J Geod (2007) 81:469–478
DOI 10.1007/s00190-007-0146-0

ORIGINAL ARTICLE

The impact of radio source structure on European geodetic VLBI measurements

V. Tornatore · P. Charlot

Received: 1 April 2006 / Accepted: 8 February 2007 / Published online: 24 April 2007

Abstract European geodetic very long baseline interferometry (VLBI) sessions (also known as EUROPE sessions) have been carried out on a regular basis for the past 15 years to study relative crustal motions within Europe. These sessions are based on observations of extragalactic radio sources, which serve as distant fiducial marks to establish an accurate and stable celestial reference frame for long-term geodetic measurements. The radio sources, however, are not always point-like on milliarcsecond scales, as VLBI imaging has revealed. In this work, we quantify the magnitude of the expected effect of intrinsic source structure on geodetic bandwidth synthesis delay VLBI measurements for a subset of 14 sources regularly observed during the EUROPE sessions. These sources have been imaged at both X-band (8.4 GHz) and S-band (2.3 GHz) based on dedicated observations acquired with the European VLBI Network (EVN) in November 1996. The results of this calculation indicate that the reference source 0457+024 causes significant structural effects in measurements obtained on European VLBI baselines (about 10 picoseconds on average), whereas most of the other sources produce effects that are only occasionally larger than a few picoseconds. Applying the derived source structure models to the data of the EUROPE5-96 session carried out at the same epoch as the EVN experiment shows no noticeable changes in the estimated VLBI station locations.

Keywords Geodetic VLBI · Source structure · Extragalactic radio sources

V. Tornatore (✉)
DIIAR, Sez. Rilevamento, Politecnico di Milano,
P.za Leonardo da Vinci 32, 20133 Milano, Italy
e-mail: vincenza.tornatore@polimi.it

P. Charlot
Observatoire de Bordeaux (OASU),
Centre National de la Recherche Scientifique/UMR 5804,
BP 89, 33270 Floirac, France
e-mail: charlot@obs.u-bordeaux1.fr

1 Introduction

The European geodetic very long baseline interferometry (VLBI) network (also designated as the EUROPE network) has been operating in an area of geophysically interesting regions since 1990. The network configuration started with a core of six radio telescopes observing on a regular basis, with an average of six sessions per year. These telescopes are located in Wettzell (Germany), Onsala (Sweden), Matera, Medicina, and Noto (Italy), and near Madrid (Spain). In 1994, the network extended eastward with a telescope located in the Crimean peninsula (Simeiz) and northward with the Ny Alesund antenna in the Arctic archipelago of Spitsbergen (Norway). Once per year, the 100 m astronomical radio telescope at Effelsberg (Germany) also participates in the network. The Yebes telescope (80 km east of Madrid) took part in these experiments until 2004 (24 experiments in the period 1995–2004), while the mobile station of TIGO (at the Wettzell site) joined the network 12 times in the period 1997–2000.

The 24-h-long observing sessions are optimized for the determination of horizontal and vertical crustal motions within Europe (Campbell 1996). Initial baseline length estimates were presented by Campbell et al. (1993) and Ward (1994), based on data until 1991 and 1993, respectively. Later on, Campbell and Nothnagel (2000a) reported crustal motion results from data up to the late 1990s, while Haas et al. (2003) extended these results with data up to 2001. Several groups are now involved in the analysis of these campaigns, producing estimates for baseline length changes and relative station velocity vectors. The main trends of motion for the European sites are reproduced by analyses that use widely different data samples and strategies, as well as software. The most-frequently used software are CALC/SOLVE (Ma et al. 1990), OCCAM (Titov and Zarraoa 1997; Titov et al. 2004), and MODEST (Sovers and Jacobs 1996). Comparison of the results from the different groups were reported by Campbell and Nothnagel (2000b).

The accuracy of geodetic VLBI results has increased steadily in the past decade. The present objectives are 1 mm accuracy in baseline length estimates and ≤ 0.1 mas accuracy in the determination of radio source positions (Niell et al. 2006; Charlot 2004). The VLBI scientific community, within the framework of the International VLBI Service for Geodesy and Astrometry (IVS) (Schlüter et al. 2002), is planning several efforts and changes for the design of a new system that would provide enhanced performance (Niell et al. 2006). Different strategies are being considered to reduce both random and systematic errors (especially those caused by the unmodelled variations in the atmosphere) in the delay observable. These include increasing the number of antennas and improving their geographic distribution, developing new observing schemes to augment the observation density, and reducing susceptibility to external radio-frequency interference.

One of the unmodelled effects in the analysis of geodetic VLBI observations is that produced by the extended brightness distribution (or structure) of the extragalactic radio sources. As shown by Fey and Charlot (1997, 2000), this effect produces delay contributions that range from the picosecond (ps) level for the most compact sources to several nanoseconds for the most extended sources. Algorithms have been developed to model such effects based on the precise knowledge of the brightness distribution of the sources (Charlot 1990a; Zeppenfeld 1991). For this purpose, continuous monitoring of the source structures is required, as these are known to vary on time scales of months to years. The rate of change in the source positions caused by varying intrinsic structure was found to be occasionally larger than 0.1 mas/year (Charlot 1993; Takahashi and Kurihara 1993). More recently, a large-scale test with massive application of source maps to model the structural delays showed that the overall effect on intercontinental baselines amounts to 8 ps on the total noise, in an root sum of squares (RSS) sense (Sovers et al. 2002; Charlot 2002). This effect is significant by current standards, even though it is not predominant in the current VLBI error budget. As noted by Sovers et al. (2002), unmodelled tropospheric or instrumental effects appear to be still bigger by at least a factor of two.

The aim of the work presented here is to examine the effect of source structure on EUROPE-type geodetic experiments. Studying a single geodetic session by imaging all the sources observed during a typical such session is useful in an initial stage to gain insight into the overall magnitude of the structural effects, as it would not be worthwhile to engage into regular imaging of all sources for every EUROPE experiment (to account for their morphological variability with time) if such structural effects are not significant. To this end, we have imaged a sample of 14 sources observed during a EUROPE session in 1996, based on data acquired with the European VLBI Network (EVN) at an epoch immediately preceding that session. The remaining 24 sources observed in the EUROPE experiment will be imaged in a second stage using the EUROPE data themselves. Once source brightness distributions are known, it will be possible to estimate the structural effects in the geodetic VLBI bandwidth synthesis delay measurements for all sources and in the case that these are significant to determine whether their modelling may improve the accuracy of the baseline length and site position estimates from the EUROPE campaigns.

In Sect. 2, we describe the characteristics of the EVN observations designed to map the angular radio structures of the extragalactic reference sources, along with the specificities of the EUROPE session considered in the present study. Section 3 summarizes the EVN data processing and reports our imaging results. The method used for evaluating the magnitude of the effect of intrinsic source structure on geodetic bandwidth synthesis delay VLBI measurements is presented in Sect. 4, while Sect. 5 provides our estimates of the overall effect on European baselines for the 14 sources mapped with the EVN. The impact on the actual data acquired during the EUROPE session is discussed in Sect. 6. Summary conclusions and future developments are given in Sect. 7 with emphasis on the studies to be carried out once the imaging of all 38 sources observed in the EUROPE session is completed.

2 Characteristics of the EVN and EUROPE observations

The EUROPE experiment considered for this work was the EUROPE5-96 session (now designated as IVS-EURO33) carried out on 3 November 1996, during which a total of 38 radio sources was observed. A detailed examination of the astronomical literature was conducted prior to the session to obtain morphological information about these sources. For 24 of them, images at S- and X-bands were already available, while 14 others had never been imaged before when this project was initiated. A proposal was thus presented to map the latter with the EVN (Tornatore et al. 1999), while the remaining sources (with a good-quality image for at least one epoch) would be imaged based on the IVS-EURO33 data themselves. A special request was also made in order to schedule the EVN experiment at an epoch as close as possible to the date of the IVS-EURO33 session so that the morphological variability of the sources could be neglected.

The EVN observations were approved and carried out during a period of 10 h on 1 November 1996 (EVN project ET003A) and a period of 18 h on 2 November 1996 (project ET003B). The following EVN telescopes were used for these observations: Effelsberg, Onsala, Noto, Shanghai, Simeiz, and Urumqi, plus four antennas mostly devoted to geodetic VLBI observing, i.e. Madrid, Matera, Ny Alesund and Wettzell. The participation of Ny Alesund together with the Chinese antennas of Urumqi and Shanghai improves the resolution of this network to a value that is even higher than that of the very long baseline array (VLBA), which also regularly observes geodetic VLBI sources (Fey et al. 1996; Fey and Charlot 1997, 2000). The 14 target sources were each observed for a total of about 2 h, divided into ten 12-min-long scans at different hour angles. Fourteen intermediate frequencies (IFs), each 2 MHz wide, were recorded simultaneously, eight at X-band (from 8.372 to 8.388 GHz) and six at S-band (from 2.262 to 2.274 GHz). Such dual-band observations are necessary in order to map the brightness distribution of the sources and model the corresponding structural effects at the standard two frequency bands that are simultaneously observed in VLBI geodesy to calibrate the frequency-dependent propagation delay introduced by the Earth's ionosphere.

The IVS-EURO33 geodetic experiment started on 3 November 1996 at 1400 UT, only 1 h after the end of the EVN observations, and lasted 24 h. The telescopes that participated in this experiment were: Effelsberg, Madrid, Matera, Noto, Ny Alesund, Onsala, Wettzell and Yebes. The participation of Effelsberg was obtained through a special request to the Director of the Max Planck Institut für Radioastronomie (MPIfR) in Bonn in order to improve the sensitivity of the network. As noted above, 38 sources were observed during the IVS-EURO33 session. Scheduling was organized with 100–200s scans over a number of different hour angles to maximize local sky coverage. Upon our request, the IVS-EURO33 scheduler also included three 760s scans on the strong and compact sources 0552+398 and 0016+731, so that we could properly calibrate the VLBI amplitudes measured in this experiment and eventually image the 24 sources not observed as part of the EVN astronomical proposal. The results of this imaging will be reported in a subsequent paper.

3 EVN data processing and imaging results

The raw data bits acquired during the two EVN segments (ET003A and ET003B) were correlated with the MK-III correlator of the MPIfR in Bonn. Correlation results were satisfactory except that no fringes were found for Urumqi during ET003B and that half of the Effelsberg data were also lost in this segment. The correlated data were calibrated and corrected for residual delay and delay rate using the Astronomical Image Processing System (AIPS) (Bridle and Greisen 1994; Greisen 1998). The initial amplitude calibration for each of the 14 IFs (8 at X-band and 6 at S-band) was accomplished based on system temperature measurements taken during the observations and the gain curves of the antennas involved in the experiments. The gain curve of the Ny Alesund antenna, not available when the project was planned, was specifically determined with an ad hoc observing campaign (Tornatore 1998). Fringe fitting was done in AIPS using solution intervals equal to the scan duration and a point-source model in all cases.

After correction for residual delay and delay rate, the data were written to flexible image transport system (FITS) disk files for further processing. The visibility measurements for each band were then self-calibrated, Fourier-inverted and CLEANed in the standard way (Pearson and Readhead 1984) using again the AIPS software. Contour plots of the final VLBI images for the 14 sources observed in ET003A and ET003B are shown in Figs. 1 and 2 for X-band and S-band, respectively. Because of insufficient data, two sources (0457+024 and 1606+126) could not be imaged at S-band; hence only 12 maps are shown for this frequency-band in Fig. 2. The parameters of these images (peak brightness, contour levels, and root mean square (RMS) noise) are given in Table 1.

4 Source structure effect calculation

As shown by Charlot (1990a), the contribution of intrinsic source structure to a geodetic VLBI bandwidth synthesis delay measurement depends on the exact form of the spatial brightness distribution of the extended radio source relative to the geometry of the VLBI baseline vector projected onto the plane of the sky. The

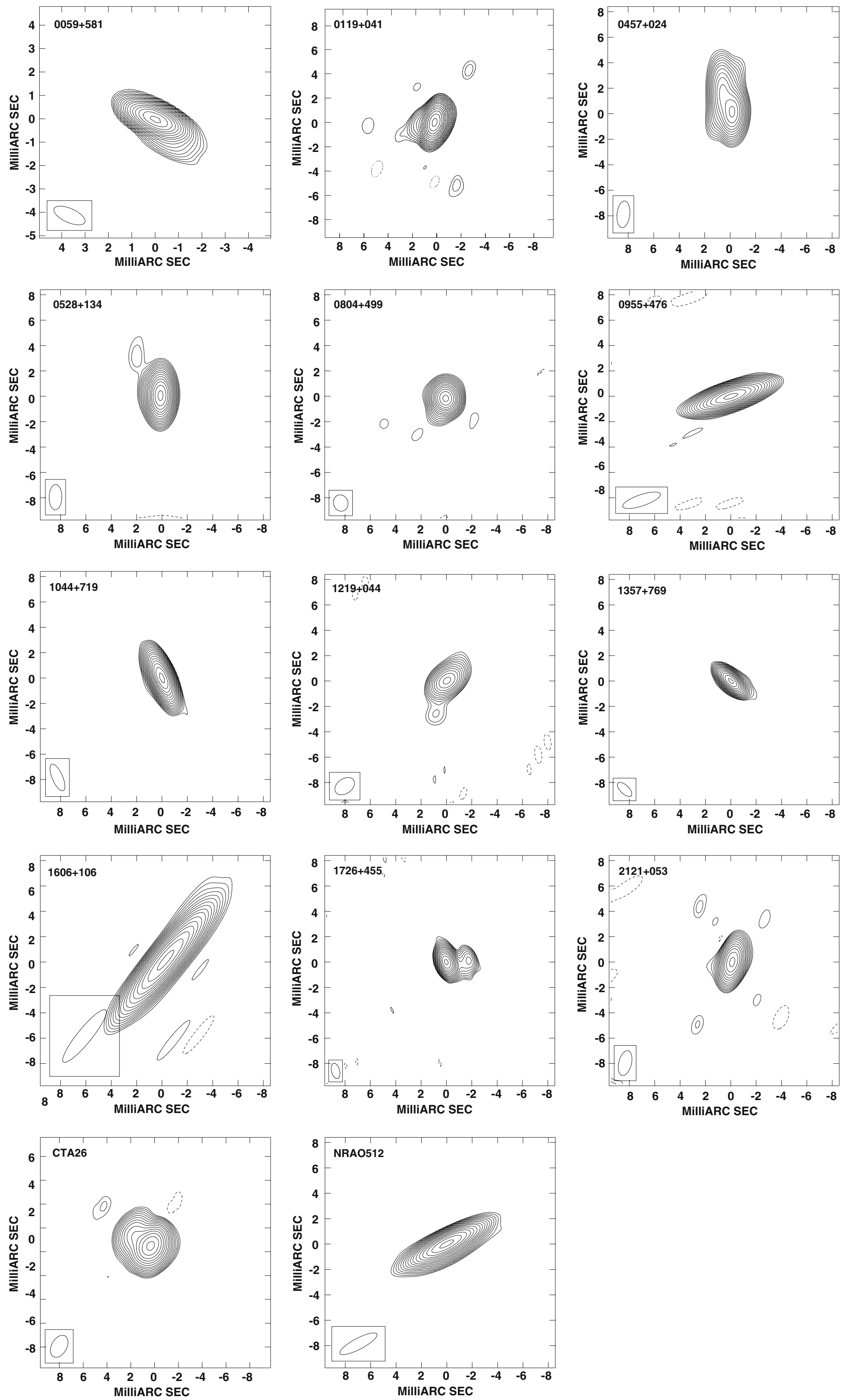

Fig. 1 Contour plots of 14 geodetic radio sources at X-band. Image parameters are listed in Table 1. The full width at half maximum (FWHM) Gaussian restoring beam applied to the images is shown as an ellipse in the lower left-hand corner of each panel

overall source structure effect magnitude for a given source is most easily estimated by calculating corrections to the bandwidth synthesis delay, based on the observed source structure, for a range of u, v coordinates (the coordinates u and v are the coordinates of the baseline vector projected onto the plane of the sky and

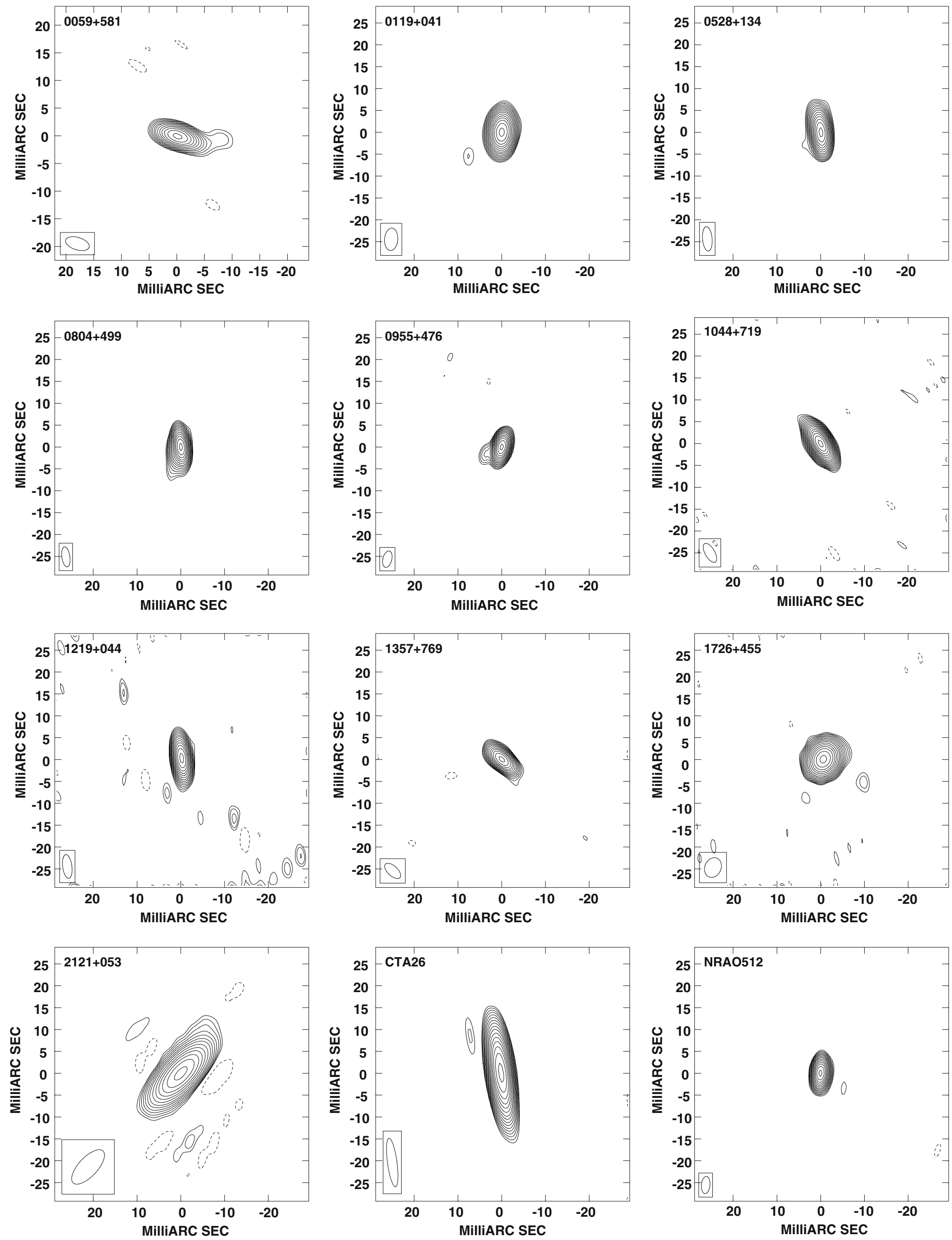

Fig. 2 Contour plots of 12 geodetic radio sources at S-band. Image parameters are listed in Table 1. The FWHM Gaussian restoring beam applied to the images is shown as an ellipse in the lower left-hand corner of each panel

are expressed in units of the observing wavelength). Following such a scheme, Fey and Charlot (1997) defined a source "structure index" according to the median value of the structure delay corrections, calculated for all projected VLBI baselines that could be possibly observed with Earth-based VLBI (i.e., for all baselines with $\sqrt{u^2 + v^2}$ less than the diameter of the Earth). This integer ranges from 1 to 4, and increasing values indicate increasing average structural VLBI delay effects, approximately on a logarithmic scale. As noted by Fey and Charlot (1997, 2000), the structure index correlates with the source position uncertainty and stability and hence is regarded as an appropriate indicator to estimate the astrometric quality of the sources for high-precision geodetic and astrometric VLBI applications.

A similar approach was adopted for the present study, but we limited our calculation to projected baselines shorter than the longest EUROPE baseline, i.e., with $\sqrt{u^2 + v^2} \leq 4780$ km (corresponding to the length of the Ny Alesund–Yebes baseline), in order to quantify the magnitude of such structure effects specifically for the EUROPE network. The structural delays were derived separately for X-band and S-band to determine the impact on the measurements obtained at each band. For consistency with the procedure used to calibrate the frequency-dependent propagation delay introduced

Table 1 Parameters of the X- and S-band images plotted in Figs. 1 and 2

Source	Band	Peak (Jy beam^{-1})	Lowest contour[a] (% of peak)	RMS[b] (mJy beam^{-1})
0059+581	X	1.83	0.35	1.13
	S	0.76	2.0	3.91
0119+041	X	0.93	0.5	1.76
	S	0.62	0.7	1.04
0457+024	X	0.49	1.0	1.07
0528+134	X	5.59	0.5	7.92
	S	1.57	1.0	3.14
0804+499	X	0.48	0.7	1.23
	S	0.54	1.0	2.23
0955+476	X	1.12	0.5	2.39
	S	0.73	1.0	2.16
1044+719	X	1.26	0.35	1.03
	S	1.04	0.35	1.35
1219+044	X	0.38	2.0	2.96
	S	0.31	1.0	1.40
1357+769	X	0.78	0.7	1.13
	S	0.44	1.4	2.11
1606+106	X	1.15	0.5	1.36
1726+455	X	0.49	0.7	1.17
	S	0.63	0.7	1.67
2121+053	X	0.43	1.0	1.76
	S	0.42	1.4	2.12
CTA26	X	0.87	0.7	1.70
	S	1.18	0.5	1.79
NRAO512	X	1.04	0.5	1.47
	S	0.58	1.0	1.70

[a] Successive contour levels are each a factor of the square root of two higher
[b] The RMS of the residuals of the final images

Table 2 Magnitude of the structural VLBI delays at X-band and S-band (in ps) for EUROPE-type baselines

Source	Band	τ_{mean} (ps)	τ_{RMS} (ps)	τ_{max} (ps)	τ_{median} (ps)
0059+581	X	0.5	0.6	1.4	0.5
	S	1.1	1.5	7.1	0.8
0119+041	X	2.2	3.0	11.0	1.6
	S	1.0	1.3	6.2	0.8
0457+024	X	13.9	21.6	112.3	9.1
0528+134	X	1.2	1.6	6.4	1.0
	S	1.7	2.2	9.0	1.4
0804+499	X	2.3	3.0	9.8	1.9
	S	1.2	1.5	4.7	0.9
0955+476	X	0.7	0.9	3.1	0.5
	S	0.7	0.8	2.9	0.6
1044+719	X	0.4	0.5	1.7	0.3
	S	0.4	0.6	2.0	0.4
1219+044	X	2.8	3.6	10.6	2.2
	S	5.7	8.2	40.7	3.7
1357+769	X	0.9	1.2	3.7	0.6
	S	1.3	1.7	6.4	1.0
1606+106	X	2.0	2.6	9.2	1.7
1726+455	X	3.6	4.6	11.1	2.3
	S	2.1	2.8	12.9	1.6
2121+053	X	3.6	4.8	18.4	2.7
	S	5.9	8.0	45.5	4.3
CTA26	X	10.6	13.8	58.4	8.1
	S	3.0	4.3	20.9	2.0
NRAO512	X	1.0	1.2	4.0	0.8
	S	1.0	1.3	5.4	0.7

by the Earth's ionosphere, the structural VLBI delays were scaled by 1.08 at X-band and 0.08 at S-band. These scale factors represent the relative contributions of the X-band and S-band delay measurements to the dual-frequency-calibrated VLBI delay, which is the quantity actually used for the determination of geodetic parameters. The interested reader is referred to Charlot (1990a) for a more thorough discussion of the algorithm developed to model source structure in the VLBI delay observable, and to Fey and Charlot (1997) for further details of the statistical approach adopted here to evaluate the magnitude of these structural effects.

5 Magnitude of the structural VLBI delays

Based on the approach presented in the previous section, we determined the mean, RMS, maximum and median values of the structural VLBI delays (absolute values) derived from all possible u, v coordinates (limited to EUROPE baseline lengths as discussed above) for each source. These values are reported in Table 2 for the 14 geodetic sources for which images were obtained in Figs. 1 and 2. As noted in Sect. 2, two of the sources in this sample (0457+024 and 1606+106) could not be imaged at S-band, hence our results are only available for 12 sources at this band. From Table 2, it is found that the median structural VLBI delays range from 0.3 to 9 ps at X-band and from 0.4 to 4 ps at S-band. The two sources that show the largest effects are 0457+024 (median structural delay of 9.1 ps at X-band) and CTA26 (median structural delay of 8.1 ps at X-band). For these two sources, the maximum X-band structure effects reach 112 and 58 ps, respectively, but such effects only occur in limited regions of the u, v plane or at the edge of it, as shown in Fig. 3. For the rest of the sources in Table 2, the structural VLBI delays are less significant with median values reaching 4 ps at most.

As an external test, we have compared our results with the structure indices derived by Fey and Charlot (1997, 2000). These indices, which indicate the overall astrometric quality of the sources, were found to be available for all but one source (2121+053). For 12 of these sources, the structure indices are either 1 or 2, an indication of excellent or good astrometric suitability for intercontinental VLBI networks according to the criterion of Fey and Charlot (1997). The source 0457+024, on the other hand, has a X-band structure index of 4, which

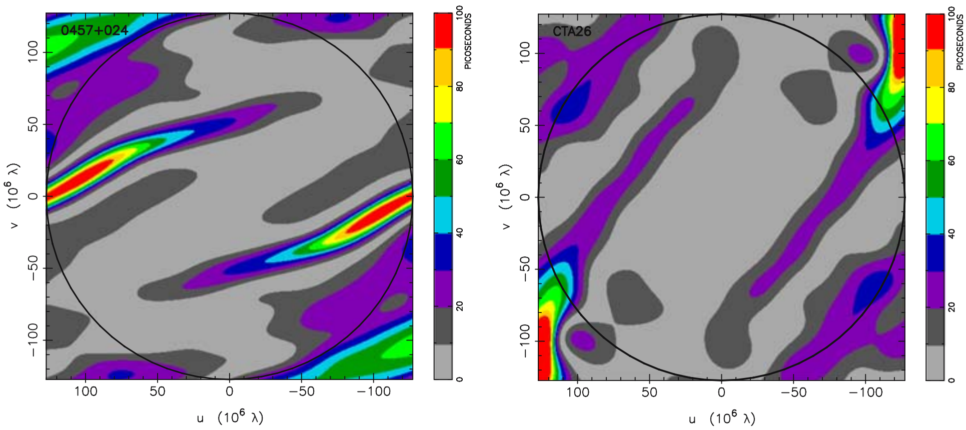

Fig. 3 Magnitude of the structural VLBI delays (absolute value) induced by the extended emission at X-band for the sources 0457+024 (*left panel*) and CTA26 (*right panel*). The structural delay is plotted as a function of the length and orientation of the VLBI baseline projected onto the sky, expressed in millions of wavelengths (u, v coordinates). The *circle drawn in each panel* has a radius of 4780 km, corresponding to the length of the Ny Alesund–Yebes baseline, the longest baseline in the EUROPE network. The mean, RMS, median and maximum values of the structural delays for all the baselines shorter or equal to that baseline (i.e., within the drawn circle) are given in Table 2

indicates very bad astrometric suitability. This structure index value is consistent with our finding of significant structural effects for this source even on the shorter European baselines (Table 2). The results for 0457+024 are also supported by the X-band image in Fig. 1 and that published by Fey and Charlot (2000), which both reveal a pronounced extension in the north-eastern direction.

6 Impact of source structure on EUROPE data

The calculation developed in the previous section provides statistics about the overall source structure effect magnitude for VLBI baselines that have lengths similar to those in the EUROPE network. However, it does not tell us about the effect in the actual data acquired by this network. For a more precise view, we also calculated the structural VLBI delays for all the observations in the IVS-EURO33 experiment that were obtained on either ones of the 14 sources with images in Figs. 1 and 2. The X-band and S-band structural VLBI delays derived from these maps were combined in the usual way to obtain the total source structure contribution for the dual-frequency calibrated VLBI delays. For the two sources that were not imaged at S-band (0457+024 and 1606+106), we assumed that the S-band contribution to the total structure delay is zero.

There was a total of 849 observations acquired on these 14 sources during the IVS-EURO33 experiment, with the number of observations per source ranging from only 3 (for 0457+024 and 1219+044) to 186 (for 0528+134). The distribution of the VLBI structural delays for all such observations is plotted in Fig. 4, while the mean, RMS, maximum and median of these are reported in Table 3. The histogram in Fig. 4 shows that 91% of the structural delays are smaller than 3 ps, while 8% are between 3 and 10 ps, with a portion of only 1% (corresponding to 7 observations) larger than 10 ps. The largest structural delay is for a measurement of 0457+024 on the Noto–Onsala baseline, which reaches 41 ps. The details for each individual source, also reported in Table 3, indicate that the actual structural delays are generally comparable to or smaller than the statistics derived over the entire u, v plane (Table 2). The source that produces the largest structural effects in

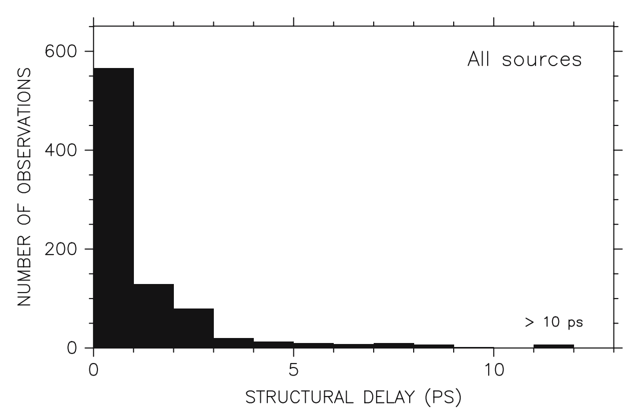

Fig. 4 Distribution of the combined S/X band structural delays for the 849 observations of the IVS-EURO33 experiment that were acquired on the 14 sources for which VLBI images are shown in Figs. 1 and 2. The largest VLBI structural delay in this data set is 41.1 ps. The median value of the structural delays for the 849 observations is 0.6 ps

Table 3 Magnitude of the S/X structural VLBI delays (in ps) for the data of the IVS-EURO33 experiment

Source	Nobs[a]	τ_{mean} (ps)	τ_{RMS} (ps)	τ_{max} (ps)	τ_{median} (ps)
0059+581	179	0.5	0.6	2.1	0.4
0119+041	30	1.1	1.6	4.2	0.6
0457+024	3	17.5	24.4	41.1	9.3
0528+134	186	0.9	1.2	3.8	0.6
0804+499	86	1.5	2.4	8.2	1.0
0955+476	6	0.4	0.4	0.8	0.3
1044+719	10	0.3	0.4	0.9	0.2
1219+044	3	1.9	2.5	4.1	0.8
1357+769	60	0.6	0.9	3.9	0.4
1606+106	50	1.5	2.3	6.8	0.9
1726+455	6	3.6	4.7	8.0	2.0
2121+053	15	0.9	1.2	2.4	0.7
CTA26	82	4.5	6.5	24.3	3.0
NRAO512	133	0.9	1.2	3.6	0.7
All sources	849	1.3	2.8	41.1	0.6

[a] Number of observations for each source

the IVS-EURO33 data (apart from 0457+024 for which only 3 observations were obtained) is CTA26. As shown in Fig. 5, there are 6 observations with structural delays larger than 10 ps for this source and the RMS of the corrections for the entire data set (82 observations) is 6.5 ps (Table 3). This finding is consistent with the statistical results of Table 2, which indicate that CTA26 is the second largest contributor to structural VLBI delay effects.

In order to estimate the possible impact of these corrections on the geodetic VLBI results, we have analysed the data from the IVS-EURO33 session by applying such corrections. The analysis was conducted with the MODEST software (Sovers and Jacobs 1996), which has the capability of modelling structural effects based on the algorithm developed by Charlot (1990a). The data were processed in the standard way, estimating clocks, troposphere and station locations, while source positions and Earth orientation parameters were held fixed. The results of this analysis show no significant differences in the estimated station coordinates (≤ 0.3 mm) when source structure is modeled. This finding is not surprising considering the sub-picosecond level of the structural VLBI delays for most of the sources (see Table 3). Imaging the remaining 24 sources observed in the IVS-EURO33 session is, however, still necessary before drawing a firm conclusion, since the present analysis modelled source structure for only about one-third of the observations in this session. As indicated above, we are planning to do this using the IVS-EURO33 data themselves; once it is done we will then resume with the present investigation.

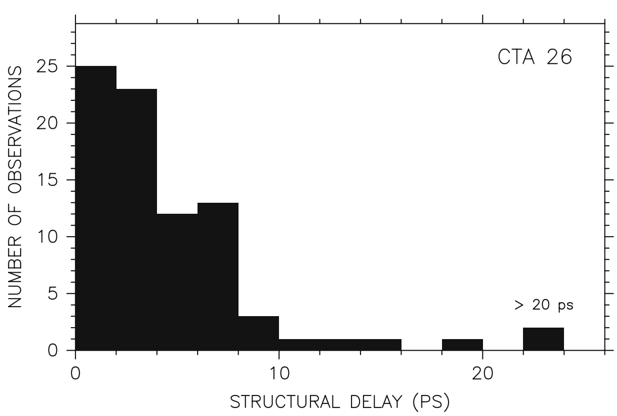

Fig. 5 Distribution of the combined S/X band structural delays for the 82 observations acquired on the source CTA 26 during the IVS-EURO33 experiment. The largest VLBI structural delay is 24.3 ps. The median value of the structural delays for the 82 observations is 3.0 ps

7 Conclusion and future developments

The goal of the work discussed in this paper was to evaluate the magnitude of radio source structure effects for baselines of the European geodetic VLBI network. To this aim, we mapped the brightness distribution of 14 sources regularly scheduled during such EUROPE sessions, using data from a dedicated EVN experiment, and calculated the corresponding structural effects for the geodetic bandwidth synthesis delay VLBI observable. The calculation was arranged in order to obtain statistics about the overall effect on European baselines for each source along with precise values of the structural VLBI delays for the measurements of the IVS-EURO33 session conducted in November 1996.

On the basis of the results obtained, we determined that the reference source 0457+024 causes significant structure effects (at the 10 ps level), both in a statistical sense (when considering all possible VLBI baselines limited in length to the size of the EUROPE network) and in the actual IVS-EURO33 data. We therefore recommend that this source be excluded from further EUROPE geodetic sessions and from all other IVS sessions as well, in agreement with the previous finding of Fey and Charlot (1997). The source CTA26 produces overall structure delays that are roughly at the same level, but calculation for the actual IVS-EURO33 measurements on this source indicates a contribution at the 3 ps level only, possibly because the coordinates of the EUROPE baselines fall into favorable regions of the u, v plane. Until further studies are developed, we recommend that CTA26 be scheduled with caution in the EUROPE campaigns. For the other 12 sources in our sample, the structural VLBI delays are at the picosecond level, i.e., below significance, in the IVS-EURO33 measurements.

Despite the apparent non-significance of the effect for most of the sources, we tentatively applied our structure models to the IVS-EURO33 data. This initial test shows no significant differences in the estimated geodetic parameters. We plan to repeat this test at a later stage when we have imaged the remaining 24 sources observed in that session, using the IVS-EURO33 data themselves. As shown by several authors (Charlot 1990b, 1993; Britzen et al. 1993), geodetic experiments can provide valuable images even though observing is conducted in snapshot mode. When we have these additional images in hand, we will have a complete view about the overall magnitude of the structural effects for the EUROPE network and therefore be able to determine whether their modelling is required to improve the accuracy of the geodetic determinations. Source structure evolution is also an important factor to consider as it may contribute structural effects that cannot be recovered from single-epoch maps as with the scheme described in the present study.

Finally, it should also be noted that the absence of significant structural effects for the EUROPE network does not imply that such effects are not significant for intercontinental networks that observe with longer VLBI baselines. For example, Sovers et al. (2002) showed that source structure produces detectable effects on the Research & Development VLBA sessions even though they do not predominate over tropospheric and instrumental errors. Similar studies for regular IVS networks such as those used in the weekly IVS-R1 and IVS-R4 sessions dedicated to monitoring the Earth's rotation would be necessary to supplement the present work.

Acknowledgments This research has been supported by the Training and Mobility of Researchers (TMR) Programme of the Commission of European Communities (CEC). The authors wish to thank the European VLBI Network (EVN), the Joint Institute for VLBI in Europe (JIVE), and the staff at the Bonn correlator and all the VLBI stations involved in these observations. We are also grateful to Antoine Bellanger for pre-processing the IVS-EURO33 data. The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes funded by their national research councils. The European geodetic VLBI network is now supported by the International VLBI Service for Geodesy and Astrometry (IVS).

References

Bridle AH, Greisen EW (1994) The NRAO AIPS Project: a summary. AIPS Memo 87, NRAO, Socorro, http://www.aoc.nrao.edu/aips/aipsmemo.html

Britzen S, Gontier A-M, Witzel A, Schalinski C, Campbell J (1993) Radio source structure and its influence on the accuracy of the geodetic VLBI analysis. In: Campbell J, Nothnagel A (eds) Proceedings of 9th working meeting on European VLBI for geodesy and astrometry, Bad Neuenhar. Mitteilungen aus den Geodätischen Instituten der Rheinischen Friedrich-Wilhelms-Universität Bonn (81), pp 157–170

Campbell J (1996) Measurements of vertical crustal motion in Europe by VLBI—further support of the European Geodetic VLBI Network by European Union. In: Elgered G (ed) Proceedings of 11th working meeting on European VLBI for geodesy and astrometry, Göteborg, pp 227–231

Campbell J, Nothnagel A (2000a) European VLBI for crustal dynamics. J Geodyn 30:321–326

Campbell J, Nothnagel A, (2000b) Comparison of European VLBI solutions from different analysis centers. In: Tomasi P, Mantovani F, Perez-Torres M (ed) Proceedings of 14th working meeting on European VLBI for geodesy and astrometry, Castel San Pietro Terme, pp 3–6

Campbell J, Hase H, Nothnagel A, Schuh H, Zarraoa N, Rius A, Sardon E, Tornatore V, Tomasi P (1993) First results of European crustal motion measurements with VLBI. Contrib Space Geod Geodyn Crustal Dyn AGU Geodyn Ser 23: 397–405

Charlot P (1990a) Radio-source structure in astrometric and geodetic very long baseline interferometry. AJ 99:1309–1326

Charlot P (1990b) Fourteen extragalactic radio sources mapped at 2.3 and 8.4 GHz with a 24-hour Crustal Dynamics Program VLBI experiment, A&A 229:51–63

Charlot P (1993) Evidence for source structure effects caused by the Quasar 3C273 in geodetic VLBI Data. In: Campbell J, Nothnagel A (eds) Proceedings of 9th working meeting on European VLBI for geodesy and astrometry, Bad Neuenhar, Mitteilungen aus den Geodätischen Instituten der Rheinischen Friedrich-Wilhelms-Universität Bonn (81) pp 171–178

Charlot P (2002) Modeling radio source structure for improved VLBI data analysis. In: Vandenberg NR and Baver KD (eds) Proceedings of International VLBI service for geodesy and astrometry 2002 general meeting, Tsukuba, NASA/CP-2002-210002, pp 233–242

Charlot P (2004) The ICRF: 2010 and beyond. In: Vandenberg NR, Baver KD (eds) Proceedings of international VLBI service for geodesy and astrometry 2004 general meeting, Ottawa, NASA/CP-2004-212255, pp 12–21

Fey AL, Charlot P (1997) VLBA Observations of radio reference frame sources. II. Astrometric suitability based on observed structure. ApJS 111:95–142

Fey AL, Charlot P (2000) VLBA observations of radio reference frame sources. III. Astrometric suitability of an additional 225 sources. ApJS 128:17–83

Fey AL, Clegg AW, Fomalont EB (1996) VLBA Observations of radio reference frame sources. I. ApJS 105:299–330

Greisen EW (1998) The creation of AIPS, AIPS Memo 100, NRAO, Socorro, http://www.aoc.nrao.edu/aips/aipsmemo.html

Haas R, Nothnagel A, Campbell J, Gueguen E (2003) Recent crustal movements observed with the European VLBI network: geodetic analysis and results. J Geodyn 35:391–414

Ma C, Sauber JM, Bell LJ, Clark TA, Gordon D, Himwich WE, Ryan JW (1990) Measurement of horizontal motions in Alaska using very long baseline interferometry. JGR 95:21991–22011

Niell A, Whitney A, Petrachenko B, Schlüter W, Vandenberg N, Hase H, Koyama Y, Ma C, Schuh H, Tuccari G (2006) VLBI2010: current and future requirements for geodetic VLBI Systems. In: Behrend D, Baver K (eds) International VLBI service for geodesy and astrometry 2005 annual report, NASA/TP-2006-214136, pp 13–40

Pearson TJ, Readhead ACS (1984) Image Formation by Self-Calibration in Radio Astronomy. Ann Rev Astron Astrophys 22:97–130

Schlüter W, Himwich E, Nothnagel A, Vandenberg N, Whitney A (2002) IVS and its important role in the maintenance of the global reference systems. Adv Space Res 30:145–150

Sovers OJ, Jacobs CS (1996) Observation model and parameter partials for the JPL VLBI parameter estimation software "MODEST"–1996, JPL Publication 83-39, Rev. 6, August 1996

Sovers OJ, Charlot P, Fey AL, Gordon D (2002) Structure corrections in modeling VLBI delays for RDV data. In: Vandenberg NR, Baver KD (eds) Proceedings of International VLBI service for geodesy and astrometry 2002 general meeting, Tsukuba, NASA/CP-2002-210002, pp 243–247

Takahashi Y, Kurihara N (1993) Continuous changes in the positions and flux densities of quasars observed in CDP VLBI experiments during 1984–1988. PASJ 45:497–504

Titov O, Zarraoa N (1997) OCCAM 3.4 User's Guide. Communication of the IAA, Saint Petersburg, No 69

Titov O, Tesmer V, Boehm J (2004) OCCAM v.6.0 software for VLBI data analysis. In: Vandenberg NR, Baver KD (eds) Proceedings of international VLBI service for geodesy and astrometry 2004 general meeting, Ottawa, NASA/CP-2004-212255, pp 267–271

Tornatore V (1998) The role of extragalactic radio source structure for improved reference frames and global change. In: Casacchia et al. (eds) Proceedings of 4th Ny-Alesund Seminar, Ravello, pp 107–111

Tornatore V, Stanghellini C, Britzen S (1999) Status report of the project 'EVN observations of radio sources used for geodetic EUROPE experiments'. In: Proceedings of 13th working meeting on European VLBI for geodesy and astrometry, Bundesamt für Kartographie und Geodäsie, Viechtach/Wettzell, pp 226–232

Ward SN (1994) Constraints on the seismotectonics of the central Mediterranean from very long baseline interferometry. Geophys J Int 117:441–452

Zeppenfeld G (1991) Source structure enhanced MKIII Data Analysis Software. In: Proceedings of 8th working meeting on European VLBI for geodesy and astrometry, Dwingeloo, pp IV-16–IV-21