VLA TEST MEMORANDUM # 153

THE TUNING RANGE AND SENSITIVITY OF THE VLA

R. A. Perley

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I. INTRODUCTION

The VLA is outfitted with receivers which allow observations within six frequency bands. In addition to the four bands which were originally provided (L, C, U, and K bands), we now have observing capability at X band (3.6 cm) and P band (90cm). A wide tuning range is allowed within each band, and previous documents have indicated the frequency range over which the system will provide close-to-optimum performance.

Within the last few years, major changes have been made to the VLA receivers. In addition to the two new bands, new electronics have greatly improved the four original bands, generally resulting in wider tuning range, lower system temperature, and better receiver reliability. Now that the improvements and installations are nearly completed, it is appropriate to measure the system performance systematically at all bands. Since a number of potential astronomical observations may require frequencies near the band edges, it is important to measure this performance not only within the standard, advertised ranges, but over all frequencies which could conceivably be tuned by the receivers. The most important system parameter to be measured as a function of frequency is the Sensitivity, S, (defined below), but it is also important to note the polarization response, and how many receivers can be expected to tune to a given frequency. This report summarizes the results of extensive tests to determine these quantities.

Readers of this memorandum who are, or will be users of the VLA will note that a large fraction of receivers will tune successfully to frequencies well outside the advertised, standard ranges. However, there is no guarantee whatever that all antennas will be available outside these ranges. The numbers quoted in this report are simply those I obtained on one given day, and should be interpreted as merely a suggestion of how many might be expected to work. The NRAO has no responsibility to ensure that receivers tune outside the advertised ranges for each band.

II. METHOD AND OBSERVATIONS

There are many techniques to measure antenna and array sensitivity, each with their own merits and disadvantanges. I take the point of view of an observer who simply wants to predict the r.m.s. noise in an image made with VLA data. The observer is not particularly concerned with antenna G/T values, antenna or correlator efficiencies, or other parameters commonly used. He wants a single value describing the array, which is then used with the bandwidth and observing time to predict the image noise. The ability to accurately predict this quantity is critical to designing experiments.

The output noise, σ_I, of a complex interferometer can be written

$$\sigma_I = \frac{\sqrt{2}k_B T_{sys}}{\sqrt{T\Delta\nu}A\eta_a\eta_c}.$$

In this expression, k_B is Boltzmann's constant, T_{sys} is the system temperature, A is the antenna physical collecting area, η_a is the antenna efficiency, and η_c the correlator efficiency. The quantities $\Delta\nu$ and T are the bandwidth and integration times, respectively. A full discussion of the origins of this expression are found in Chapter 7 of the 1988 Proceedings of the NRAO Summer School on Synthesis Imaging.

The observer is generally not interested in the antenna and correlator constants, and prefers the simpler expression

$$\sigma_I = \frac{S}{\sqrt{T\Delta\nu}},$$

where $S = \sqrt{2}k_B T_{sys}/A\eta_a\eta_c$ is a system constant, beyond the observer's control. When considering an array of N elements providing C correlations ($C = N(N-1)/2$ if all correlations are made), and noting that the noise from each correlator is independent of the others, the resultant noise is

$$\sigma_I = \frac{S}{\sqrt{CT\Delta\nu}}.$$

It has been assumed that all antennas and receivers are identical. This is justifiable for the VLA for frequencies within the standard bands. Near the band edges, the antenna performance varies widely, and use of this expression presumes a sort of 'global average' over the antennas.

This expression is appropriate for the case where the array provides one complex correlation per baseline. In fact, most arrays, including the VLA, provide four complex correlations per baseline, from which two at a time are used to provide an output image of the Stokes' Parameters I, Q, U, or V. For the VLA, these correlations are the RR, RL, LR, and LL products. Let N_{vis} represent the number of visibility measures obtained by the array, each of integration time Δt. In general, each visibility measure will consist of four complex correlations, although flagging may reduce this to two, or even one. Then, the product CT, written above, becomes $2N_{vis}\Delta t$, where the factor 2 presumes two complex correlations are being used to produce the output image. In some rare instances, only a single correlation per baseline is used – in this case, the factor of 2 becomes 1. The relation then becomes

$$\sigma_I = \frac{S}{\sqrt{2N_{vis}\Delta t\Delta\nu}}.$$

The convenient units in this expression are mJy for the flux density, hours for the integration time, and MHz for the bandwidth. With these units, the S parameter generally assumes values between 5 and 30 for the VLA.

To measure the S parameter, I took short observations, at many different frequencies, of the strong point source 3C84 (except at 90cm, where I used 3C48) and of a nearby region of blank sky. These observations were attempted within each band at frequencies covering the full range over which the receivers were thought to have any chance whatever of locking up, or over which any signal at all could conceivably be available. The observations of the strong source were used to calibrate the gain of the antennas, and these gains were then used to calibrate the blank sky data. After this calibration, the data were then used to make an image, from which an r.m.s. value was determined. Before making this image, the data were edited to remove clearly discrepant points. This is a process requiring some judgement, and is not easily described. The procedure is only judgemental at the edges of the various bands, where large differences between antennas appear. Within the standard, advertised tuning ranges, the antenna performances are nearly identical (as they should be), so no editing was required. For band edges, I retained only the better-behaving antennas. The number of antennas so retained is noted in the results. An estimate of the polarization purity was obtained by listing the cross-hand amplitudes (RL and LR correlations) for the strong point source.

Data were taken in two sessions, 19 Oct., 1988 at K band (1.3 cm), and 14 Nov., 1988, for the remaining bands. For both sessions, the data were taken late at night, under clear, dry weather conditions. After initial editing (to remove occasionally bad first records and antennas which couldn't tune to the commanded frequency), calibration proceeded along standard lines. The data were then written to an EXPORT tape, and subsequent processing done on the CONVEX, under AIPS. Here, the visibility amplitudes were plotted, and discrepant points discarded. As described above, this process was important only for data taken at frequencies near the band edges, where a wide spread in antenna performance was noted. Thus, the S factors reported below are optimistic in the sense that if all the data were used, a somewhat noisier image would have resulted in these cases. In all cases, I flagged data only when they seemed well out of range from the envelope encompassing the data from a majority of antennas which tuned to the given frequency. After this editing, an image was produced, from which the r.m.s. was measured. For P and L band data, I used a Stokes' Q image to measure the image noise, since the I image is dominated by the uncleaned sidelobes of background radio sources. At the other bands, I made an 'RCP' or 'LCP' image, since the flagging usually affected different numbers of RR and LL visibilities. (Unfortunately, AIPS does not require both RR and LL data be valid to make a Stokes' I image. This assumption is strictly valid only if there is no circular polarization. The difference is important to this test, since the imaging programs report on the number of visibilities used, but does not report on whether both complex correlations were present, when making a Stokes' I image.) Making an image of a single correlator allowed a larger number of data points to be used, since use of Stokes' parameters (Q, U) always results in the minimum amount of available data. For all frequencies within the standard tuning ranges, this distinction is moot, since no flagging was necessary. This 'differential' flagging problem is noticeable only at the edges of X, U, and K bands, where the first L.O. will often not lock up.

III. RESULTS

The main results are given in Figures 1 through 6, showing the dependence of the sensitivity factor, S, on frequency for each of the six observing bands. For all plots, the units of S are mJy(visibilities MHz hours)$^{1/2}$. In some cases, I have indicated the polarization purity of the system with a dotted line. Where this is absent, the detailed notes below will provide this information. The number of antennas which were available for this experiment are also given in the notes below.

I emphasize again that the NRAO 'supports' only those frequencies lying within the standard bands. These are shown by the horizontal bar on each plot, and are identified within the notes below. Users who attempt tuning the receivers beyond these ranges must be content with the data they receive. The NRAO can make no special effort to ensure better performance outside the standard tuning ranges.

P-band – 90cm

The standard tuning range is 308 to 340 MHz, and I attempted observations at increments of 5 MHz from 282.5 MHz to 357.5 MHz. There is no problem in tuning the receivers over this range (or to any frequency from 0 to 1 GHz), but due to the front-end filter, insufficient signal power outside the band 298 MHz to 348 MHz causes the data to be flagged bad. Within this frequency range, any frequency can be tuned. However, due to strong internal birdies at 300, 312.5, 325, and 337.5 MHz, it is not advisable to use any frequency/bandwidth combination which includes any of these frequencies.

Within the band 298 to 348 MHz, all antennas will tune up. The sensitivity as a function of frequency is plotted in Fig. 1, and displays the overall front-end filter shape. It is clear that the front-end filter limits the usable range of the band, and a future test will establish the useful tuning range with the filter removed. No measure of the polarization respose was made at this band, but it is expected to remain near 5% within the practical observing range.

L-Band – 20cm

The standard tuning range is 1340 to 1730 MHz, and observations were attempted between 1075 MHz and 2025 MHz, at increments of 50 MHz. Astronomical signals were seen between 1275 and 1875 MHz, except at 1775 MHz, where no signal was found. This is due to a notch filter which has been inserted to protect the receiver from a local Forest Service transmission frequency. The sensitivity results are shown in Figure 2. All antennas tuned to the commanded frequencies, but the variations in receiver sensitivities resulted in some data flagging at 1225 MHz (about 20% of the data) and above 1725 MHz. About half the data had to be flagged at 1875 MHz. The antenna cross-polarization dropped from about 10% at 1225 MHz to less than 2% at 1375 MHz, remains at this level to about 1700 MHz, then rises to about 10% at 1875 MHz.

C-band – 6cm

The standard band range is 4500 to 5000 MHz. Observations were attempted between 4225 MHz and 5285 MHz. Useful signal was obtained between 4285 MHz and 5085 MHz. The sensitivity plot is shown in Figure 3. All antennas tuned successfully over the entire range shown. It is not possible to tune above 5100 MHz with the current electronics. The polarization remains less than 2% throughout except below 4335 MHz and above 5035 MHz, where it rises to approximately 5%.

X-band – 3.6cm

The standard band range is 8000 to 8800 MHz. Observations were attempted between 6035 MHz and 11415 MHz, with useful data obtained between 6835 MHz and 9615 MHz. The derived sensitivies are shown in Figure 4. All antennas were available over the range 7615 MHz to 9015 MHz, but only half of them will tune successfully to the extreme ends quoted above. The number available drops roughly linearly in between. The antenna polarization is plotted with dashed lines in Fig. 4.

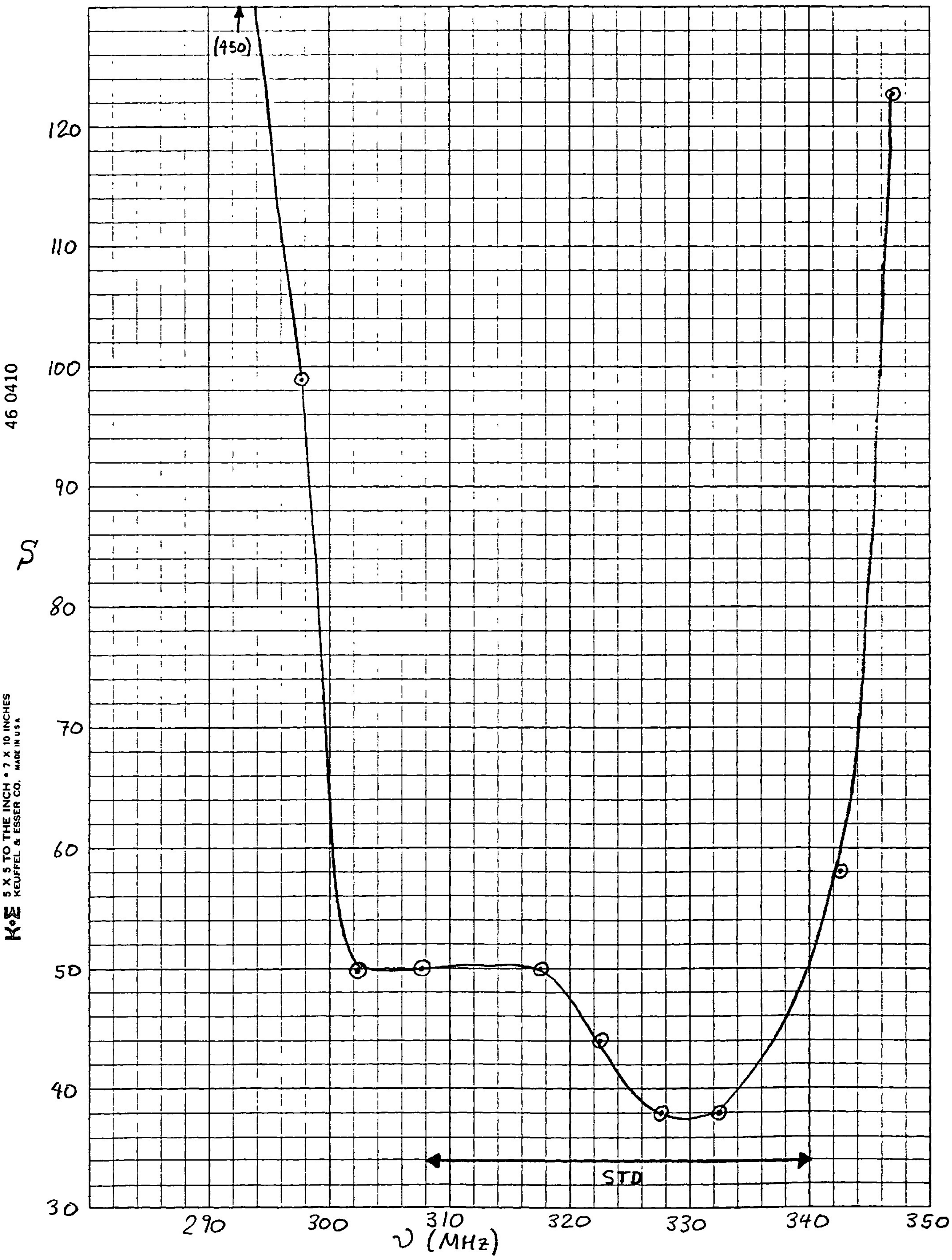
U-band – 2cm

The standard band range is 14400 to 15400 MHz, and observations were attempted between 11035 MHz and 16715 MHz. Useful data were obtained betwen 13565 and 16265 MHz. The sensitivity results are shown in Figure 5. All antennas are available between 13765 MHz and 15665 MHz, but only 20 will tune up at 13565 MHz. The number of available antennas drops from 20 at 15865 MHz to 10 at 16265 MHz. The cross-polarization is less than 3% from 14165 to 15265 MHz, and rises to 7 to 10% at the ends of the useful tunable range.

K-band–1.3cm

The standard band range is 22000 to 24000 MHz. Observations were made between 20885 MHz to 25785 MHz, with useful data available over all this range. At the time of the tests, software disallowed a first LO exceeding 21 GHz, preventing any tests at frequencies exceeding 25785 MHz. No tests were attempted below 20885 MHz. The software limitation has now been removed, and it seems likely that the antennas will tune to frequencies slightly outside the range given above. The derived sensitivity factors are shown in Figure 6. All antennas are available between 22085 MHz and 24485 MHz. Beyond this range, the number available drops approximately linearly with frequency, reaching 11 at the edges of the tested range. Antenna cross-polarization is less than 5% between 21185 MHz and 24185 MHz, and rises to 8% at 20885 MHz. On the high-frequency side, a polarizer resonance phenomonen is observed – the polarization rises quickly from 7% at 24285 MHz to $\sim$ 65% at 24785 MHz, then drops to 18% at 25385, and 12% at 25485 MHz. The polarization stays constant at this level until 25785 MHz. This resonance is responsible for the spike in the sensitivity factor seen in Figure 6, as the effect is to take nearly half the parallel-hand signal (RR and LL correlations) and put it in the cross-hand ports (RL and LR). In principle, at least, this can be corrected in software. Current software assumes a low antenna polarization, and it is not known how successful an attempt to correct this problem will be.

Fig 1. P-BAND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ν (MHz)

Fig 2. L-BAND

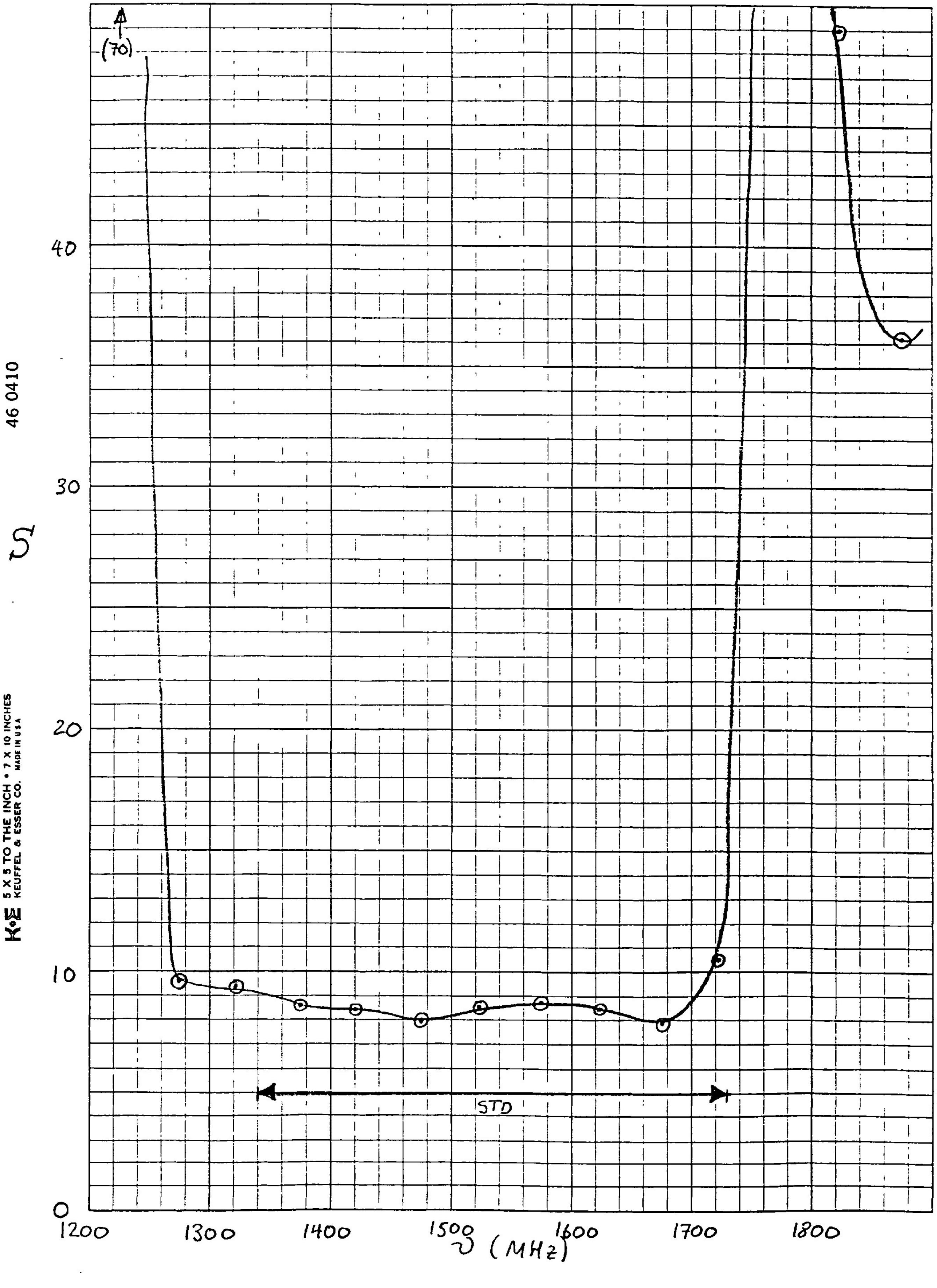


Fig. 3

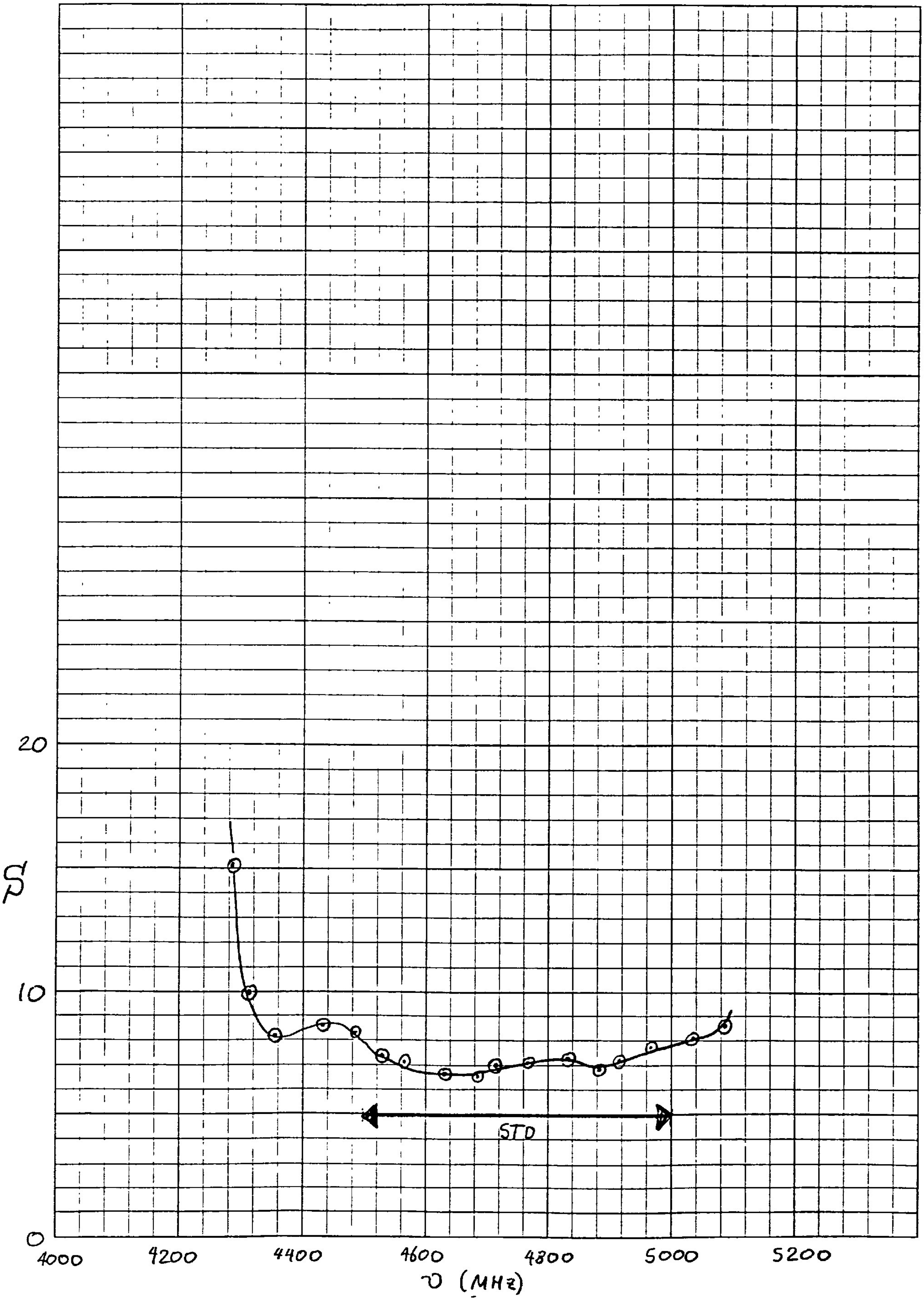
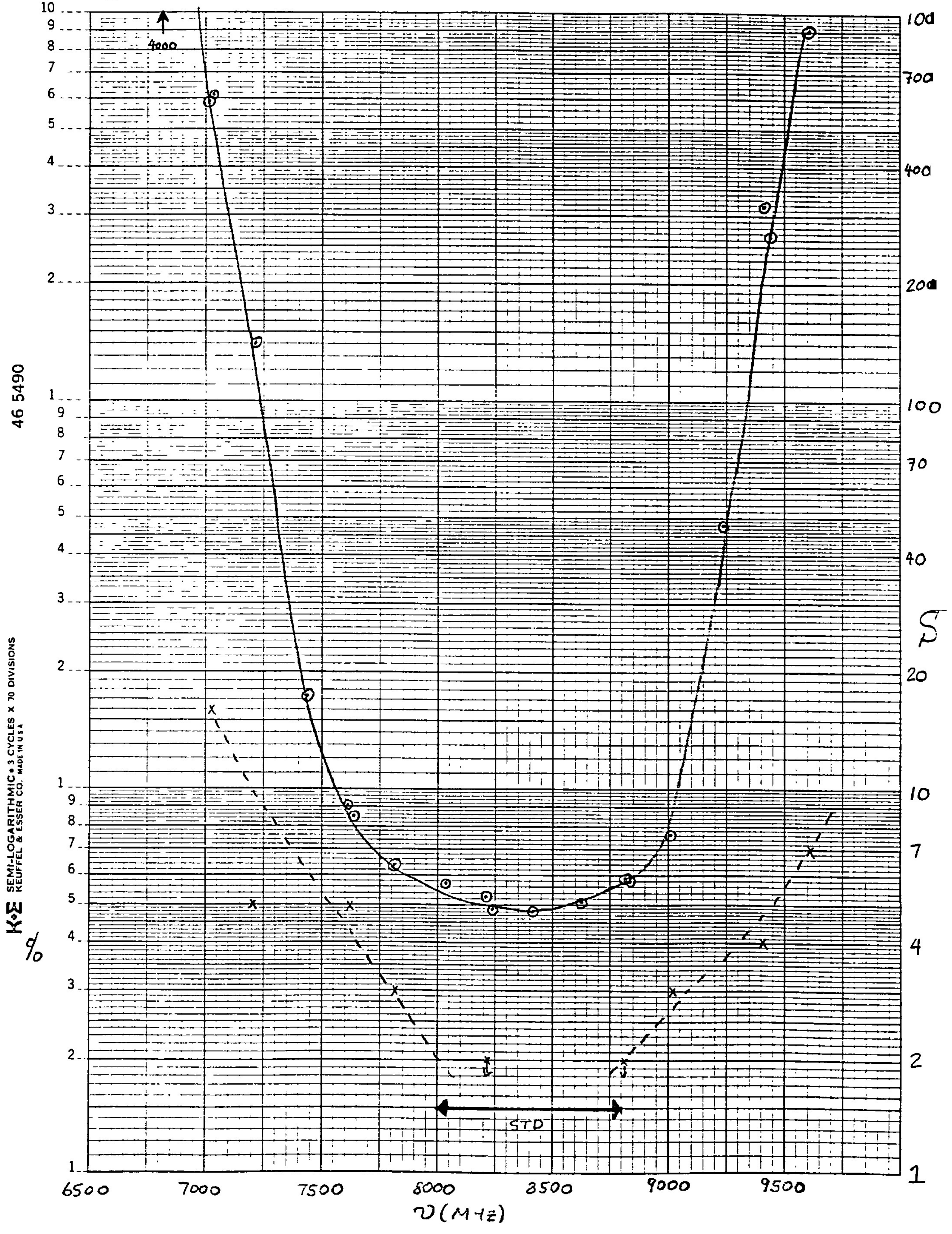


Fig. 4

X-BAND



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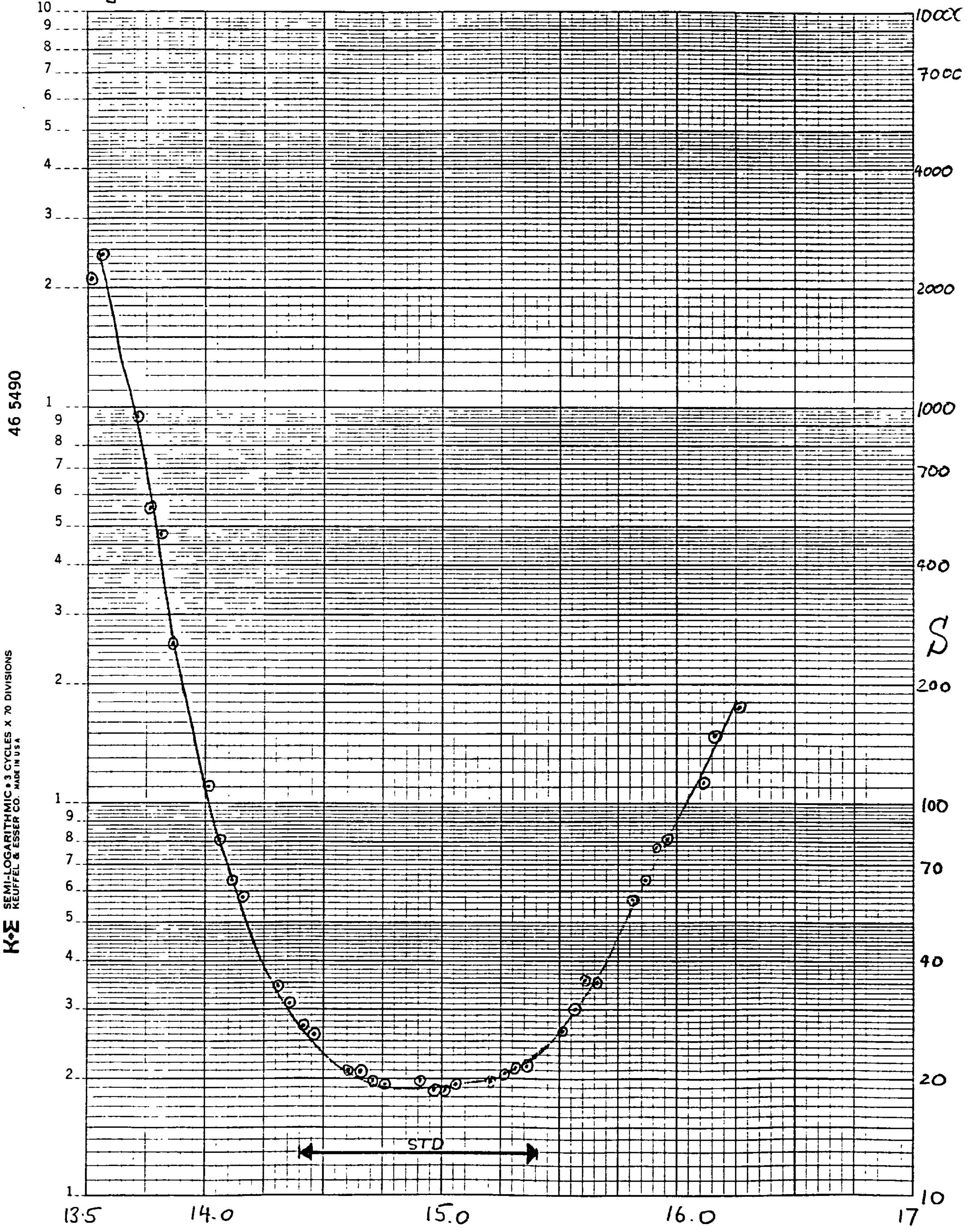
K+E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 5 U-BAND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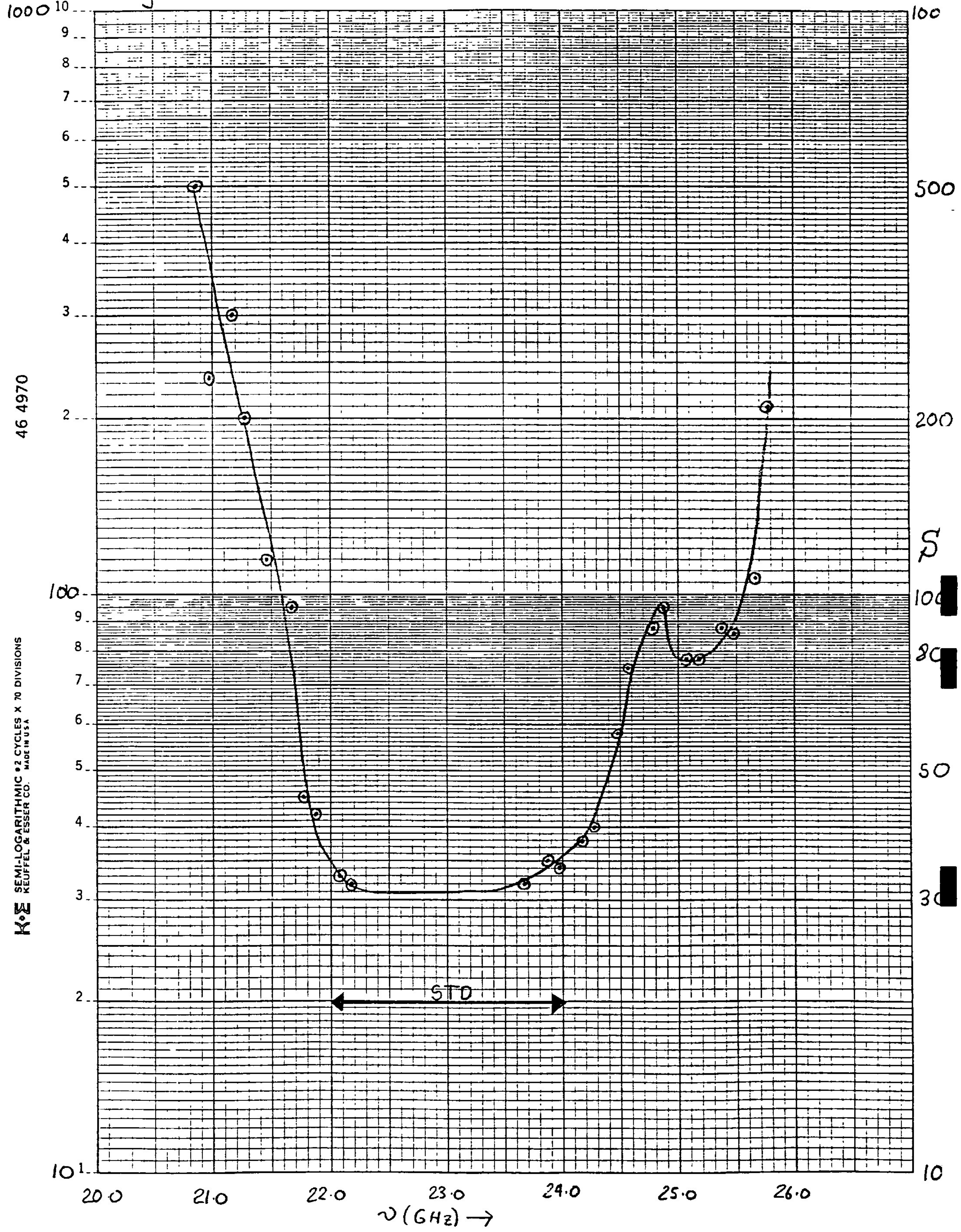
K+E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 6

K-BAND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