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Improved Positions of Non-Geodetic EVN Telescopes

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Abstract. The European VLBI Network (EVN) has conducted a dedicated non-standard 5 GHz geodetic VLBI experiment in November 2000 with the goal of improving the positions of the Torun, Westerbork (single dish) and Jodrell Bank Mk2 telescopes. The geodetic coordinates of these telescopes were previously known to a few meters only, which is not sufficient for proper reduction of VLBI observations conducted in phase-referencing mode. The experiment design and data analysis are discussed with special emphasis on the effects of the ionosphere, the dominating error source in such single-frequency observations. Based on various statistical tests, we estimate that the newly-derived telescope positions are accurate to about 5 cm. Additionally, improved geodetic coordinates of the phased-array at Westerbork, the Lovell telescope in Jodrell Bank and Cambridge antenna were obtained using locally-derived ties. Overall, these new EVN telescope positions dramatically improve phase-referencing results.

1. Introduction

The European VLBI Network (EVN) is an array of radio telescopes spread throughout Europe and Asia, which conducts VLBI observations of radio sources, generally for astrophysical purposes. Some of these telescopes also participate regularly in dual-frequency (S- and X-band) geodetic campaigns (Campbell & Nothnagel 2000), and thus have highly-accurate geodetic positions. By contrast, some other EVN telescopes, not equipped with S/X radio receivers, have poorly known positions because they have never participated in such campaigns. The major telescopes in the latter category are located at Jodrell Bank (United Kingdom), Torun (Poland) and Westerbork (Netherlands).

Inaccuracy in the terrestrial coordinates of the above antennas has been a major limitation for EVN observations with the phase-referencing technique. This technique, now commonly used for imaging weak radio sources, alternates observations between a target source and a nearby calibrator, and requires accurate knowledge of the VLBI geometrical model to be successful (Beasley & Conway 1995). To overcome this situation, a dedicated geodetic VLBI experiment was carried out by the EVN in November 2000, with the aim of improving those poorly known telescope positions. The following sections present the design of this non-standard geodetic experiment, the data analysis scheme, and the results of these observations. The accuracy of the new estimated telescope positions is discussed in Section 5.

2. Experiment design and observations

Observations were carried out during a 24-hour period starting at 9:30 UT on November 23, 2000, with a network consisting of four geodetic telescopes (Effelsberg, Medicina, Noto, Shanghai) and five non-geodetic telescopes located at Cambridge, Jodrell Bank, Onsala, Torun, and Westerbork. An additional geodetic antenna (Urumqi) was scheduled but could not observe because of technical problems. At Jodrell Bank, the Mk2 telescope was used, while at Onsala, the 25 m antenna (On-85) was employed. The option of observing with a single telescope (antenna 7) at Westerbork was preferred to using the phased-array as this avoids any possible errors in fringe rotation and delay hardware and software, and so gives an unambiguous telescope position.

Unlike standard dual-frequency geodetic observations, this experiment was carried out at the single frequency of 5 GHz, the highest frequency available at all observing telescopes. A specific bandwidth synthesis scheme recording 8 frequency channels, each 8 MHz-wide, spread over 108 MHz was designed for this experiment. This bandwidth was chosen based on the common frequency range between telescope receivers which was about 120 MHz. The individual channel frequencies were 4906.99, 4909.99, 4918.99, 4936.99, 4969.99, 4993.99, 5008.99 and 5014.99 MHz. Data from the MERLIN telescope at Cambridge were recorded at Jodrell Bank via a 200-km 28-MHz microwave link and thus had only a limited bandwidth. Due to this mode of transmission, path length variations between Cambridge and Jodrell Bank could not be measured and removed from the VLBI data in the standard automatic way.

Scheduling was carried out with the NASA SKED program in order to optimize the sky coverage at each telescope as in standard geodetic experiments. A total of 20 strong sources selected from the International Celestial Reference frame (ICRF) catalog (Ma et al. 1998), well spread in right ascension and between $-25°$ and $80°$ declination, was observed for this purpose with generally 5 to 15 scans on each of them. Integration times ranged from 1 to 6 min and were set to obtain signal to noise ratios larger than 100. Low elevation observations ($< 10°$) were avoided to limit systematic errors caused by the ionosphere.

3. Data analysis and modeling

The raw data bits were correlated with the Mark IV data processor in Bonn, Germany, and exported through a geodetic data base file. Further analysis of the bandwidth synthesis delay and delay rate was conducted with the MODEST software (Sovers & Jacobs 1996) after converting the data into ASCII format. The overall analysis strategy aimed at fixing all "known" parameters of the VLBI model to limit possible biases and systematic errors caused by improper knowledge of the ionosphere, which is the dominant error at this relatively low observing frequency.

Following this scheme, the coordinates of all extragalactic sources were held fixed at their ICRF values. Similarly, the coordinates of the geodetic telescopes were held fixed at their values in the International Terrestrial Reference Frame, namely the ITRF2000[1]. The coordinates of the non-geodetic antenna On-85 were derived from those of the nearby geodetic antenna On-60 using a local tie measured with X-band VLBI in the early 1980's (Lundqvist 1982) and were also held fixed. The Earth orientation parameters were adopted from the IERS combined series C04[2], which is consistent at the subcentimeter level with the above terrestrial and celestial reference frames. In all, only clocks (using a time-linear model with breaks when needed), tropospheric zenith delays (see below), and the coordinates of the non-geodetic telescopes (except On-85) were estimated.

The troposphere was modeled using the Niell mapping function (Niell 1996), estimating one zenith tropospheric delay per station for the whole 24-hour period with a priori values derived from meteorological measurements. This scheme differs from that used in standard geodetic experiments where new zenith tropospheric delays are estimated at much shorter time intervals, but was preferred for this specific dataset to limit the number of estimated parameters. The ionosphere was modeled using the Parameterized Ionospheric Model (PIM), which is a theoretical model of ionospheric climatology developed at USAF Phillips Laboratory (Daniell et al. 1995) and freely available. This model determines the electron density at a given point of the ionosphere (defined by latitude, longitude and height) as a function of local time, latitude, season, solar activity, geomagnetic activity, and interplanetary magnetic-field direction. Integration along a given direction then provides the total electron content (TEC), which serves as the basis to calculate the ionospheric delay. For our analysis, ionospheric delays were determined directly along the lines of sight between the stations/observed sources using a specific version of PIM developed for application to VLBI astrometry (Campbell 1999), and added afterwards to the ionospheric-free VLBI model implemented in MODEST. Examination of the vertical TEC distribution at various times during the experiment revealed that the ionosphere was relatively stable over Europe on that day, but was significantly disturbed over the eastern part of China where the Shanghai telescope is located.

4. New telescope positions

Based on the above analysis and modeling, the post-fit rms residuals were 292 ps for delay with a χ^2 per degree of freedom of 1.03, and 230 fs/s for delay rate with a χ^2 per degree of freedom of 1.05. The data from two telescopes, Shanghai and Cambridge, have not been used in the analysis. All baselines to Shanghai showed larger residuals, most probably caused by ionospheric disturbances improperly modeled by PIM (see above). It was also decided to discard the observations from Cambridge because this telescope had usable data in only one frequency channel. This was, however, not a major inconvenience for the project, since the coordinates of Cambridge could be derived from those of Jodrell Bank by using MERLIN estimates of the Cambridge-Jodrell Bank baseline (see below). Overall, the residuals show a statistically-significant increase with baseline length, which is expected if the ionosphere is the dominating error in the model. For short baselines, mismodeling is attenuated because ionospheric variations are correlated at nearby stations and partially cancel out when calculating the differential delay contribution.

The estimated geodetic positions of Jodrell Bank, Torun, and Westerbork derived from this analysis, are

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[1] ITRF2000 coordinates are available at http://lareg.ensg.ign.fr/ITRF/

[2] IERS combined Earth orientation parameters are available at http://hpiers.obspm.fr/eop-pc/

Table 1. ITRF2000 coordinates (epoch 1997.0) and shifts to original values for the four non-geodetic EVN telescopes that participated in the observations.

EVN Observatory	Telescope	X (m)	Y (m)	Z (m)
Jodrell Bank	Mk2	3822846.76 ± 0.02	-153802.28 ± 0.01	5086285.90 ± 0.02
		4.10 ± 0.02	-2.15 ± 0.01	-1.32 ± 0.02
Torun	32 m dish	3638558.51 ± 0.02	1221969.72 ± 0.01	5077036.76 ± 0.03
		0.51 ± 0.02	2.72 ± 0.01	-4.24 ± 0.03
Westerbork	Antenna 7	3828651.29 ± 0.02	443447.48 ± 0.01	5064921.57 ± 0.02
		4.11 ± 0.02	-2.54 ± 0.01	-1.51 ± 0.02
Onsala	On-85	3370966.126 –	711465.954 –	5349664.023 –
		-2.055 –	1.037 –	-0.090 –

Table 2. ITRF2000 coordinates and shifts to original values for three other non-geodetic EVN telescopes, as derived from local ties.

EVN Observatory	Telescope	X (m)	Y (m)	Z (m)
Cambridge	Cambridge	3920356.15	2542.02	5014284.42
		1.35	-3.68	-0.58
Jodrell Bank	Lovell	3822626.04	-154105.65	5086486.04
		-0.46	-0.06	-0.22
Westerbork	Phased-array	3828445.66	445223.60	5064921.57
		5.02	-2.43	-1.51

given in Table 1 together with the shifts to the original coordinates (as previously available from the station catalog of the SCHED scheduling software). These shifts are listed for each telescope on the line immediately following its estimated coordinates. For completeness, the coordinates and shifts of the non-geodetic antenna On-85 are also listed, although these were not estimated in the analysis (see above). One notes that the corrections to the original coordinates of the four telescopes are as large as several meters. Uncertainties in the individual coordinates (one-sigma error derived from the least-squares fit) range from 1 to 3 cm, which is relatively small for such single-frequency observations. To determine whether these are realistic, alternate analyses estimating "known" parameters have been carried out, as described in the next section.

Additionally, geodetic positions of three other EVN telescopes have been obtained via locally-derived ties. The position of the Westerbork phased-array was derived from the single-dish position (antenna 7) through tracing the effects of the fringe-stopping algorithm, with a resulting tie measured at the millimeter level. Coordinates of the Lovell telescope at Jodrell Bank were derived from those of the Mk2 telescope, located a few hundred meters away, based on 500 MHz interferometric measurements conducted in the mid-1980's. Coordinates of the Cambridge antenna, 200 km away from Jodrell Bank, could be derived from those of the Mk2 telescope by using estimates of the Cambridge-Jodrell Bank baseline, measured from MERLIN observations of source pairs. The new positions for these three telescopes are given in Table 2 along with the corrections to the original coordinates. As before, these corrections are up to several meters, with the exception of those for the Lovell telescope which are only up to 0.5 m.

Table 3. Estimated corrections to ITRF2000 coordinates of EVN telescopes at geodetic sites.

Telescope	ΔX (m)	ΔY (m)	ΔZ (m)
Effelsberg	0.00 ± 0.02	0.00 ± 0.01	-0.01 ± 0.03
Medicina	-0.02 ± 0.03	0.01 ± 0.01	0.03 ± 0.03
Noto	-0.01 ± 0.03	0.00 ± 0.01	-0.02 ± 0.02
On-85	0.00 ± 0.02	-0.01 ± 0.01	-0.03 ± 0.03

5. Assessment of accuracy

Validation of our analysis and results was first considered by estimating the coordinates of the geodetic telescopes. For this purpose, four alternate analyses, each estimating in turn the coordinates of one of the geodetic telescopes (including On-85) in addition to those of the non-geodetic telescopes, have been carried out. Results are given in Table 3 in terms of corrections to ITRF2000 coordinates. Since these coordinates are known to subcentimeter accuracy, any significant correction would have to be attributed to deficiencies of our analysis. Table 3 shows that this is not the case since all estimated corrections are within one-sigma error. This is an indication that our derived uncertainties, although relatively small, are probably realistic.

An additional test consisted in estimating the telescope axis offsets. Again, these should be known to centimeter

Table 4. Antenna types, a priori axis offsets and estimated corrections.

Telescope	Antenna type	Axis offset (m)	Correction (m)
Effelsberg	AZEL	0.00	0.01 ± 0.02
Jodrell Bank	AZEL	0.458	-0.19 ± 0.06
Medicina	AZEL	1.83	-0.01 ± 0.03
Noto	AZEL	1.83	0.00 ± 0.02
On-85	EQU	2.15	0.01 ± 0.01
Torun	AZEL	0.00	-0.02 ± 0.06
Westerbork	EQU	4.95	0.02 ± 0.02

AZEL = azimuth-elevation mount, EQU = equatorial mount

accuracy and no significant deviations should be found. For this test, a single analysis estimating the axis offsets of all telescopes together with the coordinates of the non-geodetic telescopes, was performed. The axis offset corrections derived from this analysis are given in Table 4, also including antenna types and a priori values for completeness. The results in Table 4 show that the estimated corrections are not significant for six of the telescopes, confirming the previous indication that parameter uncertainties derived from our analysis appears to be realistic. For Jodrell Bank, however, a correction significant at the 3-sigma level (-0.19 ± 0.06 m) is found. It is not yet understood whether this correction might be real or whether it is an artefact from our data. When estimating this parameter, the X and Z coordinates of Jodrell Bank shift by 15 to 20 cm, which is larger than the uncertainties given in Table 1. These coordinates and those tied to them (for the Lovell and Cambridge telescopes) are thus subject to caution (at such a level of accuracy) until the origin of the axis offset correction is understood.

Finally, a qualitative evaluation of our results was accomplished by comparing phase-referenced maps made with the original and newly-derived telescope coordinates. For this comparison, we used data from a 6-cm phase-reference test experiment consisting of 1-hour of interleaved observations on the close pair 3C345/J1635+380 (separation of 2.25°). As expected, the newly-derived positions produced a considerable improvement in reducing the off-source noise and focusing the flux into the source for the resulting phase-referenced map of J1635+380[3]. This decisive test validates definitively our estimated telescope positions, and alternately demonstrates that phase-referencing can only be successful if an accurate geometrical VLBI model is available.

6. Conclusion

Based on a non-standard 5 GHz geodetic experiment conducted in November 2000, improved coordinates of three non-geodetic EVN telescopes have been obtained. These newly-derived positions are accurate to about 5 cm, a factor of 100 improvement over previous values. Such improved coordinates, and those of three other EVN telescopes derived from these via local ties, will be largely of benefit to VLBI observations with the EVN, especially those conducted with the phase-referencing technique. The new telescope positions have been made available to the EVN users and VLBI correlators that regularly process data from EVN telescopes. Further investigation will continue, in particular to determine the as-yet-unidentified origin of the Jodrell Bank axis offset correction, but also more generally to evaluate the influence of the ionosphere, troposphere and clock modeling on these results.

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[3] See complete information about this test, including the corresponding phase-referenced maps of J1635+380, at http://www.evlbi.org/user_guide/stapos.html. A recipe for incorporating station coordinate improvements into AIPS analysis of already-correlated data is also available at this address.