Akilan, A., Abdul Azeez, K. K., Schuh, H., Yuvraaj, N. (2015): Large-Scale Present-Day Plate Boundary Deformations in the Eastern Hemisphere Determined from VLBI Data: Implications for Plate Tectonics and Indian Ocean Growth. - *Pure and Applied Geophysics*, *172*, 10, pp. 2643—2655.

DOI: http://doi.org/10.1007/s00024-014-0952-2

Large-scale present-day plate boundary deformations in the Eastern hemisphere determined from VLBI data: Implications for plate tectonics and Indian Ocean growth

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Abstract

Dynamics of the planet Earth is the manifestation of the diverse plate tectonic processes, which have been operational since the Archean period of Earth evolution and continue to deform the plate boundaries. Very Long Baseline Interferometry (VLBI) is an efficient space geodetic method that allows the precise measurement of plate motions and associated deformations. We analyze here the VLBI measurements made during a period of about three decades at five locations on the Eastern hemisphere of the globe, which are geographically distributed over five continents (plates) around the Indian Ocean. The computed baseline length rates show the deformation pattern and its rate at the boundaries between the major tectonic plates constituting the Eastern Earth hemisphere. The African

(Nubian) and Antarctic plates are moving apart at 13.5 mm/yr, which is mostly attributed to South West Indian Ridge spreading. Similarly, a spreading rate of 59.0 mm/yr is observed for the South East Indian Ridge that separates the Antarctic and Australian plates. Shortening at the rate of 3.9 mm/yr is estimated across the subduction boundary between Africa (Nubia) and Eurasia. Similar kind of convergence process is evident between the Australian and Sunda blocks (of the Eurasian plate). The associated deformation of -54.8 mm/yr appears to be chiefly accommodated along the Banda arc system, where the Australian plate is subducting under the Sunda block. VLBI sites within the Eurasian plate, Wettzell in Germany and Seshan on the South China block, are moving apart at a rate of 3.6 mm/yr. This relative motion between locations on the same plate is interpreted to be due to the deformation process along a large strike-slip fault, which is identified as the Western boundary of South China block. Indian Ocean expansion, at the rate of +91.5 m^2/yr, is also estimated from the deformation rate estimated within the five baselines studied here. From the Hurst exponent values, which is an indicator of the future trend of a time series data, we predict the deceleration of the various tectonic processes that are operational at present.

Key words: VLBI; Plate tectonics; Crustal deformation; Eastern hemisphere; Indian Ocean; Hurst exponent; Strain rate.

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1. Introduction

The plate-tectonic theory envisages the movement of rigid lithosphere plates (oceanic and continental) over the ductile (convecting/weak) asthenosphere and provides an explanation to the various tectonic deformations on the Earth. Diverse kinematics of the tectonic plates include the convergence, divergence, and the strike-slip motions, which are the mechanisms responsible for the distinct tectonic deformation processes, namely the subduction, seafloor-spreading, and the occurrence of earthquakes, respectively. These tectonic processes produce small to large scale plate motions and deformations (shortening, extension, upliftment or subsidence) on the Earth surface; therefore result in surface displacements (horizontal and/or vertical) on the spherical Earth. The kinematics of the tectonic plates (plate motion velocity) and deformation of the Earth surface can be studied using terrestrial and space geodetic measurements, such as Very Long Baseline Interferometry [VLBI] (Schuh and Behrend, 2012, and references therein), Global Positioning System [GPS] (e.g. Larson and Agnew, 1991; Bouin and Vigny, 2000; Sella et al., 2002), synthetic aperture radar interferometry [InSAR] (e.g. Burgmann et al., 2000, and references therein; Garthwaite et al., 2013), and Satellite Laser Ranging [SLR] (e.g. Christodoulidis et al., 1985; Smith et al., 1990).

VLBI is a space geodetic technique that allows to determine precise coordinates on the Earth to monitor the variable Earth rotation and orientation with highest accuracy, and to derive many other parameters of the Earth system (Schuh and Behrend, 2012). VLBI is thus a highly preferred tool for geodesy (e.g. Petrov et al., 2009), geodetic astronomy (e.g. Schlüter and Behrend, 2007; Doeleman et al., 2008), and geodynamics (e.g. Lyzenga et al., 1986;

Ward, 1990; MacMillan, and Ma, 1999; Campbell and Nothnagel, 2000; Haas et al., 2000). In geodetic applications of VLBI, the difference between the arrival times of radio signals emitted by deep space sources (e.g. quasars or radio galaxies) at each of the two radio telescopes is measured precisely and the distance between them (i.e. the baseline length) is computed. VLBI has the advantage of computing the baseline lengths that range from several tens of kilometers to several thousands (~10000 km) of kilometers with sub-centimeter accuracy (Herring, 1992; Schuh and Böhm, 2013), which makes it a useful and efficient tool for both large (global and intercontinental, e.g. Herring et al., 1986; Ryan and Ma, 1989) and local/regional scale (e.g. Clark et al., 1987; Haas et al., 2003) geodynamic studies (Hinteregger et al., 1972; Whitney, 1976; Yen et al., 1991; Teke et al., 2010). VLBI is the only technique today for the determination of the International Celestial Reference Frame (ICRF) (Ma et al., 1990; Schuh and Böhm, 2013) and it also contributes to the realization of the International Terrestrial Reference Frame (ITRF) (Böckmann et al., 2010; Altamimi et al., 2011; Schuh and Böhm, 2013). Though the VLBI station distribution over the globe is limited, the present array of VLBI stations is used for the precise determination of Earth deformation (horizontal and vertical displacements) due to plate motions and earthquakes (e.g. Petrov et al., 2009).

The Indian Ocean is the central stage for some of the prominent tectonic processes in the current global geodynamics as it is the meeting point of a few major tectonic plates of the Earth (Figure 1). Therefore, the kinematics and deformation of the region encompassing the active plate tectonic margins would be of some interest, particularly in the global context. The rate and extent of deformations associated with some of these geodynamic processes were studied by several authors using geodetic measurements, chiefly employing GPS geodesy (e.g. Bilham et al., 1997; Reilinger et al., 1997; Michel et al., 2001; Reilinger et al.,

2006; Gahalaut et al., 2013; Yadav et al., 2013), which are mostly limited to local/regional scale. For the first time, we study here a relatively larger scale of the globe (intercontinental scale) around the Indian Ocean to understand the deformation pattern and its estimate using the more precise VLBI technique. This is achieved by calculating the intercontinental baseline length between the available VLBI sites located on the different continents surrounding the Indian Ocean. Accurate computation of baseline lengths of intercontinental scale achieved by VLBI measurements allow us to study the large scale horizontal plate motions caused by tectonic processes in this part of globe. We also speculate on the future trend of the plate tectonic motions in this region from the evaluation of the Hurst exponent.

2. VLBI data and analysis

In this study, VLBI measurements from five stations located on the different continents/tectonic plates in the Eastern hemisphere are used. The five measurement sites are: Wettzell (Wz) in Germany (Europe), Seshan (Sh) in China (Asia), HartRAO (Hh) in South Africa (Africa), Syowa (Sy) in Antarctica (Antarctica), and Hobart (Ho) in Australia (Australian) (Figure 1). As seen from Figure 1, the continents associated with these sites surround the Indian Ocean. Most of the VLBI stations are located reasonably away from co-seismic and post-seismic deformation zones and thus can be characterized as suitable VLBI recording points for plate motion and plate boundary deformation studies. The station Seshan, however, might have been affected by co and post-seismic deformations as indicated by the ~5 mm horizontal displacement (mainly in the east direction) during the Tohoku-Oki earthquake (Mw=9.0) in Japan (Hooper et al., 2013). Measurement of relative continental movements and crustal deformations are possible when at least one site from each plate

considered for the study has taken part in a VLBI geodetic session, i.e. simultaneous VLBI recording at two different locations. If stations have a sufficient observational history in terms of number of sessions and time span, a relative linear annual drift of the plates can be estimated. This study uses the VLBI data recorded mostly from 1987 to 2013. These measurements span almost three decades and thus provide sufficient VLBI sessions to determine the rate of baseline changes (annual rate) for geodynamic and plate boundary deformation studies. The details of the VLBI sites and of the recording periods, as well as the number of sessions used for the baseline length computation are listed in Tables 1 and 2. It can be seen from Table 2 that because of operational difficulties, Syowa station located in Antarctica participated in relatively few measurements. Prior to the baseline estimation, the necessary processing of the data has been carried out. Processing contains the steps to reduce the errors including instrumental and environmental (ionosphere delay, troposphere delay, source structure delay) corrections. Details of the data reduction, corrections and further analysis to compute the baseline lengths are described in Schuh and Böhm (2013). The processing of the data is done using the software VieVS developed at Vienna University of Technology (Vienna) and the baseline lengths corresponding to each individual observing session (experiment) are computed for a particular combination of VLBI sites. The baseline length estimates for the entire period of measurements (whole data from the inception of the individual station) are further analyzed to estimate the rate of change per year, which would shed light on the ongoing tectonic movements associated with the Indian Ocean region.

Baseline length and its changes with time between five pairs of VLBI sites, namely HARTRAO-SYOWA, SYOWA-HOBART, WETTZELL-HARTRAO, HARTRAO-SESHAN, and WETTZELL- SESHAN, were analysed. These five baselines altogether form an envelope and almost completely encircle the Indian Ocean. The above five pairs are

constrained by the participation of a particular site in a VLBI session (i.e. simultaneous recordings at a pair of sites). The estimated baseline lengths for each combination of sites for the available measurements are plotted against the observation time (Figure 2). A least-squares fit for the baseline length time series is carried out. The slope of the best fit line gives the rate of change of the baseline length with time. The obtained baseline length rate for the five arms considered in this study, as well as the strain rate (ratio between rate and length of baseline length), are given in Table 3. Baseline length changes between other possible combinations of stations (e.g. SESHAN-SYOWA, WETZELL-SYOWA, HARTRAO-SESHAN, etc.) were not analyzed either due to the absence or due to the lack of sufficient measurements involving those pairs.

The law containing geological evolution can be analyzed using spectral analysis (Botezatu, 1970). The power spectra (P) of the baseline length signal observed in this study is computed using the power-law relation:

$$P(f) = P_o f^{\alpha}$$

where, α is the spectral index, P_o is a constant and f is the frequency (Agnew, 1992; Mao et al., 1999). The spectral index α calculated for each pair is shown in Figure 2. Here, a time span of ten days corresponds to 1.15×10^{-5} Hz, a year corresponds to 3.16×10^{-8} Hz, and a time span of ten years corresponds to 3.16×10^{-9} Hz. There are no yearly or monthly variations seen in the power spectra. The GPS signals generally show annual and semi-annual fluctuations (Prawirodirdjo and Bock, 2004). However, such annual or monthly variations are not present with the VLBI estimations, which is an additional advantage of the VLBI data over GPS data. But, there are dips and peaks present in the power spectrum at different frequencies (or corresponding time periods), which may be due to unmodelled signals from

oceanic, atmospheric, or hydrological loading (e.g. Scherneck, 1991). Detailed studies on these factors are beyond the scope of this paper.

The estimated spectral index, as derived from the power spectrum analysis, is further used to estimate the Hurst exponent (Mandelbrot, 1983), which helps predicting the future trend of the plate motions in the region (e.g. Akilan, 2013). The Hurst exponent (H) is defined as:

$$H = {}^{1}/_{2} (\alpha\text{-}1)$$

where α is the spectral index, which is obtained from the power spectrum analysis (Mandelbrot, 1983; Agnew, 1992). The Hurst exponent is a measure to classify any time series. It indicates random nature of the time series when H=0.5, while a reinforcing trend can be assumed when the value of H > 0.5 (e.g. Nickolaenko et al., 2000; Qian and Rasheed, 2004, 2007; Redondo, et al., 2010). Table 4 gives the estimated spectral indices and the corresponding Hurst exponents.

3. Results and discussion

The rate of baseline length per year (baseline rate) computed for the five VLBI station pairs and the average baseline length values are shown on the simplified tectonic map of the study region (Figure 1). The baselines are approximately normal to the major plate boundaries, except the baseline between Syowa-Hobart (i.e. between Australia and Antarctic plates) that makes a sharp angle. The strain rates (ratio of changes in baseline length per year

to the baseline length) are also estimated between each pair of sites and are presented in Table 3 along with its baseline length rate and the average baseline lengths. Below, we discuss these results and their relevance to the present day plate tectonic processes for each pair of VLBI sites.

3.1 HARTRAO-SYOWA

The average baseline length and its rate of change between the sites HartRAO in the African continent and Syowa in the Antarctic continent is estimated to be 4741786.094 m and +13.5 mm/yr, respectively. The annual rate of the baseline change of +13.5 mm/yr between these two sites indicates that these two points on two different continents move apart. The major plate tectonic process occurring in the region occupied by these two VLBI measuring points is the slow spreading Southwest Indian Ridge (SWIR). Hence, the observed increase in baseline length per year can be mostly associated with the spreading of SWIR, which is present between the Bouvet triple junction (54^{O} 17' 30" S, 1^{O} 5' 0" W) in the Atlanic Ocean and the Rodrigues triple junction (25^{O} 30'S, 70^{O} 0'E) in the Indian Ocean. Sempere and Klein (1995) showed a slow spreading between 13 and18 mm/yr for the SWIR, which is quite consistent with our result. DeMets et al. (1988) also previously obtained similar spreading rates (14-18 mm/yr) across the SWIR. DeMets et al. (1994, 2010) also computed spreading rates within this range. Therefore it is reasonable to conclude that the deformations occurring between the African plate and the Antarctic plate are solely due to the divergent tectonics along the SWIR. The Marion hotspot spotted near to the SWIR may possibly influence the SWIR spreading rate and the pattern due to the hotspot interaction with the ridge (Tao et al., 2011).

3.2 SYOWA-HOBART

The VLBI stations, Syowa located on the Antarctic plate and Hobart located on the Australian plate, give an average baseline length of 6035892.681 m and a higher baseline rate of +59.0 mm/year. The higher elongation rate (baseline length change per year) estimated for this pair suggests much faster divergence between the two plates (i.e. Australia and Antarctica) involved in the VLBI measurement. The prominent tectonic element separating these two tectonic plates is the (NW-SE trending) Southeast Indian Ridge (SEIR) that extends from Rodrigues triple junction (25^{O} 30'S, 70^{O} 0'E) to Macquarie triple junction (61^{O} 30'S, 161^{O} 0'E). Previously determined spreading rate values over the SEIR range from 58 to 76 mm/yr (Sempere and Klein, 1995) and our VLBI based baseline length change per year across this feature also falls within this range. DeMets et al. (1988) also reported ridge normal spreading rate of ~68 mm/yr, which later was agreed by the NUVEL-1 plate motion model (DeMets et al., 1990). The recent MORVEL (DeMets et al., 2010) plate motion model estimated values between 60-70 mm/yr spreading rate between Australia and Antarctic plates. Small (1995) showed the influence of hotspots on ridge spreading through ridge-hotspot interactions and suggested the role of Kerguelen hotspot in promoting the spreading at SEIR. Since there is no significant crustal deformation within the Australian plate (Larson et al., 1997) and the VLBI horizontal deformation rate match with the spreading rate estimated at SEIR, we can confidently argue that the +59 mm/yr baseline rate represents mostly the divergence rate across the SWIR. The findings from the present VLBI study corroborate with Conder and Forsyth (2001) who showed a region of extension in the SEIR as a consequence of which the distance between Antarctica and Australia is increasing.

3.3 WETTZELL-HARTRAO

The VLBI measurements made by the participation of Wettzell (Germany, European plate) and HartRAO (African plate) give an average value of 7832322.470 m and a rate of -3.9 mm/yr for the baseline length between them. The boundary zone between the African and Eurasian plates encompass the region of the Mediterranean Sea and Middle East and represent the collision zone between Africa and Eurasia, which lead to the progressive closure of Tethys Ocean since the Cretaceous and the deformation process still continues at present (e.g. Lustrino et al., 2011 and references therein). The computed rate of baseline length (-3.9 mm/yr) between Wettzell and HartRAO must be representing the overall deformation occurring between Eurasia and Africa, and well supports the convergent (subduction) geodynamics between the above two plates. The GPS data from the Western part of the Africa-Eurasia collision zone (plate boundary) suggests that this segment accommodates about 2-4 mm/yr of SE-NW convergence (Serpelloni et al., 2007). This estimate very well matches with our VLBI estimated convergence rate. Kreemer et al. (2003) also predicted a convergence rate of ~4 mm/yr for the subduction between African (Nubian) and Eurasian plates. The NUVEL-1 plate motion model (DeMets et al., 1990) predicted comparable values (4-6 mm/yr) for the Africa-Eurasia convergence. The recent NUVEL-1A (DeMets et al., 1994) and MORVEL (DeMets et al., 2010) plate motion models also calculated similar deformation rate of 4±0.2 mm/yr between Africa and Eurasia. The deformation within the African plate is found to be negligible for a N-S section of Africa (e.g. Royer et al., 1997) and the Eurasian plate appears to be a rigid one (Prawirodirdjo and Bock, 2004). Thus, the value of -3.9 mm/yr possibly indicates the convergence rate between the African and Eurasian lithospheres, which is totally accommodated within the collision plate boundary between the two plates.

3.4 WETTZELL-SESHAN

VLBI estimates show that the baseline length between the stations Wettzell and Seshan is lengthening at the rate of 3.6 mm/yr. Both sites (Wettzell and Seshan) are part of the Eurasian plate, which appears to be rigid at its interior (Prawirodirdjo and Bock, 2004). Station Wettzell is located in central Europe, where GPS data showed negligible intraplate velocity (e.g. Grenerczy et al., 2000). On the other hand, the site Seshan located on the South China block shows an East to Southeast movement at present as implied from GPS velocity vectors (Vergnolle et al., 2007). The seismological and geologic data together with analysis of Landsat imagery suggested no deformation within the South China block (cf. Vergnolle et al., 2007). The Western boundary of this block is marked with the large strike-slip fault zone (Longmen fault zone) and represents a localized deformation zone. The South China block in the Southeastern margin of Eurasia is thus seen to be a continuously deforming zone attached to the Eurasian plate (e.g. Kreemer et al., 2000). GPS results suggest that the South China block (as well as the North China block) is decoupled from Eurasia and moves Eastward with a velocity of 4-13 mm/yr (Heki et al., 1999; Shen et al., 2000; Chen et al., 2000). This deforming zone, representing the Western boundary of the South China block, can be therefore thought as the most responsible region where the observed divergence between the two VLBI sites on the Eurasian plate is accommodated. The divergence in this part might have been the result of the Eastward pulling of South China block due to tensional and oceanward stresses generated by the active margins of Eastern and Southeastern Asia or other subduction processes (Vergnolle et al., 2007). Previous VLBI study by Molnar and Gipson (1996) have showed similar east-southeast relative movement of south China block at ~8 mm/yr with respect to Eurasian plate. Calais et al. (2006) showed horizontal motion rates

varying from 0 to about 9 mm/yr from North to South across North and South China, which qualitatively agrees with the VLBI observation.

3.5 SESHAN-HOBART

The baseline length between Hobart and Seshan stations shows a convergence at the rate of 54.8 mm/yr. Seshan and Hobart belongs to two separate tectonic plates, i.e. Eurasia and Australia plate, respectively. The South China microplate carrying the Seshan site, as well as the Australain plate holding Hobart, do not show any significant internal deformation (Larson et al. 1997; Tregoning, 2002; Bock et al., 2003; Vergnolle et al., 2007). Three major tectonic plates, namely the Sunda block, the Philippine, and the Pacific, collectively separate the South China block from the Australian plate (e.g. Michel et al., 2001; Simons et al., 2007). This region that abuts with the Australian plate is the locus of complex active subduction zone systems involving the adjacent Philippine, the Australian, and the Indian plates. The observed convergence in our VLBI measurements can be attributed to the active deformation resulting from the ongoing Northward subduction of the Australian plate with the Sunda and the Pacific plates. It is, however, difficult from our study to point out which among these subduction/collision systems dominate the observed convergence rate, due to the complex tectonics arising from the collision/subduction that occurs between the Australian lithosphere and the complex block assemblage in the area of triple junction between the Sunda block, the Pacific plate, and the Australian plate. Nevertheless, the present study confirms the overall active subduction/collision processes in the region. GPS studies gave a convergence rate of 66-72 mm/yr between the Sunda block and the Australian plate (Michel et al., 2001). Bock et al. (2003) estimated a shortening rate of 50 mm/yr occurring between

the Australia and the Sunda block at the Banda Arc. Simons et al. (2007) estimated shortening rate of ~70 mm/yr, which showed compatibility with the MORVEL plate motion models reported varying convergence rate of 60 – 73 mm/yr along the Australia-Sunda block boundary (DeMets, 2010).

Plate boundaries are important as these are the locations where the continental crust is either generated or destroyed. The VLBI computed baseline length and its rate of change between sites located on the major tectonic plates thus provide evidence for the plate tectonic processes and associated tectonic deformations occurring along the plate boundaries between these major lithospheric plates. It is quite evident that the African, the Eurasian, and the Australian plates are drifting away from the Antarctic plate, as shown by the positive baseline rates estimated between the Antarctic VLBI station (Syowa) and the sites in the other three plates. It is reasonable to infer from the ongoing shortening between Africa and Eurasia, as well as between SE Asia and Australia, that the continents Africa and Europe are nearing each other, and similarly Asia and Australia are slowly coming closer.

The strain rate ($\Delta l/l$) computed for the baselines gives positive strain values between HartRAO and Syowa (2.847×10^{-9} y^{-1}), and Syowa and Hobart (9.775×10^{-9} y^{-1}). Such extensional strain values along the plate boundaries represented by these VLBI sites are indicative of low seismic activity. This inference agrees with the relatively low seismicity reported (e.g. see Figure 5 in Sella et al., 2002) along the SWIR and SEIR ridges separating the tectonic plates representing the above sites. Strain rates of $-6.880 \times 10^{-9} y^{-1}$ and -4.979×10^{-10} y^{-1} are computed for other two major segments, Hobart-Seshan and HartRAO-Wettzell, respectively. This accumulation of strain along these tectonic boundaries characterizes them

as prone zones for vigorous seismic activity. Our results are consistent with Kreemar et al. (2003) results, which showed high compressive strain rates along these plate boundaries. The generation of high magnitude earthquakes with relatively high frequency along these plate boundary subduction zones validates the VLBI observations. The presence of many earthquakes in the Northern part of the Indian Ocean (North of Australia), as compared to the few seismic events reported from its Southern part (South of Australia) (e.g. Bergman and Solomon, 1980) supports our present observations of higher strain concentration in the North-East Indian Ocean region between the Sunda block and the Austalian plate. Bock et al. (2003) showed strain rates below 5 x 10^{-8} y^{-1} for the larger part of the region between the Sunda block and Australia. Large earthquakes are frequently reported from the subduction boundary between the Indian plate and the Sunda block (Eurasian plate). The Indian Ocean earthquakes from the Sumatra region are some recent examples (e.g. Yadav et al., 2013; Catherine, et al., 2014). Vigorous seismicity is also evident from the subduction zone boundary between Africa and Eurasia (e.g. Bucci et al., 2010, and references therein) for which VLBI estimated a significantly high strain rate.

3.6 Implications for Indian Ocean growth

The five baselines considered in our study cut across the major deformation zones between the five major tectonic plates and form five arms that encircle the Indian Ocean (Figure 1). Deformations, either in the form of convergence or divergence, occurring across the tectonic boundaries are derived from the present VLBI data, as well as from previous geological and geophysical studies. VLBI results have shown varying rates for the expansion or contraction occurring across these boundaries and allow us to calculate the rate of change

in perimeter and area bounded by these arms. The change in perimeter (obtained from the addition of individual baseline rates) is +35.7 mm/year, which means that the boundary of the Indian Ocean is increasing at the rate of ~35.7 mm per year. Similarly, we computed the area bounded by these five baseline arms using the formula:

$$Area = \sqrt{\frac{(S-a)(S-b)(S-c)(S-d)(S-e)}{2}}$$

h ere, $S = \frac{a+b+c+d+e}{2}$; and a, , c, d, and e represent the i e sides The area computed for the region encompassed by these five baseline lengths thus shows an increase at the rate of 91.5 m^2y^{-1}. This implies that the Indian Ocean is expanding, however small it may be, regardless of the complex combination of divergence and convergence tectonic processes that operate within its vicinity. Our VLBI results showed the presence of both divergence and convergence process at major tectonic boundaries involving the Indian Ocean. The calculated annual increase in Indian Ocean area would thus mean that extensional deformation (divergence rate) dominates over the contractional deformation (convergence rate) and the whole processes put together gives the observed yearly growth of the Indian Ocean.

3.7 Speculation on the future plate tectonic processes

The Hurst exponent computed from the times series data of baseline values are presented in Table 4. It is obtained from the decay of power spectra of the observed baseline length time series for the particular pair of stations. The value of this exponent tells us the relative tendency o a time series to either regress to a long term mean alue or 'cluster' in a direction. By definition, a Hurst exponent value of 0.5 (or close to 0.5) indicates a random walk motion (a Brownian time series), which does not provide any correlation between the

future elements. But a value of the Hurst exponent less than 0.5 indicates an "anti-persistent" behavior (trend reversal) of the time series, which would mean that an increasing trend will be followed by a decreasing trend and vice-versa. A Hurst exponent value above 0.5 indicates a "persistent" nature of the time series under investigation (Qian and Rasheed, 2007).

Here, Hurst exponent values in the range of 0.3575-0.3585 were obtained for the baseline pairs considered in our study. These values are certainly below 0.5 and thus indicate an "anti-persistent" eha i or o the aseline time series or a out three decades of data analyzed in this study. The obtained low values of the Hurst exponent are indicative of the slowdown of ongoing plate tectonic processes and possibly point to the deceleration of the plate movements in the future. Such an observation was also made by Edmundo et al. (1999) and Sella et al. (2002). Their study argued a possible long-term deceleration associated with the continental collision from the relatively slow movement of the plate pairs with respect to the NUVEL-1A model. Unfortunately, the present study is unable to give any time estimate for the possible deceleration of the plate movements.

4. Summary and conclusions

In this study, the VLBI space geodetic technique is used to measure the large-scale deformation across the plate boundaries formed by the major tectonic plates of the Eastern hemisphere. VLBI measurements were available for almost three decades from five sites located over different tectonic plates, i.e. Wettzell in Germany (Eurasian plate), Seshan in China (South China block of Eurasian plate), HartRAO in South Africa (African plate), Syowa in Antarctica (Antarctic plate), and Hobart in Australia (Australian plate). Baseline

lengths corresponding to all the individual measurements, were estimated for five VLBI pairs: HARTRAO-SYOWA, SYOWA-HOBART, WETTZELL-HARTRAO, HOBART-SESHAN, and WETTZELL-SESHAN, which form five arms around the Indian Ocean region. The time series of the baseline lengths are analyzed statistically to determine its annual rate of change occurring along each arm.

Our study gives spreading rates of 13.5 mm/yr and 59.0 mm/yr for the South West Indian Ridge (SWIR) and South East Indian Ridge (SEIR), respectively. SWIR separates the African (Nubian) plate from the Antarctic plate and its spreading appears to be responsible for the movement between Africa and Antarctic plates. Similarly, SEIR acts as the boundary line between Australian and Antarctic plates and contributes the observed divergence between these two plates. A shortening/convergence of 3.9 mm/yr is observed for the subduction zone boundary between African (Nubian) and Eurasian plates. Such a convergence is clearly evident between the Australian and Sunda block (of the Eurasian plate), but the deformation is occurring at a much faster rate of -54.8 mm/yr. It appears that a major part of this deformation is accommodated along the Banda arc system, where the Australian plate subducts under the Sunda block. The South China block, a microplate within the Eurasian plate was found to be moving away from the rest of the Eurasian block with a speed of 3.6 mm/yr. We also estimate an annual increase of 91.5 m^2 in the area of Indian Ocean from the deformation rates observed along the five VLBI baseline arms surrounding the Indian Ocean. Finally, the estimated Hurst exponent values (~0.35), which can be considered as an indicator for future behavior of times series, show the deceleration of the various tectonic processes in the near future. We could here discuss only the important broader scale deformations of plate boundaries associated with the Indian Ocean. There are, however, many important and complex deformation processes happening between the

Northern and Eastern margin of the Indian plate. Thorough understanding of these processes and deformations would be possible with a more improved VLBI network including stations on the Indian plate.

Acknowledgements

First author, Akilan, sincerely acknowledges Prof. Johannes Böhm for the financial assistance, as well as other logistical and scientific support, to make a successful visit to the Department of Geodesy and Geoinformatics, Vienna University of Technology. The authors gratefully acknowledge the IVS and all its contributing components for supporting this research work with the necessary resources. Thanks also go to Dr. Y. J. Bhaskar Rao, Director, CSIR-NGRI for the kind permission to publish this work. Dr. Malaimani and Dr. V. Gahalaut are acknowledged for the support and facilities provided at NGRI. Figure 1 presented in this paper is generated using GMT software (Paul and Wessel, 1998). We acknowledge the critical comments from two anonymous reviewers that helped to improve the manuscript. The work has been carried out under the ILP-0301-28(VKG).

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Tables

Table 1: The five different VLBI stations used in this study and their details.

VLBI station Name and Country/Plate	IVS code	Latitude (Deg)	Longitude (Deg)	Height (m)
WETTZELL Germany/ Eurasian plate	Wz	49.1450 N	12.8772 E	661
HARTRAO South Africa/African plate	Hh	2.8898 S	27.6854 E	1415
SYOWA Antarctica/Antarctic plate	Sy	69.0063 S	39.5863 E	51
HOBART Australia/ Australian plate	Ho	42.8019 S	147.4387 E	41
SESHAN China/Eurasian plate [south China block]	Sh	31.0992 N	121.1996 E	5

Table 2: Details of the VLBI sessions and data duration

Between the stations	Data from	Data to	Number of sessions used for analysis
Hh-Sy	1999.858	2008.375	39
Ho-Sh	1989.965	2011.140	62
Sy-Ho	1999.858	2010.984	44
Wz-Hh	1987.026	2013.075	545
Wz-Sh	1990.256	2012.962	151

Table 3: Average baseline length, annual baseline length rate and the strain rate calculated for the five VLBI experiment pairs

Station pair	Baseline length (m)	Baseline length rate/year	Strain rate
HartRAO-Syowa (Hh-Sy)	4741786.094	+13.5 mm/yr	$+2.84 \times 10^{-9}$
Syowa-Hobart (Sy-Ho)	6035892.681	+59.0 mm/yr	$+9.77 \times 10^{-9}$
Wettzell-HartRAO (Wz-Hh)	7832322.470	-3.9 mm/yr	-4.97×10^{-10}
Hobart-Seshan (Ho-Sh)	7965495.893	-54.8 mm/yr	-6.87×10^{-9}
Wettzell-Seshan (Wz-Sh)	8003555.664	+3.6 mm/yr	$+ 4.49 \times 10^{-10}$

Table 4: The computed spectral indices of the baseline length time series for the studied VLBI pairs and the Hurst exponents computed from the corresponding spectral index values.

Baseline lengths between the stations	Spectral index *(V)*	Hurst exponent *(H)*
HartRAO-Syowa (Hh-Sy)	1.715±0.346	0.357
Syowa-Hobart (Sy-Ho)	1.715±0.317	0.357
Wettzell-HartRAO (Wz-Hh)	1.717±0.085	0.358
Hobart-Seshan (Ho-Sn)	1.716±0.264	0.358
Wettzell-Seshan (Wz-Sn)	1.716±0.164	0.358

Figure Captions

Figure 1: Major tectonic plates and their boundaries shown over the topographic relief map of the Eastern hemisphere. Some of the microplates, tectonic blocks, and tectonic features relevant to this study are also shown. Location of the five VLBI sites and the baseline lengths analyzed, along with their average values and annual rates are shown. SWIR-South West Indian Ridge; SEIR-South East Indian Ridge; CIR- Central Indian Ridge; RTJ- Rodrigues Triple Junction; OTJ- Owen Triple Junction.

Figure 2: Time series of baseline lengths (circles) estimated for the experiments made between VLBI sites (a) HartRAO-Syowa (b) Hobart-Seshan (c) Syowa-Hobart (d) Wettzell-HartRAO and (e) Wettzell-Seshan. The grey line represents the least-squares fitting for the baseline time series, the slope of which gives the rate of baseline change per year. The computed power spectra (blue line) and the spectral index value for the respective time series are also shown in the bottom panel.

Figures

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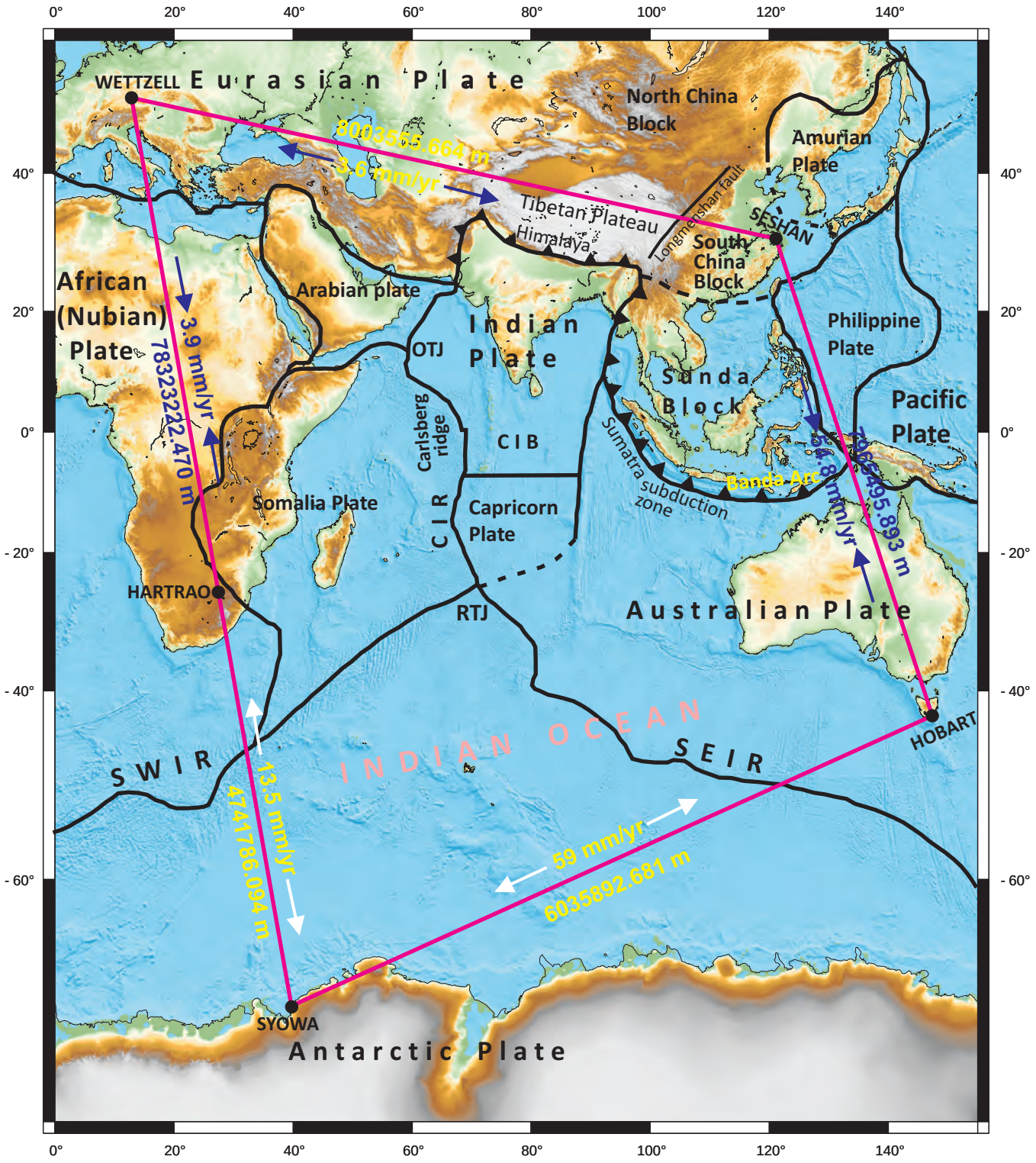

Figure 1

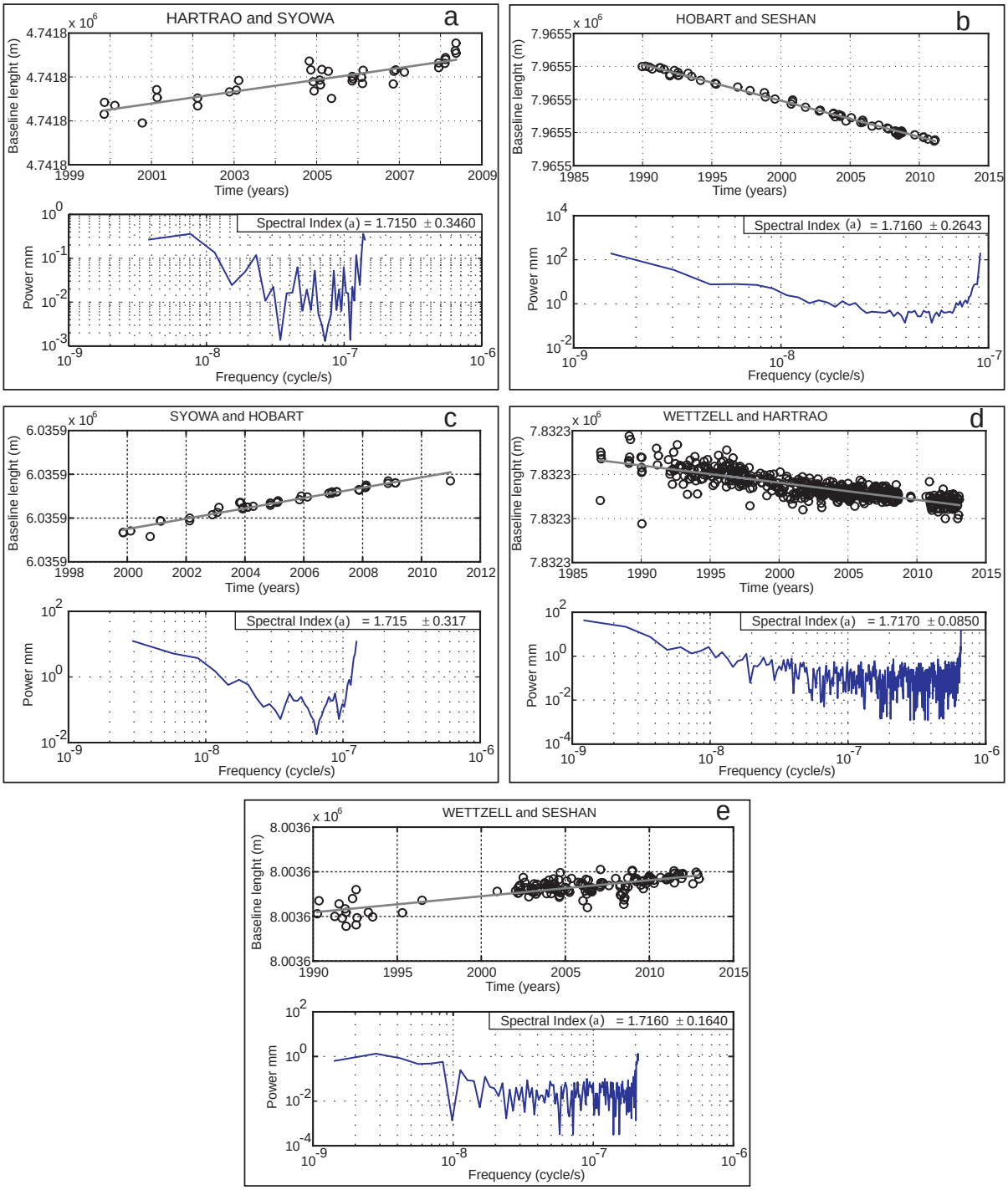
a
HARTRAO and SYOWA
x 10^6
Baseline lenght (m)
Time (years)
Spectral Index (a) = 1.7150 ± 0.3460
Power mm
Frequency (cycle/s)
b
HOBART and SESHAN
Spectral Index (a) = 1.7160 ± 0.2643
c
SYOWA and HOBART
Spectral Index (a) = 1.715 ± 0.317
d
WETTZELL and HARTRAO
Spectral Index (a) = 1.7170 ± 0.0850
e
WETTZELL and SESHAN
Spectral Index (a) = 1.7160 ± 0.1640

Figure 2