How accurate is phase referencing at L-band? An assessment
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ABSTRACT

Astrometric observations on PSR B0919+06 with standard phase referencing to a nodding calibrator are compared to observations using an in-beam calibrator. The obtained positions agree well for one observation, and disagree for the other one, leading us to conclude that nodding calibration will suffice on some occasions but not on others, depending on the ionospheric conditions. Without in-beam calibration, 4-5° is the maximum distance to useful nodding calibrators at 1.4 GHz.

Phase referencing has become a standard VLBI observing technique for weak sources at higher frequencies (above 3 GHz), as it preserves absolute positional information while allowing extended coherence times. Pulsars, because of their steep spectral fall-off, are best observed at L-band (1.4 to 1.7 GHz) or lower frequencies. Unlike tropospheric effects at higher frequencies, the dominant effects here are ionospheric: thus phase referencing at L-band poses a different set of challenges.

In order to obtain positional accuracy for weak ($\sim$few mJy) pulsars at the milliarcsecond level, phase connection techniques must be used in VLBI astrometry. Here the position of the pulsar is measured with respect to a stationary background calibrator, using alternating scans on the pulsar and calibrator to extend coherence times on the pulsar.

This method assumes that the calibration derived for the stronger calibrator source can be transferred to the pulsar, across a few degrees of sky and a few minutes of time. This is, of course, an approximation, and the ultimate positional accuracy achieved using this method depends on many factors, including the angular separation between the calibrator and source, the temporal switching cycle, the spread in frequency, etc.

One way of greatly improving this calibration is to use an in-beam calibrator, a weak source in the same primary beam as the target pulsar. Standard phase referencing, followed by self-calibration on the in-beam source, provides calibration at the sky position and times of interest, reducing the time separation across which the calibration is transferred to zero, and the angular separation to a few arcminutes instead of a few degrees.

We have used such an in-beam calibrator (10 mJy) for astrometry on the pulsar B0919+06 (4 mJy), and achieve sub-milliarcsecond precision in the measured proper motion (Fomalont *et al.* 1998, submitted to AJ). In this report, we use that data and compare the accuracy achieved using nodding calibration only, to that achieved with in-beam calibration.

Data processing and calibration

Information about the targets and their observed fluxes are collected in Table 1. The targets were observed with the VLBA on two days (Day 1: 1998 March 26, BC078A and Day 2: 1998 March 30, BC078B) for 50 minutes around UT 05:00. This was meant to provide two independent data points at nearly the same epoch, and here it allows a check on the consistency of the two calibration methods.

Table 1: Observed pulsar, calibrator and in-beam source

Target	Name	Distance from psr	Flux
Pulsar B0919+06	J0922+0638	-	3-4 mJy obs
Nodding Calibrator	J0914+0245	4 degrees	350 mJy
In-beam Calibrator	J0923+0638	12 arcmin	7-8 mJy obs

Eight observing frequencies (VLBA baseband channels, or IFs in AIPS) were used, at 1.41, 1.42, 1.44, 1.48, 1.53[1], 1.54, 1.61 and 1.62 GHz, with 8 MHz bandwidth at each IF. Data was one bit and right circular polarized, with a switching cycle of two minutes on the nodding calibrator and three minutes on the pulsar/in-beam calibrator. At the correlator, each IF was split into 16 channels and the data were averaged for 2 seconds.

Each data set was correlated twice, once at the nominal in-beam calibrator position and once at the nominal pulsar position. Processing involved *a-priori* amplitude calibration using the system temperatures, instrumental phase correction with the pulse cal tones, and data flagging based on anomalous high amplitudes, followed by fringe fitting and self-calibration on the nodding calibrator. For a pulsar without an in-beam calibrator, this is as far as we can go: this constitutes the "nodding calibrator only" calibration path.

For the "in-beam calibrator" path, we proceed to map the in-beam data with nodding calibration, followed by a round of phase-only self-calibration at the detected position of the in-beam calibrator. All IFs were averaged and a 5 minute solution interval was used. This produces a set of phase corrections that accounts for the effect of the differential ionosphere between the calibrator and pulsar (and in-beam) pointing directions. These phase corrections for the two days are plotted in Figure 1: notice that there are large phase offsets at most antennas, though their variation with time is slow.

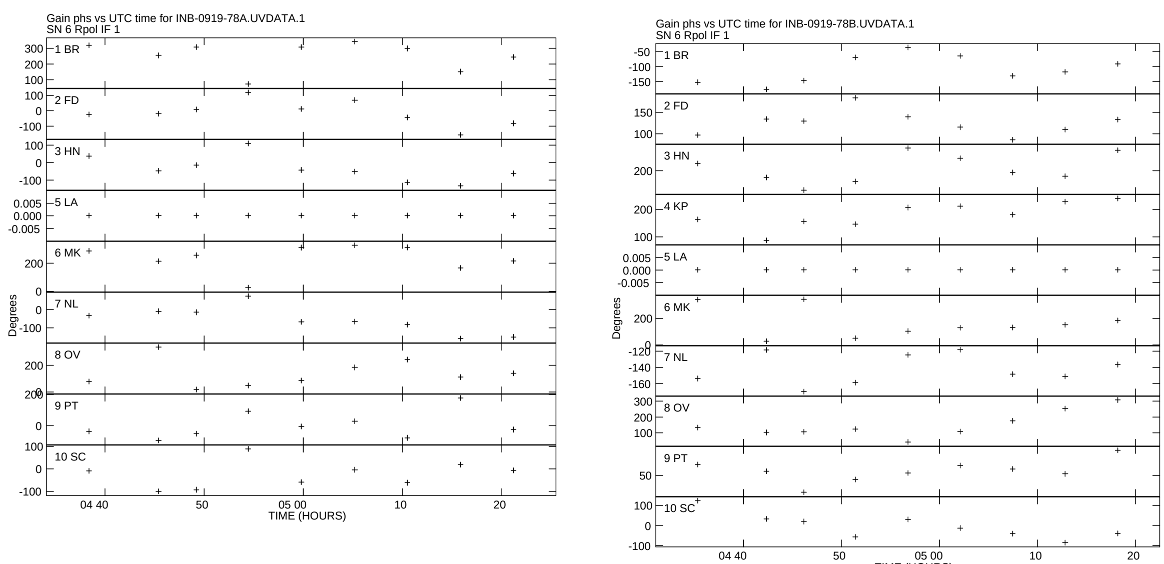

Fig. 1.— Phase corrections generated by self-calibration at the in-beam calibrator position. Data for one IF (1.41 GHz) on days 1 and 2. Los Alamos (antenna 5) was the reference antenna.

[1] All data at 1.53 GHz and some channels at 1.54 GHz were flagged because of extreme interference on both days.

Imaging and Analysis

The pulsar data, with and without in-beam calibration, was mapped using the standard Clark CLEAN (task `IMAGR` in AIPS) with a tight clean box around the observed peak in the dirty map.

The quality of the data after nodding calibration differed significantly on the two days. There was no problem in identifying the in-beam source or the pulsar on day 1, but on day 2, the in-beam calibrator image split up into multiple blobs, implying that nodding calibration was not as successful as on day 1. The reason for this is not clear: it probably reflects a disturbed ionosphere during the second day's observing. However, self-calibration of the in-beam data for day 2 at the position of the in-beam source determined from day 1 produced a satisfactory image, with a consistent flux value.

With in-beam calibration, there is no ambiguity about the pulsar position, and the mapping is nearly trivial. Given the variation in data quality, the agreement in pulsar positions seen in Figure 2 is also reassuring.

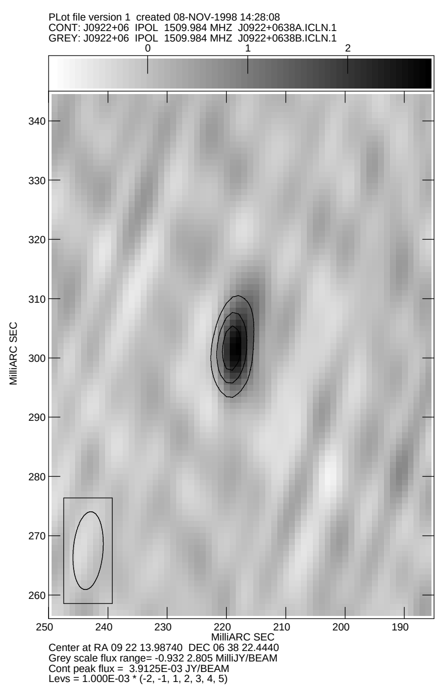

Fig. 2.— The pulsar after using in-beam calibration. Note the agreement between maps for day 1 (contours) and day 2 (greyscale): the difference is consistent with the proper motion.

Dirty and clean maps for each day's data, with and without in-beam calibration, are presented in Figures 3 through 6. Qualitatively, it is obvious that phase referencing to the nodding calibrator alone produces maps with a much poorer signal to noise ratio. More importantly, the lost power is distributed in the sidelobes, so that the true position of the pulsar might be ambiguous if we did not know the "right" answer from the maps with in-beam calibration.

Also, for the second day, the dirty map for the pulsar using nodding calibration alone is broken up into blobs (like the in-beam source), and the cleaned image is barely believable (Figure 6), but the phase corrections determined for the in-beam calibrator (shown in Figure 1) produce a perfect pulsar image (Figure 5). The in-beam source is a factor of 20 closer to the pulsar than the nodding calibrator is, and the map errors are expected to go down by the same factor because of the increased similarity of the ionospheric path.

A single component Gaussian was fitted to the cleaned maps in all four cases (task `JMFIT` in AIPS), to assess what accuracy phase referencing with the nodding calibrator alone would provide. The fitted positions and associated errors are summarized in Table 2: the results back up the qualitative discussion above. In particular, the two in-beam calibrated results are almost identical, and the difference is consistent with the measured multi-epoch proper motion (0.9 mas over 4 days). One "nodding calibrator only" map agrees well with this position, while the other is significantly in error.

Table 2: Fit results: position offsets measured from RA 09:22:14.0000 Dec 06:38:22.700.

Data from	Calibration	Offset RA (mas)	Offset Dec (mas)	Peak flux (mJy)	Comments
Day 1	With in-beam	31.1 ± 0.15	45.9 ± 0.31	3.9 ± 0.2	—
	Nodding cal only	31.0 ± 0.30	42.5 ± 0.56	2.0 ± 0.2	Position agrees
Day 2	With in-beam	30.3 ± 0.15	46.7 ± 0.34	3.0 ± 0.2	Shift matches proper motion
	Nodding cal only	23.4 ± 0.74	28.2 ± 0.98	1.0 ± 0.2	Position not consistent

Conclusions

A few straightforward conclusions can be drawn from this exercise. First, using an appropriate in-beam calibrator can eliminate almost all ionospheric effects, even in cases where the data quality is poor, as on day 2. Thus an in-beam calibrator can allow consistent astrometry at 1.4 GHz.

Second, phase referencing to a nodding calibrator alone will also allow astrometrically meaningful observations, provided that the ionosphere is cooperative, or can be eliminated in some way. While the formal errors are higher without an in-beam calibrator due to the reduced peak flux, the fit result for day 1 is consistent with the positions determined using in-beam calibration. On the other hand, if ionospheric effects at one or more antennas render the data poor, as in day 2, then it is difficult to draw meaningful conclusions about the pulsar flux or position.

This provides further justification for our observing strategy of sampling the same epoch with two closely spaced observations on different days: it is reasonable to expect that an uncorrelated ionosphere over two days will allow a better estimate of the errors in the astrometric position.

Our choice of nodding calibrator, in-beam calibrator and temporal switching cycle was appropriate for astrometry: with either the in-beam calibrator or the pulsar at the 10 mJy level, the other could be as weak as 2 mJy, and one could go further afield for a nodding calibrator (up to 6-8°). However, without an in-beam source, our choice (4-5°) is probably an upper limit for the distance to a nodding calibrator, and shorter angular distances would be better.

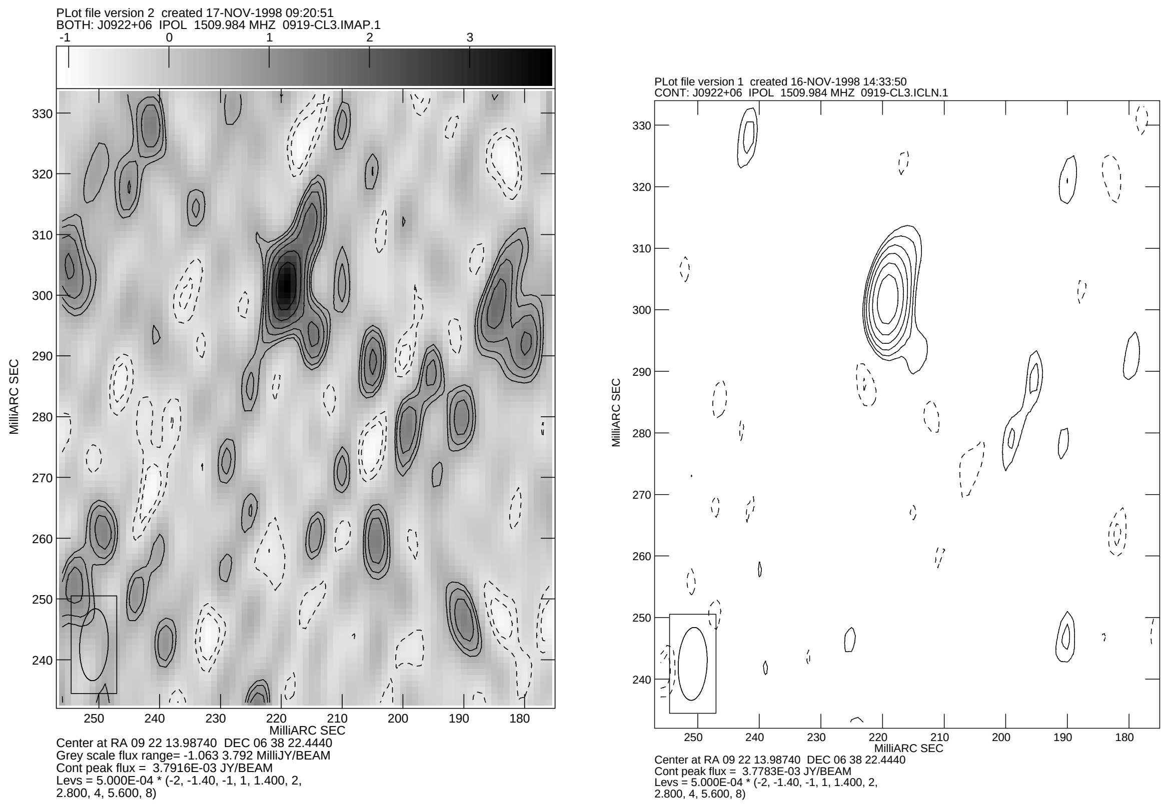

Fig. 3.— Day 1: Dirty and cleaned maps for B0919+06 *using in-beam calibration*. Contours from 0.5 mJy.

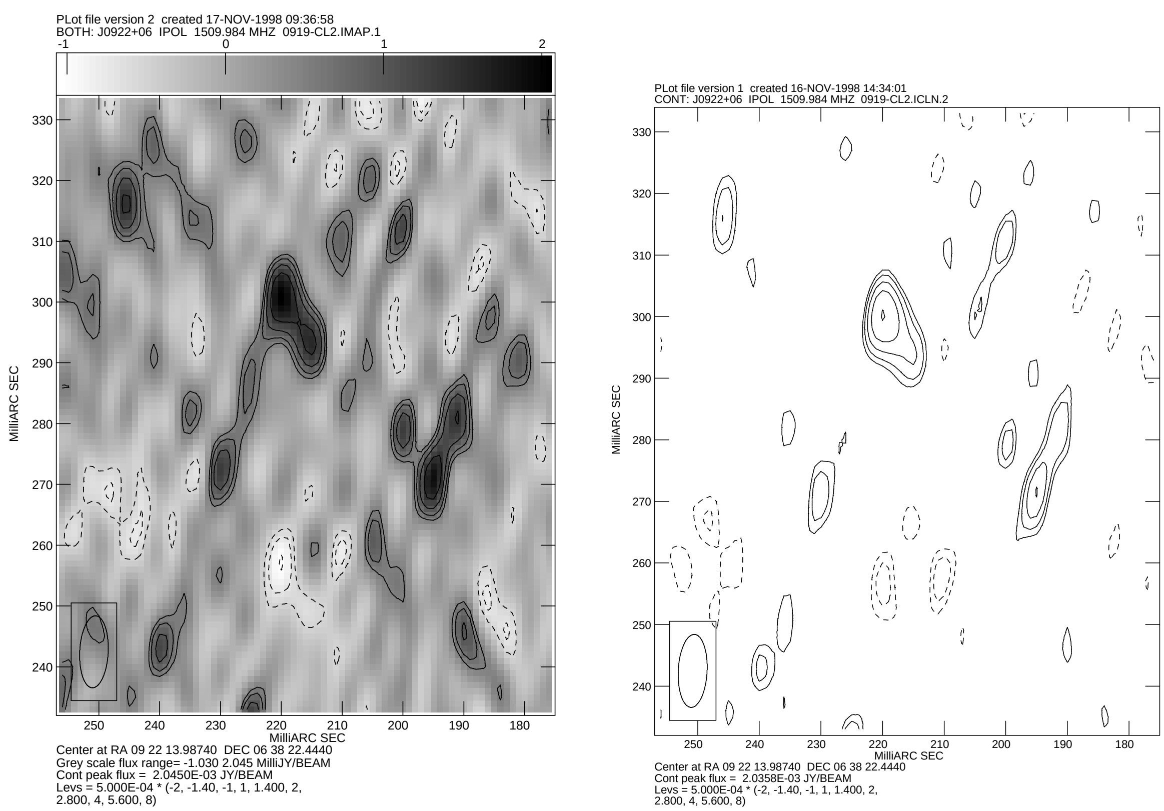

Fig. 4.— Day 1: Dirty and cleaned maps after phase referencing to a *nodding calibrator only*. In spite of lower peak flux and higher residuals, the fitted position is consistent with Fig. 3: phase referencing succeeds.

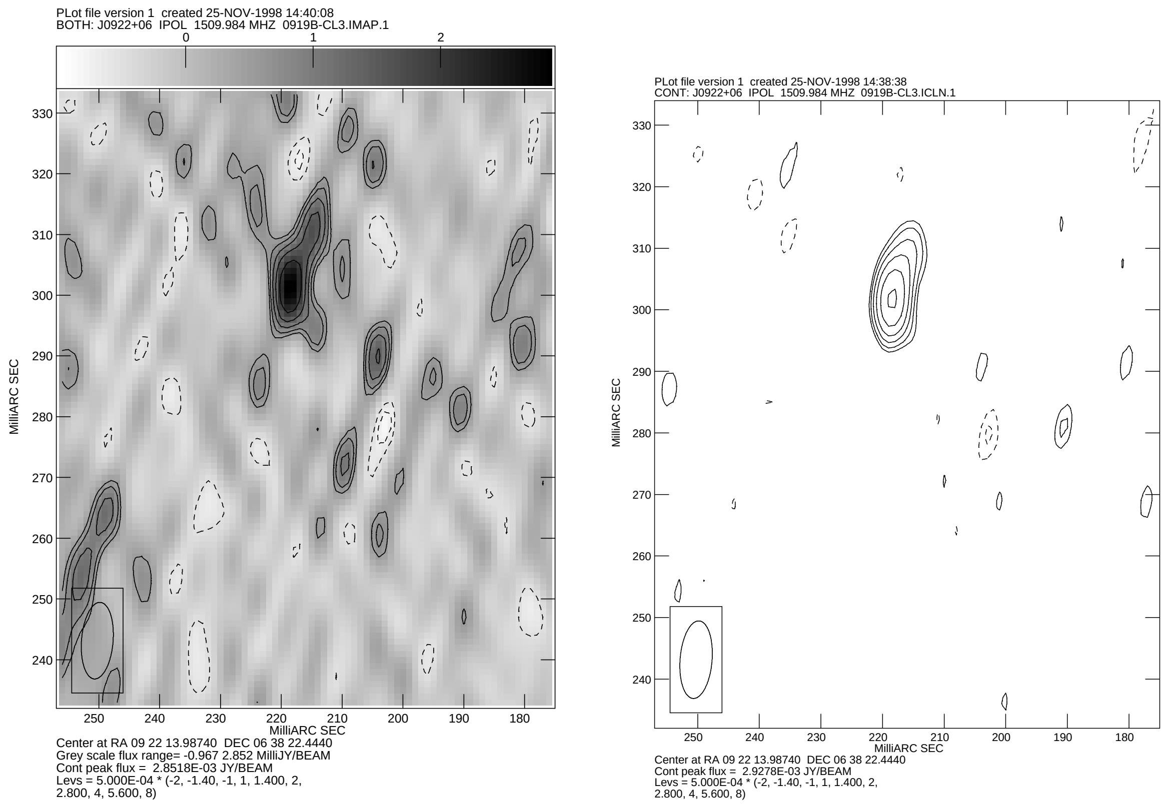

Fig. 5.— Day 2: Dirty and cleaned maps for B0919+06 *using in-beam calibration*. Contours from 0.5 mJy.

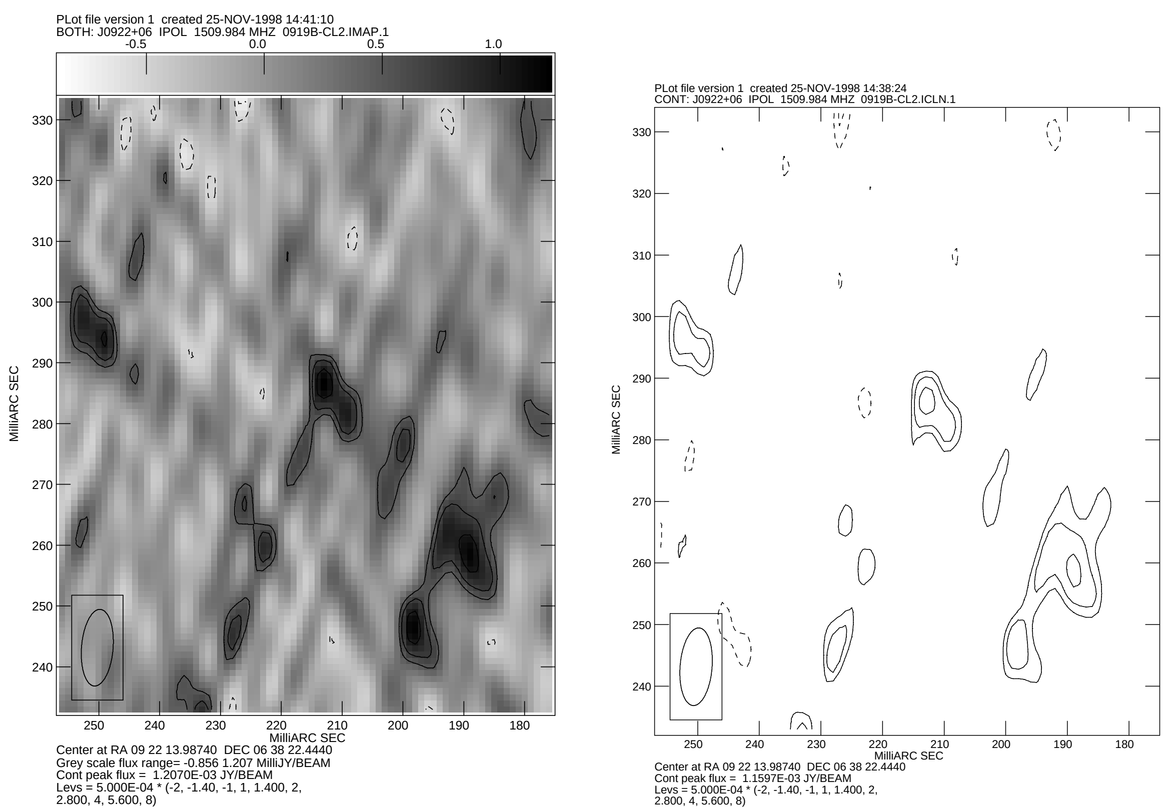

Fig. 6.— Day 2: Dirty and cleaned maps after phase referencing to a *nodding calibrator only*. The image is broken up into blobs and the fitted position is not consistent with Fig. 5: phase referencing fails here.