# A Study on Variation in Baselines B/W Indian Stations Due to Solid Earth Tides.

**Shray PATHAK and Dr. J. K. GHOSH, India.**

**Keywords:** Solid Earth Tides, Positional Variation, Surface displacements, Temporal Deformation.

## SUMMARY

In many geodetic analyses, it is important to consider the effect of earth tide on the instantaneous position of a station and its subsequent influence on the computation and interpretation of time series of coordinates as well as related data products. In this research work, effect and temporal variations in position of the IGS (International Global Navigational Satellite Systems [GNSS] Service) station at Hyderabad and some of the other Indian stations due to solid earth tide, has been carried out. Mean daily coordinates of the station has been computed using static precise point positioning (PPP) method for a month. Results show that the station undergoes temporal displacements and its coordinates varies continuously within a day and all the days in the month. It has been found that the tidal oscillations follow some periodicity, and thus need to be studied independently for all stations.

By Precise Point Positioning the variation in the position at a particular station is observed for a month of November 2013. Baseline distance is computed between the four Indian stations. Variation along baseline is observed by computing six baselines between four stations and when the effect is studied simultaneously for all baselines it follows a definite pattern. This shows that the effect on the coordinates of any nearby stations at a particular time is almost similar due to Solid Earth Tides. By studying the simultaneous effect between two stations with known baseline distance and the time taken by the tide (either high or low) to reach from one station to another, the propagation velocity of the Solid Earth tides can be computed. The propagation velocity helps in identifying the effect at any station if the effect at a known station for a particular time is known.

## 1. INTRODUCTION

Solid Earth Tides is a temporal deformation in the position of the point due to the tidal force. The tidal force is because of the presence of the heavenly bodies around the Earth. Solid Earth tide is the effect of the tidal force on the solid body of Earth. The tidal force arises because of the gravitational force between the Earth, Moon and the Sun and the centrifugal forces of the rotation system. Therefore it completely depends upon the position of the point with respect to the Sun and the moon. Due to the continuous gravitational force, the point faces continuous displacement which affects the coordinates on the daily basis. Due to the variation in the position of the stations it also affects the distances between the two stations and their baseline distances. Therefore due to the continuous variation, there is a high need to study the effect of Solid Earth Tides on any position and how this effect affects the base line.

The regular deformations on the solid earth can be calculated by knowing its elastic behavior. Love numbers are introduced to define the elasticity of earth (by Love, 1944), further described in Munk and MacDonald (1975).This technique expresses the radial and transverse displacement of a point on the Earth's crust in terms of Love and Shida numbers (h and l respectively), in addition to the perturbation in the geopotential field using the Love number k (Mathews et al. 1997).

Great efforts have been made to accurately measure the Earth tides (e.g., Richter and Warburton, 1998). There have been many theoretical studies of the Earth's structure and tidal response after Love (1909). Tidal deformations were studied for a spherically symmetric, perfectly elastic and isotropic Earth (e.g., Longman, 1963; Saito, 1967; Farrell, 1972). The response of the Earth to luni-solar attraction is expressed by amplitudes and phases of tidal constituents, together with the ocean tide loading (OTL) effects (e.g., Lambert et al., 1998).

The tidal response is mainly related to the Earth's elastic properties and local variations in elastic structure (Mantovani et al., 2005; Fu and Sun, 2007). Thus, the Earth's tidal response can be used to investigate the inner structure.

Recent studies have shown theoretically and through the use of simulated data how unmodelled periodic signals (such as ocean tide loading and errors in solid Earth tide models) propagate into GPS coordinate time series at various different frequencies (Penna and Stewart, 2003; Stewart et al.2005 and Penna et al., GPS height time series: short period origins of spurious long period signals, submitted to J.Geophys. Res., hereafter referred to as Penna et al., submitted manuscript).It is well known that the position of a point on the Earth's surface varies over a range of temporal scales due to the elastic response of the crust to the external tide generating potential(TGP) (e.g., Melchoir, 1983). The resultant response is called the solid Earth tide (also termed the Earth body tide), and can account for displacements up to ~0.4 m at predominantly semi-diurnal and diurnal frequencies (Lambeck, 1988).

On the global scale, GPS network observations have been conducted by Schenewerk et al . [2001], who estimated the vertical tidal displacements of 353 globally distributed GPS stations for eight major semidiurnal and diurnal constituents using 3 years of observations and found large-scale systematic observation-versus-model differences.

Yuan et al. [2009] used GPS data from a dense, continuous (albeit local) network in Hong Kong to evaluate the internal precision of GPS tidal displacement estimates. The results then showed that the misfits for the major semidiurnal and diurnal constituents (except K1 and K2) are less than 0.5 and 1.0 mm, respectively, for the horizontal and vertical components, implying that the GPS measurement error may not be a limiting factor to scrutinize body tide and OTL models.

Yuan and Chao [2012] succeeded in demonstrating the precision of GPS tidal displacement estimates down to the level of ~0.1 mm (horizontal) and ~0.3 mm (vertical).

Tidal oscillation has a strictly definite periodicity, therefore, there is need to study solid earth tides so that the corrections can be applied on both the GPS data and g value to calculate it for a particular place and time. In any geodetic analysis, it is important to consider how this process may affect the instantaneous site position, and hence influence the computation and interpretation of coordinate time series and related data products.

Diana Haritonova [2012], uses the special program to describe the vertical tide displacements in the territory of Latvia. Tidal deformations are the Earth crust vertical movements with maximum amplitude of up to 30 cm.

Therefore there is a need of calculating the tidal deformations and its effect on India. The study is to calculate the earth tide variation at position and the baselines between Indian stations.

## 2. BACKGROUND THEORY

The tidal force arises because of the gravitational attraction of the heavenly bodies around the earth which causes tidal acceleration. The tidal acceleration at any point on the surface of the earth is the difference between the acceleration caused by the attraction of the external body and the orbital acceleration i.e acceleration which the earth undergoes as whole, explained by *D.C.Agnew[2007]*. Theoretically earth tide phenomenon is explained by tidal phenomenon by applying newton's laws of motion. The gravitational potential is inversely proportional to the square of the distance between the body and the tide generating body whereas the tidal potential is inversely proportional to the cube of the distance between them. The tidal force is expressed by more preferred scalar quantity i.e tidal potential. Tidal Potential is calculated in two ways: either with the use of angular distance or geographical coordinates to define the position on the Earth. The expression for the tidal potential is described by *(Munk and Cartwright, 1966)* and the position is defined by the angular distance. The distance between the two masses (Earth and tide generating body) and the angular distance between the center of the tide generating body and the point on the surface of Earth is taken as the function of time. Thus it implements that the tidal potential is also a function of time.

If the tide generating body is moon and the point is on the surface of Earth where the tidal potential is to be calculated than R/D = 1/60. Where R is the radius of Earth and D is the distance between the two masses. In the case of Sun, R/D = 1/23000.

Therefore for second degree, the magnitude of $V_{tid}$ is proportional to $GM/D^3$.By normalizing this quantity to make value for the moon equal to 1, then the value for sun is 0.46, for Venus is $5\times10^{-5}$ and for Jupiter is $6\times10^{-6}$. Hence the moon and sun contributes effectively and can be visible in the actual measurements.

In the other method the distances is defined by geographical coordinates *D.C.Agnew[2007]*. In this the tidal potential is depend upon the latitude and longitude of the tide generating body as well as the point where the tidal potential is to be calculated. The tidal potential when divided by the acceleration due to gravity gives the units of potential. From this the tidal potential can be computed directly.

The location of the moon and the sun from the celestial coordinates is converted into the geographical coordinates and the distance is converted by using the standard transformations as given by *(McCarthy and Petit, 2004, Chapter 4)*.

The Love and Shida numbers are the dimension less parameters used to define the elasticity of the Earth. For the real Earth, the effective love numbers are dependent on the site latitude and tidal frequency *(Wahr, 1981; Mathews et al., 1995; Dehant et al., 1999)*. For attaining better accuracy of less than 1mm in modeling of site displacements, the various effects have to be considered on the love numbers. The motions of the moon and the sun as observed in the geocentric coordinate system is predictable by harmonic functions of the periodic variations of their respective elliptical orbits with high accuracy. Instead of two love numbers h and l used for a spherical Earth, *(Mathews et al., 1995)* the seven love numbers ($h^{(0)}$,$h^{(2)}$,h') and ($l^{(0)}$,$l^{(1)}$,$l^{(2)}$,l') are used to describe the surface tidal displacement of an ellipsoidal Earth. The surface displacement $\vec{u}$ because of the tidal term of frequency f is expressed in terms of frequency and latitude-dependent Love numbers as *(Mathews et al., 1995; Dehant et al., 1999).* The components of the tidal displacements of degree-2 can be explained as

For a diurnal cycle of frequency f:

$$\vec{u} = -\sqrt{\frac{5}{24\pi}} H_f \Bigg\{ 3h(\theta) sin\theta cos\theta sin(\varphi_f + \phi)\hat{e}_r + \left[ 3l(\theta) cos2\theta - 3l^{(1)} sin^2\theta + \sqrt{\frac{24\pi}{5}} l' \right] sin(\varphi_f + \phi)\hat{e}_\theta + \left[ \left( 3l(\theta) - \sqrt{\frac{24\pi}{5}} l' \right) sin\theta - 3l^{(1)} sin\theta cos2\theta \right] cos(\varphi_f + \phi)\hat{e}_\phi \Bigg\}$$

Where,

$H_f$ = amplitude (m) of the tidal term of frequency f ,
θ = geocentric latitude of station,
Φ = east longitude of station,
$\phi_f$ = tide argument for tidal constituent with frequency f,
$\hat{e}_r$ = unit vector in radial direction,
$\hat{e}_\phi$ = unit vector in the east direction,
$\hat{e}_\theta$ = unit vector at right angles to $\hat{e}_r$ in the northward direction.

## 3. METHODOLOGY

### 3.1 Precise Point Positioning:

It is used to observe the effect of continuous displacements on the coordinates of the station. It gives the mean daily variation of the coordinates and it is computed by Precise Point Positioning method. It gives the daily mean positional coordinates. Precise Point Positioning (PPP) is a method that started in the 1990's and involves the use of measurements from a single GNSS receiver to obtain accurate position without the use of measurements from reference stations. Such improvement is accomplished through the use of state space representation of the corrections to the observations, such as precise satellite ephemerides and satellite clock corrections produced from a network of worldwide monitoring stations. This method is implemented by GPS software Bernese 5.0. The raw data of the GPS for the IGS station is processed by using the Bernese 5.0. The software gives the mean value of the coordinates for a particular day. The Solid Earth tide corrections are already applied to the coordinates obtained by the Bernese 5.0. Therefore the variation in the coordinates obtained by Bernese 5.0 is not due to the Solid Earth tides. To study the effect of Solid Earth tides on the coordinates of the station, the coordinates are computed for the same station but without the Solid Earth tide corrections and the difference in the readings will give the affect on the position of the station due to the Solid Earth tides. Same technique is also applied for the Pune station.

To calculate the effect of positional variation due to the surface displacements on the distance between the two stations the Base line processing is done. For calculating the affect of Solid Earth tides on the Base line the two stations Hyderabad and Pune is chosen. One station is the IGS Hyderabad and the other station is taken in Pune to observe the effect of Solid Earth tides on the Base line processing. Firstly the baseline is calculated between the two stations with Solid Earth tide corrections. Second baseline is calculated between the same two stations but without Solid Earth tide correction. The difference in the baseline gives the effect of Solid Earth tides on the baseline between any two stations.

## 4. RESULTS

### 4.1 Variation in Baselines:

To study the effect along a baseline distance between any two stations is observed by doing the baseline processing of the data of the two stations. The two baseline processing is done with two types of coordinates. First baseline processing is done between coordinates of both the stations when the Solid Earth Tide correction is applied. The second baseline processing is done when between the stations without applying the Solid Earth Tide correction on the coordinates of the stations. The difference between the baselines obtained by above two processes is the effect on the slope distances between two particular stations due to Solid Earth Tides.

### 4.2 Variation in baseline b/w Hyderabad and Pune

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.1. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. As it is expected, large variation is observed in the slope distance calculated between the stations when the coordinates are obtained without Solid Earth Tide corrections as shown in figure 4.1. The difference in the baselines obtained with and without Solid Earth Tide correction is the effect on the slope distance due to the Solid Earth Tides.

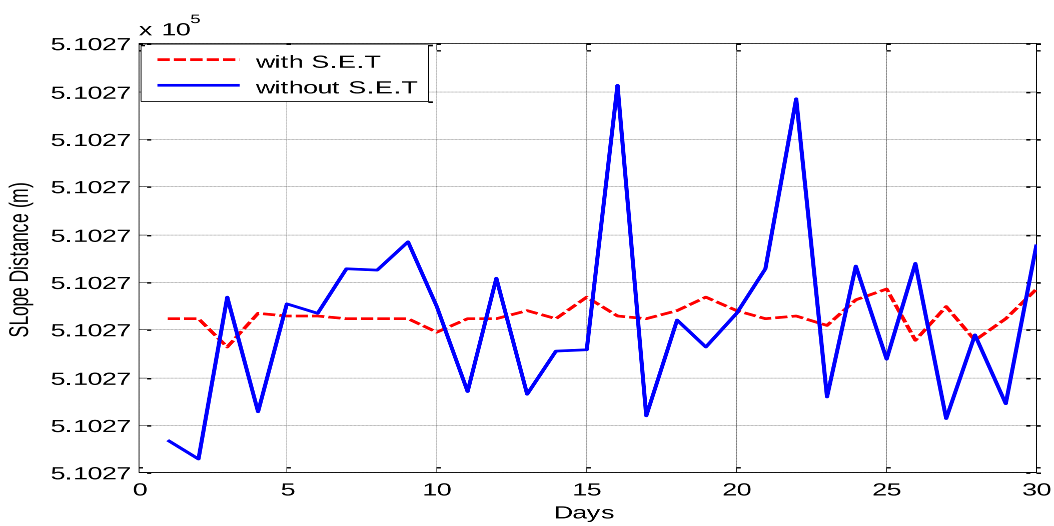


Figure 4.1: Variation in the baseline distance b/w Hyderabad and Pune with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.2. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.2 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be 1:39251622.

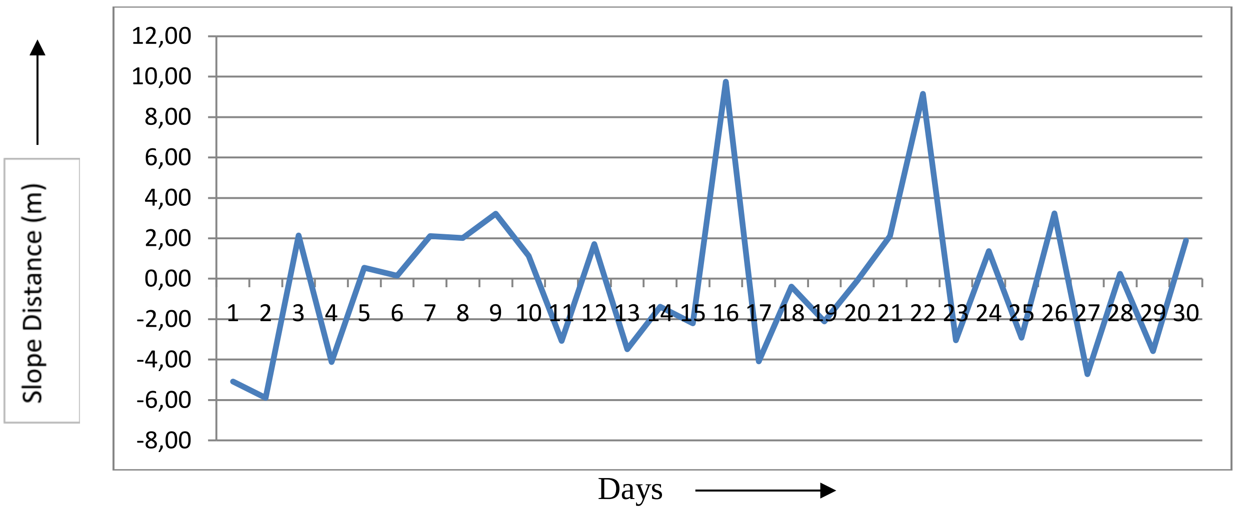


Figure 4.2: Variation in the baseline distance (Δl) b/w Hyderabad and Pune due to Solid Earth Tides.

### 4.3 Variation in baseline b/w Hyderabad and Dehradun

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.3. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. Large variation is observed when the baseline is obtained between Hyderabad and Dehradun station without Solid Earth Tide corrections.

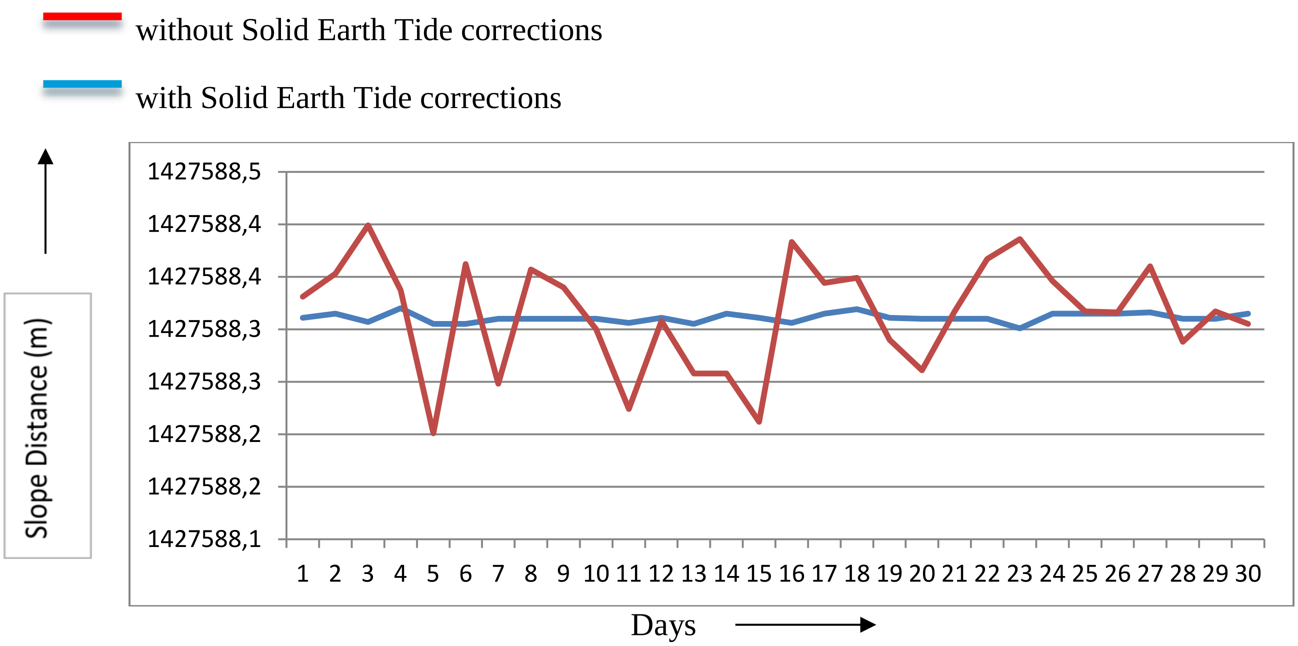


Figure 4.3: Variation in the baseline distance b/w Hyderabad and Dehradun with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.4. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.4 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be -2.45169E-09.

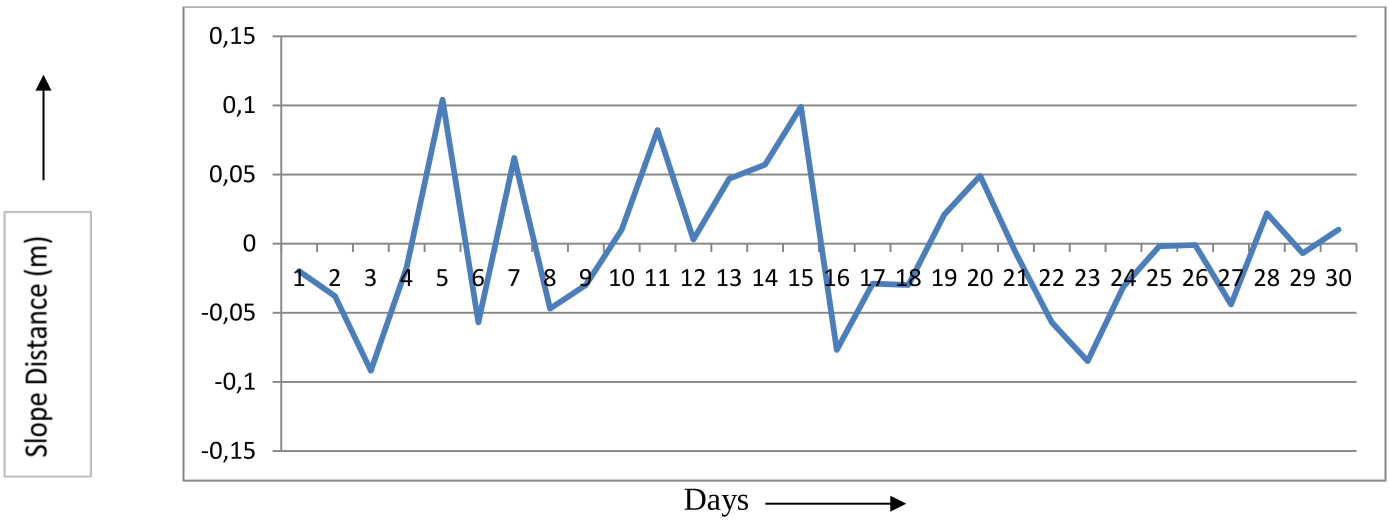


Figure 4.4: Variation in the baseline distance(Δl) b/w Hyderabad and dehradun due to Solid Earth Tides.

### 4.4 Variation in baseline b/w Pune and Dehradun

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.5. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. Large variation is observed when the baseline is obtained between Pune and Dehradun station without Solid Earth Tide corrections.

without Solid Earth Tide corrections

with Solid Earth Tide corrections

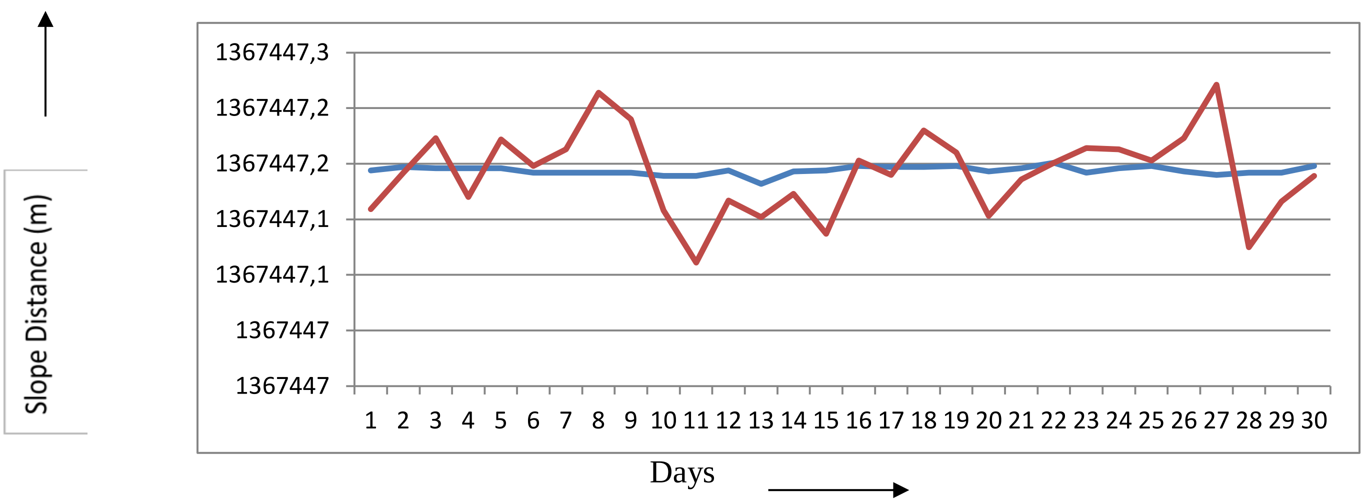


Figure 4.5: Variation in the baseline distance b/w Pune and Dehradun with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.6. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.6 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be 1.53571E-09.

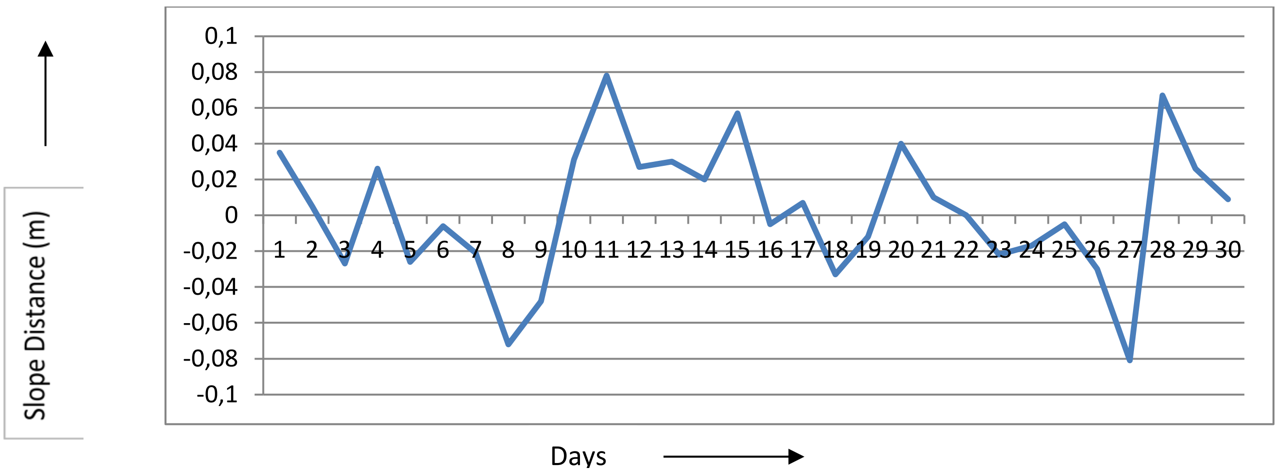


Figure 4.6: Variation in the baseline distance (Δl) b/w Pune and Dehradun due to Solid Earth Tides.

### 4.5 Variation in baseline b/w Hyderabad and Bhubaneswar

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.7. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. Large variation is observed when the baseline is obtained between Hyderabad and Bhubaneswar station without Solid Earth Tide corrections.

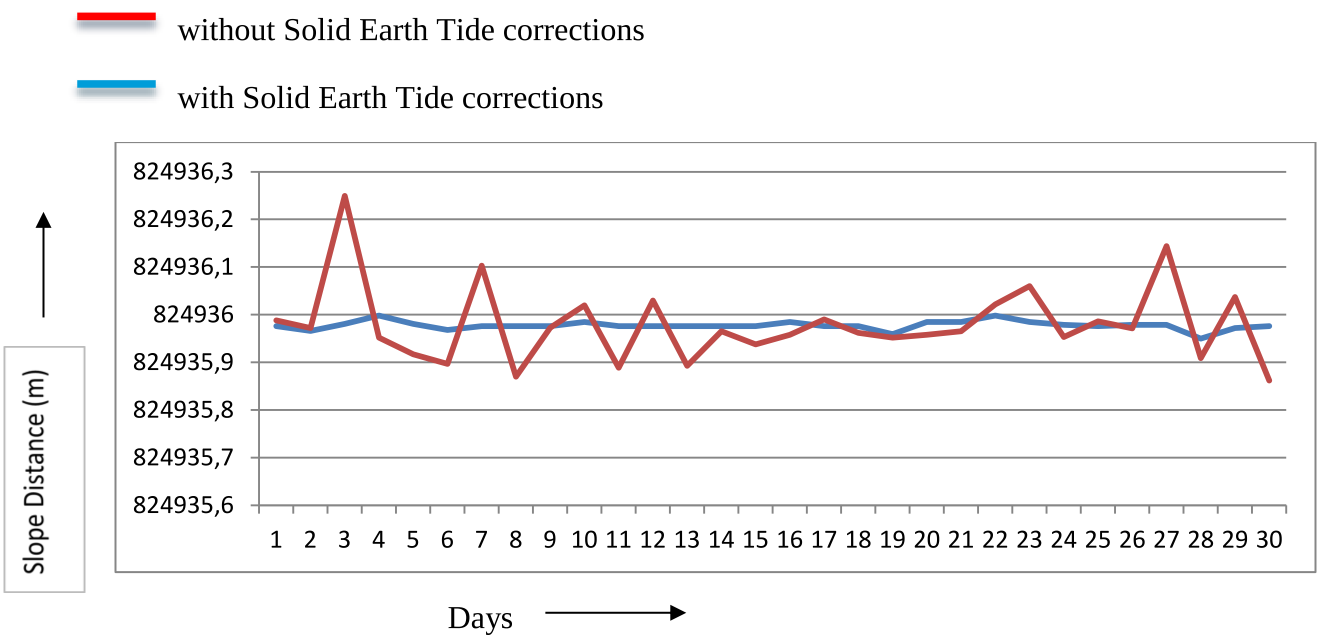


Figure 4.7: Variation in the baseline distance b/w Hyderabad and Bhubaneswar with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.8. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.8 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be -2.54565E-09.

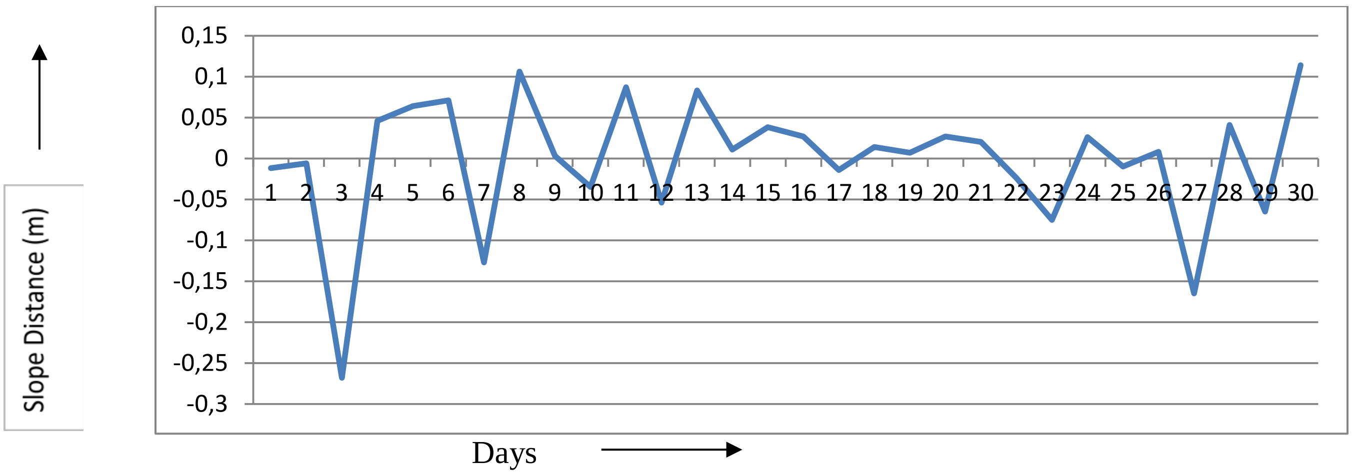


Figure 4.8: Variation in the baseline distance(Δl) b/w Hyderabad and Bhubaneswar due to Solid Earth Tides.

### 4.6 Variation in baseline b/w Pune and Bhubaneswar

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.9. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. Large variation is observed when the baseline is obtained between Pune and Bhubaneswar station without Solid Earth Tide corrections.

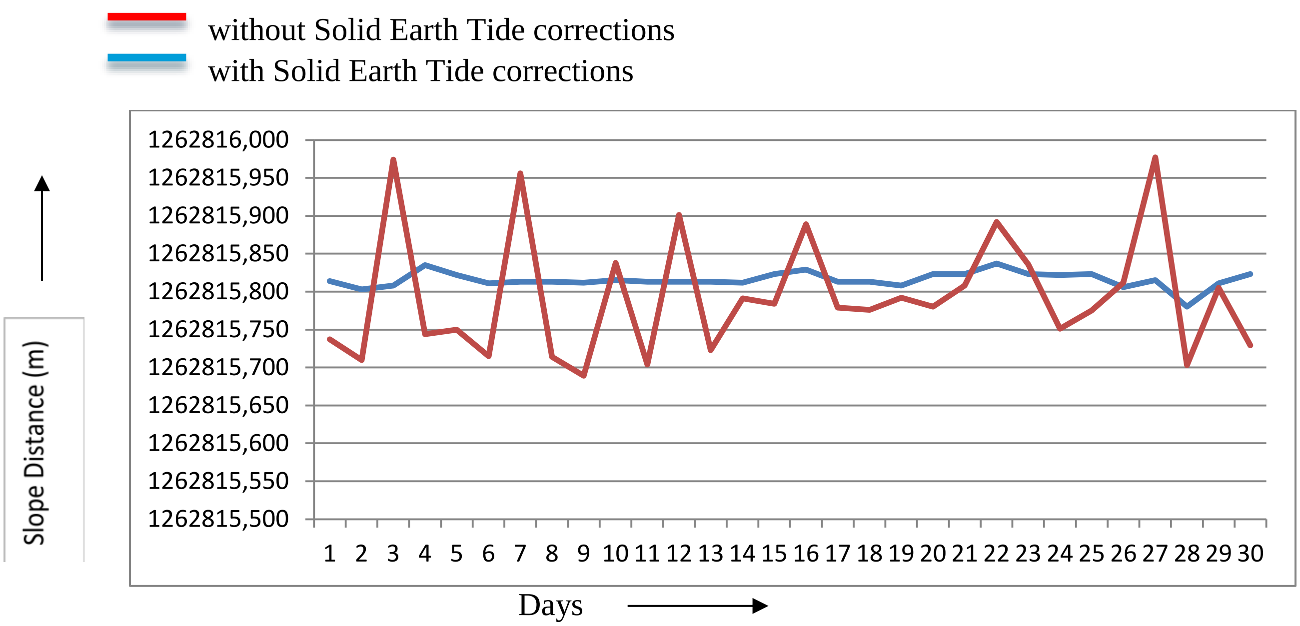


Figure 4.9: Variation in the baseline distance b/w Pune and Bhubaneswar with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.10. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.10 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be 1.66295E-08.

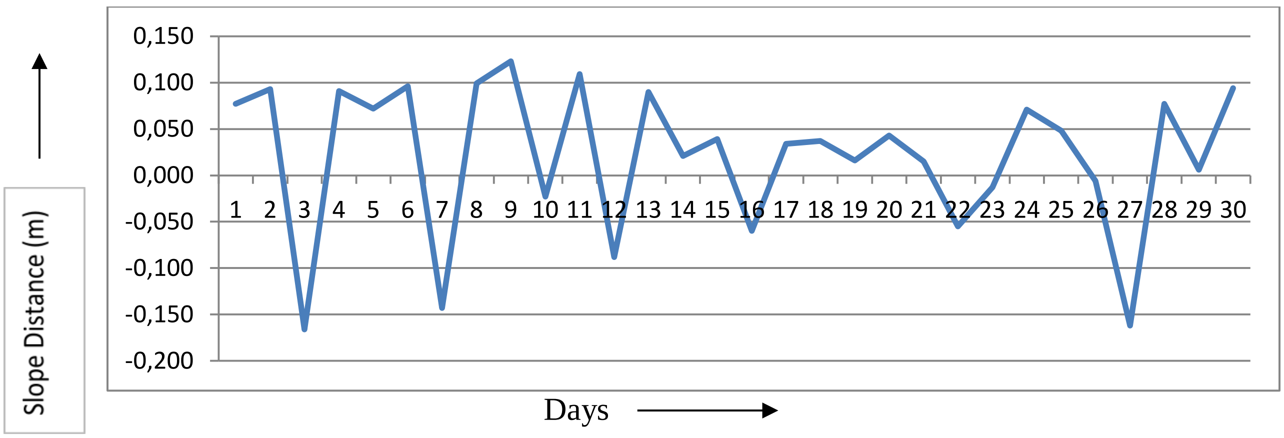


Figure 4.10: Variation in the baseline distance(Δl) b/w Pune and Bhubaneswar due to Solid Earth Tides.

### 4.7 Variation in baseline b/w Dehradun and Bhubaneswar

The difference in the baseline distance between the two stations with and without Solid Earth Tide corrections is represent by the graphical representation as shown in figure 4.11. The blue curve represents the slope distance between both the stations when coordinates are obtained without Solid Earth Tide corrections. The red curve represents the slope distance between both the stations when the coordinates are obtained with Solid Earth Tide corrections. Large variation is observed when the baseline is obtained between Dehradun and Bhubaneswar station without Solid Earth Tide corrections.

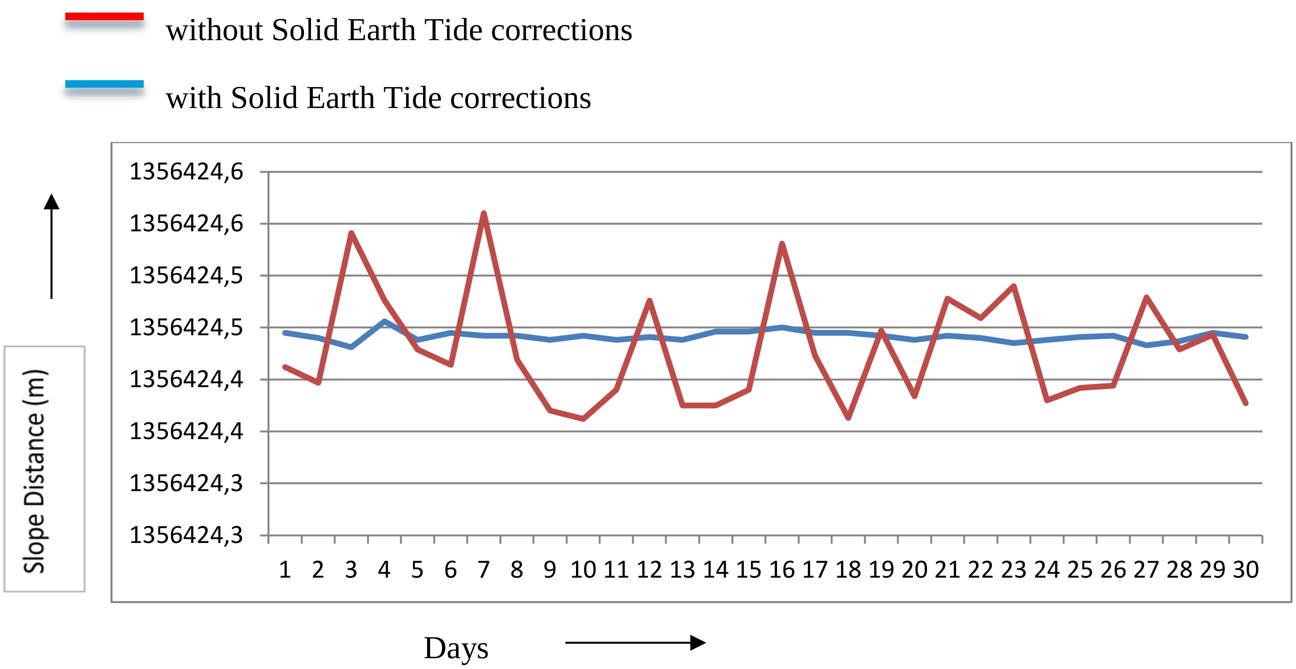


Figure 4.11: Variation in the baseline distance b/w Dehradun and Bhubaneswar with and without Solid Earth Tide corrections.

The difference in the slope distance calculated with and without Solid Earth Tide corrections is shown in the figure 4.12. The large variation is observed during the time of New and Full Moon. The variation in the slope distances as shown in figure 4.12 for a month is because of the Solid Earth Tides. Now Δl is the difference in the baseline obtained with Solid Earth Tide correction and without Solid Earth Tide correction. The daily variation is shown in figure. L is the baseline distance between the two stations which is the averaged mean value and is constant. The monthly variation of the change in baseline distance divided by the baseline distance is the ratio of the averaged mean value of the Δl to L. The monthly mean value comes out to be 9.58402E-09.

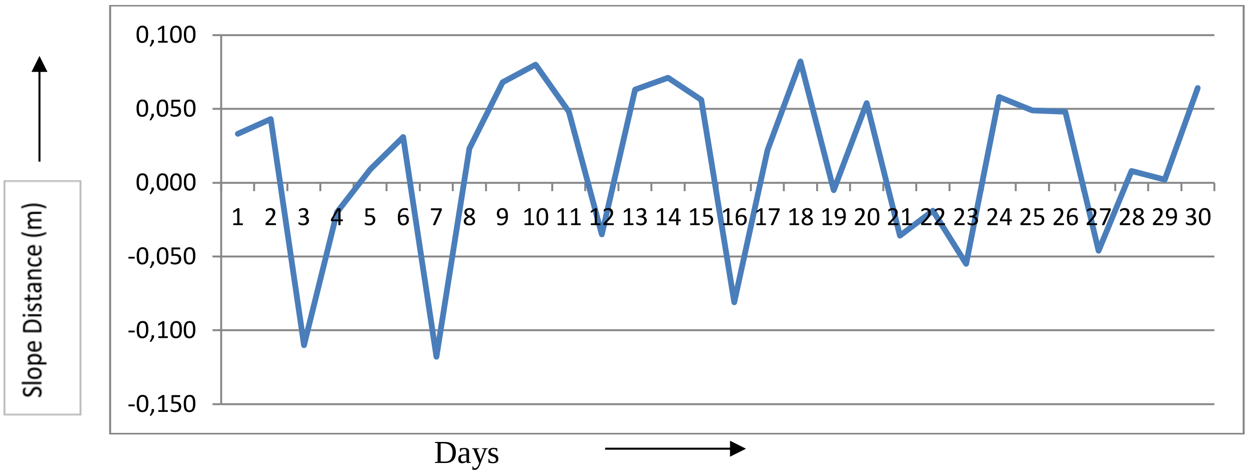


Figure 4.12: Variation in the baseline distance(Δl) b/w Dehradun and Bhubaneswar due to Solid Earth Tides.

### 4.8 Variation in the baselines between the stations due to Solid Earth Tides.

The effect of the Solid Earth Tides on the baseline distances between any two stations is calculated by subtracting the baseline distance obtained by the coordinates with Solid Earth Tide corrections with the baseline distance obtained by the coordinates without Solid Earth Tide corrections. Therefore the variation in the baseline between any two stations is only due to the Solid Earth Tides. Coordinates with and without Solid Earth tide corrections are computed at four Indian stations i.e IGS Hyderabad, Pune, Dehradun and Bhubaneswar. The six baselines are computed between these stations and the effect is studied for the month of November 2013. The effect on these six baselines is studied and the variation due to Solid Earth tides is observed simultaneously. The variation in the baselines between all the four stations seems to be follows a definite pattern. The variation in all the six baselines is due to the Solid Earth tides and thus it concludes that the position of any station varies continuously with time.

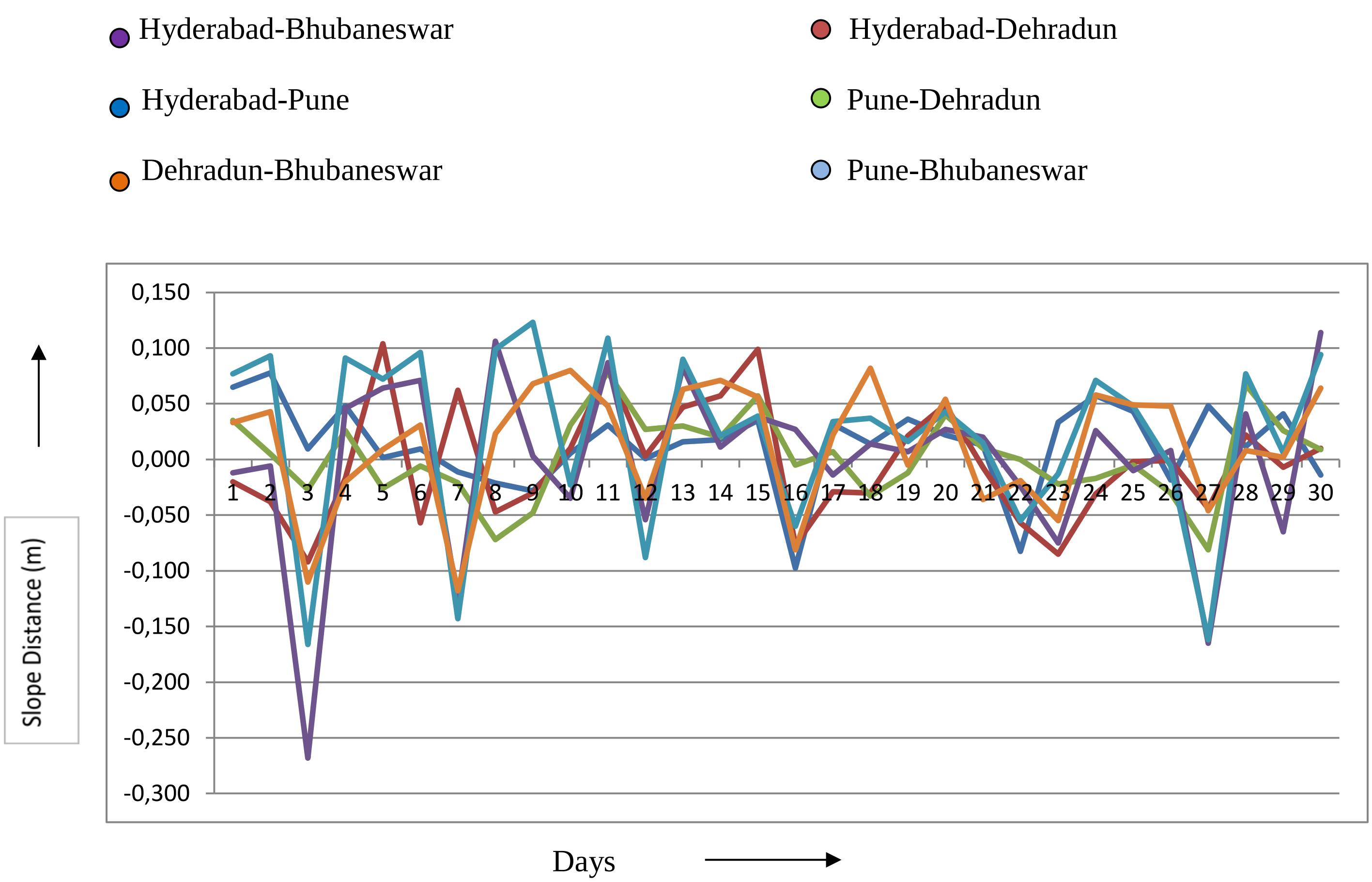


Figure 4.13: Variation in the baseline distances b/w stations due to Solid Earth Tides.

## 5. DISCUSSION

Further the baseline processing is done by taking the GPS data of four Indian stations and the six baselines is computed between these stations. The slope distance is calculated between the stations and the variation occurs in the baseline for the month which is due to the Solid Earth Tides. The effect on all the six baselines is observed simultaneously and the curve shows almost the similar pattern. This shows that the effect on the coordinates of the station is almost similar due to the Solid Earth Tides.

Therefore there is a high need to know the exact behavior of the Solid Earth tides so that the corrections can be applied to the GPS readings for finding the exact value of the GPS coordinates for a specified place and time. Therefore the corrections can be applied to the GPS readings for finding the exact value of the GPS coordinates for a specified place and time.

## 6. CONCLUSION

The Earth station displacement caused by the solid body tides, is the correction which must be observed for determining the Earth station's position. Tidal oscillation has a strictly definite periodicity, therefore the desired corrections can be applied for any instant of time. The study of the Earth tides helps us in understanding the response of the Earth's body to the internal and external forces.

## 7. ACKNOLDGEMENT

I would like to express my gratitude to Mr. Upender Mishra, director G&RB, Survey of India, Dehradun for providing the desired data required for this research work.

## REFERENCES


**Agnew D.C. [2007],** Earth Tides, University of California San Diego, San Diego, CA, USA.
**Farrell, W.E. [1972]**. Deformation of the earth by surface loads. Rev. Geophys. Space Phys. 10, 761–797.
**Fu, G., Sun, W.[2007].** Effects of lateral in homogeneity in a spherical Earth on gravity Earth tides. J. Geophys. Res. 112, B06409, doi:10.1029/2006JB004512.

**Haritonova Diana [2012]**,"Solid Earth Tides in the Territory of Lativa", Riga Technical University.
**King, M. [2006]**. Kinematic and static GPS techniques for estimating tidal displacements with application to Antarctica. J. Geodyn. 41, 77–86.
**Lambert, A., Pagiatakis, S.D., Billyard, A.P., Dragert, H.[1998]**. Improved ocean tide loading corrections for gravity and displacement: Canada and northern United States. J. Geophys. Res. 103 (30), 231–30244.
**Lambeck, K. [1988]**. Geophysical Geodesy: The Slow Deformations of the Earth. Oxford Science Publications. 718pp
**Love, A. E. H. [1944]**. Treatise on the Mathematical Theory of Elasticity. 4th ed, Cambridge University Press.
**Longman, I.M. [1963]**. A Green's function for determining the deformation of the earth under surface mass loads: 2. Computations and numerical results. J. Geophys. Res. 68, 485–495.
**Mathews, P. M., Dehant, V., and Gipson, J. M. [1997]**, Tidal station displacements, J Geophys Res, 102(B9): 20469-20478.
**Mantovani, M.S.M., Shukowsky, W., Freitas, S.R.C., Neves, B.B.B., [2005]**. Lithosphere mechanical behavior inferred from tidal gravity anomalies: a comparison of Africa and South America. Earth Planet. Sci. Lett. 230, 397–412.
**McCarthy, D., and Petit G. (eds). [2004]**. IERS Conventions (2003). IERS Technical Note No 32, Verlag des Bundesamts fur Kartographie und Geodasie, Frankfurt am Main, 127pp.
**Milbert Dennis [2011]**, *"Solid Earth tide."* February, 2011. [Online]. Available: http://home.comcast.net/~dmilbert/softs/solid.htm.
**Munk, W. H., and D. E. Cartwright[1966]**, Tidal spectroscopy and prediction, Phil. Trans. Roy. Soc. London, Ser. A, 259, 533-581.
**Munk, W. H., and MacDonald, G. J. [1975]**. The Rotation of the Earth: A Geophysical Discussion. 1st ed, Cambridge University Press, Cambridge, 323pp.
**Melchoir, P. [1983]**. The Tides of the Planet Earth. 2nd ed, Pergamon Press, Oxford, 641pp.
**Penna, N. T., and Stewart, M. P. [2003]**, Aliased tidal signatures in continuous GPS height time series, Geophys Res Lett, 30(23), 2184, DOI:10.1029/2003GL018828.
**Richter, B., Warburton, R., [1998]**. A new generation of superconducting gravimeters enables the in situ detection and elimination of offsets and interruptions from continuous gravity measurements. In: Ducarme, B. (Ed.), Proc. 13th Int. Symp. Earth Tides Brussels, pp. 545–555.
**Saito, M., [1967]**. Excitation of free oscillations and surface waves by a point source in a vertically heterogeneous Earth. J. Geophys. Res. 72, 3689–3699.

**Sato T, Miura S, Ohta Y, Fujimoto H, Sun W, Larsen C. F, Heavner M, Kaufman A. M, Freymueller J. T[2008]**, Earth tides observed by gravity and GPS in southeastern Alaska, Journal of Geodynamics 46, 78–89.
**Stewart, M. P., Penna, N. T., and Lichti, D. D. [2005]**. Investigating the Propagation Mechanism of Unmodelled Systematic Errors on Coordinate Time Series Estimated Using Least Squares. J Geod, 79(8): 479-489. DOI: 10.1007/s00190-005-0478-6.
**Schenewerk, M.S., Marshall, J., Dillinger, W., [2001]**. Vertical ocean-loading deformations derived from a global GPS network. J. Geodyn. Soc. Jpn. 47 (1), 237–242.
Watson C, Tregoning P, and Coleman R, Impact of solid Earth tide models on GPS coordinate and tropospheric time series, GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L08306, doi:10.1029 /2005 GL025538.
**Yan, H., W. Chen, Y. Zhu, W. Zhang, and M. Zhong [2009]**, Contributions of thermal expansion of monuments and nearby bedrock to observed GPS height changes, Geophys. Res. Lett., 36, L13301, doi:10.1029/ 2009GL038152.
**Yuan Linguo, Benjamin Fong Chao, Xiaoli Ding and Ping Zhong [2013]**, The tidal displacement field at Earth's surface determined using global GPS observations, JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 2618–2632, doi:10.1002/jgrb.50159.

## List of Figures



## CONTACTS

Shray Pathak, shraypathak@gmail.com, +91-8954203033, Research Scholar, Civil Engineering Department, IIT Roorkee, India.

Dr.J.K.Ghosh, gjkumfce@yahoo.com, +91-9411111721, Associate Professor, Civil Engineering Department, IIT Roorkee, India.