EVLA Memo 66
The Effect of Electronics Non-Linearity on Closure and Imaging

Rick Perley

September 26, 2003

Abstract

It is shown that raising the system temperature by $\sim$ 12 dB has negligible effect on closure properties for VLA data taken in X-band. This is an expected result, given the linearity properties of the signal chain. A more definitive test will require at least 10 db more input power.

1 Introduction

The EVLA receiver systems will be working in a hostile environment, with high powers expected from various forms of communications signals. For the 1-2 GHz band, for example, the power from man-made signals is expected to be 30 dB or more over the total noise power when observing cold sky. In such an environment, it is important that the receiver amplifier system retain excellent linearity over such a range of input powers.

Of special concern is the performance of the entire interferometer system when input powers reach a level where the output begins to saturate – *i.e.* where non-linear performance becomes appreciable. When this happens, part of the signal at any given spectral component is converted into higher harmonics. Intermodulation between these higher harmonics will reflect some of the signal back into the band, so the true astronomical signal will be distributed throughout the bandpass at incorrect frequencies. Besides increasing the noise, there will occur at some level a 'closure error'.

Closure errors will affect interferometric imaging in two ways: First they will impart small errors in phase and amplitude into the complex visibility measurements, which in turn scatters brightness from the astronomical target sources over the entire image; and second, they will reduce the accuracy of the calibration, as this implicitly assumes closure is preserved.

A perfectly linear system will preserve the closure quantities, so it is a key requirement for the EVLA to design a system as close to linear as possible, throughout the range of anticipated input powers.

The purpose of this memo is to describe a simple experiment in which amplifiers were operated at a high input power level, and the resulting loss in closure fidelity was measured.

2 Amplifiers and Headroom

In an ideal amplifier, the output power is proportional to the input power, for all input powers. In a real amplifier, the relationship is non-linear, with the output power falling increasingly below the ideal extrapolated value as the input power increases. This is illustrated in Fig. 1, which shows a standard amplifier model. The input power, normalized by the nominal operating input power $P_{in} = kT_{sys}\Delta\nu$ is plotted on the horizontal axis, the output power, normalized by the nominal output $P_{out} = GP_{in}$, is on the vertical axis. The solid black line shows the relationship. At low input power levels, there is the desired linear relation, but at higher levels, the output power falls below the line. The idealized output power is shown by the dashed black line. The separation (power ratio) between the nominal operating point and value at which the output power is decreased by 1 dB is termed 'Headroom to 1dB compression'. The EVLA engineers have defined a 2nd characteristic point – the power level at which the compression is 1%. The ratio of this power to the nominal operating point is termied the 'Headroom to 1% Compression'. These values are shown in the figure.

The non-linear characteristics of an amplifier are manifested by undesired spectral components in higher harmonics, and by intermodulation components amongst these higher harmonics. An input signal at frequency f_1 will produce output frequency components at f_1 (the desired signal), $f_1^2, f_1^3, \cdots$. In most cases, the power in these harmonics are not a problem, as they lie outside the bandpass of subsequent electronics. More troublesome are the intermodulation products between multiple input signals. If the input signal spectrum contains two signals at frequencies f_1 and f_2, the output will contain signals at $f_1 + f_2$, $f_1 - f_2$ (the so-called 2nd order intermodulation products), $2f_1 - f_2$, $2f_2 - f_1$, $2f_1 + f_2$, and $2f_2 + f_1$ (the third-order intermodulation products). Second-order intermodulation products are generally not troublesome, as they lie outside the system bandpass (unless the system is at baseband). Most troublesome are the first two of the listed 3rd order intermodulation products, which generally lie within the system bandpass.

The power in these intermodulation products is shown in Figure 1 for 2nd order (red) and 3rd order (green). [1] Their level are usually described by their (extrapolated) intercept with the (extrapolated) intercept of the total output power. Clearly, it is desirable to have devices whose intercept points (particularly those of the odd harmonics) as far from the operating point as possible to minimize non-linear behavior. The values shown in the figure are appropriate for the VLA's current X-band system.

3 Observations

The method employed was to observe a known object in two states: the normal 'cold' state, with the nominal system temperature of $T_{sys} \sim 30$, and in a 'hot' state, where the amplifiers saw a much higher input power level. This latter state was created by turning the solar noise calibrators on. The solar calibrator noise power is approximately 700 K, but as the cal is on 50% of the time, the effective noise temperature was about 350K, or ~ 12 dB above the nominal operating point.

In such an experiment, it is important to use as the target source a strong object with very simple structure. The former condition is required to allow accurate determination of the closure errors. The latter condition minimizes the closure which is due to the source itself. Although source closure quantities (NB – these are not errors) can be accounted for if the source structure is known, in practice, the supposedly known structure is itself not perfect, and a differential closure quantity will remain, which is difficult to separate from the closure errors due to the non-linearities. This problem can be avoided if the target source is perfectly unresolved – in which case the source closure quantities are zero.

The observations were of 3C84 at 8.6 GHz, in the 'A'-configuration, on 7 Sept 2003, from 3:30 to 6:30 AM, local time. The source at this frequency is very strong (about 15 Jy) with a strong, unresolved nucleus (comprising at least 99% of the flux density), and some nearby slightly extended structure. The observations were taken in an alternating sequence: 10 minutes with the solar cal noise diodes off, and 10 minutes with them on. The total integration time in each state was 90 minutes. The averaging time was set at 5 seconds to minimize any effects of atmospheric phase gradients, and the bandwidth chosen was 50 MHz for both IF pairs.

The data were calibrated using standard methods, using a carefully generated model of 3C84 derived

[1] The power in the pure 2nd and 3rd harmonics are lower by 6 dB (2nd order) and 9.5 dB (3rd order) respectively. As these nearly always lie outside the system bandwidth, they can be ignored.

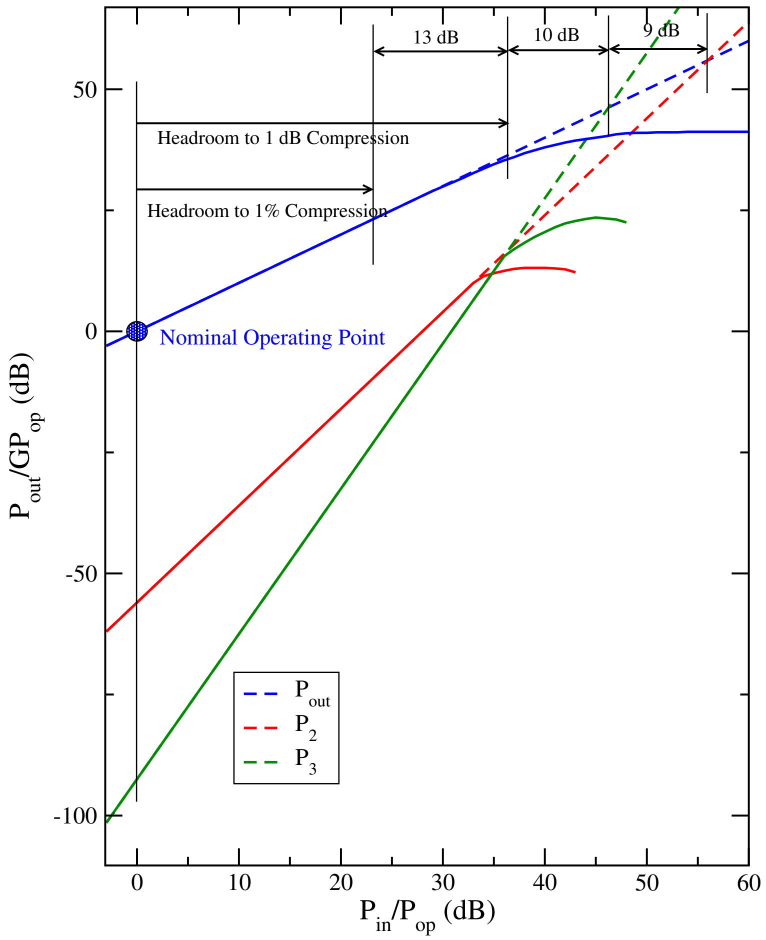

Figure 1: An amplifier model, believed to be a reasonable description of the X-band VLA system.

from the 'cold' observations. The observed system temperatures of the 'cold' state were significantly higher than expected for most antennas (above 60K, and rising through the night) – it is speculated that this was due to dew forming on the feed windows. Other than this unexpected effect, the data quality was very high, with little editing required.

After the removal of bad data, and the generation of a good model was completed, the `AIPS` program `BLCAL` was used to measure the 'closure quantities', for both amplitude and phase, for both the 'hot' and 'cold' states. As a consistency check, these correction values were applied to the data, and images of the source were made.

3.1 Results

The essential results are shown in Figs. 2 and 3.

In these figures, a gaussian was fitted to allow simple parameterization of the results. The half-width to half-power is shown in each of the figures. For both amplitude and phase, the width of the closure distribution is slightly higher for the 'hot' observations. However, for both cases, the increase is as expected due to the poorer SNR of the determined closure quantities. The program `BLCAL` reports the error in its determined closure quantities – for the 'hot' solutions, the error in the amplitude closure determinations was typically 0.002, and was 0.06 degrees for the phase distributions. These errors are sufficient to cause the small increase in the histograms over the 'cold sky' case. There is thus no indication of increased closure errors when observing at an input noise power level 10 dB above

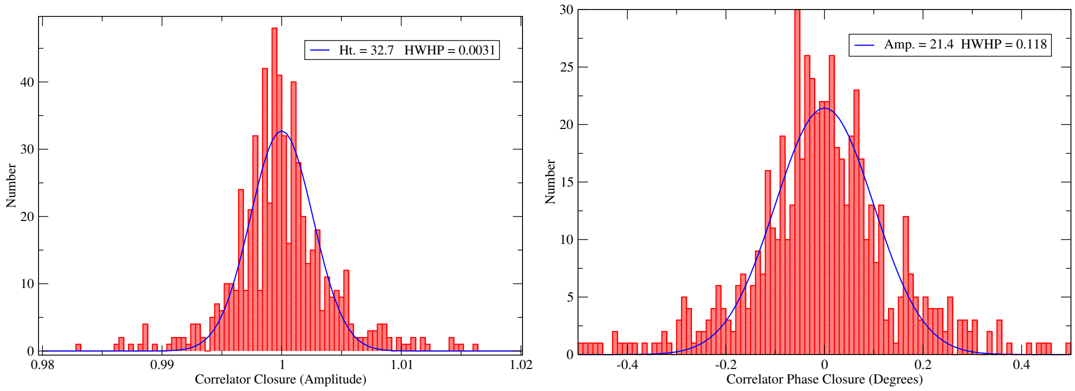

Figure 2: Showing the closure distributions for cold sky observations. Amplitude closure is on the left, phase on the right.

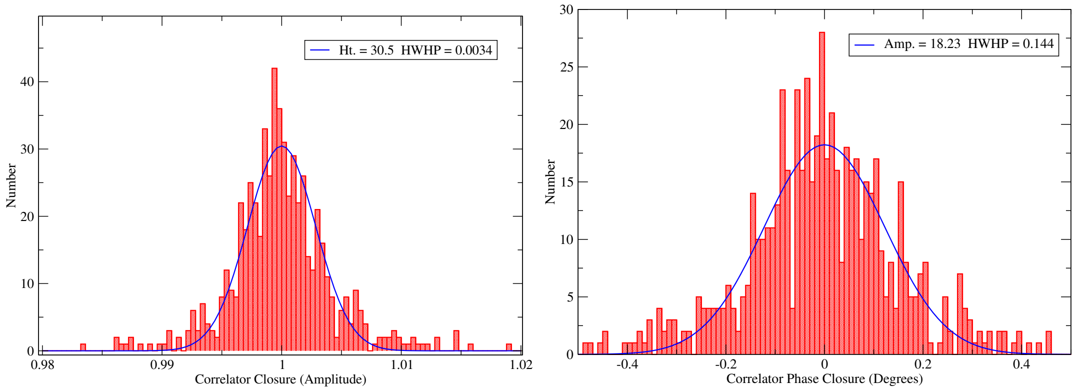

Figure 3: Showing the closure distributions for observations with the solar noise calibration diodes on. Amplitude is on the left, phase on the right.

nominal.

3.2 The Images

The derived images, for both operating points, are shown in Figure 4. For both, a 15.2 Jy point source component has been removed in order to show the underlying structure. Other than the expected higher noise level in the 'hot' observation, there is no significant difference between these images. The 'dynamic range' of the 'cold' image is very high: exceeding 50dB (defined as the ratio between the peak and the rms noise in an off-source position).

4 Discussion

This is a rather non-demanding test, as the power increment was no more than $\sim$ 10 dB. From Figure 1, we note that the 2nd order intermodulation power is -40 dB or more below the total power, and the third-order intermod is down by $\sim$ -65 dB. It is thus not surprising that no effect was seen in this test. Another problem with this initial test is that the added power is broadband noise – this has the undesirable effect of decreasing the correlation coefficients, and thus lowering our ability to accurately measure the closure errors.

A more demanding, and more realistic test is now being prepared. We intend to inject a CW tone sufficient to raise the output power level by 20 to 30 dB (or more) – well into the range where non-linear behavior should be noted. The system will be set to correlate a range of frequencies not including the

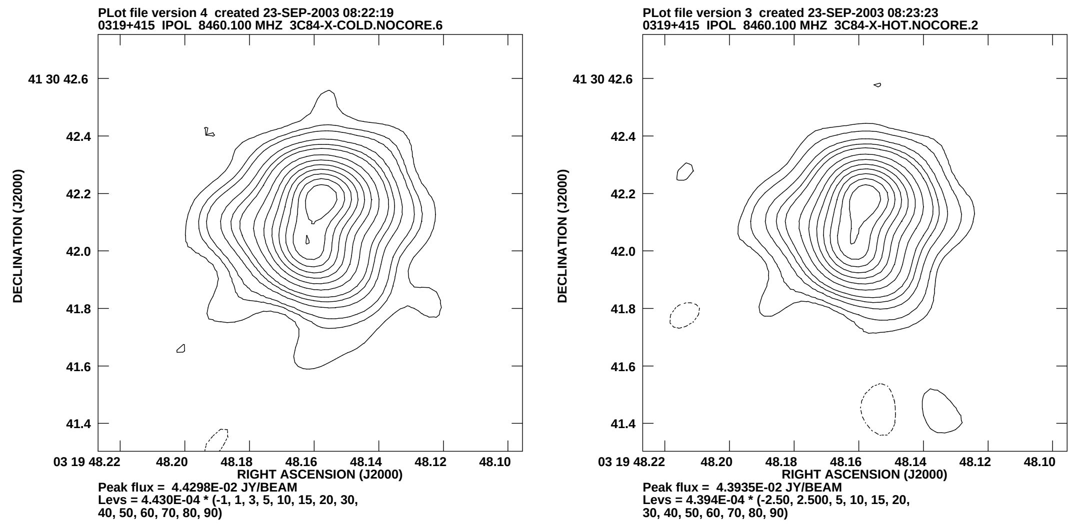

Figure 4: The images, with 15.2 Jy from the central core removed. The resolution element FWHM is 0.20 arcseconds.

tone frequency, so the thermal noise level seen by the correlator will be (largely) unchanged. Not only will this permit undegraded measures of the closure error, but will fairly accurately reproduce the actual RFI-filled observing environment, where most of the 'hostile power' is in the form of narrow-band signals.

Although the images are very good, they are not as good as they should be. The 'cold' image rms is 0.148 mJy, which may seem very good in comparison to the 15.2 Jy maximum, but is in fact a factor of 8 higher than it should be, given the nominal system temperature and quantity of data. If the true system temperature was as high as the monitor data suggest (a factor of about 2 too high), the observed noise level is still be a factor of four higher than expected. Examination of the images shows no signs of systematic error – just random noise – so there presumably exists an additional source of amplitude or phase fluctuation operating on a timescale shorter than the 5-second timescale of the self-calibration, or there is a low-level, time-variable closure error which could not be corrected by the methodology selected here. It would seem that there is an additional, unaccounted-for origin of fluctuations, which is not present in observations of blank fields, and which limits imaging fidelity for these cases where it should exceed 50 dB. A possible source of this remaining error could be the inherent non-linearity in the quantization of the signal by the digitizers. However, no analysis of this speculation has yet been attempted.

5 Acknowledgements

I thank Bob Hayward for suggesting this test, for the data on the X-band receivers, and for the loaning of a useful book on the subject. I thank Peter Napier for a critical reading and many useful suggestions.