$\boxed{\mathcal{AIPS}\ \textbf{Memo 110}}$

Strategy for Removing Tropospheric and Clock Errors using DELZN
Version 2.0

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ABSTRACT

This memo provides a guide to scheduling and reducing phase reference experiments in order to improve the astrometric accuracy and image quality of a target source. The recommended procedure includes occasional short periods of observations of calibrator sources around the sky, interspersed with the desired phase reference observations, from which the troposphere modeling errors can be determined using a new AIPS task DELZN. The recommended observing procedure, data reduction, running of DELZN and application of corrections to the phase reference data are covered.

1. Basic Strategy

In order to get accurate relative positions and good image quality with VLBI, two things are needed; a close calibrator to the target source, and a good correlator model. The VLBA correlator uses a model for the troposphere computed from seasonal models as well as the best estimates of the clocks, positions of each antenna and earth orientation parameters. Since none of these estimates are perfect, errors are introduced which effect the positional accuracy and the success of phase transfer for phase referencing. At high frequencies ($\gtrsim 5$ GHz) the largest errors are from the clocks and the troposphere. At lower frequencies the major source of error is the un-modeled ionosphere, see VLBA Scientific Memo 23 for a discussion of this. This major source of error produces a systematic phase difference between the calibrator and target which limits the target positional accuracy and image quality. The troposphere model error, however, can be estimated by observing about ten calibrators over the sky over a 30-minute period, and then correcting the model error in the calibrator and target observations. However, the model errors are generally sufficiently large so that the measured phase of the all-sky calibrator observations spans many turns and cannot be used to determine the troposphere.

The phase ambiguity problem is solved by the measurement of a related term, the multi-band (or group) delay, which is the rate of phase change with frequency. For the troposphere (or any other non-dispersive delay), the phase equals the multi-band delay (MBD) times the frequency. In order

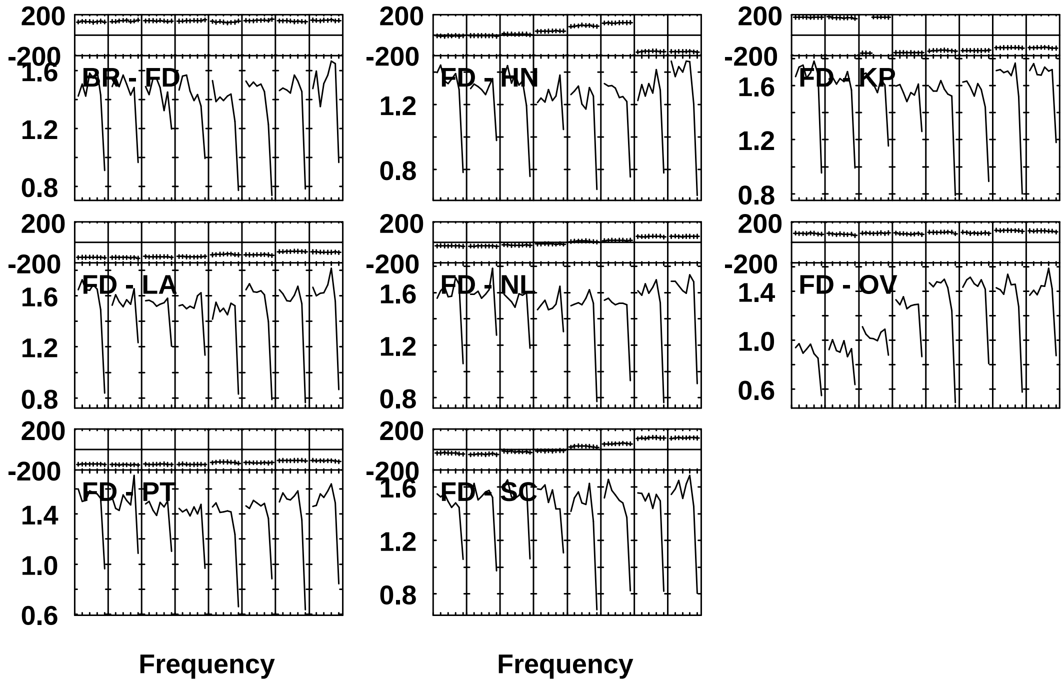

Fig. 1.— `POSSM` plot of the cross-correlation spectrum of a set of widely spaced IFs in the 4cm band. Multi-band delays are evident in the phase slopes across all the IFs.

to accurately measure the MBD, observations over a wide spanned-bandwidth must be made. An example of the measurement of the MBD is is given in Figure 1. Figure 1 shows the MBD as a phase slope over a set of widely spaced IFs. The MBD is a function of a variable clock delay, and a troposphere term which has a well-defined function of elevation (called a mapping function), times an unknown constant. Thus, from observations of many calibrators over a wide range of elevations, a smoothly changing clock term and the troposphere offset (zenith-path delay error) can be determined for each telescope. The recent $\mathcal{AIPS}$ task, written by L. Kogan, `DELZN` does such fitting. Here we describe the observation and data reduction method needed to use `DELZN` to remove the tropospheric and clock delays. Ideally, one would use a combination of `DELZN` and a method using multiple calibrators near the target to take out local atmospheric gradients between the calibrator and the target. $\mathcal{AIPS}$ Memo 111 will describe this method.

There are two basic issues to take into account while scheduling an experiment in which these errors will be solved for: 1) calibrators selection and; 2) observing frequency setup. The next two sections will discuss these issues while §4 will discuss the data reduction method.

2. Observing Calibrators

This section is not intended to describe the choosing and scheduling of calibrators for phase referencing. For more information on this see VLBA Scientific Memo 24.

First, include the time needed to observe calibrators in the amount of time proposed for; approximately an extra hour is needed for every 3-4 hours of normal experiment. Since the tropospheric delay depends on the mapping function and the clock delay does not, one wants to measure the MBD at a wide range of elevations. The sources should be strong and, to avoid delays caused by errors in the source position, use sources with most accurate possible positions. For this reason, International Celestial Reference Frame (ICRF) sources should be preferentially chosen, as they will be both strong and have good positions, a list of these can be found at the U.S. Navel Observatory website: http://rorf.usno.navy.mil/ICRF/. The VLBA calibrator list also contains ICRF sources, however some of the objects labeled as ICRF are *candidate* ICRF sources and therefore their positions are not as accurate as true ICRF sources.

The basic idea is to observe 8-12 sources over a large range of elevations every 4 hours. These sources should be observed in blocks, either 8-12 sources in a half hour block or 4-6 sources in a 15 minute block twice as often (*i.e.*, every 1-2 hours). Note that since the frequency setup will change (see next section) between these blocks and the normal observing, the schedule should not switch to these kinds of blocks more frequently than hourly because of limitations of the VLBA correlator. You should have at least two all-sky calibrator block, before and after the regular observing. If the experiment is longer than 4 hours then add at least one more block in the middle of the run. Here are the basic steps to schedule the observation (here we assume 8-12 sources every 3-4 hours):

1. Choose $\sim$ 20 strong calibrators, preferably ICRF sources, at various declinations that are up during your observation. Be sure to choose some that will be at very low elevations ($< 20^\circ$). You are choosing more sources than you will observe because some will give you better elevation coverage and shorter slewing times.

2. Observe $\sim$ 10 sources each for about a minute, scheduling them in such an order to minimize slew time and maximize elevation coverage at all stations. Unfortunately these are opposing goals, the most important thing is to maximize the elevation coverage, but slew times > 3 minutes should probably be avoided. Remember the goal is to fit about 10 sources in about 30 minutes, with one minute on source. Also, it will probably be impossible for all stations to observe all sources, particularly since it is important to get low elevation observations at all stations.

    - **Check elevation coverage with `SCHED` for each antenna**. You can do this one of two ways, the *.sum listing that `SCHED` produces for your schedule has a listing of the elevation in degrees at each station for each scan. The second option is to run `SCHED` in it plot mode, and plot the source elevation verses time.
    - **Check slew times with `SCHED`**. `SCHED` will estimate slew times. If you use `DWELL` to schedule the observing scans, then the gaps between the scans in the *.sum file will reflect the time it will take to get on source (or at least `SCHED`'s estimate).

This scheduling is the most time consuming part of the entire process.

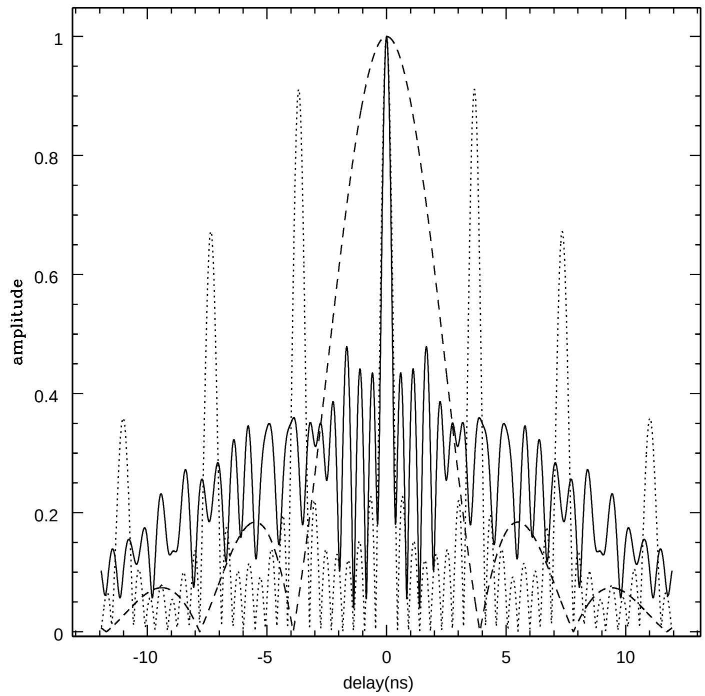

Fig. 2.— Delay function for various IF spacings. Solid line: *Golomb ruler* spacing of 8 IFs across 500 MHz; dashed line: contiguous 64 MHz; and dotted line: 8 IFs evenly spaced across 500 MHz.

3. Frequency Setup

In order to estimate the MBD most accurately, it is important to spread the observing IFs across the frequency band in the same band as the regular observing blocks. However this must be done in such a way to minimize the ambiguity in the delay solution. In other words, there should be both narrow and wide spacings between the IFs to rule out very large and very small delays. For a more thorough discussion of this see the Bandwidth Synthesis section of Thompson, Moran and Swenson (1994). Figure 2 shows the delay function for 3 possible frequency setups. The dashed line is for a standard setup, like those which come with the VLBI scheduling software `SCHED`, where the 8 IFs are joined in one continuous 64 MHz wide band. It is obvious that a MBD fit to this data would likely have an error of one nanosecond or more, which is unacceptable since the real MBD should be at most one nanosecond. The dotted line is the delay function for eight 8 MHz IFs spread evenly over a 500 MHz band. Even though the peak is narrower there are fairly high secondary peaks at $\sim$ 4 nsec. These peaks are caused by the fact that a very high delay can be easily fit to evenly spaced IFs. The solid line in is the delay function for IFs at 42.900, 42.928, 43.068, 43.166, 43.250, 43.320, 43.362 and 43.376 GHz. Figure 2 shows that this frequency spacing minimizes secondary peaks in the delay function and provides a narrow central maximum, which is exactly what is needed. This last/best option is computed by taking the maximum frequency (43.376 GHz) and subtracting 14 MHz $\times$ $(0, 1, 4, 9, 15, 22, 32, 34)$. The $0, 1, 4...34$ is the unique spacing on a *Golomb ruler* with eight marks. This set of numbers has no pair of marks the same distance apart, so this measures a unique set of gaps between 14 and 476 MHz. Although this is not necessarily the perfect frequency setup, figure 2 shows that it is sufficient and it is a nice rule of thumb.

However, there is an important issue that has been ignored, radio frequency interference (RFI). It is all well and good to find the perfect frequency setup, but the IFs must also avoid any known RFI. Plots of the VLBA RFI survey can be found at `http://www.aoc.nrao.edu/vlba/html/rfi.shtml#RFISurvey`. The frequencies of the IFs should be checked against these plots to make sure there is no significant RFI on or near them.

4. Reducing the Data

We have assumed a familiarity with *AIPS* and VLBI data reduction techniques. For more information on these topics see the *AIPS* Cookbook, particularly Appendix C (A Step–by–Step Recipe for VLBA Data Calibration in *AIPS*).

If two different frequency setups were used for observing the calibrator blocks and the standard phase referencing part of your experiment then `FITLD` will automatically separate these into two uv-data files. Calibrate both data sets using the standard method up to, but not including, global fringe fitting.

4.1. Obtaining Multi-band Delays

The next step is to find the MBD for the sources in the calibrator blocks. There are two ways to get MBD. One is to use `FRING` with `APARM(5)=2` the other is to use `FRING` with `APARM(5)=0` and the separate *AIPS* task `MBDLY`. The rule of thumb is to use `FRING` on weak calibrators and `MBDLY` on strong calibrators. Professional geodisists etc. use `MBDLY`. For most cases both methods should produce similar results. Although, running `FRING` with `APARM(5)=2` has a significantly longer running time than the combination of `FRING (APARM(5)=0)` and `MBDLY`.

For the `FRING` only method, it is as simple as running `FRING` with `APARM(5)=2` applying the previous calibration. To use `MBDLY` run `FRING` with `APARM(5)=0` to get the single band delays (*i.e.*, as if you were doing the global fringe fit). Then run `MBDLY` with `INVERS` set to the `SN` table from `FRING`. `MBDLY` fits a linear phase versus to the single band phases from `FRING`. For most cases the rest of the inputs for `MBDLY` can be left as the default. Although you may want to set `APARM(4)` to a number 1 or 2 less than the total number of `IF`s in the data, otherwise `MBDLY` will not fit a solution if all the `IF`s are not present.

Use `SNPLT (OPTYPE 'MDEL')` on the output `SN` table to check the solutions. Look for outliers, the MBD should less than than a nanosecond. Figure 3 shows a `SNPLT` of the MBD found by `MBDLY` versus time. Most of the delays are significantly less than 1 nanosecond, however there are some bigger delays for `HN` and `SC`. An examination of the MBD verses elevations (`SNPLT; XASIS 2`),

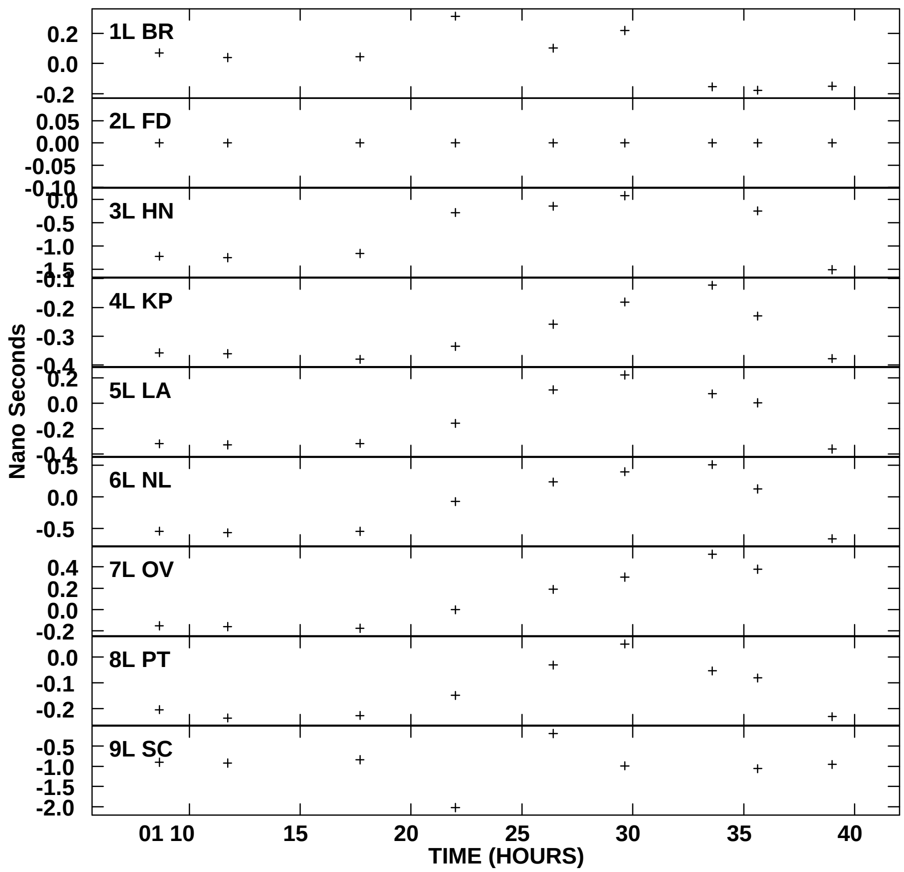

Fig. 3.— `SNPLT` of MBD verses time. The MBD were found by the *AIPS* task `MBDLY`. Note that most of the delays are significantly less than 1 nanosecond. `FD` has zero delay because it is the reference antenna.

figure 4, show that the `HN` delays are probably fine, since they seem consistent with elevation, while the ~ -2 nsec delay at `SC` is probably wrong and should be deleted. Figure 4 also shows that there may be a problem with the solutions for `BR` as well since they do not seem to smoothly vary from low to high elevation. At this time the only way to flag bad MBDs is with tasks `TABED` and `TAFLG`. If you just have outlier MDBs, which is the most common problem, you can use `TABED` to clip them. Set `OPTYPE = 'CLIP'` and set `APARM(1)` to the column number for the MBD (usually column 12) and `KEYVAL` to the range of good MBD (*e.g.*, `KEYVAL=-0.5E-09, 0.5E-09`). For `TAFLG`, first find which rows numbers to flag by running `PRTAB` this will print the `SN` table. To flag specific rows in the SN table simply set: `INEXT='SN'`; `INVERS=`*input* `SN` *table*; `BCOUNT=`*number of the row in the* `SN` *table to be flagged*; `ECOUNT=BCOUNT`; `OPTYPE='<>'`; and `APARM(1)=col#`. If there are significant problems try the other method to obtain the MBD and compare the results, with modern computers neither take much time.

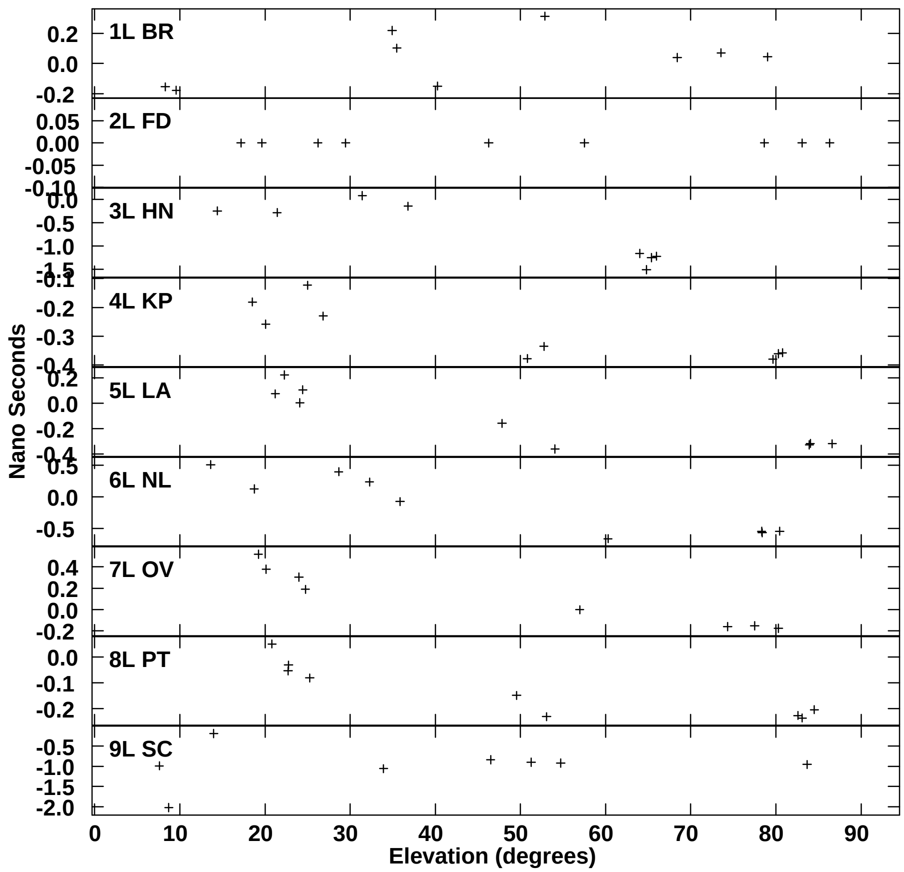

Fig. 4.— SNPLT of MBD verses source elevation. The MBDs were found by the *AIPS* task MBDLY. FD has zero delay because it is the reference antenna.

4.2. Running DELZN

Once an SN table with reasonable MBDs has been obtained DELZN can be run. As mentioned in the first section DELZN takes the MBDs and estimates the zenith atmospheric delay and, if requested, the clock error. It does this by fitting a polynomial function. If two different frequency setups were not used then DELZN can be used to correct a CL table. However, for the observing method we describe here the CL table that needs to be corrected is attached to a separate uv-dataset. For this case, DELZN will produce a file on disk which contains the atmospheric and clock corrections, which is in the right format to be read in by CLCOR and applied to a CL table attached to the normal phase referencing dataset.

However, the best way to proceed is to run DELZN *correcting the calibrators first.* This allows you to examine the correction and do additional editing or adjust the inputs to DELZN if necessary.

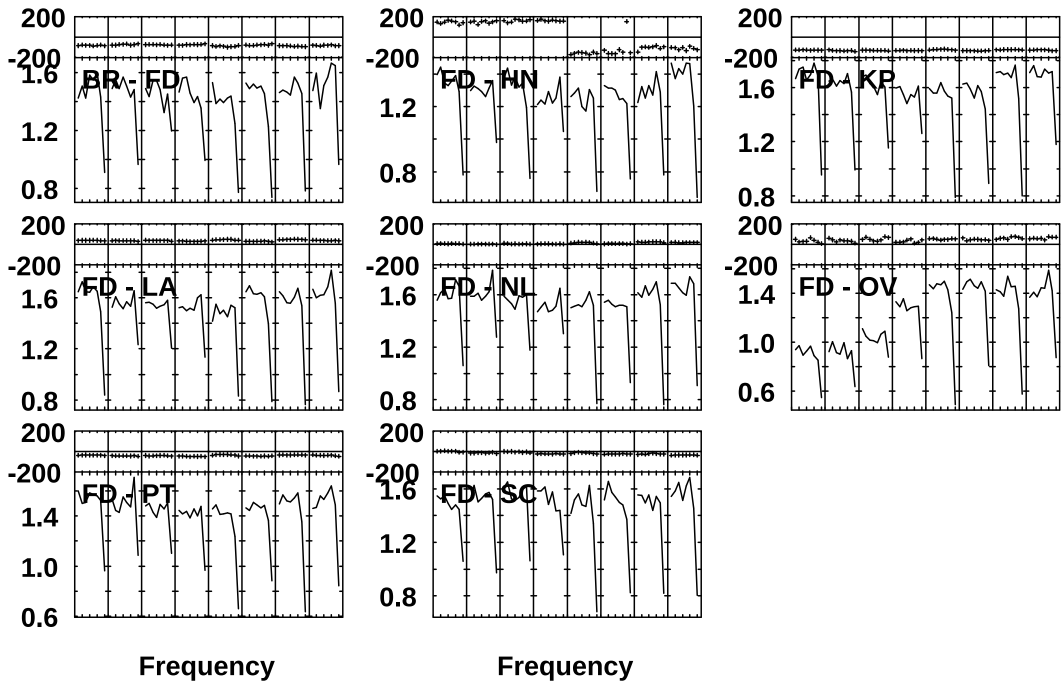

Fig. 5.— POSSM plot of the same scan seen in figure 1 after the tropospheric and clock delays were removed by DELZN.

Inputs for DELZN should be:

SNVER *snin* ⟶ SN table containing MBDs.

GAINVER *clin* ⟶ CL table to correct.

APARM(2) 3 ⟶ use 3 term polynomial to fit zenith delay

APARM(3) 2 ⟶ use 2 term polynomial to fit clock

APARM(4) 1 ⟶ create a new CL table

APARM(5) 1 ⟶ to solve for atmosphere and clocks

OPTYPE 'MDEL' ⟶ to use MBD

DOTV -1 ⟶ to make PL files

The rest of the inputs can be left as the defaults, CALSOUR and SOURCES can be left blank because all the sources in this dataset are calibrators. DELZN will produce a set of plots that show the fits it obtained. You should examine these. Although, the best way to determine the goodness of the fit is by applying the resulting CL table to the calibrator data in POSSM and seeing if the the corrections have removed the MBD, *i.e.*, flattened the phases. Figure 5 shows the same scan as figure 1, but with troposphere and clock delays fitted and removed. The phases are much flatter, although in some cases not completely flat. If you are not satisfied with the results you may want to play with APARM(6-7) which does some automatic editing of the SN table or do more editing with TAFLG.

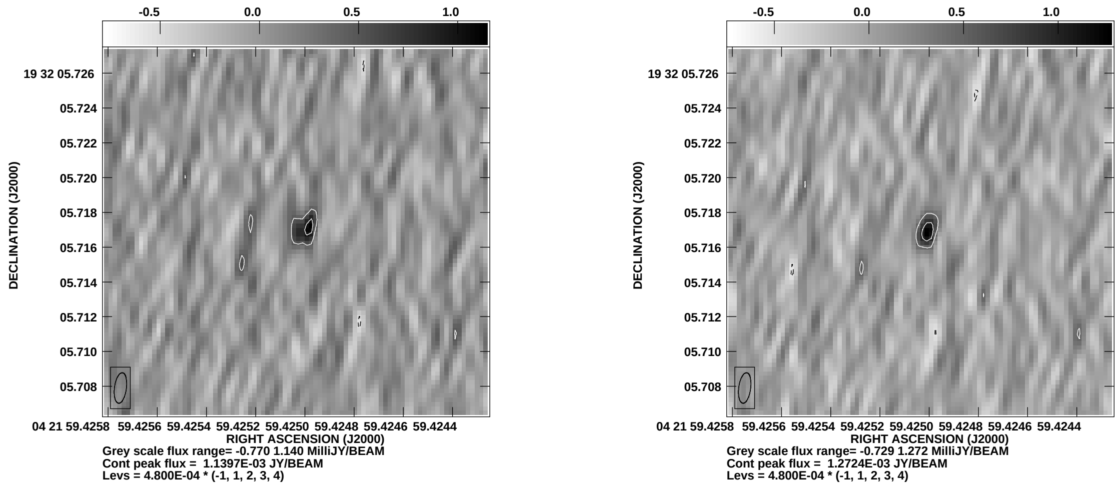

Fig. 6.— Images of same source from the same observation at 8.5 GHz. The image of the left was reduced in the standard phase referencing manner (*i.e.*, with no atmospheric/clock correction), the image on the right was reduced as described in this memo.

To correct the target dataset simply set `APARM(4)=0`, `APARM(8)=0`, and `OUTFILE=`*filename*. DELZN will then produce an output file with the zenith atmosphere and clock delays as well as their derivatives. This file is designed to be used by `CLCOR (OPCODE='ATMO')`. Run CLCOR on the normal phase referencing data set, setting `OPCODE='ATMO', INFILE` *filename* and GAINVER to the CL table with all the calibration except for global fringe fitting.

After CLCOR is run, finish processing as usual, *i.e.*, run FRING (*applying the corrected* CL *table*), CLCAL, SPLIT, and IMAGR. Figure 6 shows images of a weak source (< 2 mJy) in the same data set which was observed as described in §2 and §3. The image on the left was reduced in the standard manner (*i.e.*, no DELZN), while the image on the right was reduced as described in this section. It is obvious that using DELZN makes a significant improvement, the source on the right is more compact and has a higher peak than the one on the left. Also, the peak is shifted by ~ 0.4 milliarcsec, a significant shift if one wants to do careful astrometry with errors < 0.2 milliarcsec. This dataset was well behaved to begin with, the source was generally at high elevation ($> 40°$) and the observing frequency was 8.5 GHz, so most of the corrections where to the easternmost and westernmost antennas (St. Croix and Mauna Kea) where the source was observed at much lower elevations. It is clear that for a dataset at a higher frequency and/or with sources at lower elevations a weak target source could well be undetectable without correcting for the atmosphere.

The authors acknowledge Mark Reid for initiating the creation of DELZN and for useful comments and discussion on both the *AIPS* task and this memo. We would also like to thank Ed Fomalont, Greg Taylor and Lorant Sjouwerman for additional comments and discussion of this memo.

5. References and Further Reading

For discussion of multi-band (group) delay:

Thompson, A.R., Moran, J.M., & Swenson, G.W., 1994, *Interferometry and Synthesis in Radio Astronomy*, Krieger Publishing.

For general explanation of VLBI data reduction:

The *AIPS* Cookbook, Chapter 9 and/or Appendix C.

For phase referencing strategies including low frequency:

Chatterjee, S., 1999, *How accurate is phase referencing at L-Band, An assessment*, VLBA Scientific Memo 18

Wrobel, J.M., Walker, R.C. & Benson, J.M., 2000 *Strategies for Phase Referencing with the VLBA*, VLBA Scientific Memo 20

Ulvestad, J., 1999, *Phase-Referencing Cycle Times*, VLBA Scientific Memo 20

For atmospheric corrections including the ionosphere:

Chatterjee, S., 1999, *Recipes for low frequency VLBI Phase-referencing and GPS Ionospheric Correction*, VLBA Scientific Memo 22

Sovers, O.J., Fanselow, J.L. & Jacobs, C.S., 1998, *Astrometry and geodesy with radio interferometry: experiments, models, results*, Reviews of Modern Physics, 70, 1393

Walker, C. & Chatterjee, S., 1999, *Ionospheric Corrections Using GPS Based Models*, VLBA Scientific Memo 23