Recipes for low frequency VLBI Phase-Referencing and GPS Ionospheric Correction
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Abstract

This memo provides a recipe for planning VLBI phase-referenced observations around 1-2 GHz and calibrating the data with AIPS. It also gives details of techniques which are being developed for ionospheric calibration using Global Positioning system (GPS) data: these techniques are still evolving, and the reader should check for the most current version of this memo, available from `http://www.nrao.edu/vlba/html/MEMOS/scimemos.html`

The Earth's ionosphere delays signals in a wavelength dependent manner (delay $\propto \lambda^2$), and adds tens of meters of additional path length to astronomical signals (3-30 m at 1 GHz). Though the correlator model for the VLBA includes station positions with accuracies of few centimeters, at present there is no implemented model for this variable ionospheric path length. This results in residual rates, delays and possibly position offsets due to refraction, which are especially severe at lower frequencies.

The standard procedure for calibrating out these effects is to fringe fit, usually with a point source model. This method works for strong compact sources with known positions: however, absolute position information is lost (which is acceptable in many cases). Also, fringe fitting fails for sources which are weak, or have significant unmodeled structure.

If absolute positional information is desired, or if fringe fitting and self-calibration is not possible (due to weakness of the source or short coherence times), one has to use phase-referencing to a nearby calibrator. This memo provides a recipe for setting up phase referenced observations and reducing the data with currently available AIPS software. Detailed directions are also provided for the acquisition and use of GPS data and products for *a priori* ionospheric calibration.

1 Phase-referencing at low frequencies

Observations for weak sources and astrometric projects (where the absolute position is of interest) cannot use fringe fitting or self calibration on the target objects. Instead, phase-referencing is used, where rates and delays are calculated for a calibrator and transferred to the program source across a few degrees of sky: this requires cycling back and forth between the two (or more) sources at short intervals.

1.1 Setting up the observation

- How far away can the calibrator be from the target? At 1.4 GHz (20 cm), experience suggests a **maximum** of 4-5°. For higher frequencies, refer to VLBA Scientific Memo 20

[Ulvestad 99] or [Beasley & Conway 95]. Given a trade-off between angular distance and brightness, it is almost always better to use the nearer calibrator, so long as it is bright enough to fringe fit. The expected single-baseline RMS noise for the VLBA at 20 cm is ~5 mJy (64 MHz bandwidth, one-bit sampling, 2 minute fringe-fit interval): accounting for calibrator variability, a nominal calibrator strength of ~100-200 mJy should suffice.

- The more point-like a calibrator, and the better its position is determined, the more suitable it is for phase-referencing: an error in the calibrator position will not only produce an offset in the target position but also add to the systematic errors in target calibration. Most sources are resolved to some extent by the VLBA, but a core-dominated source with an accurately known position is acceptable.
  - The best calibrator sources are those in the USNO's Radio Reference Frame: the USNO provides a web-based search interface at `http://maia.usno.navy.mil/rorf/find-a-source.html` However, these are a small set of sources.
  - The VLBA Calibrator Manual, with a search interface at `http://magnolia.nrao.edu/vlba_calib/index.html` has a larger calibrator collection, but the positions are not (yet) astrometrically accurate, and may have 10-20 mas errors. [Patnaik *et al.* and others]
- Cycle times: at 1.4 GHz, 3 minutes on source and 2 minutes on calibrator is reasonable. Shorter cycle times may be needed, especially if one anticipates a disturbed ionosphere: the author has used cycle times as short as 60 to 90 seconds. At higher frequencies, refer again to [Ulvestad 99] or [Beasley & Conway 95].

1.2 Reducing the data in AIPS: a terse recipe

This section provides an overview of VLBA-only data reduction: for details on each task, refer to the AIPS Cookbook and `EXPLAIN` files. For non-VLBA antennas such as the phased VLA or Effelsberg, *a priori* calibration can be quite involved: specialized resources are available. (e.g. `http://www.nrao.edu/vla/vlbivla/vlbivla/`)

- Load the data using `FITLD`. For the VLBA, set adverbs `delcorr` and `digicorr`, and possibly a `wtthresh` of 0.5 for weight-based flagging.
- Run `FXPOL` and `INDXR` if needed, then use `DTSUM` and `LISTR` with `optype 'scan'` to get an overview of the data. `POSSM` and `VPLOT` provide useful displays of the data: one should be able to connect phases by eye on the calibrator.
- If your flag, T_{sys}, gain curve and pulse cal tables are not already attached, obtain them (refer to the Dear PI letter for directions) and use `VLOG` to format them correctly. Then load the tables using `ANTAB, PCLOD` and `UVFLG`. For tables attached using cal-transfer, use `MERGECAL` and the associated help files.
- For two-bit sampled data, `ACCOR` should be used to correct cross correlation amplitudes distorted by sampler errors. For one-bit samples, this is optional, and for gated data, it can be dangerous.
- Apply T_{sys} calibration using `APCAL`. Examine the SN table with `SNPLT` for each IF and antenna, and edit it if necessary with `SNEDT`. Then use `CLCAL` to apply the calibration: remember to set `snver, gainver` and `gainuse` explicitly for each use of `CLCAL`.

- Apply pulse cal correction to remove instrumental offsets: choose part of a calibrator scan near the middle of the run (60 to 90 seconds will suffice), and use `PCCOR` with `calsour` set. Check that all antennas and IFs have valid data for this time range! Then use `CLCAL` with `calsour` unset, since this is *a priori* calibration.

- Now flag your data using your favorite method (`SPFLG, TVFLG, EDITR, UVFLG, FLGIT,` etc.: `LISTR` and trial runs of fringe-fitting are favored by old hands). Then re-examine it with `POSSM` and `VPLOT`: the effects of a good pulse cal should be apparent on the calibrator.

- Fringe fit to the calibrator: `FRING` or `KRING` will do the job. Set `calsour`. Typical usage is to find single band delays, with search windows set if speed or memory is at a premium: search windows of 60 mHz and 600 ns are usually adequate. Examine the solutions, and when satisfied, apply them (`CLCAL` with `calsour` set).

- Since this is a phase-referenced observation, minor tweaking of the calibrator phases will do about as much harm as good: residual ionospheric/tropospheric phases will dominate the errors on the target source. However, occasionally the amplitude calibration of a VLBA antenna may be off by as much as 10%. At least one pass of amplitude and phase self-calibration on the calibrator source (`CALIB` with `solmode 'A&P'` and a long `solint`) will help correct the amplitude errors on different IFs.

  If the calibrator shows significant structure, one may benefit from several passes of phase-only self-cal, followed by amplitude and phase self-cal. This may be done by `SPLIT`ting out the calibrator, running `CALIB`, then `TACOP`ying the SN table(s) back to the multi source file and running `CLCAL` with `calsour` set. Many other ways exist for doing the same thing.

- Finally, `SPLIT` out the target, usually with all channels averaged within each IF, and either proceed with the imaging process or self-calibrate, depending on your objectives.

Note that the phase-referencing procedure leaves the differential ionosphere between the calibrator and the target uncalibrated. Of course, this can be fixed by self-calibration on the target, but that will not be an option for very weak sources or astrometric projects. Other aspects of the correlator model and calibration procedure have been refined to the point where this differential ionosphere appears to be a limiting factor in current astrometric work.

A modified self-cal method is under investigation, which fits a geometric and an ionospheric term to the self-cal phase corrections and restores the geometric component [Brisken *et al.* 99]. The other option is to use *a priori* information from GPS data: AIPS has some experimental tasks to do so, and detailed directions for the acquisition and use of GPS data are provided in the subsequent sections. This is very much a topic in development, and one should check the relevant `EXPLAIN` files for changes. Ultimately, one expects that some combination of these two methods will provide reasonable ionospheric corrections for VLBI data.

2 Ionospheric corrections using SATLOC

SATLOC is a commercial firm providing position information to high accuracy (∼meters) using GPS. They use approximately 15 GPS receivers, and generate maps of the Total Electron Content (TEC) across the continental US as a byproduct. These maps, which are broadcast every 11 minutes, consist of TEC values at 2° intervals of latitude and longitude, and may be used to calculate and correct for the effects of the ionosphere along lines of sight to astronomical sources. **One must acquire this data in real time,** while the observation is in progress.

2.1 Data acquisition at the AOC, Socorro

The satellite broadcasts are received by an omni-directional antenna mounted outside the Array Operations Center (near the VLBA Operations area), and processed through a sealed decoder box provided by SATLOC. This box is connected to the COM port of an ordinary PC: software provided by SATLOC monitors the COM port and writes out the received data to a plain text file. Until this point, the data acquisition process is entirely proprietary, and outside our control.

Currently (May 1999), this data acquisition process runs on the VLBA Operators' PC. It could easily be migrated to a dedicated machine - the acquisition requires neither high speed nor much processing power. The only requirement is that the machine should run Windows (95/98/NT), which is unfortunately the only platform on which the SATLOC software will work at present.

2.2 Acquisition recipe:

- Make sure there is enough free disk space to store acquired data. Expect a data rate of ~100 KB/hour.
- Launch the SATLOC application. **Make sure** the "Save data to file" checkbox is set correctly.
- Under Iono file options, the write interval should remain at the default (10 minutes). Set the "Start new file" interval based on your faith in (a) the power supply and (b) the stability of the Windows operating system. The author uses a two hour interval, which produces many small output files.
- At this point, the animated icons should look happy, and the GPS time and SATLOC Z count should be incrementing: this signifies that the signal has been acquired.
- Leaving an informative note on the PC may prevent random reboots or program shutdowns. Eventually, a dedicated PC will eliminate this problem.
- By default, the acquired data is stored in
  `C:\Users\Satloc\Iono`*ddmmyyyyhhmm*`.log`
  where *ddmmyyyyhhmm* is the date and time the file was started.

2.3 Using SATLOC data

Once acquired, the SATLOC data is simply a text file with a timestamp, latitude, longitude and ionospheric path length information (*meters* at 1575 MHz), from which TEC can be calculated.

- Translate the SATLOC data (concatenated into one file which spans the observation duration) into IONEX format: one such translator program is `satloc2ionex`, written by Alan Roy and available at NRAO. (Contact Craig Walker or the author.)
- IONEX data from this or any other source can be applied to visibility data using the AIPS task `TECOR`. `TECOR` will insert Faraday rotation ($radians/m^2$) and dispersive delay ($seconds\ at\ \lambda = 1m$) corrections into columns 7 and 15 respectively of a new `CL` table.

`TECOR` linearly interpolates the IONEX maps in time and position in a sub-solar coordinate system, and accounts for different sources in the sky having different ionospheric puncture points.

Note that ionospheric corrections should be applied *a priori*, after T_{sys} and pulse cal corrections, but before fringe fitting. The `docalib` routines within AIPS use the dispersive delay term to calibrate the data and remove the differential ionosphere between target and calibrator in phase-referenced observations.

Also note that Mauna Kea, in particular, falls outside SATLOC's grid, and Saint Croix is on the grid edge. Ionospheric corrections may be applied for these stations using archived IONEX maps, as described in section 3.2.

At present, SATLOC corrections are still being developed and tested, and as such, they are **not yet** available to users unless they are present at the AOC, or have a contact person there who is willing to collect and pre-process the data. But it is worth noting that this is the furthest advanced among the various GPS correction techniques, and some test results are very promising: for example, see Figure 1.

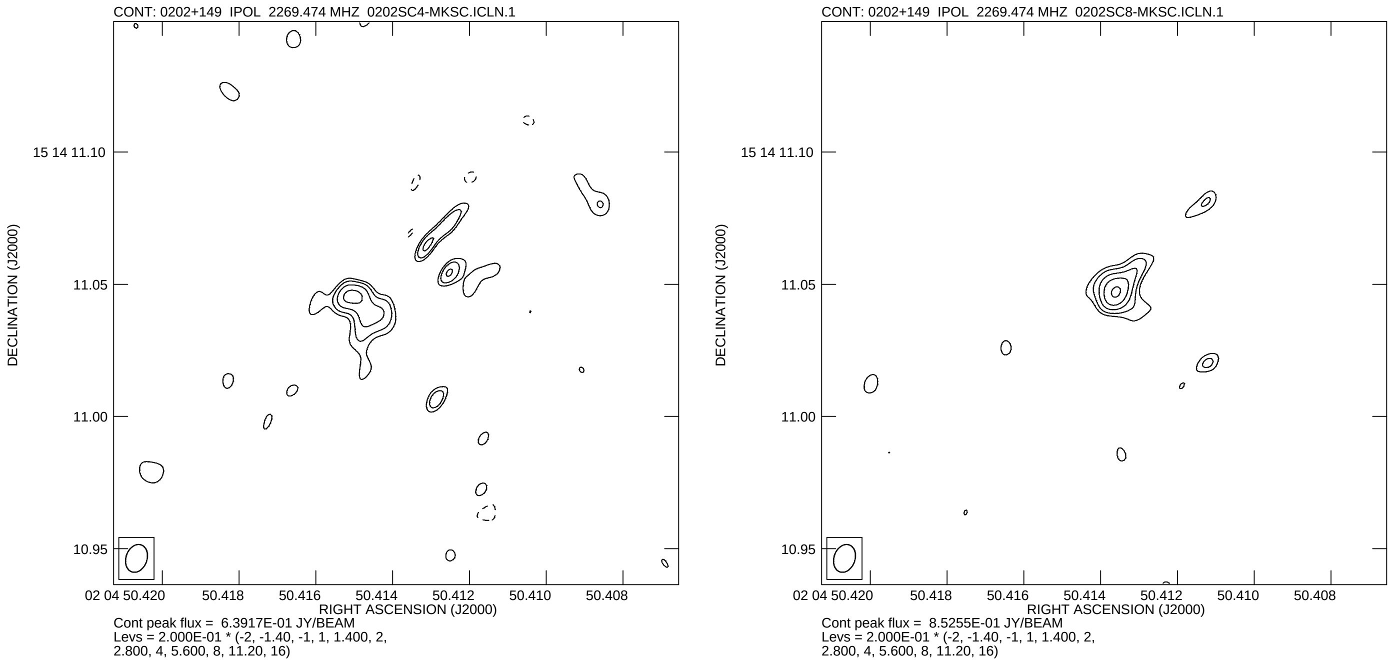

Figure 1: Demonstration of ionospheric corrections using SATLOC data.
(a) Left: Phase referenced observation of 0202+149 at 2.2 GHz, using 0229+131 (7 degrees away) as a nodding calibrator. Both sources are part of the USNO reference frame, and have well-determined positions. The map was made using two hours of daytime data (large TEC values) and only the continental VLBA (excluding MK, SC), and is centered on the "true" position. Notice the multiple blobs, poor SNR, and position offset (~17 mas) for the brightest point.
(b) Right: Same as before, except that SATLOC data was used before fringe-fitting, as outlined in the recipe. This provides a clean detection: much of the scattered flux is pulled into the center, and the position error is $\leq$6 mas. The large angular throw to the nodding calibrator causes some residual position error.

3 Ionospheric corrections using archived GPS data

Groups around the world record dual frequency GPS data in RINEX format on a daily basis - these data sets, and products like Ionex maps derived from this data, are archived by the

CDDIS at NASA Goddard. A recipe for acquiring and using this data, current as of May 1999, is provided below: see `http://cddisa.gsfc.nasa.gov/cddis.html` for documentation and further details.

3.1 Acquiring and using RINEX data

- Locate GPS receivers for the stations you wish to calibrate. The VLA site will have its own receiver: contact Rick Perley for details. Many of the VLBA sites have nearby receivers that contribute to the CDDIS archive. A partial list:

VLBA	Receiver station	Code
BR	Penticton	`DRAO`
FD	McDonald Observatory	`MDO1`
MK	Mauna Kea	`MKEA`
NL	North Liberty	`NLIB`
OV	Many, including USC	`USC1`
PT	Pie Town	`PIE1`
SC	Saint Croix	`CRO1`

- Retreive the observation and satellite navigation files from CDDIS:
  - `ftp cddisa.gsfc.nasa.gov`, with username `igs`.
    A password is available from the author, Craig Walker or the people at CDDIS.
  - For an observation in 1999, on May 3rd (day of year 123),
    `cd /gps/gpsdata/99123/99n` for the navigation files,
    then `get` files of the form `xxxx1230.99n.Z` for a receiver code of xxxx.
  - Similarly, `cd /gps/gpsdata/99123/99o` for the observation files,
    then `get` files of the form `xxxx1230.99o.Z` for a receiver code of xxxx.
- Convert these RINEX files to an intermediate format that AIPS can digest. Currently, this is LANL format, though there are plans to phase it out on a short timescale. Programs exist to translate between formats: one such is `rinex2lanl`, written by Bill Erickson and modified by Alan Roy and the author. This uses the retreived satellite observation and navigation files to produce a LANL file, and is available at NRAO with Craig Walker, or from the author.
- Task `LDGPS` will load translated data into GP tables, and this can be applied for each antenna in sequence using task `APGPS`. This is also the route for Faraday rotation corrections. The model used in `APGPS` is rather simplistic (zenith TEC, and TEC gradients in latitude and longitude), which requires that the GPS receiver be in close proximity to the antenna. Also, while this model appears to work well for Faraday rotation correction, the dispersive delay corrections it provides are not yet robust.

3.2 Archived IONEX data

For places where SATLOC data is incomplete or absent, one can use archived IONEX data from CDDIS. These IONEX maps are available on a 5° grid at 2 hour intervals, as opposed to SATLOC's 2° grid updated every 11 minutes, but the interpolation may be smoother using these maps.

For IONEX data spanning all of day 123, year 1999, follow the `ftp` procedure in section 3.1, and

- `cd /gps/products/ionex/1999/123`
- `get jplg1230.99i.Z`
  for models processed by JPL, or choose any of the other models archived there.

The corrections are applied using TECOR, as described for SATLOC data (section 2.3).

4 Contact people

This memo results from work done by the author with Craig Walker (cwalker@nrao.edu), Alan Roy (aroy@mpifr-bonn.mpg.de), Walter Brisken (walterfb@pulsar.princeton.edu), Ed Fomalont (efomalon@nrao.edu) and Miller Goss (mgoss@nrao.edu).

The ionospheric programs in AIPS were implemented by Chris Flatters (cflatter@nrao.edu) along with the other members of the AIPS group, who can be reached via daip@nrao.edu.

Much of the translation programs are cobbled together from various contributors: the source code attempts to provide appropriate credit.

The IGS Central Bureau (igscb@igscb.jpl.nasa.gov) usually responds promptly to questions about archived CDDIS data.

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References

[Beasley & Conway 95] Beasley, A.J. and Conway, J.E. 1995, "VLBI Phase-Referencing," in ASP Conf. Series 82, VLBI and the VLBA, ed. J.A. Zensus, P.J. Diamond and P.J. Napier (San Francisco, ASP), 327-343.

[Brisken *et al.* 99] Brisken, W.F., Goss, W.M. and Fomalont, E.B., to be presented, AAS Meeting 194 (Session 62: High Angular resolution science with the NRAO VLBA), Chicago, June 1999.

[Patnaik *et al.* and others] See, for example, Patnaik *et al.* 1992, MNRAS, 254, 655 (12 mas rms); Browne *et al.* 1998, MNRAS, 293, 257 (14 mas rms); and Wilkinson *et al.* 1998, MNRAS, 300, 790 (55 mas rms).

[Ulvestad 99] Ulvestad, J.S. 1999, VLBA Scientific Memo 20: "Phase-Referencing Cycle Times". Available at http://www.nrao.edu/vlba/html/MEMOS/scimemos.html