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Kinematics of the Suez-Sinai area from combined GPS velocity field

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ABSTRACT

A combined GPS velocity solution covering a wide area from Egypt to Middle East allowed us to infer the current rates across the main, already well known, tectonic features. We have estimated 126 velocities from time series of 90 permanent and 36 non permanent GPS sites located in Africa (Egypt), Eurasia and Arabia plates in the time span 1996–2015, the largest available for the Egyptian sites. We have combined our velocity solution in a least-squares sense with two other recent velocity solutions of networks located around the eastern Mediterranean, obtaining a final IGb08 velocity field of about 450 sites. Then, we have estimated the IGb08 Euler poles of Africa, Sinai and Arabia, analyzing the kinematics of the Sinai area, particular velocity profiles, and estimating the 2D strain rate field. We show that it is possible to reliably model the rigid motion of Sinai block only including some GPS sites located south of the Carmel Fault. The estimated relative motion with respect to Africa is of the order of 2–3 mm/yr, however there is a clear mismatch between the modeled and the observed velocities in the southern Sinai sites. We have also assessed the NNE left shear motion along the Dead Sea Transform Fault, estimating a relative motion between Arabia and Africa of about 6 mm/yr in the direction of the Red Sea opening.

1. Introduction

Egypt is located in the Eastern Mediterranean, at the northeastern corner of the African continent, a region dominated by the relative motion of 3 major plates. The subduction between African and Eurasian plates and the opening of the Red Sea represent the boundaries between African, Arabian and Eurasian plates.

Sinai peninsula is located north of the triple junction among the Gulf of Suez rift, the Aqaba-Levant transform fault (the southernmost part of the Dead Sea Fault System) and the Red Sea rift (Ben-Menahem et al., 1976); from a geodynamic point of view it is generally considered as an independent sub-plate of the African plate interacting with the Arabian and Eurasian plates (Saleh and Becker, 2015 and references therein).

In the last decades, many geological and seismological investigations were developed in this area, especially for petroleum researches so that the tectonic history is well known (e.g. Lindquist, 1998). From early to late Miocene, the area was subjected to different phases of motion. At the beginning the northeastward motion of the Arabian peninsula yielded the opening of the Red Sea; subsequently, the rifting propagated toward NW, along the Gulf of Suez area. The rifting is thought to culminate in early-middle Miocene when the stresses of the Red Sea rift were transferred along the Aqaba-Levant area generating a left-lateral transform fault that extends through the Gulf of Aqaba northeastward to the Dead Sea, with a minor extensional component (Steckler et al., 1988; Le Pichon and Gaulier, 1988). The question of whether the triggered motion of the Aqaba-Levant fault system has entirely or partially replaced the Gulf of Suez opening is not completely solved. The present day tectonic activity of the area is testified by an ongoing seismic activity generally characterized by small to moderate earthquakes due to the relative motions between the African, Arabian and Eurasian plates. There are three main seismic zones: the Northern Red Sea, Gulf of Suez and Gulf of Aqaba. The highest seismicity rates are detected at the eastern boundaries along the Gulf of Aqaba and the northern part of the Red Sea. Moderate seismicity is also present in the Cairo area. Studies demonstrate mainly a normal faulting mechanism with minor strike slip component generally trending parallel to the northern Red Sea, the Suez rift, Aqaba rift with their connection with the great rift system of the Red Sea and the Gulf of Suez and Cairo-Alexandria trend (Emad Mohamed et al., 2015).

Many studies based on GPS data, have been carried out to shed light on the current kinematics of this key area. Earlier studies based on very few GPS observations attempted to estimate the motion of the Sinai area from repeated surveys (Riguzzi et al., 1999) and

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elastic block model (Mahmoud et al., 2005) defining Sinai as a separate sub-plate sandwiched between the Arabian and African plates. Piersanti et al. (2001) and Riguzzi et al. (2006) found short-term deformations from GPS survey data in the Sinai area and speculated about the possible role of post-seismic relaxation. Other studies based on wider datasets, but including few GPS stations in the Egypt-Sinai region, estimated the Euler vectors of the relative motion of the Africa, Arabian and Eurasian plates (McClusky et al., 2003; Reilinger et al., 2006) and the crustal deformation due to the ongoing active processes along the Dead Sea Fault System (Le Beon et al., 2008; Sadeh et al., 2012; Palano et al., 2013).

Recently, Saleh and Becker (2015) have included in their study GPS data of permanent and non permanent stations in Egypt covering the period 2006–2012, assessing velocity and strain rate fields and estimating the relative motion between African, Eurasian and Arabian plates; they have detected no significant differential motion between Sinai and Africa.

In this paper, in order to assess more details on the kinematics of the Suez Gulf-Sinai area and the current rates across the main tectonic features of this region, we have used the largest data set, including 16 Egyptian permanent sites, many other permanent sites located in Eurasia, Africa and Arabia plates and including campaign data from Egyptian networks surveyed during the period 1996–2005.

We have homogeneously reprocessed by the Bernese software all these data (permanent and non permanent) covering a total time span of 20 years. Then, we have combined our IGb08 (IGS realization of the ITRF2008) velocity solution with the solution of Saleh and Becker (2015) and with a velocity subset of the global solution published by Kreemer et al. (2014), obtaining a final IGb08 velocity field of 457 sites in our study area.

2. GPS data and processing steps

The National Research Institute for Astronomy and Geophysics (NRIAG) established different GPS networks around active areas in Egypt, starting in 1996 in the Greater Cairo region. Subsequently, several other non permanent sites were installed in the Aswan region, Sinai peninsula, Gulf of Suez, Nile Valley (Saleh and Becker, 2015; Riguzzi et al., 2006). Finally, in 2006 NRIAG started the construction of a permanent GPS network in Egypt (EPGN—Egyptian Permanent GPS Network), consisting at present of 16 stations (Saleh and Becker, 2013).

We have collected data of 16 permanent and 36 non permanent sites in Egypt in the time span 1996–2015; in particular the GPS campaigns cover the interval 1996–2005, while continuous sites span from the end of 2006 to the middle of 2015. In addition, we have included in our processing IGS sites in the surrounding regions, in Africa, Europe, Arabia and Israel and some other permanent stations archived at SOPAC and UNAVCO (see Figs. S1–S3 in the Supplementary material).

Our analysis follows a procedure that can be summarized in 4 main steps: 1) daily processing of GPS data, 2) combination of daily solutions and reference frame definition, 3) time series analysis and velocity field estimation, 4) combination of our velocity field with other two different solutions.

2.1. Daily processing of GPS data

We have processed the GPS data by Bernese GNSS software 5.0 (Dach et al., 2007), following the Guidelines for EUREF Analysis Centers (http://www.epncb.oma.be).

We have fixed the GPS orbits and Earth's orientation parameters to the combined IGS products and assigned an a priori loose constraint of 10 m to all the site coordinates. We have applied the elevation-dependent phase center corrections and the absolute phase center calibrations. The troposphere modeling consists in an a priori dry-Niell model fulfilled by the estimation of zenith delay corrections at 1-h intervals at each site using the wet-Niell mapping function; in addition one horizontal gradient parameter per day at each site is estimated. The ionosphere is not modeled a priori, but it is removed by applying the ionosphere-free linear combination of L1 and L2 carriers. The ambiguity resolution is based on the QIF baseline-wise analysis. The final network solution is solved with back-substituted ambiguities, if integer, otherwise real ambiguities are considered measurement biases.

Thehe daily GPS solutions are not estimated in a given a priori reference frame but computed in a loosely constrained reference frame, applying loose a priori constraints (10 m) to all station coordinates. As a consequence, the positions are randomly translated or rotated from day-to-day and their covariance matrices have large errors (on the order of centimeters).

2.2. Combination of daily solutions and reference frame definition

Then, we have merged the daily "loose" solutions day by day with the daily loose solutions of a global network of about 60 IGS stations. Basically, the two sets of solutions share 9 common sites allowing the combination into a unique network solution by a classical least-squares approach (Devoti, 2012).

After these combinations, we have performed two main transformations to express the daily coordinates of the overall network in a unique reference frame and to compute the real covariance matrix. First the loose covariance matrix has been projected into the space of errors (Blewitt et al., 1992) imposing tight internal constraints (at the millimeter level), then the coordinates have been transformed into the IGb08 (Altamimi et al., 2012) by a 4-parameter Helmert transformation (3 translations and a scale factor) where the proper set of constraints is driven by the rank deficiency of the normal matrices. A comprehensive discussion of the rank deficiency of our solutions is given in Devoti et al. (2010).

2.3. Time series analysis and velocity field estimation

The site velocities have been estimated fitting simultaneously a linear drift, episodic offsets and annual sinusoids to all the coordinate time series. Offsets are estimated whenever a change in the GPS equipment induces a significant step in the time series, whereas seasonal oscillations are accounted by annual sinusoids. Data are rejected as outliers whenever the weighted residual exceeds three times the global chi square (χ^2). Finally, the formal errors have been scaled taking into account the noise content of site daily time series, modeled as a combination of white and flicker noise, as described in Mao et al. (1999). At the end we obtained a full 3D velocity solution of 126 stations in the Egyptian and Middle-East region.

2.4. Combination of velocity fields

At this stage we have combined our velocity solution with two already available velocity solutions related to the same area (Saleh and Becker, 2015; Kreemer et al., 2014). Since the latter solutions concern only the horizontal components, in our combination we neglected the vertical rates. Fig. 1 shows the three velocity fields, used as input for the combination adjustment, in a fixed Eurasian plate reference frame (Altamimi et al., 2012). About the velocity field of Saleh and Becker (2015), we have found an inconsistency in their published velocity values: there is a mismatch between their ITRF2008 velocity field (Table 1A in the Appendix of their paper) and the Eurasian fixed velocity field of their Table 5 and Fig. 10, in fact from the first it is not possible to retrieve the second after