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Relative motions in Europe studied with a geodetic VLBI network

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SUMMARY

Since 1988, the European geodetic Very Long Baseline Interferometry (VLBI) community and the NASA Goddard Space Flight Center, have set up the observation of a series of geodetic VLBI experiments with the purpose of studying possible crustal deformations in Western Europe. In this work we present the results of the analysis of the complete data set with the software package OCCAM 3.0. These results show the detection of significant motions at the centimetre per year level in the southern European stations, close to the boundary between the African and Eurasian plates. Meanwhile, they show no significant motions at that level in central Europe or the Iberian Peninsula. The extraordinary quality of the data and the consistency of the analysis have made it possible to obtain significant geodynamical results in a relatively short time-span.

Key words: geodesy, tectonic motions, Very Long Baseline Interferometry (VLBI).

1 INTRODUCTION

In Western Europe there is a complex scenario of geological structures: the Azores Triple Junction, between the African, Eurasian and American plates; the boundary between the Eurasian and African plates, running across the Mediterranean Sea, the Iberian and Italian Peninsulas, etc. (e.g. Panza *et al.* 1980; Suhadolc & Panza 1989).

To derive accurate models of plate tectonics for the European area from only geological or geophysical data is quite difficult. Although the seismic activity yields interesting data, the geological information regarding plate motions is scarce and ambiguous. A model of possible motions in a microplate deformation scheme was presented by Drewes & Geiss (1986). Udías, Buforn & Ruiz de Gauna (1989), using seismic data, predict small horizontal motions across the boundaries, and the possibility of vertical motions in the Eurasia–Africa border.

With this situation, space geodesy is an appropriate tool to provide fundamental information about the current rates of displacements between points in Europe, which can be used to test the accuracy of the existing models, and to derive better ones.

The use of Very Long Baseline Interferometry (VLBI) is providing routine geodetic measurements with a precision of few parts per billion in baselines of several thousands of kilometres (Rius *et al.* 1992).

This level of precision makes VLBI one of the best choices for the study of current relative motions between points on the Earth's crust. With this purpose, the European VLBI community and the NASA Goddard Space Flight Center (GSFC) VLBI group have coordinated several series of geodetic VLBI experiments as part of the NASA Crustal Dynamics Project (CDP) and the Dynamics of the Solid Earth Program (DOSE), using a network of six fixed VLBI stations in Europe.

Presently, the European geodetic VLBI network (see Fig. 1), is composed of antennae at Onsala (Sweden), Wettzell (Germany), Madrid (Spain) and Medicina, Noto and Matera (Italy). Possible relative motions induced by the interaction between the Eurasian and African plates could be detected with this network, which is sensitive to variations of the Italian and Iberian Peninsulas with respect to Central Europe, as well as to differential motions between the stations in Italy.

2 VLBI EXPERIMENTS

Since 1988 several series of geodetic VLBI experiments have been observed in Western Europe. The first series, East Atlantic (E. ATL), was performed in 1988 and 1989 with the participation of the European antennae of Onsala, Wettzell, Madrid, Medicina and Noto (this was in late 1989), and the USA stations of Westford (Massachusetts) and Richmond (Florida), the latter only in 1988.

In 1990 and 1991, the series EUROPE, with only European antennae including Matera, went on inside the CDP. All these experiments have been coordinated by the VLBI group of NASA/GSFC. In 1992 NASA started the programme Dynamics of the Solid Earth, in which the European groups, with the support of the VLBI group in

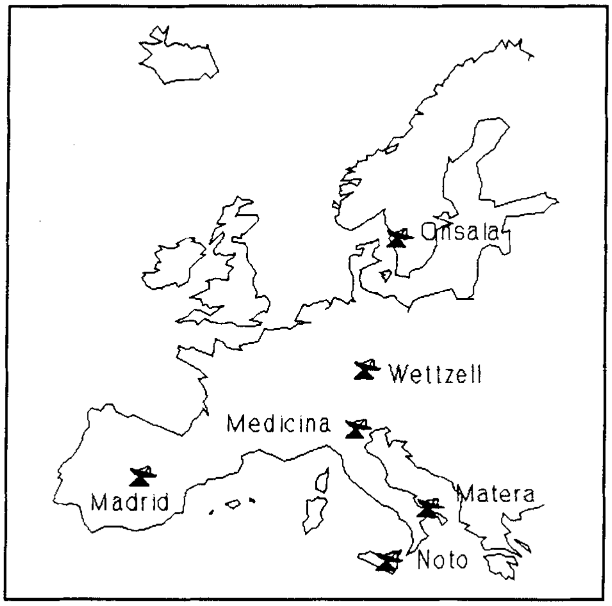

Figure 1. Geodetic VLBI network in Europe.

Goddard, coordinate the continuation of the EUROPE experiments.

The data acquired with the European Geodetic VLBI Network has been correlated at any of these three centres: Max Planck Institut für Radioastronomie in Bonn (Germany); United States Naval Observatory at Washington DC (USA) and Haystack Observatory, in Haystack, Massachusetts (USA).

The total number of experiments observed in this series since 1988 is around 20. Of these, we have used 17 for the analysis we present here.

3 DATA ANALYSIS

The analysis of the data set has been done using the software package OCCAM 3.0 (Zarraoa, Rius & Sardón 1992). The program is a PC-based software, which applies algorithms based on the 1989 IERS Standards (McCarthy 1989) to compute the theoretical model of the VLBI observables. The least-squares estimation of the parameters is done using a Kalman Filter technique.

The program has been compared thoroughly with CALC/SOLVE (Ryan 1989), one of the most standard packages currently available to process geodetic VLBI data. The comparison (Zarraoa 1992) showed that both programs produced equivalent results at the formal error level, when used with analogous options.

3.1 Individual analysis of each experiment

Each experiment of the series E.ATL and EUROPE has been analysed independently with a common procedure. The objective of the individual analysis is to obtain a series of independent baseline length results, to study the consistency of the different experiments, and also give first estimates of possible variation in the lengths.

For each session we have solved for the station coordinates and nutation corrections to the IAU 1980 theory. In addition, we have solved for corrections to the local tropospheric delay model (Davis *et al.* 1985) and for the clock offsets between stations.

The tropospheric terms have been considered random-walk stochastic processes. The clock offsets have been modelled as a linear drift plus a random-walk process. Station coordinates and nutation terms are considered constant for the time-scale of 24 hours.

The power spectral densities (PSD) applied for the random-walk processes involved were estimated from the data, using a simple algorithm described in Zarraoa (1992). Previous analyses showed that variations smaller than one order of magnitude in the PSD values produced no significant changes on the estimates (Rius *et al.* 1992).

The PSD for the tropospheric terms have been around $0.01\,\mathrm{ps^2\,s^{-1}}$, with up to one order of magnitude of variation depending on the station or experiment. For the clock-offset term, we have found a PSD of around $1\,\mathrm{ps^2\,s^{-1}}$, with up to one order of magnitude of variation, again depending on the station or session.

3.2 Global analysis

The set of parameter estimates and their covariance matrix produced as a result of the analysis of each individual experiment are considered the 'observables' of the global analysis.

To combine results from different sessions, we have to fix a unique reference frame for all of them to be able to discern between variations in the positions of the stations and rotations of the reference system. The use of a global reference system is not suitable for a small network like the European, because the data is insufficient for a precise determination of the Earth Rotation Parameters that can tie our network to the global system. Thus, we have chosen to use a 'local' reference system determined inside the network by means of fixing the coordinates of one station (Wettzell), one direction from this station to a second one (Onsala), and the plane defined by these two stations and a third one (Madrid), or equivalently, constraining Madrid to no vertical motion.

The election of Wettzell and Onsala to define the main direction fixed in our reference frame comes from the fact that all geophysical models agree in the stability of central Europe. Moreover, more than nine years of VLBI data have shown no significant motion between the two stations at the $\mathrm{mm\,yr^{-1}}$ level (Ma, Ryan & Caprette 1992). The vertical component of Madrid has been fixed because it was the only station not aligned with the main direction.

For the global process we have used a Kalman filter approach again. In this case, the calibration parameters (tropospheric delays, clock drift models and nutation corrections) estimated for the individual experiments were considered independent between sessions, and modelled as white noise stochastic processes. A rotation matrix to tie the observables from each experiment to the reference frame has also been considered a white noise process between different epochs.

The stations' positions have been modelled as linear functions with time, and we have estimated a zero epoch position plus a linear drift for the coordinates.

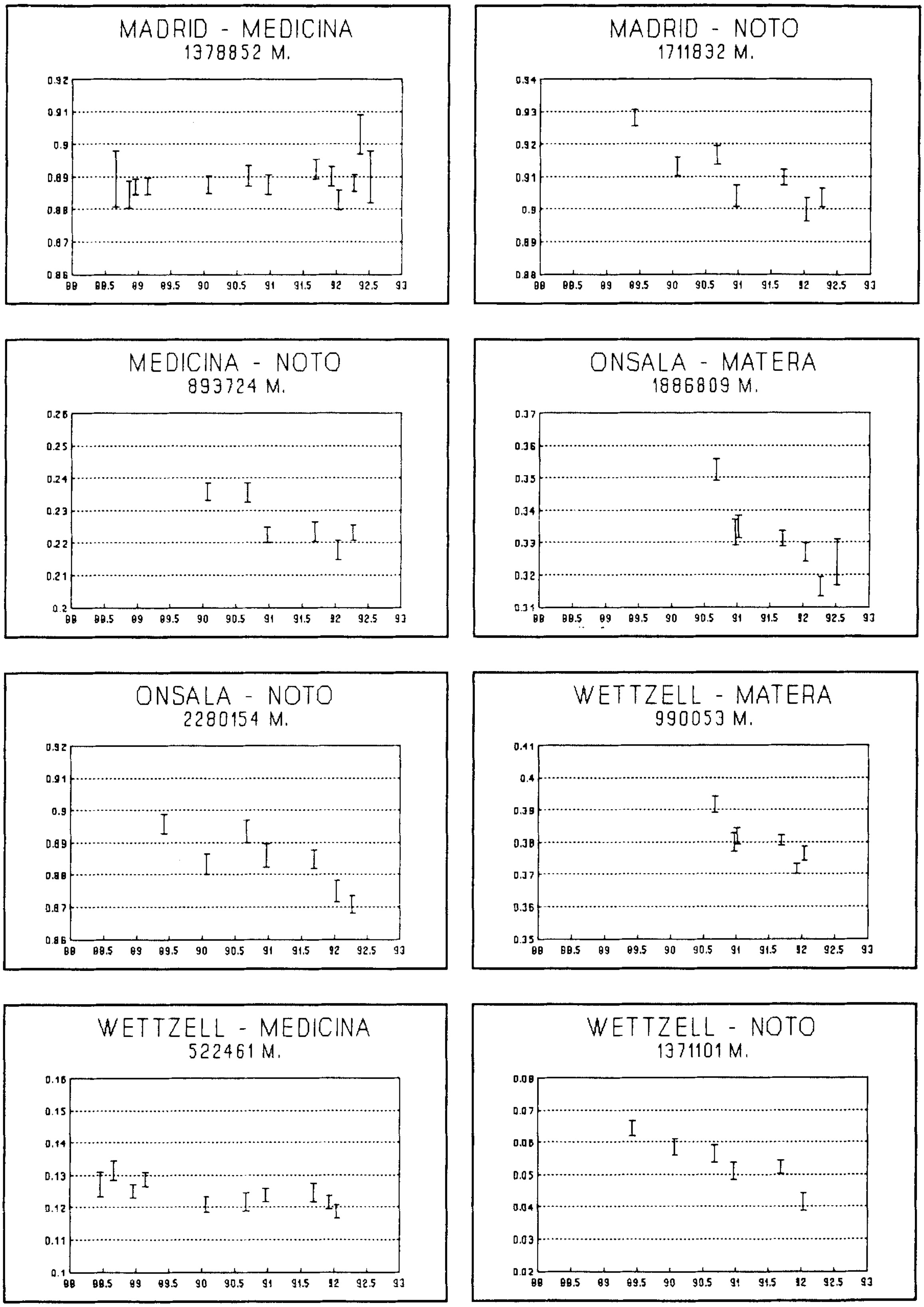

Figure 2. Lengths of several European baselines as a function of time. The X-axis time is in years. The Y-axis spans for 6 cm for all baselines. We have included here those baselines that show more interesting trends or better repeatabilities.

4 RESULTS FROM THE INDIVIDUAL SESSIONS ANALYSIS

Figure 2 shows the results obtained with OCCAM 3.0 for the European baselines included in our experiments. The repeatability of the results obtained has been found below 1 cm. We have computed the repeatability both with respect to the mean (R_1) and with respect to the regression line (R_2) for each baseline. As a function of the length L, these repeatabilities are (L in 10^3 km):

$$R_1 = 3.1\,\text{mm} + 2.5\,\text{mm} * \text{L}$$

$$R_2 = 2.7\,\text{mm} + 2.1\,\text{mm} * \text{L}.$$

The values confirm that our relative precision is at the 3 parts per billion level for European baselines.

Table 1 shows the variation rates of the baseline lengths obtained from the independent analysis. We also include the results of the analysis done with CALC/SOLVE at the NASA/Goddard Space Flight Center. Some of the values obtained are significant at the 2 sigma level, particularly in the baselines with the Italian station of Noto, in Sicily.

The baselines between Wettzell, Onsala, Madrid and Medicina show no significant motions at the 2–3 mm yr^{-1} level, some even with a three-sigma formal error, confirming the stability of the central part of Europe and also of the Iberian Peninsula.

The only discrepancy between the results from OCCAM and CALC/SOLVE appears on the Matera baselines. The reason lays on the fact that the CALC/SOLVE solutions do not take into account the first epoch for Matera (September 1990). In Fig. 2, we can see how this initial epoch is responsible for most of the rates derived by OCCAM. The main difference of this experiment was found in the vertical component of Matera and the GSFC VLBI group decided to drop Matera from that experiment. However, we decided to keep all the stations in our analysis, although Matera results may look unreliable. In the global analysis with OCCAM, we also dropped this station for the experiment, finding that it did not affect the horizontal velocities estimated, only the vertical. The baseline length rates were in agreement with those derived with CALC/SOLVE.

5 RESULTS OF THE GLOBAL ANALYSIS

Figure 3 shows the resultant horizontal motions from the global analysis using the reference system described above,

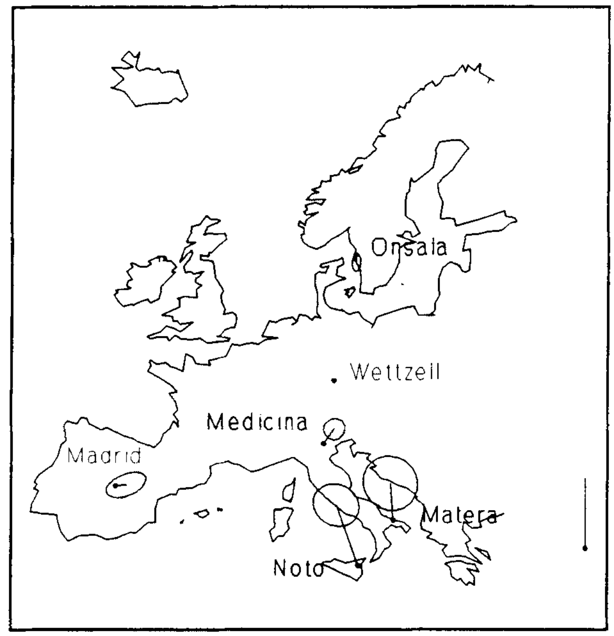

Figure 3. Horizontal movements of the European geodetic VLBI network. The error ellipses represent a three-sigma formal error. The segment to the right represents 1 cm yr^{-1} rate.

Table 1. Variation of the baseline lengths and formal errors obtained from OCCAM and CALC/SOLVE.

Baseline	Length	OCCAM Rate (mm/y)	σ (mm/y)	C/S Rate (mm/y)	σ (mm/y)
MATERA - NOTO	444 Km.	-4.9	3.1	-0.6	2.6
WETTZELL - MEDICINA	522 Km.	-2.2	0.6	-2.0	0.4
MEDICINA - MATERA	597 Km.	-8.5	3.4	-1.9	1.4
MEDICINA - NOTO	894 Km.	-6.6	2.5	-5.4	1.1
WETTZELL - ONSALA	920 Km.	-0.4	0.9	-0.3	0.2
WETTZELL - MATERA	990 Km.	-10.5	3.6	-2.0	1.2
WETTZELL - NOTO	1371 Km.	-6.9	1.5	-6.8	1.1
MADRID - MEDICINA	1379 Km.	0.8	0.7	1.2	0.5
ONSALA - MEDICINA	1429 Km.	-2.5	1.1	-2.0	0.6
WETTZELL - MADRID	1655 Km.	-0.8	1.3	-1.1	0.8
MADRID - NOTO	1711 Km.	-7.8	2.0	-5.9	1.9
MADRID - MATERA	1765 Km.	-9.5	5.6	2.6	2.5
ONSALA - MATERA	1887 Km.	-15.9	3.7	-5.9	3.8
ONSALA - MADRID	2205 Km.	-1.6	1.7	-1.3	1.0
ONSALA - NOTO	2280 Km.	-7.1	2.1	-7.6	2.7

Table 2. Velocities and formal errors derived from the combined analysis (vertical and horizontal).

Baseline	Length	Rate (mm/year)	σ (mm/year)
MATERA - NOTO	444 Km.	-2.5	1.4
WETTZELL - MEDICINA	522 Km.	-2.2	0.5
MEDICINA - MATERA	597 Km.	-5.4	1.3
MEDICINA - NOTO	894 Km.	-6.6	0.9
WETTZELL - ONSALA	920 Km.	-1.1	0.4
WETTZELL - MATERA	990 Km.	-8.0	1.3
WETTZELL - NOTO	1371 Km.	-7.5	0.8
MADRID - MEDICINA	1379 Km.	0.7	0.6
ONSALA - MEDICINA	1429 Km.	-2.9	0.6
WETTZELL - MADRID	1655 Km.	-1.5	0.5
MADRID - NOTO	1711 Km.	-6.3	0.9
MADRID - MATERA	1765 Km.	-7.4	1.4
ONSALA - MATERA	1887 Km.	-11.7	1.5
ONSALA - MADRID	2205 Km.	-2.0	0.6
ONSALA - NOTO	2280 Km.	-7.6	0.9

with their three-sigma error ellipses. The segment at the right part of the plot represents the 1 cm yr^{-1} scale.

Motions on the stations in southern Italy can be seen from Fig. 3, which are significant at the three-sigma level, especially in the case of Noto. For Matera, the results are not so clear due to the short period of data available, but the trend seems to be similar to that of Noto. Medicina shows significant motion at the three-sigma level, but the rate is rather small. For the rest of the stations there is no significant motion detected at the 2–3 mm yr^{-1} level, confirming the results of the individual solutions. The global analysis from CALC/SOLVE has produced results equivalent with OCCAM at the one-sigma error level.

Table 2 shows the projected velocities over the baselines, in order to compare them with the variation rates obtained from the single-experiment analysis. They include both the horizontal and vertical components. The vertical components derived from VLBI data are always strongly correlated with the zenith tropospheric delay, so in general they are around three times poorer than the horizontal estimates. For the European network, the vertical motions are not significant at the three-sigma error level, so we have not included the vertical motions plot from the global result. However, Fig. 4 presents the results of the vertical components of Medicina, Noto and Matera as a function of the experiment (all related to the fixed reference frame).

In the figure for Matera a strong vertical component can be seen, particularly if we consider the first experiment, which causes the differences already mentioned above. For Medicina we could see a possible schedule-dependent behaviour in the vertical component, comparing the E.ATL series (1988–1989) with US antennae, and the EUROPE series with only European stations (from 1990 on).

6 COMPARISON WITH OTHER RESULTS

The results presented in Fig. 3 agree with the expected motions from geophysical models. Noto and Matera are influenced by relatively strong tectonic activity, producing

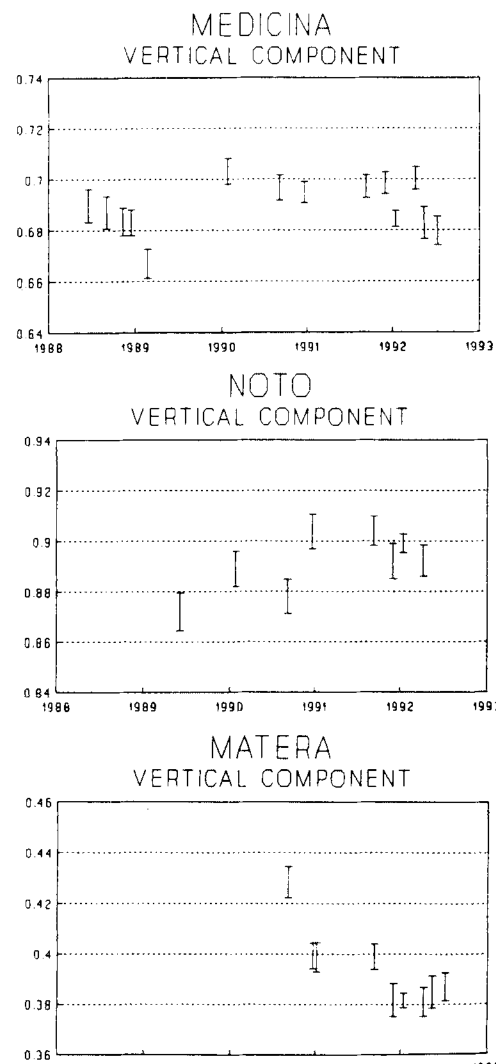

Figure 4. Vertical components of Medicina, Noto and Matera as a function of time.

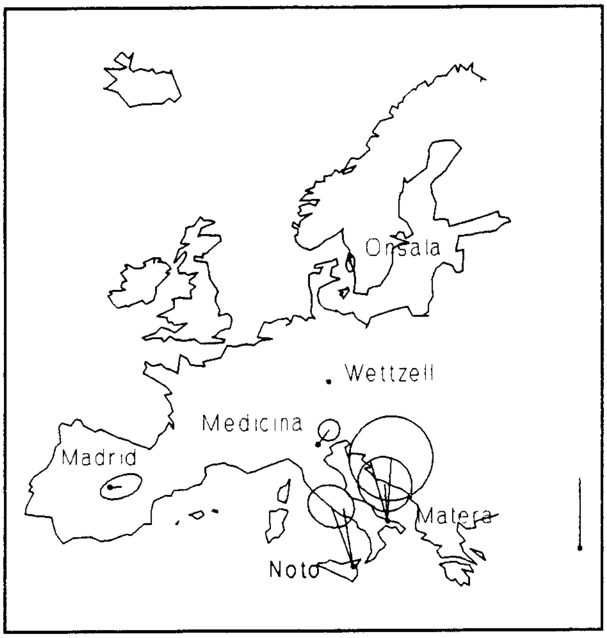

Figure 5. Comparison of our estimated motions with NUVEL-1 predictions and SLR results. For Matera the arrows are (left to right): NUVEL-1, VLBI, SLR. For Noto (left to right) VLBI, NUVEL-1.

motions close to $1\,\mathrm{cm\,yr^{-1}}$, meanwhile the rest of the stations show negligible displacements. This panorama is pretty close to the predictions made from geophysical data in Drewes & Geiss (1986) or in Patacca & Scandone (1989). They also agree with the predictions in the NUVEL-1 model (DeMets *et al.* 1990) assuming that Noto and Matera are on the African plate, as can be seen in Fig. 5, which collects the global results of the VLBI network and the predicted movements for Matera and Noto by NUVEL-1. We have also included a Satellite Laser Ranging result for Matera (Ambrosius, Noomen & Wakker 1991), with its three-sigma error level. As can be observed, the results are very close in direction, and they all agree at the level of the error ellipses.

7 CONCLUSIONS

The European geodetic VLBI network has been performing VLBI experiments with the purpose of studying relative motions in Western Europe. The data acquired from 1988 to 1992 have been of extraordinary quality, and the analysis has produced the determination of significant results about relative horizontal motions at the $\mathrm{cm\,yr^{-1}}$ level for stations in southern Italy. No significant motion larger than 2–$3\,\mathrm{mm\,yr^{-1}}$ has been found for the rest of the network, confirming the stability of central Europe and the Iberian Peninsula.

The determination of vertical motions will require an increase in the number of experiments and the time-span. However, the quality of the data already available has shown that the current repeatabilities in the vertical components are at the 1 cm level, and that some systematic behaviours could be detected, which could lead to a better determination of vertical motions.

Southern Italy and Sicily appear to have an active tectonic motion. When a longer time span is available, it could be possible to refine our results for the rest of the stations in the network, and confirm the possible existence of motions at the 2–$3\,\mathrm{mm\,yr^{-1}}$ level in the Iberian Peninsula and northern Italy that appear in our analysis.

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