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Obtaining Good u-v Coverage when Extending the VLA with a VLBI Outrigger Antenna

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Abstract — We present an observational technique whereby a Mark II style VLBI array is formed from the Pie Town VLBA station and many of the individual antennas of the VLA. Seventeen VLA antennas were used for the current test observation, while using only the equivalent equipment of three VLBI stations. The technique is based on recording multiple antennas onto a single tape, each offset from the others in delay space. We refer to this technique as "Offset Delay Summation." Ordinary VLA data can be taken simultaneously with the VLBI observation, which allows excellent u-v coverage on the size scales sampled by the VLA. The composite array has approximately twice the resolution of the VLA in its most extended configuration. The u-v coverage on the VLBI baselines is also quite good, but this is obtained by sacrificing a factor of approximately three in signal-to-noise ratio beyond that achieved by normal Mark II VLBI. This technique is therefore applicable only to very bright sources. As currently implemented, the VLBI array is not completely connected, which may potentially cause problems with self-calibration of complicated sources.

Introduction

The technique presented in this paper allows one to effectively incorporate the Pie Town station of the Very Long Baseline Array (VLBA) into the existing Very Large Array (VLA). The technique utilizes a novel application of existing Mark II VLBI equipment. The summed signals from several VLA antennas are recorded onto a single VLBI tape. Each antenna is offset from the others in delay space which later allows recovery of the source visibility function on each individual baseline. This motivates the name, *Offset Delay Summation* (ODS). The ODS technique is general, but the particular hardware and logistical requirements are such that the VLA and nearby VLBA antennas are the only current instruments likely to benefit from it.

Scientific Justification

There are many features of powerful, extended radio sources that are just barely accessible to the VLA when it is operating in its most extreme configuration. For example, high frequency observations of typical radio jet termination regions clearly indicate much fine detail at or below the apparent size scale of 0.1". Such hot spots well exceed the complexity that can be reproduced with existing beam modeling techniques. If such regions are to be understood, *matched resolution* images in many wavebands will be required. Such images are used to measure the spectral curvature of the termination regions, which in turn constrain models of particle acceleration and diffusion. The VLA is capable of producing 0.1" images when observing at 15 GHz in its "A" configuration, but cannot achieve this resolution at lower frequencies.

The locations of the VLBA antennas relative to the VLA were selected such that the data from the two instruments could be easily integrated. The VLA can be operated as a high collecting area phased array, and is optimally positioned to serve as a central anchor for the VLBA. The nearest VLBA station to the VLA, Pie Town, is situated so as to smoothly extend the u-v coverage of the "A" configuration VLA, when the VLA is operating as a correlation array and is observing high declination sources. The longest internal baseline available within the VLA is 36.6 km. The longest baseline available between the Pie Town station and a VLA antenna is 73.3 km, so the resolution of the composite array is very close to twice that of the VLA alone. Note that the ODS technique achieves its enhanced u-v coverage by sacrificing a measure of signal-to-noise ratio (SNR) on each individual baseline. Thus there is strong incentive to use the most sensitive frequency band available. It is a happy coincidence that the most sensitive frequency at the VLA is the 8.4 GHz band, which is reasonably close to half of 15 GHz. Maps made with the VLA at 15 GHz will have nearly the same resolution as those made with the composite VLA/PT array at 8.4 GHz (0.1").

Experimental Overview

The ODS technique was demonstrated in an observation on Oct. 20, 1988. The experiment used a total of four Mark II VLBI terminals. One of the terminals was located at the Pie Town VLBA station, and the remaining three were located at the VLA. For the Pie Town station, this was a completely ordinary Mark II observing run. A VLA antenna on the north arm was designated as an "anchor," and its signal recorded to tape in the normal manner for single dish Mark II VLBI. The remaining two terminals were connected to the array sum ports for the east and west arms of the array. The north arm sum port was not used for this experiment due to lack of equipment. The u-v coverage from the north arm to Pie Town was very close to that from the west arm to Pie Town, so little coverage was lost. A unique, non-geometric, antenna based delay was introduced into the signal path for each antenna on a summed arm. This delay was later removed by the VLBI correlator, which allowed the signal from each individual antenna to be separated from that of the other antennas on the same tape. This will be covered in more detail in a later section. The VLA records four 50 MHz bandwidth intermediate frequencies (IFs), two of which record right handed circular polarization (RCP) and the other two left handed circular polarization (LCP). When observing with Mark II VLBI at 8.4 GHz, it is conventional to record RCP. When the non-geometric delay is injected into the summed arms, the coherence of all VLA data on that IF is destroyed. The data on the remaining three IFs are unaffected. Hence the ODS technique leaves more than half of the VLA data intact on any given VLA baseline. If the source is detectable on the 2 MHz bandwidth Mark II baselines, then a single 50 MHz VLA IF should be more than sufficient to image the source on the internal VLA baselines. If one is not concerned about matching polarization, all three pristine VLA IFs may be used. All VLA data are preserved for antennas which do not participate in VLBI baselines.

The VLBI style baselines obtained from this experiment fall into one of several categories. We have the VLA anchor to Pie Town, a summed arm antenna to the VLA anchor, and a summed arm antenna to Pie Town. It is possible in principle to to obtain the baselines between antennas on the east and west arms, and also between antennas on the same arm. These baselines, however, are badly degraded in signal to noise, as well as by spectral contamination from other antennas. These same baselines are also sampled by the VLA alone, with much larger bandwidth. Thus they are not needed for u-v coverage purposes. These baselines have not been used in the current study, but may be needed in the future to increase the number of closure triangles for self calibration of more complicated sources. Figure 1 shows the geometry of the antennas and baselines used in this experiment.

Comparison of ODS with Similar Techniques

The straightforward way to link Pie Town and some number of VLA antennas is to treat the VLA as a collection of single dishes, and to use as many of them as one can outfit with the requisite VLBI equipment. W. Cotton and collaborators are currently exploring just such a procedure. Both Cotton's observation and our own were designed under the same set of equipment constraints. Namely, there were three Mark II terminals available for use at the VLA, and one at Pie Town. Cotton's group formed a normal four station Mark II array. The observation described here also formed a four station array, but two of the four stations were entire arms of the VLA summed together. It is interesting to contrast the strengths and weaknesses of both approaches.

First of all, both Cotton's technique and our own suffer from the usual ills of Mark II VLBI. That is, all absolute phase information is lost, and the 2 MHz bandwidth is a factor of 25 less than that of either a Mark III VLBI or VLA observation. The normal four station array suffers from very sparse u-v coverage. In this sole respect, the ODS technique is much superior, but in order to achieve this coverage the ODS technique suffers a number of other losses. On any baseline involving a summed arm, it suffers a loss of signal-to-noise ratio equal to the square root of the number of antennas on the arm. Thus with nine antennas on an arm, the SNR is reduced by a factor of three. The ODS experiment SNR on such baselines is also reduced by an additional factor of approximately 0.9. This factor arises from the fact that VLBI data from the VLA analog sum port is digitized twice, while VLBI data from a single VLA antenna is only digitized once. The quantization correction will be discussed in more detail in a later section. The ODS technique also suffers from the potential problem of antenna crosstalk. If this proves to be a more serious problem than it currently appears, future experiments can be run with a wider separation in delay space at cost in correlator processing time. It is currently not practical to correlate two summed arm tapes against each other, nor is is practical to correlate a tape against itself. Consequently the array that is formed by the ODS technique is by no means completely connected. Note that all of the missing baselines from the VLBI array are measured by the VLA with considerably higher bandwidth. The technique used by Cotton's group simply discards all VLA data on the three VLA antennas used for VLBI data, while the ODS technique discards some of the VLA data on most of the antennas. Finally, Cotton's generic four station experiment has the advantage that it is significantly easier to process, in that the data path has been explored much more throughly. This consideration will become less important as we gain more experience with the ODS technique.

In the future, it is possible that signals from individual VLA antennas could be recorded onto separate tracks of a VLBA tape. This would produce an experiment of much the same type as Offset Delay Summation, but with none of the characteristic SNR or crosstalk problems. This option would require specialized hardware for the data acquisition, however, and the correlation would have to done on the VLBA correlator, which is still in the construction stage. It should also be mentioned that *all* of the techniques mentioned here are inferior in every respect to simply integrating the Pie Town antenna directly into the VLA with a fiber optic link. This would allow full VLA bandwidth observation at Pie Town (4 times 50 MHz), real time correlation, and would expedite integration of VLA and full VLBA data. This option is fairly expensive, however, and its timescale is not clear. The ODS technique described here can be considered one of several temporary measures until such a link becomes available.

Sensitivity

Lack of sensitivity is probably the most severe liability in the ODS technique. Mark II VLBI is not tremendously sensitive by modern interferometry standards, and we lose yet another factor of three beyond that on summed arm baselines. Following [Walker 89], we can write an expression for the noise on a baseline as

$$\Delta S_{ij} = \eta_b \sqrt{\frac{T_{si} T_{sj}}{2 \Delta t \Delta\nu K_i K_j}} \tag{1}$$

In this equation, η_b is a "practical loss factor," that will be taken to be 2.5. The integration time and bandwidth are Δt and $\Delta\nu$ as usual. The T_s terms are the system temperatures for the antennas on the baseline and can be taken to be 38 $^\circ K$ for both a typical VLA antenna and for Pie Town. The K terms are antenna sensitivities and are .110 °K/Jy and .129 °K/Jy for a VLA antenna and for Pie Town, respectively. Assume 100 s to be a typical coherence time for 8.4 GHz, and use the $\Delta\nu$ = 2 MHz bandwidth of Mark II VLBI. This expression then evaluates to 40 mJy. If we wish to detect a source on a baseline for the purposes of fringe fitting, then at least $5\Delta S$ or 200 mJy is required. Since all antennas at the VLA run off of the same clock, the difficulty of finding fringes to the summed arm baselines is somewhat reduced, once one knows the clock offset between the VLA anchor and Pie Town. Still, however, the noise on the summed arm baselines can be expected to be a factor of 3/.9 greater than that above, or 133 mJy.

Sources & u-v Coverage

The observations consisted of five one-hour pieces, spread over nine hours in order to maximize u-v coverage. The time was divided between 3C84 and the northern hot spot of 3C268.1 in a 1:2 Ratio. 3C84 is the compact radio nucleus of the peculiar elliptical galaxy NGC1275. It is unresolved on these size scales. 3C268.1 is a classical double lobed radio galaxy, with hotspots separated by 2.5 arc minutes. Unfortunately, the fine scale structure of 3C268.1 was sufficiently resolved that there was no detection of the source on any baseline between Pie Town and the VLA. The northern hotspot of 3C268.1 has a total flux at 8.4 GHz of 1.6 Jy. It had resolved out to less than 200 mJy on the longest VLA baselines, so in the light of the above calculation a non-detection is not surprising. This gives a feeling as to just how bright a source must be to be detectable with these techniques. The observations described here are five twenty minute scans on 3C84, starting every two hours. This is not very much observing time by VLBI standards, but due to the high number of participating antennas the u-v coverage is quite acceptable. Figure 2 shows the model coverage for this experiment with full u-v tracks. Figure 3 shows the actual u-v coverage that was obtained. Note that while Pie Town indeed "optimally" extends the VLA u-v coverage, there is no way for a single antenna to do so uniformly due to blockage by the earth. This experiment will result in a synthesized beam with aspect ratio of about 1:2.

Correlation

The data were correlated on the NRAO Mark II spectral line correlator. There is no reason why this experiment could not be processed on a continuum processor, but the spectral line correlator allows all baselines on a single arm to be processed in one pass. This greatly simplifies the logistics of correlation. The VLA electronics have delayed the signals of all the summed antennas to the common reference point of the array. The VLBI correlator is told that the physical position of the arm is this reference position. Clearly, if we are to get fringes at all, the final delay as used in the correlator must equal the geometric delay between the physical antennas on a baseline. This condition will be satisfied for a given antenna when the delay offset from the central channel of the delay spectrum is equal to the negative of the non-geometric delay introduced into the summed arm. This criterion will be satisfied for only one antenna at a time, giving rise to a peak in the delay spectrum. All other antennas will have a grossly incorrect delay value, and will contribute only incoherent noise to the arm sum. In a Mark II correlator the delay per channel (one lag), is exactly .25 μs. The delays introduced into the summed arms were selected to be an integer number of lags, so that the peaks corresponding to each antenna are an integer number of channels apart. The antennas were typically separated by 28 channels in delay space. This number was selected from the desire to fit all nine antennas along an arm into the 288 channels allowed by the correlator, (and hence to allow simultaneous correlation of all nine antennas in a single pass of the correlator.) It turns out that delay offsets selected in this manner are within a factor of several of the maximum possible delay allowed by the VLA hardware. An example of a delay spectrum produced in just such a manner is given in Figure 4.

The issue of antenna crosstalk is a potentially worrisome one. If the antennas are too close together in delay space, they can interfere coherently with one another, producing nonclosing errors. Fortunately, a simple simulation using Fourier theory and direct summation of the contributions from each lag indicates that spectral contamination from adjacent antennas in delay space should be less than a few percent. Direct examination of the delay spectrum in Figure 4 confirms that this is a reasonable estimate. This issue is one that should probably be resolved later, by direct experiment. Should crosstalk between antennas prove to be a serious problem in subsequent observations, one could increase the delay offsets between antennas, subject to the constraints of the VLA delay lines. In this mode, one would simply correlate a window of 288 channels at a time, using as many windows as needed to cover all nine antennas. Taking this approach to an extreme, it would be possible to perform this experiment on a continuum correlator, by processing every single baseline individually.

Post Processing

There are some fairly subtle phase errors introduced by the VLBI correlator that must be removed by the NRAO/SAO spectral line package. There remains one phase error which is still unexplained. Since this phase offset can be in principle be determined experimentally, it does not by itself invalidate this proof of concept observation. It is hoped that this offset will soon be removable analytically. The majority of the post processing is done in the NRAO data reduction package, AIPS. The data from the correlator can be selected by delay channel, and read directly into the package. In this manner, one selects an antenna merely by bracketing the appropriate peak in the delay spectrum. Since all baselines from a given summed arm tape carry the same bookkeeping information, this information must be changed to reflect both the correct antenna identification numbers and the correct physical position of the antennas. Once this has been done, however, the data set is then little different from any other Mark II VLBI data set in AIPS. The mechanics of system temperature calibration are somewhat different than usual, but not conceptually different from the single dish VLBI case. At this point, the data may be calibrated and presumably imaged in the usual manner. The data from the test observation has been calibrated to the extent that flat closure phases and amplitudes have been obtained. The calibration process is still under study, and no images have yet been obtained. The VLA data taken during the run is also quite normal, once one flags out all data affected by the artificial delay offsets. Even in the worst case, one still has better than 50% of the VLA data obtainable from a "normal" observation. This data can be imaged individually, and then combined with VLBI data. A complete data path is given in appendix A.

Experimental Details

This section covers those details of the experiment which are not necessary for broad understanding of the ODS VLBI technique, but which are quite crucial to obtaining usable results at the VLA.

Delay Constraints of the VLA

As the VLA was designed for a maximum baseline length of 36.6 km = 122 μs, it has a maximum allowable correlator delay only somewhat larger than this. In particular, the governing equation is

$$TD = GD - CD + PD + OFF \tag{2}$$

where TD is the total delay, GD is the geometric delay, CD is the cable delay, and PD is the peculiar delay. OFF is an offset designed into the electronics, and is equal to 153.6 μs. GD is defined as the geometric delay relative to the reference position of the array. Normally the reference position coincides with the physical center of the array, but in the correlator mode used in this experiment it is instead the physical position of the anchor antenna. The cable delay measures the propagation time from antenna to VLA correlator. For purposes of designing an experiment it may be equated to the distance of the antenna from the array center, measured in light travel time. This number is tabulated in the **USA VLBI NETWORK Handbook**. More precise values are available on request from the VLA scientific staff. The peculiar delay is a correction which accounts for small differences in the electronic systems, and is different for each intermediate frequency (IF) and antenna. We introduced the delay offset into the system by adding our additional delay to the correct peculiar delay for any given antenna. This mechanism allowed us to modify only the IF used for VLBI, and not damage the VLA data on the other three IFs. The value of the total delay must lie within the range 10 ns $\leq TD \leq$ 163840 ns. Exceeding this limit is disastrous, in that the on-line system will give no warning, but will simply use the low order 14 bits of whatever delay happens to have been calculated. This will utterly destroy a delay peak at the expected position in the spectrum, and may possibly cause it to reappear at some other, essentially random position.

When our observing time had been assigned, we used a small program to plot the acceptable peculiar delays against time for representative antennas of the VLA. This simply involves calculating the geometric delay as a function of time and source, and using this result to solve equation 2 for peculiar delay. By constraining the total delay to be equal to the minimum or maximum allowable value, one can solve for the corresponding limit in peculiar delay. In general, this limit will be a sinusoidal oscillation around a mean value. The amplitude of the oscillation will be proportional to the antenna's distance from the array reference position. Figure 5 is a plot of acceptable peculiar delay values for our observation as a function of Local Siderial Time. In this plot, the solid vertical lines delimit the acceptable peculiar delay range for an antenna near the center of the array, and the dashed lines delimit the same range for an antenna at the extreme end of the west arm. Note that at any given time, the range of acceptable peculiar delay is exactly 163.84 μs wide. This is due to the $2^{14} \cdot 10$ ns = 163.84 μs total delay range allowed by the VLA. The difference of mean maximum peculiar delay values noted as 68.5 μs on the plot is entirely due to the different cable delay values for the two antennas. This value is essentially the length of a VLA arm, measured in μs. Unless one is working very close the maximum allowable delay range, it is wise to select a peculiar delay that can be held constant over the entire observation. The range of allowable, *constant,* peculiar delay values is determined by the maximum and minimum values of the sinusoidal envelopes. These extremal value are marked with dotted lines for the end antenna. The allowable peculiar delay range for each antenna is denoted with a heavy horizontal line. Note that one may make use of the entire range in peculiar delay from the minimum value allowed by the central antenna to the maximum value allowed by the end antenna. In our case, the magnitude of this range works out to 216.2 μs. We limited ourselves to a delay range of 72 μs for convenience in correlation, although it may be wise to utilize the largest possible delay range in future experiments.

Fringe Rotation Details

A critical issue of Mark II VLBI that must be addressed is that of fringe rotation. The VLA normally varies the phase of its local oscillator chain so as to keep the fringe frequency of the interferometry response near zero. The fringe rotation is an antenna based correction, and occurs in the antenna vertex room. This must be turned off for VLBI observations, since it will later be taken into account by the VLBI correlator. Similarly, it must be turned on in order to take VLA data. There is no explicit way to disable the fringe rotation. However, the LO phase correction for the jth antenna has the form

$$\phi_j(t) = \omega_0 \mathbf{L}_j \cdot \mathbf{s}_0(t) - 2\pi n \tag{3}$$

where $\mathbf{L}_j$ is the position vector from the center of the array, in seconds. $\mathbf{s}_0$ points towards the phase reference position, and ω_0 is the band reference frequency. The only time dependence in this expression is caused by the apparent motion of the source across the sky. The $2\pi n$ term simply reflects that this phase shift need never be greater than a turn, and will henceforth be dropped. Under normal circumstances, a single VLBI antenna is placed in its own subarray, the array reference position is adjusted to correspond to the physical position of the antenna, and $\mathbf{L}_j$ is set to zero for that antenna. (This is the VS correlator mode.) In our case, we ran the entire array in this mode, with anchor antenna on the north arm as the designated reference. Consider a triangle composed of the three vectors, $\mathbf{L}_j$, ℓ_j, ℓ_{ref}. The first is as before, and the last two are earth centered vectors pointing to the jth antenna and the array reference position, respectively. To the phase from the jth antenna, the VLA will add

$$\phi_{VLA} = \omega_0 \mathbf{L}_j \cdot \mathbf{s}_0 \tag{4}$$

and the VLBI correlator will add

$$\phi_{VLBI} = \omega_0 \ell_{ref} \cdot \mathbf{s}_0. \tag{5}$$

Thus the net fringe rotation of the jth antenna is

$$\begin{aligned} \phi_{VLA} + \phi_{VLBI} &= \omega_0(\mathbf{L}_j + \ell_{ref}) \cdot \mathbf{s}_0 \\ &= \omega_0 \ell_j \cdot \mathbf{s}_0. \end{aligned} \tag{6}$$

This is precisely what we want to stop the fringes in the VLBI correlator.

LO Offset Details

There are hardware-based reasons why it is desirable to avoid correlation of a signal with a zero natural fringe rate. The first is that the fringe rotators in the VLBI correlator produce an approximation to a sine wave that is quantized to three levels. The fringe rotator is essentially applying the negative of the natural fringe rate, in order to "stop" the fringes. If the natural fringe rate is small, and the fringe rotator does not cycle through many turns in an integration period, then severe defects in both amplitude and phase may be introduced by the coarse quantization. The second reason is that the two level samplers used in VLBI often have a significant DC offset. Consider that in the case of zero fringe frequency, the DC offsets in both samplers on a baseline would correlate perfectly with each other. This effect produces a spurious contribution to the correlation coefficient of roughly $3/4\epsilon_1\epsilon_2$, where the ϵ_i are the (non-zero) mean samples. This expression can be easily calculated directly from the definition of the correlation coefficient. Note that when correlating any of the VLA antennas against each other, one obtains exactly this worst case. As far as the Mark II correlator is concerned, all of the VLA antennas are located at the same physical point, and consequently the baseline between them has zero length and a zero natural fringe rate. Again, the spurious correlation effect will decrease quickly if the natural phase makes many turns in an integration period. In normal VLBI practice, this entire issue is largely ignored because the long baselines used ensure very high natural fringe rates. The baselines used in this experiment were short enough that we needed to introduce LO offsets to prevent these problems.

The basic idea of an LO offset is that one literally sets the local oscillator of an antenna to something other than the reference frequency of the experiment. This shifts the bandpass of that antenna by the magnitude of the LO offset. Shifting a spectrum in frequency space corresponds to convolution with a shifted delta function, or multiplication by a complex exponential in time. That is, by shifting the spectrum, we have introduced an additional phase wind into what we would otherwise have measured. Due to equipment constraints, our LO offsets in this experiment had to be multiples of 10 kHz, which is reasonably large by VLBI standards. What is worse, we had an LO offset on every antenna in the experiment. In retrospect, this was probably a mistake. Our desire to use the 288 delay channel, two-station mode of the correlator also prevented us from dodging this problem by simply always keeping the same antenna on correlator station A. That is, we were forced to have antennas with different reference frequencies on that station of the correlator. This subsequently uncovered a few regions of the data path that had not been previously explored.

In addition to the more subtle problems associated with multiple LO offsets, we were also affected by a known problem with them. One unfortunate consequence of using LO offsets with this particular correlator is that the value of the LO offsets applied back to the phase is only stored to 32 bits. In our case, this results in a quantization error of roughly a milliHertz (mHz), while the actual frequencies used are essentially exact. Thus the LO offset is not removed correctly in the correlator, and the phases will carry a residual rate on this order. If one is careful about the ordering of the baselines, is often possible to correlate such that these errors will cancel around all closure triangles. It is also possible to correct this problem with the NRAO program `AVG`, which was the approach that we took.

Coordinate Systems

When inserting the correct antenna positions into the AIPS antenna table, one must choose whether to bring Pie Town into the VLA's coordinate system or to do it the other way around. In short, one needs the connection between the two coordinate systems. While it is well known that the VLA and VLBI coordinate systems share a common z axis, and the two systems differ by both handedness and a rotation about that axis equal to the VLA's longitude, there is a subtlety not often appreciated. In a frame fixed to the antennas, the standard VLA reference position and the VLA phased-array center are one and the same position. However, the reference position passed in an AIPS 'AN' file is a *surveyed* position. It differs from the value as determined by VLBI measurements by nearly 60 meters. This offset must be included when transferring VLBI positions from one frame to the other. Of course, these positions only enter into the imaging portion of the experiment, not the correlation portion. Thus modest baseline errors are not particularly damaging.

Results and Interpretation

The results from this work consist of calibrated amplitudes and closure phases. Ratios of these calibrated amplitudes are functions of the number of antennas used in the arm sum, and the quantizations suffered by the signals. These ratios scale exactly as predicted analytically. Our test source is unresolved on the size scales that we have measured. Consequently, we expect that the measured closure phase should be identically zero. We present here closure phases that are constant in time, but non-zero. While this offset is disturbing in that it indicates a phase artifact has been introduced into the data, the constant nature of the closure phase in time clearly indicates that we have measured the astronomical visibility of the source.

Amplitude

The numbers that come out of the Mark II correlator are normalized correlation coefficients. That is, for two input signals $x_i(t)$ and $x_j(t)$, we measure

$$\rho_{ij} = \frac{\langle x_i(t)\, x_j(t) \rangle}{\sigma_i \sigma_j}. \tag{7}$$

Stating this in words, we measure the ratio of the correlated power to the total power. For astronomical purposes, however, we require the correlated power from the source. This is an invariant quantity that should be independent of the instrument used to measure it. The above equation is somewhat abstract, however, in that it assumes $x_i(t)$ and $x_j(t)$ to be the inputs to the correlator, not the flux from the source. It carries the qualitative behavior that we need, however. The numerator is proportional to the geometric mean of antenna sensitivities (the K_i, as defined back in the section on sensitivity), and the denominator is proportional to the geometric mean of the two system temperatures. (The latter statement assumes that the antenna temperature from the source is much smaller than the system temperature. For VLA antennas observing 3C84, this is an excellent approximation.)

Refer back to Figure 4, and note that the pulse heights vary by some tens of percent. Since all of these nine baselines have one station in common (Pie Town), we are looking at variations in the individual VLA antennas. One can plot these pulse heights against the square root of the measured system temperature for each antenna and discover a roughly linear trend, as one would expect. The deviations from linearity are small enough that we may ascribe them to variations in individual antenna sensitivity. We have no way of measuring the sensitivity of a given antenna, (unless one considers a delay spectrum such as this to be such a measurement), and so must simply assume that all of the VLA antennas are equal in this sense. Since such an assumption is obviously naive at some level, we note that a measurement which involves the mean level of many antennas is likely to better conditioned than a measurement that involves the level of only one antenna.

The next germane fact to consider in this analysis is that the VLA signals are sampled optimally. This means that the amplitude of the analog signal from each antenna is adjusted so as to be an optimal match to the three level sampler. The actual matching criterion is unimportant; the crucial point is that each antenna is constrained to contribute exactly the same amount of noise power to the analog sum as all the others. The three-level sampling process will of course alter the power spectrum contributed by each antenna, but it does not alter the condition that each antenna contribute equally. The noise contributed by each antenna is uncorrelated with that contributed by any other. The variance of such signals add algebraically. The standard deviation of N such signals summed together is $\sqrt{N}$ times the standard deviation of one signal. Refer once again to the simple equation 7, and see that we have deduced that the measured correlation coefficient of an antenna on a summed arm will drop with the square root of the number of antennas on that arm. Since we have two summed arms with different number of antennas in the sum, we can see if the ratio of amplitudes to a common third antenna obeys this scaling law.

We would like to compare amplitudes between the VLA anchor to Pie Town and a summed arm to Pie Town, but there is an additional factor to consider. The signal from the VLA anchor antenna has been quantized once, in the VLBI two-level sampler. The signal from a VLA antenna has been quantized twice, once in the VLA three-level sampler, and once in the VLBI two-level sampler. Both samplings occur at the Nyquist rate relative to the bandwidth at the sampler's input. (The sampling rate is 100 MHz and 4 MHz, for the VLA and VLBI samplers, respectively.) The signal from the summed arm is filtered from 50 MHz down to 2 MHz just prior to the two-level sampling. Each quantization introduces a certain amount of noise, with a corresponding loss in signal-to-noise ratio. It is possible to work out the loss in SNR relative to the SNR of an unquantized correlator for any given choice of quantization levels in the two input signals. In the limit of small correlations, (i.e. most cases of astronomical interest), the correction works out to be a constant multiplicative factor. See [Hagen & Farley 73] or [TMS 86] for an excellent discussion of this theory. For example, the correction normally used at the VLA is that for the 3-level by 3-level quantization, which is sampled at the Nyquist rate. This number is .809. The case appropriate for the normal Mark II VLBI practice is two-level by two-level, also sampled at the Nyquist frequency. This has the analytic value of $2/\pi$, or .637. Normally it is not permissible to simply multiply two such corrections together. The entire process of sampling and summing and filtering and resampling and correlation should be analyzed as a unit. While possible, this is a fairly difficult calculation. The saving grace in this instance is that the two-level quantization correction is very insensitive to the form of the input distribution, even though it was derived under the specific assumption of a Gaussian input. Second of all, we are summing nine independent signals together and then decimating in time by a factor of 25. The Central Limit theorem tells us that such a signal will tend towards a Gaussian distribution, independent of the original distributions summed. In this case, then, we may approximate the quantization correction for the entire process as the product of a correction for the VLA sampling times a correction for the VLBI sampling. Note, however, that the signal from Pie Town suffers no three-level quantization at all. Thus the correction for the three-level sampling should be that for a three-level signal against an analog signal, rather than the three against three level correction mentioned before. [Hagen & Farley 73] have worked out this case, and the appropriate correction is .902.

With these predictions in hand, we form the mean amplitude ratios for the various classes of baselines. (The amplitudes have been corrected for system temperature variations, but there is still some scatter in the measurements due to sensitivity variations between antennas.) Thus we arrive at the numbers in Table 1. Note that the ratio of the summed arms to Pie Town and the summed arms to the VLA anchor are almost identical. We do not expect the two arms to be identical, since there are different numbers of antennas on each arm, but we do expect the the ratio of the two to a common antenna to be constant. After dividing out the additional quantization correction, the ratios for the east arm are far more consistent with there having been 8 antennas on the east arm rather than 7. Close examination of the operator log file reveals that one of the two missing antennas from the east arm was missing not due to hardware malfunction or logistical reasons, but because it simply lacked an 8 GHz receiver. Since this antenna was otherwise deemed "healthy," it was not disabled in the arm sum. So one of the eight antennas on the east arm is in fact the autoleveled thermal noise of a termination resistor! With this understanding, all the ratios agree with the predictions. No ratio deviates from the predicted value by more than two percent, which is about all one could ask from an a priori amplitude calibration.

Closure Phases

The signature of an unresolved point source is a closure phase equal to zero. The closure phase is essentially immune to antenna based irregularities of clock or atmosphere. By contrast, the absolute phase on any given baseline is also zero for an unresolved point source at the observation's phase center, but it is very vulnerable to irregularities in any experimental parameter. In practice, the absolute phase of a baseline is not considered to be an observable quantity for a VLBI observation, being contaminated as it is with non-astronomical factors. Quite obviously, the closure phase is the quantity to use as a diagnostic of this technique's validity. In Figure 6, we see the raw phases for a typical closure triangle. We can clearly see variations of an irregular nature. (And in fact, this slice of the data is considerably less violently variable than some other portions.) In Figure 7, we see closure phases from several typical triangles, including that from the same data as Figure 6. While there is clearly a small Fractional Bit Shift effect that remains in the data, (see Appendix B for full details on this effect), the mean value of the closure phase is quite constant in time. This demonstrates that the data path has preserved the closure relationships in the data, even if additional effects have been introduced as well. Note that the closure offsets for the two triangles including the west arm are the same, and similarly for the east arm. The two offsets, however, are not the same. This suggests that the closure offsets are being introduced in a station dependent manner. If this is indeed the case, then it will be possible to calibrate this effect out of the data simply by observing a point source prior to the source of interest. It is desirable, of course, to understand precisely what is causing this offset. Work to this end is still in progress. It may well be that a new test observation will be necessary to completely understand this effect. At the very least, if observations of two widely spaced point sources were to produce the same closure phase offsets, it would demonstrate that the effect is sufficiently constant to be calibrated out of the data with confidence.

Suggestions for Future Experiment Design

The ODS technique seems sufficiently promising that there will likely be additional observations made in this style. This will undoubtedly use the more sensitive VLBA recorders and correlator, and hence a different data path than we have used. This is a summary of changes and advice that our experience leads us to suggest.

- **Contact the local staff first!** Contact the scientific staff at the VLA *before* submitting a proposal. The equipment used to perform this kind of observation is not stable. It would be wise to ensure that the equipment you need will be available before you request the use of it. As of this writing, (September 1992), the three summed arms of the VLA are individually available in the correlator room, but not in the electronics room. Some provision will have to be made for signal transport. It is possible that some of the cabling for the High Time Resolution Processor (HTRP) could be borrowed for this purpose, or new cables could be brought through the bulkhead. There is provision in the VLBA correlator specifications for splitting the signal from a single recorder into multiple pieces, but it will be among the last features of the correlator to be implemented. Electronics necessary to record the sums on the VLBA recorder are also not yet complete.

- **Use an asymmetric delay spectrum** For at least one arm, use an asymmetric pattern of offset delays. This will allow unambiguous identification of delay peaks with corresponding antennas. This correspondence is not immediately obvious if the delay spectrum is symmetric. Misidentification of an antenna is disastrous, and it is comforting to look at a delay spectrum and *know* that it is unambiguous! With 1024 delay channels available on the VLBA correlator, and the smaller lag size due to the higher bandwidth, there is considerably more flexibility available in delay placement than with the Mark II system.

- **Include a single anchor antenna** This will allow a number of relatively high sensitivity closure triangles which can be used as the backbone of the calibration. Correlation between at least some antennas on the same arm will be needed to provide more triangles than unknowns, so plan the delay placement accordingly.

- **Consider alternative calibration strategies** If the electronics of the two systems are stable for longer periods of time than the atmosphere, it may be possible to partially transfer a self calibration from the internal VLA data to the VLBI array, reducing the number of gains and offsets that must be solved for. This has not been investigated, but maybe prove to be useful.

- **Plot closure phases** In a experiment of this type it is essential to ensure that everything is working by direct examination of the closure phases. AIPS now has this capability and if necessary the data can be exported to the standard Caltech VLBI package for more in depth examination. It is also recommended that one include at least one observation of a point source such as 3C84 in order to obtain closure phases that can be interpreted easily. If it becomes necessary to determine the closure phase offset experimentally for each individual observation, then observation of a point source becomes mandatory.

- **Use single reference frequency (Mark II system only)** Note that if both the Pie Town antenna and the VLA anchor antenna are set to the same frequency, it will be possible to correlate the entire experiment with the same frequency on the A station of the correlator. (That is, all baselines will contain one of these two antennas on station A.) The baseline from the VLA to Pie Town is long enough that the zero fringe rate problem will probably not be too severe. The benefits of a single reference frequency probably outweigh the disadvantages of low fringe rates.

- **Consider three-station correlation (Mark II system only)** While this is much slower and labor intensive than the method used in this paper, there is far less to go wrong. At a minimum, correlation of a single triangle in this manner will give a valuable intermediate check against the same triangle correlated in two-station mode. In three-station mode, the same antenna can be used as processor station A for all baselines, and hence any problems with reference frequency vanish.

Conclusions

We have demonstrated that the Offset Delay Summation technique does conform to predicted behavior, insofar as amplitude is concerned. The existence of flat closure phases strongly suggests that the astrophysical visibility phases are being measured, and are recoverable from the measured data. However, the presence of the non-zero closure phases in the observation of a point source also indicates that we do not completely understand all artifacts that are introduced into the data. Since the artifact is a simple phase offset and in principle measurable, it does not by itself preclude ODS as a useful observational technique. It is a cause for concern, however. It is possible that additional observations may be needed to identify the cause of this artifact. Later observations may well be performed with the VLBA correlator, in which this point becomes moot.

This paper and observation can be regarded as a proof of concept. A theoretical technique is presented, along with the observations that demonstrate the ability to perform the essential foundations of this technique. While the ODS technique is not now in a position to make maps of complicated sources, there is good reason to believe that it can eventually do so. The path to demonstration of this technique has been complicated, and occasionally subtle, but has presented no insurmountable difficulties. Better still, many of these difficulties were in areas of misunderstandings or malfunctioning software or even inappropriate experimental design. These problems need not be faced again in a subsequent observation. While ODS VLBI will never be a "straight forward" technique, when compared to routine observations at the VLA, it is our hope that it can be made simple enough to be used by anyone with a need for the spatial frequencies that it can provide.

A Detailed Data Path

This appendix is both a record of the data path that was followed for this observation, and a guide list of appropriate steps to take in order to initiate a new ODS observation. All programs that were used have been enumerated, but only those not in the standard Mark II data path have been fully explained. Note also that a repeat of this observation would not necessarily use the identical data path, both due to evolution of the hardware, and due to understanding gained from the current observation.

- **Offset Delay Preparation** One must first decide on the desired spacing of antennas in delay space. Be aware of the limits of the correlator, and decide on an acceptable balance between antenna isolation and correlation convenience. A program, `DLAMAX`, was written and used to plot the acceptable peculiar delay values for representative antennas. The offset delays were entered into the system by modifying the existing peculiar delay values in a copy of the file SYSXIF. You must consult with the on-line programming staff for access to this file. The preparation of this file should occur as close as possible to the observation as conveniently possible, in order to make use of the most recent existing peculiar delays.

- **Basic Scheduling** `SCHED` is used to create the machine readable VLBI schedules. `OBSERVE` is used to schedule the parallel VLA observation. The VLA must be in VS mode during the observation, with the entire array included in the "single dish" subarray. The VLA must be directed to use the modified SYSXIF file with an LO card in the observe file. Also note that the default VLBI LO setup has both the AC and BD IF pairs overlapping, which is almost certainly *not* what is desired. Modify at least one of the synthesizer settings on the LO card to separate the IF pairs.

- **Observation** The cabling is standard, with the anchor antenna being cabled as usual for a single dish experiment. The summed arms are cabled in a similar manner to a phased-array experiment, except that the input to each formatter comes from an arm sum port, not the phased-array port. The sum port has been rebuilt since this experiment was done, so the cabling will certainly change to an extent. The individual arm sums are currently not implemented in the new sum port, but can be provided "if needed." Alternatively, the old sum port is still available. Consult with the scientific staff as to the current status of the sum port. In our observation, an LO offset was provided on all stations other than the VLA anchor antenna. One may wish to remove the LO offset from the Pie Town antenna in future observations. Take data.

- **Correlation** The ordinary suite of NRAO/SAO programs, `LOGGER` and `DECODE` are used to move the VLBI data to and from the VLBI correlator. Data may be correlated in two or three baseline mode, as is deemed convenient. If at all possible, stations with an LO offset should *not* be placed on station A of the correlator. (That is, all stations used as station A should have the same reference frequency.) The positions of the antennas given to the correlator should be that of the VLA reference position and the physical position of Pie Town. (Note that in 'VS' mode, the VLA reference position is the position of the reference position.)

- **NRAO/SAO Suite Post Processing** AVG must be used to fix the known problem with LO offset roundoff error. Simply set the DOP parameter to what it should be. Be certain to use the most modern version of AVG that is available. Several bugs in this program were fixed during the course of this data reduction. MORASS must be used to refer all reference frequencies to earth center. This is especially important if any station A was processed with an LO offset. (This program contains an updated version of the older program, CVEL.)

- **Import VLBI data to AIPS** VLBIN can select data by channel, so one can simply read the appropriate data in by selecting the appropriate peak in delay space. A new antenna file must be created with the correct physical antenna positions. Write an antenna file from a nearby VLA observation into an ASCII file using ANFIX. (This task was also written for this project.) Add the Pie Town antenna into the file with a text editor, using the equations of appendix C to convert the VLBI position of the Pie Town antenna into the VLA frame. This may be read back into AIPS as needed. ANFIX is also required to map the antenna IDs assigned by VLBIN to new antenna IDs consistent with the new antenna file. Use UVSRT, INDXR, and DBCON as needed until all of the VLBI data is in a single data set.

- **System Temperature Calibration** The process of system temperature calibration has been cleaned up considerably since the ODS experiment was run. Under the old system, both the VLA and VLBI data had to be calibrated for system temperature variations, whenever the VLA was operating in a 'VLBI' mode. The process of generating the system temperature data in a machine readable form was clumsy at best. A command file was run on the DEC-10 which generated an ASCII listing of a large number of monitor points. The DEC-10 program, MVLBI.FOR, read these files, scaled the numbers appropriately, and generated the ASCII summary that was sent to the observers. The observer generally took this summary and ran the Caltech package program, TSYS, to generate a system temperature file suitable for input to either the AIPS task ANCAL, or the Caltech program CAL. In order to obtain the calibration data necessary for this project, the original DEC-10 command file and MVLBI.FOR were both modified to produce listings for all 27 antennas instead of merely the one single dish. In retrospect, it would probably have been simpler to merely run the existing command procedures 27 times. There are two advantages to the current system. The first is that the internal VLA data will always have the system temperatures applied to it, regardless of the operating mode of the array. The VLBI data will still need to be calibrated with ANCAL, but the difficulty of producing the input data files for this task is much reduced. The on-line computer system now produces a file containing the necessary calibration information. A new program, YCAL, processes this file into the necessary ANCAL input. It is possible that the on-line system and YCAL may need to be modified in order to produce the calibration information for all 27 antennas, but the modifications needed should be minor.

  Once a system temperature data file has been produced, it must be applied to the data with ANCAL. Be aware that this program does not have a VLA geometry switch. It assumes a Mark II VLBI coordinate system, which is likely to be wrong by this point.

Worse, when it decides that a source is below the local horizon, it flags the calibration values as bad! A special version of ANCAL was created which uses the VLA coordinate system, rather than the VLBI system. This is not part of the standard AIPS package, however. It is hoped that the standard version of ANCAL will eventually acquire this ability.

- **Correction for ODS amplitude loss** The amplitude losses described in the main paper are antenna based, and can be compensated for with VBCAL.
- **Calibration** The standard AIPS editing and calibration package can be used on this data. The full interaction between CALIB and the ODS technique has not been fully studied, but it appears to work properly. This topic will undoubtedly become important again when imaging of complicated sources is attempted.
- **Imaging** This project has not produced any VLBI images. It is, however, the next logical step for further development.
- **VLA Data** The VLA data produced by this technique should be completely ordinary, once all data which have been directly affected by the non-geometric peculiar delays have been flagged. (Note the mild caveat under "System Temperature Corrections, however.) Images of 3C268.1 have been produced, although not down to theoretical noise as yet. These VLA data may be integrated with the calibrated VLBI data with DBCON. This simply combines the data as if from two separate arrays taken at different times. No account is taken of the common visibilities measured by the two different arrays. The optimum relative weight to give each data set will depend on the degree to which the source is resolved by each array. It will require experimentation on a case by case basis, but equal weights to each array is a reasonable place to start.

B Fractional Bit Shift Correction

This particular observation of a strong point source on a short baseline with a Mark II correlator happens to provide a textbook example of the effect known as the Fractional Bit Shift (FBS) correction. It is a well known effect, and of no more than academic interest. Since the effect is so strong (and not completely removable) in this data set, it is worth discussing. Figures 8 and 9 show amplitude and phase plots of the baseline between a VLA antenna and Pie Town. The data has been read into AIPS both with and without the FBS correction enabled. These plots are sufficiently memorable to ensure that one is not likely to forget this correction in the future!

The FBS error simply reflects the fact that in a traditional "lag based" correlator, the bit streams can only be aligned to the nearest lag. This gives rise to a periodic delay error that has a frequency proportional to the natural fringe rate and and amplitude of one half of a lag. Quoting from [TMS 86], the phase error produced by such a delay error is simply

$$\phi_{fbs}(\nu) = 2\pi(\nu - \nu_{LO})\Delta\tau.$$

In this expression, $\Delta\tau$ is the delay error and ν_{LO} is the signed sum of the frequencies of the local oscillator chain. This equation assumes that the system passes only the upper sideband of the radio frequency signal. It applies to the case of the NRAO Mark II correlator, where the fringe rotator corrects the phase for the zero baseband frequency. The correlator samples at the Nyquist rate, so that

$$\Delta\tau = \frac{1}{2\Delta\nu}.$$

These assumptions immediately lead to the conclusion that the oscillation is most severe at the upper end of the frequency band. At that point, the peak to peak phase error will oscillate between $\pm 90°$. Any given frequency channel will show the characteristic saw tooth shape of the FBS error. The frequency of this saw tooth will have a maximum value of

$$\nu_{fbs} = \frac{2\Delta\nu D\omega_e}{c},$$

where D is the baseline length and ω_e is the angular velocity of the earth. In the case of a 73 km Mark II baseline, this evaluates to a period of about 14 seconds. If the visibility is averaged over many of these periods, the visibility amplitude will be degraded by .64 at the upper end end of the band, and by .873 when averaged over the entire band.

The data may be corrected for the phase effect simply by multiplying the cross power frequency spectrum by $e^{2\pi i(\nu-\nu_{LO})\Delta\tau}$. The correction is incorporated into the AIPS task `VLBIN`, and some of the NRAO/SAO spectral line package programs. (In fact, these programs can also correct for amplitude loss when integrating over a non integral number of delay updates. This is a somewhat more involved correction.) `VLBIN` cannot reliably calculate the correction across an update, which gives rise to the periodic bad points in the plots. These points should be edited out before the data is used. It is also clear that VLBIN cannot remove the FBS effect completely, as careful inspection of the "after" phase plot reveals the same characteristic pattern, but with much reduced amplitude. None the less, the analytic FBS correction is obvious a great improvement.

C Equations Connecting VLA & VLBI Coordinate Systems

The coordinate system used in Mark II VLBI observations is left handed, while the coordinate system used at the VLA is right handed. In addition, the VLBI system uses Greenwich as a zero point, while the VLA $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ vectors are defined in terms of local east. That is, the the two coordinate systems are rotated with respect to each other by the west longitude of the VLA. The equations given here are all right handed. That is, when reading the VLA phased array position from Appendix C of the `USA VLBI Network Handbook`, negate the sign of the $\hat{\mathbf{y}}$ component. Similarly, when applying the results of these equations back to a program expecting Mark II coordinates, negate the $\hat{\mathbf{y}}$ coordinate back again. All coordinates are expressed in meters.

In the following, $\mathbf{B} = (B_x, B_y, B_z)$ is the antenna position measured from the VLA reference position, in the VLA coordinate system. (That is, these are the numbers found in an AIPS antenna file.) $\mathbf{B}'$ is the same vector, but its components are expressed in the VLBI coordinate system. $\mathbf{r}_{c\ VLA}$ is the VLA reference position which is found in the antenna file and the green book. $\mathbf{r}_{c\ VLBI}$ is the phase center of the phased-array, as given in the VLBI handbook. This is the same physical point as the reference position. θ is the west longitude of the VLA.

$$
\begin{aligned}
\mathbf{r}_{c\ VLA} &= (-1601162.0,\ -5042003.0,\ 3554915.0) \\
\mathbf{r}_{c\ VLBI} &= (-1601192.0,\ -5041981.4,\ 3554871.4) \\
\delta\mathbf{r}_c &\equiv \mathbf{r}_{c\ VLBI} - \mathbf{r}_{c\ VLA} = (-30.0,\ 21.6,\ -43.6) \\
\theta &= 107^\circ\ 37'\ 03.189''
\end{aligned}
$$

$$
\begin{aligned}
B'_x &= B_x \cos\theta + B_y \sin\theta \\
B'_y &= -B_x \sin\theta + B_y \cos\theta \\
B'_z &= B_z
\end{aligned}
$$

$$
\begin{aligned}
B_x &= B'_x \cos\theta - B'_y \sin\theta \\
B_y &= B'_x \sin\theta + B'_y \cos\theta \\
B_z &= B'_z
\end{aligned}
$$

$$
\mathbf{r}_{VLBI} = \mathbf{r}_{c\ VLBI} + \mathbf{B}' = \mathbf{r}_{c\ VLA} + \delta\mathbf{r}_c + \mathbf{B}'
$$

D Bugs & Problems encountered

This appendix contains a partial list of problems encountered during this project. The majority of these problems have been fixed, or no longer apply. It is hoped that this list gives an idea of the *type* of problems that might arise in future extensions of this work. It is also possible that some of these problems might arise again later due to the large number of program versions in use today.

- **NRAO/SAO VLBI Spectral Line Package**
  - **Incompatibilities with SAO versions** The NRAO/SAO spectral line package was developed jointly by individuals at the NRAO and the Smithsonian Astrophysical Observatory during the late 1970s and early 1980s. Unfortunately, the extant versions of the package at these two institutions began to diverge shortly thereafter. It has developed that several of the bugs discovered during this project have previously been discovered and fixed in the SAO versions of the programs.
  - **mHz vs. Hz confusion** The definition of an NRAO/SAO spectral line data file specifies that all LO offsets are to be in units of Hz. However, the program `AVG` has traditionally been used to make very small changes to LO offsets, for which the mHZ is a more appropriate unit. `AVG` was attempting to read the LO offsets from the correlator as mHz. More unfortunately, it *writes* this field as mHz. This is a problem that is "known but tolerated" at the SAO.
  - **LO offset roundoff** As has been mentioned before, the value of the LO offset used in the correlator differs significantly from the value that was requested.
  - **Reference frequency shift** Another point that has been discussed in the main text is the need to shift the reference velocities of all baselines to a common value. Note that shifting the reference frequency is equivalent to using an LO offset on station A. This in turn is equivalent to a phase slope across the delay spectrum, or a "channel dependent machine delay." This last form is easy to understand from direct examination of the correlator block diagram.
  - **Sign inconsistency in `ZPHASE`** It would appear that there is an inconsistency somewhere in the package as to the sign of LO offsets. In order to get `AVG` to correct our LO offset problem properly, a sign had to be toggled in the routine ZPHASE. This will almost certainly create incompatibilities with the SAO version of `AVG`.
  - **Parameter passing bug in `ZTIME`** The routine `ZPHASE` in `AVG` was passing the delay as a single precision number, while the routine `AVGDLY` was expecting a double precision number. This bug was masked on the VAX, but showed up as soon as the programs were ported to the Convex.
  - **Double accounting for `BDOP` in `ZPHASE`** Simple logic bug.
- **AIPS**

- VLBIN The FBS correction was broken in the code overhaul. There is some indication that the FBS correction has *never* worked quite properly. This is still under investigation.
- **Bad AN file column headers** Due to a deficient table initialization, antenna files were being written w/bad column headers in FITTP. As a result, files couldn't be read into the Caltech package with FITSMERGE.
- **Bookkeeping problems** DBCON, UVCOP, and SPLIT were assuming that all IFs have the same bandwidth.
- **ANFIX problems** Even code developed explicitly for this project had its share of bugs. In particular, ANFIX was not always ordering antenna IDs from low to high, and also did not conjugate the visibility when it had to reorder the IDs.
- **Calibration woes** An unknown member of the calibration suite was occasionally misindexing into the 'CL' table for the VLA data. This would create spurious points that were many orders of magnitude larger than they should be. It was never determined which program or combination of programs was responsible, but the behavior has not been observed recently.
- FILLM This task has multiple logic quirks whereby it will occasionally create the wrong kind of extension table. The most common failure mode is that it will create a 'CH' table when it should create a 'FQ' table. Note that this task is currently under active development.

• Random Restrictions

- **Too Many Antennas** The "standard" maximum number of antennas in the Caltech package is currently 20. This means that any program from this suite that is to be used on the full data set must be rebuilt from the source code. In some cases the number of antennas is not parameterized very well, and is built deep into the source code.
- **Interfaces** Unfortunately, the interface specifications between the Caltech package and AIPS is something of a moving target. In particular, when the AIPS data grew an IF axis, the data could no longer be transferred to the Caltech package until the program FITSMERGE had been modified to track the change.

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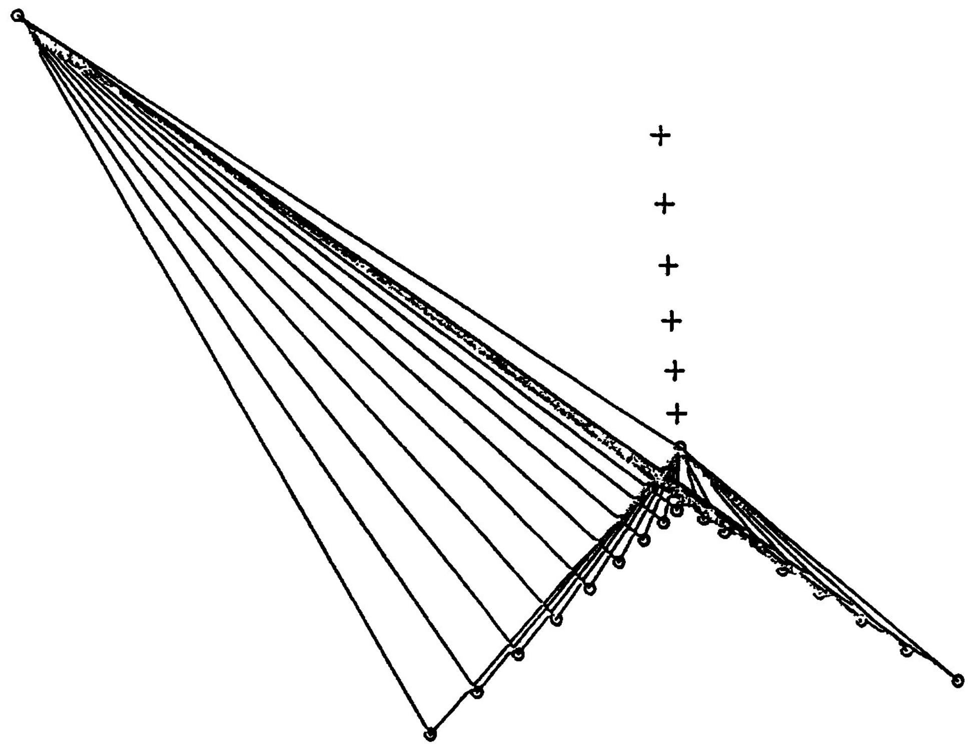

Figure 1: The geometry of the VLA and Pie Town. The antennas and baselines used in the VLBI array are marked with heavy lines and circles. Antennas used only for the VLA are marked with crosses. Three antennas were unavailable due to hardware reasons.

Baseline	Amplitude	Baseline Ratio	Value	Reference	Value
N-PT	371.9	.902 N-PT / W-PT	3.066	$\sqrt{9}$	3.000
E-PT	116.8	.902 N-PT / E-PT	2.872	$\sqrt{8}$	2.828
W-PT	109.4	E-PT / W-PT	1.067	$\sqrt{7}$	2.645
E-N	107.5	E-N / W-N	1.061	$\sqrt{9/7}$	1.134
W-N	101.3			$\sqrt{9/8}$	1.061

Table 1: Results of the amplitude calibration. The amplitudes are given in arbitrary units. The value of .902 is the quantization loss of a three-level by many-bit correlator, as discussed in the text. The right column contains possible comparison values for the baseline ratios.

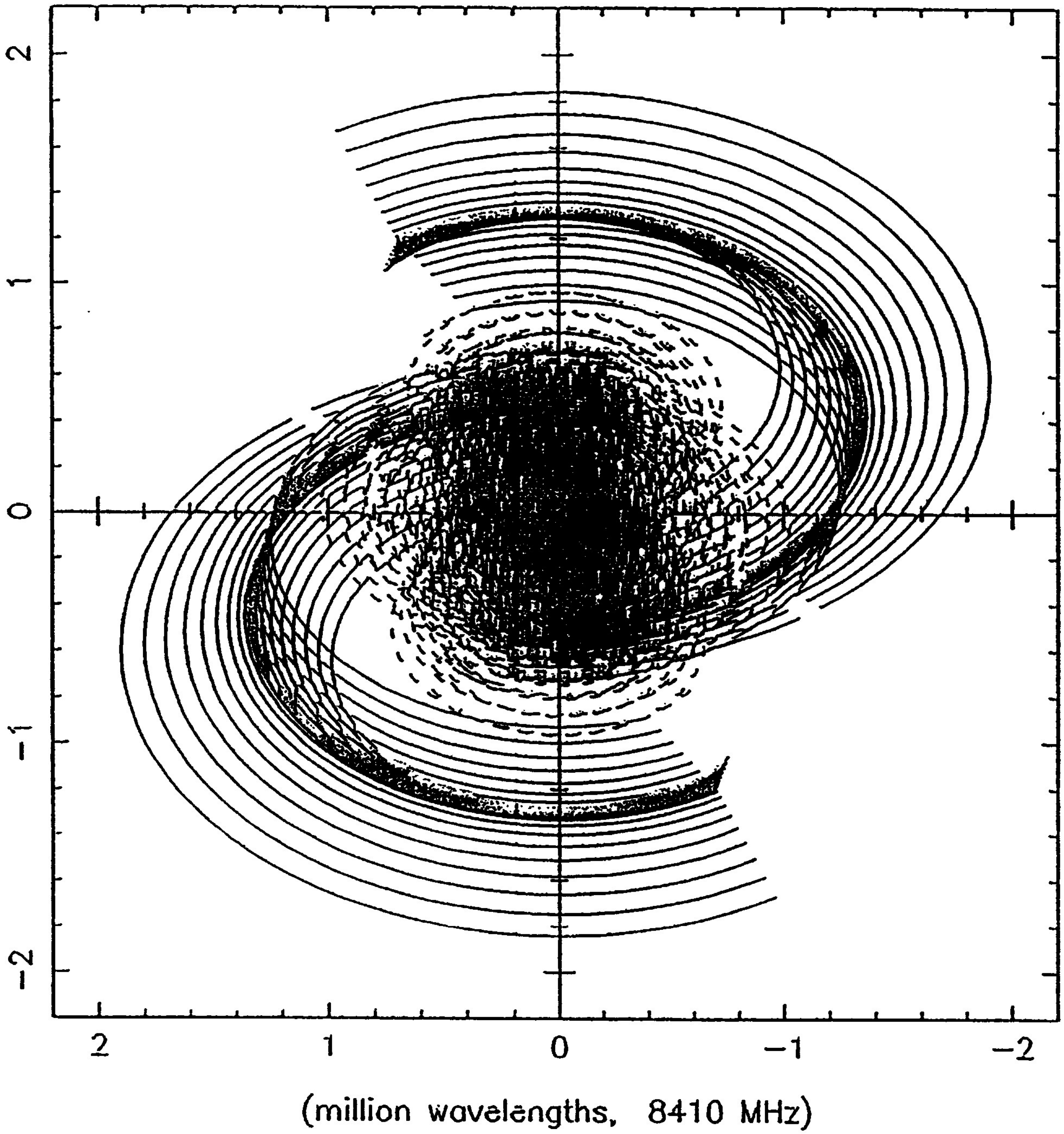

Figure 2: Model u-v coverage for the observation of 3C84 described in this paper. This is the coverage generated by a full track, 12 hour observation. The heavy lines are the baselines contributed by the ODS technique, and the dashed lines are the additional baselines from the VLA only observation.

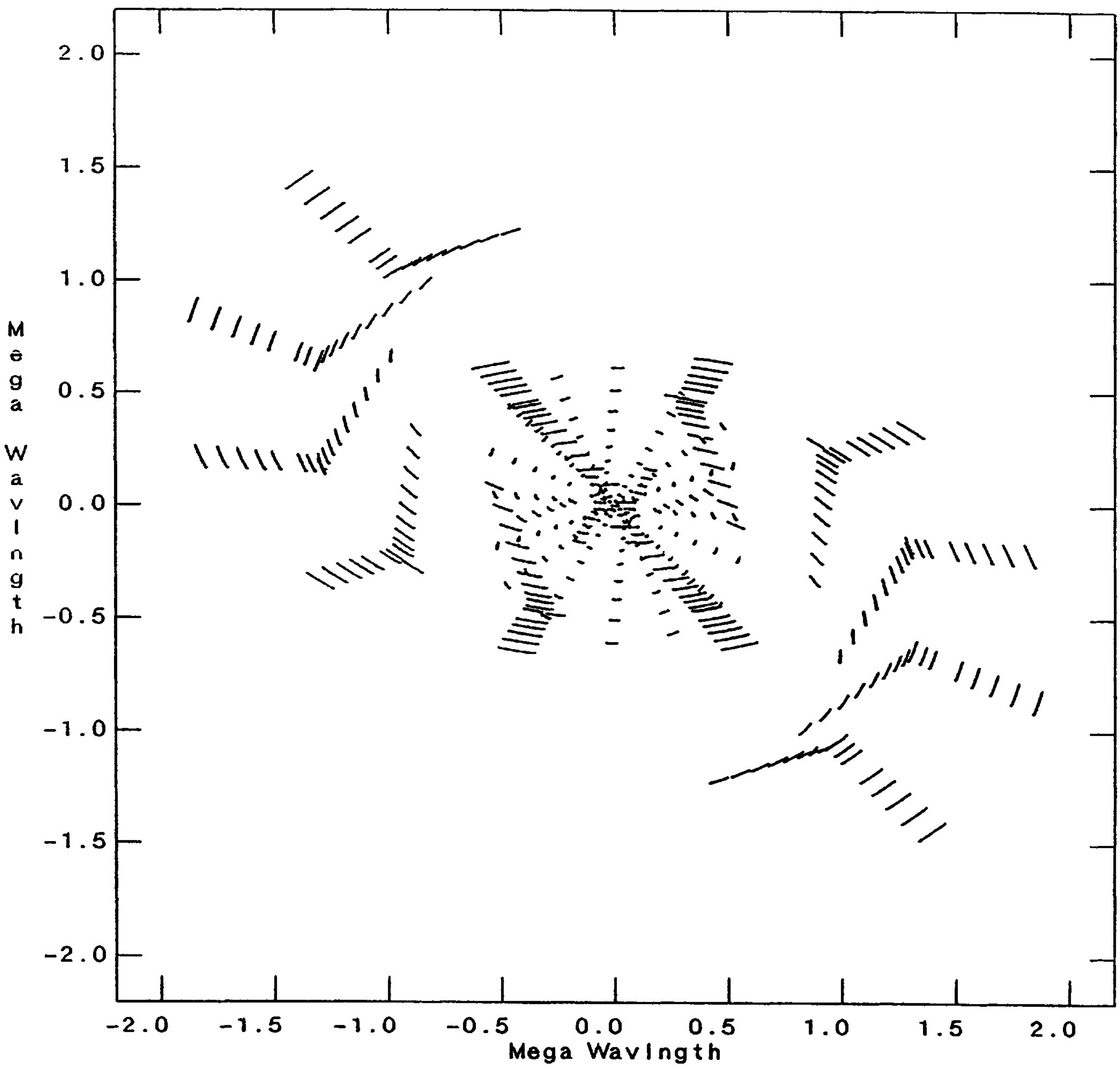

Figure 3: u-v coverage of 3C84 actually obtained in this observation. These are 5 twenty minute scans taken once every two hours. The internal VLA baselines have been deleted for clarity.

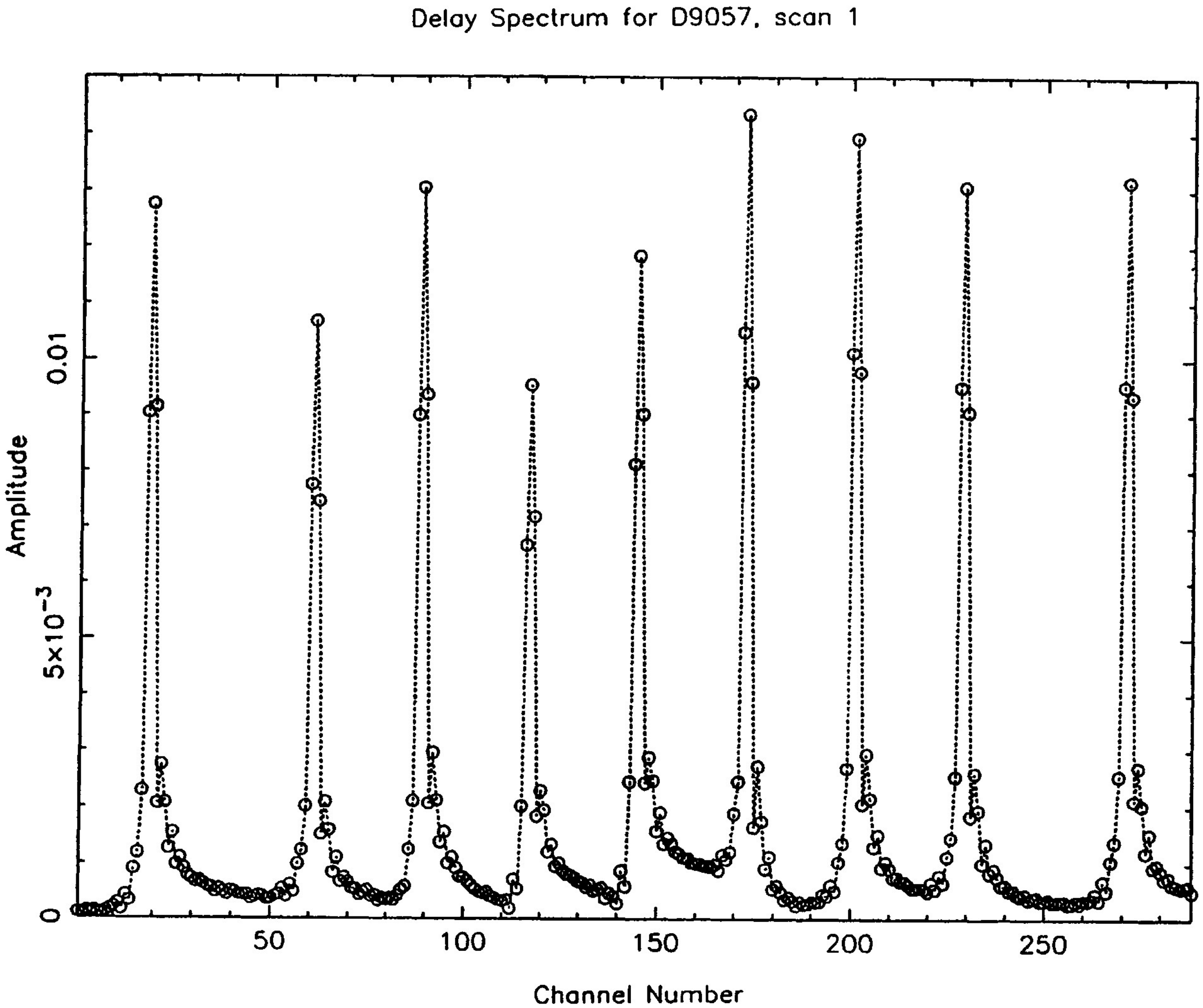

Figure 4: A typical delay spectrum obtained from the correlator. This one is between Pie Town and the west arm of the VLA. The variations in peak height are due to differences in gains and receiver temperature between antennas.

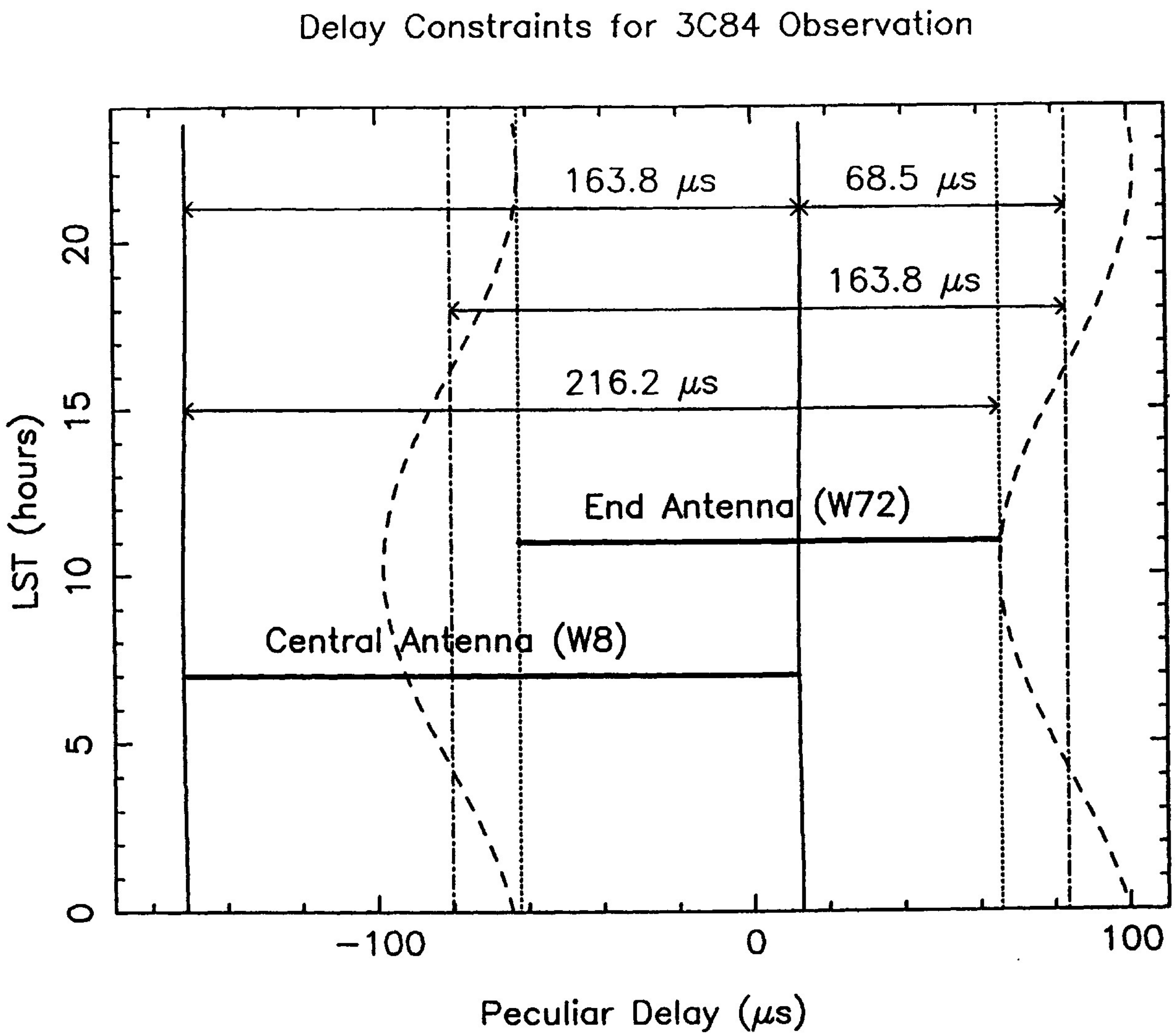

Figure 5: Acceptable peculiar delay limits for an observation of 3C84. Extreme values are plotted for the innermost and outermost antenna on the West arm of the VLA. The heavy lines indicate the largest *constant* values that may be used for a given antenna. Choice of reference antenna will change the offset of the geometric delay. Declination of the source will affect the magnitude of the geometric delay oscillation.

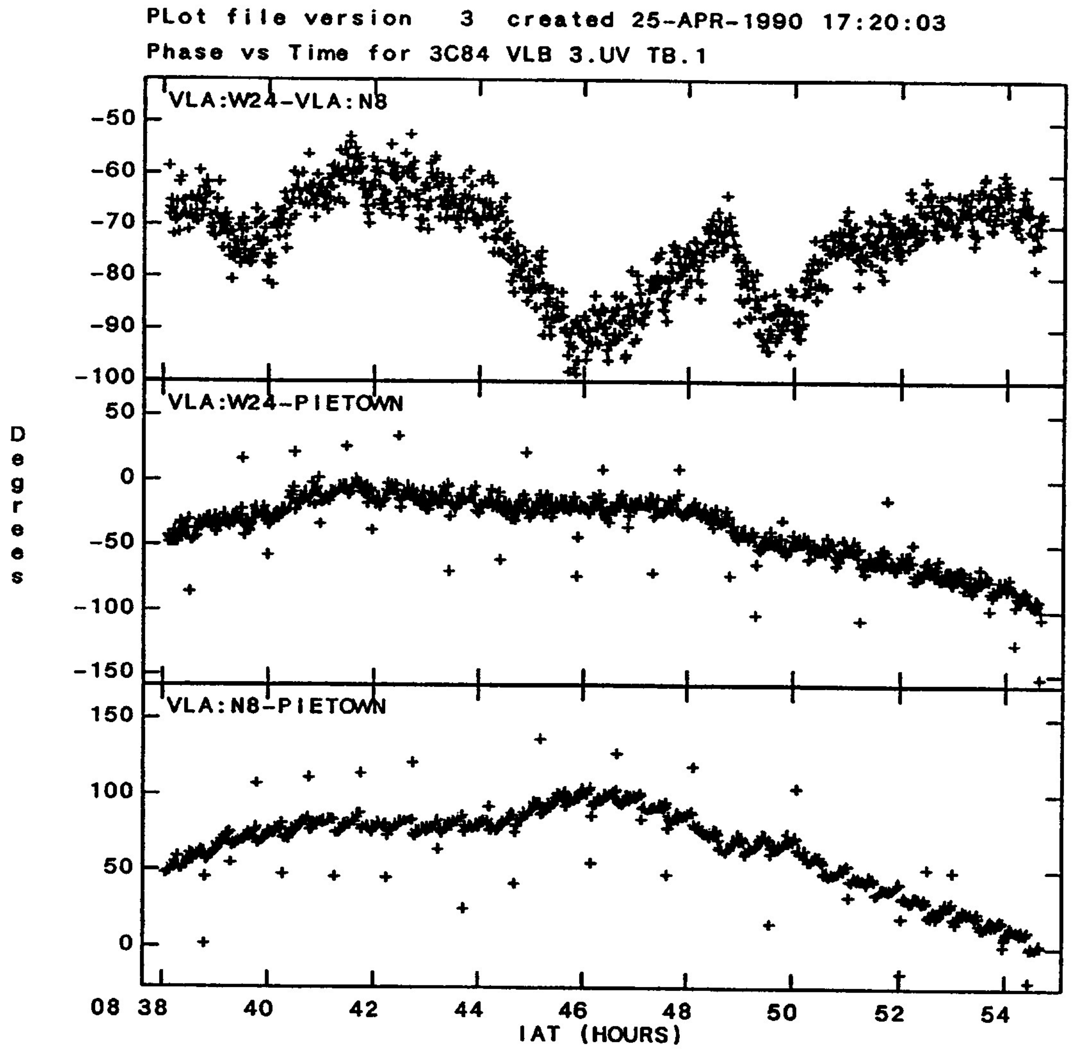

Figure 6: Raw phases around three sides of a typical closure triangle. Note the lack of Fractional Bit Shift effects on the data internal to the VLA. This is due to the high resolution of the VLA delay tracking. The remaining two baselines have had FBS corrections applied, but it obviously has not been completely successful.

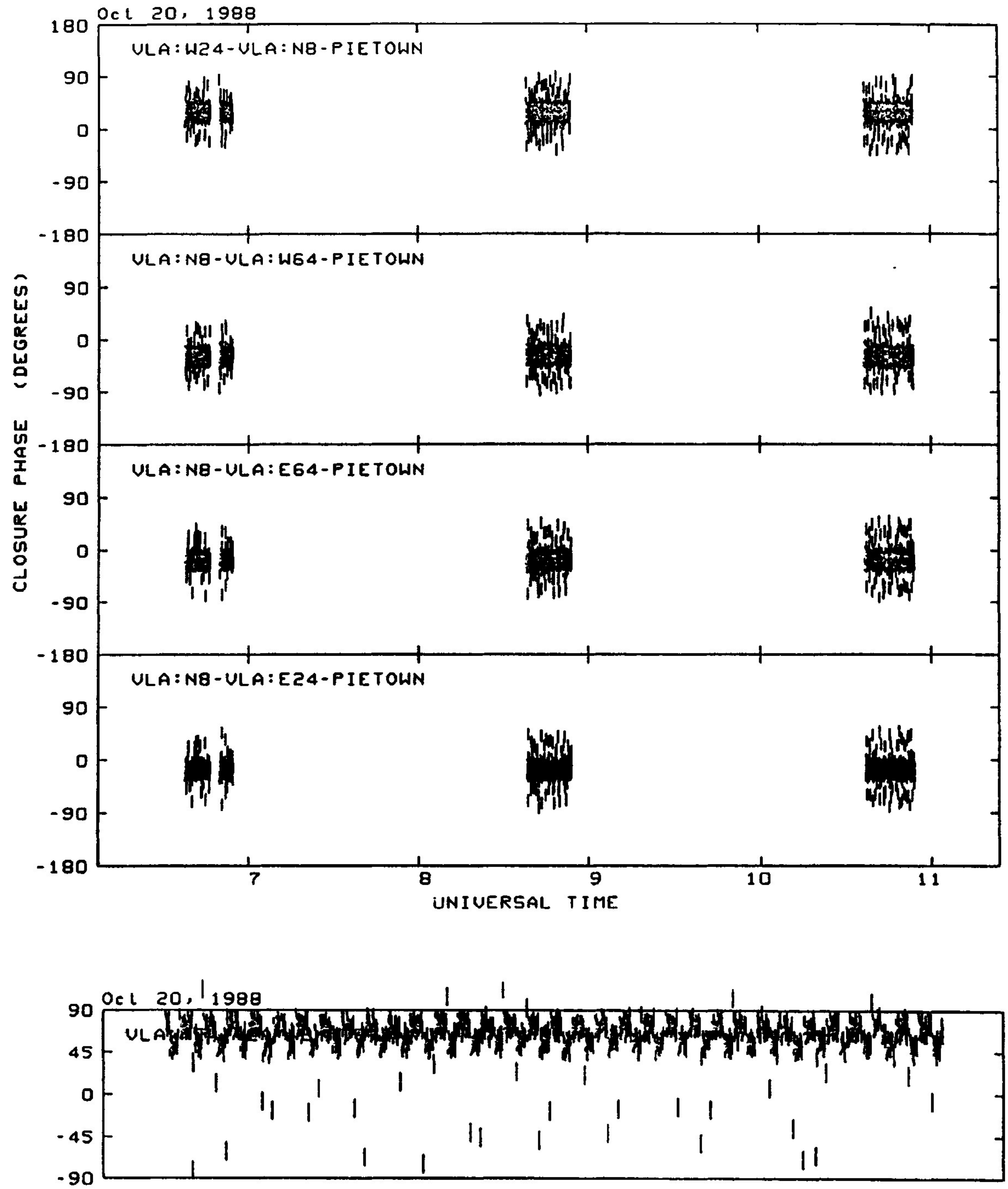

Figure 7: Closure phases for several representative triangles. Note that the closure phase is identical for the two triangles from the west arm, and similarly for the two triangles from the east arm, but that these offsets are not equal. The lowest plot is a expanded time version of the data slice at approximately 8:30. The square wave oscillation is due to a small adamixture of Fractional Bit Shift effects that have not been completely removed.

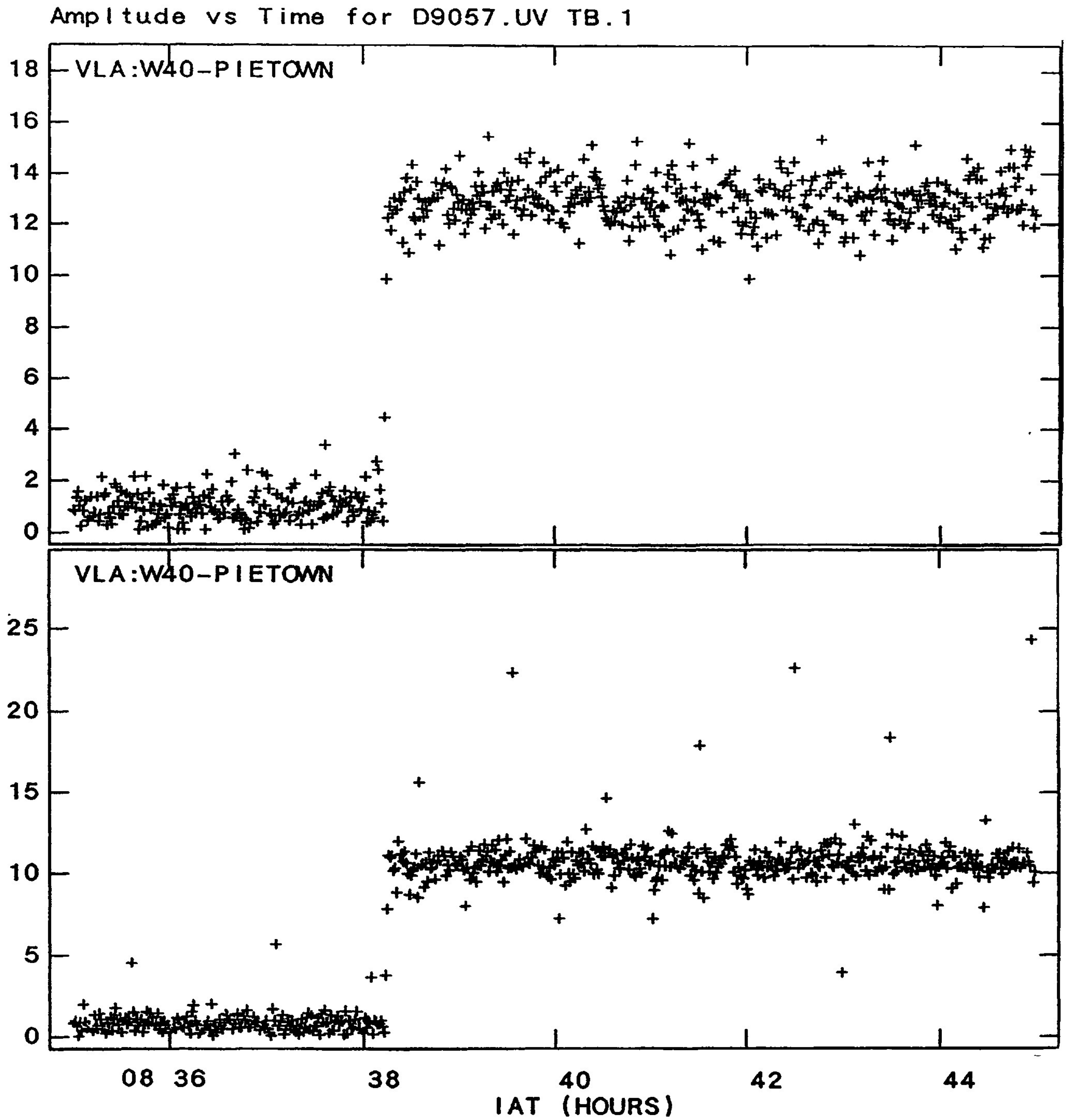

Figure 8: Amplitude of a baseline that has been read into AIPS both with and without the FBS correction enabled. Obviously the analytic correction is not particularly good across an integration period actually containing a delay update. The upper plot is with out the correction, and the lower plot is with the correction. The initial third of the plots contain no signal, and are for comparison purposes only.

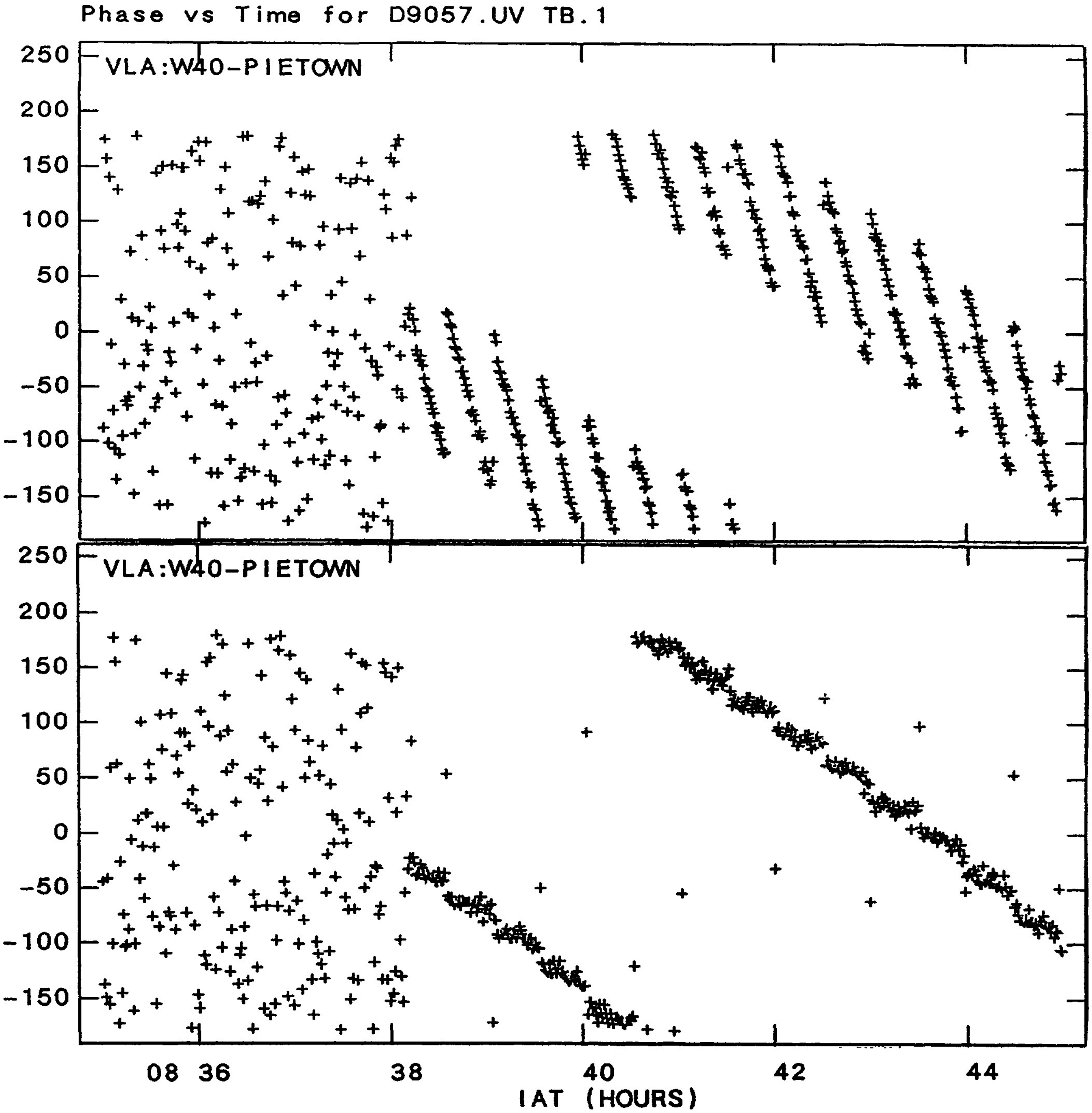

Figure 9: Phase of the same baseline, with the same conventions as the previous figure.