VLB ARRAY MEMO No. 471

GAIN CALIBRATION TECHNIQUES

Larry R. D'Addario
15 July 1985

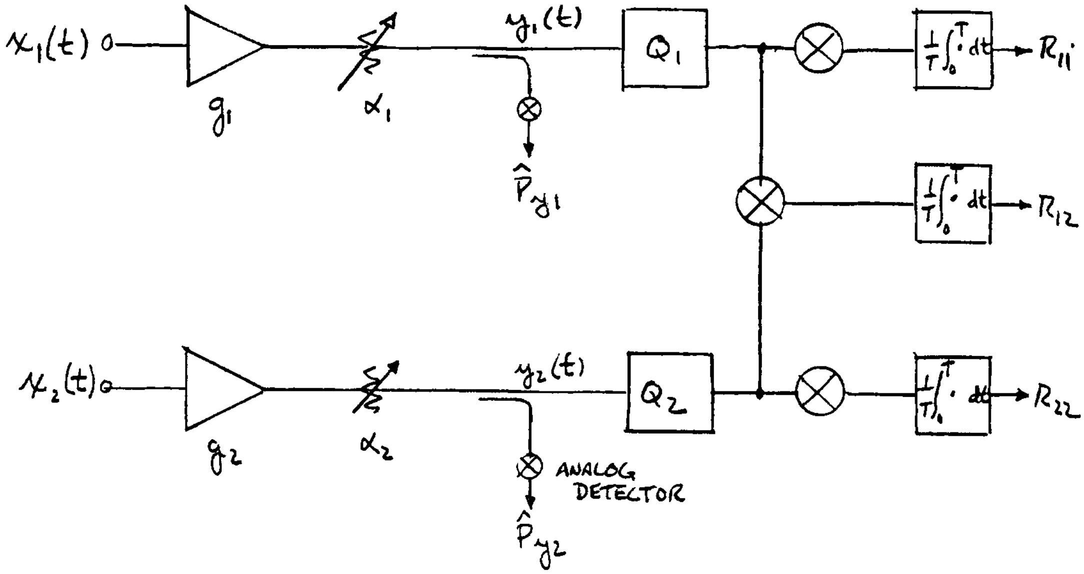
1. Introduction

In order to derive the cross power of the signals received at two antennas from digitized versions of their receiver outputs, it is necessary to know the gain of each receiver from the antenna to the digitizer. If the final result is to be referred to an astronomical calibrator, then only the ratios of the gains when observing the calibrator to those when observing the target source are of importance. If the digitizer prevents recovery of the total power from each digitized signal (as with two-level quantization), then it is also necessary to know the total power just prior to digitization. (Actually, in the latter case, it is only necessary to know the total power referred to the antenna, which is the ratio of the digitizer power to the gain; but in practice the two quantities are measured separately and the ratio taken.) The final accuracy in determining the cross power is directly affected by the accuracy with which these gains are known.

The traditional method of determining the receiver gains has been to add a controlled amount of white noise to the input of each receiver, and to detect the power at the digitizer input with the added noise on and off; the difference is a measure of the gain. This approach has some practical difficulties and can produce significant errors. In this memo, the errors are examined and an alternate methods are proposed; under some circumstances, the alternatives should be more accurate.

2. Theory

Figure 1 is a simplified interferometer block diagram containing all the elements essential to this discussion. Our objective is to measure the cross power $\langle x_1 \ x_2 \rangle$. Each receiver consists of an amplifier with voltage gain g_i and an adjustable attenuator with voltage gain α_i. These are followed by quantizers Q_i and then by (digital) correlators. (We can neglect sampling and bandwidth effects.) The attenuators are used to keep the total power to the quantizers at a reasonable level, and are normally included in ALC loops. The digitized signals are detected using a self-correlator on each one and a cross correlator, all with averaging time T.



$$y_i = g_i \alpha_i x_i$$

$$P_{yi} = \langle y_i^2 \rangle$$

Figure 1: Block diagram giving notation used in discussion of theory.

From the three measured values R_{11}, R_{12}, and R_{22} it is generally possible to determine the cross power in the amplified signals $\langle y_1\ y_2\rangle$; if we divide this by the product of the gains, we get the desired cross power referred to the inputs. However, in the case of 2-level quantization only the correlation coefficient $\langle y_1\ y_2\rangle / \sqrt{P_{y1}\ P_{y2}}$ can be determined from R_{12} (R_{11} and R_{22} contain no information); in this case one needs the total powers in addition to the gains. (For a simplified discussion, see VLBA Memo 428.)

The final estimate of the cross power is thus given by

$$\hat{P}_{12} = \begin{cases} f_2(R_{12})\sqrt{\hat{P}_{y1}\hat{P}_{y2}}\,/(\hat{g}_1\hat{a}_1\hat{g}_2\hat{a}_2), & \text{2 level quantization} \\ f_Q(R_{12},R_{11},R_{22})\ v_1 v_2/(\hat{g}_1\hat{a}_1\hat{g}_2\hat{a}_2), & \text{Q-level quantization} \end{cases}$$

where $f_2(R_{12}) = \sin(\pi R_{12}/2)$ is the inverse correlation response function for 2-level quantization; $f_Q(R_{12},R_{11},R_{22})$ is the similar function for Q-level quantization; and v_1, v_2 are the (fixed) threshold voltages of the two Q-level quantizers. The notation ^ over a symbol indicates an estimate, based on measurements, of the corresponding quantity without the ^.

3. Gain Determining Methods

A. Noise Adding

The total gain $g_i \alpha_i$ in each receiver can be measured by adding known, stable signals to the receiver input and noting the change in power measured by a square law detector at the corresponding quantizer input. The stable signal is usually white noise because the signal from the antenna is also largely white noise, thus giving a gain measurement that is properly weighted over the band. However, it is difficult to achieve high accuracy by this method, for a couple of reasons:

1. There is a tradeoff in deciding how large to make the injected signals. Very small signals cannot be detected accurately in an integrating time comparable to that used for measuring the cross power; under some assumptions, longer integrating times can be used, but this requires a complicated stategy in deciding which gain measurements to apply to a given cross-power measurement for times near when a significant change occurs (source change, frequency change, etc.). On the other hand, if the injected signal is too large, then the quantizers are operating at significantly different signal levels when the injected signal is on, and thus at a different point on the correlation response function. Since the latter is non-linear, use of the average power over time T in the above formulas will cause an error; instead, one should leave the signal either fully on or fully off during each integrating period. This may not be practical if the intergating time is to be variable and not decided until later (as in VLBI). A secondary problem with large injected signals, of course, is that the noise temperature of the receivers is increased.

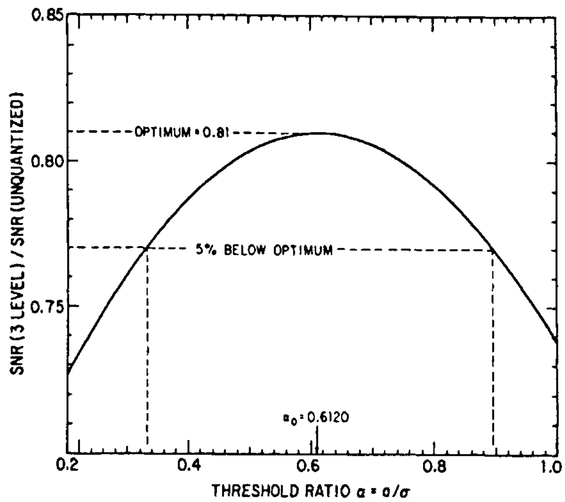
2. Square law detectors, which must be used to measure the powers at the quantizer inputs, have limited accuracy. It is difficult to obtain linearity better than 1% of full scale, and most of the time the detectors would operate at considerably less than full scale.

B. Monitored Attenuator

As an alternative, consider that nearly all of the gain change between observation of a calibrator and of a target source occurs in the attenuators α_i rather than in the amplifiers g_i. The former are typically responding to changes in antenna temperature under control of an ALC loop. That is, the major gain changes are the ones that we are deliberately introducing, rather than undesired drifts. This leads to the idea that we should be able to keep track of those gain changes without having to measure them directly all the time. The loss of each attenuator at each allowed setting can be measured once and stored; we then need only keep track of the settings, which can be determined digitally in negligible integrating time. Whether this is more accurate than real-time measurement with an injected signal depends on how repeatable the attenuators are, and on how accurately they can be calibrated initially.

It is worth noting that digitally-controlled step attenuators can now be purchased with repeatablities of better than 0.1% up to a few GHz (see, e.g., Appendix A). If we operate them at baseband, then (for the VLBA) we only need to go to 8 MHz, so repeatability may be even better. The absolute attenuation is then independent of LO frequency (both first and second LOs), and should be very flat over the baseband range; thus, one calibration will probably suffice for all frequencies and bandwidths. To achieve a gain measurement accurate to 0.1% using a switched noise source at 10% of the system temperature would require an accuracy of $10^{-4}/\sqrt{2}$ for both the on and off measurements, which takes a total of 50 sec at 8 MHz bandwidth and 6,400 sec at 62.5 kHz. From this it seems clear that the gain can be determined much more accurately from the setting of a calibrated attenuator than from switched noise measurements, especially at the narrower bandwidths.

In addition to the accuracy of gain determination, we need to consider the resolution of the gain setting mechanism. For multi-level quantization (three or more levels), this is not very critical; Fig. 2 illustrates (for 3-level quantization) the fact that the signal power can vary by -5.5 dB to +3.3 dB from the optimum value while degrading the SNR by less than 5%. Thus, for Q>=3, a resolution of 1 dB on the gain setting attenuator would be more than adequate. Unfortunately, the situation for 2-level quantization is more difficult. As noted above, this case requires an accurate total power measurement in addition to the gain determination. One way to achieve this is to rely on a square law detector, accepting the errors due to non-linearity and finite integrating time (0.1% takes .125 sec at 8 MHz and 16 sec at 62.5 kHz). Another way is to provide a very high resolution gain setting attenuator, so that the total power can be kept constant (via an ALC loop) to the required accuracy (0.1% is .004 dB). The latter avoids any problem with non-linearity because the detector is always at the same operating point; but it is still subject to the integrating time limitation via the loop time constant.



Sensitivity of the ideal three-level correlator versus normalized thresholds, relative to the sensitivity of a continuous (unquantized) correlator. The calculation assumes all normalized thresholds are equal; both inputs are band-limited white Gaussian noise; the sampling rate equals twice the bandwidth; and the correlation coefficient is small.

Figure 2: From D'Addario Thompson Schwab and Granlund (1984), Radio Science 19, 931-945.

C. Coherent Signal Adding

A third possibility is to add a sinusoidal signal (or other well-defined waveform) to the receiver input and to detect it coherently at baseband. This results in much higher sensitivity for short integrating times than can be achieved with incoherent (noise) signals, because the fluctuations due to the system noise are proportional to T^{-1} rather than $T^{-0.5}$ for integrating time T. Furthermore, if the detection is done after digitization then all requirements for analog square law devices are eliminated, even for two-level quantization; this is because the coherent signal remains distinguishable from the system noise after digitization.

There are some difficulties in implementing such a scheme. First, there is the choice of coherent signal. A single sinusoid is convenient, but requires assuming that the gain at one frequency is representative of the whole band. A comb-spectrum is probably a good choice, but the detector is more complicated than for a single line. A pseudo-random noise generator would in many ways be best, but both the generator and detector would be difficult to build (for a discussion see Thompson, VLA Electronics Memo 172, April 1978). Next, the generator must be more stable than the desired measuring accuracy (say, 0.1% over several hours). For our present purposes, this applies only to the amplitude and not to the time stability, provided that a time-insensitive detector is used. It is not clear whether a generator with the required stability can be built, especially at frequencies above 15 GHz.

Consider the following possible implementation. Fast pulse generators, similar to those used in MkIII, are used to produce a signal for injection into each receiver. The pulse repetition rate is equal to the L.O. tuning resolution at baseband (10 kHz for the VLBA), rather than the 1 MHz of MkIII. The digitized signals are then detected by cross-correlation with a (digital) pulse train of the same repetition rate, and the amplitude of the injected signal is estimated from the correlation function. Normally, the detector need only measure the central few values of the correlation function, but the offset would need to be adjustable over the full range in order to account for the total delay of the receiving channel. In principle, the same correlation function could be used to measure the total delay and phase shift of the receiving channel, but the accuracy to which this could be done is limited by other factors (to be discussed in a separate memo).

It is easily shown that the relative rms error in determining the injected power in the passband is given by

$$dP/P = (P_{tot}/P)/\sqrt{(2BT)}$$

where $P_{tot} = kT_{sys}B$ is the total power, P is the injected power, B is the bandwidth and T is the integrating time. If the injected power is 2% of the total power, the integrating time for 0.1% rms error ranges from 3 msec at 8 MHz bandwidth to 400 msec at 62.5 kHz. Even for the worst-case solar observation, where Tsys(max)/Tsys(min) = 36 dB (see VLBA Electronics Memo #30), an injected power of 2% of Tsys(min) leads to 1% rms in 1.2 sec at Tsys(max) with 8 MHz bandwidth; however, solar observations would be better handled by the monitored attenuator method.

4. Recommendations

The design of a pulse generator with sufficient power output and amplitude stability should be actively pursued. For those VLBA bands where adequate performance is obtained, coherent detection of such signals should be relied upon for gain calibration. Here "adequate performance" includes a stability of better than

.001 in power (.03 in voltage) over 3 hours, including ambient temperature changes of up to 2 C (as might be expected in the vertex room).

For any other bands, and as a backup, the monitored attenuator method should also be implemented. For this purpose, the baseband amplifiers should include a programmable attenuator with a resolution of 1.0 dB and a specified repeatability of .002 dB. Each such attenuator must be individually calibrated to an accuracy of .001 dB. The attenuator setting will be readable by the monitor computer, but will normally be controlled by an ALC loop. The loop should be allowed to update the attenuator setting only at fixed times, typically about 1 sec apart; during each period of constant attenuator setting, the power measured by an analog square law detector should be integrated and the result made available to the monitor computer. When multi-level quantization is in use, the power measurement can be ignored, relying instead on the autocorrelator results as indicated above. With 2-level quantization, the power measurement is needed only to resolve the deviation of the total power from the ALC setpoint due to the finite attenuator resolution; then only the slope of the detector characteristic is important, and since the deviation is held to 13% ($\pm$0.5 dB) this slope can vary by 0.8% from nominal while affecting the final estimate of the total power by only 0.1%. (When the total power is changing significantly and rapidly, as when changing the antenna position, the deviation can be larger. Thus, the first measurement after coming "on source" may have a larger error, but its expected value is still correct.) The loop update rate should be programmable, and must be chosen as a compromise between accuracy and keeping up with changes in the observing program. This becomes difficult at the narrowest bandwidths, but for the VLBA we can probably assume that Q=4 will be used in those cases.

Note that this approach involves no switched noise sources, and that it is applicable at all system temperatures, including solar observations. Nevertheless, it may be useful to include provisions for noise-adding in the receivers, primarily for diagnostic purposes, even though they would not be used for calibration.

If it turns out that a pulse generator adequate for all VLBA bands can be built, then not only the noise sources but also the accurate square law detectors can be eliminated. Inexpensive, loosely specified detectors would still be useful for diagnostics.

The correlators for detection of the injected pulses could be implemented at the stations or at the central correlator. There seems to be no performance or capital cost difference between these, so implementation at the correlator should be selected on the grounds of easier maintainability.

5. Discussion

The main criticism of the pulse injection scheme is likely to be that it relies on the stability of the pulse generator. Since this has not yet been demonstrated, and since it may be difficult to obtain sufficiently strong and stable pulses at the highest frequencies, we cannot yet decide to rely fully on this scheme. Work should start immediately on evaluating pulse generator designs, but a final decision can be deferred until detailed design of the correlator is undertaken. If necessary, the highest frequencies (23 GHz, 43 GHz, and eventually 86 GHz) can be handled by injecting the pulses after the first mixer, where the frequency will be 10 GHz or lower; for these receivers, the gain ahead of this point will all be in cryogenic components.

The main criticism of the monitored attenuator approach is likely to be that it relies on the stability of the receivers, since their gains are not directly measured except by astronomical calibration. If the stability is not adequate (i.e., if the gains vary by more than one could measure with a switched noise source and square law detector in a reasonable integrating time), then the overall accuracy is degraded by not using a direct gain measuring scheme.

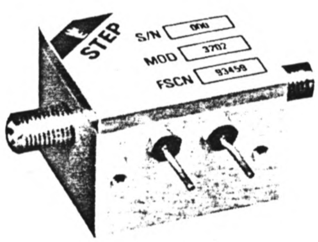
There are several reasons to believe that the VLBA receivers will be more stable than required by the latter criterion. First, most of the gain will be implemented at baseband, where very stable amplifiers can be used, with the components in a stationary room having tight environmental control. Most of the remaining gain will be (for most bands) in a cryogenically cooled dewar, where the environment is also very stable. Next, note that we are here discussing only the amplitude of the gains; for those experiments where phase measurements are important, we will certainly be relying on the receiver stability to transfer astronomical phase calibrations to target sources. The amplitude stability can be expected to be much better than the phase stability (partly because the amplitude is largely independent of local oscillator effects), and so its contribution to the total error in such experiments should be minor. (Attempts to continuously calibrate the phase and thus remove phase instabilities, such as by injecting pilot tones as phase references, will be shown in a later memo to be less accurate than the expected receiver stability.)

PROGRAMMABLE ATTENUATORS FOR OEM

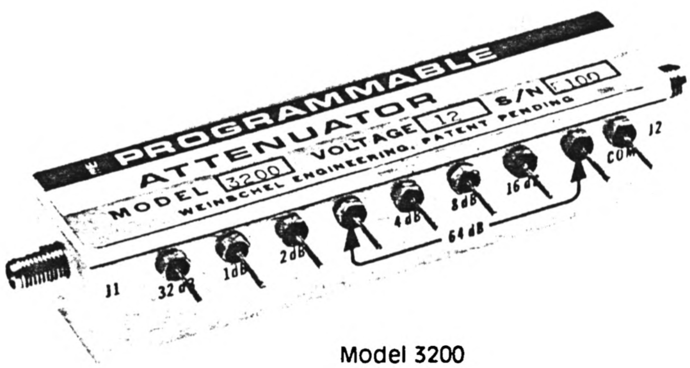
1 WATT

MODEL 3200 SERIES DC TO 2 GHz

SMA TYPE CONNECTORS



Model 3202
(1 Cell)



Model 3200
(8 cells)

FEATURES

BROADBAND — DC to 2 GHz

WIDE SELECTION OF ATTENUATION RANGES AND STEPS —
- 127 dB/1 dB steps
- 63.75 dB/0.25 dB steps
- 31 dB/1 dB steps
- 120 dB/10 dB steps
- 0.5 dB/0.5 dB steps

EXCELLENT REPEATABILITY — ±0.001 dB per cell (±3σ value for 10 cycles within 1 minute, 30 MHz, 25°C) Reference IEEE Standard 474-1973.

HIGH SPEED SWITCHING — Cell switching is completed, after electrical command, in 6 msec.

LONG SWITCH LIFE — Each cell has a rated switch life in excess of 10,000,000 switching operations.

COMPACT SIZES — Overall dimensions are 2.54 centimeters wide × 2.22 centimeters high (1 × 7/8 inches) for all units. Length varies from 10.16 centimeters (4 inches), 8 cells to 3.05 centimeters (1.2 inches), 1 cell.

WEINSCHEL ENGINEERING One Weinschel Lane, Gaithersburg, Maryland 20877