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Geodetic Tying of Antarctica and India for Geodynamical and Strain Accumulation Studies in the South of Indian Peninsula with Continuous GPS Measurements at Maitri During 25th IAE

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ABSTRACT

To holistically understand the geodynamical and crustal deformation processes in the south of Indian peninsula between India and Antarctica, two global networks (IND and ANT) have been chosen that geodetically connect the two continents. The IGS Station at Diego Garcia (DGAR) is the common station between the two networks. 10 years of data from 1997 to 2007 were used. By these global networks' analyses, the stations HYDE and MAIT are geodetically tied through DGAR. Very long baselines have been estimated from HYDE and also from Kerguelen (KERG) to other chosen IGS stations in and around India and Antarctica. Our analysis and results using ANT network show an increase in the baseline lengths between Kerguelen in Antarctica plate and other stations such as SEY1, DGAR and COCO and shortening of baseline lengths between HYDE in Indian plate and all these above stations using IND network. The analysis using ANT network also shows lengthening of baselines from Kerguelen to the sites Yaragadee (YAR1) and Tidbinbilla (TID2) in Australian plate; and Seychelles (SEY1) in Male plate, COCO in the diffuse plate boundary between India and Australia and DGAR in Capricorn plate at the rates of 5.3 cm/yr, 3.8 cm/yr, 5.6 mm/yr, 3.03 cm/yr and 5.5 cm/yr respectively. The high rate of movement of COCO Island in comparison to Seychelles could be the result of excessive strain accumulation due to the Indo-Australia diffuse plate boundary forces acting upon this region. The estimated elastic strain accumulation shows an increasing trend of $1.27\times10^{-8}\,yr^{-1}$ in the south of Indian peninsula. Our results show the precision of approximately 3-4 mm (North), 5-6 mm (East), and 10-12 mm (vertical) for the estimation of site coordinates. These results provide new information on the direction and rate of Indian plate motion, the driving mechanisms of Indian plate and intraplate seismicity of the Indian Ocean on the whole.

Keywords: Indian Ocean Basin, Strain accumulation, Geodetic tying, Very long baselines

INTRODUCTION

Very few studies have been conducted on the larger oceanic part of the Indian plate using space geodesy. To holistically determine the kinematics of the Indian OceanBasin between Antarctica and India, the data available are very sparse and characterization and the delineation of the plate boundaries especially in the Indian Ocean are poor. We, therefore, used GPS geodesy to improve the understanding of the complex plate motions, diffuse and poorly located plate boundaries, and striking intraplate deformation that characterize the Indian Ocean basin. This study addresses several of these issues mentioned below:

1. How rigid is the Indian Plate and Indian OceanBasin?
2. Does relatively high level of intraplate seismicity on the oceanic part of the Indian Plate indicates internal deformation in excess of other plates? and,
3. Is this related to Indo-Eurasian collision and the uplift of Himalayas?

All these lead to the new hypothesis that it is possible that at least part of the problem in describing the plate kinematics of the Indian Ocean Basin relates to the unique set of forces on the boundaries. These boundary forces may have lead to frequent plate boundary reorganizations in the past and generation of either small plates such as the Capricorn Plate or a diffuse boundary zone between India and Australia(Gordon et al. 1998) complicating kinematic interpretations. These boundary forces may also contribute to non-rigid behavior of the Indian Plate. In any event, the deformation of equatorial Indian Ocean lithosphere is not ephemeral, but long-lived (Gordon, 1998). The net result of these complexities is that the plate kinematics of the region remains less well described compared to other regions and the issue of plate kinematics is inextricably linked to the question of plate rigidity. Despite the extensive studies on plate tectonics using geophysical investigations in the larger oceanic part of the Indian plate, major issues remain unresolved. Motions across some of the plate boundaries seem well constrained as implied by good agreement between space geodetic and geologic models (Stein and Sella, 2004). In others apparent discrepancies exist.

GPS Data Acquisition

NGRI's permanent GPS Station at Maitri, Antarctica is continuously operational since 1997 and simultaneously having become a permanent geodetic marker, it started contributing to the Scientific Committee on Antarctic Research (SCAR) Epoch GPS Campaigns since 1998.

Two global networks namely IND and ANT have been chosen to geodetically connect the two continents. The IGS Station at Diego Garcia (DGAR) is common to both the networks. 8 years of data from 1997 to 2006 were used. The first network ANT includes Maitri (MAIT), Davis (DAV1), Casey (CAS1) in Antarctica plate and several stations in the adjacent tectonic plates surrounding Antarctica including Seychelles (SEY1), COCO, Hartebeesthoek(HARO), Yaragadee (YAR1), and Tidbinbilla (TID2). The other network IND includes Hyderabad (HYDE) in Indian Plate, COCO, DGAR, HRAO, IISC, IRKT, KIT3, LHAS, POL2, MALD, SEY1, WTZR and YAR1, but for simplicity the stations HYDE, SEY1, DGAR and COCO are shown in the Figure 3.

Since the baseline length between HYDE, India and MAIT, Antarctica is more than 10,000 km, it is mandatory to form these two different networks to improve the accuracy of the baseline measurements by GPS. This approach is to circumvent the limitation in the estimation of baseline length by GPS, maximum of which is 6,900 km. This is due to the availability of less number of double difference observables for the GPS data analysis.

Kerguelen (KERG) in Antarctica Plate was chosen as a reference station, since it is relatively a rigid plate site according to the plate characteristics propounded by IERS. The choice of this reference station provides a very good geographic coverage with respect to the global geometry of our network (Bouin and Vigny, 2000).

GPS Data Processing and Analysis

We used the optimum strategies to process. The data acquired between 1997 and 2007 were processed and analyzed using GPS data processing software Bernese version 4.2 and the time series of all the sites were estimated and the error bars are with one standard deviation. Time series of MAIT site coordinates is shown in Figure 1. The scatter observed in the MAIT time series is due to the change of receiver from Turbo-Rogue to Ash Tech and the WRMS values are within the acceptable limits.

The baselines between Kerguelen and all the other stations have been estimated. Table 1 depicts the minimal base line shortening of all the stations MAIT, DAV1, and CAS1 in Antarctica from KERG, which reveals minimum deformation in this part of Antarctica. The lengths of the baselines

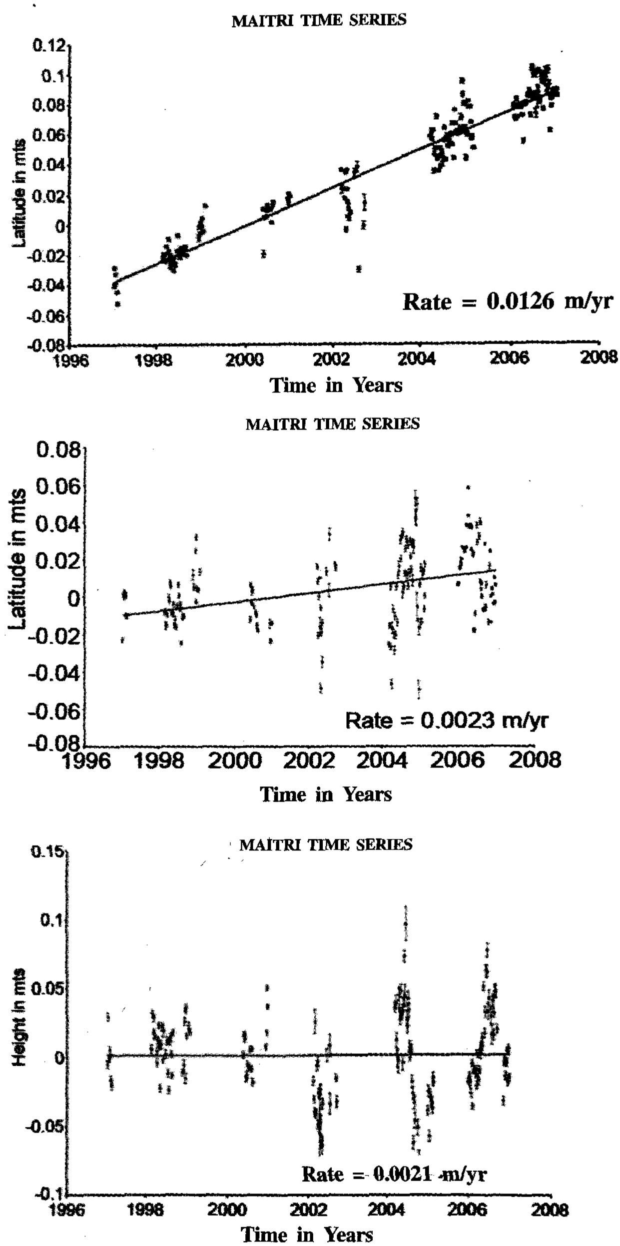

Fig. 1 : Time series of MAIT site coordinates. Site velocity is given by slope of weighted least squares line fit (solid line) through the data (solid circles). Site velocity error (1 standard error) are based on weighted least squares straight line fit, accounting for white noise approximation, total time span of observation and total number of observations

Table 1—Estimated baseline lengths between Kerguelen and other stations, rate of changes and their error (1 standard error) estimates

Sl.No	Stations	Baseline length from Kerguelen(m)	WRMS(m)	Baseline length change/year m/y
1.	Davis	2,172,481.3485	± 0.0003	-0.0019
2.	Casey	2,933,421.2862	± 0.0019	-0.0044
3.	Maitri	3,742,927.3490	±0.0006	-0.0059
4.	Yaragadee	4,323,209.3189	± 0.0883	+0.0530
5.	Hartebeesthoek	4,391,931.1371	± 0.0023	+0.0017
6.	Diego Garcia	4,564,601.5319	± 0.0393	+0.0340
7.	Coco	4,677,608.5252	± 0.0039	+0.0553
8.	Seychelles	5,005,623.2524	± 0.0270	+0.0049
9.	Tidbinbilla	6,103,757.3181	± 0.0777	+0.0378

of our network are between 2000 and more than 6500 km, which makes the ambiguity-fixing impossible.

To eliminate the errors due to non-availability of double difference observables, we included many stations between southern Indian peninsula and Maitri, which have longer time series of site coordinates in the IGS network so that the short baselines between the stations estimated could be tied geodetically.

Table 2—Estimated velocities of all the sites and their error (1 standard error) estimates

SITE	N-VEL (mm/y)	E-VEL (mm/y)	N-ERROR (mm/y)	E-ERROR (mm/y)
MAIT	11.30	2.30	1.009	1.768
CAS1	12.00	7.60	2.222	4.019
DAV1	2.90	6.40	1.495	2.542
YAR1	-50.80	-27.90	5.59	2.49
TID2	-43.50	2.20	9.399	3.472
DGAR	30.28	4.50	1.821	2.267
COCO	40.30	4.80	5.696	3.694
SEY1	3.90	17.80	22.794	11.718
HRAO	-15.80	-23.60	6.087	2.703

Table 2 shows our estimated site velocities in North and East directions and their error ellipses. The velocity vector of each site has been estimated with the weighted least squares fit to the weekly solutions and with the 95% confidence error ellipse. Figure 2 shows the estimated velocity vector map.

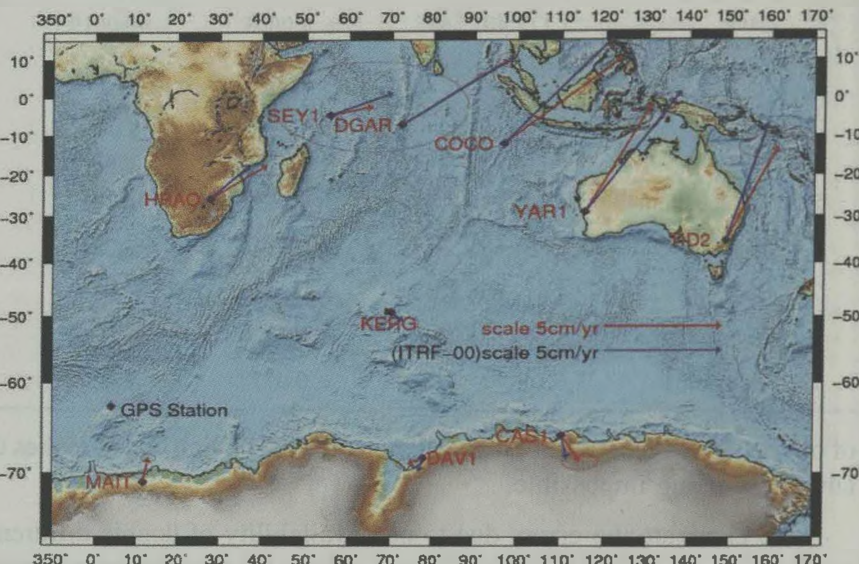

Fig. 2 : GPS site velocities with respect to KERG (red vectors) and relative to ITRF 00 (black vectors). Error ellipses are two dimensional, 95% confidence regions assuming white noise error model

Very long baselines have been estimated using ITRF-2000 from HYDE to other chosen IGS stations in and around India including DGAR. The baseline lengths from Kerguelen to all the other stations having DGAR as a common station for both these networks and the velocity vectors of each site were also estimated. Our analysis and results show increase of baseline lengths between Kerguelen in Antarctic plate and other stations and shortening of baseline lengths between HYDE in Indian plate and other common stations which is depicted in Table 3.

By this global network analyses, the stations HYDE and MAIT are geodetically tied through DGAR.

With this geodetic tie up as shown in Figure 3, having got the geodetic signatures of the geodynamical processes between India and Antarctica, continuous monitoring has enhanced the understanding of the crustal

Table 3—Estimated result of Geodetic tie up between Indian and Antarctica plate

Station	Baseline length (in m)	Baseline change from Kerguelen	Baseline length (in m)	Baseline change from Hyderabad
Seychelles	5,005,623.260381	0.0049m/yr.	3,476,844.689153	-0.0117m/yr.
Diego Garcia	4,564,601.532	0.0340m/yr.	2,790,790.349066	-0.005m/yr.
Coco	4,677,608.665675	0.0553m/yr.	3,783,980.525856	-0.0014m/yr.

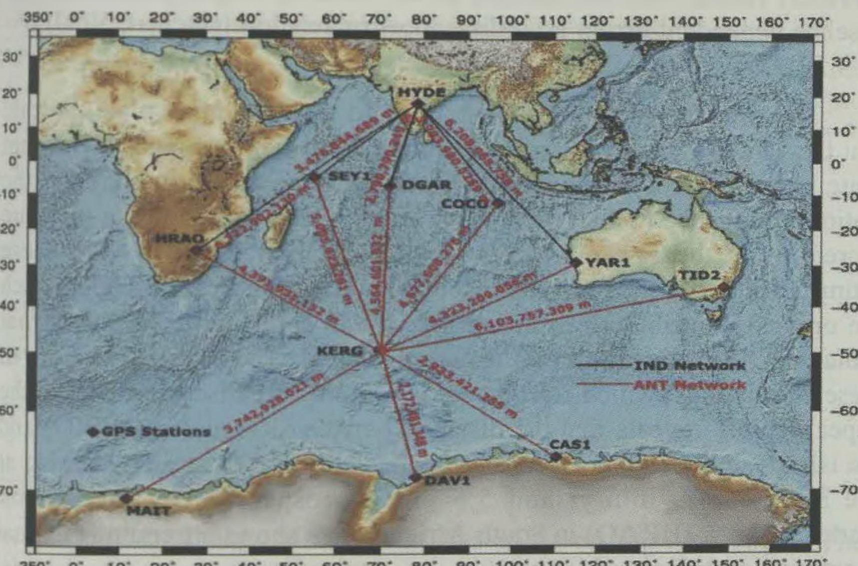

Fig. 3: Map showing the geodetic tie-up India and Antarctica through DGAR mainly and all the other GPS stations in between India and Antarctica forming two different networks with HYDE and KERG being the reference sites for two plates of India and Antarctica. The estimated baseline lengths from HYDE and KERG to all the other stations are also indicated

deformation processes between these two continents despite many plates, micro plates and ridges in this study region.

The inter-continental networks in our study and the data analysis suggest that the high rate of movement of DGAR at the edge of Capricorn plate and COCO could be the result of excessive strain accumulation due to the Indo-Australian diffuse plate boundary forces acting upon this region. Our results also conform to the genesis that the deformation of equatorial Indian Ocean lithosphere is not ephemeral, but long-lived.

RESULTS AND DISCUSSION

The overall analysis is that the estimated baseline lengths between Kerguelen and Maitri and other IGS stations namely Casey, Davis in Antarctica Plate are indeed shortening at the rates of 5.9 mm/yr, 4.4 mm/yr and 1.9 mm/yr respectively The rate of change in the order of mm in the base line lengths indicate no significant change at the one standard deviation level and may be construed as the stations in the same plate are moving together. Table 1 clearly shows the increase in weighted root mean square (WRMS) values with the increase in the baseline length, confirming the baseline dependent errors according to error relation (Litchen, 1990) $ó^2 = A^2 + B^2 * L^2$ with A= 0.5 cm and $B=10^{-8}$.

The velocity vectors of the stations in the Australian plate indicate that they are moving away from the Indian plate conforming to the recent plate tectonic theory. The baseline lengths between Kerguelen and the stations Yaragadee (YAR2) and Tidbinbilla (TID2) in Australian plate are increasing at the rate of 5.3 cm/yr and 3.8cm/yr, respectively. These estimated rates of changes in the baseline lengths of YAR2 and TID2, which are original contribution in this study, are in support of the theory that India and Australia lie in two different plates. The velocity vectors of these two stations, which corroborate this theory are discussed later in the paper. Table 1 reveals that the distance between Kerguelen (KERG) and the islands in the Indian Ocean Seychelles and COCO are lengthening at the rates of 4.9 mm/yr and 5.5 cm/yr, respectively. The station Hartebeesthoek (HRAO) in South African plate shows a trend of minimal shortening at the rate of 1.7 mm/yr.

Our estimation of the velocity vectors of the stations in and around Antarctica do conform to the estimated velocity vectors of SCAR GPS campaigns, which are consistent with rigid plate motion. Our major results provide new information on the overall direction rate of Indian plate motion and on some tectonic processes in the intraplate seismicity of the Indian Ocean, including the elastic strain accumulation. We assess the effects of elastic strain on measured site velocities.

Elastic Strain Accumulation

We computed the strain accumulation using GPS-Geodesy in our global network using the following formula:

Strain accumulation (y^{-1}) = change in baseline length (ΔL)/baseline length (L).

Significant results are emerging. Normally in the intraplate region the strain accumulation is around[6] 10^{-8} to 10^{-10} yr^{-1}. Our results of intraplate strain accumulation within Antarctica Plate covering three sites MAIT, CAS1 and DAV1 are 1.8×10^{-9} yr^{-1}, 1.6×10^{-9} yr^{-1} and 1.1×10^{-9} yr^{-1} respectively. Similarly, the estimates of interplate strain accumulation between Antarctica and other plates such as Somalia (SEY1), Africa (HARO), Australia (YAR1), and diffuse plate boundary between India and Australia (COCO) are found to be $1.1 \times 10^{-9} yr^{-1}$, $1.0 \times 10^{-10} yr^{-1}$, 1.27×10^{-8} yr^{-1} and $1.18 \times 10^{-8} yr^{-1}$ respectively, which is shown in Table 4.

Table 4—Estimated strain accumulation of all the chosen sites

Site	Strain Accumulation
MAIT	1.8×10^{-9} yr^{-1}
CAS 1	1.6×10^{-9} yr^{-1}
DAV1	1.1×10^{-9} yr^{-1}
SEY1	1.1×10^{-9} yr^{-1}
HARO	1.0×10^{-10} yr^{-1}
YAR1	1.27×10^{-8} yr^{-1}
COCO	1.18×10^{-8} yr^{-1}

The rate of change of COCO makes an interesting observation. The high rate of movement of COCO relative to all the other sites agrees with the global strain rate in the Indian Ocean near COCO, proposed by Gordon et al. (1998) and Kreemer et al. (2003).

The increase in baseline length between KERG and SEY1 at the rate of 5.6 mm/yr clearly indicates that SEY1 is moving away from KERG. The velocity vector of SEY1 shows the movement towards the Indian peninsula and this also agrees with the plate model (Gordon et al., 1989). If this rate of movement is verified upon, this may result in the increase in the strain accumulation in the southern Indian Peninsula.

It is evident from Plate kinematic studies that the strain rates are higher up to a factor of 25 in the weak diffuse plate boundaries than in the strong plate interiors particularly in the region between 75° E and 100° E longitude in the Indian Ocean (Gordon, 1998). This is also corroborated by IERS in their estimation of Plate Sites characteristics by ITRF 2000 reference frame by declaring that the region between about 75°E and 100°E longitude is a deforming zone.

CONCLUSIONS

High-precision space–geodetic data from 1997 to 2007 have been analysed to investigate the tectonic activity, plate boundary organizations, crustal deformation in the southern Indian peninsula, the driving mechanisms and the response of the Indian Ocean lithosphere.

By the two global networks (IND and ANT) that have been chosen and analysed, the stations HYDE and MAIT are geodetically tied through DGAR. With this geodetic tie up and the geodetic signatures of the geodynamical processes between India and Antarctica, continuous monitoring has enhanced the understanding of the crustal deformation processes between these two continents. GPS data from 3 sites MAIT, CAS1 and DAV1 within Antarctica plate shows in the accumulated strain of the order of 10^{-9} yr^{-1}. Similarly an order of 10^{-8} to 10^{-10} yr^{-1} for accumulated strain is the result between Antarctica and other plates where the stations SEY1, HARO, YAR1 exist and the diffuse plate boundary. GPS data at COCO suggests the high rate of movement that could be the result of excessive strain accumulation due to the Indo-Australian diffuse plate boundary forms acting upon this region. The GPS analysis confirms the emergence of diffuse plate boundary between India and Australia and relates to the late Miocene Himalayan uplift. The calculated stress field in the West of the Indian Peninsula has a roughly N-S directed tensional and E-W oriented compressional character (Bendick and Bilham 1999; Sella et al. 2002) and the velocity vectors of all other sites throw a significant insight into the plausible causes of the strain accumulation processes in the Indian Ocean and the northward movement of Indian plate.

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