Velocity field in the Mediterranean area from ASI-CGS GPS, SLR and VLBI solutions: the ASIMed solution

C. Sciarretta, V. Luceri, R. Lanotte, R. Pacione, B. Pace
e-GEOS, ASI-CGS, Matera, Italy
cecilia.sciarretta@e-geos.it; cinzia.luceri@e-geos.it; roberto.lanotte@e-geos.it; rosa.pacione@e-geos.it; brigida.pace@e-geos.it

G. Bianco
Agenzia Spaziale Italiana, CGS, Matera, Italy
giuseppe.bianco@asi.it

Abstract. Continuous GPS data processing is being carried out at Matera ASI-CGS since 1995 to support EUREF Permanent Network (EPN) products and, since 1999, meteorological applications (e.g. E-GVAP), monitoring a large amount of permanent Italian GPS sites. Moreover, SLR and VLBI global solutions are regularly issued at ASI-CGS as backbone products of the data analysis activities. They are contributing, since the 90's, to the production of the international geodetic services official products. The ASIMed solution is a combined velocity field, covering mainly the Central Mediterranean area. The combination of three geodetic technique solutions allows framing of the GPS estimates, densely covering the Mediterranean area, in the terrestrial reference frame (TRF) realized by the SLR and VLBI global solutions. The ASIMed solution is issued yearly to benefit of the dense and continuous GPS data analysis, as provided by the daily ASI-CGS European solutions: more than one hundred of GPS sites in the European/Mediterranean area are included in the ASIMed solution. The availability of two different GPS solutions, namely a network solution (based on Microcosm SW) and a PPP solution (based on GIPSY/OASIS SW), allows a continuous comparison of the sites included in both of them. This is useful to detect stations with ambiguous behavior or noisy time series and to mitigate such effects in order to recover a velocity field as stable as possible. This paper summarizes the features of the ASIMed solution, with emphasis on the velocity results for the Mediterranean area, given in terms of residual velocities w.r.t. Eurasian plate.

Keywords. Mediterranean, GPS, SLR, VLBI, Velocity field

---

1 Introduction

The ASIMed solution is a combined velocity field, covering mainly the Central Mediterranean area. It is derived from three independent space geodetic solutions (GPS, SLR and VLBI), produced at ASI-CGS, which are merged into a common reference frame. The ASIMed network includes the Italian permanent GPS network, the European SLR and VLBI fundamental sites.

2 Mono-technique solutions

2.1 SLR Solution

The SLR solution ASI10L01C provides solution site coordinates and solution site velocities (SSC/SSV) at the reference epoch 000101, 3-day earth orientation parameter (EOP) and length of day (LOD) derived from Lageos I data in the period 1983-1992, from Lageos-I and Lageos II data in the period 1993-2010. The main features of SLR solution are reported in Table 1.

The normal points collected from the worldwide network, made available by ILRS (Pearman et al., 2002), are analyzed in 15-day arc. Arc data reduction is performed using SLRF2005 (Luceri and Bianco, 2007) as a-priori site coordinates and velocities, EOP (IERS) C 04 for a-priori EOP values, EGM96 geopotential (up to degree 70), GOT4.7 ocean tides model, ocean loading from Scherneck and GOT4.7 tides, taking into account the secular drift and the influence of the dynamical pole on C21 and S21 coefficients, all the major planets perturbations as well as the relativistic effects.

Residual unmodeled effects in the orbit are minimized by the estimation of empirical accelerations: 5-day constant and once-per-rev along track acceleration and once-per-rev cross track acceleration.

The normal equations are built up for all the parameters to be estimated. At this stage, they are solved only for the arc parameters, namely those related to the orbit (state vector at the beginning of the arc and empirical accelerations) and to the laser tracking systems (range biases for some stations).

This arc inversion is performed with a Bayesian Weighted Least Square procedure implemented in the NASA/GSFC GEODYNII software. All the normal equations, with the updated arc parameters, are then combined solving for all the parameters, namely 3-D site coordinates and velocities, EOP (X,Y,UT1R-UTC) and LOD, in a least squares sense using the NASA/GSFC SOLVE software. The terrestrial reference frame is defined by estimating the global solution as a loose-constrained network, and then globally roto-translated to ITRF2008 (Altamini et. al. 2011). Some stations with two different systems and different site identification code have been tied to estimate a unique velocity.

Table 1 SLR Solution features

SLR	ASI10L01C
Data Set	2692450 NP LAGEOS 1-2 (January 1984- December 2010)
Sites	126, world-wide
Constraints	Estimated as loose-constrained network; globally roto-translated to ITRF2008
TRF	ITRF2008
Method	Site velocities and coordinates, 3-day EOP (84-92) and daily EOP (93-10) & LOD, satellite dynamic parameters, monthly satellite biases are estimated.
SW	NASA/GEODYNII – SOLVE

2.3 VLBI Solution

The VLBI solution cgs2009a, whose main features are in Table 2, is realized using NASA/CALC (v10.0)-SOLVE (rev2006.04.10) SW, and covers 3680 observation sessions, spanning from August 1979 to December 2009. It fixes the extragalactic Celestial Reference Frame, oriented by applying a No-Net-Rotation condition w.r.t. ICRF-Ext1 using 199 from its 212 sources.

The Terrestrial Reference Frame is realized by applying, as relativity scale, the Solar System Barycenter (SSB); the definition of the origin is obtained by applying a No-Net-Translation condition w.r.t. ITRF2000 for 39 stations, selected among the more stable and long-term acquiring ones. The orientation is defined by a No-Net-Rotation condition w.r.t. ITRF2000 using the same stations. A No-Net velocity adjustment condition in translation and rotation w.r.t. ITRF2000 velocity field is applied as well. About Earth orientation, IERS 1996 precession and nutation models are applied as a-priori; the short-period tidal variations in x, y, UT1 are modeled according to Gipson (1996).

The estimated parameters are right ascension and declination for 637 sources (global parameters) and for 1678 sources (local parameters) for the Celestial Frame; coordinates and velocities for 88 stations (global parameters) and for 35 stations (local parameters) for the Terrestrial Frame. For several pairs of stations velocities are constrained to a unique value, while for several stations, discontinuous positions are estimated, due to known change in the equipment or seismic events.

For the EOPs, X pole, Y pole, UT1 the EOPC04 values are assumed. X pole, Y pole, UT1, Xp rate, Yp rate, UT1 rate, dpsi and deps are then estimated as loose constrained parameters.

The station clocks are modeled as a second order polynomial plus a continuous piecewise linear function with 60 min interval and rate constraint of 5.0E-14 s/s. The wet zenith tropospheric delays are estimated as 60 min piecewise continuous linear function, with rate constraints of 50 psec/hr; troposphere gradients are estimated as hour east and north piecewise continuous linear function, at all stations, except for a set of 75 stations. The offset constraint is 0.5 mm and rate constraint 2.0 mm/day. Antenna axis offsets are estimated for 49 stations as global parameters.

Table 2 VLBI Solution features

VLBI	Cgs2009
Data Set	3680 sessions, (August 1979 – December 2009)
Sites	123(88), world-wide
Constraints	minimal constraints, no-net-translation and no-net-rotation (39 sites) on terrestrial reference frames (coordinates and velocities).
TRF	ITRF2000
Method	Site coordinates and velocities are solved for together with a set of constraint equations.
SW	NASA/CALC – SOLVE

2.3 GPS Solution

At ASI-CGS, GPS data of a European network are processed on daily basis. A loose constraint solution is obtained for each day, then transformed to ITRF2005 frame with a day-by-day Helmert transformation. Once a year, site velocities and coordinates are estimated by merging the transformed daily solutions with an in-house developed SW tool. The main features of GPS solution are reported in Table 3.

The velocity solution includes only sites having time series longer than two years. The current velocity solution (asi_gps_201012.snx) spans the period 1996-2010 and contains sites from different regional and national GPS permanent networks, such as the subset of EPN sites assigned to ASI-CGS as EUREF LAC, public INGV (Istituto Nazionale di Geofisica e Vulcanologia) stations (Selvaggi et al., 2006), some stations of FreDNet (Friuli Regional Deformation network), stations of the GNSS permanent network of Apulian region.

The daily position solutions are computed with the VMSI/Microcosm SW using GPS L1/L2 carrier phase as basic observable, modeled as double differences, ionosphere free linear combination. Code pseudo range are only used for receiver clock synchronization. The elevation angle cutoff is 15 degrees; data are preprocessed to edit outliers and detect/fix cycle-slips. The carrier phase measurements are corrected for the L1 and L2 antenna phase centers offset using IGS (Beutler et al., 1999) tabulated values.

Daily data are adjusted under a procedure implementing Bayesian Weighted least-squares iterative algorithms; the editing level for each iteration is determined by multiplying an a-priori threshold (3.5) by the RMS from the previous iteration (for the first one the value is 1.0E+12). The sigma for each observation is compared to this editing level and data are eliminated if higher.

The station coordinates are estimated as loose-constrained (1m sigma). Troposphere Zenith Delays are estimated once per hour for each station, using Hopfield model as a-priori together with the Niell (1996) mapping function. Initial ambiguity is estimated as real value with no a-priori constraints. Satellite clock biases are not estimated but eliminated when forming double-differences; receiver clock corrections are estimated during the pre-processing phase using code measurements.

The ASI-CGS GPS Network SSC solution time series is preliminarily compared to another independent ASI-CGS GPS solution, computed by means of the SW GIPSY/OASIS under a PPP strategy (Zumberge, et al. 1997), to detect eventual anomalies in the coordinate time series and eliminate them.

The set of SSC parameters from the GPS Network daily solutions is merged into a SSC/SSV solution by a s/w tool, developed at ASI-CGS, able to derive the SSV solution from the weighted linear fit of a set of ITRF-framed SSC solutions. When a change of the site configuration is known, a jump is estimated and applied.

Table 3 GPS Solution features

GPS	ASI2010
Data Set	daily RINEX files, (July 1996 – November 2010)
Sites	102, mainly in Italy
Constraints	Loose constraints: 1 m apriori sigma on daily SSC
TRF	ITRF2005
Method	Each daily loose-constrained-solution is transformed into ITRF2005 frame. Site velocities and coordinates are estimated merging the daily solutions
SW	VMSI/MICROCOSM – SV

3 Mediterranean Velocity field generation

3.1 The combination approach

The mono-technique ASI-CGS SLR, VLBI (both global solutions) and GPS (European solution) are thus available as SSC/SSV ITRF-constrained solutions. To avoid the effects from different realizations of the ITRF, each velocity solution is loosened before the combination. The Mediterranean portion of the final combined solution is then roto-translated to ITRF2008.

The ASI-CGS combination procedure is based on the direct combination of loose constrained solutions (Davies and Blewitt, 2000). This straightforward method allows handling input solutions easily, with no inversion problems for the solution variance-covariance matrix and no need to know a priori values for the estimates.

The reference frame is defined stochastically; no relative rotation between the reference frames is estimated or removed. The ASI-CGS s/w process, has been implemented in a general case, to handle site coordinates and velocities, EOP and EOP-rates, where the design equations are simple identities/time linear functions between couples of solutions:

$$\begin{pmatrix} \mathbf{X}_1(t_1) \\ \dot{\mathbf{X}}_1 \\ \mathbf{Y}_1(t_{1j}) \\ \dot{\mathbf{Y}}_1(t_{1j}) \end{pmatrix} = \mathbf{P} \begin{pmatrix} \mathbf{X}_0(t_0) \\ \dot{\mathbf{X}}_0 \\ \mathbf{Y}_0(t_{0j}) \\ \dot{\mathbf{Y}}_0(t_{0j}) \end{pmatrix} = \begin{pmatrix} \mathbf{I} & (t_1-t_0)\mathbf{I} & 0 & 0 \\ 0 & \mathbf{I} & 0 & 0 \\ 0 & 0 & \mathbf{I} & (t_{1j}-t_{0j})\mathbf{I} \\ 0 & 0 & 0 & \mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{X}_0(t_0) \\ \dot{\mathbf{X}}_0 \\ \mathbf{Y}_0(t_{0j}) \\ \dot{\mathbf{Y}}_0(t_{0j}) \end{pmatrix}$$

The combination is performed along the lines of the iterative Weighted Least Square technique, in which each contributing solution (and related variance-covariance matrix) plays the role of an 'observation' whose mis-closure with respect to the combined solution must be minimized. Each SSV solution portion is stacked using its full covariance matrix rescaled by an estimated factor. A scaling of the covariance matrix of each solution is required because the relative weights of the contributing solutions are arbitrary. Imposing $\chi 2=1$ for the combination residuals and requiring that each contribution to the total $\chi 2$ is appropriately balanced, the relative scaling factors for each solution (σ_i) are estimated iteratively together with the combined solution. If R_i represents the solution residuals (with respect to the combined product) and Σ_i the solution covariance matrix, the imposed conditions are:

$$\chi^2 = R_1^T C_1^{-1} R_1 \ldots + R_i^T C_i^{-1} R_i = 1$$

$$R_1^T (f_1 C_1)^{-1} R_1 = \ldots = R_i^T (f_i C_i)^{-1} R_i$$

The first guess for the combination is obtained with $\sigma_i=1$ for each solution.

3.2 Co-location assumptions

A key role in the combination procedure is played by the co-located sites, which allow a direct connection between the different technique solutions. In principle, the following multi-technique sites are available: Matera (SLR, VLBI, GPS), Wettzell (SLR, VLBI, GPS), Medicina (VLBI, GPS), Noto (VLBI, GPS), Cagliari (SLR, GPS), San Fernando (SLR, GPS), Lampedusa (SLR, GPS).

A careful choice of the co-located sites, to be assumed as 'pillars' in the velocity combination procedure, has to be performed since the loose combination can absorb small global roto-translations among mono-technique velocity solutions, but to avoid misleading results site-dependent velocity discrepancies must be monitored before the inter-technique combination takes place.

After a consistency check of the mono-technique velocity solutions for the co-located sites, Matera, Medicina, Noto and Wettzell have been chosen as operational co-located sites for the present ASIMed combination, while Cagliari, San Fernando and Lampedusa are kept separate even if co-located.

3.3 Spatial and temporal coverage

The geographic coverage of the present ASIMed solution (Fig. 1) is quite dense: more than 100 sites, the majority being in Italy.

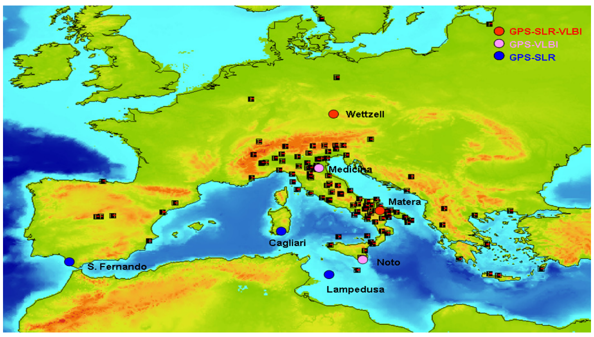

Fig. 1 ASIMed spatial coverage

The GPS network plays as the principal actor, providing alone the whole coverage. Nevertheless, SLR and VLBI have been giving a picture of the area since 80's and 90's (Fig. 2).

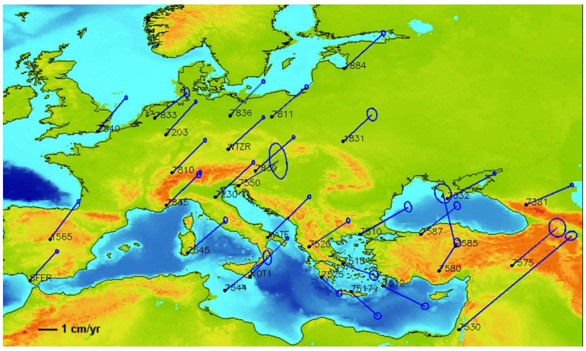

Fig. 2 SLR & VLBI combined Velocity solution

In particular, many sites in the Mediterranean have been occupied by SLR mobile stations during the WEGENER-MEDLAS campaigns (Wilson, 1987). Even if the occupations were sporadic and short, they gave the first experimental evidence of the characteristic tectonic motion features, as in the Aegeum.

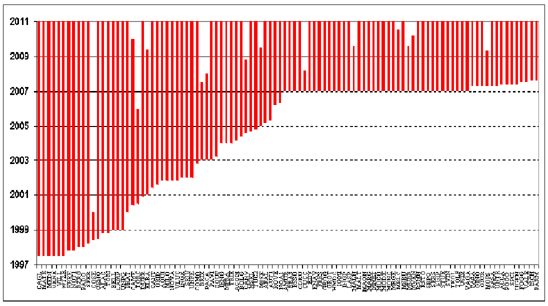

Fig. 3 GPS data coverage

The GPS data coverage (Fig. 3) in the present ASIMed solution is not uniform: GPS sites are continuously added to the network, turning out in different levels of velocity estimate accuracy. The accuracy improvement becomes a critical factor when the expected eurasiatic residual motion is of the order of a few mm/yr as in the Italian region. Nevertheless, the formal uncertainties associated to the GPS-only velocity estimates, appears to be underestimated and the combination strategy derives a final combined solution with a more realistic formal uncertainty level.

4 Residual velocity field computation

The combined SSV solution is roto-translated to ITRF2008 by using the following sites: MATE, UPAD, VILL, WTZR, CAGL, MEDI, SFER, GENO, NOT1, VENE, LAMP, 7840, 7836, 7810, 7835, 7811, 1884, 7805, 1565, 7332, 7333 (where GPS acronyms are used for co-located sites).

An Eulerian pole of the rigid block motion for the Central Europe has been computed using a set of stable European ITRF2008 sites and has been used to compute residual velocities. As expected, Central Europe does not show any significant deformation with respect to the computed pole.

4.1 Eastern Mediterranean

The Aegean area (Fig. 4) shows the largest residual motions w.r.t. Eurasian plate of the area under investigation, in agreement with geological model which predict an ongoing spreading of the Aegean sea over the African plate (Reilinger et al., 2006). GPS permanent sites (NOA1, TUC2), even if recently established, have collected a significant data history whose analysis results agree with the motion derived from SLR-only sites.

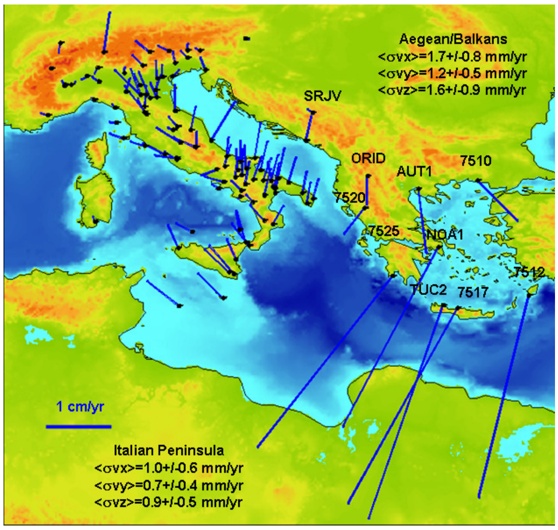

Fig. 4 Eastern Mediterranean residual velocity field

4.2 Western Mediterranean

Residual motions w.r.t. Eurasian plate seem generally really small in the Iberian Peninsula (Fig. 5). The residuals show a small rigid clockwise rotation, probably due to the reference Eulerian pole derived from Central European sites only.

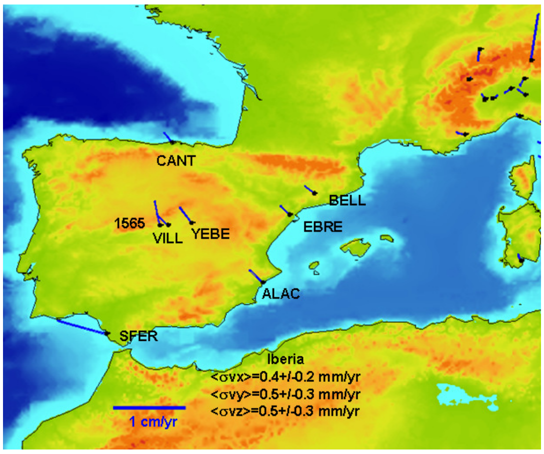

Fig. 5 Western Mediterranean residual velocity field

4.3 Italian Peninsula

The combined velocity field does not show significant residual motion w.r.t. Eurasian plate along the Alps chain; small residual motions arise along the Northern Apennines and on the nearby Po valley (Fig. 6).

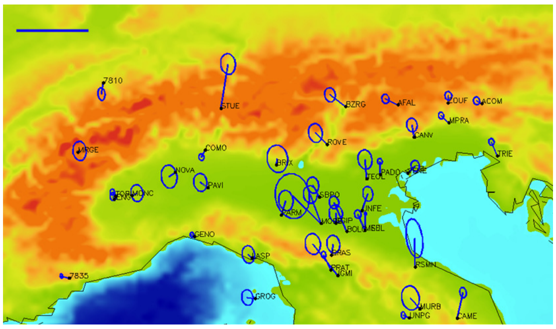

Fig. 6 Northern Italy residual velocity field

The Central part of Italy (Fig.7) shows different velocity pattern discriminated by the Apennines axis: westwards residuals in the Tyrrhenian area, north-eastwards residuals in the Adriatic area.
Southern Italy (Fig. 8) shows the greatest residual motions w.r.t. Eurasian plate in the Italian peninsula. Cagliari, on the Sardinian block, confirms its stability. Sicily and Lampedusa show a residual motion close to African one; Matera, on the Apulian platform, shows a motion with different direction w.r.t. the African one. Younger stations in the Southern Apennines show residual motions different among them, both for value and direction this could be due to a local complexity, hence further observations are needed.

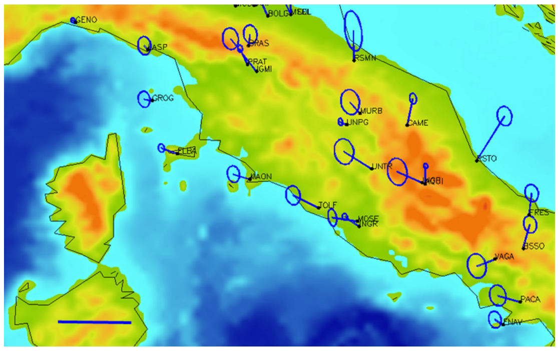

Fig. 7 Central Italy residual velocity field

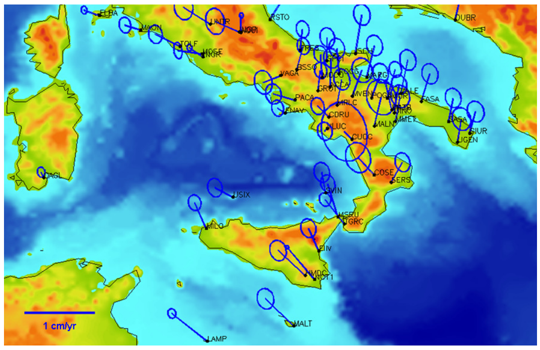

Fig. 8 Southern Italy residual velocity field

References

Altamimi Z., X. Collilieux, L. Métivier (2011). ITRF2008: an improved solution of the international terrestrial reference frame. *Journal of Geodesy*, vol 85, no 8, pp. 457-473.

Beutler G., M. Rothacher, S. Schaer, T.A. Springer, J. Kouba, R.E. Neilan, (1999): The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences. *Adv. Space Res*., 23, 631-635

Davies P. and G. Blewitt (2000). Methodology for global geodetic time series estimation: A new tool for geodynamics. *J. Geophys. Res.,* vol. 105, no. B5, pp. 11083-11100.

Gipson J. (1996). VLBI determination of neglected tidal terms in high frequency Earth Orientation Variation. *J. Geophys. Res.***,** vol. 101, no. B12, pp. 28051-28064.

Luceri, V., G. Bianco (2007). The temporary ILRS reference frame: SLR2005. *Lecture Notes*, Fall 2007 ILRS Workshop, Grasse Observatory, France.

Niell, A.E., 1996: Global mapping functions for the atmosphere delay at radio wavelengths. Journal of Geophysical Research, 101, 3227-3246.

Pearlman, M.R., Degnan, J.J., and Bosworth, J.M. (2002). The International Laser Ranging Service. *Advances in Space Research*, vol 30, no. 2, pp 135-143.

Reilinger R., et al. (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.

Selvaggi G. et al. (2006), La Rete Integrata Nazionale GPS (RING) dell'INGV: una infrastruttura aperta per la ricerca scientifica. *Atti 10a Conferenza Nazionale ASITA*, pp. 1749-1754

Zumberge, J. F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb, 1997: Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of Geophysical Research, 102, 5005-5017.

Wilson P. (1987). Kinematics of the Eastern Mediterranean region and the WEGENER-MEDLAS project. *J. GeoJournal*, vol. 14, no. 2, pp. 143-161.