Pergamon

Phys. Chem. Earth (A), Vol. 24, No. 4, pp. 355-359, 1999

1464-1895/99/$ - see front matter

PII: S1464-1895(99)00041-1

Practical Lessons from Analysis of a GPS Network Designed to Detect Movements of ≈ 1mm/year in the Eastern Pyrenees

J. Talaya[1], **K. Feigl**[2], **A. Térmens**[1] **and I. Colomina**[1]

[1]Institut Cartogràfic de Catalunya, Parc de Montjuïc, E-08028 Barcelona, Spain
[2]CNRS, UMR 5562, Observatoire Midi-Pyrénées, 14 Ave E. Belin, 31400 Toulouse, France

Received 24 April 1998; accepted 26 October 1998

Abstract.

Although the level of seismicity in the Eastern Pyrenees is currently moderate, with only one magnitude 5 earthquake recorded instrumentally, important earthquakes occurred there in the 15th century (1427-1428).

This straightforward observation suggests that the area is currently in the interseismic regime between large earthquakes separated by a long recurrence interval. In this case, strain may be accumulating as crustal deformation which we can measure by repeated geodetic surveys.

The geodetic network consists of 24 stations with a characteristic spacing of about 15 km. The monuments are concrete pillars anchored in bedrock outcrops chosen to span the traces of potentially active faults.

The network has been observed twice, in 1992 and in 1994, using dual-frequency receivers. The difficulties encountered and the experience gained processing the campaigns using the Bernese and the GAMIT software are described. For multi-epoch comparisons and velocity field determination, a new mathematical model has been developed as part of the GeoTeX software at the Institut Cartogràfic de Catalunya (ICC). It yields results similar to those obtained by the GLOBK software. The lessons learned will allow us to improve the methodology and accuracy of future campaigns. © 1999 Elsevier Science Ltd. All rights reserved.

1 Introduction

The study of the distribution of current tectonic deformation originated by the regional stress field is very important in investigating which are the most likely areas of future destructive earthquakes, and which are their return periods. Analysis of historical and instrumental seismicity data, together with research into the deformations (folds and faults) that have affected recent geological formations (Plioquaternary), enables an initial qualitative approximation of recent tectonic deformations to be made.

Historical seismicity data are fundamental in the study of seismic potentiality as it tells us of the existence of important earthquakes and of the areas most affected in relation to the epicentral area of the earthquakes. A large number of mediaeval documents have permitted us to know about the destructive crisis of 1427-1428 with great precision. Recent investigations have enabled the effects produced by the different quakes in the crisis to be separated: there are two earthquakes which caused damage in 1427. The area of maximum damage was located on the Amer-Olot axis. Another quake, the most important, took place on 2nd February 1428 and was felt over a wide area from the Pyrenees to Barcelona.

Seismic information based on seismograph readings is available for the eastern Pyrenees, in a very imprecise way, from the start of the century through to the 1970s. The recent development of the seismic network of Catalonia and in particular of the seismic network of the eastern Pyrenees has permitted the detection and location of quakes, including even those of small magnitude, which define with precision the areas of current fragility. The distribution of epicentres corresponding to the period 1986-1993 shows a significant concentration of seismic events of small magnitude at the two extremes of the NW-SE direction fault system -the system in which the areas of damage of the two 1427 quakes is concentrated- and very little activity on these faults.

Field studies carried out recently have permitted the analysis of numerous indications of recent deformations (affecting formations of the post-Miocene age), from one side to the other of the mountain range axis, Philip et al. (1992), Giménez et al. (1996). All of these observations suggest the presence of faults with recent activity, liable to be able to concentrate nowadays the regional tectonic deformations.

Correspondence to: J.Talaya

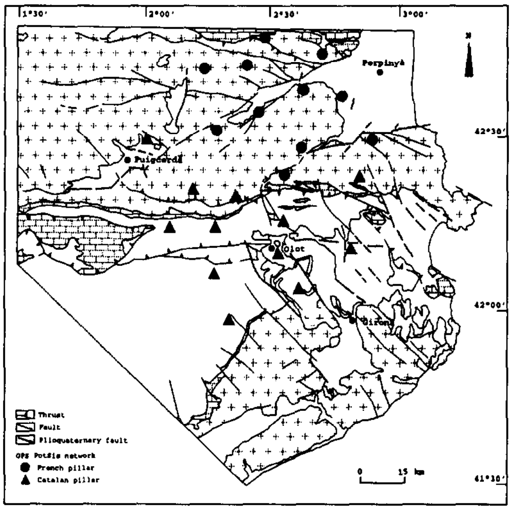

Fig. 1. PotSis network and geological map of the region. (from PotSis working Group)

1.1 The PotSis project

The PotSis [1] working group is a long term multidisciplinary collaboration between Spanish and French teams to study the present-day tectonic deformations through seismic, neotectonic and geodetic measurements.

The expected rate of deformation is of the order of 1 mm/year distributed o¡ver distances of roughly 10 km, for a strain rate of 10e-7/yr. To measure such low rates over humanly feasible time scales requires ultra-precise geodetic measurements. Here we use repeated recordings of the transmissions of the Global Positioning System (GPS) satellites, Goula et al. (1992), Goula et al. (1996), being aware that we might have still to wait 8-16 years to draw conclusions.

2 The PotSis deformation monitoring network

In 1992 a network of 24 pillars was set up covering an area of 5000 km^2. The mean distance between neighbouring pillars is about 15 km. The sites were selected according to geological criterias near the active faults, a good network geometry was also a requirement in the network design. Careful geological inspection of the sites ensured that the pillars were built on bedrock. Other important requirements for site selection were: suitability for GPS measurements, accessibility, and long term security.

To guarantee that at different occupations the antennas would be placed exactly at the same position, the Spanish pillars have an embedded bolt to which the antenna is fitted thanks to a finely-calibrated metal part. Similary, the French pillars use a standard aluminium base with three grooves and a hole.

Special care was taken to avoid confusing pillar movements with tectonic ones. The 1.60 m pillars are made of concrete with an iron framework anchored to bedrock. Three to four auxiliar points are located within fifty meters from the pillars. Four levelling marks were set up on the pilar base to monitor any inclination of the pillars. All the auxiliar points and levelling marks were measured in 1992/1993. Although the initial idea was to check the stability of the pillars in case a significant movement was detected, some of the pillars have been already checked and no local movements have been detected.

We also tried to minimize the elevation difference between pillars, this requirement was difficult to fulfill because the Pyrenees are very mountainous. The difference between the lowest and the highest points is 1280 m. This fact restricts the vertical accuracy of the network, but our main interest is to determine horizontal movements.

3 Observation strategy

The PotSis network has been observed twice, in 1992 and in 1994. The PotSis'92 survey was performed by ten teams in July 1992, days 195-199, coinciding with the IGS epoch'92 campaign. The receivers included 4 Trimble Geodesist P, 3 Ashtech P-12 ,2 Ashtech LD-XII and 1 Ashtech LM-XII. Five sessions of 17.5 hours (from 10:30 to 4:00 GMT) were recorded, the sessions were chosen according to constellation availability. The remaining 6.5 hour of the day were used for displacements between pillar. The ten teams formed two groups, one with the 4 Trimble receivers and the second one with the remaining 6 Ashtech receivers. The occupation strategy was designed to minimize the distance between receivers in the same group.

The Potsis'94 campaign was measured between 29 June and 4 July 1994, days 180-185. Again 10 receivers were used: 4 Trimble 4000SSE, 3 Ashtech Z-12 and 3 Ashtech LD-XII. The ocupation strategy was identical to PotSis'92. An additional session was carried out on day 180 by the four teams with the Trimble 4000SSE receivers. The sessions in PotSis'94 lasted from 12:30 to 6:00 GMT, retaining 17.5 hours sessions.

---

[1] X.Goula, J.Fleta, X.Roca (Seismology, ICC); I.Colomina, D.Barrot, A.Térmens, M.A.Ortiz, M.Soro, J.Talaya (Geodesy, ICC); B.Grellet, D.Carbon (GEOTER, Montpellier); C.Michel (GEOÏD); M.Cushing, F.Cotton (Institut de Protection et Sûreté Nucléaire, Pars); K. Feigl, A.Souriau, A.Rigo (CNRS, Observatoire Midi-Pyrénées, Toulouse) ; R.Bayer, H.Philip (Université de Montpellier); E.Suriñach (Universitat de Barcelona).

4 Analysis strategy

The processing of the campaigns was done simultaneously at the Institut Catogràfic de Catalunya (ICC) and at the Observatoire Midi-Pyrénées (OMP). Additional computations were also done by the Université de Montpellier and GEOÏD.

At the ICC, in a first step, interstation vectors were computed using the Bernese software. For modelling the tropospheric delay a few tropospheric parameters were estimated for each station. The ambiguities were successfully solved in most of the cases, Goula et al. (1995). Finally, a network adjustment was done for each campaign with the output of each session (station coordinates together with their covariances) using the GeoTeX software from the ICC, Colomina et al. (1992).

At the OMP the computation of interstation vectors was done using GAMIT, Oberlé (1993), Pauchet et Romieu (1995). Tropospheric parameters were also estimated in the computation and, as in the Bernese case, most of the ambiguities were successfully solved.

We compared the results of both computations and, in general the difference of the interstation vectors was smaller than 1 cm in the horizontal component. However, in a few particular cases, the differences were as large as 2.5 cm. These differences could be explained by incorrect ambiguity determination due to presence of bad quality L2 data provided by the L2-squaring receivers.

In both cases, Ashtech and Trimble data were processed independently, as if they were from different sessions. This approach avoids antenna mixing problems. Although both GAMIT Bock et al. (1986), Dong and Bock (1989), Feigl et al. (1993), King and Bock (1997) and Bernese admit antenna models, the best repeatability was obtained without mixing antennas.

Although the vertical repeatability obtained in the baselines between French pillars and in the baselines between Spanish pillars was quite good, a worse vertical repeatability was obtained in the baselines that mixed the pillars, a French pillar at one end and a Spanish pillar at the other. That could be due to resonance problems between the antenna ground plate and the pillar plate, Elosegui et al. (1995). Further research has to be done to ensure the later point.

5 Movement detection

Once both campaigns (PotSis'92, Potsis'94) were computed they were combined to estimate the velocity field and its uncertainty. Two different approaches were used.

At the Observatoire Midi-Pyrénées the GLOBK software was used. Globk is a Kalman filter whose primary purpose is to combine solutions from individual GPS / VLBI experiments, Herring et al. (1990), Herring (1991). The estimates and associated covariance matrices from station coordinates generated by GAMIT in each individual computation session where combined for estimating station velocities.

The ICC approach: begins with separate adjustments of the PotSis'92 network and the PotSis'94 network. Thereafter the station velocities V in (1) were determined in an adjustment where a set of seven datum transfer parameters T in (1) were also estimated between PotSis'92 and PotSis'94 networks. The mathematical model implemented in the GeoTeX software is:

$$\chi_{94} = T(\chi_{92}) + V.\Delta t \qquad (1)$$

Where χ_{92} is the PotSis'92 network and χ_{94} is the PotSis'94 network.

Theoretically, the reference frame of the PotSis adjusted networks should be the one provided by the precise orbits used, ITRF91 for PotSis'92 and ITRF92 for PotSis'94. So, the datum transfer parameters (T in 1) should be well known and not need for its estimation. However, the July 92 orbits were not so precise (in fact, most of the software packages used in 1992 for the determination of the precise orbits were still under development) and, therefore, it was difficult to compute a very accurate reference frame using IGS stations 1300 *km* away. To avoid apparent distortions due to changes in the reference frame imposed by the orbital trajectories between the 1992 and 1994, the ICC approach introduces the datum transfer parameters T . Similarly, the OMP approach introduces large stochastic variations in the orbital parameters. Both approaches effectively separate the reference frames at the two epochs, minimizing any distortion on the station coordinates. Otherwise, the distortion could be as large as 1 part in 10e7, or 1 mm over 10 km Larson et al. (1991).

6 Evaluation of movements

Figure 2 shows the velocity field determined using the ICC approach, were we can see that most of the velocities fall within their 3σ error ellipses and are not significant. The Toulouse approach gave very similar patterns on the velocity field determination using GAMIT, GLOBK.

In figure 2 we can notice that the error ellipses are larger at the periphery of the network than at the centre of the network. This behaviour is because the inner stations were observed 2-4 times per campaign while to the outer stations have been observed just 1-2 times per campaign. Also, the error ellipses of the peripheral points of the network tend to be larger because the adjustment accumulates the errors there.

Seven of the velocity vectors fall outside their formal error ellipses, suggesting that there may be some significant movements at those points. However, a closer analysis leads us to be cautious . All the points whose

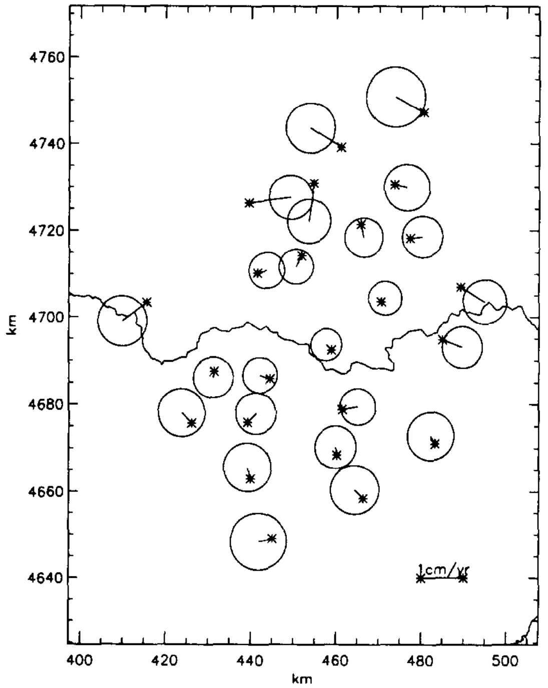

Fig. 2. Velocity field determination, (mm/year). Formal error ellipses scaled at 3σ.

velocity vector fall outside their error ellipses were located on the peripheral part of the network, with the problems described above. In addition, some of those stations were measured only once by L2-squaring receivers. Also, it should be kept in mind that even on the permanent GPS networks, when looking at day by day solutions it is normal to find 1-2 cm discrepancies. Finally we recall that estimating velocities from only two surveys separated by only two years can be misleading.

Therefore we are reluctant to accept that we have detected real movements. Future campaigns, over longer time intervals will provide a more robust estimate of the velocity field.

7 Lessons learned

During the analysis of the PoSis'92 and PotSis'94 campaigns we learned a few aspects that could be improved in future campaigns to obtain a better network accuracy.

Our test showed that even using antenna models the best results are obtained when not mixing antennas. Also, choke-ring antennas with ground planes to avoid multipath effects are needed. We recommend using of identical antennas for all the receivers used on the campaign. In fact, we plan to use ten antennas of the Dorne-Mongolin choke ring design for our next campaign, scheduled for the summer of 1999.

When building networks for crustal movements detection, it should be kept in mind possible resonance problems, Elosegui et al. (1995), that can disturb the network accuracy, the antenna type mount can affect geodetic baseline results at the centimetre level. This phenomenon can be greatly reduced placing microwave absorber material between the antenna and the top of the pillar.

Both the ICC and the OMP analysis strategies seem to minimize apparent distortions in the network caused by the change in reference frames related to long-term changes in the so-called "precise orbits" and the global tracking network used to determine them. So, we can concentrate ourselves on obtaining a very precise local network without the need for a very precise regional network needed for a good reference frame determination (specially difficult in 1992).

8 Conclusions

For the determination of very small crustal movements using geodetic measurements the best option is a network of permanent GPS stations. However, when this is not possible due to financial constrains, the network of closely-spaced pillars well anchored to bedrock and its periodic observation by GPS campaigns spaced over time becomes the best option. The results of the PotSis campaigns together with our experience in processing permanent networks suggest that the level of noise between surveys separated by two years is comparable to that between two sequential days of measurements recorded by a permanent network. That can be checked with the GPS time series available from the IGS network. The lessons learned on the processing of the first two campaigns will allow us to improve the methodology for future campaigns. An optimal geodetic arrangement would consist of a set of permanent stations providing high temporal resolution data and a geodetic network of high spatial resolution tailored to the geographical distribution of tectonic faults. The PotSis group will integrate ICC's network of permanent GPS stations and possible future permanent stations on the French side, with the ongoing "classical" geodetic approach at the epoch-by-epoch analysis. The next observation campaign for PotSis will take place in July 1999.

Acknowledgements. Our thanks go to Sergio Gonzàlez and the Escola d'Enginyeria Tècnica Topogràfica of the Universitat Politècnica de Catalunya, and the numerous French observers for their contribution to the survey in the PotSis campaigns. The stage of members of the ICC in Toulouse has been founded by DGICT grant HF95-207.

References

Bock,Y., Gourevitch,S.A., III, C. C. C., King, R. W., and Abbott, R. I., 1986, Interferometric analysis of GPS phase observations: Man. Geod., v. 11, p. 282-288.

Colomina,I., Navarro,J. and Térmens,A., 1992: GeoTeX: A general point determination system International Archives of Photogrammetry, Vol.29, Comm III, pp 656-664.

Dong,D.N. and Bock,Y., 1989, GPS network analysis with phase ambiguity resolution applied to crustal deformation studies in California: J. Geophys. Res., v. 94, p. 3949-3966.

Elosegui,P., Davis,J.L., Jaldehag,R.T.K., Johansson,J.M., Niell,A.E. and Shapiro,I.I., 1995. Geodesy using the Global Positioning System: The effects of signal scattering on estimates of site position. Journal of Geophysical Research - Solid Earth Vol.100, No.B6, 1995. pp 9921-9934.

Feigl, K. L., Agnew, D. C., Bock, Y., Dong, D., Donnellan, A., King, R. W., B. H. Hager, Herring, T. A., Jackson, D. D., Jordan, T. H., Larsen, S., K. M. Larson, Murray, M. H., Shen, Z., and Webb, F. H., 1993, Space geodetic measurement of crustal deformation in central and southern California, 1984-1992: J. Geophys. Res., v. 98, p. 21,677-21,712.

Giménez,J., Suriñach,E., Fleta,J. and Goula,X., 1996. Recent vertical movements from high precision leveling data in the Northeast Spain. Tectonophysics 263 (1996) p. 149-161.

Goula,X., Colomina,I., Fleta,J., Grellet,B., Philip,H. and Souriau,A., 1992: Project of a GPS network for the evaluation of seismic potentiality in the eastern Pyrenees Jornada Técnica: Desarrollos y aplicaciones del Sistema de Posicionamiento Global GPS. Sociedad Española de Cartografía Fotogametría y Teledetección. 5.7.92. Barcelona. pp 95 – 104.

Goula,X., Talaya,J., Térmens, A.,Colomina, I.,Fleta and J.,Saler,H., 1995. Evaluación de la Potencialidad Sísmica del Pirineo Oriental. Estudios de Sismicidad, Neotectónica y Geodesia: Primeros Resultados de las Campañas GPS PotSis'92 y PotSis'94. II Setmana Geomàtica de Barcelona, 25.4.95 – 28.4.95, Barcelona, pp 138–145.

Goula,X., Talaya,J., Térmens, A., Colomina,I., Fleta,J., Grellet,B. and Granier,T., 1996. Avaluació de la potencialitat sísmica del Pirineu oriental. Primers resultats de les campanyes GPS PotSis'92 i PotSis'94. Terra, desembre 1996, num.28, p.41-48.

Herring,T.A., 1991, GLOBK: Global Kalman filter VLBI and GPS analysis program, MIT.

Herring,T. A., Davis,J. L., and Shapiro,I. I., 1990, Geodesy by radio astronomy: the application of Kalman filtering to very long baseline interferometry: J. Geophys. Res., v. 95, p. 12,561-12,581.

King,R. W. and Bock,Y., 1997, Documentation for the MIT GPS Analysis Software: GAMIT, Mass. Inst. Tech.

Larson,K.M., Webb,F.H. and Agnew,D.C., 1991, Application of the Global Positioning System to crustal deformation measurement 2. the influence of errors in orbit determination networks: J. Geophys. Res., v. 96, p. 16,567-16,584.

Oberlé,N., 1993. Analyse de données GPS pour l'estimation des déformations tectoniques actuelles dans l'Est des Pyrénées:Étude de faisabilité. Diplôme d'ingénieur de l'École de Physique du Globe, Univ. Louis Pasteur, Strasburg I.

Pauchet,H. and Romieu,C., 1995. Utilization du GPS pour caractériser la déformation actuelle dans les Pyrénées: Préparation de réseau RESPYR 95, Analyse des donées PotSis 92-94. Université Paul Sabatier Toulouse.

Philip,H., Bousquet,J.C., Escuer,J., Fleta,J., Goula,X. and Grellet,B., 1992. Présence de failles inverses d'âge quaternaire dans l'Est des Pyrénées: implications sismotectoniques. Comptes Rendus de l'Académie des Sciences, tom 314, II p- 1,239-1,245, París.