Tectonophysics 617 (2014) 79–87

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

An alternative approach to Eulerian pole determination and unification of velocity fields of tectonic motions

Masoud Nozari [a], Mehdi Eshagh [b,*]

[a] Department of Geodesy, K.N. Toosi University of Technology, Tehran, Iran
[b] Department of Engineering Science, University West, Trollhättan, Sweden

ARTICLE INFO

Article history:
Received 9 August 2013
Received in revised form 2 January 2014
Accepted 14 January 2014
Available online 24 January 2014

Keywords:
GPS velocity filed
Unification methods
Euler pole
Nonlinear model
Gauss–Helmert model
Unique solution for Euler pole

ABSTRACT

One of the methods of unifying the global positioning system (GPS) velocity fields (VFs) of tectonic motions is based on the Eulerian vector (EV) estimation. In this method the difference between each available local VF and a reference VF (REF) is derived and an EV is estimated for the differences in a least-squares sense. After that each local VF is unified with respect to REF using the EV. The classical approach to the EV determination is nonlinear and requires the approximate EV. To solve this problem a simple linear approach is developed in this paper for estimating the EV and applied for unifying the existing local VFs in Iran. Our approach is free of the approximate parameters of the EV, faster and more efficient than the classical one. Here, both of the classical and the new approaches are numerically applied and compared to each other; and used to unify the VFs covering a large part of Iran. The unified velocity field shows an overall northward motion with respect to Eurasia with a convergence pattern around the southern Caspian Basin and a little divergence in the central and southern areas.

1. Introduction

Understanding and identification of the type and the manner of tectonic events and crustal movements require adequate knowledge about geometry of plate kinematics. The Eulerian poles (EPs) play a fundamental role in this issue. The relative motion between two plates can be regarded as a rotation around an axis derived by Euler's fixed point theorem stating that the motion of a rigid body can be described by a translation and a rotation. Therefore, any displacement of a tectonic plate on the surface of a sphere can be regarded as a rotation around the Euler's axis. This axis intersects the surface of the Earth's sphere and yields two points which are so-called the EPs and show type of plate boundaries and mechanisms of earthquakes (Cox and Hart, 1986, p. 12–14). The Eulerian pole (EP) is a point on the Earth's surface which defines a line through the centre of the Earth about which the relative motion of two plates may be described (Allaby and Allaby, 1999). The results of many ground-based observations are summarised in some tables of the EPs (DeMets et al., 1990), which contain valuable information about the plate movements and the structure of the global motion models such as e.g. Northwestern University Velocity Model (NUVEL), the Actual Plate Kinematic and Crustal Deformation Model 2000 (APKIM2000), and Resent Plate Velocities Model (REVEL) (DeMets et al., 1994; Drewes, 1999; Torsvik and Smethurst, 1999). By using the recent Space Geodesy techniques e.g. global positioning system (GPS), the EPs are determined precisely and used for different purposes. Some of the applications of the EPs are to combine velocity fields (VFs) of the tectonic plates obtained from various data (Hefty, 2007), detection of rigid blocks in different regions (Nocquet et al., 2001) and modelling various crustal movements including block modelling (Meade and Hager, 2005; Meade and Loveless, 2009) which is a procedure to model the deformation of the Earth's crustal movements in such a way that the crust can be divided by some smaller and rigid parts named rigid blocks or micro-plates. Also, DeMets et al. (1990) modelled the movements of 12 main plates using geological data to produce a global plate motion model and presented a table of the EPs. Perez et al. (2003) calculated the velocity vectors and an EP related to South American plate using the precise point positioning techniques of GPS. A method for combining different GPS-based VFs based on EPs was developed and applied by Hefty (2007) in Central Europe, Adriatic and Balkan. Palano et al. (2010) applied the weighted least-squares method to derive the EPs for studying the deformation of Mt. Etna region in Italy.

So far according to the kind of the data, the Eulerian vector (EV), which contains the position of the EP and rotation rate of the plates, is determined through a nonlinear least-squares problem (Hefty, 2007). The EV tables contain geographical coordinates of the stations and their velocity vectors in the north–south and east–west directions as well as their standard deviations. These vectors are tangent to the surface of the spherical Earth. Due to the involvement of trigonometric functions, different solutions for the EVs are derived and finding the correct one is not straightforward. On the other hand, Hefty (2007) clearly mentioned that the choice of the approximate parameters,

* Corresponding author.
E-mail addresses: m.nozari.geodesy@gmail.com (M. Nozari), mehdi.eshagh@hv.se (M. Eshagh).

0040-1951/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.tecto.2014.01.018

position and rotation rate, for the EVs is of vital importance for the convergence of iterative solution of the linearised equations to the correct position. In this paper, we reformulate the problem of determining the EVs in a much simpler way than that used so far and organise linear equations, requiring no approximate value, from which the EVs are determined. Due to the linearity of our approach no iteration is required and, therefore, the EVs will be estimated efficiently. The presented method will be applied for unification of tectonic VFs in the territory of Iran.

2. The classical approach to the Eulerian vector determination

Paleomagnetic, geological data, geodetic terrestrial and satellite observations can be used to determine the EVs. The boundaries of moving plates of the Earth's crust have been transformed to mountain ranges or oceanic trenches which are so-called fracture zones due to tectonic interactions which are in the class of terrain features. The EP position can be simply determined based on the fact that all lines drawn perpendicular to a circle will concentrate at its centre.

The Paleomagnetic data, pertaining to mountain ranges and oceanic trenches, are the simplest data for finding the rate of rotations or movements. Such information has been produced in long geological periods. This method was mainly used in the past and especially in the structure of the global tectonic motion models. Therefore, prediction of movements by such approximated EVs offered only an approximate range of long-term movements in the main plate boundaries (Cox and Hart, 1986, p. 14–21). These global models have been constructed by the Paleomagnetic data and updated by some new sources of geodetic data such as GPS, satellite laser ranging (SLR) and very long baseline interferometery (VLBI). However, these models could not be used to predict the motions and deformations in some regions like Iran due to the complicated pattern of tectonic evidences of the region. On the other hand, the global models predict the movements of main plates and cannot present the motions of the interior zones and the recent movements in the main plates. In other words, they just present very long rate of changes of the plates during millions of years and not the micro-plate motions. In contrary, the geodetic data e.g. GPS can provide data with a period of 15 to 20 years without any restriction in data coverage especially for the interior zones in the main plates and detecting the micro-plates. Today, the use of GPS techniques is simple and economic so that some GPS-based VFs can be modelled and applied. This type of data can be used for determining the EV using the following classical method (cf. Hefty, 2007; Stein and Wysession, 2003, p. 290):

$$v_N = \omega \sin(\lambda - \lambda_{EP}) \cos\varphi_{EP} \tag{1a}$$

$$v_E = \omega[\cos\varphi_{EP} \sin\varphi \cos(\lambda - \lambda_{EP}) - \sin\varphi_{EP} \cos\varphi] \tag{1b}$$

where v_N and v_E are the velocities in the north–south and east–west directions, respectively, φ and λ are the latitude and longitude of each station measuring the velocity vectors, respectively. φ_{EP} and λ_{EP} are the latitude and longitude of the EP and ω stands for the rotation rate of the movement. It should be stated that, here, we estimate an EV which has three components and two components of this vector are nothing else than the position of the EP and the third one is the rotation rate of the movement which was already explained.

Eqs. (1a) and (1b) is a nonlinear equation with respect to φ_{EP}, λ_{EP} and ω. In fact the left hand side of the equation, the velocities, is considered as the observations and using the known coordinate of each velocity station, φ and λ, in the right hand side, a system of equations is organised and solved for φ_{EP} and λ_{EP} in a least-squares sense. Eq. (1) should be linearised by the Taylor series and solved iteratively until the solution converges and some approximate values of the unknown are required. Here we name this way of determining the parameters of φ_{EP}, λ_{EP} and ω, the classical approach. In the following, the disadvantages of this method are summarised:

1. Linearisation of the model and the need for the approximate EVs.
2. Iterative time consuming computational process to converge the solution for large amount of data.
3. Sensitivity to the choice of the approximate values of the EV.

3. Alternative approach to the Eulerian vector determination

In the classical approach to determine the EV, the velocities are considered as observations and the coordinates of the stations the approximate values of the EV are used to compute the coefficient matrix of the unknowns. The standard errors of the velocities can be also considered in the least-squares solution of the linearised system of equations for proper weighting of the velocities. Hefty (2007) mentioned that the solution of this system is very sensitive to the choice of the approximate values and the convergence rate of the solution is low for large amount of data. In order to solve this problem, we reformulate the mathematical model of determining the EV in another way. Let us transform the velocities from a two-dimensional local frame to a three-dimensional geocentric frame, therefore, we can write:

$$v_x = -v_N \sin\varphi \cos\lambda - v_E \sin\lambda \tag{2a}$$

$$v_y = -v_N \sin\varphi \sin\lambda + v_E \cos\lambda \tag{2b}$$

$$v_z = v_N \cos\varphi. \tag{2c}$$

In these relations v_x, v_y, and v_z are the Cartesian components of velocity vectors, v_E and v_N are the surface velocity vector components and φ and λ are the spherical coordinates of the desired station. These relations can be seen geometrically in Fig. 1.

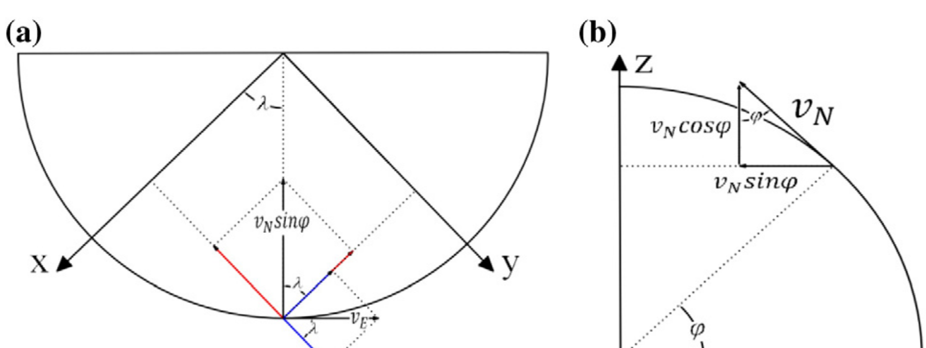

Fig. 1. Geometry of the transformation from a two-dimensional space to a three-dimensional space. In a simple geometric process, v_E and v_N transform to v_x, v_y, and v_z. (a) The XY plane. The east–west component of the velocity vector, v_E, and the projection of the north–south component, $v_N \sin\varphi$, on the XY plane disintegrate on two axes X and Y. (b) The meridian plane. The north–south component, v_N, disintegrates on the Z axis and the XY plane.