

EVLA Memo 243

On Using the JVLA Receiver Noise Diodes for Accurate Gain Calibration

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Abstract

It has been proposed that VLA observations of transient events identified by the Vera C. Rubin Observatory be amplitude calibrated without observations of calibration sources of known spectral flux density. This requires the use of the receiver noise diodes. For this to be effective, it must be shown that the spectral powers from these diodes are stable over periods of years, and that a calibration method be established to accurately determine the noise temperature of these diodes. Our investigation of the stability of the VLA's noise diodes shows that for most frequency bands, the on-board noise diodes are stable to $\sim 2\%$ over periods as long as a decade. We show how the noise diode power can be calibrated using the known flux density of 3C286, and hence how accurate amplitude gain calibration can be achieved without the need to observe a source of known flux density. Suggestions for implementation are made.

1 Motivation

Up to the present time, amplitude gain calibration of VLA observations is accomplished through one or more observations of a source of known flux density and structure, notably the stable quasar 3C286. For most observations, the time needed for this – typically 10 to 20 minutes – is a small fraction of the observation duration. However, for short ‘snapshot’ observations of a single source, this additional time can be greater than that spent on the source, suggesting that an alternate means of calibration is desirable.

With the advent of the Vera C. Rubin Telescope, there could be one to 10 new transients worthy of observation with the VLA per day¹. The NRAO is instituting a program to permit short observations of Rubin-detected transients. Each observation will be done at X-band using the 8-bit samplers, and will consist of one to two minutes on the target, plus a short calibration of a nearby phase calibrator – a total of no more than 10 minutes per transient. With these parameters, up to an hour a day may be spent on these observations. Addition of a flux density calibrator (if one is even available) would double the time spent – hence the need for on-board amplitude gain calibration. A successful on-board calibration regimen will benefit not only transient source observations. By obviating the need for regular gain calibration observations, up to an hour a day could be recovered for on-source observations.

The VLA's receivers include a noise diode which adds broadband RF power into the signal chain between the polarizers and the first amplifier. The power injected is typically $\sim 5\%$ of the system power, and is switched in at 10 Hz with a 50% duty cycle. This incremental power is detected at the correlator, and is referred to as P_{dif} . The primary purpose of this injected power is to allow correction of temporally changing system gains, but it can also be used to convert the raw correlator voltage products into calibrated visibilities. Provided the injected noise power is known and is stable over long periods of time, use of these diodes for gain calibration will save considerable observation time.

There is nothing original in the proposed procedures we describe in this memo – the VLBA utilizes a similar procedure for its gain calibration, as did the ‘original’ VLA, although in this case the calibration was intended to assist operations in evaluating data quality in real time. What is new here is its implementation on the JVLA for full amplitude calibration purposes.

All calibrations and analyses described in this memo were done in AIPS. Conversion to other data packages should be straightforward.

¹D.A. Perley, private communication

2 Amplitude Gain Calibration Basics

EVLA Memo #145 shows that the observed cross-correlation voltage product between two antennas, P_{corr} , produced by the JVLA's correlator is related to the desired calibrated visibility V in Janskys by

$$V = K \sqrt{\frac{T_{cal1}}{\epsilon_1}} \sqrt{\frac{T_{cal2}}{\epsilon_2}} \frac{P_{corr}}{P_{dif1} P_{dif2}} \quad (1)$$

where K is a system constant depending on the antenna collecting area and various efficiency factors (including correlator efficiency, atmospheric absorption, elevation gain dependency, and pointing errors), T_{cal} is the noise diode temperature, ϵ is the antenna efficiency at a canonical elevation angle², and P_{dif} is the noise diode power detected at the correlator, in the same units as the raw visibility. It will be seen from this expression that the key quantity needed for amplitude calibration is the *ratio* of the switched power to the efficiency, T_{cal}/ϵ , for each antenna.

The antenna efficiency – the ratio of the power collected at the receiver to that incident upon the antenna – can be measured from observations of a source of known flux density. The process requires use of hot and cold loads on the antenna feed and is described in a number of early EVLA Memos. It is a laborious process which has been done on one antenna only - ea24. The values determined for this antenna have been assumed to be the same for all other antennas.

The noise temperatures of the calibration diodes are initially determined using laboratory measurements prior to the receiver being installed into an antenna. These measurements are made as a function of frequency, and are contained in the science data model (SDM) for later application. The frequency grid sampling over which these are measured varies from 25 MHz at L, S, and C bands to 100 MHz at K, Ka, and Q bands.

The AIPS program TYAPL converts the observed raw correlations into calibrated visibility products using the values of efficiency and noise diode temperature as described in Eqn. 1. If the ratios of the values of T_{cal} to ϵ are correct for all antennas, subsequent gain calibration using a source of known flux density and structure will result in voltage gain values for all antennas of 1.0. However, due to errors in these quantities, the resulting gains are found to be distributed over a modest range. An example of this is shown in Fig 1, showing histograms of the distribution of voltage gains for an observation of the standard calibrator 3C286. These data were taken at 8464 MHz, with the

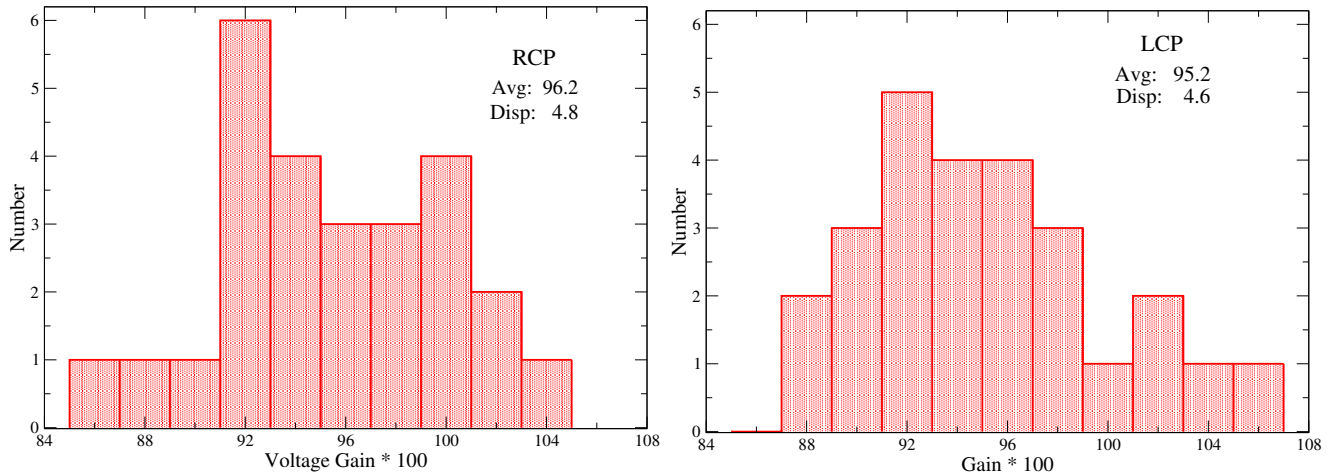


Figure 1: The antenna voltage gains distribution for an X-band observation of 3C286, taken on 31Jan2025 with the array in the A-configuration. RCP is in the left panel, LCP in the right. The offsets from the correct value of 1.0 is a result of errors in the values of T_{cal} and efficiency.

array in the A-configuration, with clear and calm weather conditions. There were 10 observations of 3C286 taken, and the spread in gains for a given antenna/polarization over the day was less than 2%. The values shown in the histogram represent median values over these observations. The figure shows that the spread in gain values between antennas is quite large – up to 10% in voltage, or 20% in power.

The convention used in AIPS is that the gain values determined from the observations are those that are needed to correct the observed data. Hence, a gain value of less than one indicates visibilities that are too high. Examination of Fig 1 shows that there is a negative offset of about 4% in the median voltage gain, indicating that the visibilities

²The antenna gain-elevation dependence is normalized to this canonical angle.

are too high, and a spread of about 5 – 10% about this mean. The offset indicates the ratio T_{cal}/ϵ is too high for this band, due to too high a value of T_{cal} , too low a value of efficiency, or a combination of both. Use of the current values of T_{cal} and ϵ will result in estimated flux densities approximately 8% too high

The origin of these offsets and spreads is easy to imagine – it is unlikely that the antenna efficiencies are known to that accuracy, and examination of the lab-calibrated values of the noise diode power shows steps of this size over frequency, suggesting problems with the lab-derived values.

3 Calibrating the T_{cal} to ϵ Ratio

As described in the previous section, accurate on-board calibration using Equation 1 requires accurate knowledge of the *ratio* of the noise diode power to antenna efficiency. It is fortunate that only the ratio is needed, as measurement of the absolute antenna efficiency is very laborious (and is completely impractical for all 28 of the VLA’s antennas for all 10 bands), while the determination of the noise diode power using known flux density calibrators is relatively simple.

The spread in antenna gains shown in Fig 1 is typical for all VLA bands. Use of these values will lead to errors in flux density of 5 to 10%. What is needed is a method for using the known flux density of a standard calibrator to determine the correct ratios of T_{cal} to efficiency. This is a straitforward operation, as described below.

In our procedure, we assume the early measurements of antenna efficiency have not changed, and are the same over all antennas, so that the procedure we recommend is to change the lab-measured values of T_{cal} .

Our procedure is as follows:

1. Observe a calibration source with known flux density and structure. For the determinations described here, this source is 3C286 (J1331+3030). It is critically important that these observations be done in clear and calm weather, and that numerous observations be taken over many hours, as pointing errors, receiver malfunctions of various kinds, and effects of antenna elevation gain, and atmospheric opacity will be identified and minimized. This is especially important for the high frequency bands.
2. Following the usual editing steps to remove corrupted data, apply the TYSMO program to remove outlier values of the P_{dif} data (mostly due to RFI and observations at the beginning and end of each scan) and to smooth the P_{dif} data to reduce noise. This is followed by application of the TYAPL program to convert the observed cross-power values to initially calibrated visibilities using the lab-measured values of T_{cal} and the assumed efficiencies.
3. Run the normal calibration procedures to determine and correct for antenna delays (FRING and CLCAL) and normalized system bandpasses (BPASS).
4. Run the gain calibration program CALIB. The resulting antenna amplitude gain values, G , should be near 1.0, with any deviations reflective of the error in the ratio T_{cal}/ϵ used in the TYAPL program. It is important to utilize an accurate model of the source structure in those cases where the flux density calibrator is partially resolved.
5. Generate, for each antenna, polarization, and spectral window, an adjusted $T_{cal,new}$ value by:

$$T_{cal,new} = T_{cal,old} * G^2, \quad (2)$$

where G is the voltage gain determined by CALIB. This step utilizes a special AIPS program CDCAL, described below.

6. Re-run the TYAPL program, using these adjusted values for T_{cal} to check if the procedure has run correctly, and to determine the flux densities of other sources in the observing run.

We emphasize here that the initial values of antenna efficiency and noise diode temperature used by TYAPL are not important! Any errors in the ratio of these two values will be reflected in the visibilities thus generated, and hence show up as gain values which depart from unity. The procedure described above will produce the ratios needed to generate correct visibilities.

4 Results

We now turn to the critical questions of whether this regimen works, and how stable the T_{cal} values are over time. To answer these, we utilized nine observations from the ‘VLA Flux Density Program’ spanning 2014 through 2025. This program, begun in 1979, was instituted to determine and to track flux densities of the standard VLA calibrators. Each observation is typically 24 hours in duration, and includes data from all ten frequency bands for both the standard calibration sources, as well as four planets, and various other calibrators. Each source is observed, at each band, typically once an hour for as long as each is above 15 degrees elevation. All observations were taken with the 8-bit samplers. A table showing the observation dates and array configurations is shown below. Included are the total observation durations in hours, and the number of observations of 3C286.

Date	Configuration	Duration	#3C286Obs
16Feb2014	A	24	10
11Oct2014	C	30	9
25Jan2016	DnC	27	10
31Jan2019	C	30	7
24Oct2019	A	8	7
09Sep2021	C	24	7
03Oct2023	A	8	8
31Jan2025	A	24	10
09Mar2025	D	24	10

This program has proven to be very useful for purposes far beyond the original intent of determining calibrator sources’ structures and flux densities.

4.1 Effectiveness

The first question to answer is whether this proposed regimen works as intended. To answer this, we used the observations taken on 9/10 March, 2025. These were taken in the ‘D’ configuration, with ideal weather conditions – clear and calm. We show here the results from a single spectral window at X-band, at 10.808 GHz. The source utilized is 3C286, and we have used the models established by the first-named author from 2014 and 2019 A-configuration observations for the calibration.

As noted above, a special AIPS program ‘CDCAL’ was written to determine the sky-calibrated T_{cal} values, using the derived gain values and the lab-calibrated T_{cal} values used to generate the visibilities. An important detail in the operation of the CDCAL program is the ability to select which gain values are used to determine the updated T_{cal} value. In a typical ‘flux density’ run, there are typically 10 observations of 3C286. A solution for each antenna, for each observation and spectral window is made. Examination of these gains often shows significant variations as a function of time. For the low frequency bands (typically Ku band and below), these gain variations are very small – a few percent at most, are smooth in time, and very likely are caused by errors in the gain-elevation corrections applied to the data. At higher frequency bands, a different phenomenon shows up – significantly higher values of the gain are seen, with no time dependence – they are nearly always ‘one-of’. The magnitude of these high values rapidly increases with frequency. It is clear that these are caused by errors in pointing, which reduce the apparent flux density, thus causing an erroneous high estimation of the gain. Use of these erroneous high values in the calculation of the sky-calibrated T_{cal} s will lead to erroneous values. Flagging the data responsible for these high values is tedious, so the CDCAL program contains an option to utilize the lowest value of gain present in the list, as this is the most likely value representing an on-source observation. The default option in CDCAL is to average all the values within a given time range. For the observations presented here, we have taken this latter option. For the high frequency bands however, we have utilized the ‘lowest value’ option.

The results of this exercise are shown in the following two figures. The first, shown in Figure 2, shows the before-and-after visibility amplitudes for the standard calibrator 3C286, normalized by the known flux density. Points in red are RCP, in blue are LCP. The left panel of this figure shows that the normalized visibilities calculated with the lab-determined values of T_{cal} and ϵ show considerable scatter, and are too high, as the mean normalized visibility is near 1.10. This offset must be due to the assumed antennas efficiencies being too low, or the utilized T_{cal} values being too high. The right panel shows the visibilities following the sky-calibration procedure. In this case, the visibilities are very tightly concentrated around 1.0, with a maximum spread of less than 5%. This result shows that the procedure works as intended. However – this is a minimal test, which is essentially circular in that we

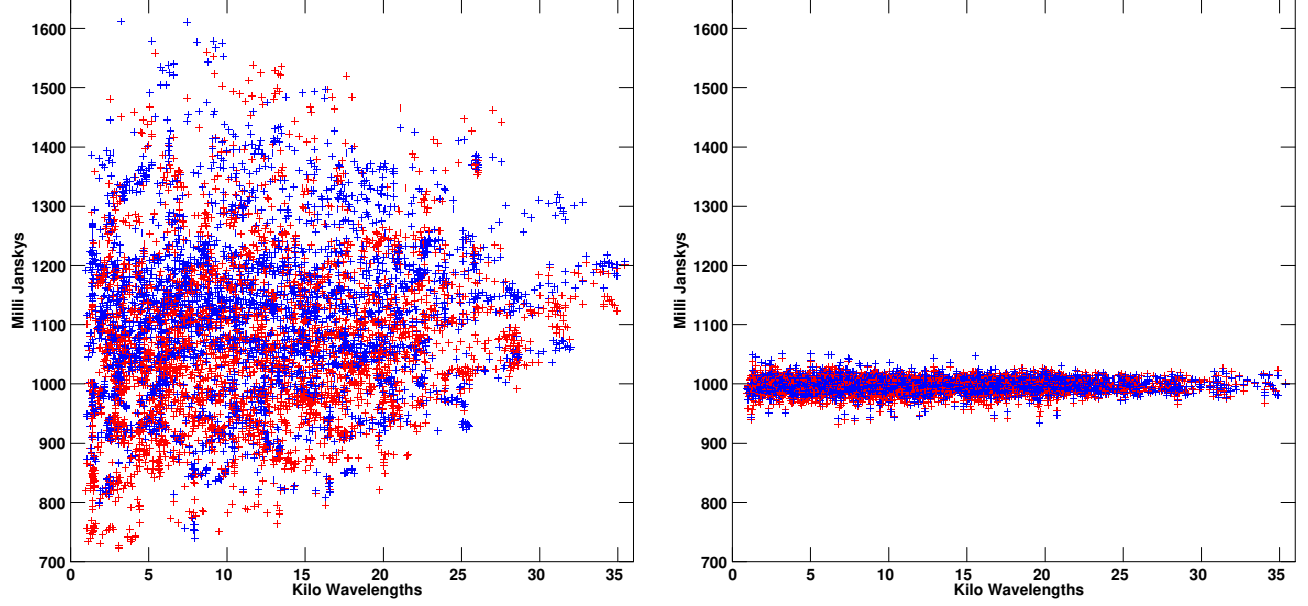


Figure 2: The normalized visibilities at 10.808 GHz for the flux density calibrator 3C286, using the lab-calibrated values for T_{cal} (left) and the sky-calibrated values (right). Red points are RCP, blue points are LCP. The vertical scale is the same for both. The small spread in visibilities about 1.0 in the right-hand panel is due to elevation-dependent gain changes.

generated values of T_{cal} to make the visibilities of 3C286 be correct, then showed that they are. A better test is to see if the corrected visibilities of a different known source observed in that same run are also correct. For this, we selected the partially-resolved calibrator 3C295. The results for this source are shown in Fig 3. 3C295 is known to

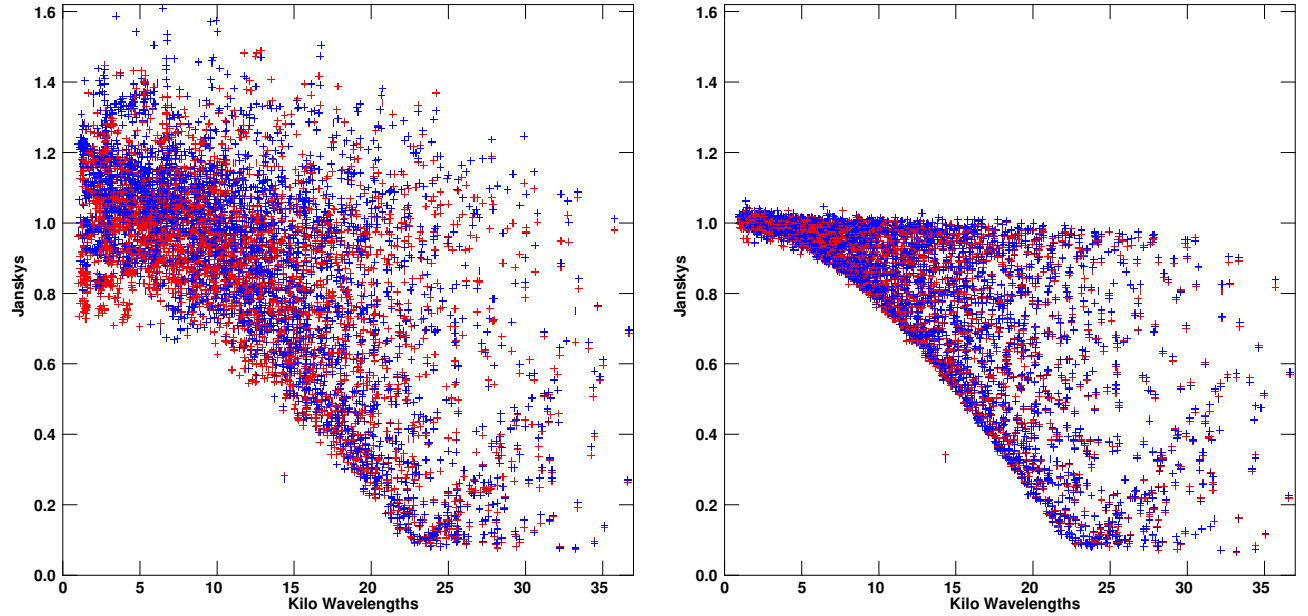


Figure 3: Same as for 3C286, but using the partially-resolved calibrator 3C295. As for 3C286, the derived flux density using the lab-calibrated T_{cal} s is about 10% too high. Following application of sky-calibrated T_{cal} s, the normalized source flux density is correct, with a small spread due to error in the elevation-gain correction.

be non-variable, but is significantly resolved, as shown in the visibilities from this D-configuration observation. The left panel also shows that the original, lab-calibrated T_{cal} values are too high, resulting in an averaged zero-spacing

flux density about 10% too high. Following the calibration procedure, the right panel shows a very much cleaner visibility distribution, with the small spread seen at the shortest spacings being due to small elevation-dependent gains not correctly removed.

These results are highly encouraging, but are not sufficient to suggest implementation of these procedures. What needs to be shown is that these corrected values of T_{cal} are stable over long periods of time, so that the determination of the adjusted values need only be done with a cadence of a year or longer. This is the subject of the next section.

4.2 Long-Term Stability

To determine the long-term stability of these corrections, we examine the adjusted sky-calibrated T_{cal} values over the 12 years extending from 2014 to 2025. We have done this for two spectral windows in each of the nine Cassegrain bands, for each of the nine observations. Of especial interest are those antennas for which the receiver was not changed. At X-band, there is only one – receiver#27, located on antenna ea08. The values of the sky-calibrated T_{cal} values over this span of time, for two spectral windows in X-band, are shown in the following table. For the

Date	T_{cal} @8450 MHz		T_{cal} @10936 MHz	
	RCP	LCP	RCP	LCP
16Feb2014	1.15	1.05	0.65	0.54
11Oct2014	1.14	1.04	0.61	0.53
25Jan2016	1.15	1.03	0.63	0.54
31Jan2019	1.21	1.08	0.66	0.56
24Oct2019	1.21	1.12	0.67	0.58
09Sep2021	1.17	1.05	0.63	0.53
03Oct2023	1.18	1.06	0.65	0.54
31Jan2025	1.12	1.04	0.63	0.53
09Mar2025	1.14	1.04	0.63	0.53

lower frequency observations, the RCP values have a mean of 1.163 K, with a dispersion of 0.030. The variations seen over time can easily be attributed to differences in opacity, elevation gain dependence changes, or changes in the temperature of the noise diodes themselves..

At X-band, there are nine antennas whose receivers have not changed since 2019. For these antennas, examination of the recalculated T_{cal} values between 2019 and 2025 gives the same result as shown above – stability over six years of better than $\sim 3\%$, with the exception of two antennas whose values changed in an irregular way by more than 10%. These will be discussed further in Sec. 4.5.

4.3 A Realistic Test

Our most realistic test for noise diode stability is to copy the sky-calibrated T_{cal} values from one observation to a later one, and then generate the updated visibilities for the later observation. For this test, we chose as the ‘source’ T_{cal} values the sky-calibrated values determined from the 09-sept-2021 observation, and as the ‘target’ data that taken on 09-March-2025 – 3.5 years later. In light of the previous discussion, we focus on the 21 antennas whose receivers at X-band did not change between September 2021 and March 2023: ea02, 03, 04, 06, 07, 08, 09, 11, 12, 14, 15, 16, 18, 19, 20, 21, 22, 24, 25, 26, and 27. Two of these, ea09 and ea11, are excluded due to large changes in their T_{cal} values³, leaving 19 antennas whose long-term amplitude stability can be tested.

Three versions of the 09-March-2025 data were made:

1. The first with the default lab-calibrated T_{cal} values.
2. The second with the sky-calibrated T_{cal} values determined from the 09-Sept-2021 data.
3. The third with the self sky-calibrated T_{cal} values, using the 3C286 observations taken that day.

Delay and bandpass calibration was done for all three databases, and the resulting normalized visibilities for 3C286 and 3C295 were generated. The results are shown in the following two plots.

³For both of these, examination of the derived T_{cal} values over all nine observations show large changes between observations, suggesting some instrumental problem.

Figure 4 shows the normalized visibilities for 3C286 at 10.808 GHz for three cases: The left panel shows the data using the default lab-calibrated T_{cal} values. The mean flux density is about 10% too high, and there is a near 30% spread in the visibilities. The middle panel shows the data using the sky-calibrated values taken 3.5 years earlier. The visibility spread is now about 5%, but the average flux density is within 1% of the known value. The right panel shows the data after calibrating the noise diodes using observations of 3C286 from the same day. The spread is reduced to about 2% which, as noted before, is due to improperly corrected elevation gains.

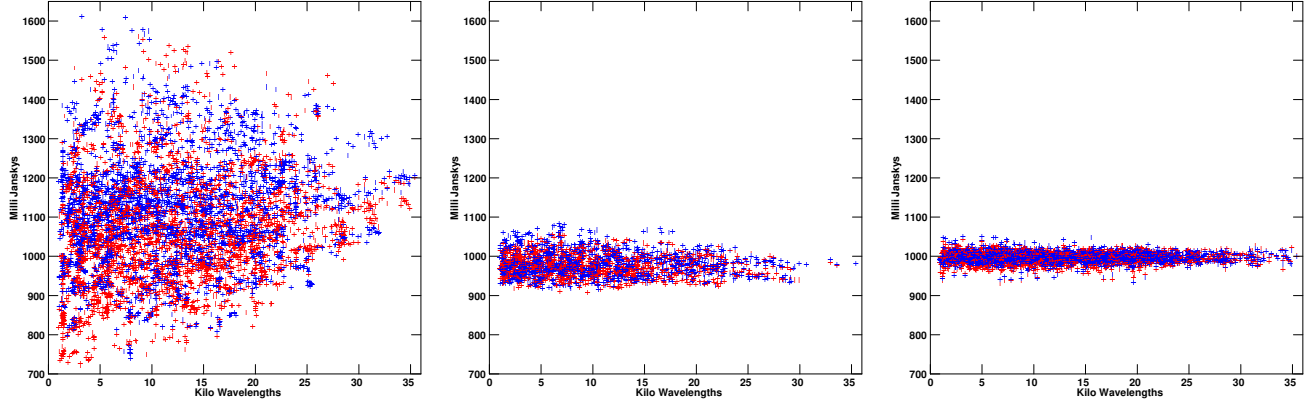


Figure 4: Showing the resulting visibility of 3C286 after applying three different T_{cal} values: The left panel uses the lab-calibrated values, the middle panel the sky-calibrated values from 3.5 years earlier, the right panel uses values determined on the day of observation. The middle plot shows only those baselines utilizing 19 antennas whose receivers did not move between 2021 and 2025.

Figure 5 shows the results for the slightly resolved, stable calibrator 3C295. The key panel is the middle one – showing the visibilities calibrated from observations taken 3.5 years earlier. We see again that these previously determined values generate correct flux densities.

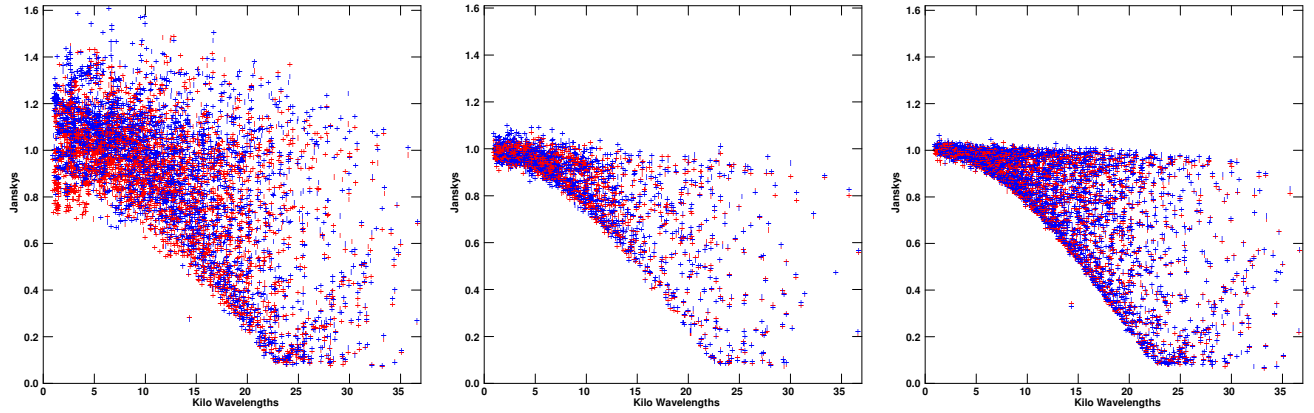


Figure 5: Showing the resulting visibility of 3C295 after applying three different T_{cal} values: The left panel uses the default values, the middle panel the sky-calibrated values from 3.5 years earlier, the right panel uses values determined on the day of observation. The middle plot shows only those baselines utilizing 19 antennas whose receivers did not move between 2021 and 2025.

These results give strong support to the successful use of sky-calibrated T_{cal} values for accurate determination of the amplitude gains. For 19 of the 21 receivers which did not change antennas in the 3.5 year period, the values of T_{cal} did not change by more than 1 or 2% between calibration and application. For X-band data, we believe that gain calibration using the noise diodes will be accurate to better than 2% over periods of years when using those antennas whose receivers have not changed. There are a few caveats, discussed in Section 7.

4.4 Frequency Dependence of T_{cal}

New T_{cal} s were derived for all sixteen spectral windows provided by the 8-bit samplers for each band and each observing session. The results at X-band for receiver#27, located in ea08, are shown in Figure 6 for the lower eight spectral windows, and in Figure 7 for the upper eight spectral windows.

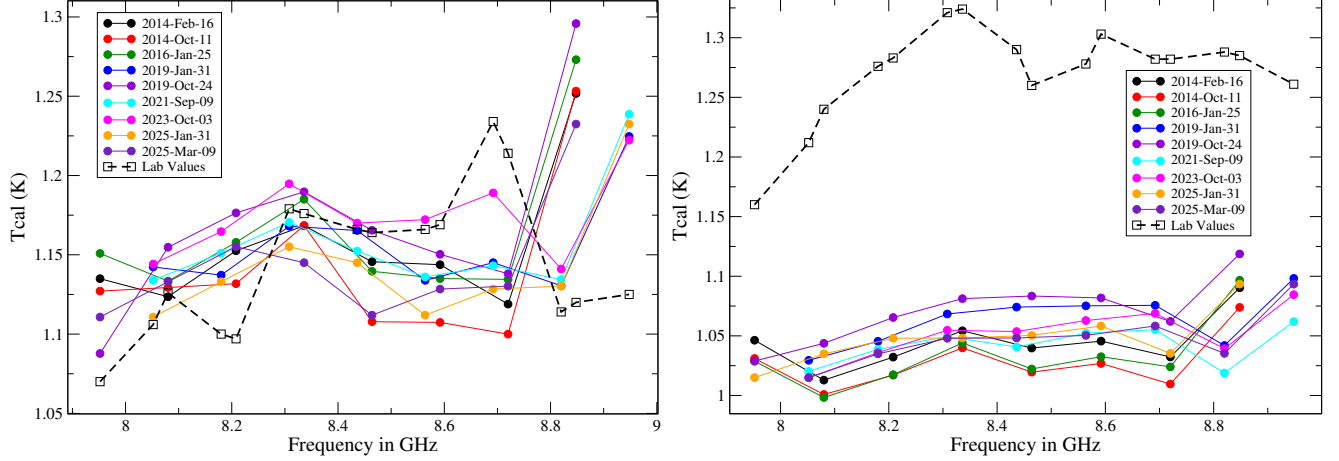


Figure 6: Showing the derived T_{cal} values for all eight spectral windows centered near 8.5 GHz, for X-band receiver #27, on antenna ea08. RCP in the left panel, LCP in the right. The lab-measured values are shown with open black squares.

The low-frequency X-band data were taken with two slightly different frequency setups, different by 100 MHz, accounting for the frequency separations in the figure. The values for the eighth spectral window (above 8.8 GHz) are affected by the analog filter roll-off, and should be discounted.

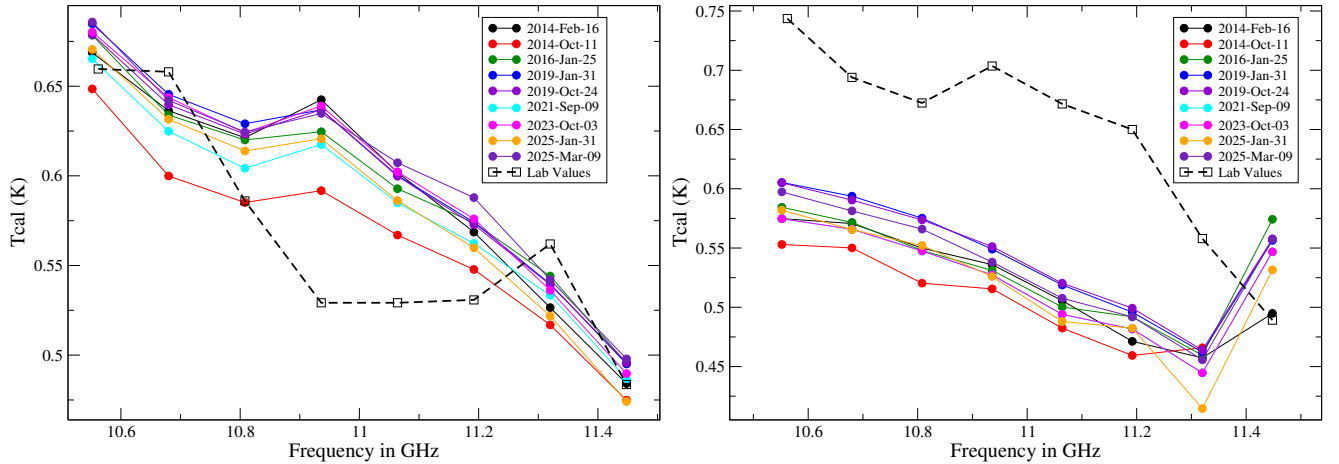


Figure 7: Showing the derived T_{cal} values for all eight spectral windows centered near 10.5 GHz, for X-band receiver #27, on antenna ea08. LCP in the right. The lab-measured values are shown with open black squares.

Although there are small offsets in the T_{cal} values from observation to observation (typically of size less than $\sim 5\%$), the overall shapes of the T_{cal} values with frequency are the same for all observations (discounting the eighth spectral window). The small offsets between observations can easily be explained by varying opacity, pointing, elevation gain corrections, or changing physical temperature of the noise diode. Note that the lab-values show considerably greater frequency structure than the sky-calibrated values.

These two figures show a large difference between polarizations in the ‘lab-calibrated’ T_{cal} values for this antenna – ea08. In general, the lab-calibrated T_{cal} values are similar for all antennas, but some – most notably ea08 – show significant differences between polarizations. In all cases, the sky-calibrated values of T_{cal} are much more similar

between polarizations than the lab-calibrated values. The origin of this discrepancy, and of the sharp changes in frequency in the lab-calibrated values is unknown.

4.5 When Receivers Move Between Antennas

It was noted that when a receiver is moved from one antenna to another, the resulting T_{cal} values are usually similar for both antennas. Small differences between these values could be attributed to differing efficiencies between the antennas – but in some cases, these differences are rather too large to be attributed to this. We show below the results for eight receivers which were moved between antennas between 2016 and 2019, and where there are at least two observations for a given receiver in the same antenna. Note that for most receivers, the changes in T_{cal} between

Rcvr	Initial Antenna	$T_{cal}@8450$ MHz		$T_{cal}@10936$ MHz		Final Antenna	$T_{cal}@8450$ MHz		$T_{cal}@10936$ MHz	
		RCP	LCP	RCP	LCP		RCP	LCP	RCP	LCP
26	24	1.13	1.04	0.74	0.75	4	1.20	1.10	0.85	0.83
23	28	1.13	1.13	0.77	0.80	7	1.16	1.14	0.83	0.78
20	4	0.73	0.78	0.86	0.75	12	0.91	0.94	1.11	0.96
6	10	1.04	1.10	0.60	0.63	15	0.96	1.05	0.59	0.62
1	7	1.40	1.53	0.76	0.78	18	1.60	1.45	0.86	0.84
5	6	1.08	1.05	0.79	0.76	21	1.13	1.10	0.79	0.85
21	15	1.20	1.19	0.91	0.90	25	1.10	1.07	0.81	0.85
3	21	1.35	1.29	0.73	0.70	26	1.79	1.77	1.25	1.20

the initial antenna and final antenna were typically 10% or less. These could be explained by a difference in the antenna efficiencies. However, for two receivers (#20, and #3), the change in T_{cal} exceeds 20%, which we regard as improbable for antennas at this band.

5 Results for Other Bands

Calibration of the noise diodes was done for selected spectral windows for the remaining seven Cassegrain bands for all nine observations. The results shown in this memo for X-band apply equally to the remaining bands, with one important caveat. It is very clear from the data that the major source of error in the determination of sky-calibrated T_{cal} s for the three highest-frequency bands (K, Ka, and Q) is antenna pointing. It is critical that only on-source observations be used for on-sky calibrations. The means for achieving this are discussed in Section 7.

6 3-bit Samplers

Our tests have used data taken with the 8-bit samplers, as these are known to be linear and to behave well over a wide range of input power. The situation with the wide-band 3-bit samplers is a bit murky. It is well known that the switched power system should not be used with these samplers. Various problems with these samplers are known – the state count histograms are very non-gaussian, their voltage levels are not uniformly spaced, they are not zero-mean, and the input voltages supplied from strong sources or low-elevation observations will cause a significant number of samples to be outside the sampling range.

Nevertheless, we have attempted the same analysis using recent wide-band 3-bit observations. Initial results suggest good stability, but some antennas gave unexpected results. We will investigate these issues at a later time.

7 Discussion

Our study strongly supports the use of the on-board calibration noise diodes for accurate amplitude gain calibration at all Cassegrain bands when using the 8-bit samplers. The stability of the noise diodes has been shown to be better than $\sim 3\%$ for most receivers at all bands over many years. There are a few exceptions, which are likely due to some form of malfunction of the switched power system.

At the present time, this recommendation is limited to use with the 8-bit samplers. Further efforts are needed to characterize stability and applicability with the 3-bit samplers.

There are a few important caveats.

- The switched power calibration cannot detect gain variations due to factors which occur before the noise diode injection between the feeds and first amplifier. Thus, antenna pointing errors (including incorrect gain-elevation corrections) and atmospheric opacities different from those derived from the weather data cannot be corrected. This limitation is of course the same as for the regular calibration methods utilizing an external flux density calibrator⁴.
- Accurate values of the T_{cal} , based on an astronomical source of known flux density and structure are essential. Because of the effects of pointing, variations in gain with elevation, and atmospheric opacity, these calibrations must be done carefully under highly controlled conditions – dry, preferably winter, weather, clear skies, light winds, and near the canonical elevation of ~ 50 degrees.
- On occasion, receiver malfunctions result in clearly incorrect visibilities. Additionally, there is some evidence that the T_{cal} values can change dramatically when no change of receiver was made. Application of the calibration regimen discussed here will need to employ a threshold in the derived gain values to ensure only well-behaved antennas whose receivers have not moved since the last sky-calibration was done are employed in the flux density calibration. Based on our studies, a threshold of $\sim 5\%$ in the voltage gain solutions (i.e., utilize only those between 0.95 and 1.05) should enable gain calibration accurate to better than 2%, in the absence of the external factors noted above.

Calibration of the T_{cal} values should be done on a regular basis – at least once every few years. The observations used to determine the values must be done under ideal conditions – clear, dry, windless, cold, preferably at night, and at an elevation near 50 degrees. To ensure an on-source determination, ‘double-reference’ pointing should be employed for Ku, K, Ka, and Q bands. Multiple observations should be done to check for repeatability.

It is highly desirable that these sky-calibrated T_{cal} values be determined for the entire frequency band spanned by the eight Cassegrain bands. It will take 25 separate tunings to do this. The minimum time for a double-reference pointing and observation will be about 5 minutes, so a little over two hours is indicated, which will likely span more than one day in order to meet the elevation requirement, although this could be relaxed for the lower frequency bands, where gain-elevation dependency and atmospheric opacity concerns are minimal. At least one repeat is desirable to check for consistency, suggesting at least two two-hour observations to enable secure calibration.

Tracking receivers which change antennas is a complicating issue. Receivers requiring maintenance are taken to the DSOC lab. The average rate at which this happens is about two per year per band. Such receivers will almost certainly be in a different antenna upon return to service. There is no assurance the new T_{cal} value will be the same as the old – especially at the higher frequency bands where differences in antenna efficiency are likely. If a special sky-based calibration cannot be made after a receiver change, it is recommended that the antenna not be included in the flux density calibration – but of course once the flux density of the phase calibrator is determined, the data from such antennas are perfectly good for imaging, once calibration is completed.

Future activities are:

- During the upcoming dry season (October, or later), determine new, updated values of T_{cal} , through observations of 3C286, for at least the frequencies utilized by the ‘flux density’ program.
- Following this, run the 24-hour ‘flux density’ program, utilizing these updated T_{cal} values. This will give us a good idea of the accuracy of these corrections, as well as the robustness of the program, as these observations entail more than 1500 observations of typically 15 different sources at all frequency bands.
- If the results of the previous item are deemed satisfactory, commit to measuring the sky-calibrated T_{cal} values for the entire frequency range, and implement the regimen for all 8-bit observations.
- We have not yet included P-band into our studies. There is no reason the same protocols will not work for this band, although a stronger calibrator will be needed for a sky calibration.
- A serious study of the use of this regimen for the 3-bit system should be undertaken. We have the data for this, and will undertake this as time allows. Far better, of course, would be to replace the underperforming 3-bit samplers with modern devices – but this subject lies well beyond the scope of this study.
- A protocol for transferring the sky-calibrated T_{cal} value into the SDM will need to be defined.

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⁴In fact, avoiding the use of a flux density calibrator should improve the accuracy of amplitude calibration, as errors associated with the calibrator observation are avoided.