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

Operational Issues of the Improved EVN Station Positions

R. M. Campbell*

Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, the Netherlands,

Abstract. Over the past year or so, significant improvements have been made in the position determinations of some EVN antennas. Incorporation of these improvements has provided commensurate improvements in phase-referencing results for some experiments. We will take time in the Users' Meeting to review the effect of these improvements and resources that allow you to incorporate them into your data.

1. Introduction

During the User's Meeting, I will make a brief presentation reviewing various operational considerations arising from the recent improvements in the position determination of several EVN antennas, as described in Charlot et al. (2001, these proceedings). Much of this information has already been promulgated through a variety of media: e-mail via the `evntech` exploder, the Users' Guide portion of the EVN web-page (`http://www.evlbi.org/user_guide/stapos.html`), and direct contact with affected PIs. We are taking the opportunity afforded by the Users' Meeting at the EVN Symposium to continue our efforts to ensure as broad a segment as possible of EVN users is aware of these improvements.

I will review the chronology of station-position and related improvements, show examples of the effects on phase-referencing tests and NME observations, and list the resources available to incorporate these improvements into your data, including tools that allow you to judge whether they are indeed important for your experiment(s). This written contribution will also dispense with some of the mathematical details and general comments, freeing more time in the Users' Meeting for practical matters.

2. EVN Station Position Improvements

During the Users' Meeting at the previous EVN Symposium in Göteborg, I mentioned that initial results of the phase-reference test experiment (FR005) suggested that the SCHED position for non-geodetic EVN antennas could be off by meters. Subsequent analysis of rate residuals from the 12-hr NME C00C1 confirmed this. Therefore, a dedicated geodetic experiment (TP001) was performed, providing positions in ITRF2000, epoch 1997.0, accurate to ∼5 cm (Charlot et al. 2001, these proceedings). It also highlighted that SCHED did not have the proper axis offset for a couple stations. The position offsets were indeed in the 1–5 m range. The non-geodetic antennas participating in TP001 were Jb_2, On_{85}, Tr, and Wb_7; positions of other nearby antennas were determined from the TP001 results via local control (*i.e.,* Jb_1 and Cm determined relative to Jb_2, and Wb_{arr} determined relative to Wb_7). Independently, Dave Graham determined improved positions for Mh and Ar.

Further, the JIVE correlator also began to include the effects of plate motion from the reference epoch in SCHED (typically 1997.0) to the observation epoch, using the NNR-NUVEL-1A model where no empirical station velocities exist.

These results have been communicated to the other (astronomical) correlators, and they should be reflected in the next release of SCHED. Correlations at JIVE automatically use the most recent antenna positions and axis offsets, so PI scheduling with older versions of SCHED will pose no problems in this regard. However, all of the above improvements were not incorporated simultaneously into the correlator model used at JIVE. Therefore, depending on when your experiment was correlated, it could have had some intermediate state of the full set of position corrections applied. The following section discusses the possible complications arising from this. Section 5 touches on some other correlator-model issues.

There was an unrelated effect from Wb, isolated during the determination of the Wb_7–Wb_{arr} offset, that can also affect phase-referencing experiments. Between the third session of 2000 and 11 February 2002, there could be phase jumps between "mosaics" (blocks of typically several hours of observation). These jumps should be detectable in the $\phi(t)$ for the reference source (assuming it has low enough residual phase-rate). Phase-referencing across any such phase jump would affect only the target-source scan between the reference-source scans on either side of the phase jump, which should be a rather small fraction of the data. Tony Foley described this effect in e-mail to `evntech` on 11 February 2002, and can be contacted for specific mosaic start/stop times per experiment.

The phase-reference test experiment FR005 was re-analyzed with the improved station positions and axis offsets. The "Updated Station Position" page under the EVN Users' Guide web-page has a description of this re-analysis, along with plots showing the improvements achieved in phase-referenced $\phi(t)$ and the phase-referenced

* The author acknowledges partial support from the EC ICN RadioNET (Contract No. HPRI-CT-1999-40003).

maps themselves. The improvement between the initial and final Wb_7–Wb_{arr} offset determinations was tested in the NME N01C3, which also has a plot there.

3. Resources for the PI

For people analyzing their data in AIPS, the task `CLCOR` provides the ability to incorporate the station position and axis-offset improvements into their data. The principle of `CLCOR` is simple: enter the difference between the actual position or axis-offset and the value used in the correlation (AIPS' use of a left-handed reference frame adds a minor complication). Subsequent iterations of corrections can be made, and the net corrections accumulate. There is a newer version of `CLCOR`, dating from June 2001, whose use is strongly recommended. It reflects any station position changes you make directly in the AN table, thus providing a ready internal record of cumulative corrections already made.

The "Updated Station Position" page under the EVN Users' Guide has a recipe for incorporating the station-position improvements into your data (`http://www.evlbi.org/user_guide/recipe.html` directly). This recipe provide the mechanics for using `CLCOR`, plus tables of pre- and post-corrected positions as well as the corrections to input into `CLCOR`, ignoring plate motion. The numbers there are given directly in a left-handed frame as expected by default in AIPS.

The inclusion of plate-motion effects adds an observation-epoch dependence to the full station-position correction required for already correlated experiments. To keep the web-based recipe relatively uncomplicated, plate-motion effects were not explicitly treated there. (The net absolute plate motions over 5 yr to 2002.0 for EVN stations range from 11.3–19.3 cm.) Rather, we sent separate e-mail in the beginning of May 2002 to the individual PIs of all phase-referencing experiments ever correlated at JIVE. The principal component of this e-mail was a table listing, for each station in the experiment:

- the position at the reference epoch,
- the cumulative plate motion to the observation epoch,
- the net position at the observation epoch,
- the correlated position, and
- the specific values to input into `CLCOR`,

together with any necessary axis-offset corrections. If you did not get such e-mail and/or would like such information for your JIVE-correlated experiment, let me know. If your experiment was correlated elsewhere, also get in touch with me. The next section will discuss whether you really need to worry about these corrections for your specific experimental goals.

4. Judging the Importance

The fundamental starting place is the interferometer phase expressed in terms of baseline components; see, for example, equation (III–15) from the write-up from my 1999 EVN School lecture (Campbell 1999a):

$$\phi = -\frac{\nu}{c}\ \{[(b_x \cos H(t) - b_y \sin H(t)] \cos\delta + b_z \sin\delta\}\,, \quad (1)$$

where δ is the declination of the source, $H(t)$ is the Greenwich Hour Angle of the source ($H(t) = GAST - \alpha$), and ϕ is in units of cycles of phase. From here on, I will drop the explicit t dependence of H. We can compute a difference phase $D\phi$ by introducing a second source at $H_2 = H_1 + \Delta H = H_1 - \Delta\alpha$ and $\delta_2 = \delta_1 + \Delta\delta$, and evaluate $\phi_2 - \phi_1$ by expanding the trig functions in equation (1) in powers of $\Delta\alpha$ and $\Delta\delta$. In this paper, I use $\Delta\alpha$ as an actual angular displacement on the sky, *i.e.*, $\Delta\alpha = (\alpha_2 - \alpha_1)\cos\delta$. Since everything is linear in b_i, a shift of $\boldsymbol{\Delta x}$ in an station's position causes a specific $\Delta D\phi$ independent of baseline length. We obtain, to third order:

$$\begin{aligned}\Delta D\phi \simeq -\frac{\nu}{c}\,[\ \ & \Delta x\,\{\ \Delta\alpha \sin H \cos\delta - \Delta\delta \cos H \sin\delta \\ & \qquad -\mathcal{C} \cos H \cos\delta - \Delta\alpha\Delta\delta \sin H \sin\delta \\ & \qquad -\,\mathcal{C}_\alpha \sin H \cos\delta + \mathcal{C}_\delta \cos H \sin\delta\ \} \\ & +\Delta y\,\{\ \Delta\alpha \cos H \cos\delta + \Delta\delta \sin H \sin\delta \\ & \qquad +\mathcal{C} \sin H \cos\delta - \Delta\alpha\Delta\delta \cos H \sin\delta \\ & \qquad -\,\mathcal{C}_\alpha \cos H \cos\delta - \mathcal{C}_\delta \sin H \sin\delta\ \} \\ & +\Delta z\,\{\ \Delta\delta \cos\delta - \frac{\Delta\delta}{2}\sin\delta - \frac{\Delta\delta^3}{6}\cos\delta\ \}],\end{aligned} \quad (2)$$

where $\Delta D\phi$ is still in cycles. Here, the three orders are on separate lines for the Δx and Δy terms, and

$$\begin{aligned}\mathcal{C} &= \frac{\Delta\alpha^2 + \Delta\delta^2}{2}, \\ \mathcal{C}_\alpha &= \frac{\Delta\alpha}{2}\left(\frac{\Delta\alpha^2}{3} + \Delta\delta^2\right), \text{ and} \\ \mathcal{C}_\delta &= \frac{\Delta\delta}{2}\left(\Delta\alpha^2 + \frac{\Delta\delta^2}{3}\right).\end{aligned}$$

Figure 1 illustrates the first-order effects on $\Delta D\phi$, spanning a 1m station-position change in each Cartesian coordinate and a reference-target source separation of 1° in each direction on the sky: the three rows show the $\Delta D\phi$ arising from Δx, Δy, or $\Delta z = 1$ m for each source-separation configuration, and the two columns show the $\Delta D\phi$ arising from $\Delta\alpha$ or $\Delta\delta = 1°$ for station-position shifts in each coordinate. Each panel shows a contour plot of $\Delta D\phi$ in degrees, for $\nu = 1$ GHz. You use these plots by following along a horizontal line corresponding to the declination of your source; this yields a full sidereal-day sinusoid. Because the panels show first-order terms, you can "combine" them linearly to match your experiment's situation, *i.e.*, frequency ν, total antenna-position correction $\boldsymbol{\Delta x}$, and target-reference separation $\boldsymbol{\theta}$ ($= \Delta\alpha\hat{\boldsymbol{e}}_{\rm east} + \Delta\delta\hat{\boldsymbol{e}}_{\rm north}$) — or you can just evaluate equation (2) with the appropriate values.

The linear-superposition of course breaks down for the higher-order terms. Table 1 gives an idea of the importance of the higher-order terms as a function of $|\boldsymbol{\theta}|$. Each

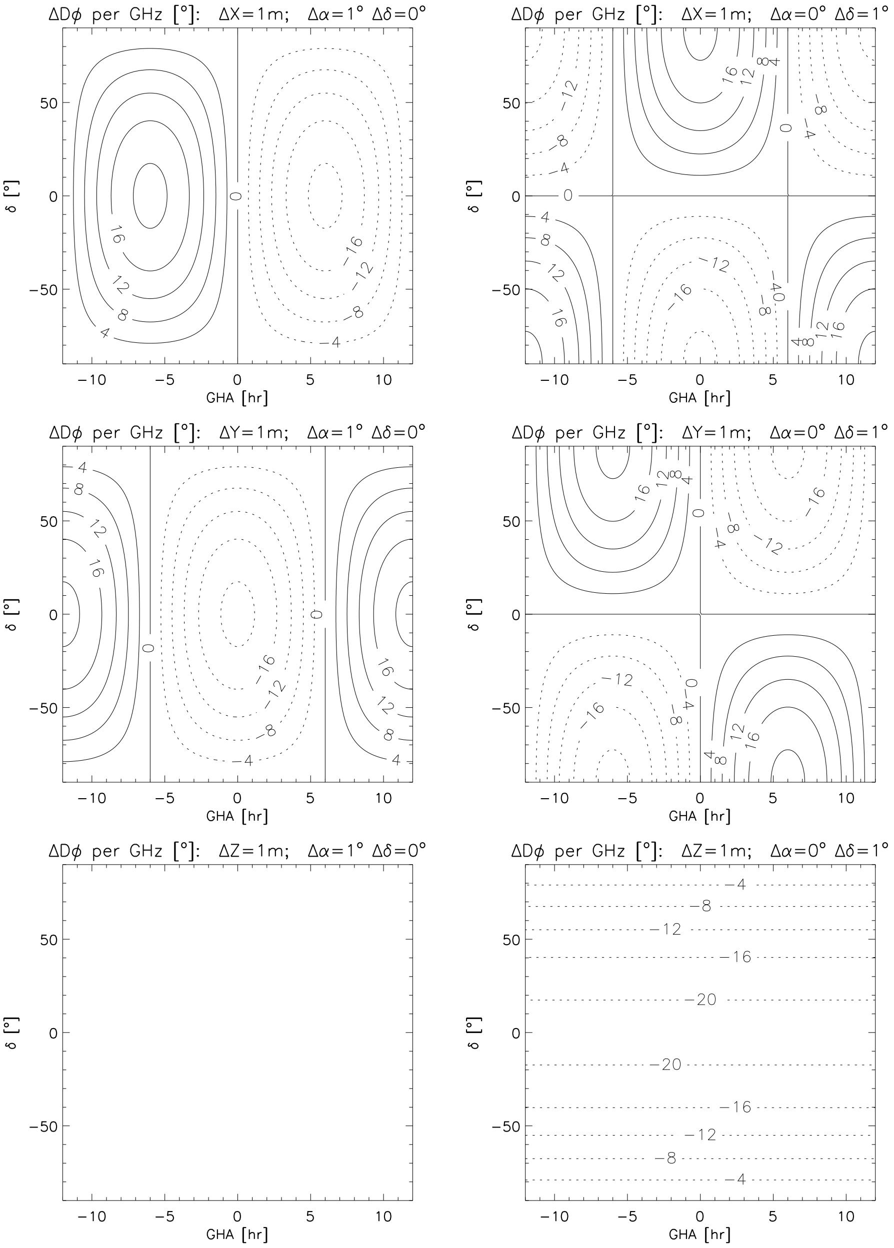

Fig. 1. "Basis" space for $\Delta D\phi$ arising from station-position corrections. All plots are for ν=1 GHz; the columns show reference-target source separations of 1° in $\Delta\alpha$ (left) and $\Delta\delta$ (right); and the rows show station-position offsets of 1m in X (top), Y (middle), and Z (bottom).

row lists the maximum $\Delta D\phi$ per GHz over the entire range of *GHA*, δ, $\boldsymbol{\Delta x} = 1$ m (in each coordinate x, y, z individually), and all possible target-reference source geometries satisfying the value of $|\boldsymbol{\theta}|$. Because of the global nature of the maximization, your specific situation in δ, $\boldsymbol{\Delta x}$, and $\boldsymbol{\theta}$ may well have lower maxima, and somewhat different ratios among the orders.

As an example of $\Delta D\phi$ as a function of time, figure 2 shows the net corrections for a full sidereal day containing the phase-referencing NME N01C3, with the three steps of improving the $\mathrm{Wb_{arr}}$ position plotted individually: the TP001 adjustment to $\mathrm{Wb_7}$, the recalculation of the $\mathrm{Wb_7}$–$\mathrm{Wb_{arr}}$ offset, and plate motion since 1997.0.

Table 1. Maximum $\Delta D\phi$ in various orders, for ν=1 GHz

$\lvert\boldsymbol{\theta}\rvert$	1st-ord	2nd-ord	3rd-ord
1°	20.°958	0.°183	0.°002
3°	62.°875	1.°646	0.°041
5°	104.°792	4.°572	0.°188
10°	209.°585	18.°290	1.°505
15°	314.°377	41.°152	5.°079

5. Other Model-based Effects

The improvement in the positions and axis-offsets of the non-geodetic EVN antennas has removed the biggest

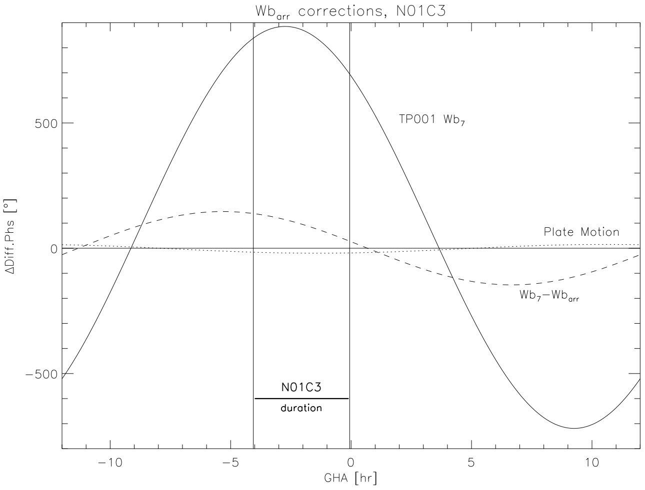

Fig. 2. Net $\Delta D\phi$ corrections for the NME N01C3 arising from three steps of $\mathrm{Wb}_{\mathrm{arr}}$ station-position corrections.

obstacle to successful phase referencing using the EVN. Of course, the station position determination may be refined in the future with further observations. Other remaining model issues include:

• Celestial pole offsets $d\psi, d\epsilon$ are not incorporated into the IAU 1980 nutation model when transforming from the mean to true equator of date. This *d*-nutation effect on the Earth's orientation, and hence on the station positions exceeds the cumulative plate motion corrections. We are currently working to correct this situation.

• The tropospheric dry and wet zenith delays use the Saastamoinen formulas, but with *a priori* values for temperature, pressure, and relative humidity. Evaluation using logged weather measurements from VLBA antennas in a couple global experiments (winter & summer) shows offsets generally under 0.1 ns, but with some outliers, especially for ZD_{wet} in high-T, high-humidity conditions.

• No explicit ionospheric model, for either induced delays or Faraday rotation. You can apply interpolations of gridded vertical Total Electron Content maps produced by the IGS using `TECOR` in AIPS (Walker & Chatterjee 1999); other approaches include Ros et al. (2000) or Campbell (1999b).

There are other factors, all likely at a level of a few cm or less. However, people's expectations of accuracy is a monotonically increasing function of time, so today's observationally immaterial model deficiency may not always remain so. On the longer term, there are a set of new IAU resolutions geared towards providing meaningful interpretation of micro-arcsecond astrometry; you can find papers discussing aspects of this ongoing process at `http://www.iers.org/workshop_2002/program.html` and `http://maia.usno.navy.mil/conv2000.html`. Once *e*-VLBI becomes operational, we may have the additional complication of having to use lower-accuracy predicted values of Earth-Orientation Parameters (polar motion, UT1–UTC), since there won't be time to wait for the final processed values.

Phase-referencing with residual phases (*e.g.*, through AIPS) is limited by the correlator model used. If the modeling of any specific physical effect is improved, it may not be easy to remove the corresponding portion of the total model and incorporate the improvement *a posteriori* (for the station position and axis-offset changes discussed here, it is easy, via `CLCOR`). Uncompensated model changes in the middle of a series of astrometric observations could lead to a discontinuity in the estimated $\Delta\alpha(t), \Delta\delta(t)$. An alternative is astrometry with "totals", where the correlator model is added back into the data before processing and the analysis software includes its own model computation, over which you would in principle have more control — examples include Ros et al. (1999; `VLBI3`), Lebach et al. (1999; `CALC/SOLV`), or Lestrade et al. (1990; `SPRINT`).

Of course, experimental design remains a principal factor in successful phase-referencing; a good experimental design can help mitigate any existing model deficiencies. Close reference sources (you can never be *too* close) and fast switching (or fancier multi-beaming or cluster-cluster techniques) need to be able to sample the temporal and spatial variations affecting the propagation paths from your sources (which will depend on the specifics of the solar-terrestrial condition during your observations — the weather, the solar activity, the solar-wind/magnetosphere coupling, the geomagnetic activity level, the season, the time of day, *etc.* — some of which are neither well predictable nor especially stable). Use of more than one reference source can allow you to monitor net unmodeled effects by tracking relative motion between two extra-galactic sources (*e.g.,* Campbell 1996), or to perform more sophisticated estimations of the "spatial fields" of the perturbations (*e.g.*, Fomalont & Kopeikin, these proceedings).

References

Campbell, R.M., Bartel, N., Shapiro, I.I., et al. 1996, ApJ, 461, L95.

Campbell, R.M. 1999a, EVN VLBI School 1999, Dwingeloo, Lecture #2, `ftp://ftp.jive.nl/pub/rmc/jvs2.ps.gz`

Campbell, R.M. 1999b, New Astron. Reviews, 43, 617.

Charlot, P., Campbell, R., Alef, W., et al. 2001, in Proceedings of the 15$^{\mathrm{th}}$ Working Meeting on European VLBI for Geodesy and Astrometry, ed. D. Behrend, & A. Rius (IEEC/CSIC, Barcelona), 194, `http://www.ieec.fcr.es/hosted/15wmevga/proceedings/charlot`

Charlot, P. et al. 2002, these proceedings.

Fomalont, E.B., & Kopeikin, S.M., 2002, these proceedings.

Lebach, D.E., Ratner, M.I., Shapiro, I.I., et al. 1999, ApJ, 517, L43.

Lestrade, J.-F., Rogers, A.E.E., Whitney, A.R., et al. 1990, AJ, 99, 1663.

Ros, E., Marcaide, J.M., Guirado, J.C., et al. 1999, A&A, 348, 381.

Ros, E., Marcaide, J.M., Guirado, J.C., Sardón, E., & Shapiro, I.I. 2000, A&A, 356, 357.

Walker, C., & Chatterjee, S. 1999, VLBA Scientific Memo 23.