Investigation of Deformations in North of Algeria with GPS Data and Kinematic Model

Radia MIR, Salem KAHLOUCHE, Saïd TOUAM, AlGERIA

Key words: GPS Positioning, Bernese, Geodynamics, Deformation, Kalman Filter

SUMMARY

The objective of this study consists on the precise estimation of the coordinates of Algerian GPS stations while integrating the IGS data and products. The Bernese v5.0 software is used to define all the parameters of the GPS network processing with a precise large area. The daily solutions (precise coordinates and velocities) and covariance matrices are the combined results of the processing and the entries for the movement model.

The kinematic model of deformation analysis using 3D Kalman filter technique is applied to detect the deformation parameters of the movement and points' displacement of the network over the time. For the evaluation of the displacement, the elements of the Kalman filter have been calculated for an optimal estimate of the state in each measurement period. The innovation vector and its covariance matrix also allowed the calculation of Kalman gain over the time. Thus, the application generates a statistical analysis to detect the importance of the used data of the movement of Italian geodetic network and Algerian stations. The Kalman filter allows the obtention of continuous state of networks stations

FRENCH SUMMARY (optional summary in one other language in addition to English, e.g. your own language)

La sismicité qui touche le Nord de l'Algérie et les mesures géodésiques locales de montre que la déformation tectonique est encore active. Cette déformation est interprétée généralement par la convergence de l'Afrique - Europe - Asie. L'étude se concentre sur la détermination des mouvements géodynamiques de la croûte terrestre par GPS et l'analyse des déformations. Elle consiste à proposer une stratégie de traitement basée sur la technique de Kalman, et de définir tous les paramètres de traitement GPS avec un test d'application. Les mesures de quatre campagnes GPS (2000 et 2006) ont été utilisées, et un réseau de cinq stations GPS situées sur le nord de l'Algérie (1998 et 2001). Le modèle de déformation ponctuel a permis de détecter les paramètres de déformation en fonction du temps qui peuvent en utilisant le modèle cinématique. Les éléments du filtre de Kalman sont calculés pour une estimation optimale du vecteur d'état dans chaque période de mesure, le vecteur d'innovation et sa matrice de covariance permettent également de calculer le gain de Kalman. En outre, d'effectuer une analyse statistique des paramètres de déplacements du réseau. Enfin, les résultats obtenus sur les réseaux Italien et sur le Nord d'Algérie ont été analysés et comparés avec une solution de référence fournie par le logiciel Bernese pour la validation.

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1. INTRODUCTION

In earth science, the GPS is actually a very useful tool to quantify the tectonic movements. The main part of the motions is very slow and we can't sense them with our human senses. Other motions are larger and more hazardous, the natural hazards as earthquakes and landslides kill or injure several people and damage many buildings, engineering structures and infrastructures every year. A method of processing GPS data has been adopted for the estimation of coordinates and velocities for specific GPS stations and tropospheric parameters. In this study, a deformation analysis procedure through a kinematic deformation model based on Kalman filtering technique is discussed. The main objective of this application is to develop a GPS monitoring system based on Kalman filter for use in active tectonic regions.

The kinematical motion model, where the GPS derived station coordinates are taken as input values, has been evaluated by Kalman filtering technique and motion parameters of network stations have been determined [Cankut D. and Sahin M., 2000]. The kinematic analysis of deformation was applied to Italian network as test areas and then extended to a network covering the North of Algeria depending to the availability of GPS data.

2. KINEMATIC DEFORMATION MODEL

Using kinematical deformation model, the motion of network stations (control points) and even their accelerations can be computed. This procedure is carried out for every point. These kinds of deformation models are called as "single point deformation models". In this study, one of these models, called as "Hannover approximation" has been applied. The objective of kinematical single point deformation model is to find a proper definition for the point displacements by means of time dependent functions without taking into account the external forces causing deformations. The unknown parameters of a single point deformation model are the velocity and the acceleration of control points. Therefore, a time-dependent function is required to estimate these parameters. The most common approach for this type of model is a quadratic polynomial function [Yalçinkaya M., 2003].

$$X_j^{(k+1)} = X_j^{(k)} + v_j(t_{k+1} - t_k) + \frac{1}{2} a_j(t_{k+1} - t_k)^2 + \qquad (1)$$

Where:

$X_j^{(k+1)}$: is a coordinate vector at time t_{k+1},

$X_j^{(k)}$: Coordinate vector at time t_k

ν_j : Velocity vector at time t_k

a_j : Acceleration vector at time t_k.

In order to compute the adjusted motion parameters for each point from the kinematical single point deformation model given above, measurements carried
out in many periods are needed. Kalman filtering technique enables us to compute the motion parameters using measurements collected in less number of periods. In the 3 dimensional models the motion model consisting of position, motion and acceleration can be formed up as follows [Acar M. & al., 2008]:

$$\begin{cases} x_j^{(k+1)} = x_j^{(k)} + \nu_{xj}(t_{k+1} - t_k) + \frac{1}{2}(t_{k+1} - t_k)^2 a_{xj} \\ y_j^{(k+1)} = y_j^{(k)} + \nu_{yj}(t_{k+1} - t_k) + \frac{1}{2}(t_{k+1} - t_k)^2 a_{yj} \\ z_j^{(k+1)} = z_j^{(k)} + \nu_{zj}(t_{k+1} - t_k) + \frac{1}{2}(t_{k+1} - t_k)^2 a_{zj} \end{cases} \quad (2)$$

Where:

$x_j^{(k+1)}, y_j^{(k+1)}, z_j^{(k+1)}$: coordinates of point j at time (t_{k+1})

$x_j^{(k)}, y_j^{(k)}, z_j^{(k)}$: coordinates of point j at time (t_k)

$\nu_{xj}, \nu_{yj}, \nu_{zj}$: velocities of X, Y, Z coordinates of point j

a_{xj}, a_{yj}, a_{zj}: accelerations of X, Y, Z coordinates of point j

K: 1,2…, i (i : measurement period number)

J: 1,2,…, n (n: number of points)

The above equations can be written in the matrix form as follows:

$$\hat{x}_{k+1}^{-} = \begin{bmatrix} x \\ y \\ z \\ \nu_x \\ \nu_y \\ \nu_z \\ a_x \\ a_y \\ a_z \end{bmatrix}_{k+1} = \begin{bmatrix} I & I(t_{k+1} - t_k) & \frac{I\,(t_{k+1} - t_k)^2}{2} \\ 0 & I & I(t_{k+1} - t_k) \\ 0 & 0 & I \end{bmatrix}_{k+1,k} \begin{bmatrix} x \\ y \\ z \\ \nu_x \\ \nu_y \\ \nu_z \\ a_x \\ a_y \\ a_z \end{bmatrix}_{k} \quad (3)$$

$\Phi_{k+1/k}$: Transition matrix from time t_k to t_{k+1}

$$\Phi_{k+1/k} = \begin{bmatrix} I & I(t_{k+1} - t_k) & \frac{I\,(t_{k+1} - t_k)^2}{2} \\ 0 & I & I(t_{k+1} - t_k) \\ 0 & 0 & I \end{bmatrix}_{k+1,k} \quad (4)$$

$\hat{x}_{k+1}^{-}$: State vector at time t_{k+1}

$\hat{x}_k$: State vector at time t_k

Equation 3 is the prediction equation that is the basic equation of the Kalman filtering. The system noise in the prediction equation is considered as the noise matrix **S** that consists of the terms of the last column of the matrix given in Equation 4 [Acar M. & al, 2004].

Actually, the filtering phase is based on classical least squares adjustment. The most important difference with the classical adjustment procedure is that, contrary to the classical approach, in the filtering the number of observations can be less than the number of unknowns. Through the filtering, adjusted values of state unknowns are computed using weighted combination of measurements and a priori estimations [Serkan D., 2006].

2.1 GPS data used from Italian and ALGEONET networks

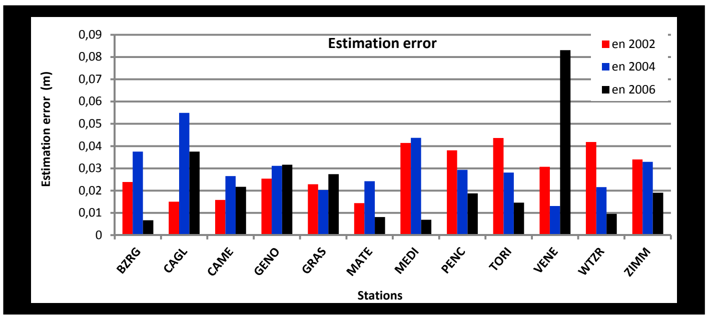
For this purpose, in the deformation area a network consisting of 13 points was selected in Italy as test. The point locations had been selected in areas according to the active zones (near the plate boundaries tectonic). The geodetic measurements used in this study were GPS measurements carried out in four periods between: July 2000, August 2002, April 2004, and November 2006 for the Italian network. The national network consists of 08 stations including 05 covering the North of Algeria and 03 IGS stations: Cagliari (CAGL), Lampedusa (LAMP), Wettzell (WTZR). The receivers used are the bifrequency (Ashtech ZXII-3 and Trimble 4000 SSE), the sampling rate is 30 s and the Cut off angle is 15o. [Kahlouche S. & al., 1998]
The deformation analysis was done using Bernese 5.0 analysis software. The standard method was based for a double-difference analysis of RINEX GNSS observation data. Station coordinates and troposphere parameters are estimated and stored in Bernese 5.0 and SINEX format to facilitate further processing and combination [Fridez P., et al., 2007].
For each session, the corresponding normal equation information is saved for a subsequent multi-session (allowing the estimation of station velocities).

3. RESULTS

3.1 Error estimation of the state vector

The problem of the adjustment by Kalman filter is translated then by calculating the error estimation of the state vector which can be given by the Euclidean error (the Euclidean distance between the point determined by GPS and its correspondent by Kalman filter estimate) [Iyiade A., 2006].

Figure 1: Error estimation of the state vector for each station.



As a validation method, the results provided by the application of the Kalman filter were compared with a reference solution (from Bernese processing).
Here, a priori variance (s_0) is computed from the preliminary adjustment. The test values (T and T_G) are computed with a priori and compared with the F-distribution table value (q) (confidence level is α=0.05) and it is decided if the deformation is significant in each periods.

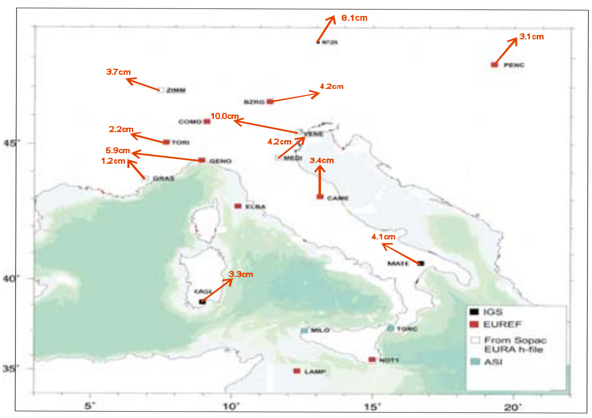
Table 2: Global test results on the innovation vector of each measurement period.

	Global test statistic on innovation vector		
	2002	2004	2006
$d_{K+1}^{T} \cdot D_{K+1}^{-1} \cdot d_{K+1}$	1.41	416.95	484.79
$n_{K+1}\, S_0^2$	0.63	18.40	19.59
T_G	2.24	22.67	24.90
Decision	Significant Deformation	Significant Deformation	Significant Deformation

3.2 Horizontal displacement by the kinematic model between 2000-2006 periods

The horizontal displacements obtained through kinematical deformation analysis are shown in **Figures 3**. As presented in the figure, horizontal displacements have been significant and detected in the all points positions in the network. One notes the displacement located on both sides, for point VENE, GENO, MATE, has only a quasi-horizontal movements of 5 to 10 cm towards western north and for BZRD, CAME, PENC a displacement from 3 to 4 cm in the North-East of the plate. Therefore, we note a distortion of the plate boundaries of the extreme boundaries of the plate.
Considering the localization of these stations, we can deduce that the movement is due probably to a geophysical phenomenon in this period, for vertical movements, the displacements are in the top for certain stations, which represent a rising which is due probably to the convergence of the African and Eurasian plates.

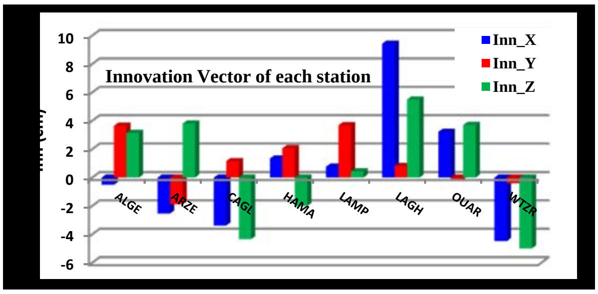
Figure 3: Horizontal displacements obtained by the kinematic model between July 2000 and November 2006.



3.3 Application of the Kalman filter on North of Algeria

To attempt to determine the deformation state on North of Algeria, we limited our study between the period of June 1998 and April 2001, for which we have two series of GPS measurements [Anzidei M., and al., 2003]. In this study, we have also used the equations above, the innovation vector d_{k+1}, state vector filtered at time t_{k+1}; $\hat{x}_{k+1}$ predicted state vector; $\upsilon_{\hat{x}^-,k+1}$ residual vector of observations at time t_{k+1}. However, the elements of the Kalman filter were calculated with only one serie of measurement (by taking as the initial state, the GPS campaign of 1998); this is due to the fact that is cannot understand the deformation evolution in function of the time in insufficiency case of the data on the North of Algeria. One can understand qualitatively that the period of time of convergence of the filter is larger if we want a good knowledge of the state according to time. The innovation provides the statistics of the difference between measurement and the prediction.

Figure 4: Vectors innovation calculated in period 2001.

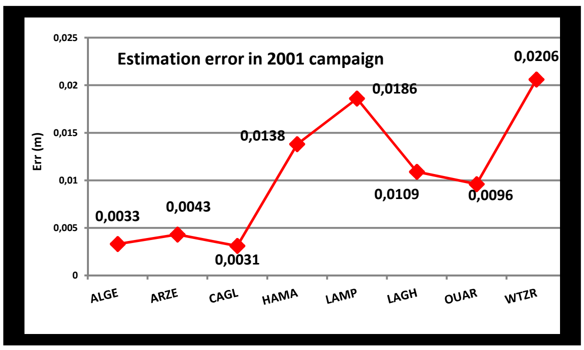


The amplitudes of the innovation vector are in centimeter order, significant innovation on the station LAGH; In addition, we note a similarity to the CAGL and ARZE stations, and a certain confidence between the measurements performed in 2001 and predicting the state vector in the same period.

3.3.1 Error estimation of the state vector

The adjustment by the Kalman filter was performed with only one serie of measurement performed in 2001 and the estimation errors were compared to the reference solution (obtained by Bernese software). These errors reflect especially the amplitude of the differences between the reference solution and that estimated by the Kalman filter. The error in estimation is about the centimeter in our case, which explains why the state in 2001 was estimated for all the stations of the network with a minimal covariance.

Figure 4: Estimation error calculated in 2001 period of ALGEONET network.



4. CONCLUSIONS

In this paper, we investigated to validate an adjustment step based on the Kalman filter technique on a relatively small number of GPS stations and data. Finally, the conclusion obtained from this study is that the statistical test can be successful only if the stochastic models are correctly known or estimated. The numerical results show that the Kalman technique is highly reliable for the monitoring of the effect and structure deformation with the geodetic networks. The preliminary results obtained can be considered as a beginning of processing by the use of the Kalman filter for the geodetic applications for the description of deformations.

If an effort was provide to analyse the results, the interpretation aspects of movement obtained were not approached, because it was not the main objective of this study.

Nevertheless, we constate a correlation between the displacements obtained in their direction and their module, with the characteristics of the limits of tectonic plates (African and Eurasian in our case), would provide interesting indications into the approach taken and the feasibility of applying the Kalman filter for monitoring geodynamical deformations. But the insufficient densification of the network to cover the North of Algeria suggested that the study doesn't give the evolution of deformation in function of the time.

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AUTHORS' ADDRESS AND CONTACT INFORMATION

Center of Space Techniques (CTS)
Division of Space Geodesy,
Po 13 Palestine Avenue ARZEW, ALGERIA

Research Director. Dr. Kahlouche Salem
Head of Space Geodesy Division
Tel: +213 41 472580
Fax: +213 41 473665
e-mail: s_kahlouche@yahoo.fr
kahlouche@asal.dz

Responsible Research. Touam Said
Tel: +213 41 472217
Fax: +213 41 473665
e-mail: s_touam@yahoo.fr

Attached researcher. MIR Radia
Tel: +213 41 472217
Fax: +213 41 473665
e-mail: mir_radia@yahoo.fr