Proceedings of the 6th European VLBI Network Symposium
Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)
June 25th-28th 2002, Bonn, Germany

Measuring Crustal Deformation in Europe by High Precision Geodetic VLBI

J. Campbell, A. Nothnagel, and and M. Vennebusch[1]

Geodetic Institute, University of Bonn, Nussallee 17, D-53115 Bonn, Germany

Abstract. At the western tip of the Eurasian plate, the European continent is besieged by thrusting and receding neighbour plates causing deformations and ruptures of the Earth's crust evidenced by earthquakes and volcanic outbursts. Measuring the extent and progress of crustal deformation has become one of the primary tasks of geodesists and geophysicists. Realizing that Europe enjoys one of the densest networks of radio telescopes especially equipped for high precision, geodetic VLBI has provided the incentive to organise a campaign of regular geodetic VLBI observations in the European network of fixed radio telescopes. The measurements have been carried out since the late eighties at an average rate of six sessions per year. From these data, site coordinates, baseline length changes and station velocity vectors have been derived with steadily increasing accuracy. The overall picture of the observed present-day site motions emulates quite well the pattern of tectonic motions inferred from the geotectonic setting of central Europe and the western Mediterranean. Interesting details are emerging for horizontal motions of the three stations in Italy, which are strongly affected by the complex interactions between the different tectonic regimes in this area. The accuracy of the vertical components is also improving with increasing length of the observational record, allowing to detect significant trends among the relative vertical motions of the sites.
The geodetic VLBI network operations have received supportive funding by the European Union under the 2nd and 4th Framework Programmes.
Key words: geodetic VLBI, crustal motion, geodynamics, tectonics

1. Introduction

In 1980, a first Working Meeting on European VLBI for Geodesy and Astrometry was held in Madrid, Spain, to explore the possibilities for precise geodetic VLBI observations in the European region using the information and experience of the already existing European VLBI Network (EVN) for astronomy and astrophysics. In this way, the EVN may be said to have been at the back of the creation of its geodetic counterpart.

With the introduction of the newly developed MkIII VLBI system in 1979, a standard for high precision astrometric and geodetic VLBI was established that formed the basis of the ensuing efforts in setting up an operational geodetic VLBI network in Europe. The standard included a wide bandwidth synthesis recording mode for high group delay resolution, dual S/X band receiving capability, and a hydrogen maser frequency standard. These rather costly requirements did not match perfectly with the needs of the astronomy VLBI community, a problem which caused a protracted deployment of the geodetic VLBI instrumentation at the European radio astronomy observatories. In Germany and in Italy special dedicated geodetic VLBI observatories were built in the mid-eighties to satisfy the need for an increased rate of observing sessions per year and for collocated observations with other geodetic space techniques.

A programme of regular geodetic VLBI observations that included European VLBI stations was started in the late eighties under NASA's Crustal Dynamics Project (CDP) and was expanded by European initiative to become a network of its own in 1990. Subsequently, funding for network operations could be secured from the European Commission in the so-called Framework Programmes to support the growth of human resources for research and development in the EU Member States.

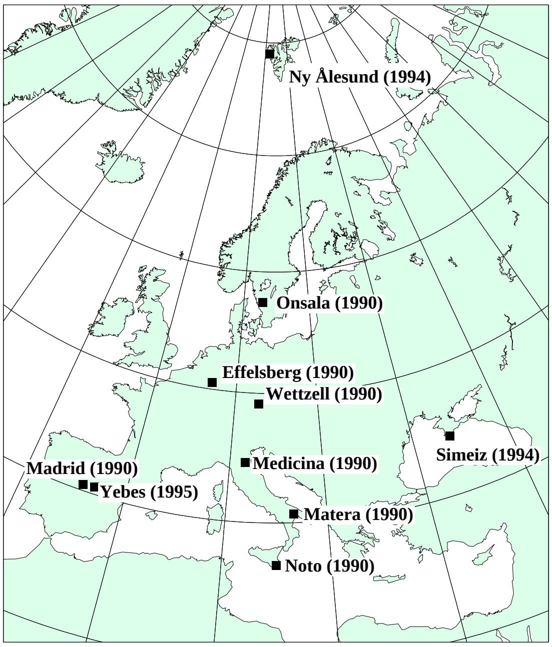

Fig. 1. European VLBI Network, year of first participation in pure European geodetic VLBI sessions in parentheses

The primary scientific objectives were focused on the measurement of crustal motion in the area defined by the network of existing European VLBI stations (Campbell 1988). In the first funding phase (1993-1996) the emphasis was placed on the determination of horizontal crustal motions, whereas the second phase (1997-2001) was concentrated on the measurement of vertical motions.

2. Current Status of the European Geodetic VLBI Network

Presently, the European Network consists of 10 stations (Fig. 1), six of which have an observing record longer than twelve years. All observing sessions are set up following the same principles, covering a period of one complete revolution of the Earth, i.e. 24 hours. With the automatic scheduling program SKED the observations of the participating telescopes are arranged in a way to satisfy all conditions regarding telescope slewing speeds and limits, tape recorder operations, integration time, and an optimised homogeneous sky distribution of the observed radio sources.

The recorded data from the observatories are sent for processing to the European VLBI Correlator Centre at the Max-Planck-Institute for Radioastronomy in Bonn, where the correlation and the subsequent processing stages in the MkIII (and now MkIV) data flow are performed. At the new 9-station MkIV correlator a 24h geodetic observing session with 8 stations produces on the average three thousand delay (and delay rate) observations. Between January 1990 and June 2002 a total of 56 observing sessions with up to 9 stations in slightly varying configurations have taken place.

3. Data Analysis

In the frame of the European VLBI Project the data are being analysed by several of the participating groups and the results are compared and discussed at regular intervals. Most of the groups are using the CALC/SOLVE analysis software developed at NASA GSFC (Ma et al. 1994), but solutions with the independent software OCCAM (Titov 1999) are also available.

The setup of a solution depends on the amount of data used:

a) global solutions using the entire global VLBI data set or a large part of it (> 90%). These solutions allow the simultaneous determination of source coordinates (CRF), Earth orientation parameters (EOP) and site coordinates as well as site velocities (Ma et al. 1994).
b) regional solutions using only the data of the EUROPE experiments. These solutions require the a priori input of the CRF and the EOP (Haas et al. 2000).

The solutions of category a) are normally referred to the NUVEL-1A frame of global no-net-rotation (Argus and Gordon 1991), while the results presented here belong to group b) and are referred to the Eurasian plate (or to one station on this plate, e.g. Wettzell). The use of only the data from the EUROPE sessions bears the benefit that no inconsistencies are introduced by baselines to non-European stations. By subtracting the NUVEL motion of the Eurasian plate, we obtain the velocities with respect to the Eurasian plate. The vertical motions are referred to an arbitrarily chosen zero motion of any one fixed station (e.g. Wettzell).

One of the preferred analysis strategies for the European Network, which has the benefit of showing the baseline and site coordinate evolution with time, is to run a combined adjustment of all sessions, but estimate station coordinates for all epochs in relation to one station fixed (for more details see e.g. Nothnagel and Campbell 1993). In this case, of course, the Earth orientation parameters have to be taken from an external source, e.g. from a global VLBI solution such as the NASA Goddard Space Flight Center solution 1102g, (August 1998) used here. In this case, we are using the inherent stability of the global solution to orient our regional network in space (the translations are inhibited by fixing one station, e.g. Wettzell). With a conservative estimate for the orientational stability of 0.3 mas (1 cm at one Earth radius) over short as well as longer time scales we may assume the influence of the reference system on a baseline vector of 1000 km length to remain below 1.5 mm (Ma et al. 1993).

The baseline length repeatability obtained from the time series has proved to be the best indicator for the inherent accuracy of VLBI because it is essentially free from orientational errors of the reference system. For the European baselines we obtain a WRMS of $\pm(2.0 \text{ mm} + 0.8 \text{ mm}\cdot b)$, where b is the baseline length in units of 1000 km (Haas et al. 2000). The horizontal coordinate WRMS repeatabilities range from ±1.5 to ±5.7 (Ny Ålesund north) whereas the values for the vertical are about three times larger, i.e. ±8.0 to ±14.4 mm. In spite of these larger uncertainties, several of the vertical rates are showing significant trends, such as Medicina in particular with a subsidence of 4.8 ± 1.1 mm/yr.

Fixing the motion of Wettzell to its value in the NUVEL-1A-NNR frame, we were also able to estimate velocity vectors from the time evolution of the coordinates of each station with respect to Wettzell (Haas et al. 2000). The results are shown in Fig. 2 and 3. To first order it is assumed that the displacements are linear with time and express the motion of the crustal portions supporting the telescopes, and that these crustal portions represent considerable units of the lithosphere, involving spacial scales comparable to the inter-station distances.

4. European Crustal Motion - Geophysical Results

The European area is broadly characterised by three distinct geotectonic provinces (Gueguen in Campbell et al. 2002, p. 133-139), i.e. the north which is represented by the relatively uniform Fennoscandian massif (craton) and its pronounced upward motion due to postglacial rebound, the more or less stable central European part and the

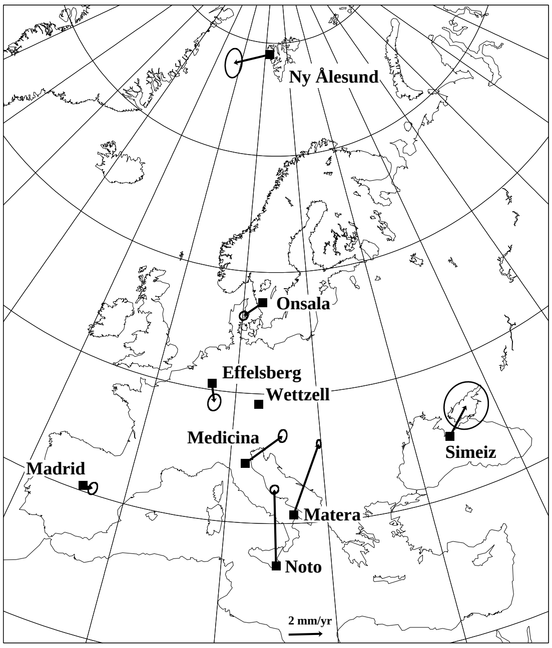

Fig. 2. Horizontal station motions with respect to Wettzell.

south dominated by the seismically active Mediterranean including the alpine systems (orogenic belt). The latter form part of the complex Eurasian plate boundary zone, a

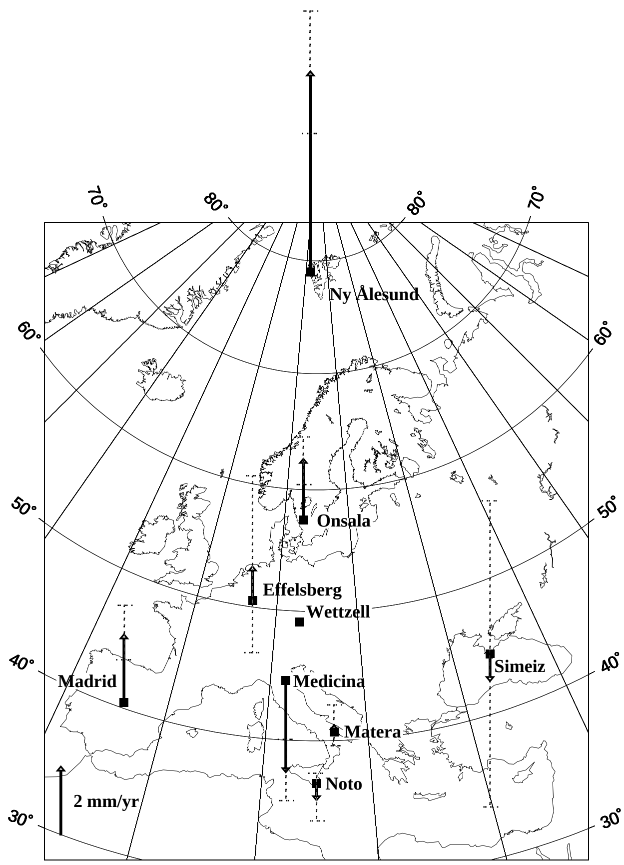

Fig. 3. Vertical station motions with respect to Wettzell.

result of the collision of the northward-thrusting African plate. Due to the anti-clockwise rotation of the African plate with respect to Eurasia, the (geological) velocities of convergence in the Mediterranean tend to decrease from east to west, from about 2 cm/yr in the Eastern Mediterranean to about 1 cm/yr in the western part. The resulting motions in the boundary zone are expected to be less, because much of the African motion is consumed by the subducting Mediterranean sea floor (Mueller and Kahle 1993). The most prominent horizontal motions are concentrated in the Italian peninsula with the effect of the northward moving African plate on the Adriatic plate being obvious at Matera and partly also at Medicina, while Noto is probably even directly affected by the African motion (Fig. 2).

On the basis of the assumption 'no local site motion' the observed vertical motions tend to agree quite well with the expected geotectonic motions at the sites. Considering central Europe to represent a stable reference for the discussion of motions in the northern and southern parts of Europe, we obtain a realistic scenario for most of the sites (the rates shown in Fig. 3 are given in relation to Wettzell fixed, i.e. its rate is set to zero). The 1-sigma uncertainties of the vertical rates are at the level of $\pm$ 0.5 to 2 mm/yr, except for those stations with significantly less observations:

- the sites of Onsala and Ny Ålesund are rising at rates of 2 and 6 mm/yr respectively, due to postglacial rebound (Ny Ålesund probably has an additional effect from the nearby North Atlantic Rift System)
- the subsidence of Medicina of about 2 mm/yr can be explained by the tectonic setting at the northern footwall of the Apennines, where geological rates of subsidence of up to 1.6 mm/yr during the past 5 Million years have been found. In addition, the influence of ground water and natural gas withdrawal in the Po-plain may also play a significant role.
- the uplift of the station of Madrid (located at Robledo, 40 km to the west of Madrid) of almost 3 mm/yr has no tectonic explanation at present.
- the measured vertical motions of Matera (south-eastern Italy) and Noto (south-eastern Sicily) are below the present level of significance (+1 mm/yr and -1 mm/yr respectively). Both sites are located in the stable parts of larger crustal blocks and are not expected to show pronounced vertical motion.

Extensive comparisons with the results from the collocated permanent GPS-stations yield a good agreement for both the horizontal as well as the vertical velocities, although some of the GPS-time series have been degraded due to changes in the local antenna setup.

The comparison with other types of data which give information about vertical crustal motion, such as mean sea level records from tidal stations and absolute gravity measurements, constitutes an important subject for further studies of vertical change in Europe. In the present project, initial steps have been made using the data from the Permanent Service of Mean Sea Level for the European coastlines. Assuming a 1 to 1.5 mm/yr eustatic sea level rise, the first comparison with the measured vertical motions on the European land masses shows a general agreement of today's motions with the 100-yr trends from the sea level records within bounds of ± 1 mm/yr (Campbell and Nothnagel in Campbell et al. 2002, p. 110-124).

5. Outlook

Plans are to continue to operate the European geodetic VLBI network at a rate of at least four 24h-sessions per year. The numerous problems besetting the permanent GPS stations have shown that an independent standard of measurements is indispensable to distinguish between true motion and artefacts from all sorts of external influences. The strength of GPS has to be seen in the dense coverage provided by the large number of stations in the field and the continuous data collection which ensures a high temporal resolution of the observed phenomena.

The scale and the long term stability of the European reference frame (coordinates *and* velocities) can only be guaranteed by continuing geodetic VLBI observations. We would very much welcome further augmentation by the numerous radio telescopes in Europe which sometimes only need minor additional hardware to become compatible with the geodetic MkIV standard. In this respect we look forward to the completion of two new VLBI telescopes in the Mediterranean, i.e. the 40 m antenna at Yebes (presently under construction) and the planned telescope near Cagliari/Sardinia.

Acknowledgements. The project has been supported by the EU (grants SCI CT92-0829 and FMRX CT96-0071)) from Feb. 1993 to Sept. 30, 2001. We gratefully acknowledge the contribution of many individuals from the participating groups as well as the technical and logistic assistance of the NASA/GSFC VLBI group and the support of the Max-Planck-Institut für Radioastronomie (VLBI Correlator Centre) in Bonn, Germany under the BKG/MPI agreement. J.C. and A.N. acknowledge partial support from the EC ICN RadioNET (Contract No. HPRI-CT-1999-40003).

References

Argus, D.F., and R. G. Gordon, No-net-rotation model of current plate velocities incorporating plate motion model NUVEL-1, Geophys. Res. Lett., 18, 2039-2042, 1991.

Behrend, D., A. Rius: Geodetic Control of the Madrid DSS65 VLBI Antenna. Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Viechtach/Wettzell, Feb. 12-13, 1999, Eds. W. Schlüter, H. Hase, Publ. by BKG, Wettzell, p. 42-50, 1999

Campbell, J.: European VLBI for Geodynamics. Proc. of the 3rd Int. Conf. on the WEGENER/MEDLAS Project, Bologna, May 25-27, 1987, P. Baldi, S. Zerbini Eds., The University of Bologna, p. 361-374, 1988

Campbell, J., H. Hase, A. Nothnagel, H. Schuh, N. Zarraoa, A. Rius, E. Sardon, V. Tornatore, P. Tomasi: First Results of European Crustal Motion Measurements with VLBI. Contributions of Space Geodesy to Geodynamics: Earth Dynamics, AGU Geodynamics Series, Vol. 24, p. 397-405, 1993

Campbell, J., R. Haas, A. Nothnagel (eds.):2002, Measurement of Vertical Crustal Motion in Europe by VLBI, TMR Networks Scientific Report, European Commission, Catal. No. KI-NA-20-084-ENC, Geodetic Institute, University of Bonn

Haas, R., E. Gueguen, H.-G. Scherneck, A. Nothnagel, J. Campbell: Crustal Motion Results derived from observations in the European Geodetic VLBI network. Earth Planets Space, Journal of the Japanese Geophysical Societies, Vol. 52, p. 759-764, 2000

Mueller, S., S.-G. Kahle: Crust-Mantle Evolution, Structure and Dynamics of the Mediterranean-Alpine Region. Contributions of Space Geodesy to Geodynamics: Earth Dynamics, AGU Geodynamics Series, Vol. 24, p. 249-298, 1993

Ma, C., J.W. Ryan, D. Gordon, D.S. Caprette, W.E. Himwich: Reference Frames from CDP VLBI Data. Contributions of Space Geodesy to Geodynamics: Earth Dynamics, AGU Geodynamics Series, Vol. 24, p. 121-145, 1993

Ma, C., J.W. Ryan and D.S. Caprette: NASA Space Geodesy Program - GSFC Data Analysis - 1993. NASA Technical Memorandum 104605, GSFC Greenbelt MD, 1994.

Müskens, A.: Improvements of the Geodesy MKIV Correlation during the last year. Proc. of the 15th Working Meeting on European VLBI for Geodesy and Astrometry, Sept. 7-8, 2001, in Barcelona, Spain IEEC, CSIC 2001, p. 50-54.

Nothnagel, A., J. Campbell; European Baseline Rate Determinations with VLBI; Proceedings of the 9th Working Meeting on European VLBI for Geodesy and Astrometry; Bad Neuenahr, FRG; Sept. 30 - Oct. 1, 1993; in Mitteilungen aus den Geodätischen Instituten der Rheinischen Friedrich-Wilhelms-Universität Bonn, Nr. 81, Bonn, 1993

Nothnagel, A.: Local Survey at the Effelsberg Radio Telescope 1997 - Preliminary Results. Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Viechtach/Wettzell, Feb. 12-13, 1999, Eds. W. Schlüter, H. Hase, Publ. by BKG, Wettzell, p. 25-31, 1999

Plag, H.-P.: Measurement of vertical crustal motion in Europe by VLBI: Station Report for Ny-Alesund; Norwegian Mapping Authority. Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Viechtach/Wettzell, Feb. 12-13 1999, Eds. W. Schlüter, H. Hase, Publ. by BKG, Wettzell, p. 65-77, 1999

Ryan, J.W.,C. Ma, D.S. Caprette; NASA Space Geodesy Program - GSFC Data Analysis - 1992, Final Report of the Crustal Dynamics Project VLBI Geodetic Results 1979-91; NASA Technical Memorandum 104572, Greenbelt, 1993

Titov, O.: Tectonic motion of European VLBI sites. Proc. of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, Vietach/Wettzell, Feb. 12-13, 1999, Eds. W. Schlüter, H. Hase, Publ. by BKG, Wettzell, p. 186-191, 1999.