A two-step approach to analyze European geodetic Very Long Baseline Interferometry (VLBI) data

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Abstract

Since 1990 the European fixed station geodetic Very Long Baseline Interferometry (VLBI) network has been observing on a regular basis in order to determine crustal motion in Europe. Usually the analyses of geodetic VLBI data are set up in two different ways: a) to produce station coordinates for each observation epoch from independent parameter adjustments and b) to compute station coordinates at a reference epoch together with drift rate components simultaneously from solutions where station drifts are modeled directly using vector representation. In this paper we present an alternative analysis strategy which uses a two step approach. In a first step all station coordinates are estimated as independent parameters for each session. Then in a second step topocentric drift rate vectors are computed from the individual series of station coordinates and their covariance matrices.

1 Introduction

The first purly European geodetic Very Long Baseline Interferometry (VLBI) session was observed in January 1990. With this initial session the European geodetic VLBI group started a routine observing programme with usually 6 observing sessions per year in the European fixed station geodetic VLBI network. Until the end of 1998 a total number of 46 sessions was carried out. The analyses of geodetic VLBI data are usually set up to produce two different representations of the station coordinates from a least-squares or Kalman Filter adjustment of the observations. In the first type of solutions each observing session is adjusted independently and a series of station coordinates with respect to a reference station in the network is determined. In geodetic VLBI a reference station or some type of constraint is always needed in order to resolve the translational degrees of freedom of the network. Adopted from satellite orbit determinations this type of solutions is a so-called 'arc solution' with station coordinates as 'arc parameters'.

The second type of adjustment estimates station coordinates at a reference epoch plus station drift parameters in the form dx/dt, dy/dt, dz/dt. Since these parameters are determined from all observation sessions together they are called 'global parameters' determined in a so-called 'vector solution'. Additionally, in both types of solutions a number of parameters have to be estimated in each session which model effects valid only within the individual sessions. These are mostly parameters which describe the behaviour of the station clocks, the refraction of the atmosphere and some or possibly all Earth orientation parameters (EOP).

The arc solution gives a good insight into the quality of the individual observing sessions since the individual results may be displayed graphically on an epoch by epoch basis. Currently it is common use to depict these in three dimensional baseline components [e.g. Ryan et al. 1993]. The repeatability of baseline length measurements which are invariant against any rotations are a useful measure to derive the measurement accuracy. Here, the rotational degrees of freedom of the network are fixed by using an external EOP series.

The vector solution directly produces station related annual displacement vectors. For its central location and the good agreement of its annual motion due to continental drift with the NNR-Nuvel-1A model [De Mets et al., 1994] most often the coordinates and drift rate of Wettzell are held fixed in adjustments of European VLBI data. Earth orientation parameters may be estimated if the first epoch EOP are fixed. Subtracting the NNR-Nuvel-1A model drift from station motions estimated in vector solutions thus yields annual displacement vectors in a European/Wettzell fixed frame.

2 Modified Analysis Strategy

In the least squares adjustment of a vector solution the scatter of the individual sessions as it is present in the arc solutions is constrained into one single vector for each station. Any large deviations of individual sessions and stations in particular are not discernable any more. In addition, from our experience with vector solutions the annual drift vectors of the European regional network with Wettzell as a fixed reference station and fixed EOP has a tendency to display a small spurious rotation about the central station. The reason of this is still unknown but deficiencies of stations in the earlier sessions may be suspected.

In order to overcome these deficits and to have a better way of visualizing the session to session evolution of a station's coordinates we devised a third analysis strategy which consists of two steps. In a first step we perform an usual arc solution, i.e. we determine relative station coordinates for all stations with respect to a reference station in the network which moves according to the NNR-Nuvel-1A [De Mets et al., 1994]. The results are series of geocentric station coordinates but also the full covariance matrices for each observing session which are saved for further use. In order to create a European plate fixed frame plate motion according to the NNR-Nuvel-1A model is subtracted.

With the parameters of the WGS84/GRS80 ellipsoid the geocentric cartesian station coordinates are transformed into geocentric ellipsoidal ones with a conventional transformation procedure. In order to also transform the formal errors of the cartesian station coordinates the full covariance matrix between all station coordinates of the solution, i.e. between the three dimensional coordinates of each individual station and between the coordinates of all participating stations, is transformed into the ellipsoidal system as well. The results of the transformations are ellipsoidal station coordinates for each participating station in the session and the covariance matrix between the ellipsoidal coordinates of all stations in the specific session.

In the second step the series of station latitude and longitude together with the geocentric height is used to determine the topocentric annual station drift in the respective tangential plane. In order to express the motions of the stations in mm per year a mean value for longitude, latitude and height for each station is subtracted and the angular positions are transformed into metric North and East components. Finally, least squares adjustments are performed to estimate offsets and rates of linear regressions for each station. Again the whole covariance information for each session is applied, so e.g. the rate for the height component depends on the results for the east and north components according to the covariance matrix, too.

In the series some of the stations suffered abrupt changes in the station position due to track and wheel repairs. At epochs where we have good evidence for these changes we introduce discontinuities in the linear trends. In these cases the same linear rate before and after the discontinuity but two different absolute values, one before and one after the modification, is estimated in the least squares adjustments.

3 Topocentric station drift rate results

The European geodetic VLBI session from January 1990 to October 1998 were analyzed with the two-step analysis approach described in the previous section. In the first step we performed an 'arc-solution' using the the CALC/SOLVE/GLOBL VLBI data analysis software package [Ma et al., 1990]. Clock parameters with respect to a reference clock in each session were estimated with second order polynomials and additional piecewise linear components every 6 hours. Atmospheric wet zenith path delays were estimated as piecewise linear functions every 60 minutes using the NMF 2.0 mapping function [Niell, 1996]. Additionally, horizontal delay gradient parameters in North and East direction were estimated in a piecewise linear mode every 8 hours. Relative station coordinates with respect to a reference station were estimated for each station except for the reference station itself which we chose to be Wettzell. Since we wanted to refer to a single reference station we had to leave out three sessions in 1992 and one in 1998 where Wettzell did not participate. Coordinates of radio sources were kept fixed at values of the International Celestial Reference Frame (ICRF) 1995 and a priori coordinates for the observing sites were introduced according to the International Terrestrial Reference Frame (ITRF) 1996. Earth orientation parameters (EOP) were adopted from a recent global VLBI solution by the GSFC VLBI group [Ma and Ryan, 1998] while daily nutation offsets with respect to the IAU 1980 nutation model were estimated for each session.

In the second step we used the results of the first step transforming the coordinates of the stations and determining topocentric station drift rates using the strategy described before. Table 1 displays the results for horizontal and vertical station drift rates and figures 1 and 2 show these results in a graphic representation. Ny Ålesund, Simeiz and Yebes were not considered in the second step because of their short observational history which produces fairly insignificant and unreliable results.

Tab. 1: Topocentric station drift rates of six stations in the network.

station	East [mm/y]	wrms [mm]	North [mm/y]	wrms [mm]	height [mm/y]	wrms [mm]
Effelsberg	$+1.45 \pm 1.27$	3.26	-0.36 ± 0.89	2.68	-0.21 ± 3.16	9.21
Madrid	$+0.01 \pm 0.48$	4.36	$+0.17 \pm 0.37$	3.10	$+2.57 \pm 1.35$	13.29
Matera	$+1.95 \pm 0.29$	3.07	$+4.14 \pm 0.25$	4.00	$+0.55 \pm 0.87$	11.56
Medicina	$+2.82 \pm 0.41$	2.93	$+2.05 \pm 0.31$	2.16	-4.39 ± 1.12	7.75
Noto	-0.81 ± 0.38	4.32	$+4.45 \pm 0.36$	4.38	-1.05 ± 1.21	10.63
Onsala	-1.89 ± 0.45	3.93	-0.55 ± 0.29	3.81	$+2.34 \pm 0.98$	14.63

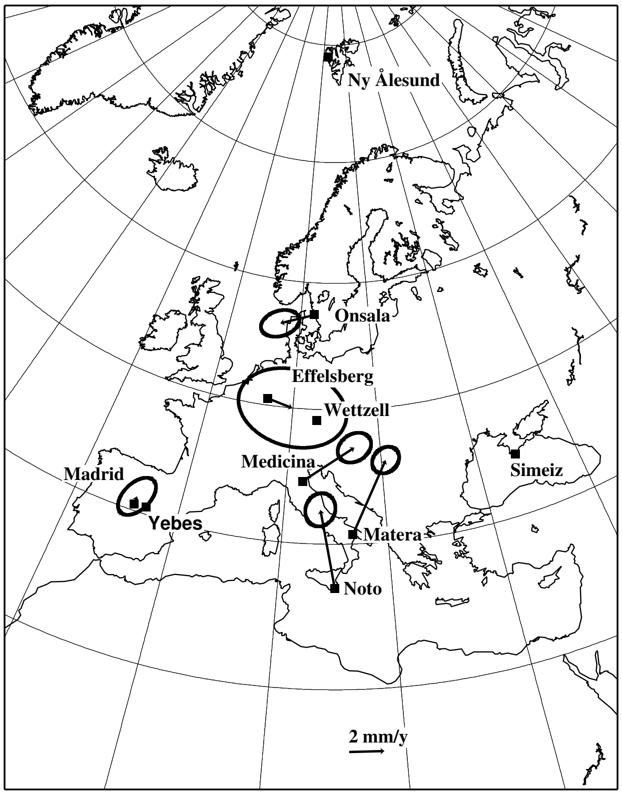

Fig. 1: Horizontal station drift rates in a European plate fixed frame with respect to Wettzell.

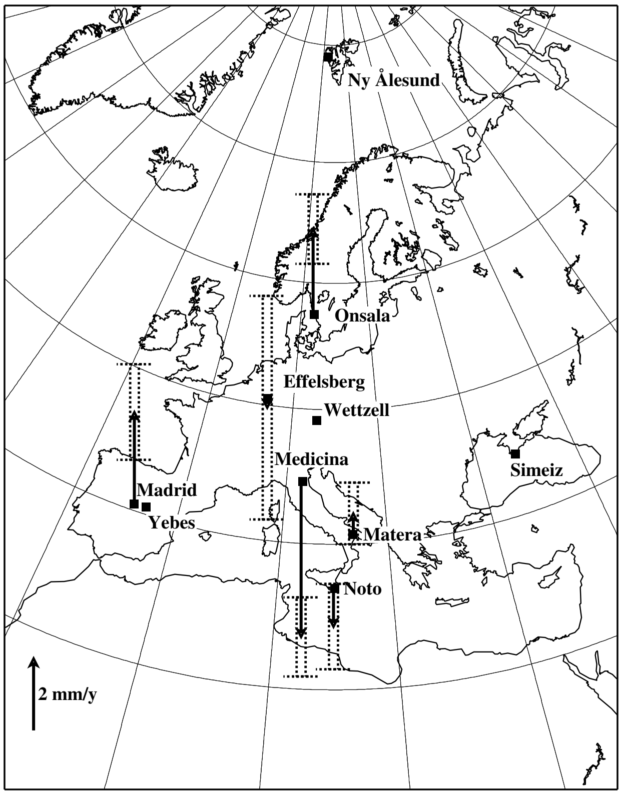

Fig. 2: Vertical station drift rates in a European plate fixed frame with respect to Wettzell.

As mentioned already the annual horizontal motion of Wettzell agrees very well with the NNR-Nuvel-1A continental drift model. Thus, fixing the motion of Wettzell to this model and using high accuracy Earth rotation parameters from external sources places a reliable bound on the long term drift of the European continent as represented by the observing sites. Only the EOP have an effect on the determination of the drifts of the stations relative to Wettzell. Since the long term stability is extremely reliable and the short term variations only increase the scatter of the results, the drift vectors determined up to date deserve a high level of confidence.

The estimated vertical motions are linked directly to the vertical rate of Wettzell which is set to zero in our analysis. Thus, these rates can only be considered relative to Wettzell which may not have a constant height over the years. Although global solutions of the world-wide VLBI data set suggest a small subsidence of Wettzell [e.g. MA and RYAN, 1998] local and regional surveys have not confirmed this [SCHL"UTER, pers. communication].

For the three stations Effelsberg, Madrid and Medicina we introduced discontinuities in their positions due to track and wheel replacements at those stations. Table 2 displays the resulting station offsets with their formal errors. The latter are computed applying the error propagation law to the differences of the positions before and after the displacements. Since the observation epochs after track repairs are relatively short for all three stations the magnitudes of the resulting offsets have to be considered very preliminary. More observations are needed to compare the VLBI estimates of the height changes with local geodetic measurements which are currently underway.

Tab. 2: Displacements due to track and wheel replacements

station	date	East offset [mm]	North offset [mm]	height offset [mm]
Medicina	96/07/01	-5.69 ± 3.73	$+2.50 \pm 2.85$	$+14.36 \pm 10.19$
Effelsberg	96/10/01	-6.61 ± 7.99	$+0.22 \pm 5.55$	$+17.35 \pm 19.85$
Madrid	97/04/30	-2.64 ± 4.98	-11.03 ± 4.01	-9.61 ± 14.02

4 Discussion

The advantage of the two-step analysis approach is that from the graphical representation of the individual station coordinate series any abnormal results are discernable. In addition, the scatter of the results as presented in a topocentric systems gives an impression of the repeatability of the coordinate series of a station rather than a baseline component representation. Since the separation between horizontal and vertical components is much easier than in a geocentric cartesian system an easier interpretation is permited.

It should be emphasized here that the significance of the station drift components are the more obvious the larger the annual drift. On the contrary stations with hardly any motion suffer from the fact that the results will arbitrarily scatter about an average position before the number of sessions is large enough to establish stability. Consequently the azimuth of the drift vector will take up arbitrary values when additional sessions are added but the magnitude will become smaller and smaller eventually.

From the session by session display of the horizontal coordinate results it is clear that the scatter in most cases will inhibit a suitable visual impression (e.g. Fig. 3). In order to give the display a higher degree of significance annual averages were calculated and plotted in the same fashion (e.g. Fig. 4). Especially in the years since 1993 when 6 sessions per year were observed the averages are a good representation of the respective station positions. On the other hand the averages of the earlier years are often computed from three or less sessions and thus lack the required stability. It should be noted again that from all series a constant drift component according to the NNR-Nuvel-1A model is subtracted already.

Since the least squares solution setup selected here relies on fixed coordinates of the station Wettzell and on an external series of Earth orientation parameters (EOP) the coordinate results of the individual session days are affected by the Earth orientation parameters. Although any uncertainties in the ERP series may create additional noise in the components of the coordinates the longterm trend of the station drifts should not be disturbed.

Figure 3 shows the individual coordinate results for the station of Noto as determined from the solution with the drift of Wettzell and the apriori EOP fixed. In the representation of the annual averages (Fig. 4) the visual impression becomes much clearer. It can be seen that the results of the earlier session which are those in the South lack the stability as seen in the later sessions.

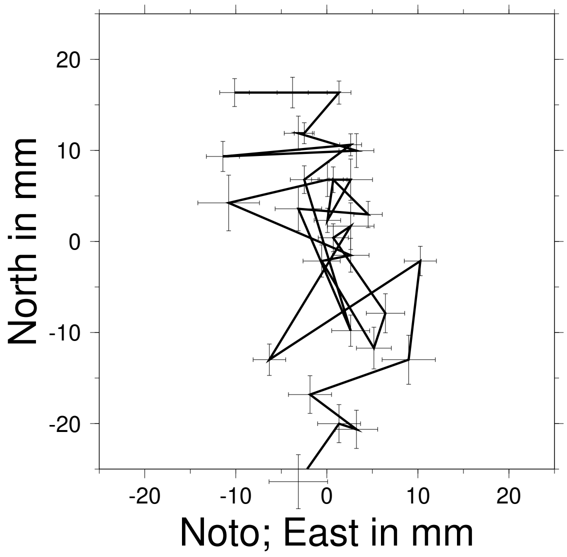

Fig. 3: Session by session results in the horizontal components with a constant part subtracted.

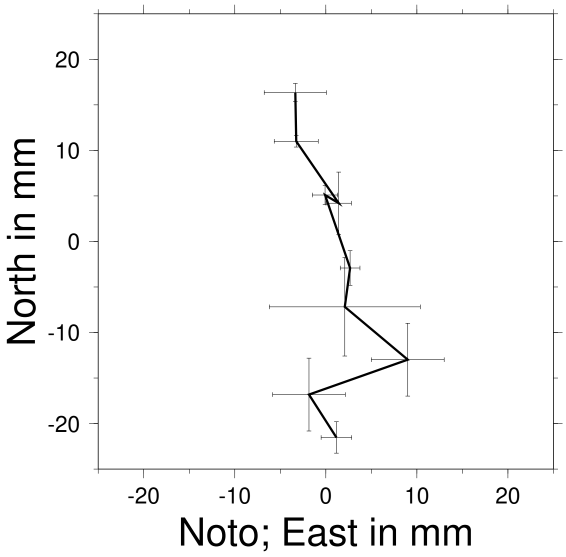

Fig. 4: Annual session averages in the horizontal components with a constant part subtracted.

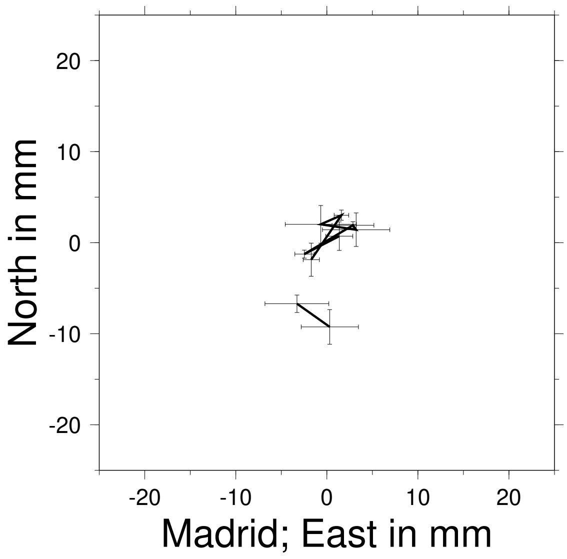

Fig. 5: Annual session averages in the horizontal components with results of the years 1997 and 1998 disconnected due to mechanical displacement of the VLBI reference point.

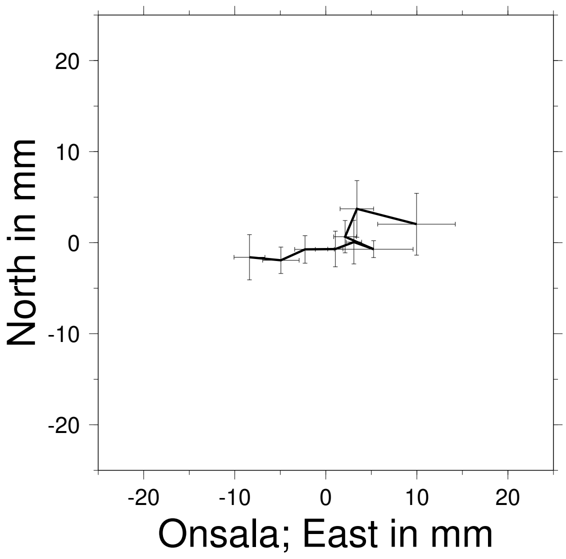

Fig. 6: Annual session averages in the horizontal components with a constant part subtracted.

In Figure 5 the annual averages of the Madrid horizontal components are displayed. The results of the years 1997 and 1998 are disconnected from the earlier years due to the fact that local modifications for track repairs have shifted the VLBI reference point to the South. The remaining series of points shows only very little scatter and no significant trend.

The evolution of the station coordinates of Onsala suggests a significant westward motion of the site (Fig. 6). However, this motion only stabilized in the years since 1993. If a displacement rate is computed with all the data a smaller magnitude can be expected than if only the data since 1993 would be used.

The graphical representation of the vertical components displays a much larger scatter than the horizontal components (e.g. Fig. 7) and thus significant vertical rate determinations will need a longer time base. The example of Matera in this figure represents the current situation at most of the European stations where the scatter of the individual results still inhibits a definite conclusion whether or not there is a significant height change.

Only Medicina (Fig. 8) already shows a significant subsidence, a fact which is supported by the information of heavy ground water extraction in the Po Valley. Unfortunately, the continuous series is interrupted by a telescope uplift due to necessary modifications of the antenna track as can be seen in figure 8. Even though there is this discontinuity in the series, the Medicina height results produce the least scatter in the network which is also obvious in the weighted RMS results (see table 1). The superior quality of these height results may in part be a consequence of the fact that Medicina has the shortest distance to Wettzell.

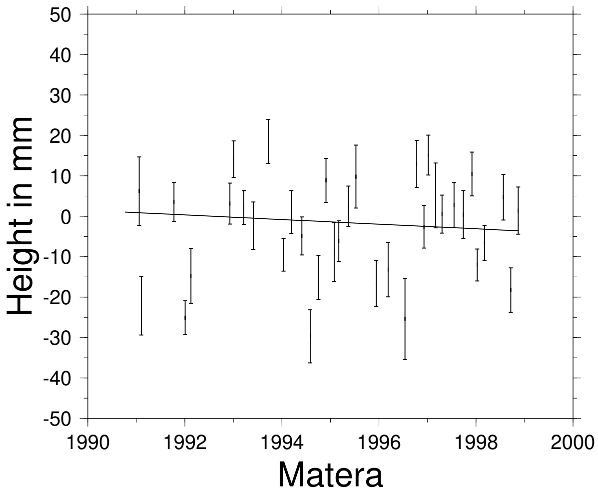

Fig. 7: Vertical components with a constant part subtracted.

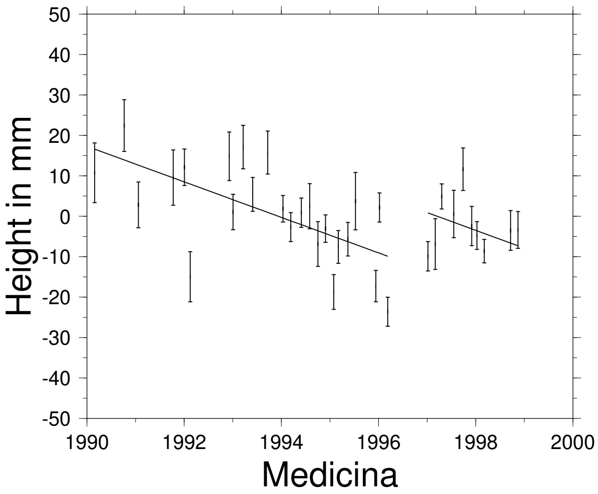

Fig. 8: Vertical components with a constant part subtracted.

Concerning the quoted formal errors of the results it should be emphasized that the inverse squared of the formal errors of the individual topocentric coordinate components were used as the weights for the linear regressions. Taking into account that the χ^2 per degree of freedom ranged between 4 and 6, the sigmas of the coordinate components are too optimistic by a factor of 2 to 3. However, the errors quoted for the annual rates are based on the scatter of the individual results of the series and thus represent the overall repeatabilty from session to session. They are, therefore, rather more realistic than those from batch vector solutions [see e.g. LANOTTE et al., 1999 this issue] where the large number of delay observables heavily affects the formal errors of all parameters.

5 Conclusions and Outlook

We developed an alternative two-step analysis strategy to derive station drift rates from the analysis of individual VLBI sessions. This method permits a visual inspection of the series of coordinate results and it reduces any cross-talk of station deficiencies in individual sessions with annual drift rates of 'healthy' stations. In order to end up with reliable drift vectors from time series, results from individual sessions for a single station may be selected for exclusion if obvious deficiencies suggest to do so. The advantage of this as compared to vector solutions is that deviations are made obvious and that not the whole session has to be discarded. The disadvantage of the method is that it has to rely on a single station whose coordinates and drift rate have to be fixed in the analysis. Any necessity for a new fixed station in sessions added to series, for example due to a failure of the initial reference station, would impose a shift onto the results of the other stations. Therefore, applications of this two-step method to the combination of different networks are not readily available. Only in confined series where one single site can be fixed for the majority of the sessions this method provides a good basis for scrutinizing the data on a station by station basis. Currently a method is being developed which permits the inclusion of additional sessions where the initial reference station is for any reason not part of the session. A further extension of the method would be the combination of different networks.

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