to collect satellite data for several hours or days (preferably). For the continuous GNSS mode, once the monitoring network is designed the identified network stations are monumented and fitted with permanent GNSS receivers that run continuously throughout the observation period; this could be for months or even years. This method provides temporally dense data that make it possible to measure displacement both during an earthquake and after (Limpach et al., (2016)). Establishment of the continuous GNSS monitoring network is costly because the GNSS receivers need a constant power supply (mostly solar power, since most of the monitoring stations are in remote areas) and a means to transmit the recorded data to the control center (this can be via GSM or LAN). For this study the campaign or epoch GNSS mode was adopted where GNSS receivers were set up on the five selected KENREF stations and data logged for 24 hours.

4.2 KENREF Stations

Figure 2 below shows the distribution of the KENREF Zero order network stations across the country. All the stations are concrete pillars in a block on bedrock (see figure 3). For this research a total of five stations were selected. Two stations on the Nubian plate (Kapenguria and Kilgoris), one on the floor of the rift valley (Eldama Ravine) and two on the Somalian plate (Maralal and Namanga).

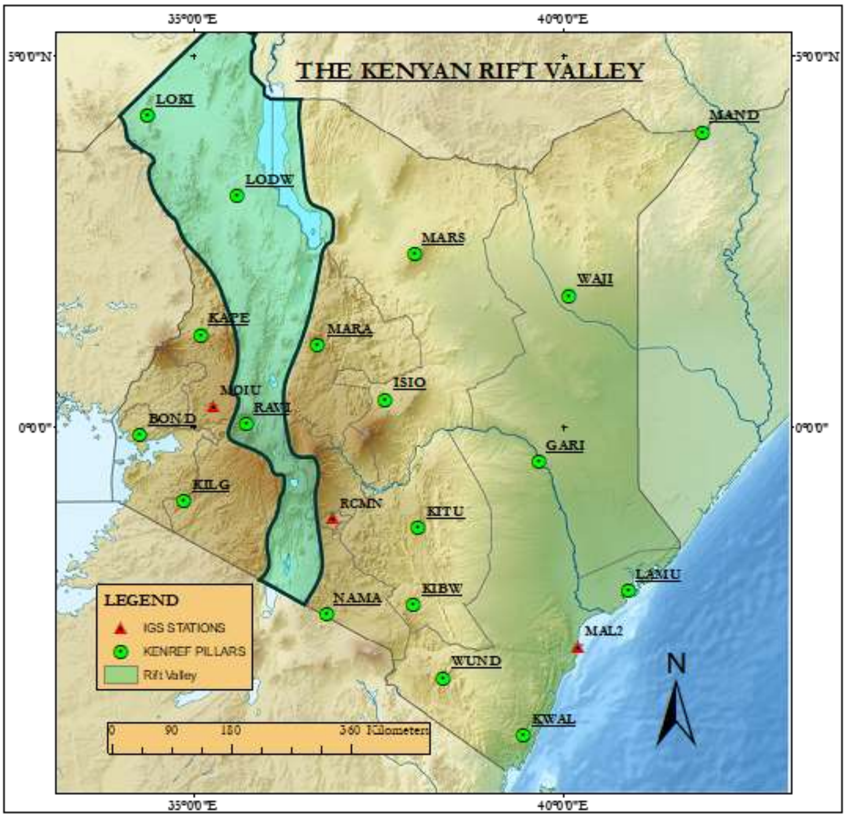

Figure 2: Selected IGS and KENREF Stations for GNSS Observation.

IGS stations within Kenya are Moi University (MOIU), Regional Center for Mapping of Resources for Development (RCMN) and Malindi (MAL2).

Eldama Ravine (RAVE)	Kapenguria (KAPE)

Figure 3: KENREF Pillars

4.3 GNSS Data Collection

Two sets of data have been acquired so far. The first set of data (referred to as the zero epoch) was obtained from the Survey of Kenya based on a GNSS campaign that was carried out over the eighteen Zero order KENREF stations across the country in November 2012.
The second set of data was obtained through a field campaign that was conducted on 16th and 17th October 2019 for 24 hours over five stations (Namanga, Kilgoris, Kapenguria, Maralal and Eldama Ravine). In this second campaign, the commercial geodetic GNSS receivers used were from one manufacturer in order to limit the introduction of errors in the final coordinates computed arising as a result of using different antenna calibration parameters.

4.4 Data Processing

GNSS static observations were carried out at a sampling rate of 1s, the data recorded was then converted to RINEX Version 2.11 format at a sampling rate of 30s; this is because the available IGS products and data for post processing are sampled at 30s, similarly, in order to compute the station coordinates in different software environments RINEX Version 2.11 was the accepted format. The RINEX file was further converted to Compact RINEX format using RNX2CRX software (HATANAKA Compression) before carrying out station coordinate computation. Namanga, Kilgoris and Eldama Ravine stations had one continuous file for the period of 24 hours while Kapenguria had 3 files and Maralal had several files since the equipment could only log static data for one and a half hours (this data was combined into one file using TEQC before processing).
KENREF pillars were occupied at all the selected stations except Kapenguria where there is a fire brigade office building being constructed one meter away from the pillar (see figure 3). The ongoing construction meant that in the next six months the pillar will be obstructed. The researcher therefore chose to carry out the observations on an Iron Pin in Concrete on the roof top of the County Lands Office.
The data obtained was processed using various software, in this case Bernese version 5.2, GipsyX, GAMIT/GLOBK and online processing engines; Natural Resource Canada – PPP (NRCAN) and Geoscience Australia Online GPS data processing service (AUSPOS)

GipsyX and NRCAN platforms compute the station coordinates based on Precise Point Positioning (PPP) approach, while Bernese, GAMIT and AUSPOS adopt the least squares adjustment of baseline vectors (carrier-phase relative positioning).
Based on recent research using latest software there is a better agreement between velocities obtained from Precise Point Positioning (PPP) and relative positioning. An agreement between the two velocity solutions in the order of 0.12 mm/year and 0.37mm/year for the horizontal and the vertical component, respectively has been found (Gianniou et al., (2019)). For both data epochs station coordinates were computed in International Terrestrial Reference Frame 2014 (ITRF 2014) (Altamimi et al., (2016)), to ensure uniformity of results obtained.
During station coordinate computation a number of corrections are applied on the input data as listed below:

- Ocean Tide Loading files
- Clock biases correction parameters
- Antenna calibration parameters
- Earth orientation parameters
- Ionospheric corrections.

5. RESULTS

This study aimed to answer the research question: "*What is the current magnitude of horizontal and vertical tectonic movements in the Kenyan Rift Valley?"*
The choice of the location of GNSS observation sites was dictated by the objectives of the study; namely, the need to quantify plate motion related to the rifting mechanism. In crustal deformation studies geodetic monuments must be relatively stable and safe since the parameters involved are in the order of millimeters. Random motion of geodetic monuments introduces uncertainties in the estimated station velocities, Hadley et al., (1995). To minimize the effects of these errors, the stations selected are established on stable platforms. See Figure 3.
A comparison of the computation results as obtained by Bernese Version 5.2 versus GipsyX for the November 2012 campaign data is shown in Table 1, which confirms that generally, same results are obtained as long as the computation parameters are the same irrespective of the software.

Table 1: KENREF Station Coordinates

Station	**KILGORIS (KILG)**		
Software	**X**	**Y**	**Z**
Bernese V5.2	5232802.924	3648104.249	-110900.879
GipsyX	5232802.926	3648104.248	-110900.876

Δ	-0.002	0.001	-0.003
Station	**NAMANGA (NAMA)**		
Bernese V5.2	5104032.895	3816587.219	-281430.803
GipsyX	5104032.894	3816587.214	-281430.796
Δ	0.001	0.005	-0.007
Station	**ELDAMA RAVINE (RAVE)**		
Bernese V5.2	5179435.705	3725800.340	5153.466
GipsyX	5179435.705	3725800.339	5153.468
Δ	0.000	0.001	-0.002
Station	**KAPENGURIA (KAPE)**		
Bernese V5.2	5217963.901	3668972.459	137989.397
GipsyX	5217963.908	3668972.460	137989.399
Δ	-0.007	-0.001	-0.001
Station	**MARALAL (MARA)**		
Bernese V5.2	5114971.488	3811537.774	120777.486
GipsyX	5114971.490	3811537.774	120777.486
Δ	-0.002	0.000	0.000

Table 2 shows the individual station displacement for the past 7 years. Based on this result there is an average horizontal station displacement of 35 mm/year. These results are consistent with computations of station velocities for a set of 12 IGS stations to the West and East of the EARS. Table 3 gives a summary of the annual station velocities for these IGS stations.

Table 2: KENREF ITRF 2014 Station Coordinates and Station Displacement for a period of 7 Years

Station	Epoch 1 (2012) – ITRF 2014 Station Coordinates			Epoch 2 (2019) – ITRF 2014 Station Coordinates			Station Displacements (mm) 2012 – 2019 (7 Year Period)			Annual 2D Displacement (mm/yr)
	X(m)	Y(m)	Z(m)	X(m)	Y(m)	Z(m)	ΔX(mm)	ΔY(mm)	ΔZ(mm)	
RAVE	5179435.7050	3725800.3400	5153.4660	5179435.4690	3725800.3710	5153.5930	236.00	-31.00	-127.00	34.004
NAMA	5104032.8950	3816587.2190	−281430.8030	5104032.6340	3816587.2520	−281430.6710	261.00	-33.00	-132.00	37.583
KILG	5232802.9240	3648104.2490	−110900.8790	5232802.7110	3648104.2940	-110900.7460	213.00	-45.00	-133.00	31.100
MARA	5114971.4896	3811537.7744	120777.4864	5114971.2260	3811537.8090	120777.5820	263.60	-34.60	-95.60	37.980
KAPE	5217963.9010	3668972.4590	137989.3900	5217979.5060	3668962.4310	138025.0810	-15605.00	10028.00	-35691.00	-

Table3: Annual IGS Station Velocities in the Nubia and Somalia Plates

Plate	IGS Station	ΔN (mm/yr)	ΔE (mm/yr)	ΔH (mm/yr)	2D (mm/yr)	3D (mm/yr)
Nubia (Western Plate)	**MOIU**	18.387	24.326	-0.979	30.493	30.509
	MBAR	17.595	24.329	-0.283	30.025	30.026
	NURK	17.743	25.296	-2.887	30.898	31.033
	ADIS	18.769	24.503	-1.512	30.865	30.902
	EBBE	15.536	25.19	-6.256	29.596	30.250
	DODM	17.504	23.746	-0.74	29.500	29.509
	ZAMB	18.586	20.01	0.89	27.310	27.325
	Average	17.731	23.914	-1.681	29.813	29.936
Somalia (Eastern Plate)	**MAL2**	16.029	26.165	-0.306	29.715	29.854
	RCMN	17.361	26.731	-2.187	29.671	29.830
	SEY1	11.96	25.07	1.483	29.496	29.658
	ABPO	14.594	18.785	-0.663	29.300	29.480
	VACS	11.236	17.174	-0.944	29.258	29.370
	Average	14.236	22.785	-0.5234	29.223	29.351

It is important to note the huge displacement discrepancies at KAPE (Kapenguria), in Table 2 are due to the fact that year 2019 observations at KAPE were not done on the KENREF pillar as was the case in 2012 because the site is now obstructed by ongoing construction (see Figure 3).

The average station displacements are organized according to the two plates. Although the overall average for the two plates is about 29.6mm/year, it can be observed that the stations in the western plate were displaced more than those in the eastern plate by an average of 0.6mm/year this implies that the Nubia plate is moving at a faster rate than the Somalia plate. The average continental displacement is also comparable with the preliminary average station displacements so far obtained of 35mm/year.

Based on the station coordinates in Table 2, interstation displacement (plate divergence) was computed and found to be 2.775 mm per year.

6. CONCLUSION AND FURTHER WORK

With continuous observations over several years, it is possible to analyze the temporal variations of the displacements and the displacement rates of geodetic network stations and this information is useful in the design and definition of a semi-dynamic geodetic reference frame.

Two more epochs of data collection and further computations will be carried out using online scientific GNSS data processing platforms for validation purposes.

GNSS Observations will also include existing legacy geodetic network stations in the country to estimate the current displacements on these stations and their effect on the accuracy of cadastral and engineering survey projects carried out based on the legacy network.

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BIOGRAPHICAL NOTES

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