J. Ind. Geophys. Union ( January 2012 )
**Vol.16, No.1, pp.21-28**

# Current scenario of crustal deformation and strain distribution around the equatorial Indian Ocean region using GPS-Geodesy

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## ABSTRACT

The crustal dynamics, strain distribution and the cause and effect of the geological processes in the equatorial Indian Ocean region were analysed using the Mahendragiri GPS data along with the network of stations around this region. The Mahendragiri GPS station is in the southern tip of the Indian Peninsula and forms a shorter baseline length with other nearby GPS stations. This has led to provide greater accuracy and lesser errors. The GPS data were processed using the Bernese 5.0 software which revealed that the baseline length changes from station Mahendragiri (MADG) to stations such as Maldives (MALD), Diego Garcia (DGAR), Seychells (SEY1), Cocos (COCO) are 0.0028±0.0009 m/yr, 0.0050±0.0008 m/yr, 0.0352±0.0019 m/yr and -0.0086±0.0.0020 m/yr respectively and the corresponding strain rates per year are $4.41102 \times 10^{-9}$, $2.76637 \times 10^{-9}$, $1.25036 \times 10^{-9}$ and $-2.79168 \times 10^{-9}$ respectively. Further, the horizontal velocity of the MADG station is 0.0418 m/yr, moving towards N53°E.

The baseline length changes in negative values indicated the convergence and the positive values indicated the divergence of plate boundaries. Between Indian and Capricorn plates, north to south slow divergence in the western side of the Capricorn plate and north to south slow convergence in the eastern side are taking place. The propagation of strain rate differs from place to place which may be due to the asymmetry of the spreading rates of Mid-oceanic ridges. Most of the stress generated by the plate driving forces at the Mid-oceanic regions was transferred through the southern India to the northern part of India as evidenced by the visible creation of the Himalayas and the rise of the Himalayas in recent times.

The study has also revealed that there is very less deformation between MALD and MADG and it is not significant. Similarly, very less deformation exists between Chagos ridge and the southern tip GPS station of the Indian Peninsula viz Mahendragiri. The seismicity is varying from west to east in the equatorial Indian Ocean region. The GPS estimated strain rates have a good correlation with the seismicity of the Indian ocean region.

## INTRODUCTION

The Geodetic data such as GPS is useful to understand the relative motion of the plates. Much cannot be inferred from the conventional plate motion data. The equatorial Indian Ocean region has plates and continental blocks, comprising of Carlsberg ridge which divides the African and the Indian plates. The Mahendragiri (MADG) GPS station represents the southern tip of the Indian Peninsula. The COCO GPS station acts as the representative of southern end of the plate deformation zone between India and Australia, the Diego Garcia (DGAR) GPS station is representative of Capricorn plate, the Seychells (SEY1) and Maldives (MALD) GPS stations represent for Somalian and Chagos ridge plates respectively. The equatorial Indian Ocean region consists of Central Indian Ridge (CIR), Ninety degree East Ridge and southern Bay of Bengal, constituting diffuse boundary zone between India and Australia. The major earthquake region Sumatra-Andaman have been excluded where sudden changes due to earth quakes may cause inconsistency in data analysis.

The Central Indian Basin has distributed crustal deformation (Demets and Royer., 2003). The GPS velocity estimation can validate the geological findings estimation in a shorter time. Therefore, the objective of the present GPS study is (1) to ascertain the motion between the diffuse plate boundary zone and southern Indian peninsula, (2) to know the horizontal strain rate in the equatorial Indian ocean region, (3) to know the rigidity of the oceanic plate between Mahendragiri (MADG) and Maldives, (MALD) (4) to know the relative motion between Diego Garcia (DGAR) near the inferred boundary and the Mahendragiri (MADG) in the southern Indian peninsula, (5) to know the impact of the Mid-oceanic ridge activities in the study area and (6) to investigate the movement of Capricorn plate.

In this context, the crustal dynamics, strain distribution and the cause and effect of the geological processes in the equatorial Indian Ocean region were analysed using the Mahendragiri GPS data along with the selected network of stations around this region.

## GPS DATA ARCHIVING AND PROCESSING

In the present study, the International GNSS which includes two GNSS (Global Navigation Satellite System), GPS and Russian GLONASS stations named Poligan (POL2), Brauchweig (PTBB), Seychells (SEY1), Cocos (COCO), Diego Garcia (DGAR), Hartbeesthoek (HARB), Hyderabad (HYDE), Bangalore ( IISC), Irkut (IRKT), Kitab (KIT3), Lhasa (LHAS), Maldives (MALD), Yaragaee (YAR2), Shangai (SHAO) and Mahendragiri (MADG), the NGRI's second GPS permanent station were monitored for network solution which are all in good geographic distribution to facilitate in data processing. The data from the stations around the study region (Figure. 1) were included for geometric reason. The Table 1 shows the data of all the stations which were analyzed in the present study and all other stations data in the network were excluded from the analysis. The MADG GPS station data from the inception i.e from 2002 to 2009, were taken for the analysis. Due to instrument failure, there was no MADG GPS data available during 2005. The data available at MADG is too sparse due to various operational difficulties and the station DGAR data is only available up to 2004. During the data processing, weekly solution was adopted so that processing will be within the manageable limit and the GPS estimates were highly correlated over a period of several days. Data from the sites participating in the IGS( International GNSS Service) network data center were downloaded from the global data centers via internet.

In the area of study, only four IGS stations data were used for the analysis of equatorial Indian Ocean region. The IGS released phase eccentricity file was used for the phase centre correction for various antenna types.

At MADG station, from 2002 to 2004, Turbo Rogue multi-channel dual frequency receiver with choke ring antenna was operated. Since 2006 onwards, Topcon GNSS receiver with a choke ring antenna was operated to avoid multi-path signals. The GPS receivers were set to track at 30 sec interval.

In this paper, a global set of stations was processed to get network solution. The baseline between few stations and velocity vectors of MADG station only

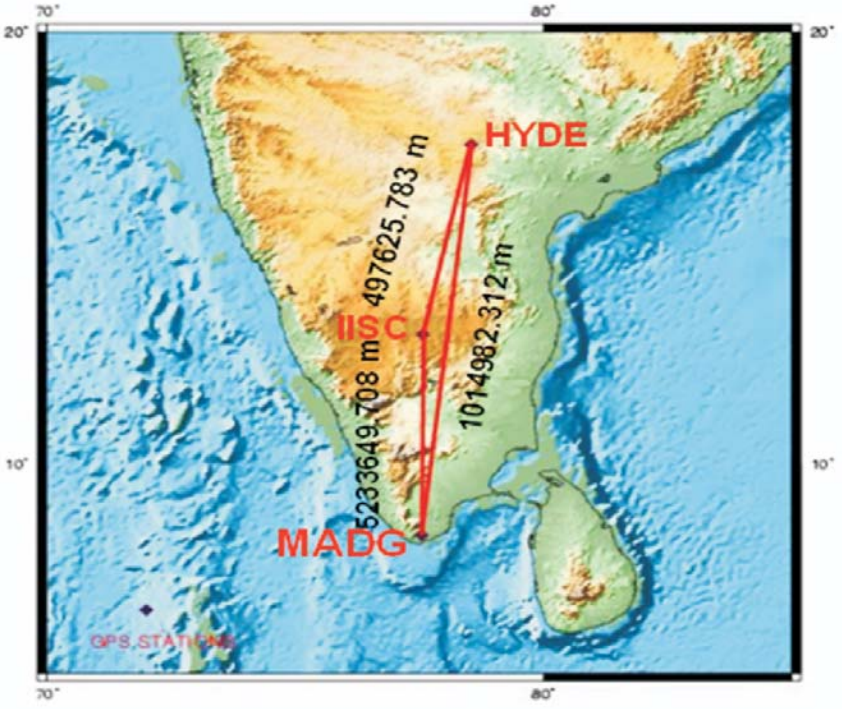

**Figure 1.** The baseline length between MADG-IISC-HYDE of Southern India

**Table 1.** GPS stations data analyzed in the present study

| Site | Lat (deg) | Lon (deg) | GPS measurement ( in years) | Remarks/ Station Abbreviation |
|---|---|---|---|---|
| MAHENDRAGIRI | 8.28 | 77.55 | 2002-2005<br>2007-2009 | NGRI's GPS station,MADG |
| COCO | -11.82 | 96.83 | 2002-2005<br>2007-2009 | IGS station, COCO |
| MALDIVES | 4.18 | 73.51 | 2002-2005 | IGS station, MALD |
| DIEGO GARCIA | -6.73 | 72.27 | 2002-2005<br>2007-2009 | IGS station, DGAR |
| SEYCHELLS | 4.67 | 55.47 | 2002-2005<br>2007-2009 | IGS station, SEY1 |

**Table 2.** Baseline length changes and strain accumulations between MADG, IISC and HYDE:

| Between the stations | Baseline length (m) | Rate/year | RMS Error | Strain Rate |
|---|---|---|---|---|
| IISC-HYDE | 4,97,625.7831 | -0.0015 | 0.0057 | $-3.12744 \times 10^{-9}$/yr |
| MADG-HYDE | 10,14,982.3115 | -0.0002 | 0.0044 | $-1.97048 \times 10^{-10}$/yr |
| MADG-IISC | 5,23,649.7084 | 0.0009 | 0.0005 | $-1.71871 \times 10^{-9}$/yr |

were discussed in detail in this paper. All sites which have more than two years of data have been included in our data processing since velocity uncertainties are sensitive to the time spanned GPS data set. In the present study, GPS data around the equatorial Indian Ocean region only were focused and analyzed.

All the GPS data were processed and analyzed using Bernese version 5.0 software developed by the University of Bern. The data of both L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies were combined and used in the processing. The ionosphere delay was estimated and the error caused by the ionosphere was removed. During the GPS data processing, the satellite elevation cut of angle was set to 15°. Cycle slips were found and removed by automatic editing. The error due to GPS receiver and satellite clock errors were estimated and canceled. In Tropospheric dry delay model, Saastamoninen model was used to remove tropospheric path delay. Precise orbital data available at JPL data centre after two weeks was used for data processing. Only 24 hours GPS data was considered for the data processing. The coordinates and velocity estimations are in the ITRF 2005 reference frame. The data points which are in extreme deviation from the mean have been removed.

## DATA ANALYSIS, RESULTS AND DISCUSSION

The strain accumulation was estimated by the ratio between the changes in the baseline length and the length of the baseline using minimum two locations. The strain accumulation indicated the probability of seismicity. The GPS station locations can also be used to estimate the strain rate precisely. The positive strain rate indicated low seismicity of the region. The baseline length changes indicated the convergence and divergence of plate boundaries significantly.

### Internal stability of South India

The baseline length shortening is not significant between MADG-HYDE, MADG-IISC and IISC-HYDE (Tables 2 and Figure 1). This suggested that there is no significant deformation in the southern India. The changes in the baseline lengths are close to zero. The internal plate stability is very high in Southern India and as such the stress received at one end of the plate might be transmitted to the other side of the plate. The Southern India convergence rate is also nearly zero.

The significant strain accumulation $7 \times 10^{-9}$ can be able to generate earthquakes (Paul et al., 2001). However, no significant strain accumulation exists across the Indian plate. The present analysis and results also explain that there is less significant strain rate in the Southern India and beyond up to Maldives. The strain rate per year between the stations in South India viz MADG-HYDE, MADG-IISC and IISC-HYDE are -1.97048 x $10^{-10}$, -1.71871 x $10^{-9}$ and -3.12744 x $10^{-9}$ respectively (Table 3).

## Crustal deformation and strain distribution around the Equatorial Indian Ocean

The Central Indian Ridge (CIR) extends north of Rodriguez triple junction that separates African and Indo-Australian plates. The CIR is continued by Carlsberg ridge to the north of the equator. The Carlsberg Ridge (CR) extends from 2° S to 10 ° N, forming a NW-SE trend. The CIR spreads at the rate

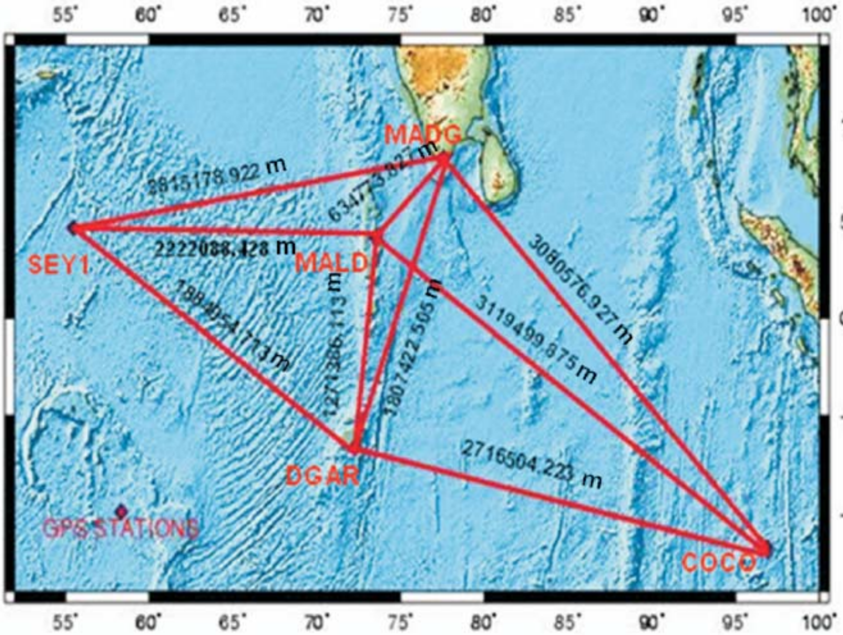

**Figure 2.** Geographical distribution and Baseline between the stations MADG, SEY1, MALD, DGAR and COCO.

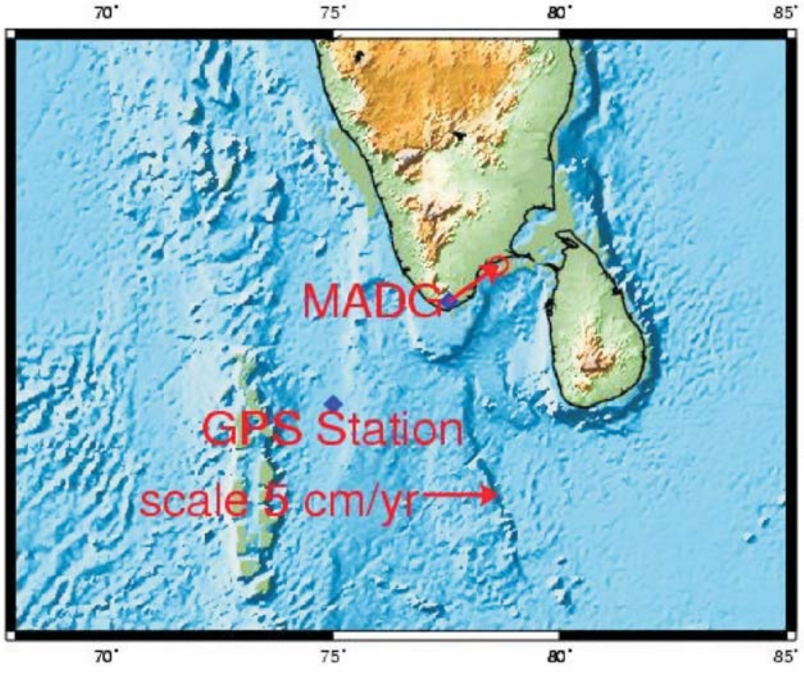

**Figure 3.** The velocity vector of the Mahendragiri GPS station in the southern tip of Indian peninsula

that varies about 54 mm/yr near the Rodriguez triple junction to about 30 mm/yr north of equator. The slow-spreading CIR (Sempere and Klein., 1995) may be influencing the GPS station in the southern tip of Indian peninsula viz Mahendragiri (MADG) station's movement.

The velocity vector map of MADG station is shown in Figure 3. The MADG station's north velocity is 0.0245 ±0.0031 m/yr. Its east velocity is 0.0338 ± 0.0035 m/yr. These are shown in Table 3 and Figure 4. The resultant velocity of Mahendragiri station is 0.0417 m/yr towards N53°E. Since the southern India is rigid, the stress transferred in the direction of the velocity vector has been further transferred to the North and East directions. The consequences of this are the visible creation and continuous rising of the Himalayas.This block or the part of the plate is receiving the stress from Central Indian Ridge (CIR), influenced by the Reunion hot spot. The height increases at the rate of 0.0027 ± 0.0033 m/yr, which may be due to horizontal shortening and the vertical thickening that must be occurring between the diffuse boundary zone and between India and Cocos. This may cause the vertical movement. The horizontal velocity is slower than the corresponding NUVEL-1A estimation ( Demets et al., 1994).

**Table 3.** Estimated baseline length changes between NGRI's Mahendragiri and the IGS GPS stations in the equatorial Indian ocean region.

| Between the Stations | Baseline length (m) | Baseline length Changes (m/yr) | Error (m) |
|---|---|---|---|
| MADG-MALD | 6,34,773.827 | 0.0028 | 0.0009 |
| MADG-DGAR | 18,07,422.505 | 0.0050 | 0.0008 |
| MADG-SEY1 | 28,15,178.922 | 0.0352 | 0.0019 |
| MADG-COCO | 30,80,576.927 | -0.0086 | 0.0020 |
| SEY1-MALD | 22,22,088.428 | 0.0224 | 0.0019 |
| DGAR-MALD | 12,71,386.113 | 0.0048 | 0.0009 |
| COCO-MALD | 31,19,499.875 | -0.0056 | 0.0018 |
| COCO-DGAR | 27,16,504.223 | -0.0052 | 0.0036 |
| SEY1-DGAR | 18,84,954.713 | 0.0196 | 0.0020 |

**Table 4.** Estimated strain accumulation between the NGRI's Mahendragiri GPS Station and the IGS GPS stations in the Equatorial Indian Ocean region

| S. No | Between the Stations | Strain rate |
|---|---|---|
| 1 | MADG-MALD | $4.41102 \times 10^{-9}$/yr |
| 2 | MADG-DGAR | $2.76637 \times 10^{-9}$/yr |
| 3 | MADG-SEY1 | $1.25036 \times 10^{-8}$/yr |
| 4 | MADG-COCO | $-2.79168 \times 10^{-9}$/yr |
| 5 | SEY1-MALD | $1.00806 \times 10^{-8}$/yr |
| 6 | DGAR-MALD | $3.77541 \times 10^{-9}$/yr |
| 7 | COCO-MALD | $-1.79516 \times 10^{-9}$/yr |
| 8 | COCO-DGAR | $-1.91422 \times 10^{-9}$/yr |
| 9 | SEY1-DGAR | $1.03981 \times 10^{-8}$/yr |

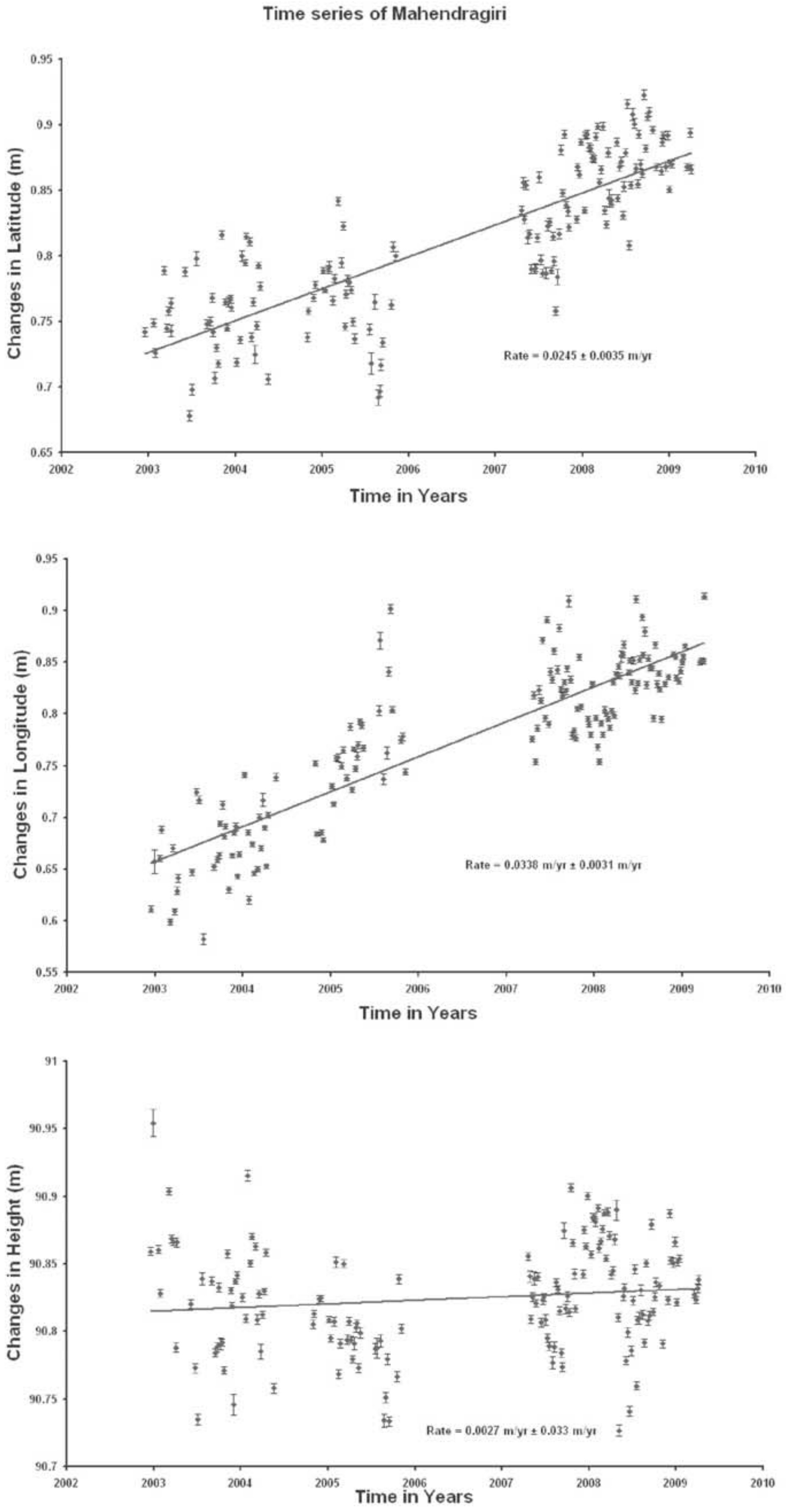

**Figure 4.** Time series of MADG GPS station.

The Geographical distribution of the GPS stations and changes in the baseline length between MADG, SEY1, MALD, DGAR and COCO are shown in Figure 2. The baseline lengths, estimated from SEY1 to other stations such as DGAR, MALD and MADG are 0.0048 ± 0.0009 m/yr, 0.0224 ± 0.0019 m/yr and 0.0352 ± 0.0019 m/yr respectively (Table 4). This indicates that spreading rates are increasing at Central Indian Ridge (CIR) from south to north. There is a continued spreading along the Indian ocean ridge system (Subrahmanya, 1994). The strain rates estimated from station SEY1 to stations DGAR, MALD and MADG are 1.03981 x $10^{-8}$/yr, 1.00806 x $10^{-9}$/yr and 1.25036 x $10^{-9}$/yr respectively and shown in Table 4. The spreading rates are asymmetrical and the propagation of the strain accumulation also differs accordingly. All the values are positive due to the spreading ridge between SEY1 and the stations such as DGAR, MALD and MADG. In most of the cases, wherever the plates are diverging, less seismicity is observed. More seismicity is observed in the eastern side of study region owing to Indo-Australian plate convergence. Due to the positive strain rate, there is less seismicity in the western part of Equatorial Indian Ocean region (http:// asc-india.org/seimi /seis-kerlak.html). The collision of Indian plate with the Eurasian plate is due to the spreading plate boundaries in the Indian Ocean region. In this process the stress is transferred from the spreading centers towards north (Merkouriev and Sotchevaove., 2003).

The occurrence of earthquakes in the Equatorial Indian Ocean region shows the deformation in that region. The Table 3 shows the baseline length changes between MADG and COCO at the rate of -0.0086 ± 0.0020 m/yr, which indicates that there is a North-South convergence across the eastern side of the Indian plate. The strain accumulation between MADG and COCO is -2.79168 x $10^{-9}$/yr (Table 4). It is noted that the baseline length changes in negative values indicate convergence and the positive values indicate divergence. The distance between the Australian and the Indian continents is decreasing (Demets et al. 1990). The station MADG is in the southern Indian Peninsula and the COCO is in the southern diffuse plate boundary that is stress tensions between India and Australia. In the western side of the Indian plate, the baseline length changes at the rate of 0.005 ± 0.0008 m/yr between DGAR and MADG (Table 3). There is a divergence between Indian and Capricorn plates, represented by MADG and DGAR stations respectively. The strain rate differs from the western portion of the zone of N-S stretching to the eastern portion of diffuse boundary zone between the Indian and the Capricorn plates (Kreemer et al., 2003).

The boundary, which trends in E-W from the Central Indian Ridge (CIR) near Chagos bank to the Ninety degree East ridge and the boundary trending in N-S along the Ninety degree East ridge to the Sumatra trench are in a zone of concentrated seismicity (http://earthquake.usgs.gov/earthquakes). The baseline length between GPS stations COCO near Ninety degree East Ridge to DGAR and MALD in the Chagos ridge is shortening at the rate of -0.0052±0.0036 m/yr and -0.0056±0.0018 m/yr respectively (Table 3). The strain rates are -1.91422 10 x $10^{-9}$ /yr and -1.79516 x $10^{-9}$ /yr respectively (Table 4). These strain accumulation rates are slow and this might have produced the earthquakes in the equatorial Indian Ocean region. (Royer and Gorden., 1997).

The baseline length changes between MALD and MADG is 0.0028 ±0.0009 m/yr (Table 3). The deformation between MADG and MALD is not significant and appears to be rigid. The baseline lengths between the SEY1 and MALD and SEY1 and DGAR are 0.0224±0.0019 m/yr and 0.0196±0.0020 m/yr respectively (Table 3). Both the baseline lengths are increasing. The strain rates are 1.00806 x $10^{-8}$ /yr and 1.03981 x $10^{-8}$ /yr respectively (Table 4). This generates low level of seismicity along this zone (http:/ / asc-india.org/seismi/seis-lerlak.html). Good correlation exists between the seismicity and the strain accumulation. Both the seismic and GPS data are complimenting with each other.

Between Indian and Capricorn plates, a north to south slow divergence in the western side of the Capricorn plate and north to south slow convergence in the eastern side of the plates are observed (Demets and Royer, 2003). There is not much significant deformation in the fracture zone between Indian plate and Capricorn plate. The baseline length between the DGAR and MADG is 0.0050 ± 0.0009 m/yr (Table 4) and the corresponding strain rate is 2.76637 x $10^{-9}$/yr (Table 4). There is very little deformation occurring between edge of DGAR and MADG. A north-south extension occurs near Chagos bank (Stein et al., 1978).

## CONCLUSIONS

The significant inference made in this study is that Cocos is converging towards Indian plate. The strain accumulation rate between Mahendragiri (MADG) and COCO is -2.79168 x $10^{-9}$/yr. The Somalian and South Indian plates are moving away from each other. The strain rates in a year estimated from SEY1 to DGAR, MALD and MADG are 1.03981 x $10^{-8}$, 1.00806 x $10^{-9}$ and 1.25036 x $10^{-9}$ respectively. The spreading rates are asymmetrie and the propagation of the stress also differs accordingly. The study has also revealed that there is very less and insignificant deformation between MALD and MADG. Similarly, very less deformation exists between Chagos ridge and the southern tip of the Indian peninsula viz Mahendragiri. In the western side of Indian plate, the baseline length between DGAR and MADG is moving away at the rate of 0.005 ± 0.0008 m/yr. There is a divergence between Indian and Capricorn plates. In the Southern Indian Peninsula, the convergent rate is close to zero. Most of the stress generated by the plate driving forces at the Mid-oceanic regions is transferred through the South India to the Northern part of Peninsular India. The seismicity is varying from west to east in the equatorial Indian Ocean region. The GPS estimated strain rates have a good correlation with the seimicity in this region. Between Indian and Capricorn plates, north to south slow divergence in the western side of the Capricorn plate and north to south slow convergence in the eastern side were observed. To understand precisely the tectonic environment and the strain distribution in this region additional GPS station data of longer duration is needed.

## ACKNOWLEDGEMENTS:

We thank Dr. Y.J Baskar Rao, Director, NGRI for the permission to publish and Dr. V.P.Dimri former Director, NGRI for his constant encouragement. We also thank Sri. Sampath Paul, Safty Engineer and Mr. Gopal Swamy, Former General Manager of LMF, Mahendragiri for providing us logistic support for operation of Mahendragiri GPS permanent station.

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