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

Phase Referencing Using Several Calibrator Sources

E. B. Fomalont[1] and S. Kopeikin[2]

[1] National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
[2] Dept. of Physics and Astronomy, University of Missouri-Columbia, 223 Physics Bldg., Columbia, MO 65211, USA

Abstract. Phase referencing techniques are used to image weak sources, and to measure sub-mas position changes of radio sources. The fast switching (or simultaneous observations) between a calibrator and target source decreases the effects of temporal fluctuations of phase, but does not remove persistent spatial phase difference between the sources. In March 2002 multi-calibrator test observations at 2.3/8.4 GHz were made with the VLBA on three different days. By suitably combining the phase measurements from two calibrators near the target source, higher quality images were obtained. The astrometric precision, as measured by the target position jitter among the three days, decreased from 40 μarcsec using one calibrator to 20 μarcsec using two calibrators. The systematic position difference between the two calibration methods was ≈ 130 μarcsec, indicating strong coupling between the phase errors and position determination.

1. Introduction

The technique of phase referencing (PR) is now commonly used with many VLBI arrays in order to image weak radio sources, and to measure the accurate position and motion of radio sources. The simplest PR scheme alternates observations every few minutes between a calibrator source and a target source which are separated by five degrees at most, but the closer the better (Beasley & Conway 1995).

Motivated by the Jupiter−J0842+1835 near encounter on September 8, 2002, from which it is possible to measure the speed of propagation of gravity (Kopeikin 2001, and these Proceedings), we were allotted three days of VLBA test observations for five hours on 2002 March 11, 24, 29, to investigate observing and reduction methods which might improve the accuracy of VLBI observations. The Jupiter-calibrators configuration in September 2002 is shown in Fig. 1. The observing schedule alternated between J0839 (we will truncate the names of the radio sources) and J0842, one minute each, with the addition of source 3, 4 or 5 in turn, after each pair. The source J0842 is an ICRF-quality calibrator (Ma et al 1998) and J0839, separated by 0.82°, is a VLBA calibrator (Beasley et al 2002). We observed with eight independent frequency channels, each of 8 MHz bandwidth; four IFs at X-band between 8.4 and 8.9 GHz and four IFs at S-band between 2.3 and 2.4 GHz, a mode used by geodetic observations to determine group delays at S- and X-band in order to measure the plasma refraction in the earth ionosphere (Ma et al 1998). Since the Jovian magnetosphere could produce a non-negligible refraction when J0842 is within 5′ of Jupiter, dual frequency observation may be needed in the September 2002 experiment to remove this anomalous bending.

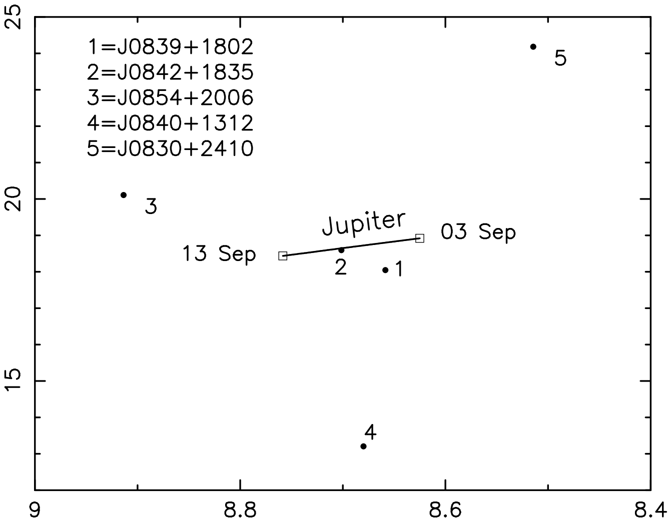

Fig. 1. September 2002 Jupiter Configuration with Nearby Calibrators. The abscissa is right ascension in hours and the ordinate is declination in degrees. The five calibrator source positions are denoted by the dots, and the path of Jupiter in 2002 September is shown. The RA and DEC scales are not the same.

2. Phase Referencing to J0842+1835 and Phase Errors at 8.4 GHz

We chose the source J0842 as the primary calibrator in the March 2002 test observations, and determined the antenna-based phases for each of the eight IFs for each scan of duration one-minute, using the AIPS tasks FRING and CALIB. In order to remove structure dependent phase changes during the calibration process, the source was imaged using standard self-calibration (SC) techniques (see Fig. 4a). The measured antenna-IF phases were then interpolated between each of the J0842 scans, separated by five minutes, and applied to the other four sources.

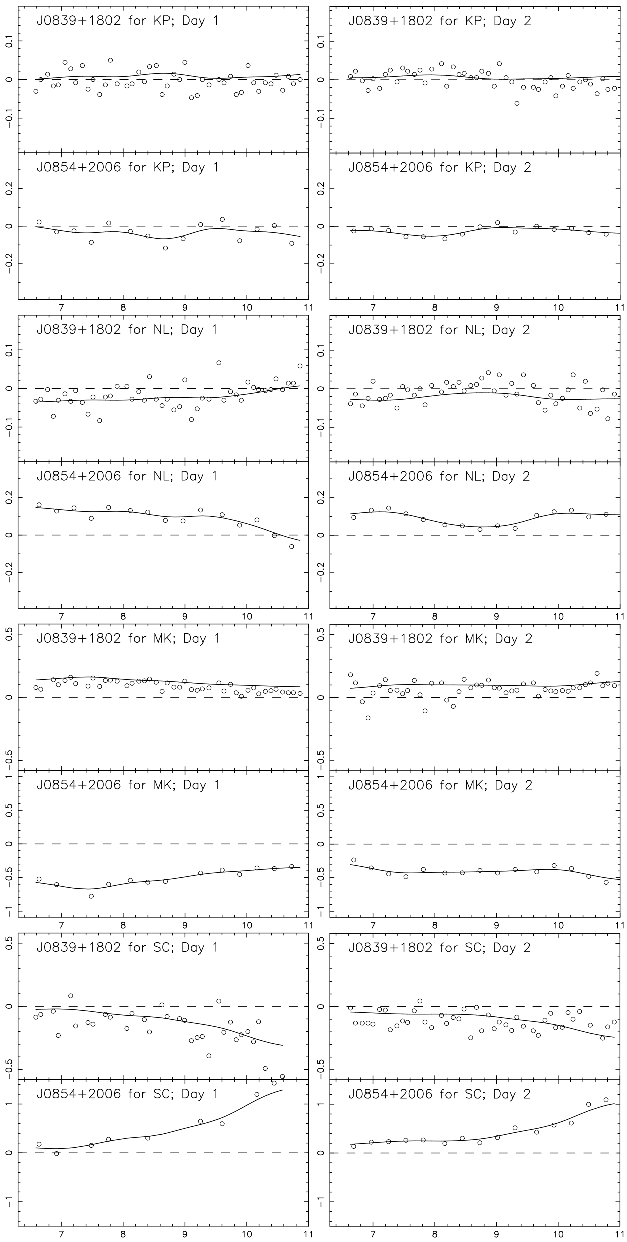

Fig. 2. Comparison of Phase Errors at 8.4 GHz for J0839 and J0854: The phase errors introduced by PR to J0842 with reference antenna LA are shown for 2002 March 11 (left) and March 24 (right), for telescopes KP, NL, MK, SC, (top to bottom) in pairs with J0839 above and J0854 below. A smooth curve has been drawn through the J0854 phases. The curve drawn through the J0839 phase is the J0854 curve scaled by -0.24 (see text). The ordinates are given in lobes and the abscissa are given in sidereal time in hours at Los Alamos.

Images at 8.4 GHz of the other four sources were then made using this PR data. Because all of the sources were strong enough to be detected in one minute, an accurate image for each was obtained using the SC technique. For the starting model in the SC loop, we used the PR image in order to minimize any position changes between the PR and SC source structure. The PR images are of much lower quality than the SC images since the phase calibration derived from J0842 observations are only approximates to those which should apply to the other sources (see Fig. 4b,c). By using CALIB with the SC source model on the PR data, we determined the phase correction needed to change the PR image into the SC image. These phases are clearly the errors introduced by the PR technique: most of the phase error distorts the source structure; part of the phase error shifts its position.

These phase errors for J0839 and J0854 for selected antennas are shown in Fig. 2 for 2002 March 11 and March 24. The reference antenna was Los Alamos (LA). For antennas less than 1000 km from LA (e.g., Kitt Peak-KP), the phase errors are dominated by short-term phase scatter of ≈ 0.03 lobe (1 mm path length), presumably caused by small-scale tropospheric disturbances passing above each telescope with a time scale of ten minutes or less. However, for the longer baselines, there are relatively large phase errors which persist for hours. These errors are larger for J0854 (separated 3.7° from J0842) and in the opposite direction as compared with those associated with J0839.

In fact, the correlation of the long-term phase errors for J0839 and J0854 are consistent with a wedge-like phase screen over each antenna. That is, above each antenna within about 5° around J0842, there is a spatial change of phase which is *linear* and persists over several hours. Since J0854 is located 4.1 times further from the calibrator J0842, nearly in the opposite direction of J0839, the linear wedge model suggests that the phase error of J0839 should be -0.24 times the phase error of J0854.

This relationship is indicated by the smooth curves in Fig. 2. The curves in the J0854 plots are a smooth fit to the data, whereas the curves drawn in the J0839 plots are **NOT** fits to the J0839 data, but the J0854 curves rescaled by the factor -0.24. Although the scaling law does not fit perfectly, the assumption of a persistent wedge-like phase screen over each telescope is reasonable. This approximate linearity of the residual phase error with distance from the phase reference calibrator is also observed for J0840 and J0830. For the longer baselines (MK and SC to LA) the phase slope of the wedge is approximately 4 mm (36° of phase) per degree separation in the sky. An antenna position error of about 20cm would produce the same phase slope.

3. Cause of Spatial Phase Errors

The spatial correlations of the phase errors shown in Fig. 2 are, of course, not surprising. Errors in the correlator model (antenna location, UT, nutation and polar motion parameters) produce large angular-scale phase errors, but these parameters are known to about 1 cm accuracy, whereas the observed phase slopes are a factor of 20 times larger. The a priori VLBA calibration models above each antenna are not well-known, with simple seasonal models used for the dry troposphere and no model for the wet troposphere and ionosphere, although a GPS-based iono-

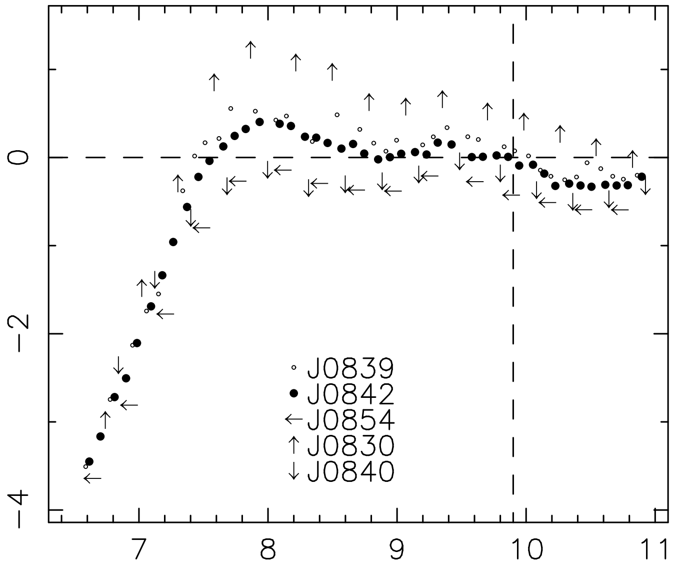

Fig. 3. Ionosphere Refraction on the MK-LA baseline on 2002 March 11: The ordinate is ionospheric refraction at 8.4 GHz in lobes and the abscissa is sidereal time at LA. The arrowed markers for J0854, J0830 and J0830 indicate their relative position in the sky with respect to J0842.

spheric model (TECOR in AIPS) was applied to the data during the reductions.

Using the difference of the measured X-band and S-band group delay for each observation, the ionospheric refraction was determined, and it appears to be the main contributor to the spatial dependence of the phase, even at 8.4 GHz. This is illustrated in Fig. 3 which shows the temporal ionospheric refraction for the LA-MK baseline for all five sources on 2002 March 11. The ionosphere refraction for J0842 was set to zero at 9.9 hr by virtue of the IF-to-IF phase calibration.

The systematic ionospheric phase difference amongst the sources is clearly evident in Fig. 3. For example, The phase offsets of J0830 and J0840, compared with J0842, are large, systematic, and in the opposite sense, as expected from their position with respect to J0842. The ionospheric phase offset of J0854 from J0842 is about 0.4 lobe for the middle segment of 11 March, and is nearly equal to the offset observed in the 8.4 GHz phase in Fig.2 for the MK-LA baseline. Thus, we believe, that for this observation period, the major cause of the spatial phase difference is the ionosphere refraction, although the tropospheric contribution becomes significant at lower elevations.

4. Multi-Source Phase Referencing

Whatever the cause of the phase wedges over each antenna, their effect can be lessened by PR techniques which use more than one calibrator. In general three calibrators which surround the target source are needed to determine the slope and angle of the phase wedge over each antenna. If two calibrators can be found to be collinear with the target source (as is the case with J0839, J0842 and J0854), only two calibrators are needed. The calibrators must be sufficiently strong and compact and lie within about 7° of the target source.

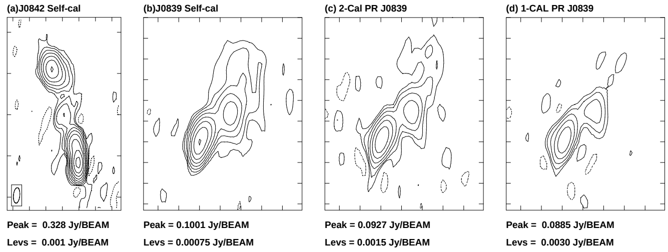

Fig. 4. (a) Self-calibrated Image for J0842. Images for J0839: (b) Self-calibrated Image; (c) 2-cal phase referencing; (d) 1-cal phase referencing.

To illustrate the gain using two calibrator sources, we have compared the image quality and positional accuracy derived for J0839 with PR using J0842 alone, and with PR using both J0842 and J0854. In the one-calibrator case, the measured phase of J0842 was transfered to J0839. In the two-calibrator case, the measured phase of J0842 $-0.24\times$ (the measured phase of J0854) was transfered to J0839. Proper phase interpolation in time and attention to possible lobe ambiguities (phase errors may be larger than ± 0.5 lobe) were necessary.

The comparison of the one-calibrator PR image and the two-calibrator PR image for J0839, as well as the self-calibration image, are shown in Fig. 4b,c,d. The dynamic ranges are 300, 120, 60, respectively, indicating that the two-calibrator phase referencing has improved the image quality by about a factor of two. Similar image improvements were made on day 2 and day 3.

5. Astrometric Accuracy

The determination of the accurate separation between J0842 and J0839 requires some discussion about what is actually being measured. First, in the analysis we have assumed that the radio structure of each source, although complicated, does not change form over the experiment duration. The structure of each source can be determined accurately from SC techniques and high dynamic range images were made for J0842, J0839 (see Fig. 4a,b) and for J0854 (not shown). We used the best a priori position for each source (estimated error ≈ 400 μarcsec) and minimized the position slippage between the SC image and the original PR images using J0842 alone. If the radio structure changes form, then complications arise over the interpretation of what a position determination means.

The relevant AIPS calibration programs permit the removal of the phase effects caused by the non point-like structure of a source. Hence, the position analysis is equivalent to dealing with point sources, although the visibility amplitude is not constant over the (u-v) plane, and imaging of the data will produce distorted, symmetrized source structures.

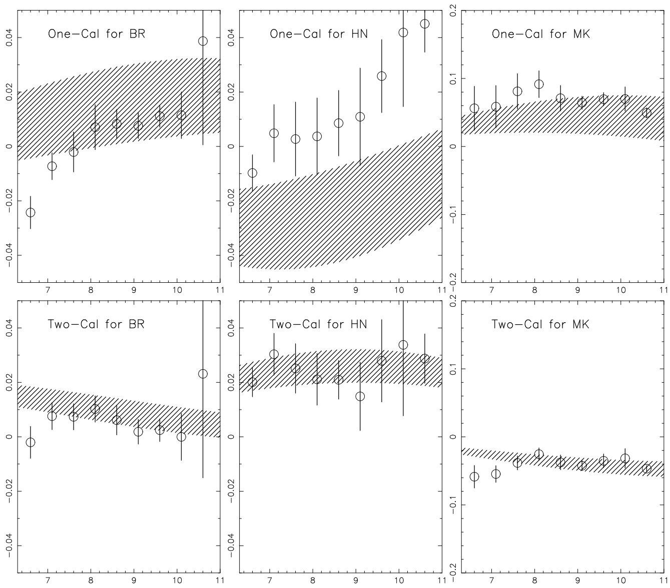

Fig. 5. Comparison of Position Fit to Phase Residuals: (top) Fit to BR, HN, MK phase errors with 1-calibrator phase referencing; (bottom) Fit with 2-calibrator phase referencing. The plotted points and error bars are calculated by combining the phases over all three days, and then averaging over 30-min sidereal time blocks. The shaded regions show phase range expected for the best position fit and error estimates, listed at the bottom of Table 1.

Although precise positions can be obtained from images, the fitting of a position offset to the calibrated phases is better for many reasons: by dealing directly with the data, discrepant points and other isolated problems can be noticed and removed; a source position can be obtained over a small part of an observing day; and error estimates can be more reliably obtained. For the one-calibrator PR, the position of the target source (J0839) is tied directly to the assumed image of the calibrator (J0842) with its corresponding assumed position. For multi-calibration PR, the position of the target source (J0839) is tied to the assumed images and locations of the calibrators (J0842 and J0854) as weighted in the calibration process. As long as the calibrator(s) are stationary and do not change structure, any changes in the position of J0839 over the experiment should reflect its motion. Motion of one or the other calibrator will be reflected in J0839, with the appropriate weight used for the multi-source phase calibration.

Fig. 5 shows the phase fits for three antennas, after calibration using one calibrator (top) and two calibrators (bottom). The error bars the points are significantly smaller for the two-cal PR, indicating less day-to-day variation of the phase after this calibration. Also, the fit to the best position offset of J0839 for the one calibrator PR shows large systematic residuals (see HN) which, although somewhat similar on all three days, are inconsistent with the source position derived from all baselines.

The best fits for the two calibration methods for each day are shown in Table 1. The astrometric accuracy using two calibrators is about a factor of two more accurate than with one-calibrator. Surprisingly, the difference between the average position between the two calibration methods is 130 μarcsec, much larger than their internal errors. This large systematic position change is probably caused by a strong coupling between the source position and the spatial phase errors (for example the phase errors are generally elevation dependent), and by the similar spatial phase errors (see Fig. 2) which repeat over many days. The two calibrator PR removes a significant part of this systematic position error, as well as decreasing the internal phase scatter.

Table 1. Position Fits.

Day	One-Calibrator		Two-Calibrators	
	Offsets in μarcsec			
	e/w	n/s	e/w	n/s
Mar11	−125	110	35	120
Mar24	−80	50	40	85
Mar29	−40	30	65	60
AVG	-82 ± 25	63 ± 26	42 ± 10	88 ± 20

6. Conclusion

From three days of test observations at 2.3 and 8.4 GHz using the VLBA, we have demonstrated that there are systematic phase errors between sources, even as close as one degree, which significantly decrease the imaging quality and astrometric accuracy. These errors are mainly associated with the large-scale ionospheric and tropospheric refraction over each telescope. By using several calibrator sources which surround a target source, a positional accuracy approaching 10 μarcsec can be reached, and the quality of the radio images is also increased in dynamic range by about a factor of 2.

The position change of J0842 produced by the motion of Jupiter at closest approach on September 8, 2002 is 57 μarcsec for an assumed speed of the propagation of gravity of c. With the experience of the test observations in March, we expect to easily detect this bending component.

References

Beasley, A. J. & Conway, J. E., 1995 in ASP Conf. Ser. 82, Very Long Baseline Interferometry and the VLBA, eds. J. A. Zensus, P. J. Diamond & P. J. Napier (San Francisco: ASP), 327

Beasley, A. J., Gordon, D., Peck, A. B., Petrov, L., MacMillan, D. S., Fomalont, E. B. & Ma, C. 2002, ApJS, in press.

Kopeikin, S. M., 2001, ApJ, 556, L1.

Ma, C., Arias, E. F., Eubanks, T. M., Fey, A. L, Gontier, A.-M., Jacobs, C. S., Sovers, O. J., Archinal, B. A. & Charlot, P., 1997, AJ, 116, 516