VLBA PHASE-REFERENCING

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Abstract. Residual delay errors in VLBI data limit the image sensitivity and dynamic range attainable using current calibration techniques such as self-calibration. Applying phase corrections derived from regular observations of nearby calibrators (phase-referencing), the residual delay errors on a target source can be reduced, increasing coherent integration times. In this paper we present the results of a series of observations made with the VLBA to examine the effectiveness of phase-referencing for improving instrumental phase stability. Optimum observing strategies when studying weak (~ mJy) sources are discussed.

Key words: Phase-referencing – VLBA – calibration – atmosphere

The phase measured by a radio interferometer contains the effects on wavefront propogation of the ionosphere, the wet and dry troposphere, and the receiving electronics; systematic errors due to inaccurate geometry (e.g. source/station position errors & antenna axis offsets) and clock errors are also included. Using self-calibration (e.g. fringe-fitting) these errors can be reduced to some extent, however: (1) absolute position information is lost; and (2) typical self-cal procedures require sufficient signal-to-noise to identify a solution in delay/delay-rate space (typically S/N~7).

One strategy to remove these constraints for VLBI observations, termed **phase-referencing**, involves regular switching to a strong nearby (typically $\leq 5°$) reference calibrator to determine a phase correction to be applied to the target source. This process removes the effects of any clock errors, and reduces the effects of geometry and atmospheric variations by a factor roughly equal to 1/(target-reference separation in radians). The result is a increase in the coherent integration time used for determining self-cal corrections, or sufficient phase stability to enable direct imaging of the data (i.e. fourier inversion and CLEANing). There are, however, a number of parameters related to phase-referencing that are not yet clearly known, e.g. the optimal target-reference separation and switching-cycle time, the effects of temporal and spatial variations in the atmosphere, and the overall success rate of phase-referencing in improving phase stability at different frequencies. In this paper we present some results from a series of VLBA 8.4 and 1.6 GHz observations using pairs of calibrator sources of various separations to examine some of these parameters.

* The NRAO is operated by Associated Universities, Inc., under agreement with the National Science Foundation.
** This work was supported in part by the NSF under grant AST-9117100

J.G. Robertson and W.J. Tango (eds.), Very High Angular Resolution Imaging, 105–108.
© 1994 *IAU. Printed in the Netherlands.*

https://doi.org/10.1017/S0074180900107387 Published online by Cambridge University Press

The observations to date are summarized in Table 1; Sep is the source separation in degrees, N_{obs} the number of observations. Each observation consists of 1 hr at both 8.4 GHz and 1.6 GHz with a 6 minute switching-cycle time (i.e. 3 mins on src A, 3 minutes on src B); typically 3-6 antennas were used. The observations were made between 1992 Jan 17 and 1992 Jul 14 using the MKII recording system, the tapes correlated on the NRAO MKII processor. We have written an AIPS task to recalculate delays and apply phase-corrections to VLBI data, at present based on the UVGEOM code (Conway & Vermeulen 1993, in preparation).

TABLE I
VLBA Phase-reference data

Src pairs (T/R)	Sep(°)	N_{obs}
1222+037/1226+023	1.9	6
1611+343/1641+399	8.9	4
0913+391/0923+392	0.7	2
1638+398/1641+399	0.3	1

After correlation, the data were read into AIPS where the antenna–earth centre delay for each data point are recalculated; at present, we incorporate corrections for source/station positions, polar wobble, antenna axis offsets, and the wet+dry troposphere delay. These delays are then compared to those used at correlation time (as written in the CL table), and an appropriate phase correction inserted. The reference source is then fringe-fitted, and the resultant phase corrections are interpolated to the target source.

Some typical phase-referencing results are shown in Fig. 1, from the observation 1992 Jan 17/1222+037-1226+023/8.4 GHz. The typical residual fringe rate before phase-referencing was ~5 mHz; Fig. 1 shows the target residual phases after phase-referencing on the calibrator source. The phases are stable over 1 hr, with residual fringe rates $\ll$0.3 mHz.

1. Results

Summarizing our findings for both frequencies:

- **8.4 GHz** - Coherence times $\gg$1 hr were obtained 100% of the time (6/6 obs) at 1.9° separation on baselines ranging from ~200-5000 km. Equivalent phase stability was found only 50% of the time (2/4) at 8.9° separation.
- **1.6 GHz** - Coherence times of ~20-30 mins were obtained 66% of the time (4/6) at 1.9° separation, and 50% of the time at 8.9°. A coherence time $\gg$1 hr was obtained for the 0.3° separation observation. In most cases, the phase stability was limited by the large (~100°) coherent variations possibly due to travelling ionospheric disturbances (TIDs, discussed below).

In Fig. 2(a,b) examples of the 1.6 GHz phase stability are shown; these data are for 0.3° and 8.9° separations, observed at a fairly low elevation for 1611+343 (~20°).

https://doi.org/10.1017/S0074180900107387 Published online by Cambridge University Press

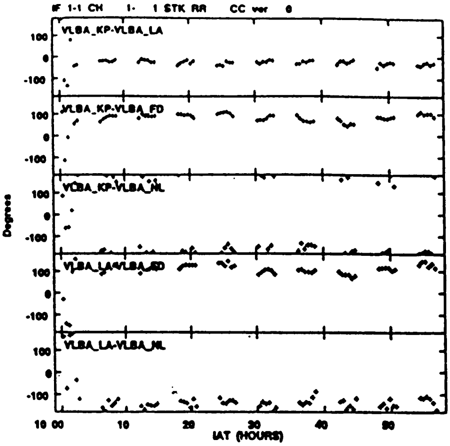
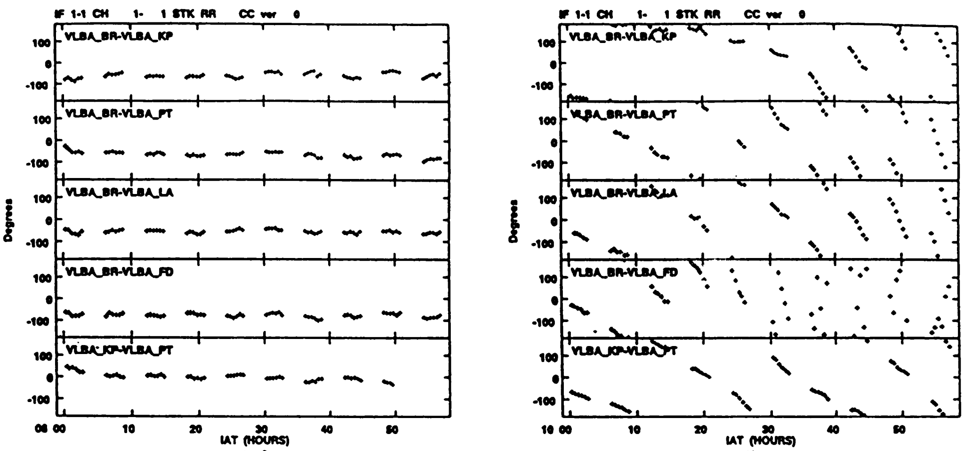


Fig. 1. Target residual phases after phase-referencing. Coherence time ≫1 hr.



(a) (b)

Fig. 2. Target residual phases using 0.3° (a) and 8.9° (b) separation phase-reference calibrator.

During the atmospheric/ionospheric conditions prevalent during this observation a reference source 8.9° away appears unsatisfactory at both 8.4 and 1.6 GHz for significantly improving coherence times.

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The major source of residual error after phase-referencing the 8.4 GHz data appears to be errors in the estimation of the zenith delays due to the ionosphere and troposphere; for example, the tropospheric delay (assumed to be ~2.1 m here) can be estimated only to a 2 cm accuracy (Elgered 1982, IEEE Tran. Ant. & Prop., AP30, 502). Such errors lead to slowly varying (~few hrs) phase residuals such as those seen in Conway & Vermeulen (1993). Errors in zenith delays lead to differential phase residuals due to the different elevations of the target and reference sources, i.e. the assumption of isoplanicity breaks down.

Our results seem to indicate that a target-reference separation of $\sim 2°$ is sufficient for phase-referencing to increase coherence times to $\gg 1$ hr at 8.4 GHz. The distribution of flat-spectrum phase-calibration sources with flux-densities above 200 mJy described by Patnaik *et al.* (1992, MNRAS, 254, 655) indicates a 71% chance of a reference source within 2° of any target source, and 94% within 3°. Our simulations suggest that after phase-referencing, target sources above ~2 mJy can be self-calibrated, while sources below 2 mJy can be directly imaged as long as the zenith path delay can be estimated within $\sim 1\lambda$. For both 8.4 and 1.6 GHz, a switching-cycle time of 6 mins appears sufficient for elevations above 20° to allow phase connection (i.e. there is no 2π ambiguity in phase interpolation), although there are exceptions (e.g. Conway & Vermeulen 1993).

The success of phase-referencing at 1.6 GHz is more limited due to the variable components of the ionosphere such as TIDs. Variations in electron density and therefore ionospheric delay lead to spatial gradients in delay, a typical example of which may be seen in Fig. 2(b) (see van Velthoven 1990, Ph.D. Thesis, Univ. Eindhoven). Smaller target-reference separations (e.g. $\leq 1°$?) may be need to significantly improve coherence times beyond 10-20 mins. The static ionospheric zenith delay can be more accurately derived from multi-wavelength data (i.e. "S/X" calibration).

2. Future Work

We are currently testing an implementation of the Goddard CALC program to recalculate delays, which should provide ~1 picosecond delay accuracy using more accurate geometrical and atmospheric modelling (currently the VLBA correlator is using CALC for delay modelling). Further modelling of the effects of the ionosphere and TIDs on VLBI data is also underway. We are also pursuing more extensive observations to explore the effects of different separations, elevations and weather on the phase-referencing technique, including longer tracks on source pairs to investigate longer-term (i.e. 12 hr) residual errors.

Discussion:

Napier:
For VLBI phase referencing, how big a problem is resolved structure in most of the calibrators, and what is the solution?
Beasley:
Significant structure in the calibrator source will need to be modelled as part of the phase-referencing process. A cycle of self-calibration and mapping will be required when using reference sources with inaccurate positions and/or structure.

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