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CARMA Calibration Requirements

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ABSTRACT

This memo discusses the CARMA calibration requirements. We list the various calibrations needed including instrumental parameters which are rarely changed, such as IF fiber and cable lengths, IF delay centers, power levels, correlation coefficient corrections, receiver and phase lock tuning parameters, pointing parameters, receiver feed and TV camera offsets

We calculate the sensitivities for calibration of the antenna gains and bandpass for different sub-arrays of the CARMA antennas.

Errors in the pointing and primary beam illumination limit the image fidelity in mosaicing observations; these calibrations are discussed in some detail.

The calibration of atmospheric decorrelation, fast switching, and water line radiometry are research projects which are important for the success of CARMA and ALMA.

We briefly discuss single dish and phased array observations and calibrations.

1. Introduction

CARMA is a research, development, and teaching facility. It is desirable that all phases of the calibration procedures be accessible to both staff and students. We must strike a balance between observing efficiency and teaching calibration procedures. The best plan is to involve students in all aspects of the calibration done in the most efficient and productive way. The calibration of an interferometer array can be broken into 3 groups:

1) component values, such as cable lengths, which change only when the system is re-built.

2) array parameters which change after antenna moves.

3) instrumental parameters which change with time or ambient conditions.

In most of the existing millimeter wave arrays, (1) and (2) are handled by the array staff, whilst (3) is the responsibility of the user.

There are several ways in which system parameters can be stored, each providing different levels of access to, and protection from, the user. E.g. built into the hardware, programmed into chips, coded into software, binary tables, ascii tables, user parameters. It is desirable that the calibration parameters at all levels be kept in a transparent and obvious way so that the parameters and procedures can be developed as the system evolves. Protection from corruption should be sought by being able to restore default parameters for each or all subcomponents of the system in a simple way.

2. Requirements

We list here the various calibrations which are required, and will discuss each in turn with an obvious bias to past experience.

1) IF fiber and cable lengths, IF delay centers.

2) Power levels, correlation coefficient corrections.

3) Receiver and phase lock tuning parameters.

4) Pointing parameters, receiver feed (horn) offsets , TV camera offsets

5) Primary beam patterns, focus, subreflector position, Holography

6) Antenna positions, antenna geometry, array geometry.

7) System temperature, opacity, atmospheric model.

8) Flux density scale, antenna Jy/K.

9) Polarization, leakage corrections.

10) Bandpass, IF and RF frequency response.

11) Gains: amplitude and phase versus time; frequency switching.

12. Atmospheric decorrelation, fast switching, and water line radiometry.

13) Single dish

14) Editing, flagging and blanking.

15) VLBI, phased arrays.

Many of these calibrations can, and should, be made more accurately in the laboratory or with specialized measuring equipment. However, some calibrations must be made with astronomical measurements taking time from source observations, so we need to consider the sensitivity of the CARMA telescope.

3. Sensitivity

The measured source visibility must be corrected by various calibration factors. For each calibration, the error in the measured visibility is given by:

$\delta V = \delta g \times V + thermal\ noise \qquad — \qquad (1)$

where V is the true source visibility and g is the calibration factor. It is desirable that the measured visibility be limited by random thermal noise, rather than by calibration errors, which are more systemic. Astronomical calibrations are themselves limited by thermal noise, so we must strike a balance between time spent calibrating and integration time on the target source.

The sensitivity for each baseline is given by:

$\delta S = Jyperk \times Tsys/\sqrt{2\ B\ t} \qquad — \qquad (2)$

CARMA sub-arrays may be comprised of combinations of six 10.4 m, nine 6.1 m and eight 3.5 m antennas. Table 1 gives the sensitivity per baseline for each combination of antennas assuming 80% aperture efficiency, Tsys=200 K, and 1 minute integration. The table lists the sensitivity for calibrating antenna gains (amplitude and phase) in a 4 GHz bandwidth, the bandpass with a 1 MHz spectral resolution, and the brightness sensitivity at $5''$ angular resolution. The calibration sensitivity is greatly enhanced by using correlations with larger antennas. This is especially useful for calibration of the bandpass for the smaller antennas at millimeter wavelengths where strong calibrators are hard to find. For antenna based calibration, the RMS is reduced by the sqrt of the number of reference antennas (a factor $\sim 2 - 3$).

We may not wish to make all possible correlations, but divide the antennas into sub-arrays to optimize the useage of the CARMA antennas and limit the size of the correlator required (see BIMA memo 84). The best sub-array for calibration may not be the same as the best sub-array for the target source observations. With the initial CARMA correlator it will not be convenient to change the routing of the signals from the antennas to the correlator, but some astronomical calibrations which are made at infrequent intervals could be made with special sub-arrays.
In future CARMA correlators the routing of the antenna signals to the correlator may use a

Table 1: Sensitivity per baseline

Antennas	Equivalent diameter	JyperK	RMS (4 GHz)	RMS in 1 MHz	RMS in 5”
m x m	m	Jy/K	[mJy]	[Jy]	[K]
10.4 x 10.4	10.4	41	13	0.8	4
10.4 x 6.1	8.0	69	23	1.4	7
6.1 x 6.1	6.1	118	39	2.4	12
10.4 x 3.5	6.0	122	40	2.5	12
6.1 x 3.5	4.6	208	68	4.3	21
3.5 x 3.5	3.5	359	118	7.4	36

commercial switch, allowing much greater flexibility in the choice of antennas for observing and calibration.

4. Discussion

4.1. IF fiber and cable lengths, IF delay centers

The CARMA system plans to use fixed length fibers for the LO and IF connections to the antennas and a digital delay system with sufficient range to handle the different length across a 2 km array. (Maximum delay 4 km). These fiber lengths must be measured and stored so that the appropriate delay centers can be calculated for each antenna configuration. There will also be different lengths of fiber and cable on each antenna, and in umbilical cables connecting the antennas to the stations. These must all be measured and stored. The fiber and cable lengths may change with temperature or flexure on the antennas, so we will install a fiber length measurement system. The main correction is to the LO phase. A 30 m fiber length on the antenna with a coefficient $10^{-5}K^{-1}$, gives a 0.1λ K^{-1} change at 100 GHz. The current plan is to continuously measure 1 fiber in the bundle to each antenna and use this to correct both the LO phase and the delay center. In the first cable length measuring system installed at Hat Creek, the IF/LO cable length was measured at $\sim$ 5 min intervals and interpolated to correct both LO phase and delay center. The correction used is stored with the visibility data. In the current Hat Creek system, the cable length is measured and stored, but it is not applied on-line because it adds a few degrees of phase noise and occasionally much more on some antennas. The cable length correction is currently inspected, edited and averaged, and applied off-line. If the length changes are sufficiently slow then the LO phase correction can be interpolated directly from the quasar phase measurements. This is not possible if the cable or fiber length changes between source and calibrator observation due to flexure on the antennas. The changes in the delay center are smaller, 0.1λ across a 4 GHz bandwidth for a 25 K change in a 30 m fiber on the antenna, or for a 0.25 K change in a 3 km buried fiber. The delay center can be determined from astronomical observations from the phase slope across the bandpass provided that the error in the initial guess is less than the reciprocal of the frequency resolution.

4.2. Power levels, correlation coefficient corrections

The power levels, receiver gains and attenuator settings needed for the optimum performance of the array should be recorded and stored in accessible tables to enable easy component changes and special experiments. The CARMA correlator will have an AGC, obviating the need for the time consuming attenuator setting currently used on the BIMA correlator. The correlation coefficient correction at the pre-determined power levels will be done in the correlator software.

4.3. Receiver and phase lock tuning parameters

Traditionally the receiver and phase lock tuning has been part of the lore of millimeter wavelength observing for single dish observers. The use of arrays of more than a few antennas requires reliable automatic tuning. It is most convenient to measure the entire tuning range in the laboratory before installing the receivers. The tuning parameters for each receiver and LO system can then be interpolated to the optimized setting on the telescope. The actual tuning algorithm takes account of things like backlash in tuning motors and aging of components, and should include a harmonic check to validate the correct tuning. It should be possible to re-tune during an observation without action from the observer. The selection of the best harmonic multiplier numbers should be automatic, although an observer specified harmonic number is also needed for special experiments like VLBI.

4.4. Pointing parameters, receiver feed (horn) offsets , TV camera offsets

The antenna pointing is usually characterized by parameterized pointing equations which describe the errors in the alignment of antenna axes, encoder offsets and refraction. For AZ-EL telescopes, errors describe the tilt of the azimuth axis, the elevation axis misalignment with the azimuth axis, and the reflector axis misalignment with the elevation axis (collimation error). The pointing errors can be measured from total power observations or voltage pattern measurements with the interferometer, or by observations of star positions using an optical or IR telescope attached to the antenna. Star observations with an automated frame grabber are very quick, enabling several hundred star observations on the 9 BIMA antennas in 2-3 hours. The optical and radio pointing have different collimation and refraction parameters.

There may be other differences between radio and optical pointing; these must be identified and characterized to exploit optical pointing. Radio pointing can then be used to adjust a subset of the optically determined pointing parameters. The pointing parameters are determined by fitting the pointing equations to the pointing data. For small misalignments the pointing equations can be written as linear equations. Additional pointing parameters may be derived from an analysis of the pointing residuals. For the BIMA antennas, Fourier analysis resulted in additional parameters which describe the eccentricity of the azimuth and elevation axes. For the BIMA antennas, the tilt of the azimuth axis is measured after the antenna is moved; for the OVRO antennas the tilt is measured continuously and is used to correct the antenna pointing. After correction, the antenna pointing is generally adequate for nighttime observations, with and RMS of a few arcsec. Significantly larger errors appear during the day especially at sunrise and sunset when strong anisotropic heating is occurring. For the 6.1 m antennas, by using good insulation on the antenna tripod, and forced airflow in the reflector backup structure, feedlegs and subreflector these pointing errors have been isolated to the yoke support structure of the elevation axis. However, we have been unable to characterize the residual errors with temperature and tilt measurements. Insulation increases the time constant of residual pointing errors to $\sim$ 1 hour. At 1 mm, additional pointing corrections are needed on this time scale for daytime observations. For heterogeneous arrays, the use of the 10.4 m antennas can improve the speed and accuracy of voltage pattern radio pointing measurements. A commercial IR pointing camera is being evaluated for continuous offset radio pointing, which could greatly improve the quality and efficiency of 1 mm observations. Each receiver will have its own collimation error which must be measured and stored.

4.5. Primary beam patterns, focus, subreflector position, Holography

The primary beam pattern illuminates the source brightness distribution, and is an important calibration for imaging sources which are large compared with the primary beam. The antenna focus, and subreflector position also affect the primary beam illumination. Errors in primary beam pattern, focus, subreflector position and pointing errors between the pairs of antennas dominate the image errors in a mosaic observation.

Table 2 lists the primary beam FWHM at 230 GHz. The values listed are based on a Gaussian illumination. In practice the illumination is typically tapered to about -13 db at the edge of the dish, and the primary beam pattern is well fitted by a Gaussian with a FWHM about 6% larger. For a Gaussian illumination pattern, the primary beam radius at the 5% point is 1.04 $\times$ the FWHM. Beyond the 5% point the beam pattern may have substantial variations with antenna elevation, subreflector position and temperature etc.

A primary beam model is used in mosaic imaging algorithms. It is necessary to truncate the primary beam model. This should occur at a radius where the primary beam correction is sufficiently small and before the errors become significant. Errors in the primary beam model can give substantial mosaic imaging errors. The alignment of the tapered illumination with the reflector axis also leads to imaging errors as recently discussed in ALMA memo 402.

For a Gaussian illumination pattern truncated to -13 db at the edge of the dish, the effective primary beam between 10.4 and 6.1 m antennas is within about 1% of a Gaussian pattern corresponding to an 8 m antenna. The primary beam pattern for the 3.5 m antenna is not yet known; Table 2 lists the geometric mean for Gaussian patterns.

The uncertainties in the primary beam pattern are greater than the errors made by treating the 10.4 to 6.1 m antenna beam as a Gaussian. For the 10.4 to 3.5 m correlations, large uncertainties in the 10.4 m voltage pattern lie well within the illumination pattern of the 3.5 m antennas. Similarly if the pointing centers of the antennas are offset, there are large uncertainties in the resulting product of voltage patterns. Herein lies an opportunity and a challenge. If we can determine the primary beam patterns well enough, then including 10.4 versus 3.5 m correlations and offset pointings between all antennas provides additional information in the mosaicing process; the sky is multiplied by quite different primary beam patterns from the different combinations of antennas, in principle providing data to deconvolve the primary beam responses from the image. If we can not determine the primary beam patterns well enough, the errors will degrade the image fidelity. The current mosaicing algorithms can handle heterogeneous array imaging, but do not give realistic estimates of the image errors. A Chisq image gives some idea of the limiting noise. There is clearly a need for research in both determining the primary beam performance, and developing the mosaicing algorithms for heterogeneous array imaging.

The primary beam voltage pattern can be measured by holography using either an astronomical source or a remote transmitter as a signal source. An astronomical source allows the antenna pattern to be measured at various antenna elevations; the remote transmitter at only one, but provides more signal power allowing the antenna pattern to be mapped in greater detail. If the antenna allows elevations over the full range 0 to 180 deg, then additional information on antenna surface deformations is available by observing the same source at its elevation and 180 – elevation. The same observing program can be used for astronomical and fixed sources.

For compact sources it may be sufficient to treat the effects of the subreflector position elevation dependence as a radio pointing correction. At high frequences (1 mm) the resulting coma can be a significant error in the primary beam pattern, and control, or calibration of the primary beam pattern may be necessary. In order to keep the number and parameterization of the primary beam models manageable, the most convenient way to make mosaicing observations is to control the subreflector position as needed and use the same pointing pattern for all antennas at the sample interval required for the largest antenna in the sub-array being used. In view of the discussion above this mode is also likely to produce the best image fidelity.

Table 2 lists the Nyquist sample interval for each antenna. Larger areas of sky may be imaged using a larger sample interval at the cost of reduced image fidelity and variation of the noise level across the image (see BIMA memo 73).

4.6. Antenna positions, antenna geometry, array geometry

After each antenna move, the antenna position must be determined to an accuracy $\sim \lambda/10$. An initial guess for the antenna position is obtained from the array geometry, surveyed and historical

Table 2: Primary Beam at 230 GHz

Antennas	Equivalent diameter	FWHM	Nyquist interval
m x m	m	arcsec	arcsec
10.4 x 10.4	10.4	28	12.5
10.4 x 6.1	8.0	36	
6.1 x 6.1	6.1	47	21.3
10.4 x 3.5	6.0	48	
6.1 x 3.5	4.6	63	
3.5 x 3.5	3.5	83	37.1

record of station positions, and measurements of antenna offsets w.r.t. the station position. Observations of quasars over wide range of HA and DEC, then provide data from which the antenna position is determined. If the antenna position is in error by many wavelengths, lobe (2π) phase ambiguities may make this process difficult, especially when the atmospheric phase coherence is poor on long baselines. In this case the antenna position can be first determined from the phase difference between upper and lower sideband in a double sideband system, or across the widest bandwidth in a single sideband. The effective observing frequency is the difference frequency, enabling an antenna position to be determined to $\sim \lambda/10$ at this lower frequency. In addition to the antenna position, there may be axis offsets on the antennas which can be fitted from the baseline data, and/or measured mechanically. These offsets should be stable and not change when the antennas are moved.

4.7. System temperature, opacity, atmospheric model

The correlator output is calibrated w.r.t. a temperature controlled, or measured, ambient load. By chopping between the sky and the load, we can determine (with some approximations) the system temperature corrected for atmospheric attenuation, and the scaling factor between correlator output and antenna temperature units. An atmospheric model is used to correct the total power measurement and determine the system temperature as a function of frequency across the band and in each sideband for a double sideband system. In stable weather, this measurement made at intervals of $\sim$ 10 minutes in the source direction, gives a reliable calibration of the temperature scaling factor. The opacity can not be determined separately by a sky-ambient measurement. A sky dip or loads at two temperatures can be used to determine the opacity, but may not give a better calibration of the visibility data. Semi transparent loads, or loads installed in the subreflector give a calibration signal which is better matched to the power levels on the sky and avoid receiver saturation problems, but need a separate calibration of the coupling factor. The system temperature as a function of frequency should be stored with the data.

The opacity can also be estimated from the measured system temperature and the atmospheric model if the receiver noise temperature has been calibrated independently and is stable. This is useful for dynamic scheduling.

4.8. Flux density scale, antenna Jy/K

The flux density scale is usually determined from planet observations at short baselines where the planets are not heavily resolved. At longer baselines the details of the planet brightness distribution become significant. From the planet observations and a model for its surface brightness, we can use self-calibration to determine the gain, in Jy/K, for each antenna. From these measurements we can determine the flux density of quasars which can then be used as secondary amplitude calibrators on longer baselines when the planets are too resolved. The quasars are variable and their flux density must be monitored and interpolated to be used for flux density calibration. The quasars may also have significant linear polarization which causes a parallactic angle dependence of the measured amplitude. It is quite difficult and time consuming to include an accurate flux density measurement for each project, and it is more efficient to provide a default at the system level. The antenna gains should be quite stable. The antenna gain may be a function of frequency, but the measured reflector surface RMS is better than $\lambda/20$ at 1 mm wavelength, so the degradation of performance at 1 mm should be small. The variations in antenna gain sometimes observed at the existing sites may be due to atmospheric decorrelation, and pointing errors rather than the antenna gain.

4.9. Polarization, leakage corrections

The CARMA receivers each have a single linear polarization. Polarization switching has been implemented on both BIMA and OVRO arrays in order to obtain polarization observations. For linear polarization measurements we sample LL, LR, RL, and RR, where L and R designate the sense of circular polarization for a pair of antennas. For circular polarization measurements we sample XX, XY, YX, and YY, where X and Y are combinations of the linearly polarized antennas. At BIMA there are several sets of 1/4 wave and 1/2 wave plates at fixed frequencies. These plates are narrow band, $\sim$ 3 GHz, but provide a stable polarization leakage which can be calibrated to $\sim$ 0.2%. At OVRO there is a tunable polarizer on each antenna, but the polarization leakage is less stable. Polarization calibration is obtained by observing a strong quasar over a wide range of parallactic angles.

At BIMA a Walsh function of length 16 provides orthogonal series for switching the polarization on up to 15 antennas. A complete polarization cycle takes 16 integrations, which may be too long for good uv-sampling on long baselines. Walsh function switching takes no account of how many baselines simultaneously observe total intensity, which may be a problem for calibration. In particular, the calibration cycle must be shorter than the time scale for significant atmospheric phase fluctuations since we must use total intensity measurements at each antenna to calibrate the cross polarization observations. Another possibility is to switch the polarizations in groups with a common polarization. This gives more rapid sampling of the total intensity, for better calibration, but fewer baselines with all 4 Stokes parameters sampled. On long baselines it may be necessary to use self-calibration of each integration. This can be done by having a reference antenna observe in linear polarization whilst the rest of the antennas follow a switching cycle of circular polarizations.

For short baselines, switched polarization data can be averaged into pseudo dual polarization data records, and follow conventional polarization calibration using the measured total intensity to correct for polarization leakage in each record. For long baselines, the uv-data can not be averaged without spoiling the uv-sampling. In this case the data can be corrected by using a total intensity image as a model from which to derive total intensity visibility data, which is then used to correct for polarization leakage in each record. This process has been used to make polarization images of Cygnus A on 1 km baselines at Hat Creek. The combination of mosaicing and polarization observations requires switching through both a polarization and pointing cycle.

4.10. Bandpass, IF and RF frequency response

Ideally the complex gain of the array is a function of only time and frequency. Almost all the gain (amplitude and phase) is associated with each antenna and the atmosphere above it, so that the gain can be written as a product of the voltage gains for each antenna pair. In this case the calibration can be antenna based resulting in a higher signal to noise (SNR), and enhanced imaging performance resulting from self calibration procedures. Any residual baseline based calibration, such as closure errors in the correlator should be minimized and eliminated if at all possible. E.g. by using orthogonal switching patterns in the antennas and correlator.

Also ideally, the time and frequency dependence can be separated as the product of time dependent gains discussed below, and frequency dependent gains or bandpass measurements. In practice the bandpass may be a slow function of time and require periodic measurements. The poor SNR of an astronomical measurement of narrow bandwidth IF characteristics in the bandpass requires an auxiliary measurement with a noise source or using the total power. The RF bandpass is smoother and in a stable temperature controlled receiver environment, and can be determined from periodic measurements of an astronomical source. Traditionally this calibration has been the responsibility of the observer, but in practice the calibration is done at a system level to an accuracy of a few percent, and improving on this takes a large amount of observing time. The typical user's passband calibration may actually introduce systematic errors into the visibility data. As an example, the 3-antenna BIMA correlator had a phase offset between the wideband setting used for quasar gain measurements and the narrow band setting used for spectral line source observations requiring a wide-narrow-wide calibration sequence of the correlator. Although the current BIMA correlator has no measurable offset, the tradition of making such a calibration persists probably due to advisors insisting their students make every possible historical calibration. A desirable goal is to provide a bandpass calibration which will suffice for most (80-90%) of the users, leaving the few who need a more accurate bandpass to request and schedule time to do so. This will greatly improve the scheduling and efficiency for most of the observations.

4.11. Gains: amplitude and phase versus time, frequency switching

The complex gains versus time are usually measured at $\sim 10 - 40$ min intervals by an observation of an unresolved quasar close to the direction of the target source. The calibration interval is determined in order to follow the slowly varying instrumental amplitude and phase; a shorter interval may be needed at sunrise and sunset. The integration time on the calibrator is determined from the measurement equation (1), with the desire to obtain a calibration error which does not dominate the thermal noise on the target source. Errors in the gain measurement come from thermal noise $\delta S/S$, calibrator position errors, $2\pi/\lambda \times b \times \delta s$ radians, and residual errors in the interferometer antenna positions, $2\pi/\lambda \times \delta b \times s$ radians, where δs is the distance between source and calibrator, and δb is the baseline error. A partially resolved calibrator with well determined structure can also be used provided the visibility function can be calculated with sufficient accuracy. The integration time, distance to the calibrator, and its flux density must be balanced against the need to observe the target source! The thermal noise is reduced by using an antenna based calibration with the widest available bandwidth, and if possible in an array which contains the 10.4 m antennas (see table 1). For 1 mm observations the errors in the gain calibration may be reduced by observing at a lower frequency, where there is a larger selection of stronger calibrators, and the system noise is lower. Frequency switching between target and calibrator requires an additional calibration of the phase offset between the target and calibration frequencies. This can be obtained from self-calibration using a common reference antenna at the two frequencies. Successful frequency switching requires a stable phase offset between the observing bands, and a switching time $\sim$ the slew time to the calibrator.

For compact target sources which are small compared with the primary beam, the amplitude of the gain calibration can be used to correct for antenna gain variations, pointing and focus errors, but such correction is miss-applied for larger target sources.

The gain calibration does not follow fast atmospheric phase fluctuations which may dominate the errors on longer baselines or in unstable weather.

4.12. Atmospheric decorrelation, fast switching, and water line radiometry

Atmospheric phase fluctuations limit the observations at millimeter wavelengths on all but the shortest baselines. On longer baselines there is a significant loss in sensitivity due to atmospheric decorrelation. The CARMA site is expected to be better than the present sites, but not by as large a factor as the opacity, as the fluctuations occur in atmospheric boundary layers and are not proportional to the water vapor content. In order to make best use of the instrument we need to change the observing schedule according to the weather conditions. This is usually done by monitoring the opacity and the atmospheric phase fluctuations. An interferometer array directly observes the path difference through the atmosphere between the two antennas on each baseline. Observations of quasars provide a direct measure of the atmospheric phase RMS and the phase structure function. Satellite phase monitors are often used for dynamic scheduling. Interferometers monitoring geostationary satellites at 12 - 18 GHz on a fixed baseline provide a continuous record of the RMS, but must be extralolated to the current array configuration using an estimated phase structure function.

Phase fluctuations may be calibrated with radiometric water line monitoring, or fast switching between target and calibrator using switching times of a few seconds. Both techniques need further research and development for CARMA. Switching times of a few seconds are beyond the capabilities of the current telescope drives. However in good weather, switching between target and calibrator with $\sim$ 10 s integrations does reduce the atmospheric phase noise to tolerable levels with a reasonable observing efficiency. Table 3 show the results of some fast-switching tests with the BIMA antennas on 3 quasars separated by 0.8, 2.2, and 8 degrees from the target source.

The flux density recovered (vector average / amplitude average) is a measure of the success of the calibration. A source - calibrator separation of 8 degrees recovered 50 - 60% of the flux density. A source - calibrator separation of 2.2 degrees recovered 65 - 77% of the flux density. An integration time of 23 seconds recovered 10% less than 11 seconds integration time. An integration time of 5 seconds was not better than 11 sec and the observing efficiency is very poor. The data were too noisy to fit phase structure functions, but are roughly consistent with turbulence height of a few km ($1 < h < 10km$) and a mean turbulence velocity of a few $m\ s^{-1} (1 < v < 10m\ s^{-1})$. The effective interferometer baseline is $\sqrt{(h\ \delta s)^2 + (v\ \delta T)^2)}$ where δs is the source-calibrator separation and δT the calibration interval.

Atmospheric phase correction using water vapor radiometers is discussed in BIMA memo 78. The conclusions therein seem valid for the CARMA telescope:

1. Gain fluctuations in the WVR currently limit the atmospheric phase correction. These might be reduced by using correlation radiometers

2. The WVR correction should be averaged synchronously with the interferometer data and applied at intervals of a few seconds. The interferometer data can then be averaged.

3. Both corrected and uncorrected averaged visibility data should be archived.

4. Thermal noise can be reduced by using cooled WVR receivers, and by replacing the swept frequency spectrometer with a multichannel or correlation spectrometer.

5. Changes in the atmospheric scale factor due to multiple layers or variations in the height of the fluctuations could be calibrated by observing two quasars close to the astronomical target.

6. The offset between the WVR beam and the observing primary beam may be a problem for fluctuations at large distances from the antennas, but is not the limiting factor.

There is a substantial loss in coherence with the currently available techniques, requiring a calibration of the coherence loss on source, and of the phase transfer efficiency on applying the

Table 3: Observing efficiency: half-cycle time for various integration times

	source – calibrator separation		
integration time	8 degrees	2.2 degrees	0.8 degrees
23	37	32	30
11	25	21	20
5	20	15	14
average slew time:	15	10	9

calibration to the target source. Observation of two quasars provides one means of measuring the coherence in the calibrated target. One quasar serves as the phase calibrator; a second quasar closer to the target serves as a test source. Both test source and target are calibrated in the same way using the calibration quasar. The coherent amplitude of the test quasar gives a measure of the coherence factor. Both quasars and the target source are included in an observing sequence with $\sim$ 10 s. integrations, with appropriate total integration time on each. The test quasar only needs to be strong enough to measure a calibration factor from a coherent integration.

Both fast switching and water vapor radiometry are an active field for research. The best solution may be a combination of both, with multiple quasar observations providing a calibration of the WVR measurement.

4.13. Single dish

Although providing a single dish facility is not a prime consideration, a position switching single dish observation is very similar to an interferometric mosaicing observation, and the same code can be used with very few changes. A single dish observing program is very useful for developing and debugging. The quality of the data depends on the stability of the atmosphere and of the receivers and correlator. For the current BIMA correlator, single dish observations are possible in good weather at bandwidths or 25 MHz or less. At larger bandwidths the stability of the correlator limits the SNR rather than thermal noise.

4.14. Editing, flagging and blanking

There are 3 ways in which we handle bad data at the telescope: don't record it, flagging, and blanking. For example, at Hat Creek data from antennas which are not in use, or more than 50% shadowed are not recorded; data from antennas which are between 0 and 50% shadowed are flagged; data blanking is not used. Flagging marks each correlation; it is reversible and extendible. Flags may be multidimensional or shared, e.g. by spectral window, which may be appropriate for a correlation spectrometer. Blanking excludes bad data within each integration; the integration time and duration may vary from record to record and baseline to baseline. Data blanking can cause significant closure errors and degrade self-calibration techniques.

4.15. VLBI, phased arrays.

The phased CARMA array has an effective collecting area of a 30 m antenna and is an important telescope for millimeter wave VLBI experiments. VLBI must use a hydrogen maser or other very coherent phase reference for all the LO's in the IF downconversion, and for the time standard. The coherent integration time is currently limited by the atmosphere; if atmospheric phase correction is successful, the hydrogen maser stability will become the limiting factor. Phase stable electronics must be used in the LO chain into a wide bandwidth recording device. A built-in test tone generator to inject a phase stable signal into the front end receivers would be nice, but not essential once the phase stability of the LO system has been established. Observing modes should include array phasing, dual polarization and rapid switching from local to VLBI modes. Multiple phased sub-arrays are required for simultaneous observations of dual polarization, different target sources or observing frequencies, such as multiple SiO transitions, or simultaneous 1 mm and 3 mm continuum observations. Multiple phased arrays will be also important for wide fields of view with sparse array configurations. For both multifrequency synthesis and for observations of multiple spectral lines, we want to select the recorded bandwidth from several windows across the available bandwidth.

For VLBI the phase correction must be applied before the IFs are summed, e.g. as a phase offset to the LO. The phase might be derived some combination of: i) WVR, ii) self-calibration on a strong target source, iii) rapid switching to a nearby reference source.

We must also measure the phasing efficiency in order to calibrate the data. It is best if the CARMA correlator allows correlation of the summed antenna IFs with a reference antenna. This gives a direct measure of the effective gain of each phased array. Alternatively, the phasing efficiency can be derived from measurement of the relative phase of each antenna in each phased array, as measured for example on baselines to a reference antenna, and, in addition, a measurement of the weight, or contribution of the IF from each of the phased array antennas to the summed output into the VLBI recording system. For best SNR it should be possible to attenuate each IF before the summer, in order to weight the IF according to the antenna noise in Jy units. The CARMA correlator should support local correlations simultaneous with VLBI recording. VLBI observations are usually made in circular polarization to correlate with other VLBI stations.

The possibility has been raised of using a phased sub-array of the 3.5 m antennas as the 16th antenna in the CARMA configuration designs for 16 antennas. Whilst possible, there are some important caveats. The primary beam pattern of a phased array has complex structure within the envelope of the other antennas, which would make it difficult to use for imaging extended sources. It is however quite reasonable for sources smaller than the resolution of the phased sub-array. A second caveat is the compatibility of the available observing bands; the 3.5 m antennas will not have 1 mm receivers, and the 6.1 m will not have 1 cm receivers at first light.

Other uses of phased sub-arrays include special experiments to provide simultaneous dual polarization measurements of transient sources, simultaneous observations at multiple frequencies, and using the correlator in special modes to provide a larger bandwidth or spectral resolution than is possible with separate antennas. It is likely that these developments will not have high priority !

5. Conclusion

Whilst this memo presents a quite formidable list of requirements, it should be remembered that it closely follows our current practice or is a small extrapolation. The current procedures have evolved and been developed over years of observing with the existing telescopes. As a research and development facility, the calibrations should continue to develop and improve on CARMA.

Two time frames should be kept in mind. CARMA should seek to exploit the early advantage of the existing, working arrays before ALMA is finished. We should merge the arrays as quickly as possible. What works is OK; we need to rebuild things that don't work. The critical path for a 15-antenna array is a working 15-antenna correlator and its associated software, debugging and calibration.

This should not prevent us from planning for the future in formulating the software. What to do when ALMA is built ? ALMA is bigger (10 × the collecting area), faster (100 × for single field, 40 × for mosaicing) and on a better site. The role for CARMA is in education and research. We need student participation in all aspects of the calibration hardware and software. We need to be able to quickly exploit new avenues for research. The software should allow access to rudimentary functions of the hardware to enable new observing modes and calibration procedures to be easily implemented.