CARMA Memorandum Series #45

Bandpass Calibration for CARMA

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July 7, 2008

ABSTRACT

Ideally, one would calibrate the shape of the spectral bandpass with observations of a strong astronomical source with a flat spectrum. In the narrower bands, however, such observations would be prohibitively costly in observing time in order to reach sufficient signal-to-noise. In this memo we present bandpass calibration techniques for different correlator modes at CARMA, with focus on the bandpass calibration for narrowbands (31 MHz and below) utilizing the noise source.

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1. Introduction

There are many components of an array which can affect the phase of interferometric observations – the signals from astronomical sources pass through many mixers, amplifiers, and filters before reaching the correlator. These components affect the delay, phase, and spectral shape of the astronomical signals. To calibrate out such effects in the bandpass, we ideally would like to have observations of a strong astronomical source with a flat spectrum. Though this calibration method works for the wider correlator bands[1] (500 MHz and 62 MHz), there is usually not enough signal-to-noise in the narrower bands (31 MHz and below) to calibrate the bandpass astronomically in a reasonable amount of time. In this memo we describe different methods of bandpass calibration for different bands.

2. The Signal Path

Figure 1 shows the major components in the signal path. After passing through the atmosphere and telescope optics the signal reaches the cooled low noise double sideband mixer. This mixer converts the radio frequency (RF) signals down to the 1–5 GHz intermediate frequency (IF). Signals in the range from 1–5 GHz below and above the first local oscillator frequency (LO1) show up in the IF. All of the components before this mixer, including the sky and telescope optics, contribute to the RF gain, $G_{RF,antA}(f_{RF})$. Note that the phase of LO1 is switched through a series of Walsh sequences so that the correlator can separate the upper sideband ($f_{RF} = LO1 + f_{IF}$) signals from the lower sideband ($f_{RF} = LO1 - f_{IF}$) signals. So each correlator band gives you two spectral windows in the CARMA data. All bands receive their signals from the same RF components and $G_{RF,antA}(f_{RF})$ depends only on the sky frequency, f_{RF}, and not on the particular band used.

The IF signals in the 1-5 GHz range pass through amplifiers and attenuators in the antenna, are converted to light and sent along fiber to the control building, converted back to microwaves, amplified and attenuated some more before reaching the second mixer. These are all broadband components and can be characterized by the IF gain, $G_{IF,antA,bandN}(f_{IF})$. Although many of the components in the IF path are in common across all bands, there are components like the second mixer in the down-converters which are separate for each band and each band will have its own gain function $G_{IF,antA,bandN}(f_{IF})$. The second mixer is a single sideband mixer in the down-converter modules. Its base band output contains either the upper sideband signals above the 2^{nd} LO ($f_{IF} = LO1 + f_{BB}$) or the lower sideband ($f_{IF} = LO1 - f_{BB}$). This choice is determined by

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[1] In this document we often use the word "band", not to be confused with "spectral window" — CARMA currently has 3 bands, each corresponds to 2 spectral windows, one in the upper sideband and one in the lower sideband. Band 1 = Windows 1 & 4, Band 2 = Windows 2 & 5, Band 3 = Windows 3 & 6. When we do calibrations in Miriad, we use `select=win(#)` to select the spectral window we wish to process.

the `configband`[2] command but is normally set to LSB.

The baseband components include everything from the down-converter mixer to the actual cross-correlation calculated in the correlator FPGAs (programmable logic devices). The center of the baseband is 750 MHz. The gain for this set of components is $G_{BB,antA,bandN}(f_{BB})$. The correlated noise gets injected at the beginning of this chain of baseband components. The noise signal passes through all of the correlator configuration dependent components and filtering at the astronomical signals. In particular the selectable analog filters for 500 MHz and 62 MHz or narrower modes plus the finite impulse response (FIR) filtering that takes place in the digitizer cards are all measured by the noise source. The power measurement of P_{sys} used for the system noise temperature measurement is after the analog filters and before the automatic level control (ALC) amplifier which ensures that the digitizers operate at a constant level. Note that there are goblins and magic beyond the digitizer. The signal is shifted in frequency a couple of time but for the purposes of this memo, you can consider this as more baseband filtering. The baseband filters can have fine scale structures and it is more important to carefully determine $G_{BB,antA,bandN}(f_{BB})$.

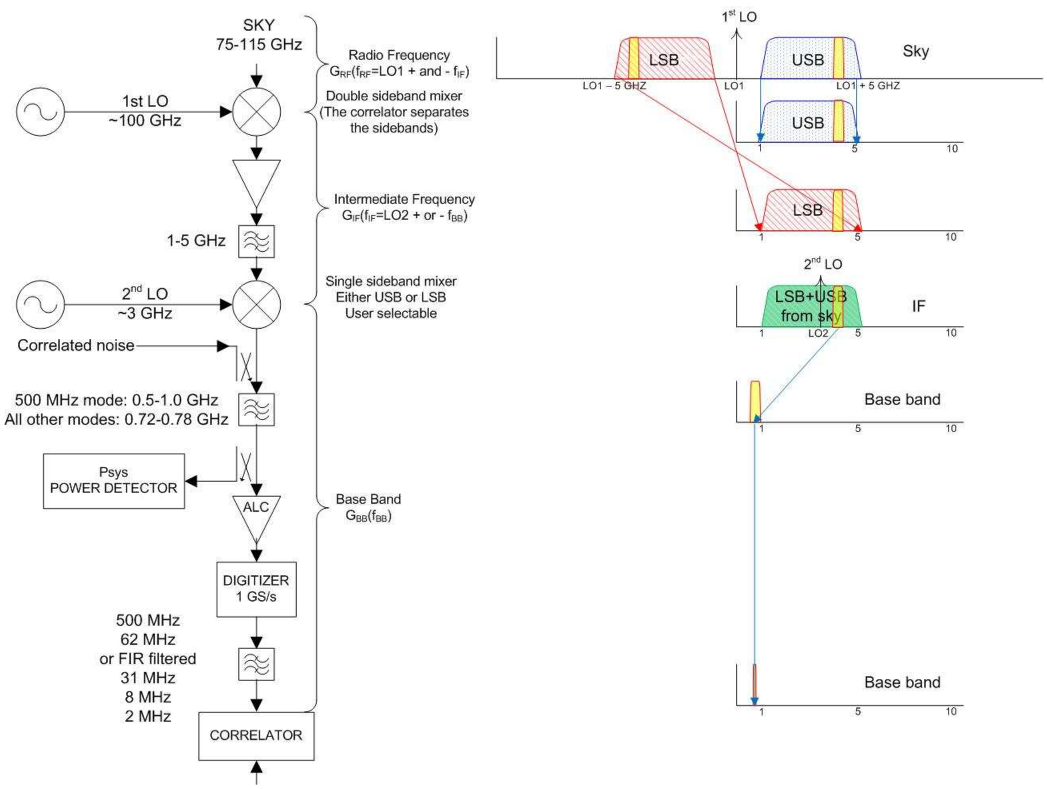

Fig. 1.— Signal path through the CARMA system.

[2]All miriad and scriptWriter commands in this document will be written in `this font`.

3. Astronomical Bandpass Calibration

3.1. Observations

The default scriptWriter setup for bandpass calibration is 15 minutes on a calibrator that is > 4 Jy in flux. This is sufficient for astronomical bandpass calibration of 500 MHz and 62 MHz, and, in the case of a bright calibrator, 31 MHz. To achieve a specific signal-to-noise for a given correlator configuration, the observer can specify the on-source time for the bandpass calibrator in the observing script.

We estimate the integration times required to reach a signal-to-noise of 30 per channel, per antenna for 3mm observations at different bandwidths on a 4 Jy calibrator in Table 1. A signal-to-noise level of 30 corresponds to phase errors $\sim 2^\circ$. [3]

Making some standard assumptions about the antenna gain of the two different telescopes (G_{10m}, G_{6m})[4], the aperture efficiency ($\eta_{ap,10m}$,$\eta_{ap,6m}$), correlator efficiency (η_{cor}), system temperature ($T_{sys,10m}$,$T_{sys,6m}$), and atmospheric decorrelation (η_{atm}), we calculate the RMS per channel, per baseline as follows:

$$\sigma_{10m-10m} = \frac{G_{10m} \cdot T_{sys,10m}}{\sqrt{2} \cdot \eta_{ap,10m} \cdot \eta_{cor} \cdot \eta_{atm} \cdot \sqrt{BW \cdot \Delta t}} \quad (1)$$

$$\sigma_{6m-6m} = \frac{G_{6m} \cdot T_{sys,6m}}{\sqrt{2} \cdot \eta_{ap,6m} \cdot \eta_{cor} \cdot \eta_{atm} \cdot \sqrt{BW \cdot \Delta t}} \quad (2)$$

$$\sigma_{10m-6m} = \sqrt{\frac{G_{10m}}{\eta_{ap,10m}}} \sqrt{\frac{G_{6m}}{\eta_{ap,6m}}} \frac{\sqrt{T_{sys,10m} \cdot T_{sys,6m}}}{\sqrt{2} \cdot \eta_{cor} \cdot \eta_{atm} \cdot \sqrt{BW \cdot \Delta t}} \quad (3)$$

Where the BW is the channel width in Hz, and Δt is the integration time in seconds. All the values we assumed are listed in Table 2. Combining the baselines to get antenna-based noise per channel:

$$\sigma_{antenna} = \sqrt{\frac{1}{\frac{N_{10m-10m}}{\sigma^2_{10m-10m}} + \frac{N_{6m-6m}}{\sigma^2_{6m-6m}} + \frac{N_{10m-6m}}{\sigma^2_{10m-6m}}}} \quad (4)$$

Since we want to calculate the integration time per channel, **per antenna**, we put in the appropriate number of baselines for each antenna. For each of the 10-meter antennas, there are 9 baselines with 6-meter antennas, and 5 baselines with the other 10-meter antennas. For each of the 6-meter

[3] In the case of strong signal, S/N $\sim 1/\sigma_\phi$ with σ_ϕ in radians.

[4] 10m = the 10-meter OVROs, 6m = the 6-meter BIMAs

antennas, there are 8 baselines with the other 6-meter antennas, and 6 baselines with the 10-meter antennas.

For the observer who wishes to calculate integration times for specific setups, we rewrite this equation to give the signal-to-noise per channel, per antenna as a function of integration time in seconds, flux of the bandpass calibrator in Jy, and channel width in Hz. Because the number of baselines with each type of antenna are different, we have two equations, one for the 6-meter antennas and one for the 10-meter antennas.

$$\frac{S}{N}(6\text{m}) = 3.22 \cdot 10^{-4} \cdot \text{Flux} \cdot \sqrt{BW \cdot \Delta t} \tag{5}$$

$$\frac{S}{N}(10\text{m}) = 4.37 \cdot 10^{-4} \cdot \text{Flux} \cdot \sqrt{BW \cdot \Delta t} \tag{6}$$

The observer then can easily solve for the variable of their choice using these equations. To calculate the integration time, we used Equation 5 for the 6-meter antennas since the smaller collecting area requires longer integration time to achieve the same signal-to-noise as the 10-meter antennas.

Bandwidth (MHz)	Channelwidth (MHz)	Int. Time (minutes)
500	31.25	0.3
62	0.977	9.3
31	0.488	18.5
8	0.122	74.2
2	0.0305	296.6

Table 1: Estimated integration times for a 4 Jy bandpass calibrator for different correlator bandwidths at 3mm required to achieve a signal-to-noise of 30. Values are calculated using Equation 5 and using the values listed in Table 2. Please note that T_{sys} for both the 6- and 10-meter antennas are higher at CO, so the integration time needed to achieve a signal-to-noise of 30 would increase by about a factor of 4.

Variable		Value
10m Antenna Gain	G_{10m}	33 Jy/K
6m Antenna Gain	G_{6m}	96 Jy/K
10m Aperture Eff.	$\eta_{ap,10m}$	0.55
6m Aperture Eff.	$\eta_{ap,6m}$	0.65
Correlator Eff.	η_{cor}	0.87
10m Typical T_{sys}	$T_{sys,10m}$	140 K
6m Typical T_{sys}	$T_{sys,6m}$	110 K
Atm. Decorr.	η_{atm}	0.96

Table 2: Typical CARMA values for antenna gains, aperture efficiency, correlator efficiency, and atmospheric decorrelation at 3mm. Note that T_{sys} at CO is slightly higher — 250 K for the 10-meters and 230 K for the 6-meters.

3.2. Reduction: Bandpass of 500 MHz Band

Bandpass calibration in the wideband (500 MHz) is very straightforward since there is plenty of signal-to-noise in the wideband. To bandpass calibrate the wideband observations, use `mfcal` with a short interval on the bandpass calibrator at the beginning of the reduction process. For example:

```
mfcal vis=bpcal.mir interval=0.2 refant=9
```

`mfcal` solves for the bandpass response per frequency across each spectral window while simultaneously solving for the amplitude and phase correction over time. A short interval is necessary to avoid changes in the atmosphere, so the brighter the bandpass source, the better. Pick a reference antenna that's near the center of your array configuration with the best system temperature and size.

Once the bandpass solution is obtained, copy the bandpass gains table over to your phase calibrator and source and apply the solutions with `uvcat`:

```
gpcopy vis=bpcal.mir out=source.mir options=nocal
uvcat vis=source.mir out=source.bp.mir options=nocal
```

The `options=nocal` is important because you don't want to apply the amplitude and phase calibrations calculated by the `mfcal`, you want to do that separately with the phase calibrator later on the in the reduction.

Depending on the observing frequency, weather conditions, and the flux of the bandpass calibrator, there's usually enough signal-to-noise to bandpass calibrate the 62 MHz narrowband with the same method as the 500 MHz wideband provided that one of the brighter calibrators can be observed.

3.3. Reduction: Bandpass of One 500 MHz + Two Narrower Bands

In some cases, it is useful to set up the correlator with two narrowbands and an overlapping wideband, which allows the observation of a fainter phase calibrator without changing correlator setups. In this scenario, we consider only narrowbands that can be bandpass calibrated astronomically (62 MHz and maybe 31 MHz if the bandpass calibrator is bright). The advantage of this kind of setup is a simpler reduction method, which involves only calculating the phase offset between the narrow and wideband using the astronomical bandpass calibrator. Please refer to Section 3.1 for suggested integration times for the two narrowbands.

In this example, we have a 500 MHz wideband in band 1, and 62 MHz narrowbands in bands 2 and 3, and we're only interested in the upper side band (windows 4–6). Split up the data into different sources (bandpass calibrator, source, phase calibrator) but keep all three windows in the same Miriad file. After the appropriate flagging has been done, bandpass calibrate all three windows at the same time on an integration-by-integration basis to avoid temporal atmospheric effects:

```
mfcal vis=bpcal.mir interval=0.2 refant=9
```

Then copy and apply the bandpass gains table to your phase calibrator and source:

```
gpcopy vis=bpcal.mir out=source.mir options=nocal
uvcat vis=source.mir out=source.bp.mir options=nocal
```

The `uvcat` command applies the bandpass calibration, and like the example in the previous section, the `options=nocal` is important because we don't want to apply the phase calibrations calculated by the `mfcal`, you do that later with the phase calibrator. Running `mfcal` on all three windows at the same time calculates the offset between windows, which allows the observer to use the phase and amplitude solutions from the 500 MHz observations of the phase calibrator on the source data in the narrowbands. Extensive tests by Misty La Vigne and Jin Koda have found that this offset is constant over a period of a few days, so you only have to calculate this offset once in the track. For more information on phase/amplitude calibration, please see the CARMA cookbook.

4. Calibrating the Bandpass with the Noise Source

In the narrower bands, one runs into the problem of low signal-to-noise, which inhibits the use of an astronomical source for bandpass calibration. Hence we rely on the noise source, injected at the baseband, to relate the wideband astronomical passband to the narrowband. The theory is that we can still use wideband data to take out the RF and IF behavior, while the noise source takes out the baseband components.

4.1. Visibilities

A single antenna's contribution to the visibility of a point-like astronomical source is:

$$V_{astro,antA}(f_{RF}) = \sqrt{A_{astro}(f_{RF})}G_{RF,antA}(f_{RF})G_{IF,antA,bandN}(f_{IF})G_{BB,antA,bandN}(f_{BB}), \quad (7)$$

where $f_{IF} = |f_{RF} - LO1|$ and $f_{BB} = |f_{IF} - LO2| = |f_{RF} - (LO1 \pm LO2)|$. The $+$ sign in the last term is for the upper sideband signals from the down-converter and the $-$ sign for the lower sideband. Signals with $f_{RF} > LO1$ are the upper sideband spectral windows in the Miriad data whereas signals with $f_{RF} < LO1$ are the lower sideband spectral windows. Note that the center of the final spectral band corresponds to $f_{BB} = 750$ MHz. The correlated noise source signal is injected into the base band and its single antenna component of the visibility is:

$$V_{noise,antA}(f_{BB}) = \sqrt{A_{noise}(f_{BB})}G_{BB,antA,bandN}(f_{BB}). \quad (8)$$

The correlated noise source is designed to be wideband and have a reasonably flat spectrum. If LO1 and LO2 are kept at the same values as used for the astronomical observations then noise source visibilities will appear to come from the same sky frequencies, f_{RF}, as the astronomical observations. The noise source at baseband are phase switched to look like a lower sideband signal from the sky. A Miriad task is used to move a complex conjugate copy of the lower sideband spectral window to the upper sideband spectral window and hence the noise source appears to have both sidebands from the sky (see Section 4.4.2 for more details).

4.2. Bandpass Calibration

Calibrating the astronomical visibilities of source X using the noise source observation is equivalent to dividing the astronomical visibilities by $V_{noise,antA}(f_{BB})$ giving:

$$V_{Ncal,astro,X,antA}(f_{RF}) = \sqrt{\frac{A_{astro}X_{RF}}{A_{noise}(f_{RF})}}G_{RF,antA}(f_{RF})G_{IF,antA,bandN}(|f_{RF} - LO1|). \quad (9)$$

This normalizes the astronomical observations to the correlated noise source and ideally removes the fine scale spectral features caused by the analog and FIR filters.

The normal procedure for bandpass calibrating astronomical data is to use a strong continuum astronomical source, X, to measure the bandpass in the same correlator configuration as the target, Y. This gives the bandpass calibrated signal:

$$V_{Xcal,astro,Y,antA}(f_{RF}) = \sqrt{\frac{A_{astro,Y}(f_{RF})}{A_{astro,X}(f_{RF})}}. \tag{10}$$

if the same noise calibration had been previously applied to both X and Y, the noise calibration is effectively removed by the astronomical bandpass calibration.

The bandpass calibration source observed at wide resolution and the observation of the target source at narrow resolution can be linked using the correlated noise source. The trick is to normalize each astronomical observation by a noise source measurement with the **same** correlator configuration and with **same** LO1 and LO2 values for both sets of observations, i.e. only change the BW# in the "configband" command. The Miriad processing needs to be done in sky frequency or VLSR space so that Miriad can properly interpolate the wideband calibration onto the narrowband channels. The wideband observations are essentially giving the smoothed value for the gains and spectra. Over the RF frequency range of interest for the narrowband observations Equation (3) after noise calibration of the wideband observation of X becomes:

$$\overline{V_{Ncal,astro,X,antA}(f_{RF})} = \sqrt{\frac{\overline{A_{astro,X}(f_{RF})}}{\overline{A_{noise}(f_{RF})}}} \overline{G_{RF,antA}(f_{RF}) G_{IF,antA,bandN}(|f_{RF} - LO1|)}. \tag{11}$$

Applying astronomical bandpass calibration using noise calibrated wideband observations of source X to noise calibrated narrowband observations of source Y gives:

$$V_{N\&Xcal,astro,Y,antA}(f_{RF}) = \sqrt{\frac{A_{astro,Y}(f_{RF})\overline{A_{noise}(f_{RF})}}{\overline{A_{astro,X}(f_{RF})}A_{noise}(f_{RF})}} \frac{G_{RF,antA}(f_{RF}) G_{IF,antA,bandN}(|f_{RF} - LO1|)}{\overline{G_{RF,antA}(f_{RF}) G_{IF,antA,bandN}(|f_{RF} - LO1|)}} \tag{12}$$

Over the bandwidth of the narrow spectral bands the RF and IF gains as well as the noise source spectrum should be smooth so that their fine scale spectra shapes divided by their averages is unity. Equation (6) then becomes:

$$V_{N\&Xcal,astro,Y,antA}(f_{RF}) = \sqrt{\frac{A_{astro,Y}(f_{RF})}{A_{astro,X}(f_{RF})}}. \tag{13}$$

This has the benefit of calibrating the bandpass for narrowband target observations for high signal-to-noise wideband observations of the bandpass calibrator.

4.3. Writing an Observing Script

A quick step-by-step for implementing the noise bandpass calibration for narrowbands is outlined below, with the scriptWriter and Miriad steps associated with it.

The CARMA scriptWriter has an option to observe the source in all narrowband mode and the calibrator in all wideband mode. Note that the center of the 500 MHz band will be lined up in frequency with the center of the narrowband during astronomical and noise observations. To set up the observations, modify the '`reconfig`' parameter in the observing script from `None` to `od.CORR_BW500` like below:

```
# Correlator configuration for calibrators
# reconfig:  Sets correlator configuration for calibration observations
# None :  same as for science targets
# od.CORR_BW500LO6:  500 MHz, non-overlapping bands in BIMA IF
# od.CORR_BW500LO : 500 MHz, non-overlapping bands (not recommended for 3mm)
# od.CORR_BW500 :  change bands to 500 MHz without changing IF
# hybrid:  Correlator configurations to calibrate band offsets (see FAQ page!).
# Needed only if all bands have width < 500 MHz.
# tintHybrid :  integration time for each of the hybrid correlator modes
correlator = {
'reconfig' :  od.CORR_BW500,
'hybrid' :  None,
#'hybrid' :  [ [BW500, BW62, BW62], [BW62, BW500, BW62] ],
'tintHybrid' :  5.0,
}
```

This will observe the bandpass calibrator and noise source in both the wideband and narrowband modes. Make sure you leave the noise source observations with its default settings.

4.4. Reduction

The calibrations should be done on a band-to-band basis, and it's best to split the spectral windows and sources (noise and astronomical) up to avoid confusion. In the example, we're only calibrating the lower sideband part of band 1 (= window 1), which we split up already. Please flag all your bad data before starting the bandpass calibration, otherwise the bandpass solution may not converge! **Note - it is critical not to do baseline or linelength corrections on the noise source - bad things will happen to the noise bandpass calibration if you do. It is recommended that you `uvcat` the noise data out before you apply the baseline and/or linelength corrections (if needed).**

1. Bandpass calibrate the 500 MHz wideband noise source. Figure 2 shows the amplitude and phase of the noise source vs. channel in the 500 MHz band after noise bandpass calibration.
   ```
   mfcal vis=noise500win1 refant=9 interval=0.2
   ```

2. Copy the noise bandpass from step (1) to the 500 MHz wideband astronomical calibrator, apply the solution, then bandpass calibrate the **astronomical** bandpass calibrator. Figure 3 shows the amplitude and phase of the astronomical source (3c273) vs. channel after noise **and** astronomical bandpass calibration.
   ```
   gpcopy vis=noise500win1 out=source500win1 options=nocal
   uvcat vis=source500win1 out=source500win1noise options=nocal
   mfcal vis=source500win1noise refant=9 interval=0.2
   ```

3. Bandpass calibrate the 31 MHz narrowband noise source. Figure 4 shows the amplitude and phase of the noise source vs. channel in the narrowband after noise bandpass calibration.
   ```
   mfcal vis=noise31win1 refant=9 interval=0.2
   ```

4. Copy the 31 MHz narrowband noise source to the narrowband **astronomical** source, apply.
   ```
   gpcopy vis=noise31win1 out=source31win1 options=nocal
   uvcat vis=source31win1 out=source31win1noise options=nocal
   ```

5. Copy the 500 MHz wideband calibrations from step (2) to the narrowband **astronomical** source, apply. Figure 5 shows the amplitude and phase of the astronomical source (3c273) vs. channel in the 31 MHz narrowband after all the bandpass calibrations have been applied.
   ```
   gpcopy vis=source500win1noise out=source31win1noise options=nocal
   uvcat vis=source31win1noise out=final options=nocal
   ```

The offset of phase from zero in Figure 5 reflects the window-to-window offset between the narrow and wideband. This is ideally taken out by bandpass calibration on a bright astronomical calibrator, but we lack the signal-to-noise to do this in the narrowest bands. The offset can be calculated (after the bandpass calibration steps above) by doing a `selfcal` on the wideband astronomical source with `interval=0.2` to remove temporal atmospheric effects, copy and apply the gains to the corresponding narrowband observations of the bandpass calibrator, then carry out `selfcal` on the narrowband data with `interval=9999` to average over the entire bandpass observation (to maximize the signal-to-noise). The resulting gain solution contains the window-to-window offset. This offset can then be applied to the source data for that narrowband window. For more information please see the CARMA Cookbook.

4.4.1. Checking the Noise Bandpass Method

As a check, we do a final bandpass calibration on the narrowband astronomical source in the last step. **This is not a part of the reduction!** This is to check for differences between an astronomical bandpass calibration on a very bright source (the ideal way to do bandpass calibration, but it takes a lot of integration time and is too noisy for the narrower bands), and the noise bandpass technique described in the steps above. Figure 6 shows the amplitude and phase vs. channel of the astronomical source — the very flat amplitude and phase imply that there isn't much difference between the two techniques.

4.4.2. Copying the Noise Source to the USB

If the data you want to work with is in the upper sideband (USB), where these is no noise source, the data will have to be conjugated into the USB in Miriad. One simple step does the trick:

```
uvcal vis=data.mir out=data.conj.mir options=noisecal
```

4.5. Phase Calibration

The map quality is improved when a nearby astronomical point source calibrator is used to track the instrumental phase drifts and even some of the atmospheric delay changes. This usually results in using weaker phase calibrators which require as much correlated bandwidth as possible to get reliable phase measurements. The bandpass calibration described above uses the 500 MHz mode but with the same 2nd LO setting as used for the target observations. For narrow line observations this will result in large overlap among the three bands. The bands can be spread out to cover more bandwidth by changing the 2nd LO in the `configband` command. This changes the band positions in the RF and IF bands. Another calibration step is required to link the RF and IF gains at the frequencies used for phase calibration to the target observation frequencies. This calibration is best done using the bandpass calibration source since the target observations are already linked to the bandpass source. Typically all bands and the phase calibrator observations will be calibrated relative to the wideband measurements of the bandpass source in band 1.

5. Calibration in the 62 MHz – CARMA Hybrid Mode

5.1. The Hybrid Method

Though the bandpass calibration technique utilizing the noise source discussed in the previous Section works well for the narrowbands (31 MHz and below), it introduces some unpleasant ripples in both amplitude ($\sim$10%) and phase ($\sim 10^\circ$). Though this may be ignored for some projects, PIs who wish to avoid introducing such noise into their maps should either bandpass calibrate the 62 MHz bands with a very bright astronomical source, or utilize the CARMA Hybrid Mode at the cost of longer bandpass calibrations ($\sim$30 minutes).

Though this document is focused on bandpass calibration, the main goal of the 62 MHz Hybrid mode is actually for observing a science source in 3 overlapping narrowband (62 MHz) modes, and observing the calibrator in 3 wideband (500 MHz) modes as discussed in the previous section. The wideband calibration observations will result in better signal-to-noise, which allows the PI to select fainter but closer calibrators. Hybrid passband observations are acquired during the track in the the following correlator setups:

```
wide [BW500, BW500, BW500]
narrow [BW62, BW62, BW62]
hybrid [BW500, BW62, BW62]
hybrid [BW62, BW500, BW62]
```

in order to (1) calculate phase offsets between the wide and narrowband and (2) address atmospheric phase fluctuations. Differences in phase can be determined, in principle, when observations are made with (two) alternating wide and narrowband setups, but atmospheric phase fluctuations can introduce significant phase errors in the measured band offset which are in principle avoided by the hybrid approach.

5.2. Writing a Hybrid Observing Script

The CARMA scriptWriter is versatile and has been formatted with all of the tools necessary to observe a source with three 62 MHz bands.

In the example given below, the bands have been overlapped by 6 channels. The `chanoffset` variable defined by the observer, which is in GHz, is calculated as follows (add these lines to the scriptWriter generated observing script):

```
chanoffset = [bandwidth - ((#ofchannels_overlap + 0.5) * delta_nu)]/1000GHz
bandwidth = 62.5 MHz #(= 62.5 MHz / 63 channels)
delta_nu = 0.977 MHz
```

To overlap the Bands, set the tuning in the generated script as follows:

```
# Tuning options
tuning = {
'restfreq' :  linefreq('12CO(1-0)'), # Alternate way to specify rest frequency
#'restfreq' :  95.0, # [GHz] Line rest frequency
'sideband' :  USB, # Sideband for first LO (LSB or USB)
'IFfreq' :  1.79, # [GHz] IF frequency
}

# Correlator configuration for science target
chanoffset = 0.0560195
```

```
configband(1, BW62, tuning['restfreq']-chanoffset)
configband(2, BW62, tuning['restfreq'])
configband(3, BW62, tuning['restfreq']+chanoffset)
```

An observer can adjust the number of channels they wish to overlap with '`# ofchannels_overlap`'. The first 3 beginning and ending channels in the 62 MHz mode are known to have a large rms noise. Therefore, it is advisable to overlap at least 6 channels to be safe. The noisy channels should be flagged during reduction to avoid introducing more noise into the data. Furthermore, it is also advisable to overlap an even number of channels so that a symmetric number of channels/velocities are flagged later. As always, the correlator configuration should be checked using the Correlator Configuration Tool on the CARMA tools webpage.

To observe the calibrator in 3 wideband, 500 MHz modes, set `reconfig` to one of the three `od.CORR_BW500` options as shown below.

```
# Correlator configuration for calibrators
# reconfig:  Sets correlator configuration for calibration observations
# None :  same as for science targets
# od.CORR_BW500LO6:  500 MHz, non-overlapping bands in BIMA IF
# od.CORR_BW500LO : 500 MHz, non-overlapping bands (not recommended for 3mm)
# od.CORR_BW500 :  change bands to 500 MHz without changing IF
# hybrid:  Correlator configurations to calibrate band offsets (see FAQ page!).
# Needed only if all bands have width < 500 MHz.
# tintHybrid :  integration time for each of the hybrid correlator modes
correlator = {
'reconfig' :  od.CORR_BW500LO6,
#'hybrid' :  None,
'hybrid' :  [ [BW500, BW62, BW62], [BW62, BW500, BW62] ],
'tintHybrid' :  5.0,
}
```

If observing 3mm, `od.CORR_BW500LO6` is the best option. To observe the passband source in the hybrid setup in addition to the wideband (for calibrator) and narrowband (for source) setups, uncomment the

```
'hybrid' :  [ [BW500, BW62, BW62], [BW62, BW500, BW62] ],
```

command and comment out or delete the '`'hybrid' :  None,`' option. The '`tintHybrid`' parameter sets the integration time for each of the the hybrid modes on the passband calibrator. I.e. For the setup above, you would get a total of 10 minutes for bandpass calibration, 5 minutes with setup `[BW500, BW62, BW62]` and 5 minutes with setup `[BW62, BW500, BW62]`.

Setting up Passband Observations:

```
Passband = {
```

```
'doPassband' :  True, # If True, observe passband calibrator
'doPoint' :  False, # Point up on passband calibrator if needed
'forcePoint' :  False, # Force pointing if source is available
'tint' :  5.00, # [minutes] Passband calibrator integration time
'minflux' :  4.00, # [Jy] Minimum flux density for passband cal
'preferred' :  '3c273,1058+015', # Preferred passband calibrator
'middle' :  False, # OK to observe in middle of phase/source cycle?
'ncal' :  1, # Maximum number of calibrators to observe per track
'interval' :  None, # [hours] How frequently to perform passband cal
}
```

An example setup for passband observations is given above. First, to observe a passband source, set '`doPassband`' to `True`. To set the integration time for the wide band and narrow band passband observations set '`tint`' to a value in minutes. It is important to set a minimum flux for the passband source with '`minflux`', particularly if a preferred passband source is not set. It is possible to set multiple preferred passband sources as in the example given above; the script will first look to see if 3c273 is up and then 1058+015. To allow the passband source to be observed in the middle of a track, set '`middle`' to `True`. To point on the passband source if pointing is needed, set '`doPoint`' to `True`.

5.3. Reduction

Reduction of the 62 MHz Hybrid Mode is relatively complicated right now, and done by a C shell script calling various Miriad commands. Please see the CARMA Cookbook for more information.

6. Acknowledgments

We would like to thank Stephen White, Alberto Bolatto, Nikolaus Volgenau, James Lamb, Jin Koda, John Carpenter, Stuartt Corder, Kevin Rauch, Dave Hawkins, and Leslie Looney for all their helpful comments and suggestions.

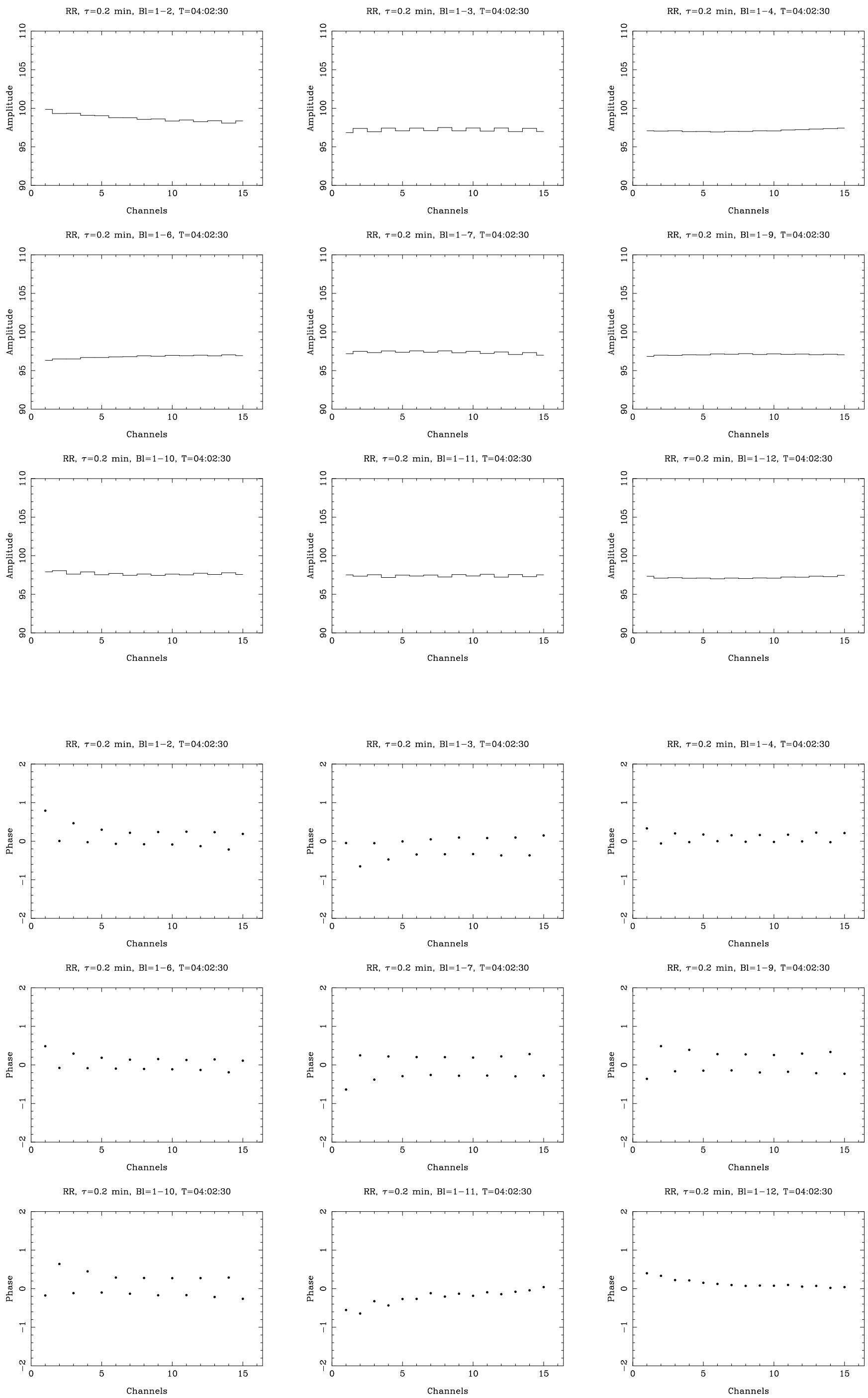

Fig. 2.— Amplitude (top) and phase (bottom) of the noise source vs. channel in the 500 MHz band after noise bandpass calibration for baselines with Antenna 1. The bimodality in the phases are known and very small ($\sim 1^{\circ}$), and do not affect the bandpass calibration. The Miriad command used to make these plots is:

```
uvspec vis=visfilename device=visfile.ps/ps axis=channel,amp
```

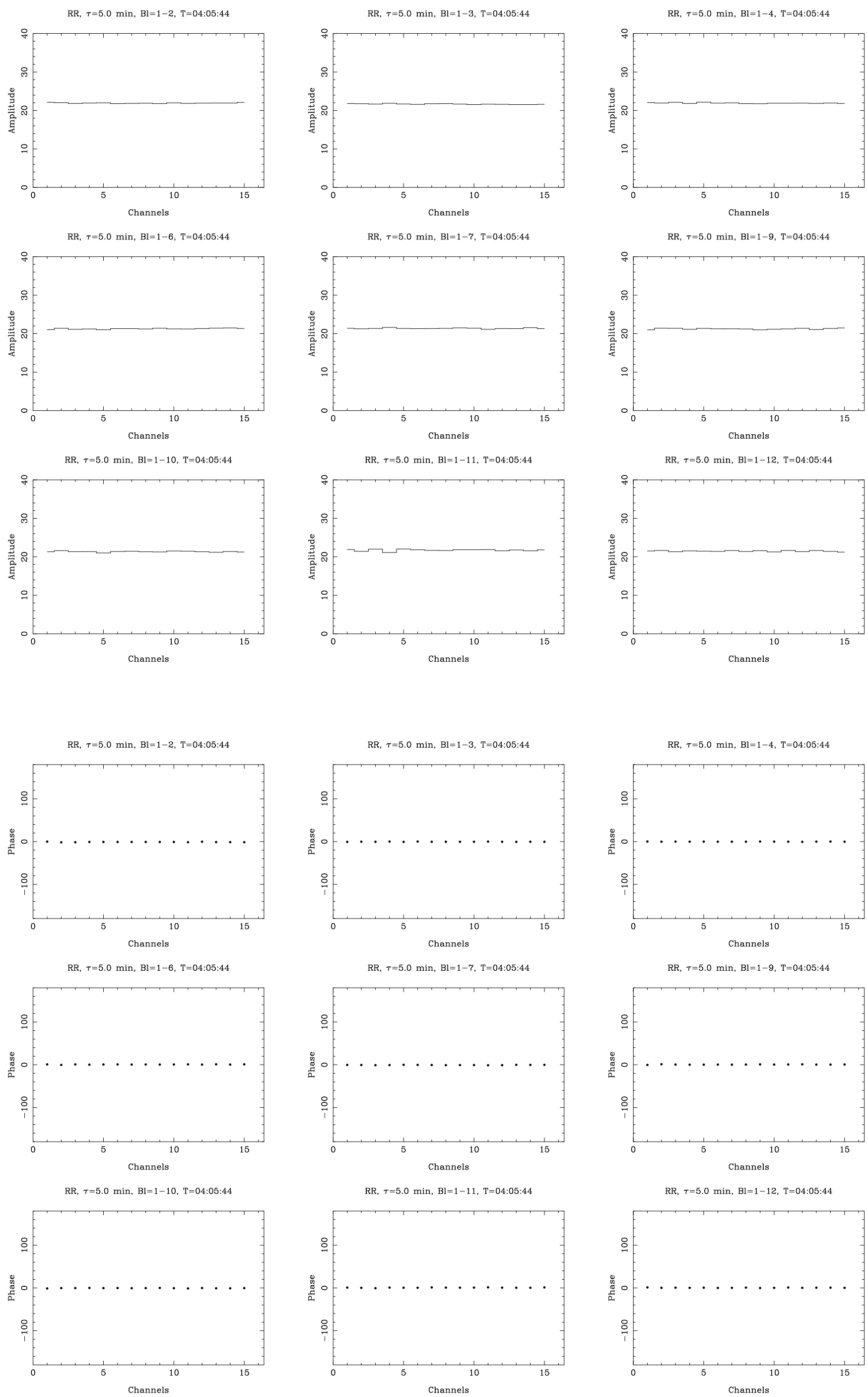

Fig. 3.— Amplitude (top) and phase (bottom) of the astronomical source (3c273) vs. channel in the 500 MHz band after noise and astronomical bandpass calibration.

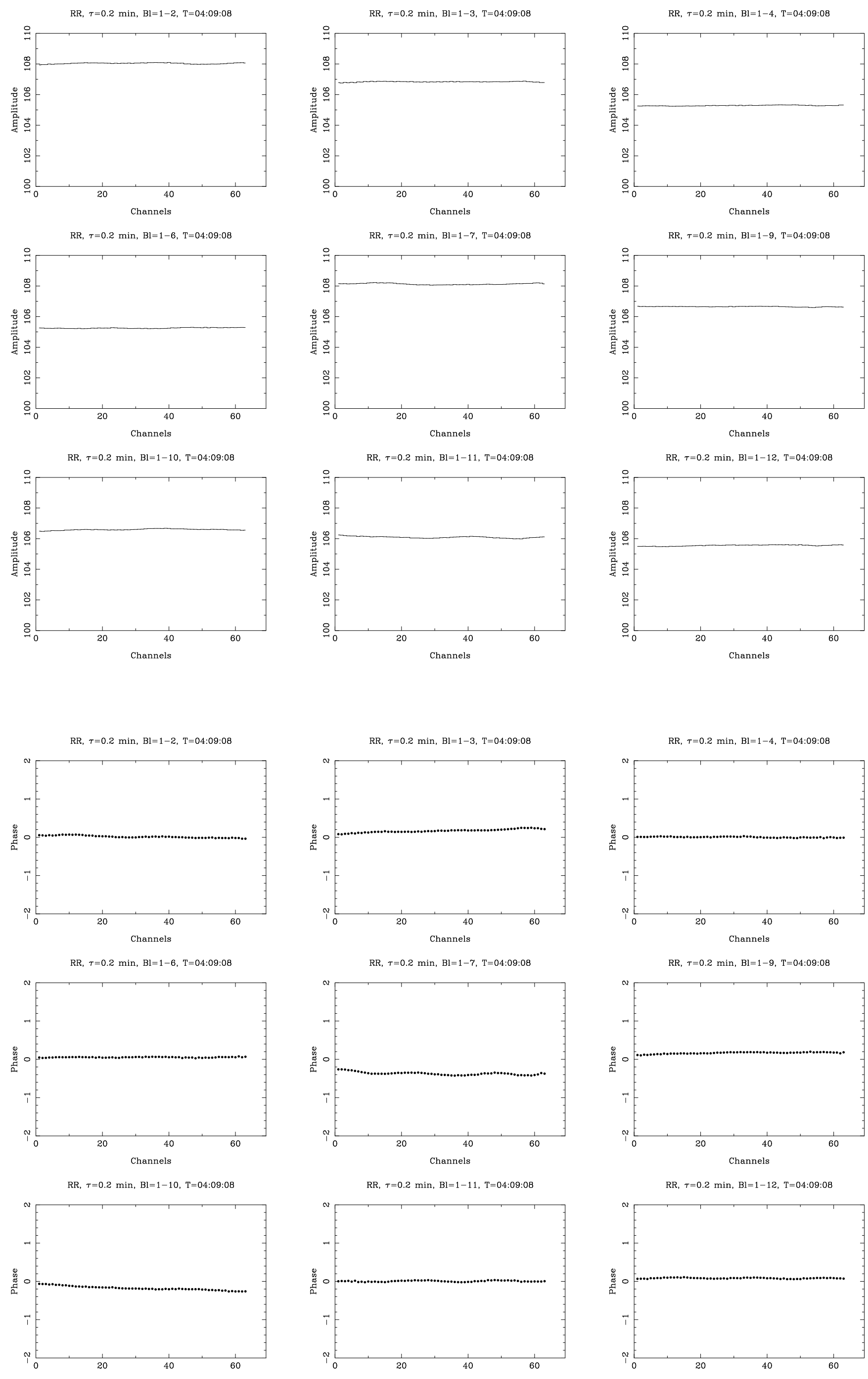

Fig. 4.— Amplitude (top) and phase (bottom) of the noise source vs. channel in the 31 MHz narrowband after noise bandpass calibration.

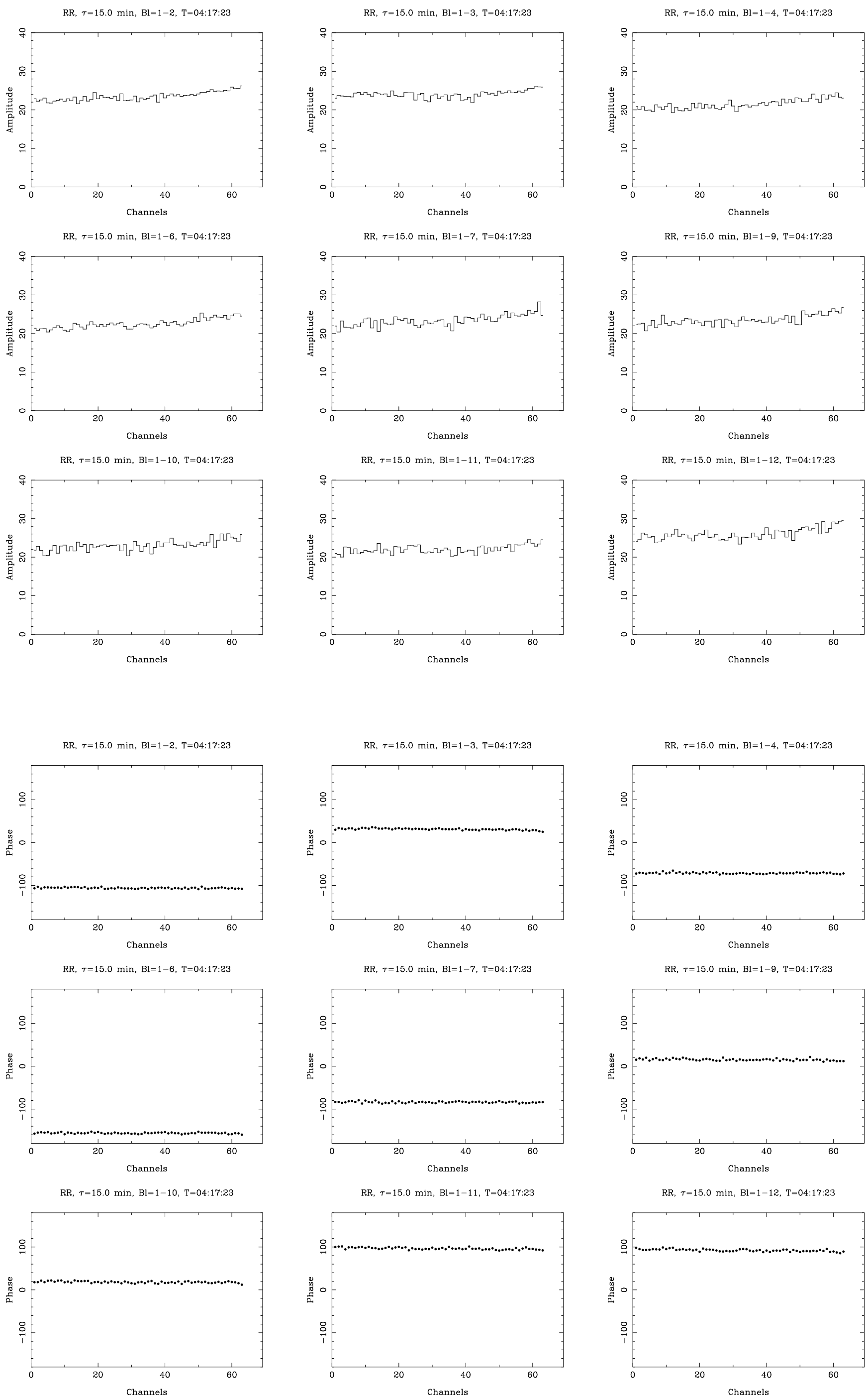

Fig. 5.— Amplitude (top) and phase (bottom) of the astronomical source (3c273) vs. channel in the 31 MHz narrowband after all bandpass calibrations have been applied. Phase offsets from zero are corrected by the gain calibration later on in the reduction process.

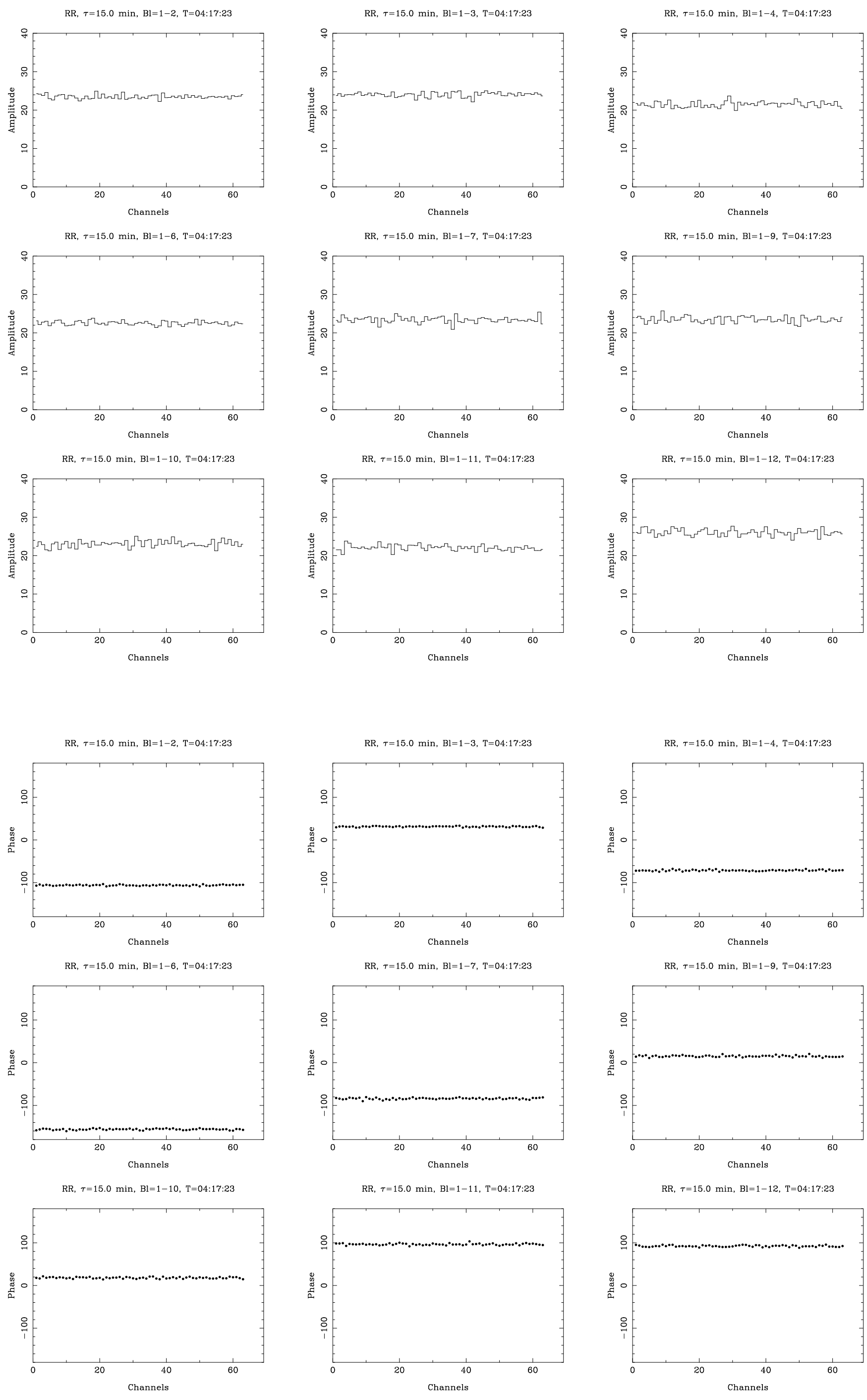

Fig. 6.— Amplitude (top) and phase (bottom) of the calibrated 31 MHz astronomical source vs. channel after another astronomical bandpass — this is done as a check to look for differences between the noise bandpass calibration technique described in Section 4.4 and a pure astronomical bandpass calibration. The flat amplitude and phase implies that there isn't much difference between the two techniques.