EVLA Memo # 202
Astronomical Calibration of Tcal and Antenna Efficiency for the Jansky Very Large Array

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Abstract

Accurate gain calibration, and estimation of system temperatures are possible in principle through accurate knowledge of various system parameters. In practice, our knowledge of the on-board calibration diode power and antenna efficiencies are not sufficiently accurate. I propose here a calibration regimen to accurately determine both of these quantities based on the principle that the atmospheric and spillover power contributions to the system temperature are the same for all VLA antennas for both polarizations at any given frequency – provided that weather and ground conditions are the same for all antennas. The regimen requires only a elevation tip and an observation of a source of known flux density.

1 Introduction

The Jansky VLA receivers are equipped with on-board switched power calibration systems whose primary purpose is to enable correction for electronic gain variations. A small wideband noise power (typically ∼5% of the system power) is synchronously added at 10 Hz to the astronomical signal following the polarizer and before the first amplifier. This additional power is synchronously detected at the station boards in the correlator, providing power measurements with the noise diodes both off and on. From this, the system calculates the sum $P_{sum} = P_{on} + P_{off}$ and the difference $P_{dif} = P_{on} - P_{off}$. The latter quantity tracks and permits correction for variations in the system electronic gains.

However, the system can also be used for accurate calibration of the visibility amplitudes and calculation of the system temperature. EVLA Memo 145 shows that the visibility, V, in Jy, is related to the correlator cross-power P_{corr} by

$$V = K\sqrt{\frac{T_{cal1}}{\epsilon_1}}\sqrt{\frac{T_{cal2}}{\epsilon_2}}P_{corr} \tag{1}$$

where $T_{cal} = P_{cal}/k\Delta\nu$ is the noise diode power in temperature units, and $\epsilon = A_{eff}/A$ is the antenna aperture efficiency. K is a constant dependent on antenna area A, atmospheric absorption η, correlator efficiency η_c, and measurements of the switched power P_{dif}:

$$K = \frac{2760}{\eta_c\sqrt{A_1A_2}\sqrt{\eta_1\eta_2}\sqrt{P_{dif1}P_{dif2}}}. \tag{2}$$

This equation will provide correctly calibrated visibility amplitudes if all the factors are known. However, in general, the values of T_{cal} and ϵ actually employed in equation 1 will be incorrect, so that the derived visibility amplitude, V_{meas} will depart from the true value V_{true} as given below:

$$V_{meas} = V_{true}\sqrt{\frac{T_{m1}}{T_{cal1}}}\sqrt{\frac{T_{m2}}{T_{cal2}}}\sqrt{\frac{\epsilon_1}{\epsilon_{m1}}}\sqrt{\frac{\epsilon_2}{\epsilon_{m2}}} \tag{3}$$

where the 'm' subscript means the values actually applied. Thus, values of T_{cal} which are too high, and values of ϵ which are too low both result in overestimation of the visibility amplitude.

The weights used in imaging also depend on the system temperature. For a single visibility measurement, the weight is given by $W = (\sigma_1\sigma_2)^{-1}$, where σ is the rms noise in the measurement, with units of Jy. The rms noise is related to the system temperature through the radiometer equation, so that we have

$$W = \frac{K2}{T_{sys1}T_{sys2}} \tag{4}$$

where $K2$ is another constant which includes bandwidth and time averaging factors. The system temperature is determined from the following equation

$$T_{sys} = \frac{P_{sum}}{2P_{dif}} T_{cal} \tag{5}$$

Thus, estimates of the system temperature are dependent on the measured noise diode power in the same way as the visibilities.

It is thus clear that accurate determinations of both the T_{cal} and antenna efficiencies are important for accurate calibration and imaging.

2 Illustration of Typical Switched Power Data

Figure 1 shows typical data from the switched power system, showing the P_{dif}, P_{sum}, and T_{sys} values from S-band data for five sources, as a function of antenna elevation. Note that any errors in the tabulated values of T_{cal} are linearly coupled to errors in the derived system temperature. In practice, the noise diode power is measured in the lab, as a function of frequency, using the hot/cold load methodology. The accuracy of this lab measurement is expected to be of the order of 5%. For various reasons, on-antenna measurements of the calibration power differ by up to 10% from those measured on the bench.

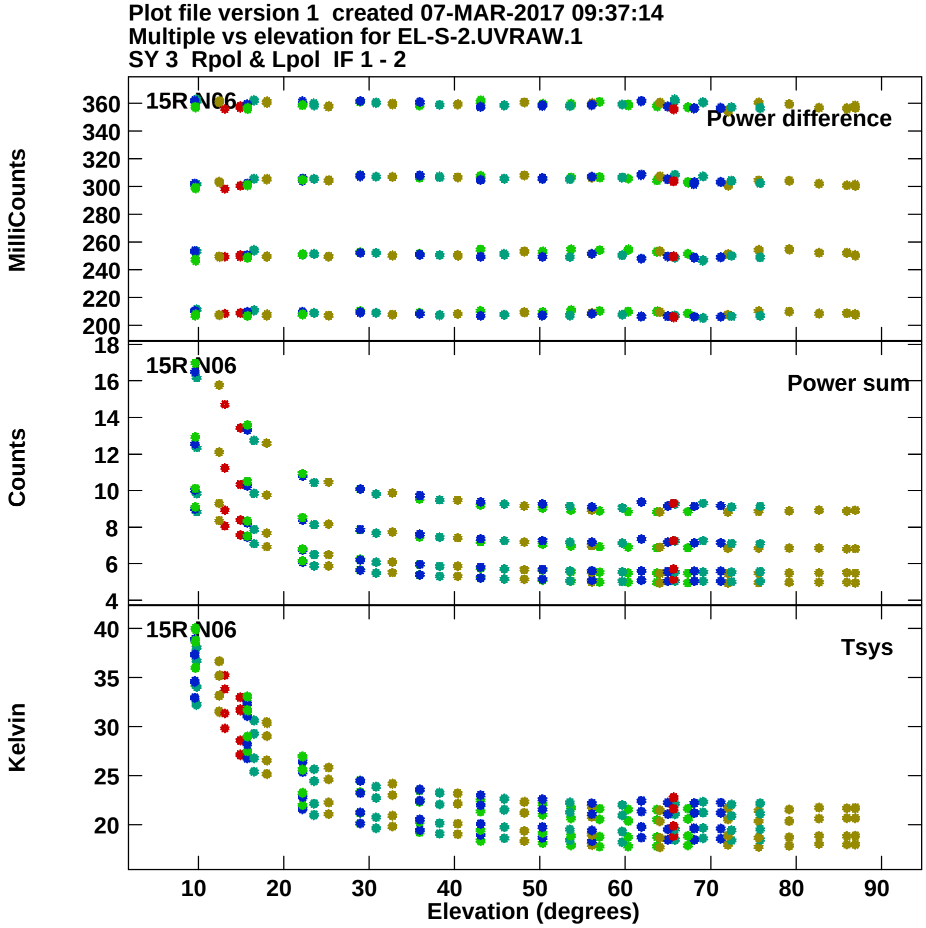

Figure 1: Showing typical data from the switched power system. Plotted on top are the raw P_{dif} values for two frequencies at two polarizations at S-band as a function of antenna elevation. In the middle are the corresponding values of P_{sum}, and at the bottom are the resulting measurements of the system temperature, $T_{sys} = T_{cal}P_{dif}/(2P_{sum})$. The colors discriminate the five individual sources.

The primary purpose of the switched power system is to permit correction for any gain variations in the electronics. Primary amongst these is the temperature sensitivity of the analog electronics. A good example of the size of this effect is shown in Figure 2. These data were taken on February 05, starting at 3AM, local time. The outside temperature reached a minimum of 18F at 7AM, and rose steadily to 53F at the time the observations ended at 1PM local time. The system gain variations at all bands inversely follow the outside temperature, maximizing at dawn at all bands, then steadily dropping through the morning hours. The changes in switched power shown here are closely matched to changes in source visibility amplitude – application of the switched power reduces the magnitude of the diurnal visibility amplitude variations to less than ∼3%. The residual is presumably due to the temperature sensitivity of the noise diode itself.

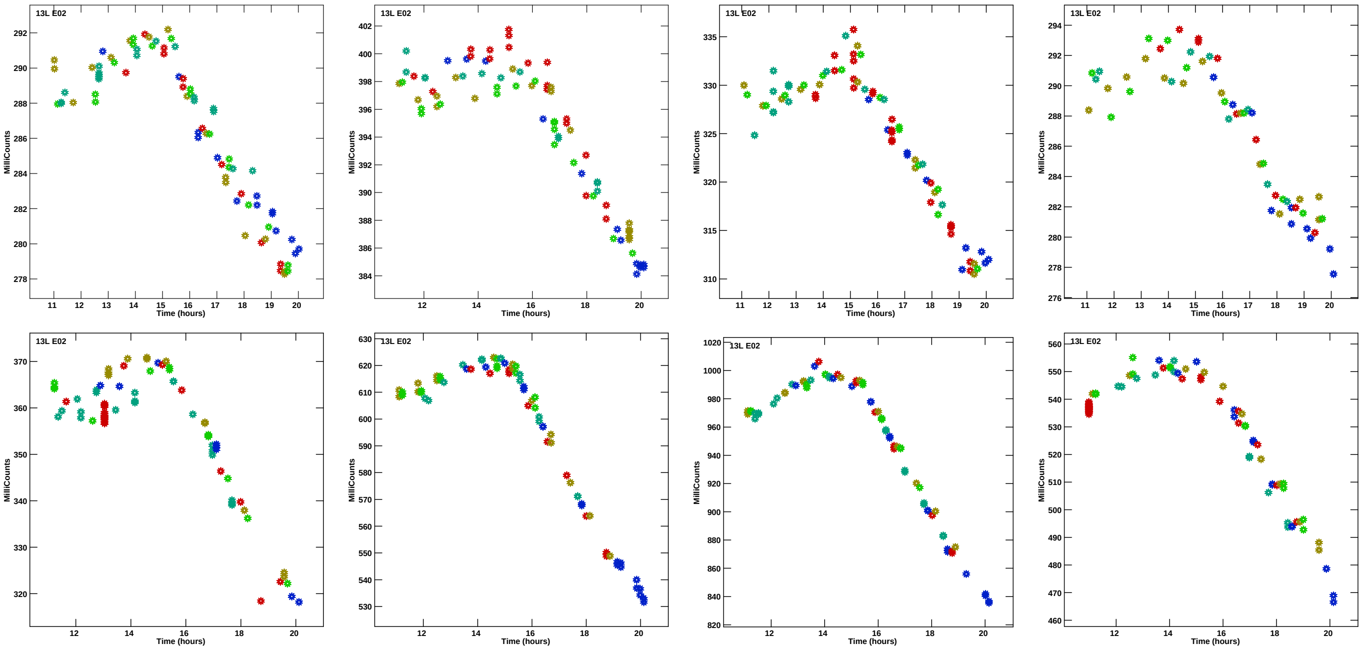

Figure 2: Temperature sensitivity of the analog system gains. Shown are the values of P_{dif} for all eight Cassegrain bands, with the four low-frequency bands L, S, C, X across the top row, and the four high frequency bands, Ku, K, Ka, and Q across the bottom row. All eight bands show the same temporal dependency, with the maximum gain occurring near 7AM local time, with the gain dropping as the day progresses. The amplitude of the gain signature varies greatly – the four low frequency bands vary by only 5%, while the four high frequency bands vary by 15%.

It has long been thought that the gain variations are a manifestation of a 'heat pipe' – the metallic feed horns extend into the night air, and provide a good conduction path to the post-amplifiers, which are bolted to the sides of the horns. However, this model would predict a significant lag in the time of maximum gain at L and S bands – and none is seen. Furthermore, the Q and Ka band horns do not in fact extend outside the housing – yet their gains vary in an identical manner to those at K and Ku bands, whose horns do extend out into the atmosphere. It appears that a more immediate temperature coupling mechanism is needed to explain these variations. Further discussion of this issue lies beyond the scope of this memo.

3 Calibrating the Noise Diode Power

Errors in the derived visibility amplitude are a function of both the errors in the values of the calibration diode power and errors in the antenna efficiency. Equation 1 shows that visibility measurements alone cannot separate these errors. The most direct way to separate these is to perform fundamental system temperature measurements on individual antennas through 'hot-cold' loads – the same procedure as when done in the lab. This procedure calibrates the noise diodes, after which an observation of the power increment due to a source of known flux density will establish the antenna efficiency. As part of the commissioning of the EVLA, this exercise was done on a limited number of VLA antennas (primarily ea24) – the results from some of these tests are given in various EVLA memos. Unfortunately, these tests are extremely labor-intensive, and are not practical to perform on all VLA antennas at all bands. The antenna efficiencies measured in these tests on ea24 are utilized for all antennas in the current calibration software.

I propose here an easier method for measuring the noise diode calibration values, which can be done both quickly and remotely. Like all easier methods, there is a flaw – in this case, the measurements are relative to an assumed standard.

The proposed method is based on the principle that the *increment* in power received by an antenna between a high and low elevation is, to good accuracy, independent of the antenna efficiency. Thus, if we measure the system power from an antenna as a function of elevation as the antenna moves from low to high elevation, the increment in the power is largely independent of the forward gain of the antenna. Details of the antenna optics, such as the focus, or misalignment of various panels, have little influence on the increment of power received by that antenna as it moves from high to low elevation. Thus, all VLA antennas, at both polarizations at any given frequency, should show the same increment in power as the antennas move from one elevation to another.

This statement can be justified as follows: The effects of misfocus or panel misadjustments are of course reflected in a change of the antenna's spatial gain properties. But, so long as these errors are small, the changes are largely in the direction of the main beam. Thus, the reduction in on-axis forward gain is offset by an increase in the gain of the near-in sidelobes and a broadening of the main beam. So long as the spatial scales of the atmospheric and ground emission which are responsible for the increase in noise power are larger than the scales associated with the major gain changes from small aberrations, the power received at a given elevation will remain independent of small aberrations.

The lack of variation of system power as a function of feed focus has been directly measured by Bob Hayward and me during early EVLA testing – while in the vertical position, we observed the total power as a function of deliberately misfocussing the subreflector. We were surprised to note there was virtually no change in received power.

In order to utilize this principle for calibration purposes, it must also be true if all antennas are observing through the same atmosphere, and over essentially the same ground. The VLA, in wintertime in D configuration, and in stable weather, should meet these requirements. Providing these caveats are true, any apparent differences in system temperature increment between antennas and polarizations over some range of elevation must be caused by an error in the calculation of the system temperature – which by equation 4 can only be due to an error in the presumed value of the noise diode temperature, T_{cal}.

4 A Trial Experiment

To explore the potential of this method, I analyzed data taken on 10/11 February 2017. This run was intended to provide new elevation gain curves at two frequencies in each Cassegrain band. The observations ran from 10PM in the evening through 6AM the following morning. Two sources were tracked from meridian transit through setting, and two others from rising through meridian transit. Observations of the two pairs of sources were interleaved, so that high and low elevations were being observed throughout the observation. The declinations for all four sources were between 31 and 39 degrees. The weather was dry, calm, and clear throughout. The array was in the D-configuration, except for two antennas (ea16 and 26) located at W72 and E72, respectively. The close packing of the antennas was a problem – two antennas at the center of the array had to be left out of the analysis as shadowing prevented them from observing at the low elevations needed to provide a significant increase in system power. To minimize the data volume, the observations included just two spectral windows from each observing band, with the two frequencies chosen to span each band. Referenced pointing was done, using X-band, for each observation. This is of no importance for the measurements of system temperature, but is of critical importance when antenna gains are required.

The temperature dropped steadily throughout the night, with the result that the post-amplifier gains rose in response to their temperature change. All the data taken in this run had their gains corrected through use of the switched power. There does remain a small residual effect – the noise diodes themselves have a small (∼2%) temperature sensitivity. This small residual temporal gain will not affect the key results reported below.

To demonstrate the similarity of the spillover and atmospheric components to the system temperature, I show in Figure 3 two plots, showing the change in system temperature as a function of zenith distance for both polarizations for five antennas at 42 GHz. The left panel shows the ten curves on their original scales – the shapes look similar (as expected), but the curves are vertically displaced, since the antenna system temperatures are not the same, and the errors in calibration diode temperature will be different. The right hand panel shows the result of applying a correction to the y-axis scaling by assuming the difference between the system temperatures at 80 and 20 degrees zenith distance must be the same, then vertically adjusting each plot so they are the same at ZD = 20 degrees. Differernces in the shapes of each of the ten traces is barely distinguishable, supporting the notion that the elevation

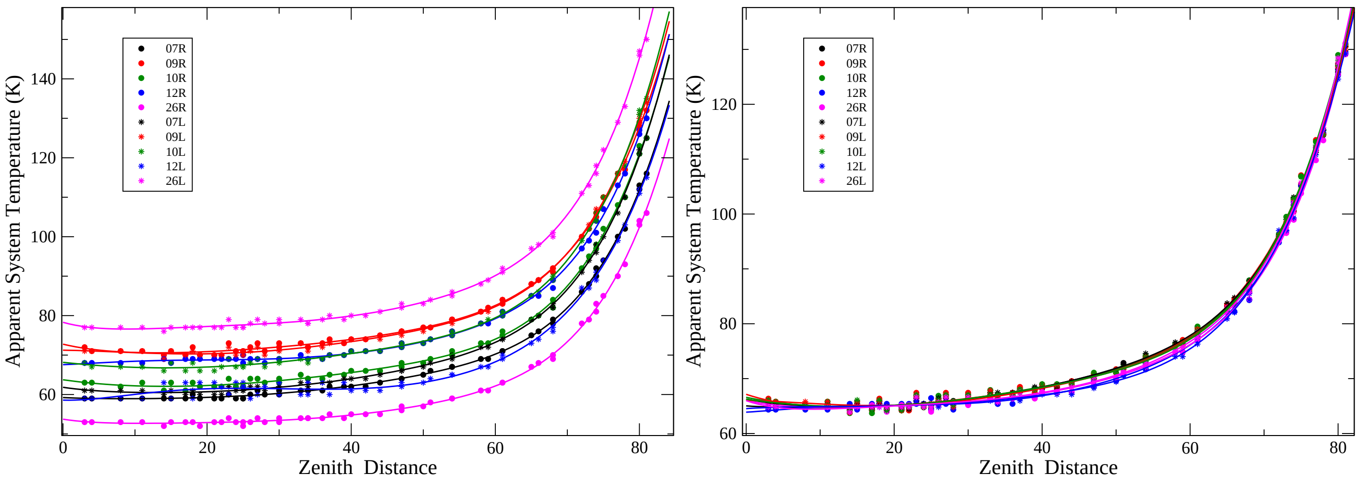

Figure 3: The left panel shows the system temperatures for both polarization for five unblocked antennas at 42 GHz. The vertical spreads between the traces are due to differences in receiver temperature (a constant offset) and scaling errors due to incorrect values of T_{cal}. To demonstrate the similarity of the shapes, the right panel shows the result of: (a) scaling the traces such that $T_{sys}(80) - T_{sys}(20) = 60$K, and (b) vertically adjusting each trace so $T_{sys}(20) = 65$. All antennas show nearly identical runs of atmospheric and spillover power as a function of zenith distance.

power increment is the same for all antennas and both polarizations. Note that the values utilized for the temperature increment, and the value chosen for the normlalization at 20 degrees AD are arbitary. For this particular example, I took the median values for each – this in effect assumes the lab measurements are correct in the median.

5 A Calibration Procedure

The exercise above shows good evidence in support of the hypothesis that all antennas see the same spillover and atmospheric emission power over elevation – provided the skies are clear, the antennas are unblocked and are sufficiently separated that ground reflections and other coupling effects are negligible, and that the atmospheric and ground emissions are stable over the duration of the measurement.

To give quantiative measures of the effects of the proposed calibration regimen, the following procedure was implemented on all the data taken on 10/11 February:

1. Basic editing, including review of the switched power (SY) tables to remove data affected by RFI. (This was only a problem at L-band). The SY table data were then smoothed with a 20 second boxcar to reduce noise fluctuations.

2. The new AIPS program ELFIT was utilized to fit a polynomial to the system temperature data. The program returns the difference in system temperature between two fiducial elevations – nominally 10 and 70 degrees. A typical fit (at 48 GHz) is shown in Fig 4

3. The median difference in system temperature ΔT_{ref} over all antennas and both polarizations for a single tuning frequency was generated. This is the 'reference' value. The median rather than the mean was utilized to reduce the effect of a few antennas whose T_{sys} values are clearly wildly incorrect.

4. The ratios between the reference ΔT_{ref} value and the peculiar values for each antenna and polarization, $C_T = \Delta T_{ref}/\Delta T$ were determined. This is the correction factor needed to adjust the Tcal values: $C_T = T_{cal}/T_m$.

The adjusted values of Tcal will ensure that the increment in system temperature between the reference elevations will be the same for all antennas and both polarizations at a given observation frequency. How effective is this procedure for permitting accurate calibration of visibility amplitudes? To explore this, I utilized the visibility data from the observation of 3C286 taken in this same run. 3C286 is a standard calibration source whose flux density is believed to be well known.

AIPS and CASA provide calibration programs ('CALIB' in AIPS) which estimate the antenna gains (G_i) needed to put the data on the correct amplitude scale defined by the calibrator flux density. In AIPS, these are defined as

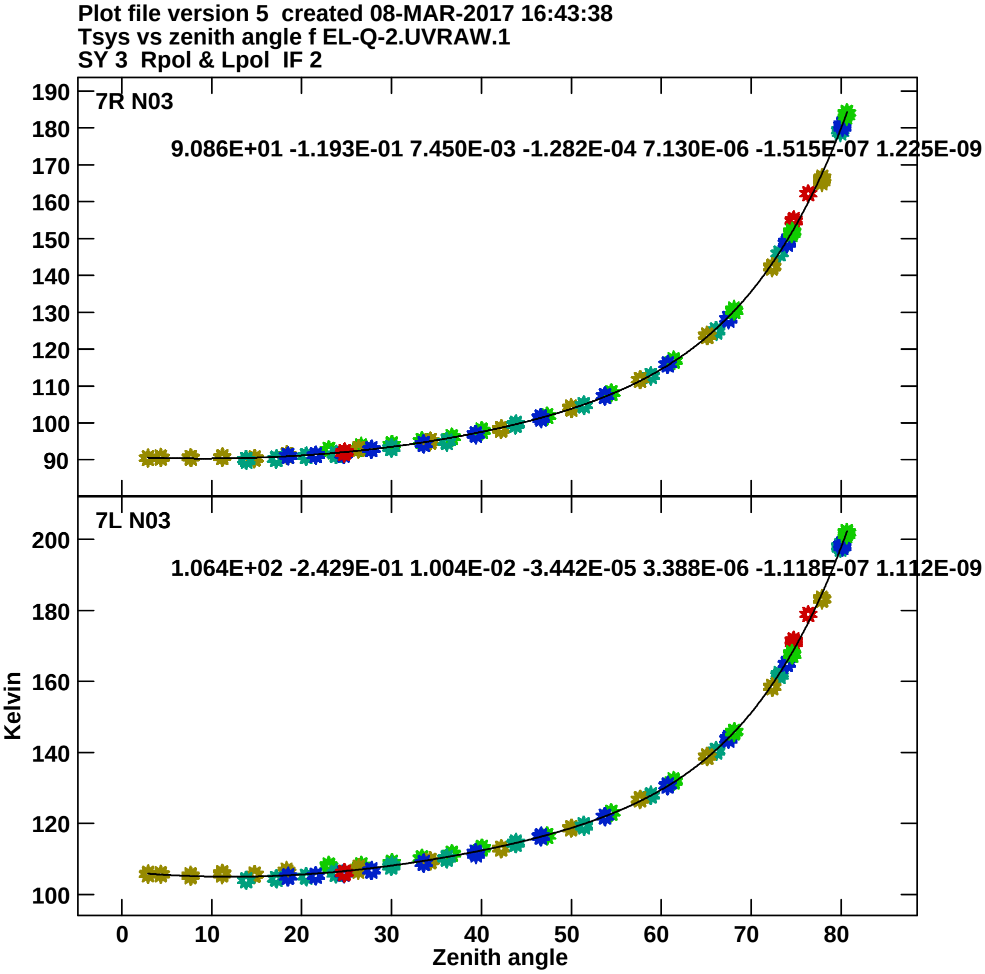

Figure 4: A typical fit, for ea07 at 48 GHz. The coefficients of the polynomial are given within each panel.

the *voltages* needed to correct the visibilities to the scale defined by the calibrator. If the 'default' values of T_{cal} and ϵ are correct, these gains should be unity for all antennas, polarizations, and frequencies.

In the general case where the employed values are not correct, analysis shows that the derived voltage gains G_i for a given antenna/polarization/spectralwindow are related to the real and assumed Tcal and efficiencies as:

$$G_i = \sqrt{\frac{T_i}{T_{mi}}}\sqrt{\frac{\epsilon_{mi}}{\epsilon_i}} = \sqrt{C_T}\sqrt{C_A} \tag{6}$$

where I have introduced a second correction factor for the efficiencies: $C_A = \epsilon_m/\epsilon$. Errors in either the Tcals or the efficiencies will create gain values different than 1. For example, if the T_{cal} value utilized is too low, (or the efficiency assumed is too high), then the derived visibility amplitudes are too low, resulting in a gain correction greater than 1.

AIPS antenna voltage gains were derived from the observed visibilities for 3C286, for both polarizations at both frequencies at all bands, for all unblocked antennas at three stages: (a) Using the visibilities generated with the standard values of T_{cal} and ϵ; (b) after adjustment of the visibililities for C_T – that is, after adjusting the T_{cal} values following the regimen described above; and (c) after adjustment for both C_T and C_A. For the last step, it was assumed that the efficiency for both polarizations at a given frequency for each antenna were the same, so the corrections for the two polarizations were averaged.

6 Results

The results are shown in the following table, showing the mean and dispersions in the amplitude gain corrections derived from the calibration procedure described above, for each band. For this analysis, only unblocked antennas with the full range of elevation, which showed no errors in the switched power data and for which the gain factors could be calculated were utilzed – typically 20 antennas at each band. The table contains four lines:

1. The top line shows the mean voltage gain required to obtain correct visibility amplitudes utilizing the default values for T_{cal} and ϵ.
2. The next line shows the dispersion in the gain solutions using the default values.
3. The next line shows the dispersion in the gain solutions after the T_{cal} values were adjusted following the procedure described in the previous section.
4. The last line shows the dispersion in the gain solutions after correcting both the T_{cal} and ϵ values.

The table is organized by band, with the lower and higher frequencies within each separated by a forward slash, with the higher frequency on the right side.

Table 1: **Antenna Gain Averages and Dispersions**

	L	S	C	X	Ku	K	Ka	Q
Mean Gain	0.98/0.99	0.99/0.94	0.95/0.97	0.96/0.95	0.95/1.0	0.98/0.99	0.99/0.99	1.10/0.98
Orig. Disp.	.056/.070	.059/.046	.048/.049	.058/.069	.084/.109	.070/.067	.100/.113	.155/.238
T_{cal} Disp.	.061/.075	.023/.028	.027/.022	.026/.042	.030/.037	.034/.027	.040/.050	.105/.174
ϵ Disp.	.016/.012	.005/.007	.015/.012	.010/.008	.010/.012	.018/.012	.013/.019	.017/.055

Top line: The mean antenna voltage gain corrections using the default values for T_{cal} and ϵ. Next line: The dispersions in these original gains. Next line: The dispersion in the voltage gains before after correcting the T_{cal} values using the described procedure. Bottom line: The dispersion in voltage gains after correction for both T_{Cal} and antenna efficiency.

Some immediate observations are noted here:

- The mean correction amplitude, for all bands, is already very close to unity. This means that the tabulated measures of antenna efficiency and noise diode temperature are close to correct, at least in the mean.
- The dispersion in these basic gains (line 2) is fairly large, especially at the higher frequencies. The immediate conclusion is that this is primarily due to similar-scaled errors in either/both the noise diode temperature and efficiencies. However, at the highest frequencies, it is very likely that errors in pointing (hence, in aperture efficiency) are dominant.
- The dispersion in gain solutions is reduced by a factor of two to three for most bands by rescaling (correcting) the noise diode values. No improvement is seen at L-band – the reason is not at all obvious – and the improvment is small at Q-band, no doubt because the dominant error is pointing offsets.
- The dispersion in gain solutions is dramatically reduced by subsequent inclusion of corrections for antenna efficiency – to a level of 1 to 2% at most bands. The mean gain for all bands is not listed, but is equal to 1.00, due to the procedure adopted.

7 Discussion and Recommendations

It should not be surprising that the dispersion in gains is dramatically reduced by implementation of these procedures. The better questions are: Are they physically meaningful, and are they stable?

For astronomical calibration purposes, the latter question is more important. The answer is: I don't know. An appropriate test is to repeat the procedure a number of times over a significant period of time, and examine the stability of both sets of corrections.

The proper answer to the former question cannot be answered without a much more elaborate measurement regimen on each antenna. However, the rather small corrections required to both the T_{cal} and ϵ values gives us some hope that the suggested procedures provide physically meaningful corrections. The suggested regimen cannot provide 'absolute' calibration values. Use of the mean or median value for the noise diode calibration essentially assumes that the laboratory hot/cold load procedure utilized for measuring the T_{cal} values provides unbaised values whose mean (or median) are correct. The offsets seen in the gain mean in Table 1 are thus assumed to be due to incorrect efficiencies – this is a physically reasonable assumption, as accurate total-power efficiency measurements are quite difficult to make with precision.

The suggested regimen for future measurement of these corrections is quite different from the procedures used in this memo – which utilized data taken from an experiment with entirely different goals. It is not necessary – nor is it desirable – to utilize long observations of astronomical sources, since atmospheric and ground temperature changes over such long periods change the emission power received by each antenna. Nor is it desirable to make these observations in the 'D' configuration – shadowing and antenna coupling effects reduce considerably the reliability of the data. The suggested procedure would be more like the following:

1. Execute a 'sky dip' in both directions (up to down, and down to up) at each band. Each takes about 4 minutes. Including overhead, all eight cassegrain bands will be completed in about one hour. If time is tight, this can be cut in half by changing bands at the completion of each dip. This is best done in ideal weather, and in the 'C' of 'B' configurations, so antenna shadowing and coupling effects can be avoided through judicious choice of antenna azimuth. Unfortunately, since we still have not worked out how to safely utilize the digital power when in 3-bit modes, this will have to be done with the 8-bit system.

2. To measure the antenna efficiency corrections, a single interferometric observation, at each band, of a source of known flux density is required. This should be done at an intermediate elevation, to minimize the effects of the antenna forward gain dependency on elevation (particularly important at high frequencies).

In principle, these corrections should be very stable over time – so that once done, further observations should not be needed for a year or more. In any event, any notable changes will be quickly noted through astronomical calibration of system gains, so that followup and correction can be easily scheduled after examination of the results of normal observing.

It is a pleasure to acknowledge Eric Griesen's efforts in rapidly producing the 'ELFIT' task, needed to efficiently analyze the system temperature data.