Studies of Tectonic Movements in Saudi Arabia Using CORS

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Key words: tectonic movements, deformation, earthquake, CORS, GNSS

SUMMARY

This paper presents the scientific applications of GNSS in general and CORS in particular. Amongst others, these applications include: monitoring plate tectonics, deformation, meteorological studies using CORS data. The paper also discusses case studies of scientific applications such as the results of the velocity of Arabian plate.

Earthquakes have been the great natural hazard that threatens the Middle East region socially and economically. Hence, it is crucial to have knowledge on the characteristics and dynamics of the tectonic fault lines to mitigate this hazard. This mission is partly accomplished by the outcomes of the CORS networks by looking at the results of CORS data process obtained from an 10 year measurement period in Saudi Arabia as presented in this paper.

The precise positions of 12 x GFN (CORS) sites in Saudi Arabia at epochs 2004.0 and 2014.03 were compared to determine the tectonic movement of the Arabian Plate. The results show a displacement of about 40.6 cm in NE direction corresponding to a velocity of about 4.1 cm / year in the same direction. The same data was also used to determine internal deformations in the Arabian Plate.

In The Kingdom of Saudi Arabia, there are already 186 CORS sites. By the end of 2014, the number or CORS sites shall reach about 300. These sites shall affectively serve for geodetic positioning and engineering surveys. They will also serve scientific applications such as tectonic movement of the Arabian Plate, crustal deformation studies and modeling of the atmosphere (troposphere and ionosphere) over The Kingdom of Saudi Arabia.

However, this network needs to be expanded to cover the Arabian plate so that it can greatly contribute to scientific studies related to geohazards and disaster management in the region.

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1. BACKGROUND

This paper presents the scientific applications of GNSS in general and CORS in particular. Amongst others, these applications include: monitoring geodynamic crustal movements (e.g., plate tectonics, earthquake and volcanic deformation) and meteorological studies using GNSS / CORS data, manly focus on discussion of a case studies of scientific applications such as the results of the velocity of Arabian plate.

National CORS effectively serve the scientific studies related to atmosphere and ionospheric phenomena, especially the determination of the Total Electron Content (TEC) in the ionosphere and water vapor in the troposphere. Actually, the Earth's ionosphere is an important source of error for GNSS signals. Besides, L-band RF signals experience propagation delays dependent on pressure, temperature and humidity in the neutral atmosphere. This effect can be measured using GNSS receivers and atmospheric properties can be extracted. Thus, over the past decade meteorologists have exploited GNSS in weather forecasting and climate change studies. A common technique is the estimation of integrated water vapor over a GNSS reference station. By using differential or precise point positioning techniques and then forming ionosphere-free carrier phase observables, it is possible to isolate the wet delay contribution for each satellite slant path. An absolute zenith wet delay (ZWD) is then modeled as the average of all satellite slant delay observations scaled to zenith (Lachapelle et al, 2006). Many GNSS reference networks worldwide currently employ this approach for meteorological applications. The availability of Galileo signals, together with those of GPS and GLONASS, will enable more accurate estimates of water vapor using CORS, with higher temporal and spatial resolution.

Another scientific contribution of national CORS is the precise determination of displacements due to earthquakes, plate tectonics, volcanic eruptions, landslides, etc. Precise geodetic positioning measurements, combined with satellite radar data (e.g., SAR interferometry), seismic data, and other geophysical measurements (prior to, during, and following the events) lead to a better scientific understanding of these events. Thus, the vulnerability of populations to geologic hazards can be significantly reduced by a systematic preparation for hazardous events.

It is a well-known fact that the Earth is made of many plates (Figure 1). The Arabian plate moves towards the Eurasian plate squeezing Anatolian plate (Figure 2) and earthquakes have been the great natural hazard that threatens the Middle East region socially and economically. Hence, it is crucial to have knowledge on the characteristics and dynamics of the tectonic fault lines to mitigate this hazard. This mission is partly accomplished by the outcomes of the CORS networks (Eren et al., 2009). This is demonstrated here by looking at the results of

GNSS data process obtained from an 10 year measurement period and presented in this paper.

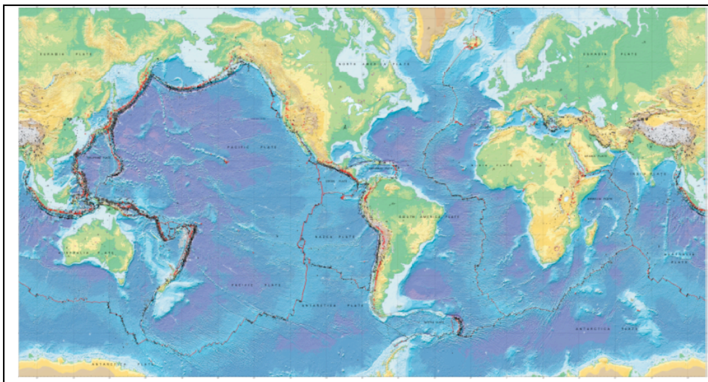

Figure 1. Tectonic plates of the Earth

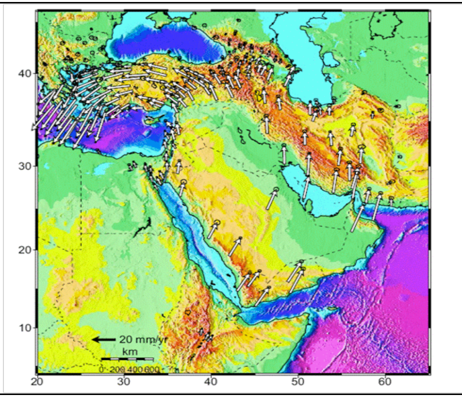

Figure 2. Tectonic setting of Turkey together with Arabian Plate (from Reilinger et al., 2006)

Earthquake prone countries like Turkey need to take precautionary measures in advance to mitigate the consequences of natural hazards. There are many different areas of study: some focus on analyzing the characteristics of strong ground motions, others on developing structural design guidelines, and still others on understanding the plate mechanisms that cause earthquakes. During recent decades, the studies aimed at learning the plate mechanisms accelerated after the introduction of space-based application tools such as GNSS and radar image acquisition systems. We exhibit here the versatility of space based monitoring systems and their immediate use in Turkey where active fault lines and surface deformations (subsidence) exist.

Turkey is located on the Anatolian plate where the Arabian, Eurasian and the African plates conjunct (Figure 2). Recent studies showed that the Anatolian plate has been squeezed by the Eurasian and Arabian plates due to the global plate tectonics (McClusky et al, 2000; Okumura et al., 1993). As a result, all around the Anatolian plate, high fault slip rates reaching 24 mm/year have been observed (King et al, 2002). A detailed study regarding GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions can be found in (Reilinger et al., 2006).

The GAMIT/GLOBK process of 141 CORS stations' data collected in Turkey in 2009 has already represented the motion of the Anatolian plate with respect to the Eurasian plate (Figure 3). The maximum displacement estimated ranged 19.9 mm/year toward southwest and 23.2 mm/year toward northwest (Al Rajhi et al., 2012) . Keeping in mind that several researchers have commented that the Anatolian Plate has a slip rate of 24mm/year after studying many years of data, a comparable result from processing CORS-TR observations encourages the reliability, stability and effectiveness of such a young network (Uzel et al., 2010).

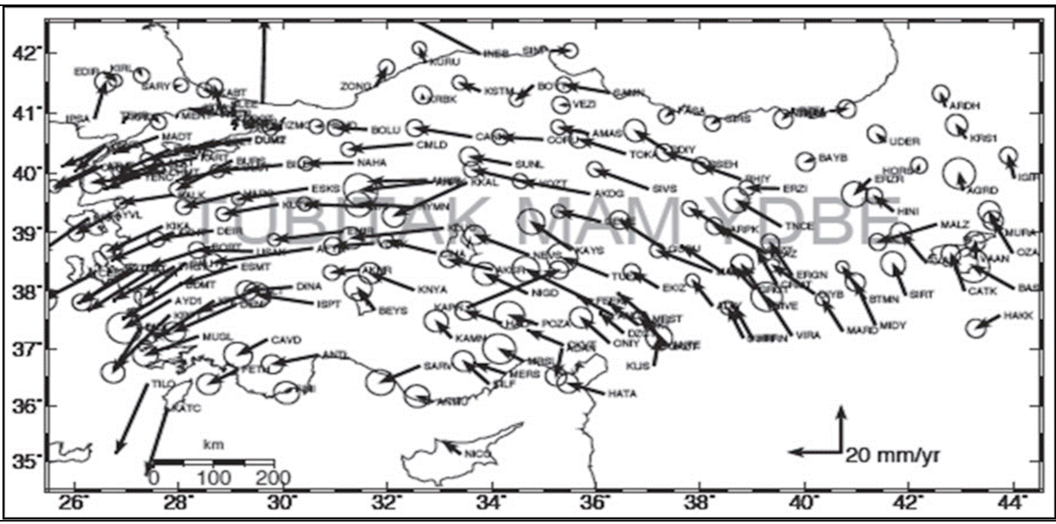

Figure 3. Plate displacements from 11 months CORS-TR surveys in 2009

2. GEODETIC NETWORK OF SAUDI ARABIA AND FIDUCIAL STATIONS

The old National Geodetic Network (NGN) of Saudi Arabia was established during 1966-1969 and 1979-1982. This network suffers from the weak geometry of traversing and the technology of its time used then. In addition, most of geodetic data throughout the world are defined with respect to the mean earth ellipsoid and best international datum, namely GRS80 ellipsoid and International Terrestrial Reference Framework (ITRF). Therefore, Saudi Arabia established a new geodetic network in 2004 based on the ITRF datum using GRS80 ellipsoid.

2.1 GFN Of Saudi Arabia In 2004.0 Based On ITRF2000 Datum

Ministry of Municipal and Rural Affairs (MOMRA) of Saudi Arabia started a project in order to establish a new geodetic network based on ITRFyy datum. The project started in 2003 and completed in 2004. This new network is known as Saudi MTRF2000 consisting of two parts:

(i) Geodetic Fiducial Network (GFN: 13 stations)
(ii) Geodetic Main Network (GMN: 659 stations)

The GFN comprises thirteen (13) highly accurate fiducial stations across Saudi Arabia (see Figure 4), each with a permanently tracking iCGRS Ashtech Global Positioning System (GPS) receiver, therefore, serving at the same time as Continuously Operating Reference Stations (CORS). The coordinates of all GFN stations were determined together with eight IGS stations using 10 days observations.

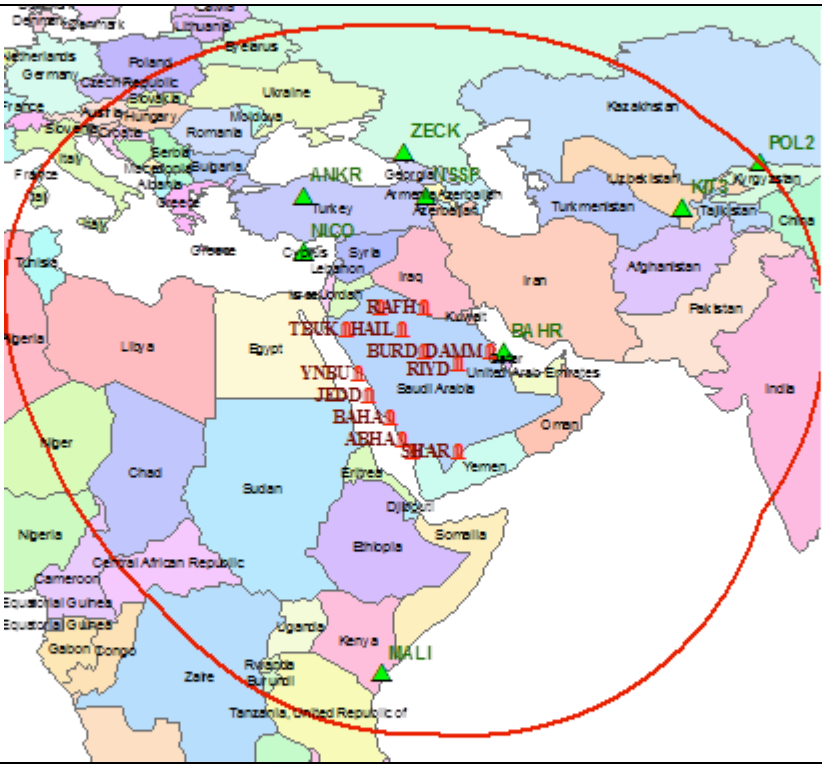

Figure 4. IGS Stations used for the computation of GFN stations

The statistics of GFN GPS Surveys and Computations are listed below:

- 8 x IGS stations were used as fixed reference stations (ANKR, BAHR, KIT3, MALI, NICO, NSSP, POL2, ZECK),
- 10 days data in 2004 (DOY 96-101, i.e. 5 – 10 April 2004) collected in 13 GFN sites (ABHA, BAHA, BURD, DAMM, GZAN, HAIL, JEDD, JOUF, RAFH, RIYD, SHAR, TBUK, YNBU),
- ITRF-2000 datum used,
- The data was processed for 1997.0 and 2004.0 epochs using the Geo++ GPS software,
- Network adjustment was carried out and positional precision of about 1 mm and relative precision of 0.01 ppm were obtained for each GFN station.

Thus, a new datum called MTRF-2000 was established in Saudi Arabia which is based on the ITRF-2000 datum at epoch 2004.0. The definition parameters of MTRF-2000 are listed in

Table 1.

Table 1. MTRF-2000 definition

Datum	MOMRA Geodetic Datum -2000 (MGD-2000)
Reference Frame	ITRF-2000 (International Terrestrial Reference Frame 2000), Epoch:2004.0
Ellipsoid	GRS80
Semi-major axis (a) **Inverse flattening (1/f)**	6,378,137.0 meters 298.257222101
Grid coordinates(Universal Transverse Mercator)	Map Grid of Saudi Geodetic Datum 2000

2.2 THE COORDINATES OF GFN STATIONS AT 2014.03

The iCGRS receivers of the GFN stations (Figure 4) were replaced with Leica GR25 GNSS receivers in 2013 capable of measuring, GPS, GLONASS and Galileo signals.

The new coordinates of all GFN stations were determined together with eight IGS stations using 11 days observations. The statistics of GFN GNSS Surveys and Computations are listed below:

- 8 x IGS stations were used as fixed reference stations (ANKR, DRAG, HYDE, KIT3, MBAR, NICO, RAMO, ZECK)
- 11 days data in 2014 (DOY 14-24, i.e. 14 – 24 January 2014) collected in 12 GFN sites,
- ITRF-2008 datum used,
- The data was processed for 2014.03 epoch using Bernese software package,
- Network adjustment was carried out and mm-level positional accuracy was obtained for each GFN station (corresponding to about 0.01 ppm relative precision).

The final adjusted geodetic coordinates of 12 x GFN sites and tehir precision (2014.03 epoch and ITRF2008 datum) are listed in Table 2.

Table 2. BERNESE SOLUTION of 12 x GFN (2014.03 Values / ITRF2008)

No	STATION	Latitude	Longitude	ELL HGT	σLat. (m)	σLong. (m)	σElv. (m)
1	ABHA	18.2434667	42.4776464	2345.9204	0.0029	0.0029	0.0041
2	BAHA	20.0134546	41.4681971	2201.3081	0.0029	0.0029	0.0041
3	BURD	26.3512373	43.9549520	633.7926	0.0029	0.0029	0.0043
4	DAMM	26.4256483	50.1161978	-3.1312	0.0029	0.0029	0.0042
5	HAIL	27.5217768	41.6967208	1062.9910	0.0029	0.0028	0.0041
6	JEDD	21.5512003	39.2098681	41.4001	0.0029	0.0029	0.0041
7	JOUF	29.9617880	40.1975753	581.4426	0.0029	0.0028	0.0040
8	RAFH	29.6386106	43.5082862	451.5157	0.0030	0.0029	0.0043
9	RIYD	24.6804149	46.7563370	635.6847	0.0029	0.0029	0.0041
10	SHRH	17.4863812	47.1170641	713.6732	0.0029	0.0029	0.0041
11	TBUK	28.4094673	36.5641290	796.0396	0.0029	0.0029	0.0040
12	YNBU	24.1562279	37.9564067	15.9337	0.0029	0.0029	0.0041

3. TECTONIC DISPLACEMENTS FROM 2004 TO 2014

The precise positions of GFN sites at ITRF2000 datum (Epoch: 2004.0) was transformed to ITRF2008 datum and were compared against the precise positions determined at ITRF2008 datum (Epoch: 2014.03). The results are presented in **Error! Reference source not found.** and illustrated in Figure 5. The results show a displacement of about 40.6 cm in NE direction between 2004.0 and 2014.03, corresponding to a velocity of about 4.1 cm / year in NE direction (see **Error! Reference source not found.** and Figure 5).

Table 3. Displacements at CORS sites during 2004.0 and 2014.03 (IGS stations constrained)

STATION	2014.03 - 2004.0 Differences					
	dN (m)	dE (m)	dh (m)	Azim (o)	ds (m)	ds/year (m)
ABHA	0.297	0.337	-0.135	48.6068	0.449	0.045
BAHA	0.268	0.325	-0.155	50.5227	0.421	0.042
BURA	0.285	0.291	-0.153	45.5998	0.408	0.041
DAMM	0.299	0.294	-0.199	44.6013	0.419	0.042
HAIL	0.268	0.269	-0.150	45.0855	0.380	0.038
JEDD	0.270	0.316	-0.193	49.4319	0.416	0.042
JOUF	0.261	0.254	-0.154	44.2568	0.365	0.036
RAFH	0.294	0.245	-0.185	39.8809	0.383	0.038
RIYA	0.293	0.297	-0.199	45.3933	0.418	0.042
SHAR	0.291	0.348	-0.168	50.1550	0.454	0.045
TABU	0.247	0.264	-0.179	46.9191	0.362	0.036
YANB	0.254	0.289	-0.183	48.6337	0.385	0.038
RMS (m) →	0.278	0.296	0.172		0.406	0.041

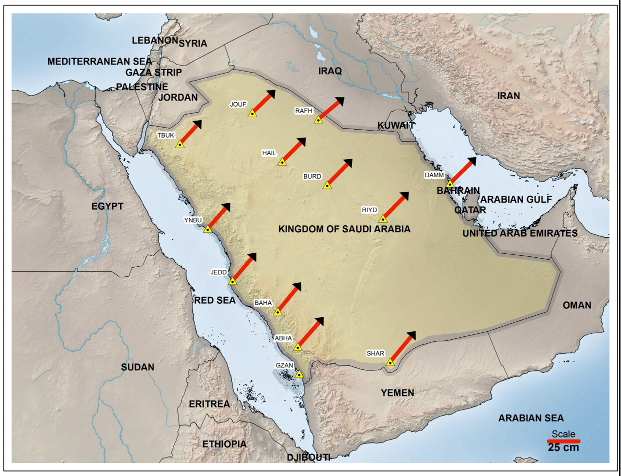

Figure 5. Plate Displacements at CORS sites from surveys in 2004.0 and 2014.03 (IGS Stations constrained)

The displacements presented above can be interpreted as the tectonic movement of Arabian plate with respect to African and Asian plates.

We also wanted to see the displacements / deformation within the Arabian plate as far as Saudi Arabia concerned. After fixing Riyadh CORS site in both epochs to the same value, the precise positions of GFN sites in both epochs were calculated and were compared against each other. The results are presented in **Error! Reference source not found.** and illustrated in **Error! Reference source not found.**.

Table 4. Displacements at CORS sites during 2004.0 and 2014.03 (Riyadh station constrained)

NAME	2014.03 - 2004.0 Differences					
	dN (m)	dE (m)	dh (m)	Azim (o)	ds (m)	ds/year (m)
ABHA	-0.004	-0.028	-0.064	-98.3219	0.028	0.003
BAHA	0.025	-0.019	-0.044	-36.4419	0.031	0.004
BURA	0.008	0.002	-0.046	14.6127	0.008	0.001
DAMM	-0.005	-0.002	0.000	-162.1253	0.006	0.001
HAIL	0.025	0.024	-0.048	43.9590	0.034	0.004
JEDD	0.023	-0.012	-0.006	-28.7141	0.026	0.003
JOUF	0.032	0.033	-0.045	46.5725	0.046	0.005
RAFH	-0.001	0.045	-0.014	90.8081	0.045	0.005
RIYA	0.000	0.000	0.000	0.0000	0.000	0.000
SHAR	0.003	-0.038	-0.031	-86.0376	0.038	0.004
TABU	0.045	0.027	-0.020	30.3888	0.053	0.006
YANB	0.039	0.011	-0.016	15.5798	0.040	0.005
RMS (m) →	**0.022**	**0.024**	**0.033**		**0.032**	**0.004**

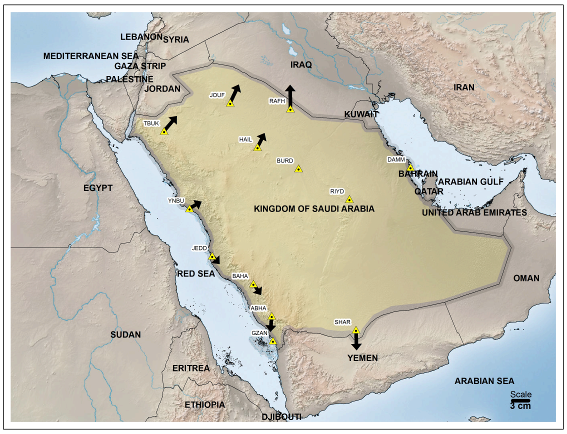

Figure 6. Displacements at CORS sites during 2004.0 and 2014.03 (Riyadh CORS site fixed)

The results show a displacement of about 3.2 cm between 2004.0 and 2014.03, corresponding to a velocity of about 4 mm / year in NE direction as listed in **Error! Reference source not found.**.

4. CONCLUDING REMARKS

Since the mid 1980's GNSS has been serving users throughout the world with navigation and geodetic positioning data. With the introduction of network based national and regional CORS, GNSS is now providing these services more accurately and economically. In fact, it goes beyond simple positioning, with a capacity for very precise geodetic positioning for engineering and scientific studies. The GNSS data together with other types of data such as InSAR, seismic, etc. shall effectively serve studies related to geohazards, disaster management, and early warning.

As part of the project mentioned in previous section, very precise coordinates (mm-level precision) of the GFN stations were determined in the latest ITRF2008 datum and epoch 2014.03. Thus, once again, Saudi Arabia has very precise fiducial stations to be used as reference throughout the Kingdom.

The results show that a displacement of about 40.6 cm in NE direction between 2004.0 and 2013.04, corresponding to a velocity of about 4.1 cm / year in NE direction although relative displacements within the Kingdom is only 4 mm /year. These numbers show that the coordinates based on MTRF2000 datum has about 41 cm offset in NE direction with respect to the coordinates computed at the present with reference to IGS stations.

The results presented above encourage us that KSA-CORS, established in 2013-2014, shall further serve for geodetic positioning and engineering and scientific applications such as crustal deformation studies and modeling of the atmosphere (troposphere and ionosphere) over Saudi Arabia. However, this network needs to be expanded to cover the Arabian plate. All these networks shall greatly contribute to scientific studies related to geohazards and disaster management in the region.

REFERENCES

Lachapelle G., & Petovello M. (2006). GNSS Solutions: Adaptive antenna arrays, multi-GNSS tropospheric monitoring, and high-dynamic receivers, Inside GNSS, April 2006.

Eren K., Uzel T., Gulal E., Yildirim O., & Cingoz A. (2009). Results from a Comprehensive Global Navigation Satellite System Test in the CORS-TR Network: Case Study, Journal of Surveying Engineering, ASCE, February 2009a.

Eren K., &Uzel T. (2009). CORS-TR Project (in Turkish)", Final Report, Istanbul Kultur University, Istanbul, Turkey, 2009b.

Reilinger, R., McClusky, S., Vernant, P., Lawrence, S., Ergintav, S., Cakmak, R., Ozener, H., Kadirov, F., Guliev, I., Stepanyan, R., Nadariya, M., Hahubia, G., Mahmoud, S., Sakr, K., ArRajehi, A., Paradissis, D., Al-Aydrus, A., Prilepin, M., Guseva, T., Evren, E., Dmitrotsa, A., Filikov, S. V., Gomez, F., Al-Ghazzi R., & Karam, G. (2006).GPS constraints on continental deformation in the Africa-Arabia-Eurasia continental collision zone and implications for the dynamics of plate interactions, J. Geophys. Res., 111(B05411):1-26, 2006.

McClusky S., Bassalanian S., Barka A., Demir C., Ergintav S., Georgiev I., Gurkan O., Hamburger M., Hurst K., Hans-Gert H.-G., Karstens K., Kekelidze G., King R., Kotzev V., Lenk O., Mahmoud S., Mishin A., Nadariya M., Ouzounis A., Paradissis D., Peter Y., Prilepin M., Reilinger R., Sanli I., Seeger H., Tealeb A., Toksoz M.N., & Veis G. (2002). Global Positioning system constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, Journal of Geophysical Research, 105 (B3), pp. 5695-5719, 2002.

Okumura, K., Yoshioka, T. & Kuscu, I. (1993).Surface Faulting on the North Anatolian Fault in These two Millennia, U.S. Geological Survey Open-file Report, 94-568, 143-144, 1993.
King M., Edwards S., Clarke P, (2002). Precise Point Positioning: Breaking the Monopoly of Relative GPS Processing, Engineering Surveying Showcase, October 2002.

Al Rajhi M., Al Omar Ali, Yanar R., Eren K., Kartal F., Arslanoglu M., Uzel T. (2012).

Studies of Tectonic Movements in Saudi Arabia, The 35th Plenary and Working Group Meeting of (ISO / TC211) Workshops and Exhibition, 8-12 December 2012, Jeddah Hilton Hotel. Saudi Arabia.

Uzel T., Eren K., & Dindar A. (2010). Monitoring Plate Tectonics and Subsidence in Turkey by CORS-TR and InSAR, FIG Congress 2010, Facing the Challenges – Building the Capacity, Sydney, Australia, 11-16 April 2010.

Rizos, C. (2007). Alternative to current GPS-RTK services and some implications for CORS infrastructure and operations, GPS Solut., 11(3):151-158, 2007.

GEO - Geo Group on Earth Observations, "The Geohazard Supersites, White Paper and Implementation Plan", Third Draft, FA, 10 June 2010

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