Research Article

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GPS measurements on pre-, co- and post-seismic surface deformation at first multi-parametric geophysical observatory, Ghuttu in Garhwal Himalaya, India

DOI: <https://doi.org/10.1515/jogs-2020-0114>

Received August 27, 2020; accepted November 28, 2020

Abstract: We investigate the surface deformation pattern of GPS station at MPMO Ghuttu (GHUT) to find out the cause of anomalous behavior in the continuous GPS time series. Seven years (2007-2013) of GPS data has been analyzed using GAMIT/GLOBK software and generated the daily position time series. The horizontal translational motion at GHUT is 43.7 ± 1 mm/yr at an angle of $41^\circ \pm 3^\circ$ towards NE, while for the IGS station at LHAZ, the motion is 49.4 ± 1 mm/yr at $18 \pm 2.5^\circ$ towards NEE. The estimated velocity at GHUT station with respect to IISC is 12 ± 1 mm/yr towards SW. Besides, we have also examined anomalous changes in the time series of GHUT before, after and during the occurrences of local earthquakes by considering the empirical strain radius; such that, a possible relationship between the strain radius and the occurrences of earthquakes have been explored. We considered seven local earthquakes on the basis of Dobrovolsky strain radius condition having magnitude from 4.5 to 5.7, which occurred from 2007 to 2011. Results show irrespective of the station strain radius, pre-seismic surface deformational anomalies are observed roughly 70 to 80 days before the occurrence of a Moderate or higher magnitude events. This has been observed for the cases of those events originated from the Uttarakashi and the Chamoli seismic zones in the Garhwal and Kumaun Himalaya. Occurrences of short (< 100 days) and long (two years) inter-seismic events in the Garhwal region plausibly regulating and diffusing the regional strain accumulation.

Keywords: Convergence, Central Himalaya, Ghuttu, India, Offset time series

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1 Introduction

The subsurface kinematics that lead to an earthquake is very complex and a topic of immense research. Earthquake occurrence is directly related to plate tectonics, such that the movement of tectonic plates over the asthenosphere; but the mechanism which controls the generation of an earthquake is still not well defined (De Agostino and Piras, 2011). Crustal deformation and the associated rupture takes place when the accumulated strain exceeds a particular limit of bearing strength (De Agostino and Piras, 2011). Since 1970, a lot of research work has been reported towards earthquake prediction and scientists were confident that earthquake forecasting may be possible (Cicerone et al., 2009). This was mainly based on the results of first successful short term prediction of a Major M 7.4 Haicheng-China earthquake in 1975 (Adams, 1976). However; since then, there are no reported cases or concrete evidences of any short term earthquake prediction or forecasting. Short term earthquake prediction is extremely difficult and scientists are exerting hard to achieve this goal. Worldwide many researchers are working to identify earthquake precursors based on different geophysical parameters. These observations are such as -a seismic gap- that signifies the absence of particular size earthquake (mainly Major and above) in a seismogenic area for a long period (Papadopoulos et al., 2009) and -seismic quiescence- the temporal drop in seismicity below its normal level. The physical properties of the soil such as subsurface resistivity, radon emission, electro-magnetic field (Varotsos et al., 1993., Gladyshev et al., 2001; Richon et al., 2003; Dologlou, 2008., Konstantaras et al., 2008; Choubey et al., 2009), groundwater levels, chemical composition of groundwater, aquifers temperature (Choubey et al., 2009; Ryabinin et al., 2011), geodetic variations (Sobolev, 2011; Cirmik et al., 2016), ionospheric electron density and animal behavior are the well-known observations to understand the tectonic mechanism in the subsurface. Now a

days researchers are also considering real time and existing seismicity including advance analysis of seismicity in new time domain (natural time) for short term prediction of Moderate and Major Magnitude earthquakes (Murru et al., 2009; Uyeda et al., 2009; Varotsos et al., 2011; Tiampo and Shcherbakov, 2012; Sarlis et al., 2015).

Fig. 1. Base map (a) illustrates the seismotectonic setting of Ghattu region with earthquakes events of $M \geq 2.5$ for the period of 1999–2010 (Lyubushin et al., 2010; Kumar et al., 2012). Focal mechanisms of recent earthquakes are shown by beach balls and red stars represent the event considered for precursory signature. Inset (b) represents the map of India with International boundaries and black shaded portion shows the study area Garhwal-Kumaun Himalaya in Uttarakhand, India.

Topographical variations over the sub-surface geological structures along with occurrence of earthquakes in the Himalaya indicate the continuation of collision and subsequent convergence of India and the Eurasian plates with convergence rate increases from west to east along the Himalayan Arc (Banerjee and Burgmann, 2002). The entire Himalayan belt contains a very complex geotectonic setup. Major geological boundaries like the Himalayan Frontal Thrust (HFT), the Main Boundary Thrust (MBT), the Main Central Thrust (MCT), the South Tibetan Detachment (STD) and the Indus Tsangpo Suture Zone (ITSZ) exist nearly E-W throughout the Himalayan Arc, apart from N-S orienting non-Himalayan ridge like the Delhi-Haridwar (DHR) ridge (Fig. 1). In addition several minor tectonic faults are formed with local extent making the whole geological setup complex. Because of these major and local tectonic features in the Himalaya, the earthquake mechanisms are variable with location and size. Never-

theless, for earthquake precursory research, Wadia Institute of Himalayan Geology (WIHG) has established first Indian Multi-Parametric Geophysical Observatory (MPGO) in 2007 at Ghattu (30.53N, 78.74E), Garhwal Himalaya, Uttarakhand, India (Fig.1). The observatory is equipped with Multi-Geophysical high precision instruments, and continuously operating permanent GPS (GHUT) is one of the instruments that integrated with a Meteorological (MET) sensor. We used this tool to obtain pre-, co- and post-seismic surface positional anomalies for earthquake precursory research. In precursory aspect a few large magnitude earthquakes have been analyzed in the earlier works (Plotkin, 2003; Banerjee et al., 2005; Gahalaut et al., 2006; Borghi et al., 2009; Huang et al., 2009; Singh et al., 2009; Liu et al., 2010; Hasbi et al., 2011; Gautam et al., 2017, 2019; Yadav et al., 2019; Kannaujiya et al., 2020; Sharma et al., 2020; Saji et al., 2020) on the basis of geodetic measurements. But still there were no concrete scenario emerged toward the precursory signals using GPS data. In this work, we have analyzed continuous seven years of GPS data from 2007–2013 at GHUT station and processed using GAMIT/GLOBK software (King and Bock, 1999; Herring, 2002) in order to obtain the temporal variation of station positional anomalies. We also considered earthquakes occurred within and outside the strain radius with respect to the GHUT station during the period from 2007 to 2011 to understand the station characteristic temporal surface deformation.

2 Seismo-Tectonic Setting

The ongoing India-Eurasia tectonic collision has formed the Himalayan inter-plate zone that developed into numerous faults, folds, windows, nappe etc (Gansser, 1964). The continued deformation had formed wide spread tectonic features (Fig.1) named as ITSZ, STDZ, MCT, MBT and the HFT. These tectonic discontinuities have divided a nearly east-west extended Himalayan Arc into different geological subsections across the arc known as the Higher Himalayan Crystallines (HHC), the Lesser Himalaya (LH) and the Sub Himalaya (SH). The MPGO was established just south of the MCT on the northern margin of LH, where fossiliferous Riphean sediments (Valdiya et al., 1980) are present. The uppermost part of the crust at the hanging wall of the MCT is denoted as the Himalayan wedge that is being compressed and squeezed out between India and the Eurasian plates and seating above the Main Himalayan Thrust (MHT). The MHT is described as a detachment plane that separates the under-thrusting Indian

plate from the above strata of Himalaya. The whole region is highly deformed, but at present micro-earthquake activity is concentrated only in the central part, which aligned along the surface trace of the MCT (Kumar et al., 2012: Fig.1). This highly seismically active zone is described as the Himalayan Seismic Belt (HSB). The seismic data for the period from 1999 to 2005 was analyzed by Gitis et al. (2008) to obtain spatial models for seismicity and b-value. Lyubushin et al. (2010) did the seismic catalogue completeness of this region (minimum magnitude threshold) and observed along the strike variation of these parameters.

Almost all the earthquakes of higher magnitude ($M \geq 5.0$) in the Himalaya have occurred at a depth range of 15 to 20 km, and deeper and distributed around the MCT zone. The near MCT seismicity distribution mainly causing thrust tectonics in the detachment zone along the northerly dipping Indian plate and that mirrored as dominantly Thrust fault mechanisms in the Focal Plane solutions (Ni and Barazangi, 1984). Focal mechanisms plotted in Fig. 1 for the recent strong earthquakes in the Garhwal-Kumaun Himalaya region, also indicate thrust dominated mechanism. This part of Himalaya around the MCT is described as the transition zone (Bilham and Gaur, 2001) between the locked shallow portions of the fault that rupture during great earthquakes and would be smoothly sliding deeper zone without any earthquakes. It has also been observed that the present seismicity of smaller magnitude is mainly occurring at shallow depth above the detachment surface along the imbricate planes arising from the detachment zone around the MCT (Kumar et al., 2012).

The MPGO is located in the Garhwal Himalaya on the northern edge of the Lesser Himalayan sequence and has been known as a narrow region of concentrated seismicity centered in and around of the MCT (Arora et al., 2012; Kumar et al., 2013). This region of the Garhwal Himalaya lies in the central seismic gap where two Strong earthquakes have occurred named as 1991 Uttarkashi and the 1999 Chamoli earthquakes having magnitudes of M_b 6.6 and M_b 6.8 respectively. Banerjee and Burgmann (2002) also indicated that the region is locked and critically stressed to produce one or more great earthquakes.

3 Methodology and Data

In the region around the earthquake focus, it is supposed that the cracks are developed in the rocks during the earthquake preparation process under the influence of tectonic stresses. Dobrovolsky et al., (1979) developed relation for

the estimation of surface deformation around the epicenter zone. The relation is valid for a homogeneous isotropic medium where the shear modulus decreases. It mainly depends upon the earthquake size and is described by an equation below

$$\rho = 10^{0.43M} \quad (1)$$

where, ' ρ ' is the strain radius in km and ' M ' is the magnitude of the earthquake.

As per the Eq. (1), the zone of effective manifestation of the precursor deformation on the surface of the earth is a circle with the centre at the epicenter of the earthquake preparation zone. The investigation of anomalous changes in surface deformation is analyzed from the radius of the circle. In this study data has been analyzed by considering the following aspects, 1) although, the Dobrovolsky equation is valid for a homogeneous isotropic medium; but we attempted to implement it in the Himalayan region, where the geology is complex. We considered relatively bigger earthquake events ($M \geq 4.0$) in the data span from 2007 to 2011 and evaluated the strain radius. Accordingly, seven earthquake events of magnitude range from 4.5 to 5.7 (Table 1) shown with red star in Fig.1 are selected to identify their precursory signatures. 2) Our assumption is that if any GPS station lie within the strain radius, then the horizontal positional variation should be affected comparatively more with respect to those stations lie outside the ambit of the strain radius. Based on the aforementioned criteria five years of continuous time series data has been analyzed to understand the behavior of positional changes if the earthquake happens within or outside the ambit of the strain radius from the GHUT station. Analysis of daily time series of each year has been plotted individually in order to identify the precursory signatures in deformation from the anomalous changes in the time series.

3.1 GPS Data Acquisition and Processing

Continuous GPS data from the observatory is acquired since 2007 using Legacy E+ TOPCON receiver with CR3 geodetic choke ring antenna along with the MET sensor at two sampling intervals in 15 and 30 seconds at an elevation angle less than 12 degree. The geodetic antenna is erected on the top of a nine feet high concrete pillar situated on the summit of a hillock within the observatory premises with good site visibility and reception of satellite signals from all the 2π azimuth within the cutoff elevation angle. In the present work only 30 sec sampling interval data was analyzed. The pre-processing is done through TPS2RIN/TEQC available in the UNAVCO utilities

Table 1. Earthquake events, epicenter distance and estimated strain radius

E.Q Events	Date	Julian Day	Time (UTC)	Lat (N) (Deg.)	Long (E) (Deg.)	Focal depth (F_d) in km	E.Q Mag. (M)	Radius of E.Q Preparation Zone ρ in km	Epi. Dis. (E_d) from Ghut in km	Region
1	22.07.2007	203	23.02.12.0	31.2	78.2	33	5	141.25	64	Uttarkashi (Kharsali)
2	15.06.2008	167	03.27.26.5	29.6	80.2	33	4.5	86.1	152	Pithoragarh
3	15.05.2009	135	18.42.45.0	30.6	79.3	10	4.5	86.1	52	Chamoli
4	21.09.2009	264	09.43.47.0	30.9	79.1	13	4.7	104.95	64	Uttarkashi
5	22.06.2010	173	23.14.08.0	29.6	79.7	18	4.7	104.95	152	Pithoragarh
6	04.04.2011	94	11.31.40.0	29.6	80.8	10	5.7	282.49	225	Indo-Nepal Border
7	20.06.2011	171	06.27.18.0	30.5	79.4	12	4.6	95.06	52	Chamoli

software and post processing is performed with additional global IGS-GPS stations (POL2, KIT3, TEHN, BAH, BHR1, BHR2, HYDE, BAN2, IISC, LHAZ, KUNM and SELE) using the Linux based software package GAMIT/GLOBK (King et al. 1999) version 10.4 developed by the Massachusetts Institute of Technology (MIT).

Daily loosely constrained solutions from GAMIT were combined with permanent tracking solutions of global GPS stations (Herring 2002) archived at the Scripps Orbital and Permanent Array Center (SOPAC) and then processed by GLOBK. The basic algorithm and explanation on processing methodology are given by Herring and King (1990) and its application to GPS data is formulated by Feigl et al. (1993). The site coordinates and velocities of each site are estimated from these combined quasi-observations (Dong et al. 1998) with reference to ITRF08 (Altamimi et al. 2002).

4 Results and Discussion

Yearly time series at GHUT station for the period 2007 to 2011 is illustrated in Figs. 2[a-e] with the earthquake events mentioned as Day of Year (DoY) in the corresponding year. Estimated earthquake source parameters such as Magnitude (M), Focal depth (F_d), Epicentral distance / distance of GPS station from the earthquake epicenter (E_d) and strain radius (ρ) are also mentioned in the format of (M, F_d , E_d , ρ) in the Figs. 2[a-e]. Each figure consist of three sub plots with the top plot represents the N-S positional anomaly components, while the subsequent mid and lower plots represent the E-W and the vertical components respectively. Velocity estimation of GHUT station also shows an uncertainty of 1 mm/yr in the horizontal

component, whereas large errors are present in the vertical component. The base map (a) in Fig.3 the velocity estimate of GHUT station in ITRF08 reference frame is shown along with the ITRF08 velocities of IGS stations HYDE, IISC and LHAZ. The observed velocity at GHUT is towards NE-SW and in tandem with the direction of IGS station velocities in the global reference frame. The time series of GHUT station from 2007 to 2013 is shown at the left inset (b) and the respective yearly velocities in ITRF08 (Table 2) are shown as colored arrows in the right inset (c) of Fig.3. The red arrow pointing towards south is the velocity of GHUT with respect to the stable IISC (Fig.3, base map (a)). GHUT and LHAZ indicate their resultant horizontal velocities of 43.7 ± 1 mm/yr and 49.4 ± 1 mm/yr translational motion with rotation angle of $41^\circ \pm 3$ and $18^\circ \pm 2.5$ respectively (Fig.3, base map (a)). Shortening rates across Himalaya obtained in previous studies are within a range of 14-20 mm/yr (Bilham et al., 1997; Larson et al., 1999; Paul et al., 2001; Banerjee and Burgmann, 2002). The convergence rate of ~15 mm/yr is estimated in the Kumaun Himalaya by Ponraj et al., (2010), however in this study the estimated surface convergence rate at GHUT is ~12 mm/yr. In the present study we tried to pickup any significant changes before the earthquake occurrence and also analyzed the change in behavior in the horizontal position of GHUT after the earthquake. GPS data with earthquake epicenter and strain radius calculated based on Eq. 1 is assessed in the form of two case studies. In the first case study we considered the GHUT station is within the radius of earthquake preparation zone (ρ), while in the second case, only those earthquakes that are far from the station, and at greater distance from the radius of earthquake preparation zone.

Fig. 2. The horizontal and vertical offsets with uncertainty of GHUT are shown in the time series plots of the years 2(a) 2007 2(b) 2008, 2(c) 2009 2(d) 2010 and 2(e) 2011.

4.1 Case I: GHUT Station within ρ ($E_d < \rho$)

The distance of GHUT station from the epicenters of earthquake events 1,3,4,6 and 7 as mentioned in Table 1 and located within the earthquake preparation radius have been marked with the event numbers and shown in the time series plots in Figs. 2[a, c and e]. Figure 2a is a plot of three components of GPS time series for the year 2007 showing more secular rate of displacement in the north and east components with a few data gaps. Perceptible change in the slope of the trend line of the north offset is observed from DoY 125 to till the occurrence of event ‘1’ with Magnitude 5.0 on DoY 203. This shows a reduction in the pre-seismic velocity of station in the north component and was continued around 78 days before the event. Otherwise, re-

duction in the North component velocity had cause substantial accumulation of precursory strain, which got culminated and released as Magnitude 5.0 event on DoY 203. The post seismic relaxation phase is quite short around ten days and appears subtle; followed which, the velocity trend regain to its pre-seismic level. However, no co-seismic, pre- or post-seismic offsets are observed for the case of E-W and the vertical components. Figure 2c shows two earthquake events 3 and 4 that occurred within a span of 130 days at an epicenter distance of 52 and 64 km from GHUT on DoY 135 and DoY 264 with Magnitudes 4.5 and 4.7 respectively. Anomalous change in the trend of the N-S offset is observed around DoY 60 before the event 3 and encircled in Fig.2c. Similar, anomalous change in the north

Table 2. Velocity of GHUT station along with IGS stations in ITRF 2008

Long(E) (deg)	Lat(N) (deg)	East rate (mm/yr)	North rate (mm/yr)	Esig (mm/yr)	Nsig (mm/yr)	Result Rot. (deg)	Result Vel. (mm/yr)	Site code
2007								
91.10403	29.65733	46.05	15.19	0.3	0.25	18.26	48.49	LHAZ
78.74744	30.531	30	27.89	0.43	0.44	42.93	40.96	GHUT
78.55087	17.41726	42.09	31.6	0.29	0.26	36.92	52.63	HYDE
77.57038	13.02117	43.55	38.94	0.29	0.27	41.82	58.42	IISC
2008								
91.10403	29.65733	50.21	14.82	0.32	0.27	16.45	52.35	LHAZ
78.74744	30.531	28.63	27.73	0.37	0.37	44.11	39.86	GHUT
78.55087	17.41726	40.61	37.24	0.26	0.24	42.54	55.1	HYDE
77.57038	13.02117	42.08	35.82	1.12	0.79	40.43	55.26	IISC
2009								
91.10403	29.65733	43.02	14.19	0.31	0.26	18.26	45.3	LHAZ
78.74744	30.531	30.74	28.52	0.36	0.36	42.88	41.93	GHUT
78.55087	17.41726	41.25	35.03	0.33	0.3	40.36	54.12	HYDE
77.57038	13.02117	43.74	36.46	0.31	0.29	39.83	56.94	IISC
2010								
91.10403	29.65733	43.74	12.08	0.29	0.26	15.45	45.38	LHAZ
78.74744	30.531	29.64	24.5	0.37	0.36	39.60	38.45	GHUT
78.55087	17.41726	42.09	37.36	0.32	0.29	41.61	56.28	HYDE
77.57038	13.02117	42.57	37.43	0.31	0.29	41.34	56.69	IISC
2011								
91.10403	29.65733	41.93	15.72	0.35	0.29	20.56	44.78	LHAZ
78.74744	30.531	32.07	27.33	0.37	0.36	40.46	42.14	GHUT
78.55087	17.41726	39.82	36.58	1.54	1.2	42.59	54.07	HYDE
77.57038	13.02117	39.08	38.94	0.32	0.32	44.92	55.17	IISC

offset is also observed around 14 days before the event 4 and marked as circle in Fig.2c. These two events constitute a classic example which shows how the strain accumulation is taking place when the inter-seismic period is quite short, around 129 days. During the inter-seismic period the north offset trend line is sub-parallel to the time axis, which suggest reduced velocity or gradual increase in the strain accumulation till the occurrence of second event 4. The post seismic relaxation after the event 4 shows the regaining of slope of the trend line to the level before the occurrence of event 3. This suggests that the residual strain that might have accumulated after the event 3 has contributed to a short inter-seismic time period that leads to relatively earlier occurrence of the event 4. This also suggest that short inter-seismic period is an effective mechanism to relieve the accumulated strain energy as moderate earthquakes and there by diffusing the possibility of huge strain build up and subsequent development of Strong or Major magnitude earthquakes. However, the contribution

of strain build up in the east component is not as prominent as that of the earlier case. The north offset shown in Fig.2e shows two events having magnitudes 5.7 and 4.6 denoted as events 6 and 7 occurred on DoY 94 and DoY 171, respectively. In this case appreciable change in the offset slope or trend line (marked as circles) is observed around DoY 140 and become sub-parallel to the axial line on the day of event 7 and continued till DoY 225 before regaining the slope to the level of pre-event '6' on DoY 94. In this case the east offset also show a slight reduction in the slope around DoY 225. It is observed that the north component movement shows beginning of strain accumulation on DoY 140 during the inter-seismic period after the event 6 and lead to culmination and subsequent occurrence of event 7 on DoY 171. Here, the residual strain after the event 7 leads the post seismic relaxation phase of around 54 days and subsequently regained the strain level before the initial event 6. An interesting aspect is that both the north and

Fig. 3. In the base map (a) blue arrows pointing toward northeast show the station velocities in ITRF08 Reference Frame and red arrow pointing towards southeast is the velocity estimated for GHUT station with respect to IISC. Top-left Inset (b) shows the time series of GHUT and the right-below inset (c) illustrates yearly motion pattern of GHUT station (in color vectors) along with IGS stations in ITRF08.

east offsets show consistent change in the trend line at the end of the post relaxation phase around DoY 225.

4.2 Case II: GHUT Station out of ρ ($E_d > \rho$)

In this case, the earthquake events 2 and 5 are located at distances more than ' ρ ' from the GHUT station. The time series plot of year 2008 is shown in Fig.2b with the event of Magnitude 4.5 is marked as '2' and occurred on DoY 167. The initiation of shift in the pre-seismic trend line is observed concurrently in both north and east offsets around 42 days before (from DoY 125) the event of DoY 167, although the station is far from the ambit of strain radius. This pre-seismic shift is around 10 mm towards east and prominently observed in the east component, unlike the previous cases of north component. We also observed a sudden shift in the slope of the east offset just 12 days before the event. The post seismic relaxation phase appears quite steady for a duration of 26 days (en-circled in Fig.2b) till DoY 200 for both north and east offsets; but the shift is relatively larger in the east offset. Similarly, an earthquake event 5 of Magnitude 4.7 has been observed on DoY 173 and shown in Fig.2d. A slight sinusoidal shift in the positional anomalies on DoY 110 and DoY 150 in the East component, while less changes are observed in the North component before the earthquake event. However, we have noticed

more disturbances in the North component compare to the East component after the occurrence of event 5 (Fig.2d).

Our analysis suggests that changes in the behavior of horizontal offsets depend on the earthquake parameters, radius of earthquake preparation zone and the geology of the study region. Results, indicate definite pre-seismic positional anomaly changes about 72 to 75 days before the occurrence of a Moderate or larger magnitude events at MPGO Guttu as a precursory deformation. Although that needs to be established further through the analysis of long term deformation data and appropriate scaling of the strain radius and other source parameters. Nevertheless, the observations are promising, especially the occurrences of long (more than two years) and short (around 130 days) term Moderate or larger inter-seismic events in the study region. In fact, such inter-seismic events have a role in regulating the strain accumulation process and hence would be reducing the chances of a Major or a Great earthquake in the study region.

5 Conclusion

We attempted to understand the pre-, co- and post-seismic deformational characteristics through continuous GPS measurements with the objective to explore the plausibility of deformational precursory at the first Multi-parametric Geophysical Observatory in the north western Himalaya in Ghuttu (GHUT). GPS measured daily positional solutions at GHUT from 2007 to 2011 has been analysed by considering different magnitude earthquakes originated from different azimuths as well as from different strain radii from the GHUT station. To check the consistency of our processing we computed the observatory velocity (43.7 ± 1 mm/yr) with respect to ITRF08 reference frame along with the known IGS station LHAZ velocity (49 ± 1 mm/yr), and the results are found consistent within the error limit.

Yearly analysis of GPS time series for the case of those events that occurred within the strain radius showed that the GHUT station had consistently responded to north component offsets during the pre-seismic or the inter-seismic strain accumulation phases. Accordingly the events '1' and '3'; namely, the Uttarkashi (M 5.0) and the Chamoli (M 4.5) had occurred after a relatively long (two years) quiescent or a long inter-seismic period and produced nearly consistent pre-seismic duration of 78 and 75 days of deformational precursory. We have also observed a classic example of how short duration (130 to 77 days) inter seismic events could prevent the plausible

occurrence of very large magnitude earthquakes in the region as the case of events '3' and '4' in the Garhwal and '6' and '7' in the Kumaun-Indo-Nepal border regions, respectively. Similarly the post seismic relaxation phases are also observed at the GHUT station from the aforementioned earthquakes and lasted around 10 to 56 days. However, the shift in the station surface deformational anomalies caused by those far events (events '2' and '5' originated from Pithoragarh) from the strain radius show concurrent variation in the pre-seismic anomaly trend (initiated around 42 days before the events) of north and east component offsets; but with enhanced offset towards the east component. Our observations suggest that, in general the MPGO-Guttu is appropriately located to study the deformational precursory characteristics of those moderate or greater magnitude earthquakes that occurred within or outside the station strain radii in the Garhwal region; especially, from the well-known seismic zones in Uttarkashi and Chamoli in the Garhwal and Kumaun Himalaya.

Acknowledgments: Authors are thankful to the Director, WIHG for providing necessary support and encouragement. Authors are also thankful to Ministry of Earth Sciences, Government of India for sponsoring MPGO-EPR project and the staff of the project (MoES/P.O.(Seismo)/1(256)/2015) is thanked for data collection. Anonymous reviewers are thanked for constructive suggestions to improve the quality of the manuscript.

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