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GPS-Geodesy with GNSS Receivers for Indian Plate Kinematics' studies with the recent plate velocities estimated from GNSS data

E.C.Malaimani, N.Ravi Kumar, A.Akilan and K.Abilash
National Geophysical research Institute, Uppal Road, Hyderabad – 500 606
E.mail : malaimani@gmail.com

ABSTRACT
Already estimated Indian Plate motion at the rate of 37 ± 0.2 mm/yr towards NNE direction with respect to Eurasian Plate has been revalidated with the new state-of-the art GNSS receivers and a new global network spreading the geographical and azimuthal coverage, which almost includes all the plates surrounding India. 12 years of GPS data from 1995 to 2007 from the Hyderabad IGS GPS Permanent Station (HYDE) have been processed in the global network solution along with the data from other 11 stations. The baseline lengths from Hyderabad to other chosen sites and the rate of changes were also estimated. The angular velocity of Indian plate motion with respect to ITRF 05 reference frame and Indo-Eurasia plate pair have also been estimated. The global network solution has resulted in the estimation of the pole of the angular velocity vector of India with respect to Eurasia to be about a pole of rotation at 29.44 ± 1.2° N, 13.2 ± 7.3° E with an angular velocity of 0.356 ± 0.035° Myr^{-1}. Our results mostly conform to the REVEL-2000 Plate motion model but differs considerably from NUVEL-1A and other earlier studies. This departure could be attributed to the difference in geologic and geodetic estimations. The longer time span of GPS data from the central part of India yields more accurate estimations. This analysis is in the global network solution, which doesn't take the plate- interior site velocities into account.

INTRODUCTION

The GPS-Geodesy program was initiated in 1995 by establishing an International GPS Services for Geodynamics (IGS) Permanent Global Positioning System (GPS) Tracking station at National Geophysical Research Institute (NGRI), Hyderabad (HYDE), India for the studies on Indian Plate Kinematics. The India–Eurasia collision zone and Indian Plate Motion have been the focus of intense studies by the Space geodetic community. Global plate motion models predict that approximately 5.0cm/yr of northward directed convergence is taken up between India and Eurasia (DeMets et al., 1990,1994). But geologic and seismic evidence suggests that 1.8 ± 0.7cm/yr of the convergence is expressed as shortening across the Himalaya (Molnar & Deng 1984, Armijo et al., 1986, Molnar & Lyon-Caen 1989) meaning that the remaining two thirds of the total convergence is accommodated elsewhere. The plausible causes and mechanisms for this accommodation have been widely discussed by Larson et al., 1999. So far space geodetic studies by GPS have been made in southern and central India that bears on the rigidity of the Indian plate (Malaimani et al., 2000, Paul et al., 2001), whose velocity data for 2 sites fit the rigid plate model within uncertainties, estimated to be about 3.7 cm/yr for HYDE and 3.9 cm/yr for IISC. The mean rate residual (1mm/y) is also compatible with earlier plate kinematics studies of Indian Plate. This original estimation significantly differs from NUVEL-1A plate model but in perfect agreement with the recent plate motion model proposed by Sella et al., (2002) and Gordon, Argus & Heflin (1999). It is unclear whether the difference between the geodetic and geologic rates reflects a true deceleration in the relative velocity of Indian Plate with respect to Eurasian Plate or a Systematic error in NUVEL-1A.

Very recent global network solution with the inclusion of additional IGS GPS stations such as HYDE, IISC, MALD and mahe, the second permanent station of NGRI at Mahendragiri, Tamil Nadu in the south which was installed in December 2002 in Indian Plate, Seychelles (SEY1) in Somalian Plate, COCO on the southern edge of Indo-Australia diffuse boundary, apart from Lhasa (LHAS), Kitab (KIT3), Bishkek (POL2), Irkutz (IRKT), and Wettzell (WTZR) in the Eurasian plate and Yaragadee (YAR1) in Austalian Plate and Hartebeesthoek (HRAO) in the African Plate has improved the geographic and azimuthal coverage. In this study the Indian Plate is defined using two sites HYDE, and Bangalore (IISC) and the Eurasian plate by two sites (LHAS), (IRKT) and (POL2) for estimating the angular velocities.

1.3. Inclusion of the site mahe at the southern most tip of India and SEY1 and COCO helps us to understand holistically the Indian plate kinematics and also the strain accumulation processes in the southern Indian peninsula.

GPS DATA ACQUISITION AND ANALYSIS

The data acquired since 1995 to 2006 from the IGS Permanent GPS Tracking station at NGRI have been used in the analysis along with the data from all the other IGS stations and the permanent station *mahe* and the data was processed in the global network solution using Bernese version 4.2. The strategy used in the data processing and analysis is given in Table 1.

Table 1. Strategies adopted for GPS Data processing.

Parameters	**Description**
GPS Processing Software	Bernese Version 4.2
Sessions	24hours
Earth orientation parameters	IERS Bulletin B
Elevation angle cut-off	15º
Ambiguity Resolution	Free-Not Resolved
Tropospheric dry delay Model	Saastamoinen
Tropospheric Wet Delay	Estimated every 4 hrs.
Apriori station positions	ITRF 00
Station Position constraints	Free Network Approach

Time series for the time span of this study for all the stations have been estimated. The data processing was with reference to ITRF-2000.Very long baseline lengths have been estimated from HYDE to all the other stations. Table 2 shows the baseline lengths and their WRMS values.

Finally the velocity vectors of all the stations have been estimated with the error ellipse of 95% confidence limit. The angular velocity for India and Eurasia and also the India-Eurasia plate pair have been estimated using the program of Ward (1990).

Table 2. Estimated baseline lengths from Hyderabad to all the other stations with their WRMS value.

From Hyderabad to	Baseline lengths in m.	WRMS in m.
IISC	497,625. 7884	± 0.003025
MAHENDRAGIRI	1,014,982. 1927	± 0.004122
MALDIVES	1,558,701. 8940	± 0.005545
LHASA	1,856,738. 4141	± 0.007693
KITAB	2,640,353. 3932	± 0.007716
POL2	2,801,709. 03251	± 0.009038
SEYCHELLES	3,476,844. 6149	± 0.031368
COCO	3,783,980. 6255	± 0.041793
IRKUTZ	4,381,644. 0656	± 0.051269
YARAGADEE	6,208,968. 8268	± 0.052618
WETZELL	6,481,302. 5592	± 0.056789
HARTEBEESTHOEK	6,905,048. 2338	± 0.07888

RESULTS AND DISCUSSION

The evolution of the time series of HYDE (Fig.1) has been estimated for the time span of 1995 to 2006. As observed in this study, the horizontal components of 10-year time series will be in the range from < 0.5 to 1.5 mm/yr. However, in order to obtain adequate geographic and azimuthal coverage, we have also used stations like ***mahe*** with time span of about 3 years. This type of station will have horizontal component velocity uncertainties of ~2-5mm/yr with the best analytical technique adopted.

Similarly the coordinates of all the stations involved in this study were estimated to compute the individual site velocities. Velocity estimates are based on the weighted least squares linear fit to the daily position estimates and the site velocities are derived from the slope of the linear fit. Table 3 gives the north and east velocities of all the stations with the sigma values with 95% confidence limit.

The sigma value ranges between 0.13mm/yr for POL2 and 1.04mm/yr for SEY1 indicating the quality of data processing. Figure 2 shows the estimated velocity vectors and the error ellipses.

The baseline vectors and the rate of change of baseline lengths from HYDE to other chosen stations have been estimated to the sub-centimeter accuracy. Table 3 shows the baseline lengths and the weighted root mean square (WRMS) values for all the stations. The increase in WRMS values with the increase in baseline lengths can be seen in the table 3.From the

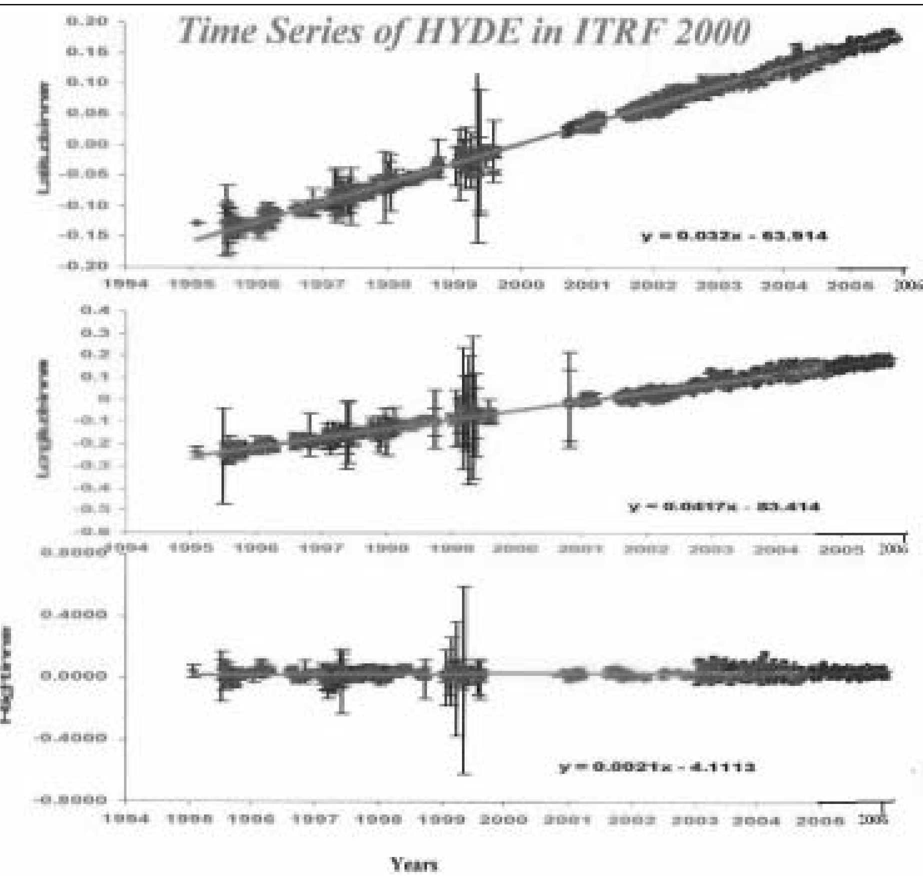

Figure 1. Evolution of the time series of geodetic coordinates of HYDE IGS station over the time span of 1995 to 2006 in ITRF 00 Reference Frame.

Table 3. Station velocities with respective standard deviations with 95% confidence limit.

Station	Evel cm/yr	Nvel cm/yr	E sigma mm/yr	N sigma mm/yr
COCO	2.95	3.53	0.44	0.32
HRAO	2.26	0.17	1.63	0.48
HYDE	4.28	2.10	0.34	0.18
IISC	4.38	2.12	0.36	0.20
IRKT	2.87	-0.81	0.35	0.14
KIT3	3.03	3.14	0.27	0.14
LHAS	4.62	0.24	0.35	0.14
MAHE	1.90	0.14	0.36	0.21
MALD	6.32	1.6	0.39	0.25
POL2	4.76	0.004	0.28	0.13
SEY1	1.78	0.40	1.94	1.04
YAR1	2.79	5.08	0.55	0.24

estimated baseline lengths for all the stations, it can be confidently construed that the baseline lengths between HYDE and other IGS stations beyond Himalayas are indeed shortening, clearly revalidating the earlier estimation of Malaimani et al.2000.

From the site velocities data listed in Table 3, we computed the best-fit angular velocity vector (Euler vector) describing the relative motion of adjacent plates. For the Eurasian plate three sites LHAS, IRKT and POL2 and for the Indian plate HYDE and IISC have been chosen to compute the angular velocities of India, Eurasia and relative angular velocity for India-Eurasia plate pair with Eurasia fixed. The site velocity data was inverted to derive the best fit angular velocities for each plate with reference to ITRF 00 minimizing the weighted lease squares misfit to the data for a given plate as described by Ward (1990) and Mao (1998). The estimated angular velocity with reference to ITRF-00 for Eurasia is 59.82° N, -102.60 ° E and 0.3409° Myr^{-1} and for India 46.44° N, -16.59° E, and 0.4904° Myr^{-1} respectively. Relative angular velocities for pairs of adjacent plates are then derived by differencing the ITRF-00 angular velocities. Our

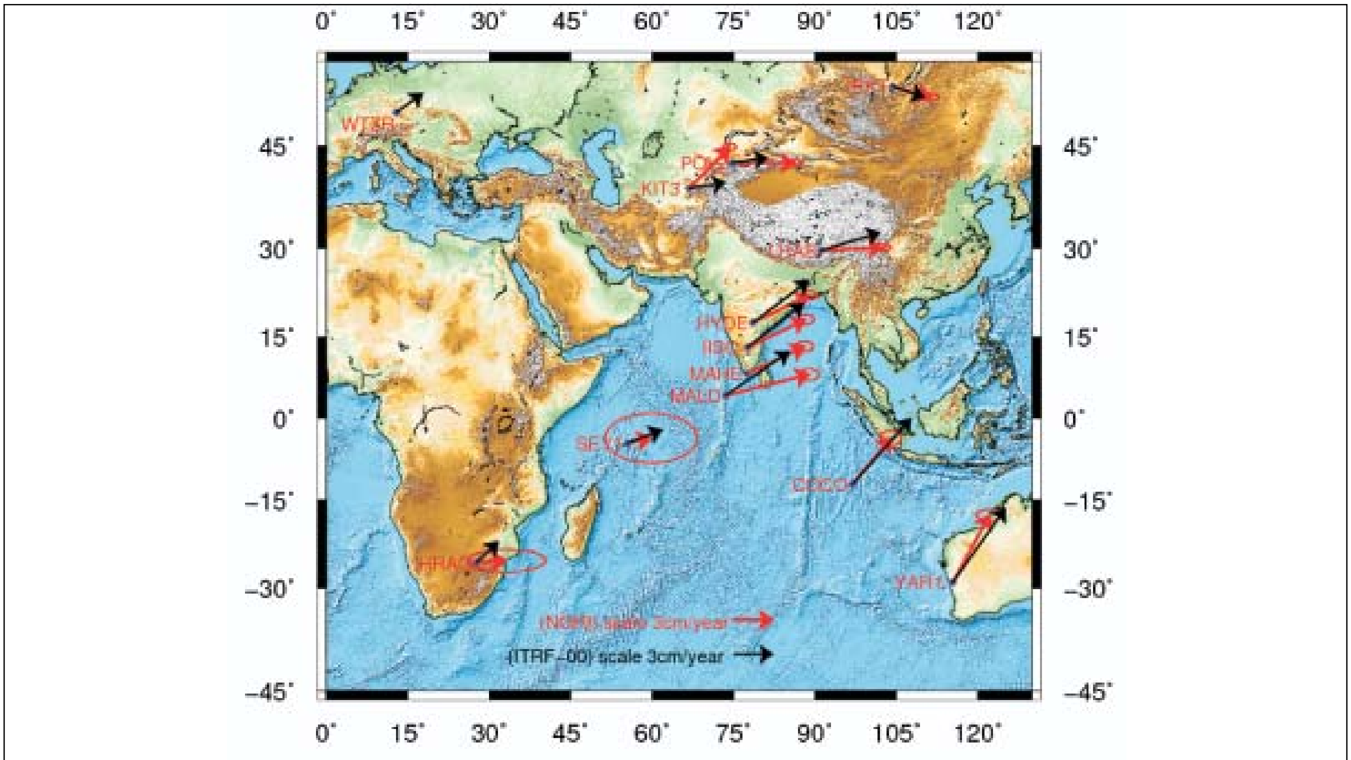

Figure 2.Estimated GPS station velocities with 95% error ellipses. These estimated site velocities are compared with ITRF 00 velocities. The Red line indicates our estimation and the black line indicates the ITRF 00 velocities.

global network solution has resulted in the estimation of the pole of the angular velocity vector of India with respect to Eurasia to be about a pole of rotation at 29.44 ± 1.2º N, 13.2 ± 7.3º E with an angular velocity of 0.356 ± 0.035ºMyr^{-1} (Malaimani & Ravi Kumar 2006). Table No.4 shows the comparison of results.

NUVEL1-A plate motion rates that are constrained only by seafloor spreading data, transform-fault strikes, and focal mechanisms estimates the angular velocity vector for India to be 24.5 ± 1.8º N, 17.7 ± 8.8º E at 0.51 ± 0.06º Myr^{-1} which is 5º E and 30.2% faster than our estimate. Holt et al., (2000) use a combination of Quaternary fault slip rates and GPS observations and estimated the angular velocity vector to be at 29.88º N, 7.50º E with an angular velocity of 0.35 Myr^{-1}. This is 6ºE and 1.7% slower than our estimate but still almost conforms to our estimate as it is well within the 95% confidence limit. REVEL-2000 (Sella et al., 2002), the recent global plate motion model includes recent plate velocities of 19 plates and continental blocks and uses primarily the GPS data and for a longer period of time span from 1993 to 2000. The angular velocity vector estimate given by this model is 28.56 ± 14.4º N, 11.62 ± 1.1º E at 0.357 ± 0.033º Myr^{-1}. This is 2º E and just 0.28% slower than our estimate. This small difference between REVEL-2000 and our estimate (the angular velocity of 0.357º Myr^{-1} by REVEL and 0.356º Myr^{-1} by us) is very much negligible and hence it could be construed that our estimate is in perfect agreement with REVEL-2000. Figure 3 shows the comparison of angular velocity vector poles and rates of India-Eurasia relative motion from NUVEL1-A, combination of regional GPS and Quaternary fault slip data of Holt et al., (2000), REVEL-2000 by Sella et al., (2002) and geodetic data using GPS by us in this study.

Table 4. The comparison of Angular velocity poles and rates of Eurasia –India relative motion from our study with NUVEL1-A data, REVEL-2000 data (Sella et al., 2002) and combination of regional GPS and Quaternary fault slip data of (Holt et al., 2000)

Studies	**N**	**E**	**Angular Velocity (ω°/Myr^{-1})**
Our Study	29.44 ± 1.2° **N**	13.20 ± 7.3° E	0.356 ± 0.035
REVEL-2000	28.56 ± 14.4° **N**	11.62 ± 1.1° E	0.357 ± 0.033
Holt et al.,	29.88° **N**	7.50° E	0.35
NUVEL- 1A	24.50 ± 1.8° **N**	17.70 ±8.8° E	0.51 ± 0.06

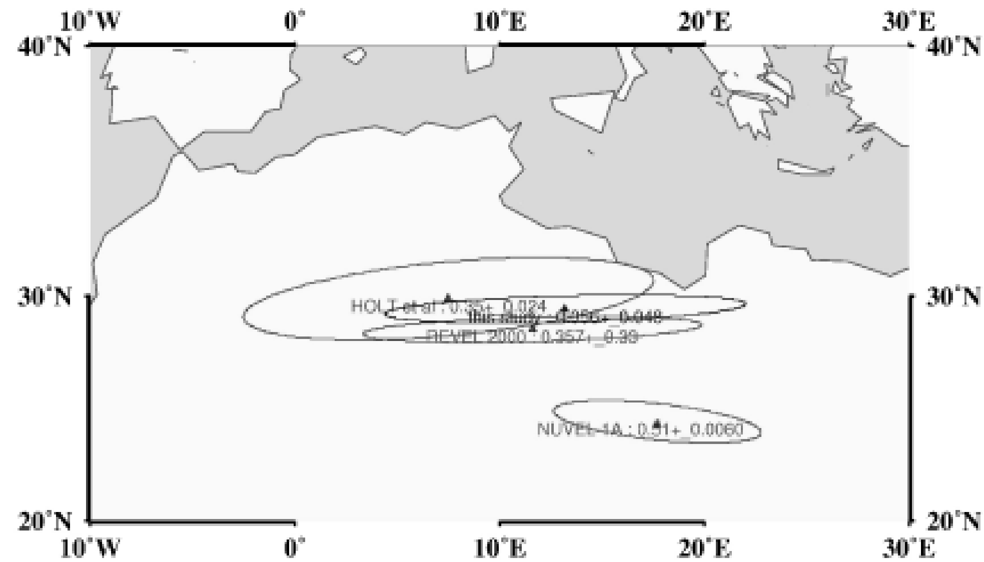

Figure 3. Comparison of Angular velocity poles and rates of Eurasia –India relative motion from our study with NUVEL1-A data, REVEL-2000 data (Sella *et al* 2002) and combination of regional GPS and Quaternary fault slip data of (Holt *et al*., 2000). The blue color indicates our study.

CONCLUSIONS

The new global network with the inclusion of an IGS permanent GPS station HYDE in the central part of India and a longer time span of 11 years of GPS data when analyzed and processed in the global network solution revalidate the earlier studies of Indian plate motion relative to Eurasian plate. This new global network also agrees well with the earlier studies that the Indian plate is moving slower than that predicted by the global plate motion model NUVEL1-A. The GPS derived angular velocity vectors are in perfect agreement with REVEL-2000 global plate motion model and the studies by Holt *et al* (2000), though there is a considerable departure from NUVEL1-A. The inclusion of Seychelles and Coco in the network, the estimation of high rate of movement of COCO and the estimation of the strain accumulation are very significant pointers to the increase in the elastic strain accumulation in the south of Indian peninsula.

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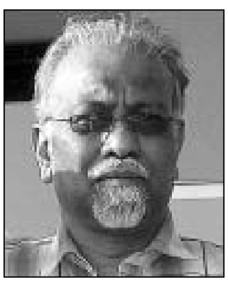
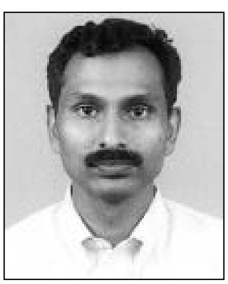
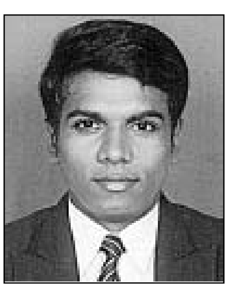
Dr.-Ing.Mrs.E.C.Malaimani is basically an Electronics and Telecommunication Engineer from College of Guindy, Chennai. She has served in Defence Electronics Research Laboratory, Hyderabad before joining NGRI. She has the distinction of being the first Indian to be awarded Ph.D by University of Bonn, Bonn, Germany in 1999.Currently she is the Project Leader of GPS and Antarctic Studies. Her interest includes GPS Studies for crustal deformation, continental dynamics, Indian Plate Kinematics, seismotectonics, Real Time Kinematics using DGPS, Digital Cartography and Mapping Applications, Plate tectonics and Geodynamics. She has supervised many masters and doctorate students from various universities. She has about 35 papers in all the reputed scientific journals.



Mr. N.Ravi Kumar is basically an Electrical and Electronics Engineer from College of Guindy, Chennai. He has served in CSIO, Hyderabad before joining NGRI. He has the expertise in Digital Signal and Image processing apart from Space-Geodetic techniques. Currently he is the Co-Project Leader of GPS and Antarctic Studies. His interest includes GPS Studies for crustal deformation, continental dynamics, Indian Plate Kinematics, seismotectonics, and Real Time Kinematics using DGPS,Plate tectonics and Geodynamics. He has about 35 papers in all the reputed scientific journals.



Mr. A. Akilan is currently working as Scientist-B in NGRI. He did his B.E (ECE, 1992) from Madurai Kamaraj University and M.Tech (IT, 2005) from Punjabi university. Currently he is pursuing M.S (Spatial information Technology) at JNTU. He also received his Post-graduate diplomas (PGDPM, PGDPR and DLL) from Annamalai University & HDCM from National Council for Co-operative Training. He got his professional training from IIT, Bombay in GPS Technology and its applications. He has presented several papers in national & international conferences and published papers in the field of GPS-Geodesy. Currently he is working on the relative motion between India and Antarctica using GPS Technology. He participated in XXII and XIII Indian Antarctic Scientific expeditions.



Mr. K. Abilash is currently working as Project Assistant in NGRI. He did his Bachelor of Engineering (ECE, 2006) from Anna University. He has undergone various software-training programs. He got experienced in computer hardware, networking and software. Currently he is pursuing his research in crustal deformation studies using GPS Technology.