

Received:
27 September 2018
Revised:
22 January 2019
Accepted:
25 March 2019

Cite as: Abdel Karim Yelles-Chaouche, Kamel Lammali, Amar Bellik, Amina Bougrine, Abdel Hakim Mahsas, Wahab Bacha, Toufik Terki, Othmane Meliani, Fares Ouzzani, Yacine Lakehal, Ahcene Ait Amir, Kamel Khellaf, Sid Ahmed Khentar, Abdelkader Chouiref, Abdelhamid Bendekan, Eric Calais. REGAT: A permanent GPS network in Algeria, configuration and first results. *Heliyon* 5 (2019) e01435. doi: [10.1016/j.heliyon.2019.e01435](https://doi.org/10.1016/j.heliyon.2019.e01435)



REGAT: A permanent GPS network in Algeria, configuration and first results

Abdel Karim Yelles-Chaouche^a, Kamel Lammali^a, Amar Bellik^a, Amina Bougrine^{a,*}, Abdel Hakim Mahsas^a, Wahab Bacha^a, Toufik Terki^a, Othmane Meliani^a, Fares Ouzzani^a, Yacine Lakehal^a, Ahcene Ait Amir^a, Kamel Khellaf^a, Sid Ahmed Khentar^a, Abdelkader Chouiref^a, Abdelhamid Bendekan^a, Eric Calais^b

^a Centre de Recherche en Astronomie, Astrophysique et Géophysique (CRAAG), Bouzareah, Algiers, Algeria

^b Ecole normale supérieure, Dept. of Geosciences, Université PSL, Paris, France

* Corresponding author.

E-mail address: bougrine.am@gmail.com (A. Bougrine).

Abstract

The REGAT (“REseau Géodésique de l’Atlas”) geodetic network is composed of 53 continuously-recording GPS stations distributed in the Algerian Atlas. It spans the whole width of the Algerian coast and reaches 300 km inland, with inter-sites distance of about 100 km. One additional site is located in Tamanrasset in the southernmost part of the country. The network, whose oldest stations started operating in 2007, encompasses the main active tectonic features of the most seismically active segment of the Nubia-Eurasia plate boundary in the Western Mediterranean. Here we describe the network configuration, the data collection and analysis strategy, as well as some preliminary results on horizontal GPS velocities. A detailed analysis of the velocity field in terms of plate boundary kinematics is the topic of a separate publication. The REGAT network fills an important gap in our knowledge of present-day plate boundary deformation in the Western Mediterranean. It will soon be enhanced by an additional 100 sites in order to improve deformation monitoring with a higher spatial resolution for a better assessment of the regional seismic hazard.

Keywords: Atmospheric science, Geology, Geophysics, Geoscience, Natural hazards

1. Introduction

The past decade has seen a rapid growth in the number of continuously–recording Global Positioning System (GPS) sites around the globe for applications to mapping and navigation, reference frame determination, and deformation monitoring for geodynamics. The distribution of continuous GPS (cGPS) stations remains however uneven amongst countries and continents. Africa, except for a few countries such as South Africa (Figure 2), remains poorly covered in spite of international efforts such as the “AFRICan REference Frame” (AFREF) sub-commission of the International Association of Geodesy (e.g., Saria et al., 2013). As a result, the determination of the present-day kinematics of the Nubian plate and of its internal deformation still need significant improvement. In addition, the paucity of cGPS measurements in northern Africa is still preventing us to accurately resolve the present day kinematics of plate boundary deformation in the Mediterranean where three major tectonic plates – Nubia, Eurasia and Arabia – interact (Nocquet and Calais, 2004; Serpelloni et al., 2007; Nocquet, 2012).

In this paper, we present efforts performed in Algeria over the past decade to increase GPS monitoring in the northern, most tectonically active, part of the country thanks to a 54–site network of continuously–recording GPS stations, the REGAT (“REseau Géodésique de l’ATlas”) geodetic network. This network fills a hole in the description of kinematics of the Nubia – Eurasia plate boundary in the Mediterranean and complements existing networks elsewhere in the Mediterranean, for instance RING in Italy (Avallone et al., 2010) and NOANET in Greece (Chousianitis et al., 2015). Along the Algerin segment of the plate boundary, kinematic models all show a counter-clockwise rotation of Nubia with respect to Eurasia, resulting in a NW-SE convergence oblique to the direction of the plate boundary, with a rate increasing from 2–4 mm/yr in Gibraltar to 3–8 mm/yr in the Sicily Strait (Nocquet, 2012). REGAT will help understand how this motion is partitioned on the various active tectonic structures in Algeria, on land and offshore (e.g. Domzig et al., 2006; Meghraoui and Pondrelli, 2012).

2. Background

2.1. Motivation for the REGAT network

The country of Algeria occupies a wide segment of the Nubia-Eurasia plate boundary (Figure 1) along which the oblique convergence between the two plates is accommodated by active faults and folds in the Algerian Atlas (e.g., Meghraoui and Pondrelli, 2012) and offshore (e.g., Yelles et al., 2009), both accompanied by significant seismicity (e.g., Yelles-Chaouche et al., 2017). The 1980 El Asnam

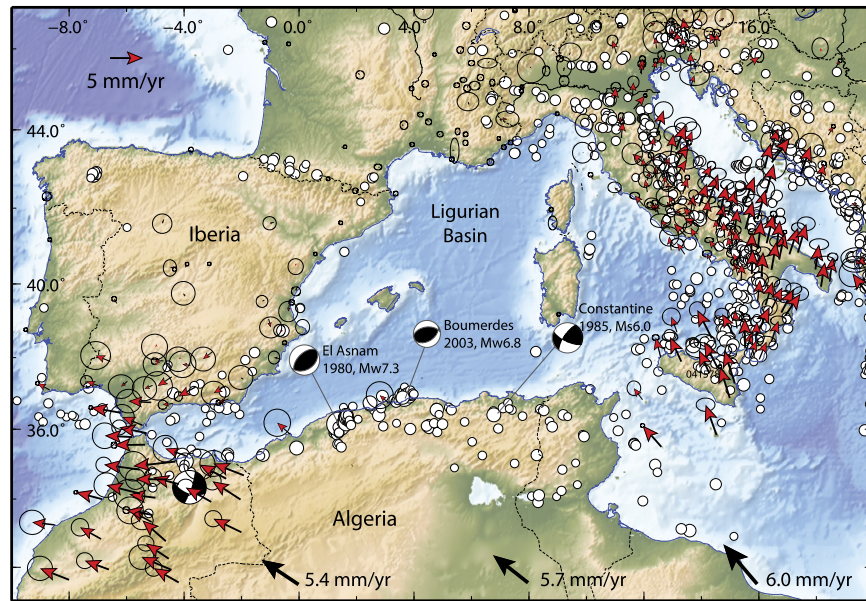


Figure 1. Active tectonic setting of the Western Mediterranean. White circles show earthquakes with magnitude greater than 4.5 (NEIC database, earthquakes.usgs.gov). Black arrows at the bottom of the figure show model velocities for the Nubia plate with respect to Eurasia Calais et al. (2003). Red arrows are selected GPS velocities from a regional compilation by Nocquet (2012).

earthquake (Ouyed et al., 1981) triggered the first geodetic measurements for tectonic purposes in Algeria. Ruegg et al. (1982) quantified the associated co-seismic vertical displacement using terrestrial geodetic techniques. Soon after, the Algerian institution in charge of seismic hazard determination, the *Centre de Recherche en Astronomie, Astrophysique et Géophysique* (CRAAG) densified the initial network and regularly remeasured it from 1986 to 1994 in order to monitor post-seismic deformation (Dimitrov et al., 1987; Bezzeghoud et al., 1995; Lammali et al., 1997).

The first GPS network for crustal deformation monitoring was installed and measured by the CRAAG around the Thenia fault in the Boumerdes–Zemmouri area in 2002. GPS data were collected during two campaigns before the region was struck by the M_w 6.8 Boumerdes earthquake on May 21, 2003 (Yelles et al., 2003). A third measurement campaign in the days following this event allowed us to directly measure the associated co-seismic deformation, which provided strong constraints on the rupture location, geometry, and source mechanism (Yelles et al., 2004).

The May 21, 2003, M_w 6.8 Boumerdes earthquake (Yelles et al., 2003; Delouis et al., 2004; Yelles et al., 2004) was a motivation for important changes in the seismic monitoring strategy of the CRAAG. A significant upgrade of the analog telemetric network was performed, with the installation of a new digital seismic network (Yelles-Chaouche et al., 2013). Also, the Boumerdes earthquake sparked new efforts to increase deformation monitoring capabilities over the most seismically active part

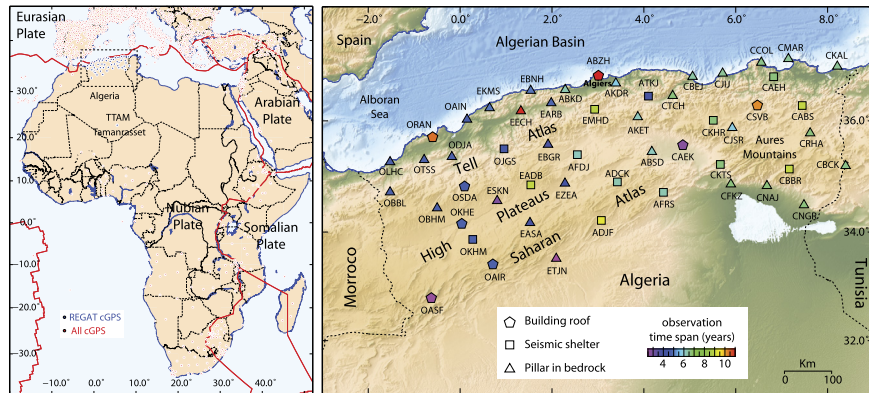


Figure 2. Left: map of continuously operating GPS stations in and around Africa (red dots) from the University of Nevada, Geodetic Laboratory web site (geodesy.unr.edu). The REGAT sites are indicated by blue dots, with 53 sites located in northern Algeria and one located in southern Algeria (TTAM, Tamanrasset). Right: map of the REGAT network. Symbols show monument type (building roof, seismic shelter roof, concrete pillar in bedrock, see Figure 4), colors indicate site observation time span.

of Algeria through campaign measurements in selected areas and the installation of a cGPS network. In 2007, the CRAAG started implementing the REGAT project and purchased 76 GPS stations, 22 of them to be used in campaign measurements around identified active structures and Neogene basins in Algeria, and 54 stations for continuous measurements. The objectives are to better constrain the regional tectonics and contribute to global kinematics models, and to better assess seismic hazard in Algeria.

The campaign measurements concern four target areas where observations are repeated every 2 to 3 years. A first network is installed in Eastern Algeria to monitor the Ain Smara fault, locus of the 1985, M_s 6.0 Constantine earthquake and belonging to a poorly-known strike-slip fault system in eastern Algeria. A second one is located around the Mitidja basin close to the capital city Algiers, bounded by active faults such as the one that ruptured during 1989, $M_{5.9}$ Chenoua earthquake. A third one replicates the old geodetic network of the Chellif basin that was measured periodically from 1981 to 1992 (Lammali et al., 1997) following the 1980, M_w 7.3 El Asnam earthquake (Ouyed et al., 1981; Philip and Meghraoui, 1983; Yielding et al., 1989). A fourth one is installed in the Oran area encompassing the Murdjadjo range identified as the locus of the historical 1790 earthquake (Bouhadad, 2001). This paper focuses on the 54-site continuous GPS network, described in detail hereafter.

2.2. Configuration and management of the REGAT network

The REGAT network is composed of 53 cGPS stations distributed along the Algerian Atlas (Tellian and Saharan Atlas, and the High Plateaus in-between them), and one

Table 1. Main characteristics of the REGAT sites. Monument types: P = pillar, 1.5 m–tall concrete pillar anchored in bedrock, R = building roof, S = top of seismic station shelter. Power: A = AC power, B = battery, S = solar panels. Co-located: site located at existing seismic station.

Site	GPS equipment		Monument type			Power			Communication				co-located
	Receiver	Antenna	P	R	S	A	B	S	ADSL	GSM	VSAT	NO	
ABKD	GRX1200+	AR25	X			X	X	X		X			X
ABSD	GRX1200+	AR25	X				X	X		X			X
ABZH	GRX1200-pro	AT504		X		X	X		X				X
ADCK	GRX1200+	AR25			X		X	X		X			X
ADJF	GRX1200+	AT504			X		X	X		X			X
AFDJ	GRX1200+	AR25			X		X	X		X			X
AFRS	GRX1200+	AR25			X		X	X		X			X
AKDR	GRX1200+	AR25	X				X	X		X			X
AKET	GRX1200+	AR25	X				X	X		X			X
ATKJ	GRX1200+	AR25			X		X	X		X			X
CABS	GRX1200-Pro	AT504			X		X	X			X		X
CAEH	GRX1200+	AR25			X		X	X		X			X
CAEK	GRX1200+	AR25		X			X	X		X			
CBBR	GRX1200+	AT504			X		X	X		X			X
CBCK	GRX1200+	AR25	X				X	X		X			
CBEJ	GRX1200+	AR25	X				X	X		X			
CCOL	GRX1200+	AR25	X				X	X		X			
CFKZ	GRX1200+	AR25	X				X	X		X			
CJIJ	GRX1200+	AR25	X				X	X		X			
CJSR	GRX1200+	AR25	X				X	X		X			X
CKAL	GRX1200+	AR25	X				X	X		X			
CKHR	GRX1200+	AR25			X		X	X			X		X
CKTS	GRX1200+	AR25			X		X	X		X			X
CMAR	GRX1200+	AR25	X				X	X		X			
CNAJ	GRX1200+	AR25	X				X	X		X			
CNGR	GRX1200+	AR25	X				X	X		X			X
CRHA	GRX1200+	AR25	X				X	X		X			X
CSVB	GRX1200-Pro	AT504		X		X					X		X
CTCH	GRX1200-Pro	AR25	X				X	X		X			X
EADB	GRX1200-Pro	AT504			X		X	X		X			X
EARB	GRX1200-Pro	AR25	X				X	X		X			X
EASA	GRX1200+	AR25	X				X	X		X			X
EBGR	GRX1200+	AR25	X				X	X		X			X
EBNH	GRX1200+	AR25	X				X	X		X			X
EECH	GRX1200-Pro	AT504	X			X	X		X				X

(continued on next page)

Table 1. (continued)

Site	GPS equipment		Monument type			Power			Communication				co-located
	Receiver	Antenna	P	R	S	A	B	S	ADSL	GSM	VSAT	NO	
EKMS	GRX1200+	AR25	X				X	X		X			X
EMHD	GRX1200-Pro	AT504			X		X	X		X			X
ESKN	GRX1200+	AR25	X				X	X		X			X
ETJN	GRX1200+	AR25	X				X	X		X			
EZEA	GRX1200+	AR25	X				X	X		X			X
OAIN	GRX1200-Pro	AR25	X				X	X		X			
OAIR	GRX1200+	AR25	X			X	X		X				
OASF	GRX1200-Pro	AR25		X			X	X		X			
OBBL	GRX1200+	AR25	X				X	X		X			X
OBHM	GRX1200+	AR25	X				X	X		X			X
ODJA	GRX1200+	AR25	X				X	X		X			X
OJGS	GRX1200+	AR25			X		X	X			X		X
OKHE	GRX1200+	AR25		X			X	X		X			
OKHM	GRX1200+	AR25			X		X	X		X			X
OLHC	GRX1200+	AR25	X				X	X		X			X
ORAN	GRX1200-Pro	AT504		X			X	X	X				X
OSDA	GRX1200+	AR25		X			X	X		X			
OTSS	GRX1200+	AR25	X				X	X			X		X
TTAM	GRX1200-Pro	AT504		X		X	X					X	X

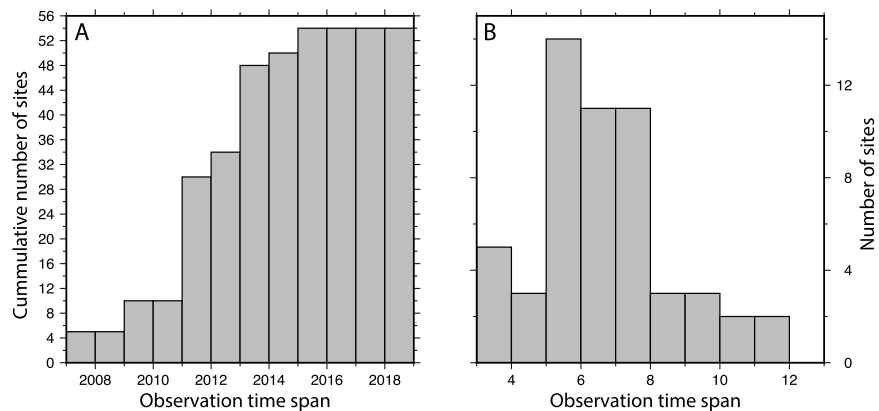


Figure 3. (A) Number of REGAT cGPS sites as a function of observation time span. (B) Cumulative number REGAT GPS as a function of time.

station located in Tamanrasset on the Saharan platform (Figure 2, Table 1). The 53 Atlas stations cover northern Algeria over 1200 km in the east-west direction and from the coast to 300 km inland to the south. The network was designed to cover the seismically active part of Algeria as evenly as possible, since little prior information was available on strain rates or slip rates on active structures in the country. Given the number of equipments available, this leads to a mean inter-site distance of about 100 km.

The REGAT network was installed in two steps. Twelve stations were first installed from 2007 to 2010, followed by the installation of an additional 42 starting in 2011 (Figure 3A). As a result, data time span varies significantly between stations (Figure 3B). In 2015, the REGAT network was fully operational, with the youngest stations having a minimum of 3 years data time span. The oldest stations (ABZH, EECH, TTAM, ORAN, CSVB) are located with regional GRAAG centers, which allowed for an easier and faster installation. Many of the REGAT stations are colocated with seismic monitoring instruments from the CRAAG broadband seismic network in order to benefit from site security, power, and communication.

The REGAT network operates dual frequency Leica GRX1200+ and Leica GRX1200PRO GPS receivers with Leica choke-ring antennas (AT504 and AR25), as described in Table 1. In most cases, the GPS antenna is installed on top of a 1.5 m-high concrete pillar directly anchored into the bedrock (Figure 4). Some of the antennas are installed on a building roof or on top of a small shelter building hosting seismic instruments. As always, the antenna support chosen is a compromise between optimal location for geodynamic monitoring together with site security, logistics, and access.

The receivers are connected to AC power if possible, and in most cases benefit from solar power and a DC battery. Data are currently recorded at 30 seconds intervals with a 1 Hz ring-buffer and transferred daily to the CRAAG data center in Algiers



Figure 4. Types of monuments used in the REGAT network. Left: building roof, middle: seismic station shelter, right: 1.5 m-tall concrete pillar anchored in bedrock.

via ADSL, GSM, or VSAT (Table 1). In the few cases where remote communication is not available, the data is collected manually by an operator and saved to disks that are then sent to the data center.

The network is managed via 3 software suites developed at the CRAAG. The first one manages data acquisition from the remote stations, collects information on station health status, and sends real-time alerts to network operators in case of problems. This information is saved in a database in order to monitor the network status and detect possible anomalies at the stations. The second software suite manages data archival, which includes data conversion from raw Leica format into Receiver Independent Exchange (RINEX) format and data quality control using TEQC (Estey and Meertens, 1999) controlling that way the number of observation per day, slips, multipath (mp1 and mp2) that are all represented in graphics for each site. The third one compiles daily station statistics site by site for the entire network.

3. Calculation

3.1. Data processing strategy

Once the data is archived and the precise satellite orbits from the International GNSS Service (IGS) available, we process data from the REGAT network using the GAMIT-GLOBK software package (Herring et al., 2015). We use double-difference phase measurements to estimate daily station coordinates, satellite state vectors, seven daily tropospheric delay parameters per site, two parameters for horizontal tropospheric gradients, and phase ambiguities. We use Earth orientation parameters from the International Earth Rotation Service (IERS), apply corrections for solid-earth tides, polar tides, time-variable ocean loading following the IERS conventions 2010 (Petit and Luzum, 2010), apply antenna phase-center variations using the latest IGS tables (Schmid et al., 2007), and use data from 34 IGS sites in Africa and Europe to tie our solution to the International Terrestrial Reference Frame (ITRF2014, Altamimi et al. (2016)), shown by blue squares on Figure 5.

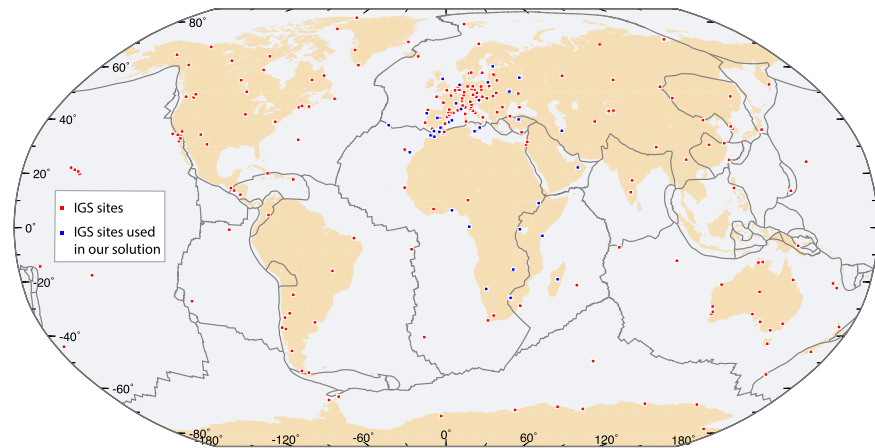


Figure 5. Distribution of global IGS GPS sites used in the reference frame implementation (red squares) and of the sites included in the regional solution computed using GAMIT-GLOBK (blue squares).

We compute daily position time series which we analyze visually to identify discontinuities, position offsets, or data gaps. At this stage, we use the First-Order Gauss-Markov Extrapolation (FOGMEx) algorithm of Herring (2003) to compute station-dependent variance scaling factors to be applied to formal errors in order to obtain, at the final stage described below, velocity uncertainties that account for the level of colored noise present in the time series. Independent analyses (e.g. Saria et al., 2013; Craig and Calais, 2014) show that applying the FOGMEx algorithm leads to velocity uncertainties that are similar to those obtained using an explicit maximum likelihood estimation of white/flicker or combined white/flicker/random walk noise (Williams, 2003; Langbein, 2004), in particular as the time series durations increase. We make no attempt to correct for the annual and semiannual signals as velocity estimates use time series with a minimum observation time of 3 years (Figure 2, Figure 3), consistent with Blewitt and Lavallée (2002) who show that the minimum data time span needed to average out seasonal signals unrelated to the long-term motions is 2.5 years.

In a second step, we combine the complete, loosely-constrained, REGAT daily solutions – *i.e.*, vector of estimated parameters and their associated variance–covariance matrix – with the daily global solutions for the whole IGS network provided by the Massachusetts Institute of Technology IGS Data Analysis Center into weekly position solutions. The combination consists of estimating a set of positions and the corresponding 7-parameter similarity transformation (rotation, translation, scale) that aligns the REGAT and IGS solutions onto ITRF2014 using IGS stations common to the two solutions. While doing so, we only retain stations that are part of the core IGS network, *i.e.*, stations whose positions and velocities are well-determined in ITRF2014 (red squares on Figure 5). This procedure, performed using a Kalman filter estimator coded in GLOBK (Herring et al. 2015), is similar to

a weekly position average and helps improve signal resolution over the noise level. In the end, we obtain one global, loosely-constrained solution per week that includes up to 500 globally-distributed sites among which the 54 REGAT sites. These weekly combinations allow for an optimal tie of the REGAT network to the ITRF.

We finally combine the weekly global solutions into a single position/velocity solution while accounting for the FOGMEx variance factors determined above. We tie this solution to the ITRF by minimizing position and velocity deviations from the globally-distributed set of the core IGS reference sites via a 12-parameter Helmert transformation (translation and rotation) as described in Nocquet and Calais (2003).

4. Results

4.1. Position time series

The daily position time series of 42 of the 54 REGAT sites are linear with a weighted RMS – or long-term repeatability – that does not exceed 2 mm on the horizontal component and 6 mm on the vertical, with limited seasonal displacements (Figure 6). As an example, Figure 7 shows detrended time series at two of these well-behaved sites, EECH installed in February 2007 and ADCK installed in October 2011 as part of the second stage of implementation of the REGAT network. Data gaps are typically due to loss of power at the sites.

Unfortunately, 12 of the 54 REGAT sites show time series that are non-linear and sometimes – not always and not systematically on all components – show an erratic, quasi-periodic behavior. Three of them are located on, or at very close proximity to, operational dams that contain large water reservoirs (sites OBBL, EBGR, and EKMS, Figure 8). Their horizontal time series show periodic signals that are more pronounced on the vertical, which is indicative of a tilting of the monument, most likely as a result of the reservoir discharge/recharge cycles. Nine additional sites, not located on or near dams, also show non-linear behavior unlikely to be of tectonic origin (Figure 9). As for dam sites, some show a quasi-periodic signal that is more pronounced on the horizontal than on the vertical component, suggestive of monument tilt (sites OJGS, OSDA, OTSS, CAEH, and EBNH). Except for the dam sites, we could not find a correlation between time series behavior and monument type (Table 1). We checked daily multipath values but could not find a correlation between multipath noise (MP1 or MP2 values from TEQC) and time series behavior. We replaced the GPS antenna at two of the low-quality sites, AKET and EBNH, but this had no impact on the quality of the time series. At this point we can only attribute the low-quality position time series at these sites to local soil instabilities and/or to the monument construction.

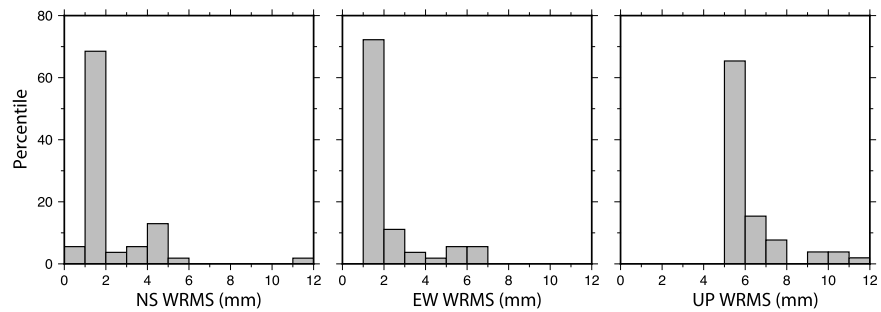


Figure 6. Precision of the GPS solution presented here as examined from the daily scatter (repeatability) of individual daily positions.

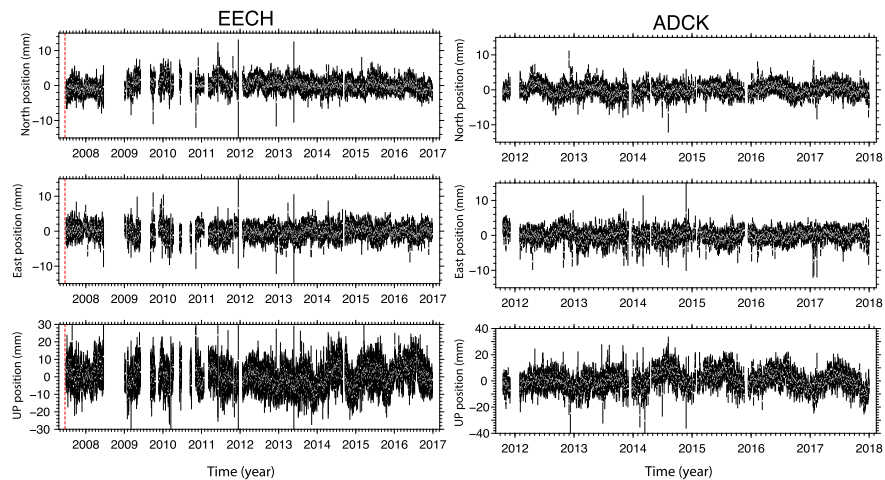


Figure 7. Detrended daily position time series at two sites with good quality data, with horizontal weighted RMS < 1.5 mm/yr and vertical weighted RMS < 5.5 mm/yr. EECH was installed in early February 2007. ADCK was installed in mid-October 2011.

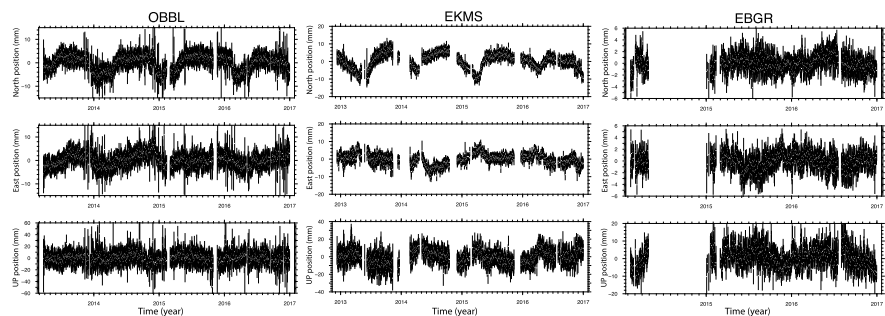


Figure 8. Detrended daily position time series of 3 REGAT sites, OBBL, EBGR, and EKMS, located in vicinity of operational dams. Time series show a non-linear behavior with a periodic signal more pronounced on the horizontal than on the vertical components.

4.2. Site velocities

The resulting velocities at the REGAT sites show uncertainties that range between 0.5 and 0.1 mm/yr for the horizontal components and between 1.8 and 0.4 mm/yr

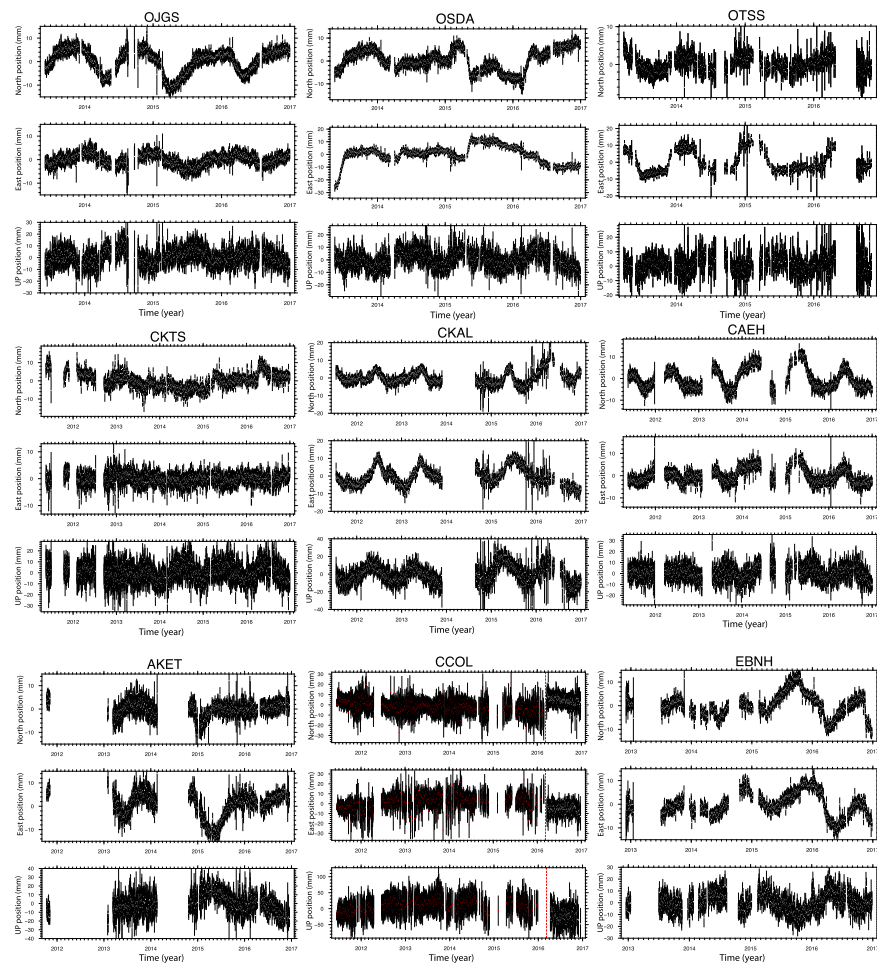


Figure 9. Detrended daily position time series of 9 other REGAT sites with low-quality time series: OJGS, OSDA, OTSS, CKTS, CKAL, CAEH, AKET, CCOL, and EBNH.

for the vertical components except the one of the identified bad sites where their uncertainties are higher reaching 1.4 mm/yr for the horizontal components (Figure 10). As expected, both vertical and horizontal uncertainties decrease with observation time span (e.g., Saria et al., 2013). This is consistent with observations at many other regional cGPS networks.

Figure 11 shows horizontal velocities in a Eurasian-fixed frame defined by minimizing horizontal velocities at 58 located on stable Eurasia. We find that velocities at most of the sites identified above from their poor-quality time series (Figures 8 and 9) have velocities that disagree with their nearest neighbors. Until these sites are upgraded or the reason for their erratic behavior is understood, they should not be used for tectonic interpretation.

In western Algeria, we observe velocities that are collinear with the Nubia-Eurasia relative plate motion, directed N50W. Velocities are on the order of 3 mm/yr,

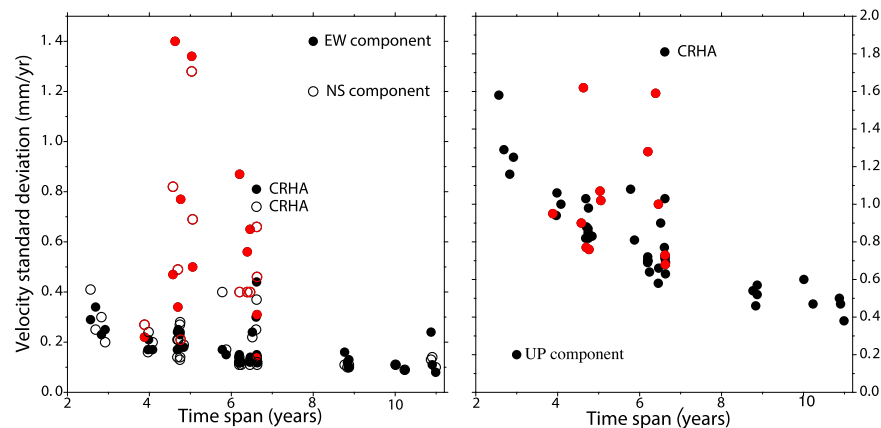


Figure 10. Velocity uncertainties at REGAT sites as a function of observation time span. Red dots show poor-quality sites identified from their time series (Figures 8 and 9). Uncertainties decrease rapidly during the first few years, then much slower after about 3 years of observation.

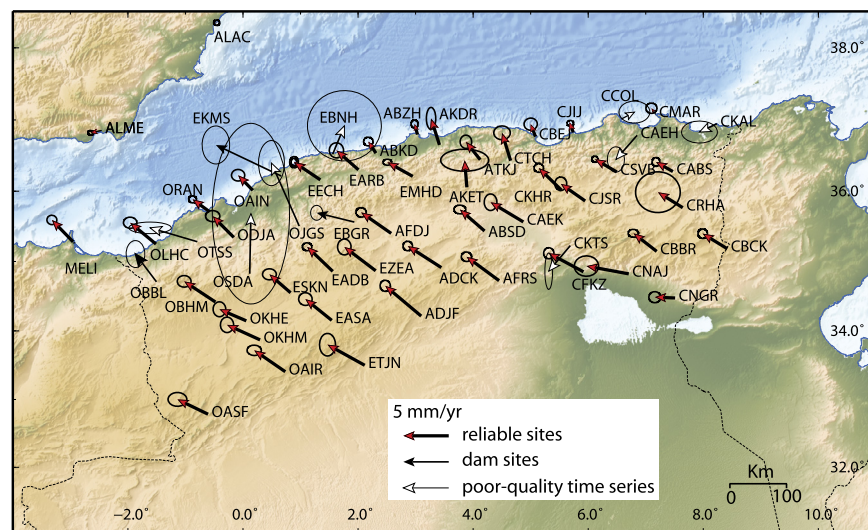


Figure 11. Horizontal GPS velocities shown with respect to stable Eurasia. Error ellipses are 95% confidence. Sites with poor-quality position time series are indicated with white arrows. Black arrows indicate sites located at operational dams.

close to those predicted by the rigid EU-NU plate motion. Deformation is therefore concentrated in a narrow coastal region, while the western High Plateaus appear to belong to stable Nubia. East of longitude $\sim 3^{\circ}\text{E}$, the pattern of velocities is more complex. Velocities at coastal sites deviate significantly from the NU-EU plate motion direction. In the south, velocities remain parallel to the NU-EU plate motion, but with slower magnitudes, indicating shortening within the High Atlas and/or between this region and stable Nubia.

A detailed kinematic analysis of this velocity field, presented in Bougrine et al. (2019), shows that the REGAT horizontal velocities (1) are consistent with the

presence of an active, reverse, offshore fault system running along the toe of the Algerian margin, with a slip rate that decreases from west to east, (2) require slip on an east-west right-lateral strike-slip fault in the eastern half of Algeria. Its surface trace, located 50 km inland, corresponds to the Ghardimaou fault in Tunisia (Bahrouni et al., 2013), which extends westward along-strike as the North Constantine fault in Algeria (Coiffait et al., 1992).

5. Conclusion

The 54-site REGAT cGPS network fills an important gap in our knowledge of present-day plate boundary deformation in the Western Mediterranean. Although position time series at some of the REGAT sites show a spurious behavior most likely related to local instabilities rather than regional tectonics, 42 good-quality sites prove new information on regional kinematics and the spatial distribution of plate boundary deformation.

The current REGAT cGPS network will soon be enhanced by the addition of 100 new stations in order to improve deformation monitoring with a higher spatial resolution for a better assessment of the regional seismic hazard.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This work was supported by the Algerian Interior Ministry for the REGAT project.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

We acknowledge and thank the CRAAG teams from the five centers operating and maintaining the permanent GPS stations of the REGAT network. EC acknowledges support from the Institut universitaire de France.

References

- Altamimi, Z., Rebischung, P., Métivier, L., Collilieux, X., 2016. ITRF2014: a new release of the international terrestrial reference frame modeling nonlinear station motions. *J. Geophys. Res., Solid Earth* 121 (8), 6109–6131.
- Avallone, A., Selvaggi, G., D’Anastasio, E., D’Agostino, N., Pietrantonio, G., Riguzzi, F., Serpelloni, E., Anzidei, M., Casula, G., Cecere, G., D’Ambrosio, C., Martino, P.D., Devoti, R., Falco, L., Mattia, M., Rossi, M., Obrizzo, F., Tammaro, U., Zarrilli, L., 2010. The RING network: improvement of a GPS velocity field in the central Mediterranean. *Ann. Geophys.* 2.
- Bahrouni, N., Bouaziz, S., Soumaya, A., Ben Ayed, N., Attafi, K., Houla, Y., El Ghali, A., Rebai, N., 2013. Neotectonic and seismotectonic investigation of seismically active regions in Tunisia: a multidisciplinary approach. *J. Seismol.* 18 (2), 235–256.
- Bezzeghoud, M., Dimitrov, D., Ruegg, J.C., Lammali, K., 1995. Faulting mechanism of the 1954 and 1980 earthquakes from vertical movements modelling. *Tectonophysics* 249, 249–266.
- Blewitt, G., Lavallée, D., 2002. Effect of annual signals on geodetic velocity. *J. Geophys. Res.* 107.
- Bougrine, A., Yelles-Chaouche, A.K., Calais, E., 2019. Active deformation in Algeria from continuous GPS measurements. *Geophys. J. Int.* 217, 572–588.
- Bouhadad, Y., 2001. The Murdjadjo, Western Algeria, fault-related fold: implications for seismic hazard. *J. Seismol.* 5 (4), 541–558.
- Calais, E., DeMets, C., Nocquet, J.M., 2003. Evidence for a post-3.16 Ma change in Nubia–Eurasia–North America plate motions? *Earth Planet. Sci. Lett.* 216, 81–92.
- Chousianitis, K., Ganas, A., Evangelidis, C.P., 2015. Strain and rotation rate patterns of mainland Greece from continuous GPS data and comparison between seismic and geodetic moment release. *J. Geophys. Res., Solid Earth* 120, 3909–3931.
- Coiffait, B., Guellal, S., Vila, J. Carte géologique au 1/50.000 d El Aria. Division Hydrocarbures, Sonatrach, 1992.

- Craig, T.J., Calais, E., 2014. Strain accumulation in the new Madrid and Wabash valley seismic zones from 14 years of continuous GPS observation. *J. Geophys. Res., Solid Earth* 119 (12), 9110–9129.
- Delouis, B., Vallée, M.A., Meghraoui, M., Calais, E., Maouche, S., Lammali, K., Mahsas, A., Briole, P., Benhamouda, F., Yelles, K., 2004. Slip distribution of the 2003 Boumerdes-Zemmouri earthquake, Algeria, from teleseismic, GPS, and coastal uplift data. *Geophys. Res. Lett.* 31 (18).
- Dimitrov, D., Benhallou, H., Khalfoun, A., Lammali, K., 1987. Mesures géodésiques liés aux déformations de l'écorce terrestre dans la région d'Ech Chelif (ex-El Asnam), Algérie du Nord. *C. R. Acad. Sci. Paris* 305 (II), 1365–1368.
- Domzig, A., Yelles, K., Le Roy, C., Deverchère, J., Bouillin, J.-P., Bracène, R., Mercier de Lépinay, B., Le Roy, P., Calais, E., Kherroubi, A., Gaullier, V., Savoye, B., Pauc, H., 2006. Searching for the Africa–Eurasia Miocene boundary offshore western Algeria (MARADJA'03 cruise). *C. R. Géosci.* 338 (1–2), 80–91.
- Estey, H.H., Meertens, C.M. TEQC: the multi-purpose toolkit for GPS/GLONASS data 3, July 1999 42–49.
- Herring, T., 2003. MATLAB tools for viewing GPS velocities and time series. *GPS Solut.* 7 (3), 194–199.
- Herring, T.A., King, R.W., Floyd, M., McClusky, S.C., 2015. Introduction to GAMIT/GLOBK. Release 10.6. Technical report. Massachusetts Institute of Technology.
- Lammali, K., Bezzeghoud, M., Oussadou, F., Dimitrov, D., Benhallou, H., 1997. Postseismic deformation at El Asnam (Algeria) in the seismotectonic context of northwestern Algeria. *Geophys. J. Int.* 129 (3), 597–612.
- Langbein, J., 2004. Noise in two-color electronic distance meter measurements revisited. *J. Geophys. Res.* 109 (B9).
- Meghraoui, M., Pondrelli, S., 2012. Active faulting and transpression tectonics along the plate boundary in North Africa. *Ann. Geophys.* 55 (5), 955–967.
- Nocquet, J.M., 2012. Present-day kinematics of the Mediterranean: a comprehensive overview of GPS results. *Tectonophysics* 578, 220–242.
- Nocquet, J.M., Calais, E., 2003. Crustal velocity field of western Europe from permanent GPS array solutions, 1996–2001. *Geophys. J. Int.* 154, 72–88.
- Nocquet, J.M., Calais, E., 2004. Geodetic measurements of crustal deformation in the Western Mediterranean and Europe. *Pure Appl. Geophys.* 161 (3), 661–681.

- Ouyed, M., Meghraoui, M., Cisternas, A., Deschamps, A., Dorel, J., Fréchet, J., Gaulon, R., Hatzfeld, D., Philip, H., 1981. Seismotectonics of the El Asnam Earthquake. *Nature* 292 (5818), 26–31.
- Petit, G., Luzum, B. IERS Conventions (2010). Verlag des Bundesamts für Kartographie und Geodäsie, 2010.
- Philip, H., Meghraoui, M., 1983. Structural analysis and interpretation of the surface deformations of the El Asnam Earthquake of October 10, 1980. *Tectonics* 2 (1), 17–49.
- Ruegg, J.C., Kasser, M., Tarantola, A., Lepine, J.C., Chouikrat, B., 1982. Deformations associated with the El-Asnam earthquake of 10 October 1980: geodetic determinations of vertical and horizontal movements. *Bull. Seismol. Soc. Am.* 72 (6), 2227–2244.
- Saria, E., Calais, E., Altamimi, Z., Willis, P., Farah, H., 2013. A new velocity field for Africa from combined GPS and DORIS space geodetic solutions: contribution to the definition of the African reference frame (AFREF): an African geodetic REference Frame. *J. Geophys. Res.* 118 (4), 1677–1697.
- Schmid, R., Steigenberger, P., Gendt, G., Ge, M., Rothacher, M., 2007. Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas. *J. Geod.* 81 (12), 781–798.
- Serpelloni, E., Vannucci, G., Pondrelli, S., Argnani, A., Casula, G., Anzidei, M., Baldi, P., Gasperini, P., 2007. Kinematics of the Western Africa-Eurasia plate boundary from focal mechanisms and GPS data. *Geophys. J. Int.* 169 (3), 1180–1200.
- Williams, S.D.P., 2003. The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. *J. Geod.* 76 (9–10), 483–494.
- Yelles, K., Djellit, H., Hamdache, M., 2003. The Boumerdes-Algiers (Algeria) earthquake of May 21st, 2003 (Mw = 6.8). *CSEM/EMSC Newsl.* 20, 3–5.
- Yelles, K., Domzig, A., Deverchère, J., Bracène, R., de Lépinay, B., Strzeczynski, P., Bertrand, G., Boudiaf, A., Winter, T., Kherroubi, A., Le Roy, P., Djellit, H., 2009. Plio-quaternary reactivation of the Neogene margin off NW Algiers, Algeria: the Khayr al Din bank. *Tectonophysics* 475 (1), 98–116.
- Yelles, K., Lammali, K., Mahsas, A., Calais, E., Briole, P., 2004. Coseismic deformation of the May 21st, 2003, Mw = 6.8 Boumerdes earthquake, Algeria, from GPS measurements. *Geophys. Res. Lett.* 31, L13610.
- Yelles-Chaouche, A.K., Allili, T., Allili, A., Messemén, W., Beldjoudi, H., Semmane, F., Kherroubi, A., Djellit, H., Larbes, Y., Haned, S., Deramchi, A.,

- Amrani, A., Chouiref, A., Chaoui, F., Khellaf, K., Nait Sidi Said, C., 2013. The new Algerian digital seismic network (ADSN): towards an earthquake early-warning system. *Adv. Geosci.* 36, 31–38.
- Yelles-Chaouche, A.K., Kherroubi, A., Beldjoudi, H., 2017. The Large Algerian Earthquakes (267 A.D.-2017). *Física de la Tierra*, vol. 29, pp. 159–182.
- Yielding, G., Ouyed, M., King, G.C.P., Hatzfeld, D., 1989. Active tectonics of the Algerian Atlas mountains—evidence from aftershocks of the 1980 El Asnam earthquake. *Geophys. J. Int.* 99, 761–788.