National Radio Astronomy Observatory
Charlottesville, VA 22903

MMA MEMORANDUM NO. 91

MORE REMARKS ON MMA SYSTEM DESIGN

John Granlund
September 29, 1992

I was concerned to read, in MMA Memo No. 85, Barry Clark's recommendation that all-digital signal processing, as used in the VLBA correlator, be the basis for MMA system design. The VLBA design made the best of a difficult situation in which the LO's, and even the sampling clocks, at the receiving sites cannot be synchronized, and the received signals have to be quantized (and sampled) before being recorded and sent to the correlator. At the correlator, the required phasing and fractional sample-time adjustment of the quantized signals produces nonlinear distortion that limits the dynamic range of the cross-power spectra produced, particularly when the signals are strongly correlated. The required additional delaying of the quantized signals by integer numbers of sampling intervals, done by reordering the samples, of course, produces no distortion. But because the MMA, even in the A configuration, is so small, it should be quite possible to synchronize both the sampling clocks and the LO's. I must therefore recommend consideration of an MMA design in which all signal phasing -- excluding that directly associated with the FFT computations -- and all fractional sample-time adjustments be completed before quantization.

My work on fringe rotation after quantization is contained in VLBA Correlator Memo No. 82/VLB Array Memo No. 593. A final memo is in preparation that discusses the errors due to both phasing- and delay-correction after quantization. These errors are comparable. Also discussed is an iterative determination, suggested by Barry Clark, of the true cross-power spectrum from the spectrum obtained with post-quantization phasing- and delay-correction. Unfortunately, these iterations involve excessive computations that will require at least hardware FFT's, if they are to be completed in real time.

How bad are the errors caused by post-quantization phasing- and delay-correction? The errors are least for a flat spectrum and for a concentrated single emission line spectrum. They are greatest for a deep and narrow absorption line in an otherwise flat spectrum. I have used the V-notched IF filter gain shown in Figure 1 as a cross-power test spectrum; it is nearly worst case.

The errors are determined by simulating VLBA processing on the test spectrum. Fractional sample-time changes are approximated -- as in the VLBA correlator -- by changing the test spectrum sample phases in proportion to their frequencies, and signal phase is changed by applying a fixed phase shift to each of the (complex) analytic correlation samples and taking the real parts of the results. The correlation samples are then normalized -- to produce correlation coefficient samples -- and quantized. In this case, quantization does not mean using the two- or four-level quantization that applies to waveform samples, but rather doing the inverse of the quantization correction operation that, without errors, converts correlator counts to correlation coefficients. The resulting correlator counts are next fringe rotated by giving them phase shifts opposite to those applied before quantization, and the fractional sample-time advances applied before quantization are removed. These counts are then averaged separately over uniformly-distributed phase shifts θ within $0 \le \theta \le 2\pi$ and over uniformly-distributed fractional sample-time advances τ within $-T/2 \le \tau \le T/2$, where T is the sampling interval. The effect of the average over θ alone is merely to smooth the quantization curve, leaving the phase of the averaged correlator count in agreement with the phase of the input correlation coefficient. This allows the average over θ to be eliminated altogether by calculating the smoothed quantization curve once, before the start of any simulation runs. Finally, in some cases I have applied quantization correction to the averaged correlator counts before presenting their spectra. More often than not, this has made the spectra negative in certain frequency bands, but what I present are spectral magnitudes in decibels.

As shown in Figures 2, 3 and 4, the phase and delay errors produce distortion in the correlator output spectrum that partially fills the notch, to a depth that depends on the maximum correlation coefficient "Rhomax" of the signals being correlated. Rhomax = 0.4 for each of these three figures. In Figure 2, only phase errors have been inserted, two-level quantization has been used, and post-simulation quantization correction has been omitted. In Figure 3, only phase errors have been inserted, four-level quantization has been used, and post-simulation quantization correction has been applied. In Figure 4, only delay errors have been inserted, two-level quantization has been used, and post-simulation quantization correction has been omitted.

As a crude measure of dynamic range, I have used the decibel attenuation of the 22 MHz component of the final spectrum, which is at the frequency of the bottom of the test spectrum's notch. Figure 5 gives plots of this dynamic range against Rhomax for two- and four-level quantization; only phase errors have been inserted, and post-simulation quantization correction has been applied. With the notch only 60 dB deep, it seems strange that the curves hook to the right to report a dynamic range in excess of 60 dB at small Rhomax. The reason is that over the range of Rhomax plotted, the 22 MHz components of the final spectra are negative. To reach the positive, 60 dB down values expected when Rhomax is <u>really</u> made small, these spectral components must be driven through zero, at which point the crude measure would give a dynamic range of infinitely many decibels.

Figure 6 gives plots of dynamic range against Rhomax with delay error only and with both phase and delay errors inserted; two-level quantization has been used, and post-simulation quantization correction has been omitted. Is it really true that dynamic range is greater when both errors are present than when only one is present? Yes! It has been noted that the effect of averaging over all phase shifts is to smooth the quantization curve. Although averaging over all fractional sample-time advances cannot be described so simply, its effect is also a reduction of quantization nonlinearity.

From the foregoing, it is clear that the decision as to whether or not all signal phasing and fractional sample-time adjustments for the MMA should be completed before quantization depends in part on the Rhomax of the signals to be observed. Dick Thompson has been helpful in examining this question. In conversations with Bob Brown and Al Wootten, he has concluded that, for the MMA, the largest values of Rhomax may come from observations of the silicon monoxide line at 86 GHz. Maximum source power density is estimated to be 1,000 Jy, and, corresponding to a velocity spread of 40 km/sec, the line width will be 12 MHz. For observations within this bandwidth, I find the maximum signal-to-noise ratio to be

$$SNR = \frac{1/2\ A\ S\ \Delta f}{k\ T_s\ \Delta f} = \frac{1/2\ A\ S}{k\ T_s},$$

in which

$A = (\pi \times 4^2 \times 0.6)$ = effective aperture area (m^2)

S = 1,000 Jy = 10^{-23} (MKS units)

k = Boltzmann's constant = 1.38×10^{-23} (MKS units)

T_s = 100 K = receiver system temperature.

Then, for correlations measured over the shorter baselines,

$$Rhomax = \frac{SNR}{1 + SNR} = 0.1$$

Since this estimate puts the dynamic range below what may be required for possible future observations, I'll let my recommendation stand.

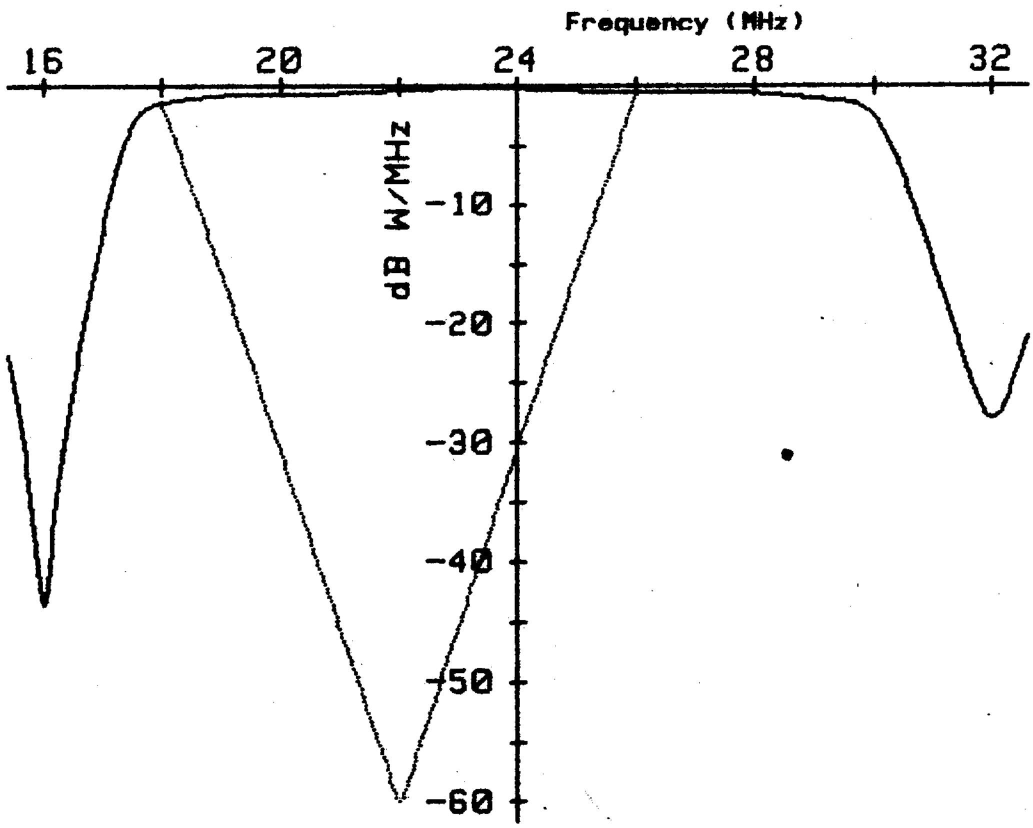

Figure 1. IF Filter and Notched Test Spectrum.

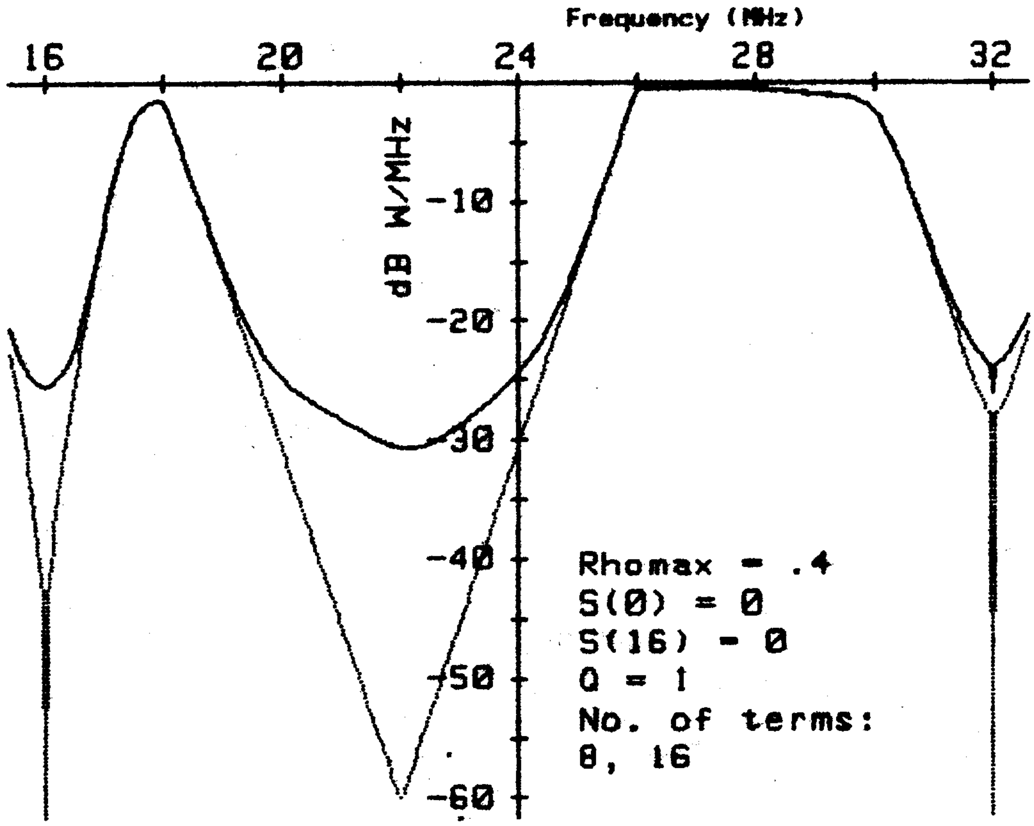

Figure 2. Phase Error Only, Two-Level Quantization, and No Quantization Correction.

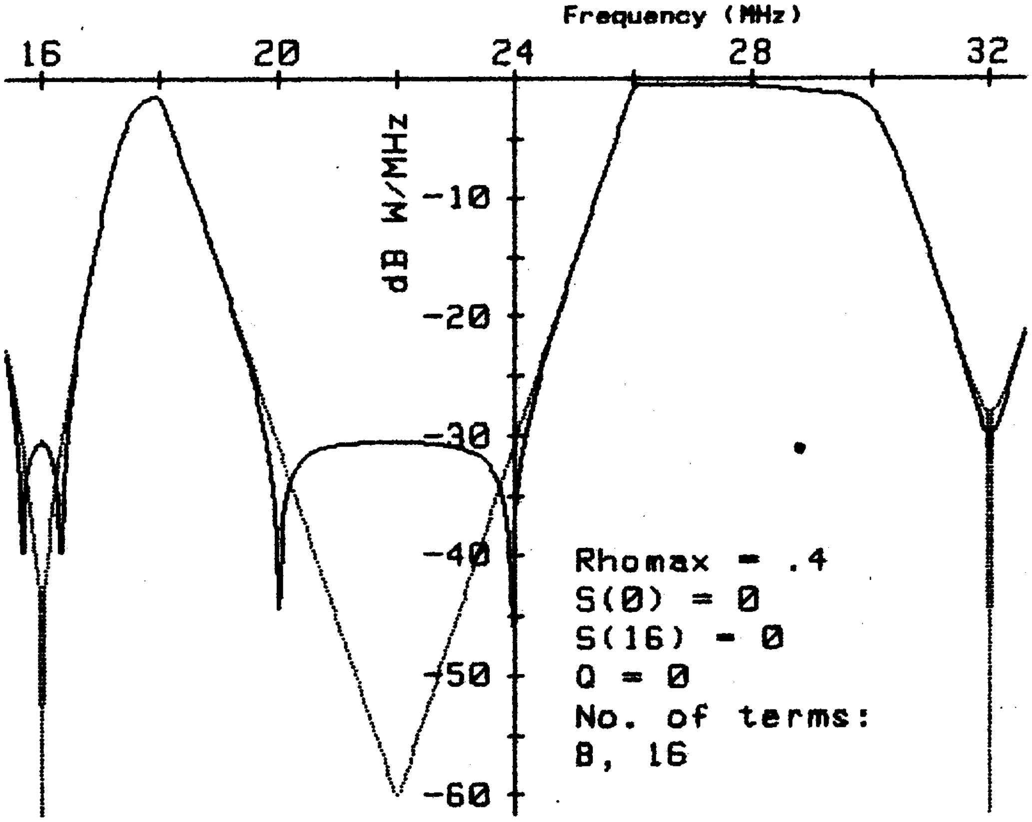

Figure 3. Phase Error Only, Four-Level Quantization, and Quantization Correction Applied.

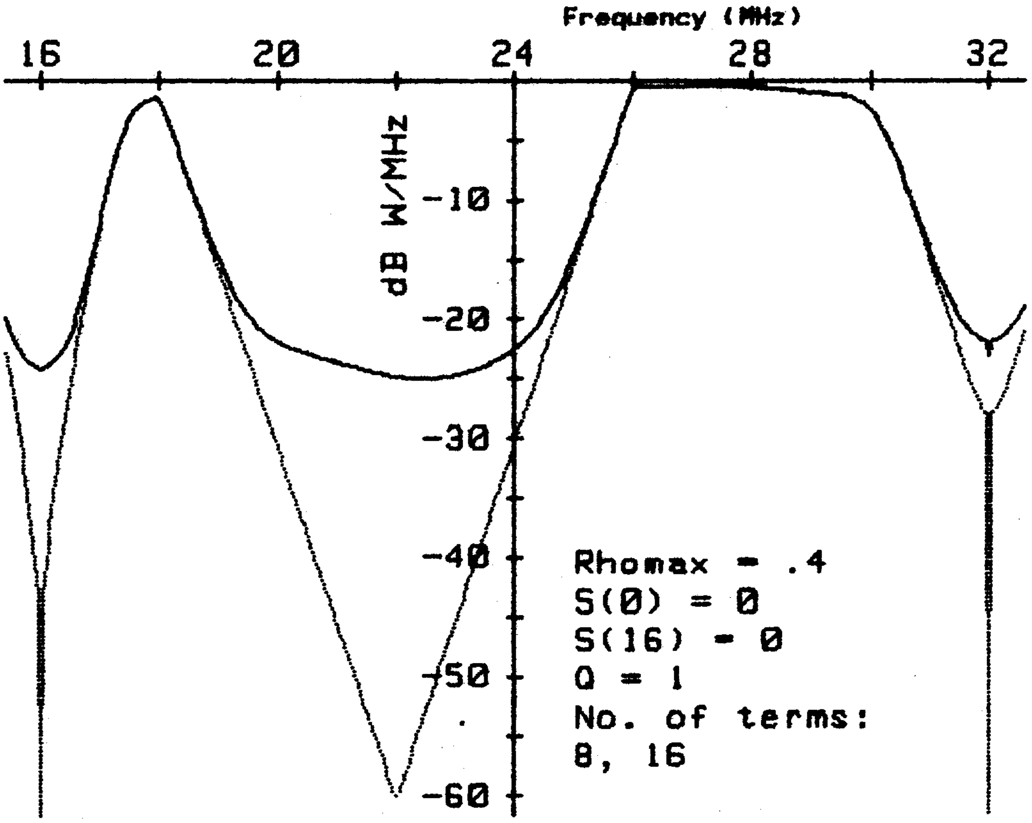

Figure 4. Delay Error Only, Two-Level Quantization, and No Quantization Correction.

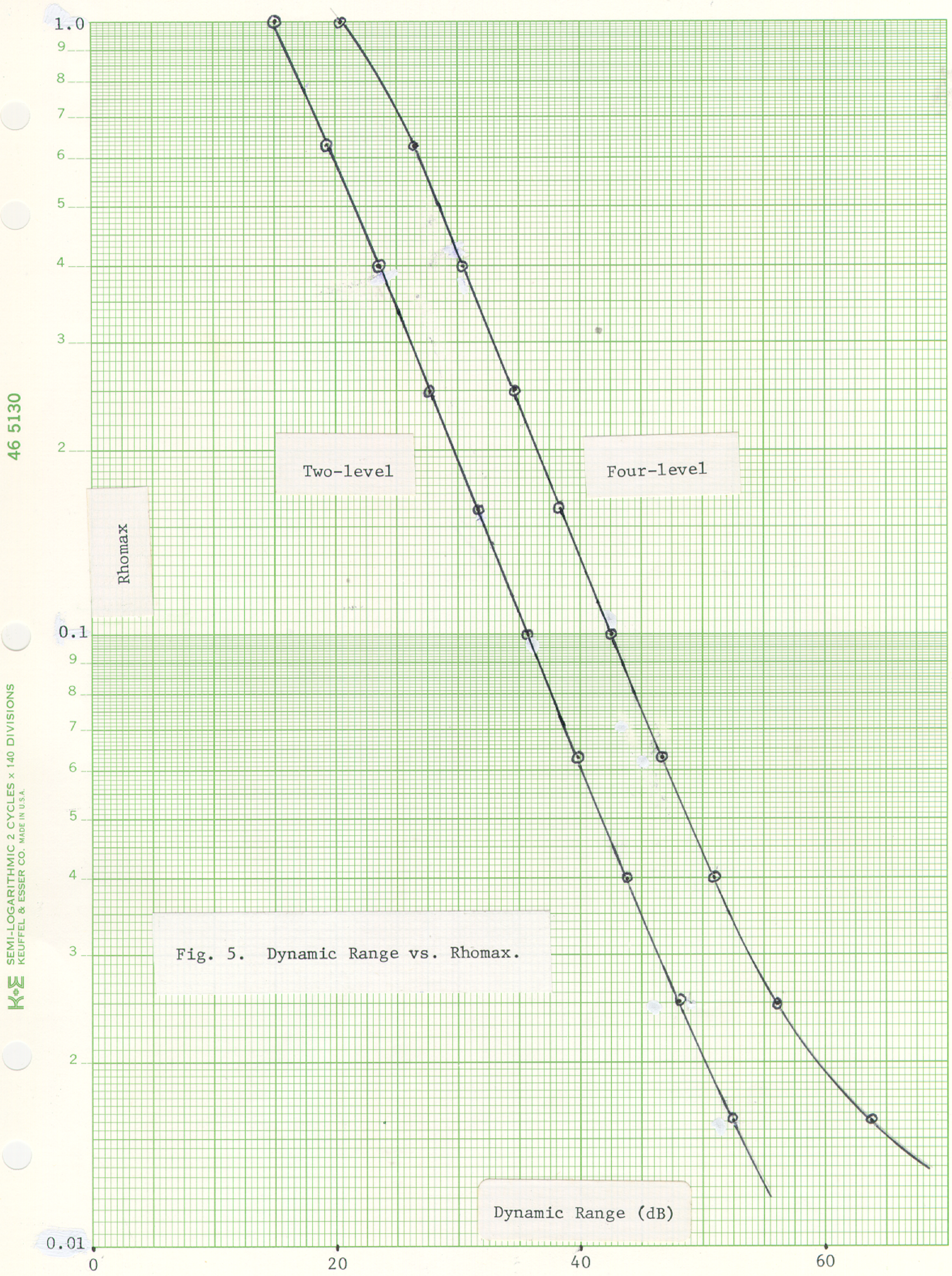

Fig. 5. Dynamic Range vs. Rhomax.

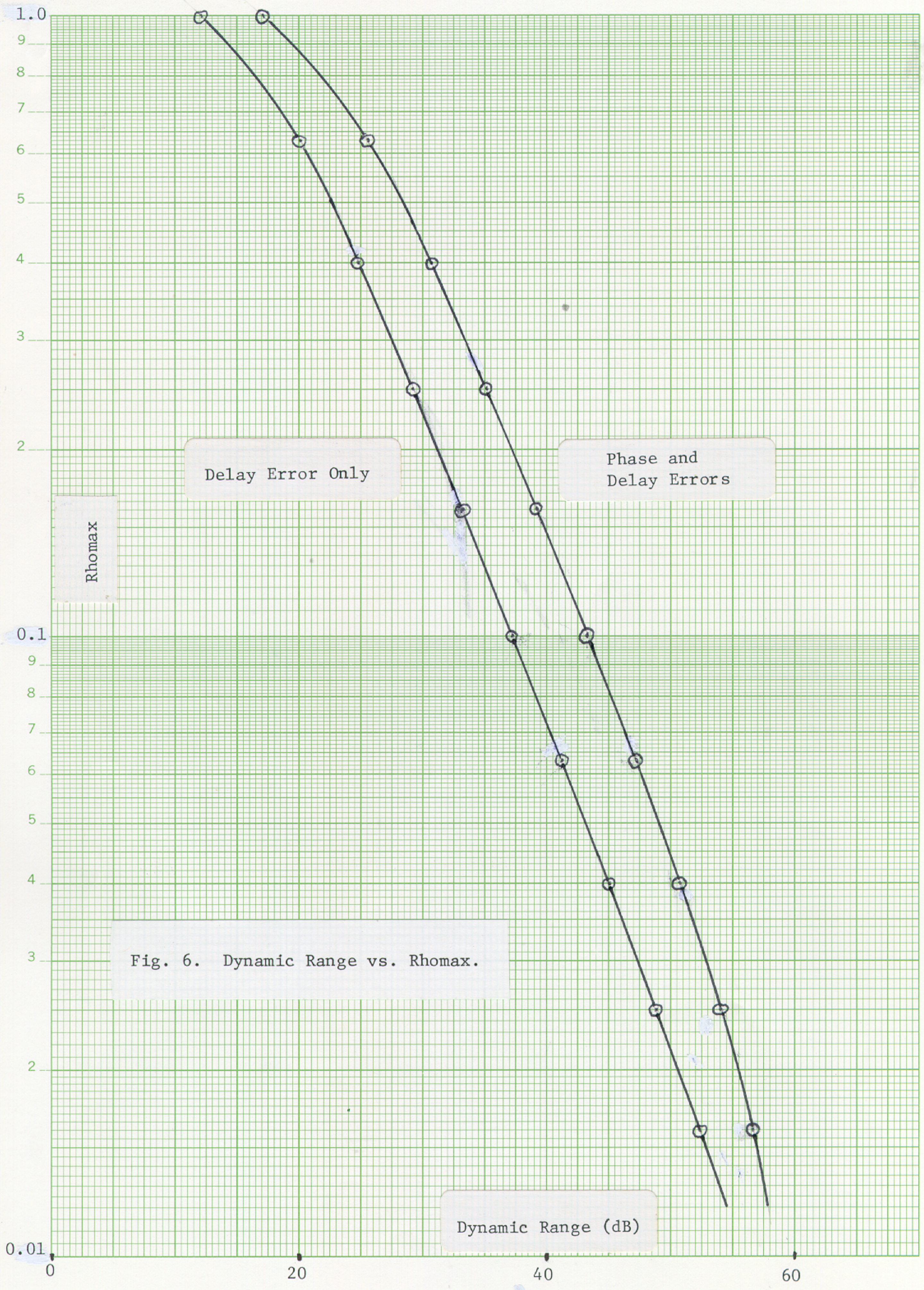

Fig. 6. Dynamic Range vs. Rhomax.