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JINDALEE PAPER 130

AN EVALUATION OF THE PERFORMANCE OF THE JINDALEE
STAGE A SURVEILLANCE RECEIVER

G.F. Earl, B.D. Ward and R.E. Garrett

S U M M A R Y

The performance of the Jindalee Stage A surveillance receiver is evaluated using the HF spectral data recorded during the period October 1977 to September 1978.

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1. INTRODUCTION

During the development of the Jindalee Stage A Frequency Management System a specification of the surveillance receiver was undertaken. In the absence of measured data relating to the h.f. environment at Alice Springs, the specification was largely the result of a compromise between somewhat arbitrary speculation as to the likely h.f. environment, and an assessment of the cost and effort required to produce a receiver capable of providing satisfactory (if not optimum) surveillance data. The receiver was constructed to this specification and was used to collect data over a two year period which concluded in December 1978. The objective of this report is to assess the extent to which surveillance data recorded using the Stage A Surveillance receiving system are contaminated by inadequacy of the receiving system in terms of the prevailing h.f. environment. In this manner, contaminated data should be readily identified and thus the possibility of erroneous interpretation on this account avoided. In addition, the results presented in this report will prove of immense value in the planning and specification of the surveillance receiver to be used in Stage B of Project JINDALEE.

2. SURVEILLANCE DATA BASE

The Stage A data logger scanned the spectrum from 6 to 30 MHz and provided 12000 calibrated spectral measurements with a 2 kHz spacing. A detailed discussion of the surveillance receiver and the data processing algorithms used to record the data is presented in reference 1. Spectral measurements were alternated between an omnidirectional whip antenna and the directional +3 degree beam of the radar system with an interval of approximately 30 minutes between each scan of the spectrum.

Much of the analysis in this report requires comparison of large signals with the background noise level. The background noise level was determined at 0.5 MHz intervals by finding the lower decile of the 250 measurements over each 0.5 MHz section of the spectrum. Although the surveillance receiver may have suffered some limitations in performance in the presence of the largest signals, analysis of the surveillance data (reference 2) shows the lower decile was not in general affected and represented an accurate measurement of the background noise level. There were two exceptions where the lower decile was not an accurate measurement of the background noise level. Analysis revealed that the spectrum through the broadcast bands were either contaminated by receiver limitations or the signal levels in these bands frequently exceeded the background noise level outside the bands by more than 10 dB across the whole band. Consequently the broadcast bands were specifically excluded from the measurements used to determine the background noise level. An additional problem was encountered with data recorded on the +3 degree beam between 2100-0700 local time. During these times the large numbers of strong signals in the broadcast bands resulted in such a large number of IMD products (discussed in Section 7.2) that the background noise level was completely masked by the spurious IMD responses. The whip was not subject to the same degree of contamination since the signal levels at the receiver input were smaller and the IMD products appeared as discrete signals. During those periods of the day when the +3 degree beam measurements were contaminated by IMD effects the whip data was used to estimate the background noise level, resulting in an error of less than 3 dB in the noise estimates.

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The data analysis discussed in this report is based on a representative sample of the surveillance data. One typical 24 hour period was chosen for each month between October 1977 and September 1978. With the exception of the intermodulation distortion (IMD) performance of the receiver the data analysis revealed that there were no significant seasonal variations in the data analysed. Although there is a small seasonal change in the distribution of large signals, particularly in the broadcast band, this change is insignificant when considered as a percentage of the total data analysed and consequently seasonal variations are imperceptible in the cumulative distributions. However in the case of the IMD the effect of changes in the distribution of large signals was to cause channels which had previously been clear of IMD products to become contaminated. Since the data is plotted as the percentage of a fixed number of channels, rather than as the total sample size, seasonal variations were evident in the IMD data.

3. DESCRIPTION OF RECEIVER

The h.f. environment was measured by using a receiver to translate 20 kHz segments of the h.f. spectrum to the range of 3 to 23 kHz which was suitable for input to an analogue to digital converter. Figure 1 is a simplified block diagram of the receiver. The receiver used triple conversion, with a first I.F. of 40.113 MHz. This was then mixed with 40 MHz to produce signals in the range 103 to 123 kHz before being finally mixed with 100 kHz to give the baseband output frequencies. The receiver was tuned by varying the first local oscillator frequency between 46 and 70 MHz in 20 kHz steps.

Selectivity of the receiver was initially determined by a 30 kHz bandwidth crystal filter centred at 40.112 MHz. Additional selectivity was obtained in the second I.F. with an 8 pole LC bandpass filter and finally at baseband with an 8 pole low pass active filter. To maintain reasonable inband third order intermodulation distortion the receiver gain from the input to the output of the last mixer was only 10 dB. The required overall gain values of 60, 81, 99 and 120 dBv were obtained by selectable gain stages at the baseband frequencies.

4. ANALOGUE-TO-DIGITAL CONVERTER RESOLUTION

4.1 Theory

Consider the case depicted in figure 2 of a receiver connected to an antenna, the output of the receiver being in turn connected to an analogue-to-digital converter. The amount of power (referred to the receiver input) which, as a result of filtering within the receiver, passes to the A/D converter is P dBW. The external noise level at the receiver input is E dBW Hz⁻¹. The A/D converter is characterised by n bits, and has a quantisation step size of ε volts. Now define a parameter α such that

$$\alpha = \frac{V_p}{V_{rms}}$$

where V_p = peak value of A/D converter input

V_{rms} = r.m.s. signal voltage at A/D converter input

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The quantisation step size is seen to be

$$\epsilon = \frac{2 V_p}{2^n}$$

Suppose, in accordance with the bandwidth of the signal being processed, the A/D converter has a sampling rate f_s resulting in a Nyquist frequency

$$f_N = \frac{f_s}{2}$$

The finite resolution of the A/D converter results in the production of an error signal with an associated noise spectral density, and if the receiving system shown in figure 2 is to be used to measure the external noise level E dBW Hz⁻¹, the contaminating effect of the A/D converter quantisation noise must be small in comparison to the equivalent external noise level. In reference 3 it is shown that

$$n = \frac{1}{6} (P - E + 10 \log_{10} \frac{\alpha^2 Q}{3 f_N})$$

where Q is the factor by which the quantisation noise is to be attenuated in comparison to the equivalent external noise e.g. if $Q = 1$ there would be zero attenuation and the resultant contamination would be 3 dB, if $Q = 10$ there would be 10 dB attenuation and the contamination would be 0.4 dB, whilst for $Q = 100$, 20 dB of attenuation would result in the estimates being corrupted by 0.04 dB. In this study Q is set equal to 10, and α to 5.

4.2 Results

Cumulative distributions of the required number of A/D converter bits are shown in figure 3 for both the whip and +3° beam, for the September 1978 data. Note that the minimum (and most probable) number of bits is 4, which may be explained on the following basis. If an entire 20 kHz band is clear i.e. it consists of 10 channels each characterised by the background noise spectral density, then

$$\begin{aligned} P &= E + 33 + 10 \text{ dBW} \\ &= E + 43 \text{ dBW} \end{aligned}$$

where 33 dB has been included to allow for the bandwidths of 2 kHz and 1 Hz, and 10 dB is included for the effect of integrating over 10 channels. Then with

$$\begin{aligned} \alpha &= 5 \\ Q &= 10 \\ f_N &= 2.5 \times 10^4 \text{ Hz} \\ n &= \frac{1}{6} (43.0 + 10 \log_{10} (3.3 \times 10^{-3})) \end{aligned}$$

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$$= \frac{1}{6} (18.22)$$

$$= 3.04$$

The program is arranged to round to the closest integer greater than the value calculated using the above expression, and so the value 4 results. The A/D converter used to acquire Stage A surveillance data had 12 bits, a value which proved adequate in 99.5% of cases for the whip data and 99.4% of cases for the +3° beam, and these results are typical of data relevant to other months.

Figures 4 and 5 show the distribution (as a function of frequency) of channels requiring more than 12 bits. In both cases the effect of the 9, 11, 15 and 17 MHz broadcast bands is clearly evident.

Figures 6, 7 and 8 are equivalent to those of figures 3, 4 and 5 and were generated by omitting the broadcast bands from the analysis. As expected, the effect of excluding the broadcast bands is to marginally relax the A/D converter requirements, most notably at the tail of the distribution. In particular, with the broadcast bands excluded, a 12 bit A/D converter proved adequate for 99.8% of the whip data and for 99.9% of data recorded on the +3° beam.

With regard to the largest number of bits identified in any of the whip antenna data analysed, on day 133 at 0201Z, the total power in the band 15.400 MHz to 15.420 MHz was -67.9 dBW, due principally to a signal on 15.411 MHz. The corresponding background noise spectral density estimate was -192 dBW Hz⁻¹. The necessary number of bits required to have digitised this data with the specified degree immunity from quantisation noise would have been

$$n = \frac{1}{6} (-67.9 - (-192) - 24.8)$$

$$= 16.54 \text{ i.e. } 17 \text{ bits.}$$

In the case of the +3° beam, on day 42 at 1718Z the total power in the band 15.300 MHz to 15.320 MHz was -49.9 dBW, due principally to a signal on 15.311 MHz recorded at -50 dBW. The corresponding background noise spectral density was -173 dBW Hz⁻¹, and the resultant number of bits was again 17.

As is evident from the cumulative distributions of figures 4 and 5, such instances are very rare but are interesting from the point of view of the technology required to support the most demanding environment.

5. RECEIVER FILTER CHARACTERISTICS

5.1 Theory

Consider the I.F. passband characteristic shown in figure 9. The 2 kHz surveillance data channels are labelled

$$j-12, j-11 \dots, j-1, j, -j+1, \dots, j+22$$

with channel j lying between 121.0 and 123.0 kHz. When the receiver is tuned to a particular frequency e.g. 17.460 MHz, data relevant to that frequency and the next 20 kHz (in the present example 17.460 to 17.480 MHz) is processed. Due to the choice of local oscillators and preceeding up/down mixer conversions, the required surveillance information

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lies between 123.0 kHz and 103.0 kHz at I.F., and between 23.0 and 3.0 kHz at baseband following the final (100.0 kHz L.O.) mixer operation i.e. increasing frequency at h.f. or receiver input, corresponds to decreasing frequency at I.F. and baseband. Note that increasing channel number i.e.

j, j+1, j+2 etc.

corresponds to increasing frequency at the receiver input i.e.

17.460, 17.462, 17.464 MHz etc.

5.1.1 Requirements of the Low-Frequency (< 100 kHz) Portion of the I.F. Filter

The requirement of this portion of the filter is to suppress out-of-band signals which would otherwise appear at in-band frequencies following the 100 kHz final mixing operation e.g. a signal at 90 kHz (out-of-band) would appear at 10 kHz (in-band) following the final mixing operation. Consideration of figure 9 shows that, in general, channel $j+11+n$ will alias into channel $j+11-n$, the 10 relevant values of n (i.e. the 20 kHz passband) being 2 through 11.

5.1.2 Requirements of the High-Frequency (> 125 kHz) Portion of the I.F. Filter and of the Final Low Pass Filter

In this case the filters are required to suppress signals at frequencies > 25 kHz at baseband, which would otherwise be aliased into the signal path by the sampling process of the surveillance channel A/D converter, which has a sampling rate of 50.0 kHz. Again, consideration of figure 9 shows that, in general, channel $j-(n+1)$ will alias into channel $j+(n-2)$, the 10 relevant values of n being 2 through 11.

5.2 Analytical technique

A computer program was developed which evaluated the difference in level between each in-band channel which had been recorded and the 2 channels identified above as capable of contaminating the true surveillance spectral estimate by aliasing.

Two forms of analysis were undertaken. In the first instance, referred to as 'signal statistics' in the following sub-section, the analysis proceeded as described above. This case evaluates the filter requirements of unmodified surveillance spectra. An interesting alternative is to consider the requirements when the in-band signals are replaced by values derived from the background noise estimates i.e. the in-band signals are replaced by their clear channel equivalents, the out-of-band contaminants remaining untouched. The filters are now required to suppress the out-of-band signals to such an extent that in-band signals consisting exclusively of external noise estimates remain uncontaminated. This case clearly imposes more stringent filter requirements, and in the following sub-section is termed 'noise statistics'.

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The required filter attenuation is defined as the difference between the spectral estimates i.e. the unwanted out-of-band signal and the wanted in-band signal plus 10 dB in order that the allowed degree of contamination is 0.4 dB.

5.3 Results

5.3.1 Signal statistics

Cumulative distributions of the filter requirements are shown in figure 10 for the whip antenna and $+3^{\circ}$ beams for the September 1978 data, which is representative of similar data collected in other months. The Stage A surveillance receiver was characterised by filter rejection in excess of 70 dB and for the data shown this included 99.99% of data for the whip, and 99.99% of data for the $+3^{\circ}$ beam. As discussed in section 4.2, if it were not for temporal fluctuations in signal levels, no data could be recorded with the in-band and out-of-band signals differing by more than 70 dB. Accordingly, in the case of signal statistics in the region of 70 dB filter rejection, caution is required in the interpretation of the data. However, even if the data is not extended beyond a requirement for 60 dB of filter rejection, which is permissible if collected with a receiver characterised by 70 dB of filter rejection, 99.90% of cases are satisfied for the whip and 99.95% of cases for the $+3^{\circ}$ beam. Accordingly, the present filter rejection is deemed quite satisfactory for the signal statistics.

5.3.2 Noise statistics

Cumulative distributions of the noise statistics as defined in the previous sub-section are presented in figure 11 for the whip and $+3^{\circ}$ beam antennas, for the September 1978 data, which is typical of that recorded in other months. The effect of replacing in-band recorded signals by their clear channel equivalents is to demand more filter rejection at the same percentile values (compare figures 10 and 11).

In the case of the noise statistics, the mechanism for limiting the apparent required filter rejection to the filter rejection of the receiver used to perform the measurements does not exist, as it did with the signal statistics, and accordingly the data of figure 11 is capable of straightforward interpretation. It is apparent that even in this most demanding filter requirement (to the extent that the in-band signals have been artificially set to the minimum possible), 70 dB of filter rejection provides entirely satisfactory performance, being adequate to cope with 99.90% of data recorded on the whip and 99.90% of data recorded on the $+3^{\circ}$ beam. When the small number of instances demanding more than 70 dB filter rejection are identified as a function of frequency as shown in figures 12 and 13 the high dynamic range requirements imposed by the 9, 11, 15 and 17 MHz broadcast bands become apparent. If the data is

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analysed with the broadcast bands excluded, the results shown in figures 14 to 16 are obtained. The 70 dB filter rejection is then adequate for 99.96% of cases for the whip, and 99.98% of cases for the +3° beam.

With regard to the most demanding filter requirement encountered in the analysis of whip data, on day 133 at 0201Z, a signal was recorded on 15.411 MHz at a level of -68 dBW. The relevant background noise spectral density was -192 dBW Hz⁻¹ i.e. -159 dBW in the 2 kHz bandwidth relevant to the estimate of -68 dBW. Thus in order to prevent contamination of clear channels at 15.425 MHz and 15.395 MHz (see sections 5.1.1 and 5.1.2 and/or figure 9), beyond the specified 0.4 dB, the necessary filter rejection would be (-68 - (-159) + 10) dB = 101 dB.

In the case of the +3° beam, the most demanding filter requirement encountered was 100 dB.

6. FIRST I.F. IMAGE REJECTION

6.1 Theory

Consider the block diagram of the receiver shown in figure 1. Signals at the input of the second mixer which combine at its output to produce products in the range 103 to 123 kHz are thereafter within the receiver passband. Consequently, at the first I.F. it is necessary to pass the in-band signals (40.103 to 40.123 MHz) and reject the image signals 40 MHz - 103 kHz (39.897 MHz) to 40 MHz - 123 kHz (39.877 MHz) to prevent contamination of in-band signals.

The relationship between signals at the first I.F. and the receiver input is given by

$$f_{IF} = f_{LO} - f_{HF} \quad \text{where } f_{IF} = \text{IF frequency (MHz)}$$

$$f_{LO} = \text{first local oscillator frequency (MHz)}$$

$$f_{HF} = \text{receiver input frequency (MHz)}$$

And at the first I.F. the image frequency is given by

$$f_{IF}' = 40 - (f_{IF} - 40)$$

$$f_{IF}' = 80 - f_{IF}$$

Hence at the input to the receiver the image frequency is given by

$$f_{HF}' = f_{LO} - (80 - f_{IF}')$$

$$f_{HF}' = 2 f_{LO} - 80 - f_{HF} \tag{1}$$

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6.2 Results

Using the formula (1) for the image frequency, statistics of the difference between the in-band signal and image signal were accumulated so that the required image rejection could be determined. Throughout this analysis the required image rejection was defined as the difference (in dB) at the receiver input between the wanted signal and the image signal where the image signal alters wanted signal by 0.4 dB at the receiver output. To meet this criterion 10 dB was added to the difference between the image signal and in-band signal. Results of this analysis for both the whip and +3° beam are shown in figure 17 and this is representative of all data analysed.

Since all image data values are also used as in-band data values in the analysis we would expect that half the total sample should return a negative signal difference and hence the 10 dB image rejection point (zero signal difference) should correspond to 50% of the total sample. It can be seen from a comparison of figure 17 and 18 that the inclusion or exclusion of the large signals which exist in the 9, 11, 15 and 17 MHz broadcast bands makes only a small difference to the tail of the cumulative distributions.

This method of analysis is not valid when the image rejection of the receiver determines the maximum signal difference possible. For the actual receiver image rejection of 60 dB, the statistical analysis revealed that 99.89% of all measured data was corrupted by less than 0.4 dB for the whip and 99.91% of the +3 degree beam data was corrupted by less than 0.4 dB.

Histograms of image signals which do demand an image rejection $> = 60$ dB are shown in figures 19 and 20 for the whip and +3 degree beams respectively. For the same data, but with the broadcast bands omitted, the histograms shown in figures 21 and 22 are the result. Comparison of the corresponding histograms for the whip and +3 degree beam show that greater than half of the troublesome signals lie within the broadcast bands. This result is typical for all data analysed.

A worst case indication of the image rejection, independent of the actual receiver image rejection, can be obtained by considering the case where the in-band signal is replaced by its clear channel or background noise value. Figure 23 is a cumulative distribution of the difference between signals and the background noise values. The background noise estimates are computed for each 500 kHz segment and vary by a small amount across adjacent segments. Since the image frequencies are always between 206 to 246 kHz greater than the receiver tuned frequencies this form of analysis can be used to determine the worst case image rejection requirements.

Figure 23 shows that the majority of signal differences are less than 50 dB. In fact, 99.6% of all comparisons on the whip data and 99.8% of all comparisons on the +3 degree beam, reveal a signal difference of less than 50 dB (the value corresponding to 0.4 dB contamination of background noise data as a result of a receiver image rejection of 60 dB).

For all data analysed in this way the largest signal difference on the whip occurred on day 133 of 1978 at 2:01Z and was 91 dB. This condition occurred because of a -68 dBW/2 kHz signal at 15.411 MHz and a background noise of -159 dBW/2 kHz. For the +3 degree beam the largest signal difference of 90 dB occurred on day 42 of 1978 at 17.18Z as a result of a -50 dBW/2 kHz signal at 15.311 MHz and a

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background noise estimate of -140 dBW/2 kHz. Hence the largest signal difference would have required an image rejection of 101 dB.

7. OUT-OF-BAND INTERMODULATION DISTORTION

7.1 Theory

Given two signals at frequencies f_1 and f_2 , the receiver will produce second-order intermodulation distortion (IMD) products at frequencies $f_I = 2f_1, 2f_2$ and $f_1 \pm f_2$, and third-order IMD products at frequencies $f_I = 3f_1, 3f_2, 2f_1 \pm f_2, 2f_2 \pm f_1$. The level of these spurious responses is dependent on the level of the signals at the input to the receiver and on the IMD performance, as measured by the second- and third-order intercepts, of the receiver. If the IMD performance of the receiver is inadequate spurious signals will be observed when the receiver is tuned to the distortion product frequencies. The Stage A surveillance data has been used to determine the values of the second- and third-order intercepts which would be required to ensure that the receiver was entirely free of spurious signals generated by IMD. In this study the receiver was deemed to be free of IMD if all products were 10 dB below the background noise level.

The relationship between the power levels of signals at the input to the receiver, the second- and third-order intercepts, and the power level of the IMD products has been discussed in reference 4. The relations presented in that report can be inverted to obtain the values of the second- and third-order intercepts which would be required to keep all IMD products 10 dB below the background noise level. We define the power levels of two signals f_1 and f_2 as P_1 and P_2 (dBW), the background noise as N_I (dBW), the power level of the IMD product as P_I (dBW), and the second- and third-order intercepts as I_2 and I_3 (dBm) where all are measured relative to the input of the receiver. The second harmonic will be 10 dB below the background noise if the second-order intercept of the receiver is

$$I_2 = 2P_1 + 34 - N_I \quad (2)$$

The other second-order products ($f_I = f_1 \pm f_2$) will be 10 dB below the background noise level if

$$I_2 = P_1 + P_2 + 40 - N_I \quad (3)$$

Similarly, the third harmonic will be 10 dB below the background noise level if the third-order intercept is

$$I_3 = 1.5 P_1 + 30 - 0.5 N_I \quad (4)$$

and the other third-order products ($f_I = 2f_1 \pm f_2$) will require an intercept

$$I_3 = P_1 + 0.5 P_2 + 35 - 0.5 N_I \quad (5)$$

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The surveillance data for one 24 hour period within each month was analysed and a table of all signals above -100 dBW/2 kHz was assembled for each scan of the HF spectrum between 6 and 30 MHz. The values of I_2 and I_3 defined by the above relations were then calculated, using the above relationships, for those IMD products which occurred between 6 and 30 MHz. A table of the maximum values of I_2 and I_3 required to keep each of the 12000 2 kHz channels free of IMD was compiled for the 24 hour period and a cumulative histogram produced for each month.

The level of -100 dBm/2 kHz was chosen to restrict the computation time required since signals weaker than this would require intercepts $I_2 < 0$ dBm and $I_3 < -20$ dBm, values which were well below the performance of the Stage A surveillance receiver. Although it was known that the surveillance data was contaminated by IMD responses the technique used to measure the background noise levels ensures that the levels on the whip antenna were unaffected. However, the levels of IMD products on the directional antenna were so large that the background noise estimate was unreliable between 2100-0700 L.T. During this time period the whip data was used to supply background noise estimates, resulting in an error in the noise estimates of less than 3 dB for the directional antenna.

7.2 Results - Second-Order IMD

Figure 24 shows the percentage of the 12000 2 kHz channels between 6 and 30 MHz which would be unaffected by IMD products over a 24-hour period for a given second-order intercept I_2 (dBm) measured relative to the receiver input. There was usually no insignificant variation between the curves for two days within the same month but there was a small amount of variation from month to month. The two curves in figure 24 represent the two most extreme cases measured over the twelve month period. The remaining months lay between these two curves, with the majority being closer to the distribution measured on 30 October.

The whip antenna was connected directly to the surveillance receiver whereas the directional radar $+3$ degree beam was connected via a pre-amplifier. The signal levels at the input to the receiver were larger in the latter case and consequently a higher IMD performance is required of a receiver connected to the directional antenna. Since the surveillance receiver possessed a second-order intercept of $+25$ dBm it can be seen that when connected to the whip antenna approximately 50% of the 12000 2 kHz channels were at least 10 dB below the background noise level at all times over a 24 hour period. When the surveillance receiver was connected to the $+3$ degree beam approximately 30% of the 2 kHz estimates were not affected by IMD products at some stage during the 24 hour period.

Figures 25 to 28 provide a histogram of the large signals which gave rise to IMD products which were greater than 10 dB below the background noise level in the Stage A surveillance receiver. Comparison of figures 27 and 28 reveals that the reason for the month to month variations is a variation in the number of large signals present. As could be expected the majority of large signals occur in the broadcast bands. The distribution of signals does spread beyond the broadcast band but this was due to signals outside of the broadcast band with levels -90 to -100 dBW combining with broadcast band signals with levels of -55 to -70 dBW.

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There is a limit to the degree of improvement that can be economically achieved in the IMD performance of a receiver and the values required to completely free the receiver of second-order IMD products exceeds that which can be readily achieved. The second-order, and some third-order, effects can be reduced by the addition of bandpass filters in front of the receiver in order to attenuate out-of-band signals prior to any active stages in the receiver. Since it was known that the Stage A surveillance data measured on the +3 degree beam was corrupted by IMD effects a series of filters were installed. Figure 29 shows the frequency variation in the lower decile of the 250 2 kHz estimates over each 0.5 MHz as a function of local time for October 1977. The effect of the IMD during the period 2100-0700 L.T. is to artificially raise the noise level over extensive portions of the spectrum. Figure 30 shows the frequency variation during October 1978 when data above 18 MHz were recorded with an 18 MHz high pass filter inserted in front of the receiver, thus attenuating the 7, 9, 11 and 15 MHz broadcast bands. The spurious IMD products are no longer present and the noise levels from 20 to 30 MHz are equal to the internal noise level, since the system was known to be internally noise limited above 20 MHz.

7.3 Results - Third-Order IMD

Figure 31 shows percentage of 2 kHz channels between 6 and 30 MHz which would be unaffected by third-order IMD products as a function of the third-order intercept of the receiver. Since the Stage A surveillance receiver possessed a third order intercept of -5 dBm it can be seen that approximately 90% of the 2 measurements made on the whip were never contaminated by third-order IMD products over a 24 hour period whereas only between 15 to 30% of the measurements made on the +3 degree beam were never contaminated at some time or other over a 24 hour period.

Figures 32 to 35 show the distribution of the large signals giving rise to third-order IMD effects within the Stage A surveillance receiver. Again it is clear that the majority of third-order IMD products arise because of the large signals in the broadcast band. Although it is possible to combat the third-order sum products ($f_I = 2f_1 + f_2$) with the use of filters in front of the receiver many of the difference products ($f_I = 2f_1 - f_2$) will lie close to the frequencies of interest and cannot be filtered out.

8. IN-BAND INTERMODULATION DISTORTION

8.1 Theory

Another form of IMD occurs when two large signals appear within the passband of the receiver in which case IMD products may occur which also lie within the passband of the receiver. Second-order in-band IMD products are dependent on the distribution of gain throughout the receiver and were not amenable to the type of analysis presented here and consequently have not been considered. The major source of third-order in-band IMD terms arises from the difference products of two large signals within the passband. The Stage A surveillance data has been examined to determine the value of the in-band third-order

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intercept which is required to ensure that the receiver was free of such effects in that all in-band third-order products were 10 dB below the background noise level.

Analysis of the surveillance data was similar to the technique adopted for the out-of-band IMD analysis. Each scan of the spectrum was examined in 20 kHz steps, finding the value of the third-order intercept (using equation 5) required to keep in-band IMD products 10 dB below the background noise level. A lower threshold of -120 dBW/2 kHz was placed on the level of signals included in this analysis, limiting the analysis to values $I_3 > -50$ dBm.

8.2 Results

Figure 36 shows the percentage of 2 kHz channels between 6 and 30 MHz which would be corrupted by third-order in-band IMD effects for a given value of the third-order intercept. Analysis has revealed that there is very little difference from one month to the next, unlike the out-of-band IMD performance. This result occurs because of the distribution of large signals across the broadcast bands. Figures 37 and 38 reveal that the majority of signals causing in-band IMD are located in the broadcast bands. Consequently if one were to operate the receiver in sections of the spectrum other than the broadcast bands, then the receiver would be almost completely free of in-band IMD effects.

The performance demanded by figure 36 can be compared with the actual performance of the Stage A surveillance receiver. However, the third-order in-band intercept of the surveillance receiver was dependent on the input level of the large signals as given in Table I. This result suggests that the in-band IMD performance of the surveillance receiver was not adequately described by a third-order polynomial with constant coefficients as was assumed in the derivation of equation 5. The analysis of the surveillance data would suggest that the in-band IMD performance of the receiver was entirely adequate in all regions of the spectrum except the broadcast bands.

Level of two Tones at Input dBm	Typical 3rd Order Distortion Level dBm	Computed 3rd Order Intercept dBm
-40	-87	-17
-52	-100	-28
-61	-114	-35

TABLE I SURVEILLANCE RECEIVER IN-BAND THIRD ORDER DISTORTION PERFORMANCE

9. RECIPROCAL MIXING

9.1 Theory

A large signal entering the receiver at a frequency not far removed from the signal being measured can combine with the noise spectrum accompanying the first local oscillator and produce noise at the

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receiver I.F. frequency. This interference is referred to as reciprocal mixing. Figure 39 diagrammatically illustrates the effect. A detailed description of reciprocal mixing can be found in References 5 and 6.

9.2 Results

Since figure 23 is a cumulative distribution of the difference between any signal and the background noise estimate for that band, then this data may be used to determine the required reciprocal mixing performance. This approach can be considered a worst case situation since the actual environment does not always have adjacent estimates at the background signal level. On the other hand, however, it does not take into account the integration of local oscillator noise where more than one large signal is close to the channel being measured. The results below will show that reciprocal mixing was not a significant problem in the surveillance receiver.

By adding an additional 10 dB to the (signal-background noise) axis, the cumulative distributions plot shown in figure 23 becomes the required worst case reciprocal mixing performance for a single adjacent signal. Comparison of figures 23 and 40 shows that only the tail of the cumulative distribution is effected by the inclusion or exclusion of the large signal broadcast bands.

The largest difference recorded on the whip occurred on day 133 of 1978 and was 91 dB. The signal was -68 dBW/2 kHz at 15.411 MHz and the background noise -159 dBW/2 kHz. For the +3 degree data the largest difference was 90 dB on day 42 of 1978 with a signal of -50 dBW/2 kHz at 15.311 MHz and a background estimate of -140 dBW/2 kHz.

The Stage A surveillance receiver performance was such that an interferer 2 kHz away had to be greater than 78 dB above the level of the required signal before the low level estimate would be altered by more than 0.4 dB.

Analysis has shown that 99.998% of the whip data is uncontaminated by reciprocal mixing products and the figure for the +3° beam is 99.999%.

In summary it can be stated that the threshold level for an adjacent interferer of 78 dB above the background noise has been exceeded, in Stage A, only an average of 0.2 times per sweep across the HF spectrum. The integration of reciprocal mixing noise can be safely considered to have presented no problem.

10. RECEIVER GAIN VARIATION

10.1 Background

Following each surveillance sweep of the h.f. spectrum, the receiver was tuned to 18 MHz and the input connected to a broadband reference noise source. The processed output was then used to calibrate the input surveillance data and it was also recorded on magnetic tape as ten floating point numbers corresponding to the 10 averaged 2 kHz spectral estimates across the receiver passband.

10.2 Results

One of the ten estimates recorded was used to accumulate the histograms shown in figures 41 and 42. These figures cover four

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complete months of data and are representative of the data collection period. The results show that the typical average gain variation from month to month was less than 0.1 dB and the statistical spread of the data was consistent.

11. CONCLUSION

An analysis, largely of the adequacy of the dynamic range of various portions of the spectral surveillance receiver used to acquire Stage A data, has been completed. The extent and mechanism of the contamination of data by lack of dynamic range has been presented throughout the report. The surveillance receiving system has been shown to be entirely adequate in respect of the A/D converter resolution, selectivity, first I.F. image rejection and reciprocal mixing and of reasonable IMD performance on the whip. The IMD performance was lacking on the +3 degree beam until the installation of filters at the front of the receiver.

The data base will enable the Stage B surveillance receiver design to be undertaken with a great deal of confidence with regard to necessary design objectives.

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REFERENCES

No.	Author	Title
1	Earl, G.F., Garrett, R.E.	"Project Jindalee: Frequency Management System for Stage A" (in preparation).
2	Ward, B.D.	"Project Jindalee: HF Environment at Alice Springs during Stage A operations" ERL-B134-TR (Restricted)
3	Earl, G.F.	"Consideration of Receiver Gain and Analogue to Digital Converter Resolution in OTH Radar Systems" ERL-B133-TR (Restricted)
4	Ward, B.D.	"Project Jindalee: Assessment of Receiver Intermodulation Distortion Effects in Stages A and B" ERL-TR-B116 (Restricted)
5	Stone, K.	"Local Oscillators and Electromagnetic Compatibility", pp 205-210 Proc. IREE, July, 1975
6		Various papers in the IERE Conference Proceedings No. 24 "Radio Receivers and Associated Systems" Held at the University of Swansea, July, 1972

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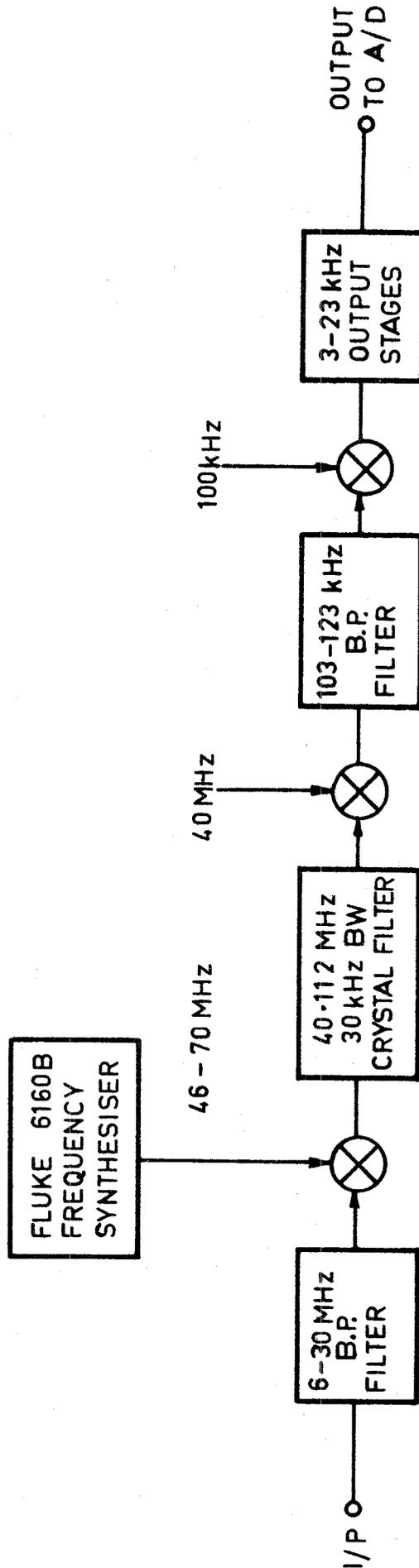


Figure 1. Surveillance receiver block diagram

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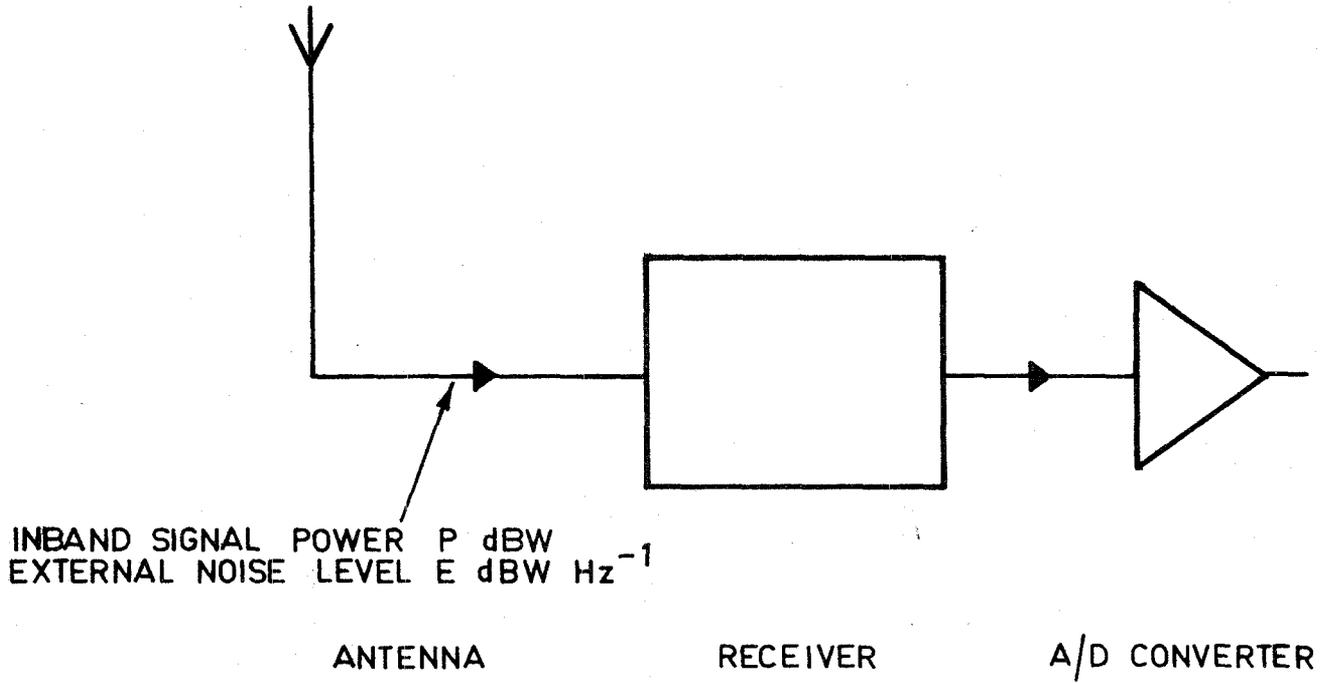


Figure 2. Surveillance receiving system

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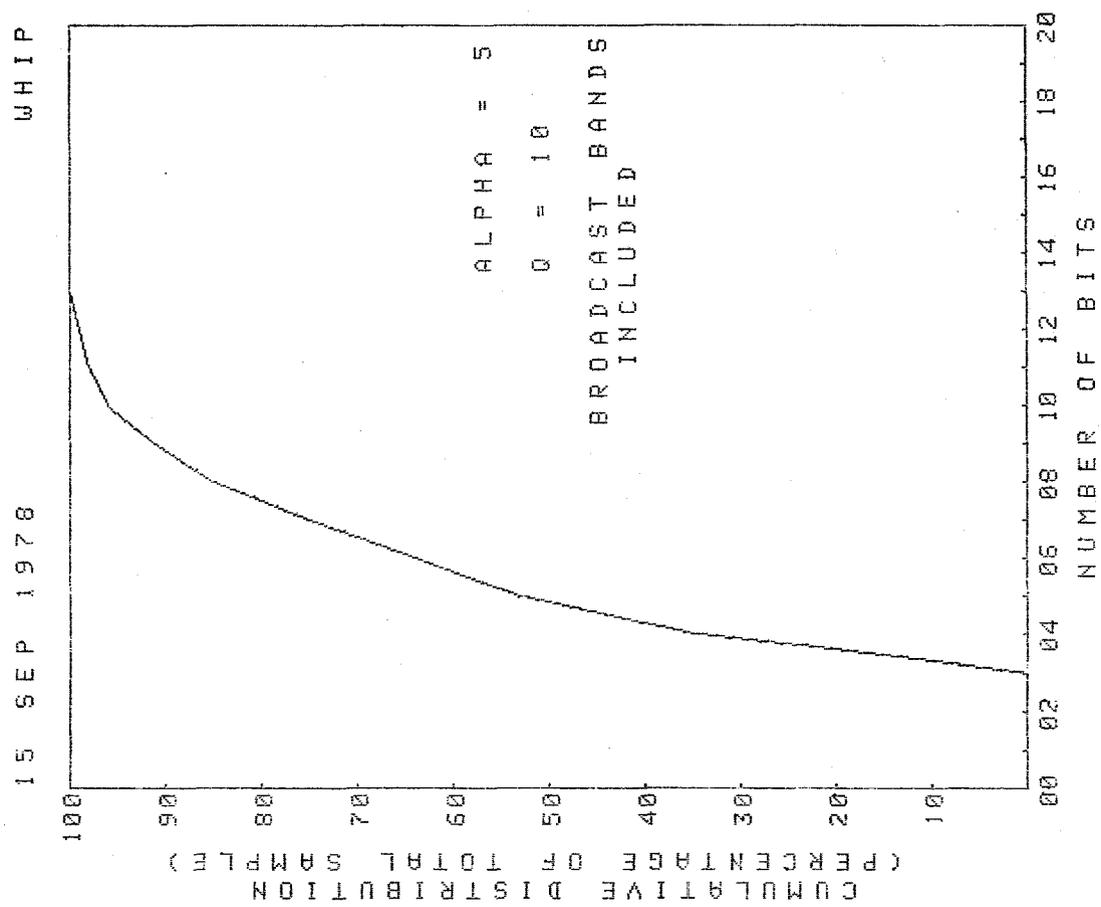
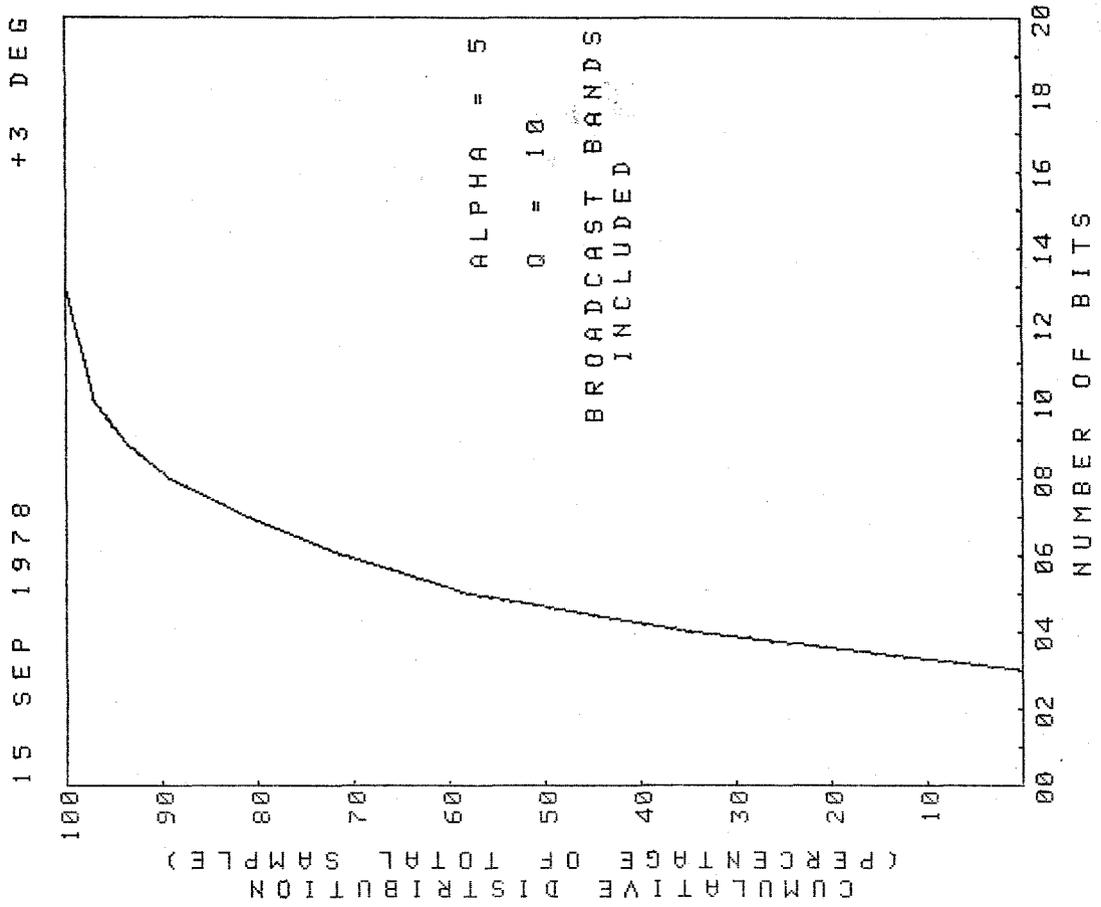


Figure 3. Surveillance data A/D resolution statistics (broadcast bands included)

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15 SEP 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.36E+05
BROADCAST BANDS INCLUDED

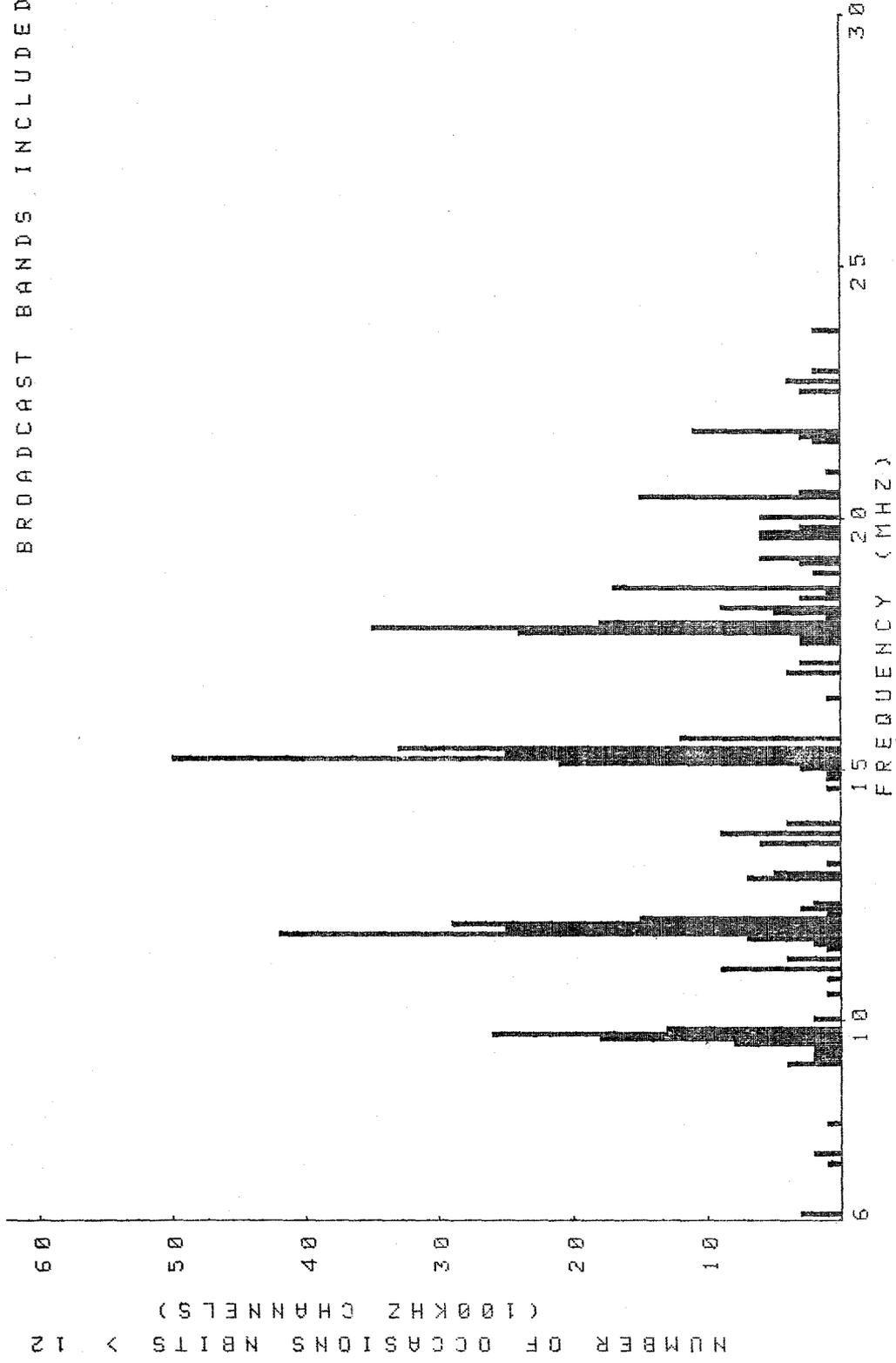


Figure 4. Histogram of channels requiring > 12 A/D converter bits (broadcast bands included)

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15 SEP 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.36E+05
BROADCAST BANDS INCLUDED

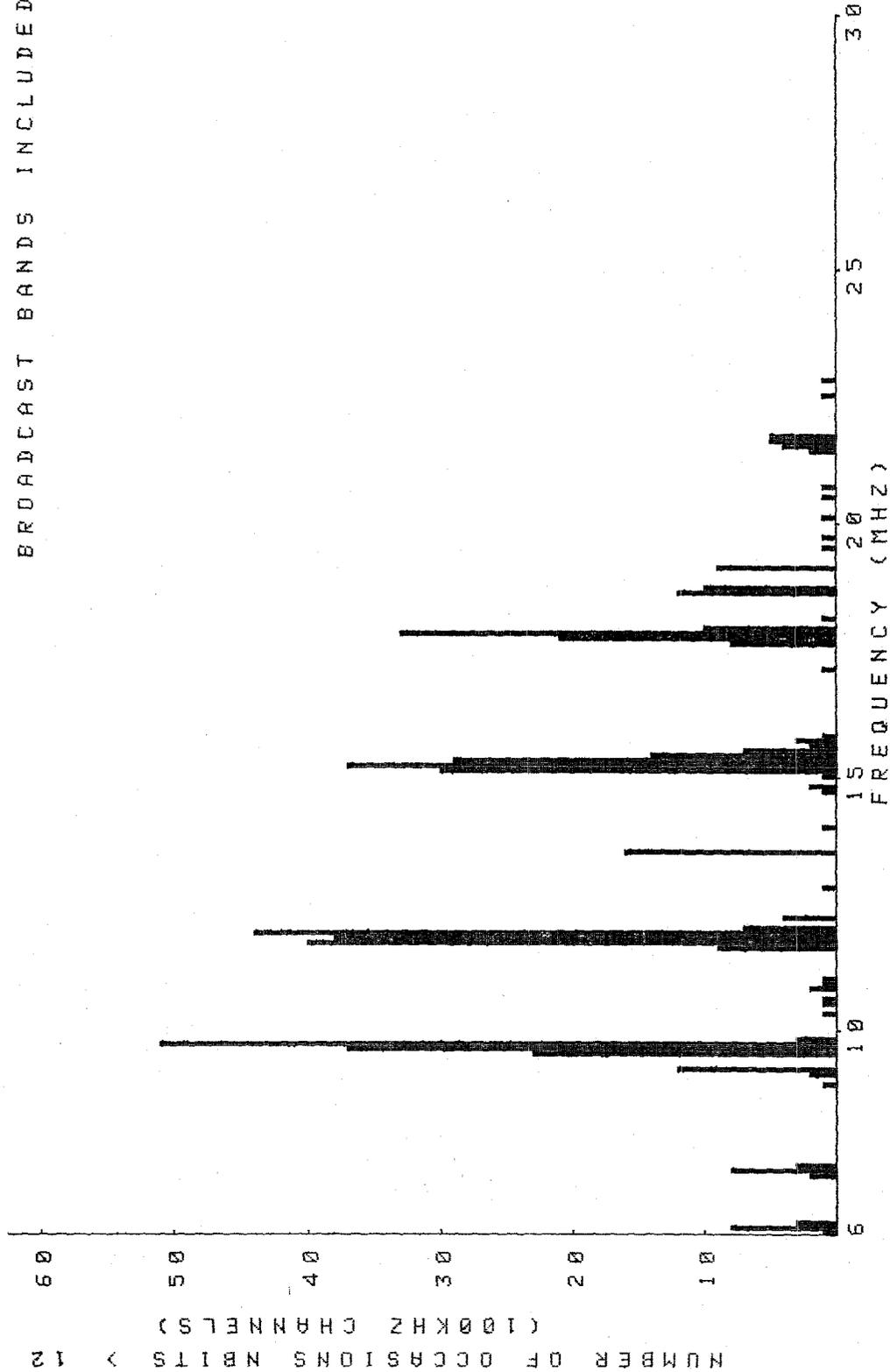


Figure 5. Histogram of channels requiring > 12 A/D converter bits (broadcast bands included)

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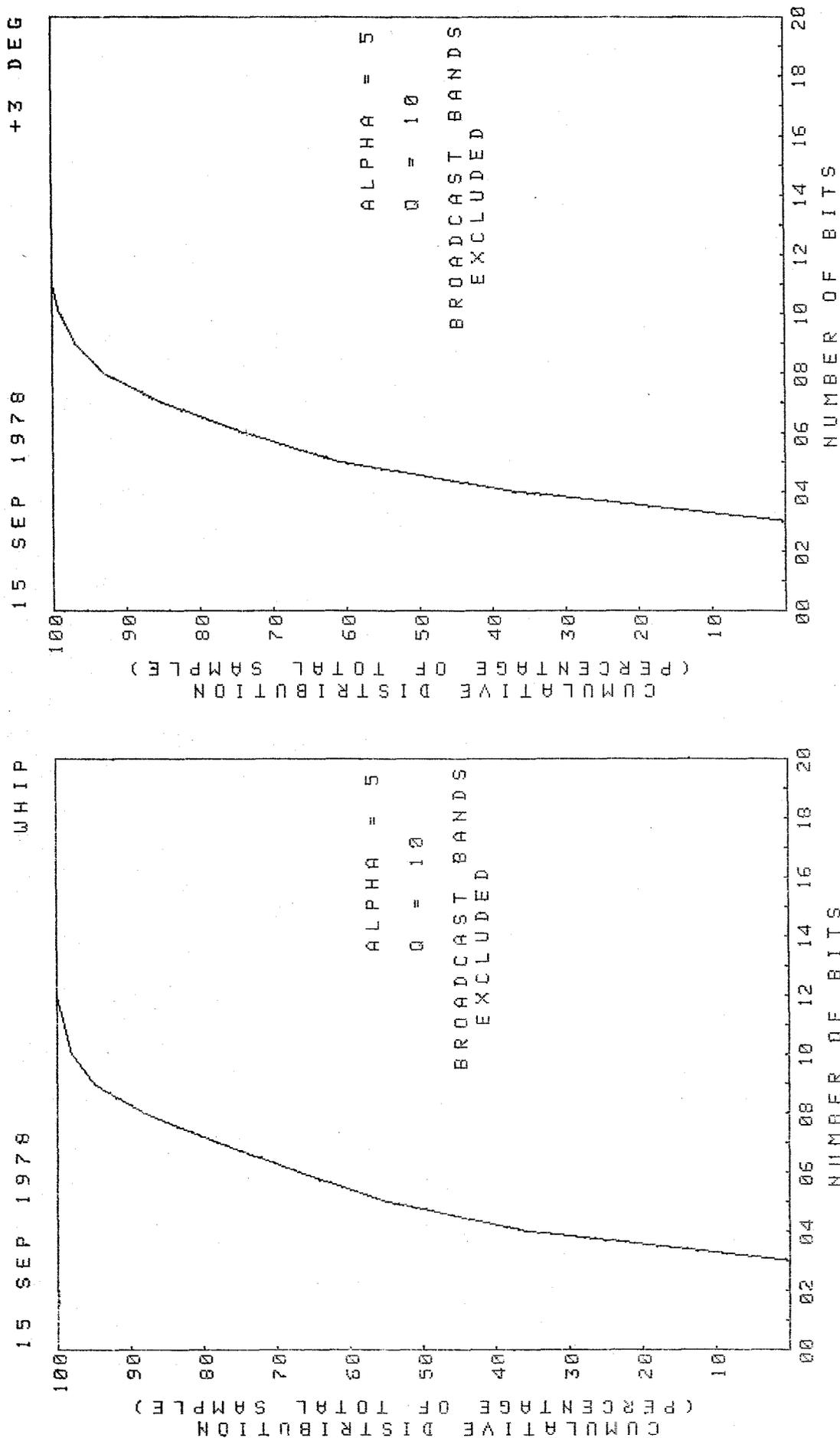


Figure 6. Surveillance data A/D resolution statistics (broadcast bands excluded)

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15 SEP 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.32E+05
BROADCAST BANDS EXCLUDED

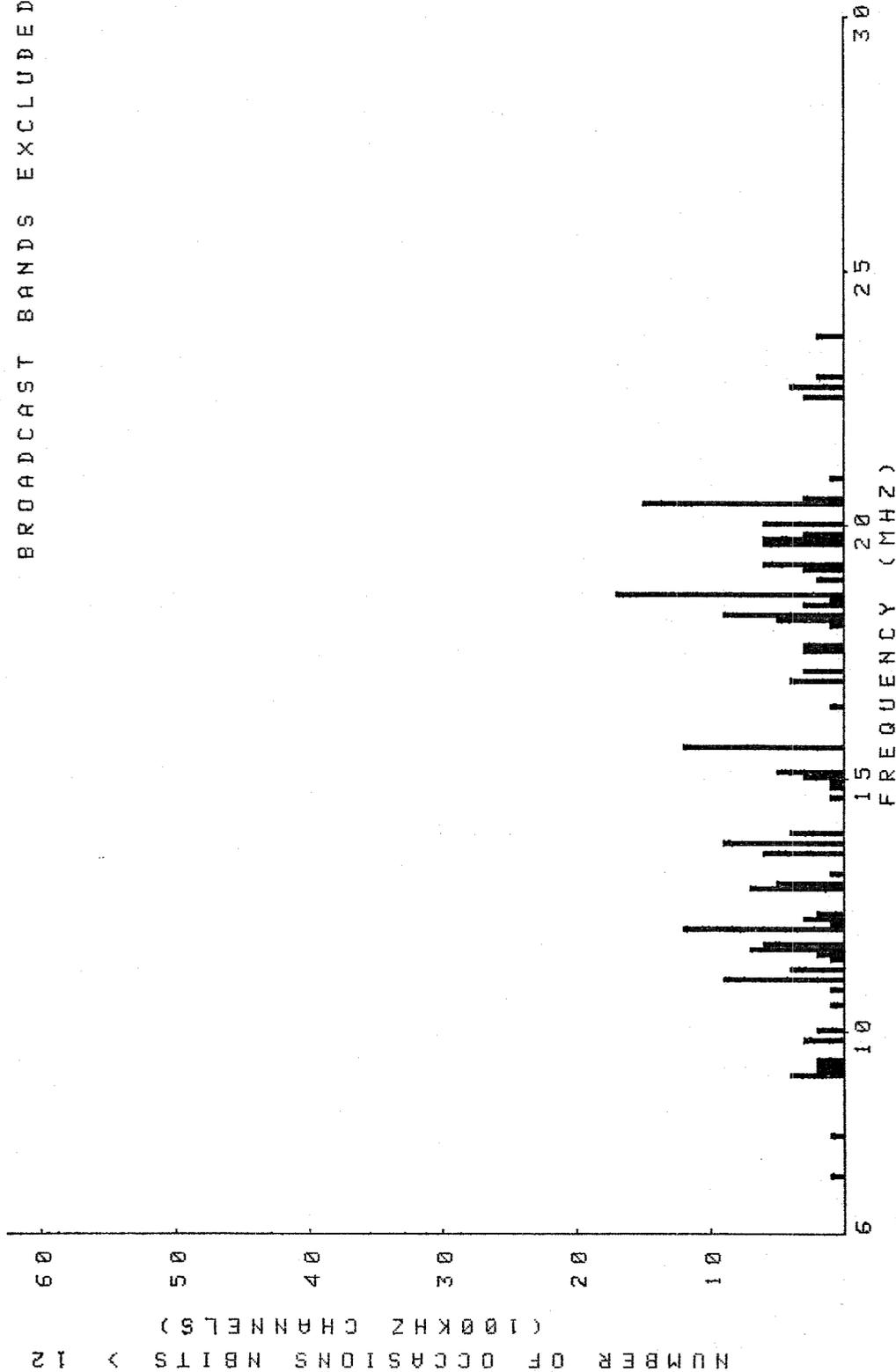


Figure 7. Histogram of channels requiring > 12 A/D converter bits (broadcast bands excluded)

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15 SEP 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.32E+05
BROADCAST BANDS EXCLUDED

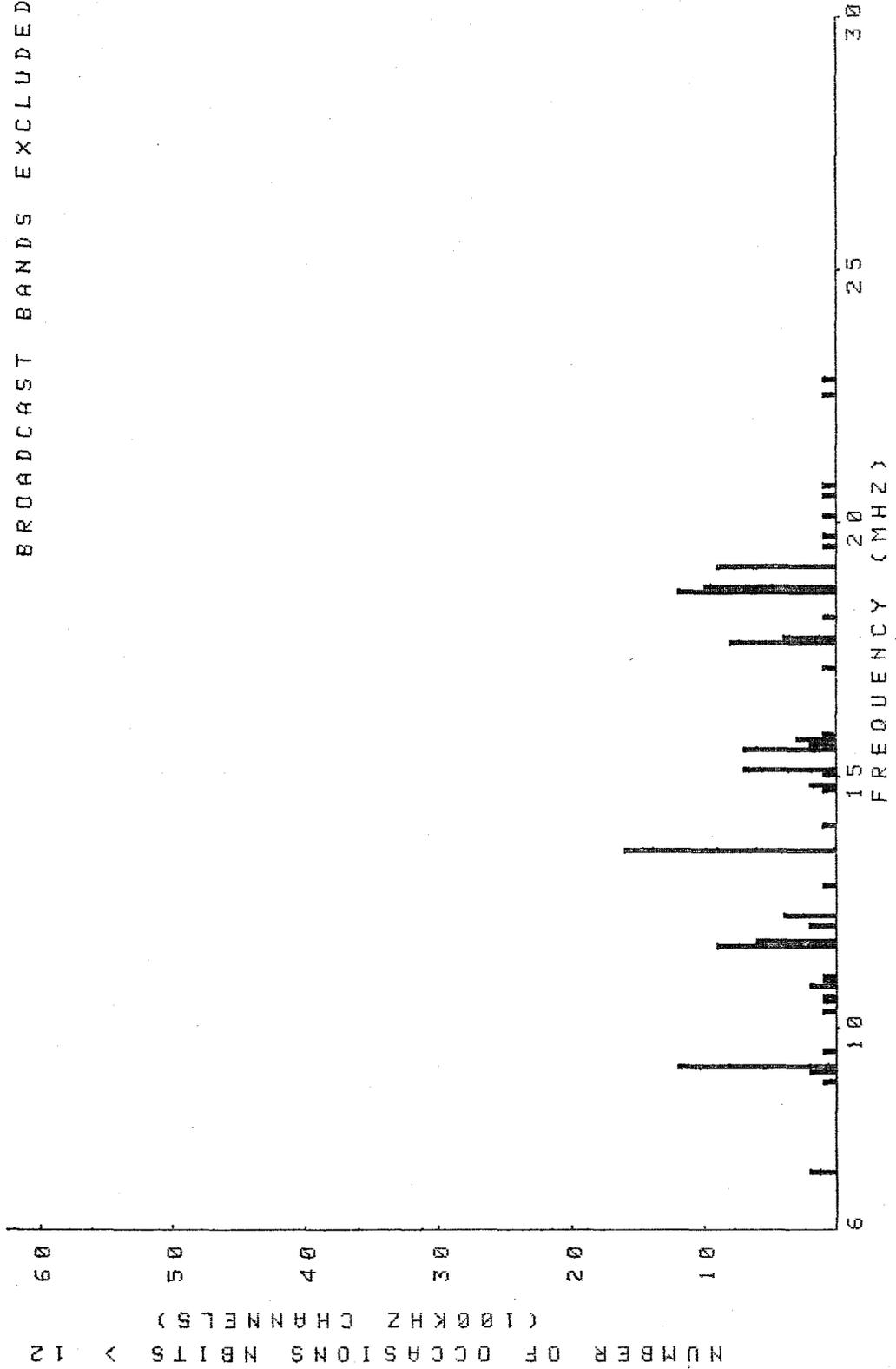


Figure 8. Histogram of channels requiring > 12 A/D converter bits (broadcast bands excluded)

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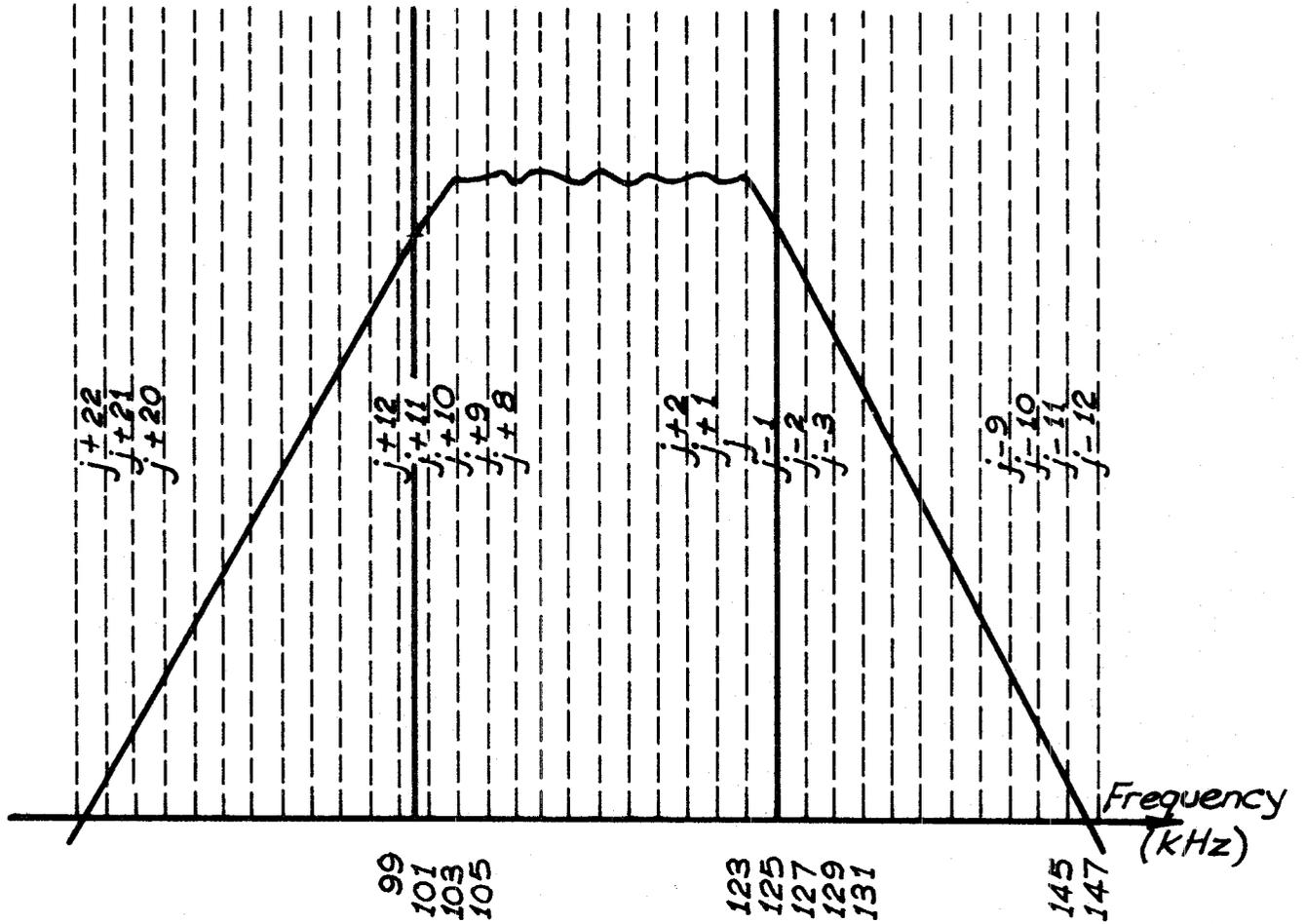


Figure 9. Receiver I.F. filter characteristic

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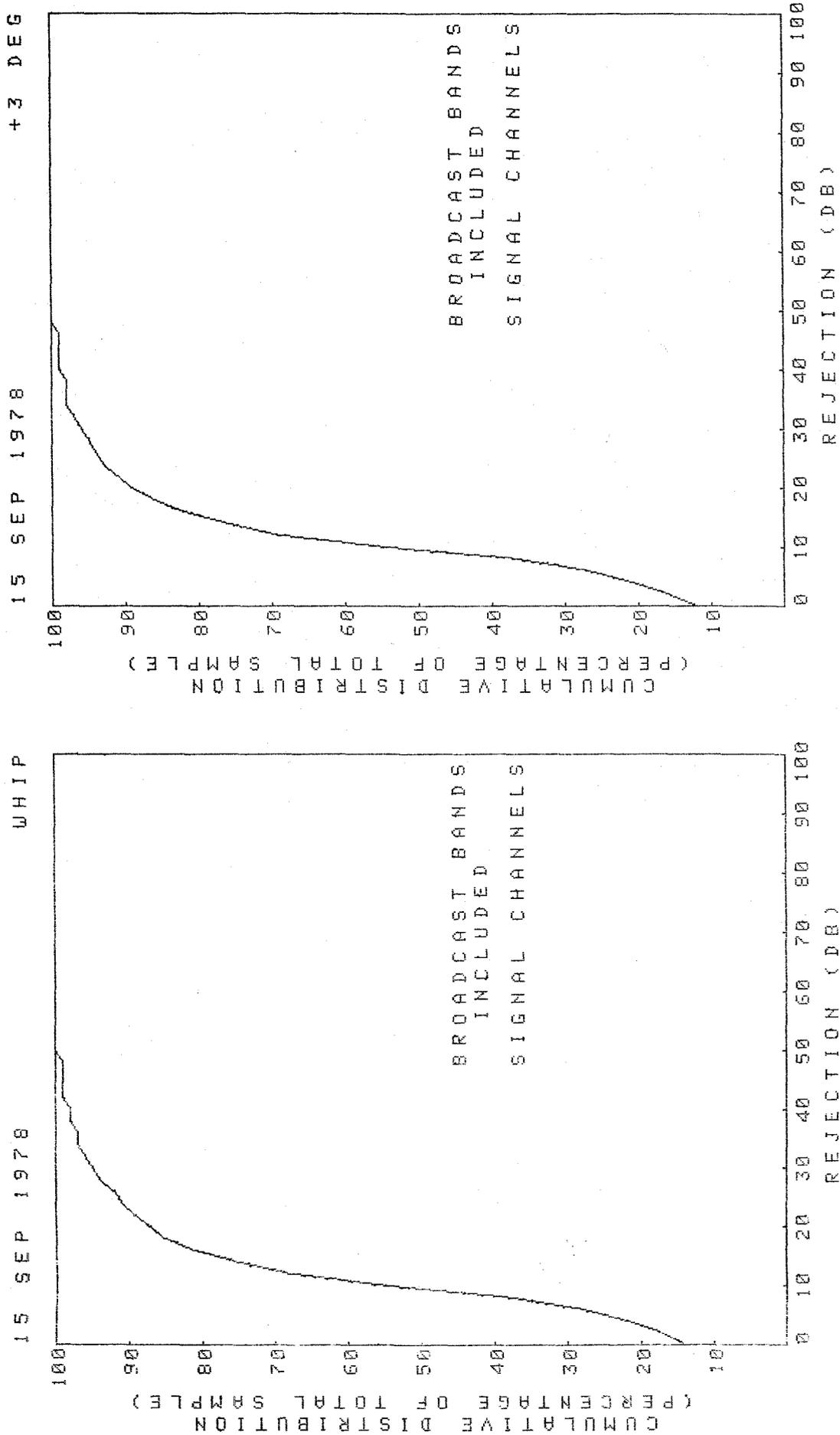


Figure 10. Surveillance data filter rejection (broadcast bands included)

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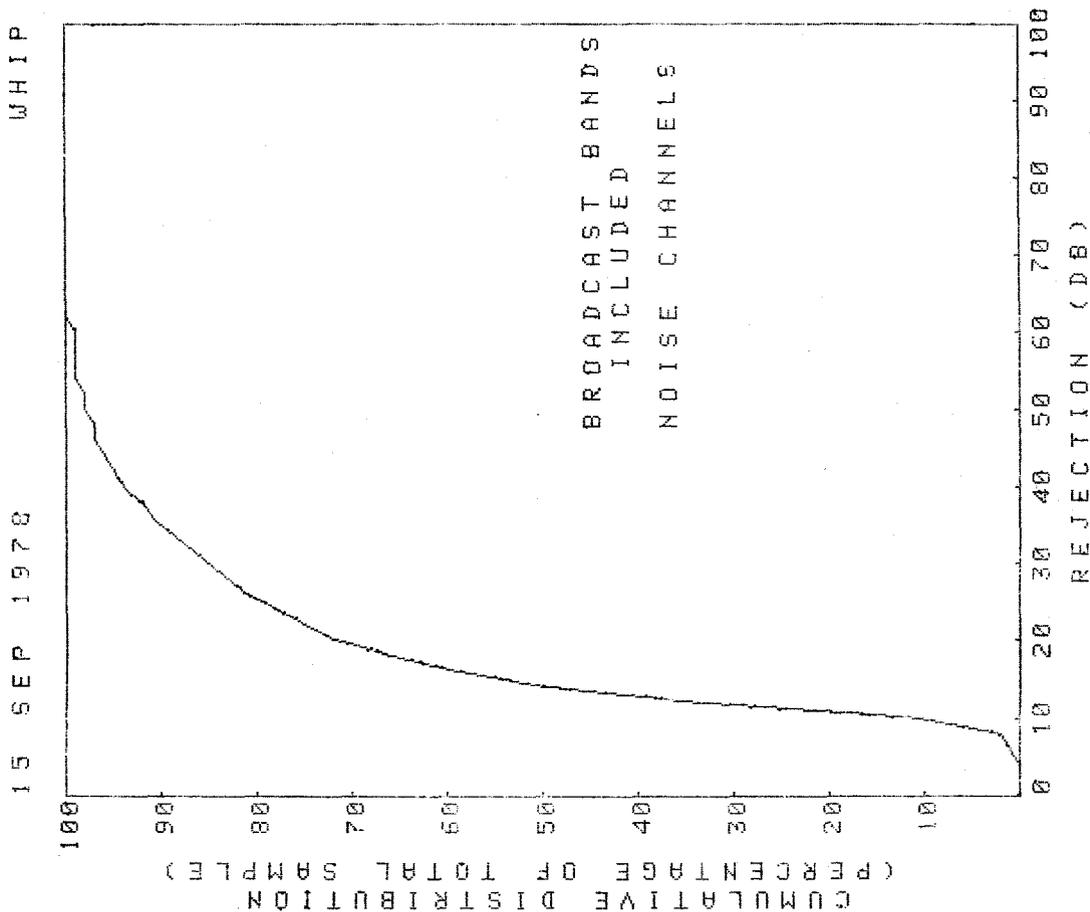
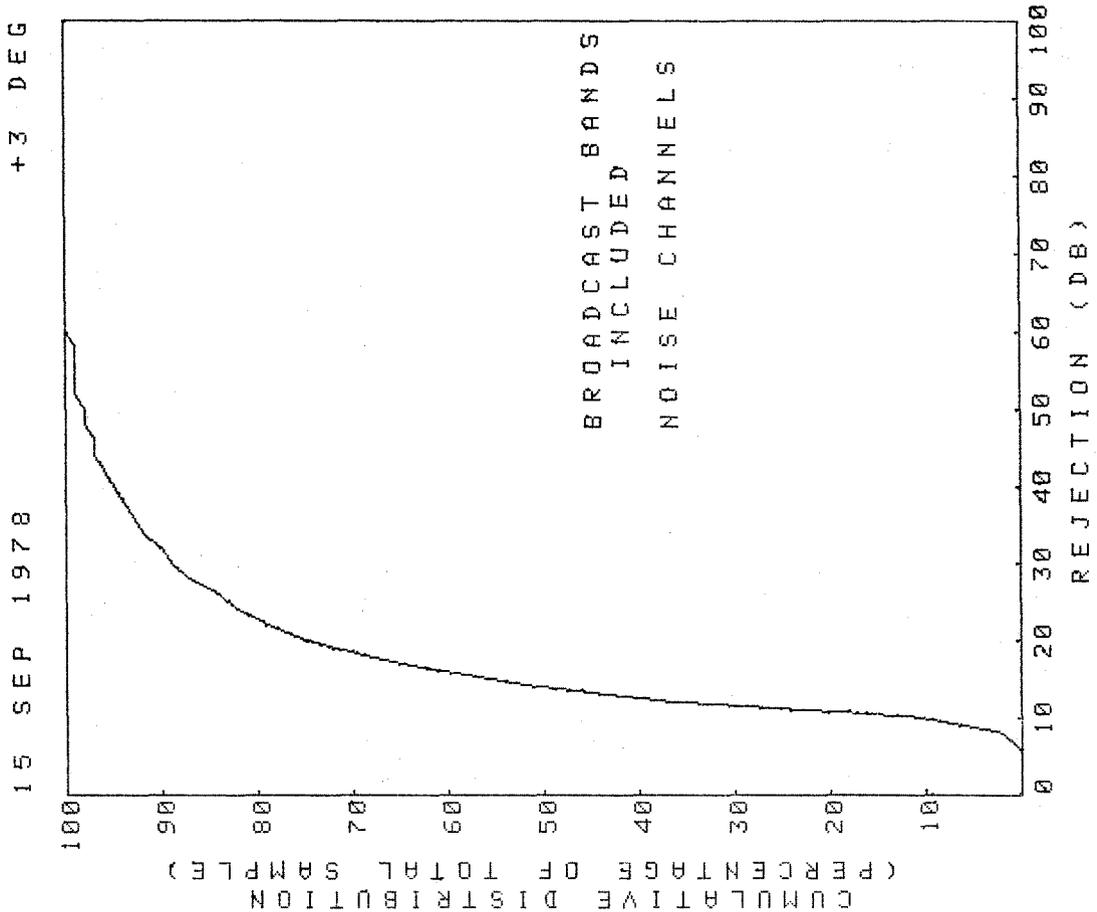


Figure 11. Surveillance data filter rejection (broadcast bands included)

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15 SEP 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.71E+06
BROADCAST BANDS INCLUDED
NOISE CHANNELS

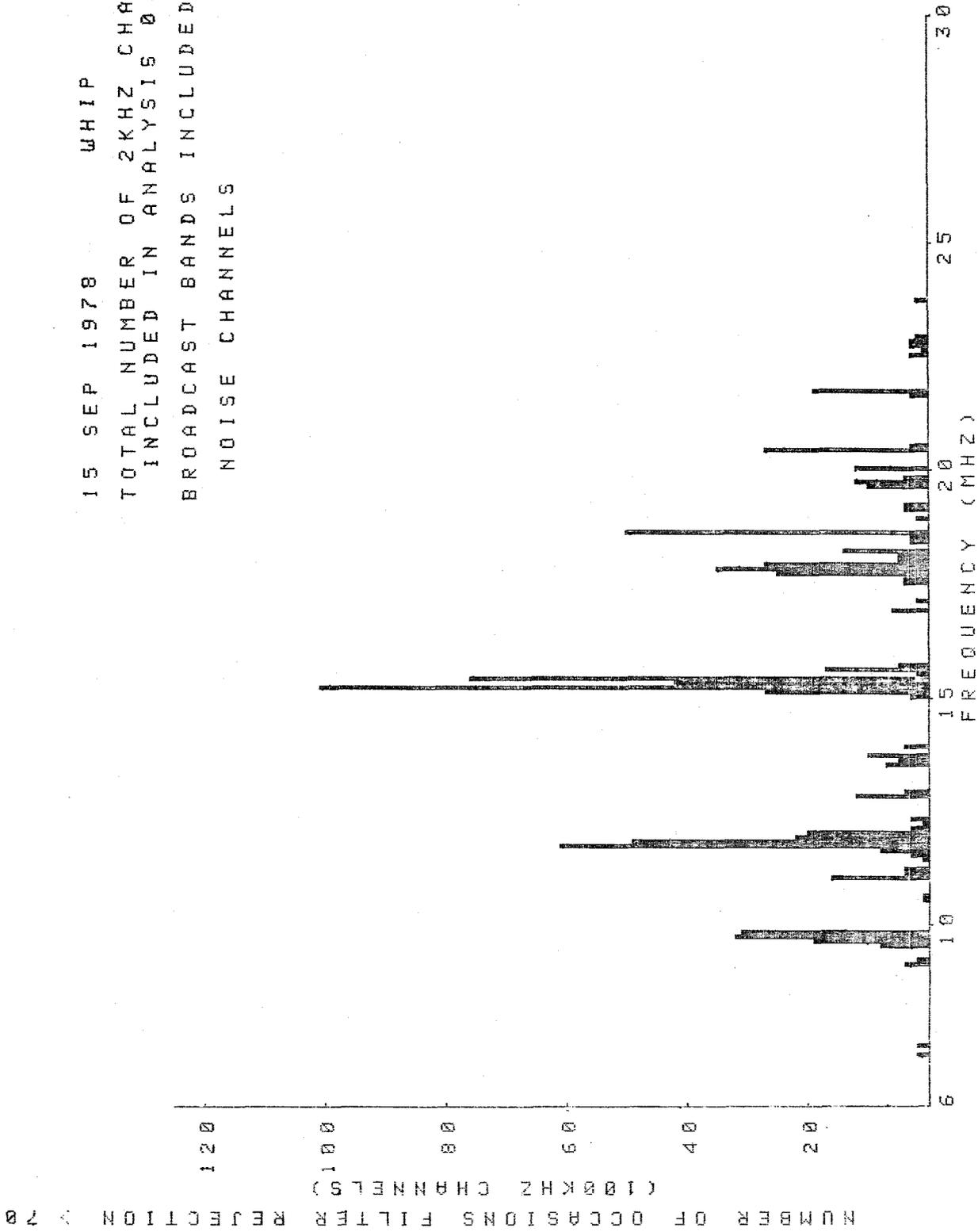


Figure 12. Histogram of channels requiring > 70 dB filter rejection (broadcast bands included)

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15 SEP 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.71E+06
BROADCAST BANDS INCLUDED
NOISE CHANNELS

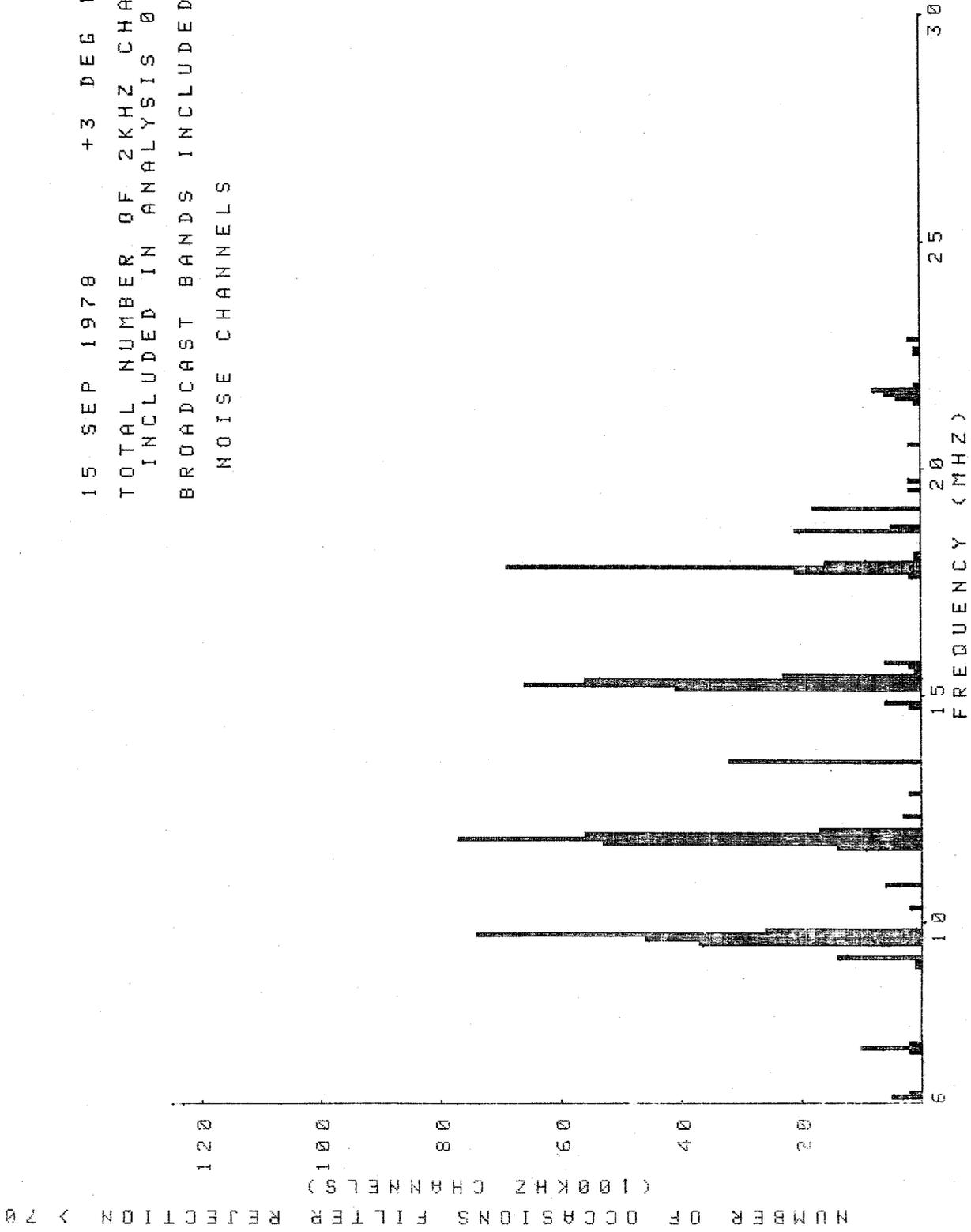


Figure 13. Histogram of channels requiring > 70 dB filter rejection (broadcast bands included)

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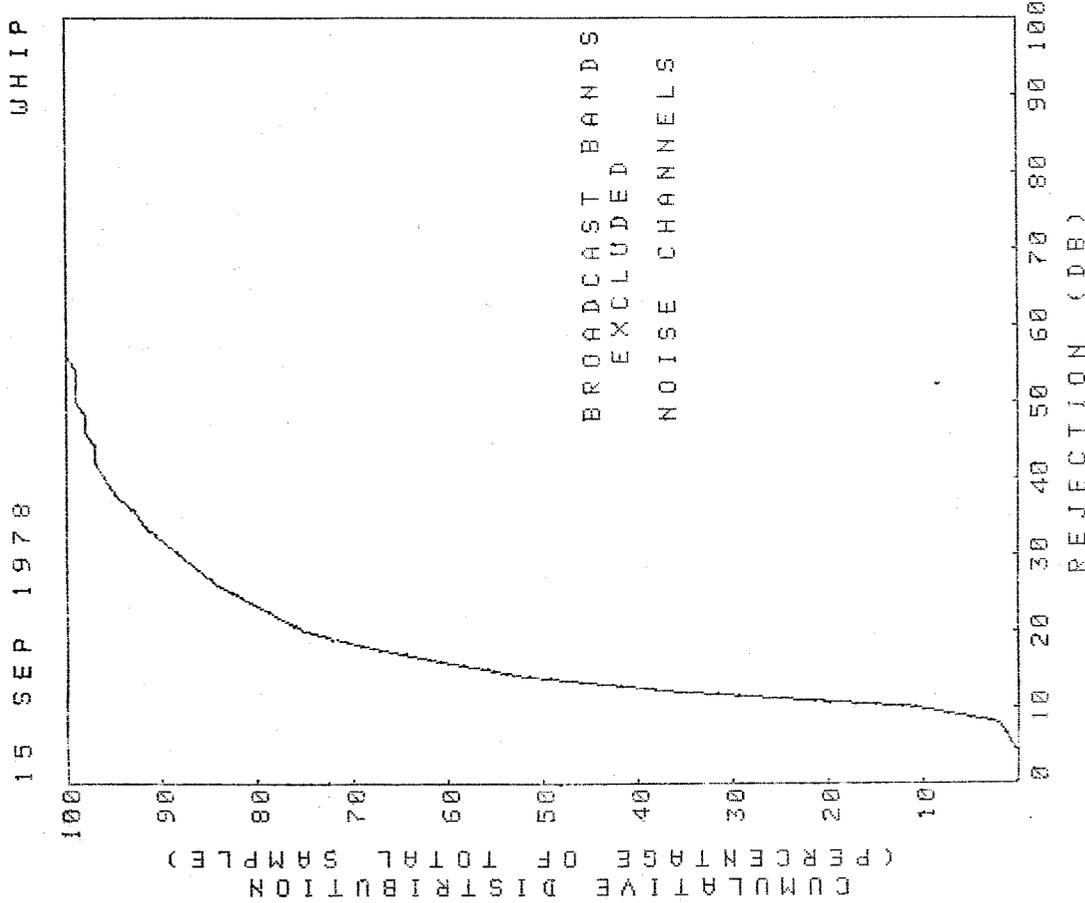
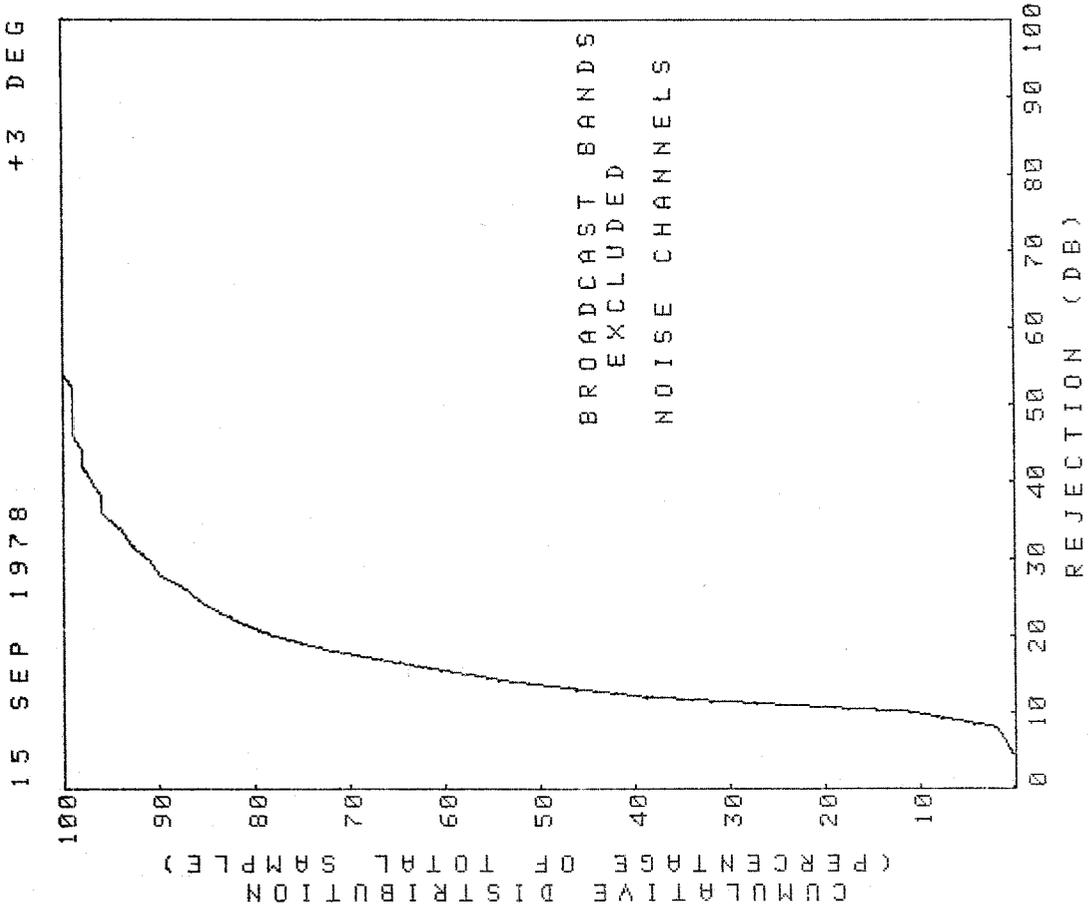


Figure 14. Surveillance data filter rejection (broadcast bands excluded)

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15 SEP 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.63E+06
BROADCAST BANDS EXCLUDED
NOISE CHANNELS

NUMBER OF OCCASIONS FILTER REJECTION > 70
(100KHZ CHANNELS)

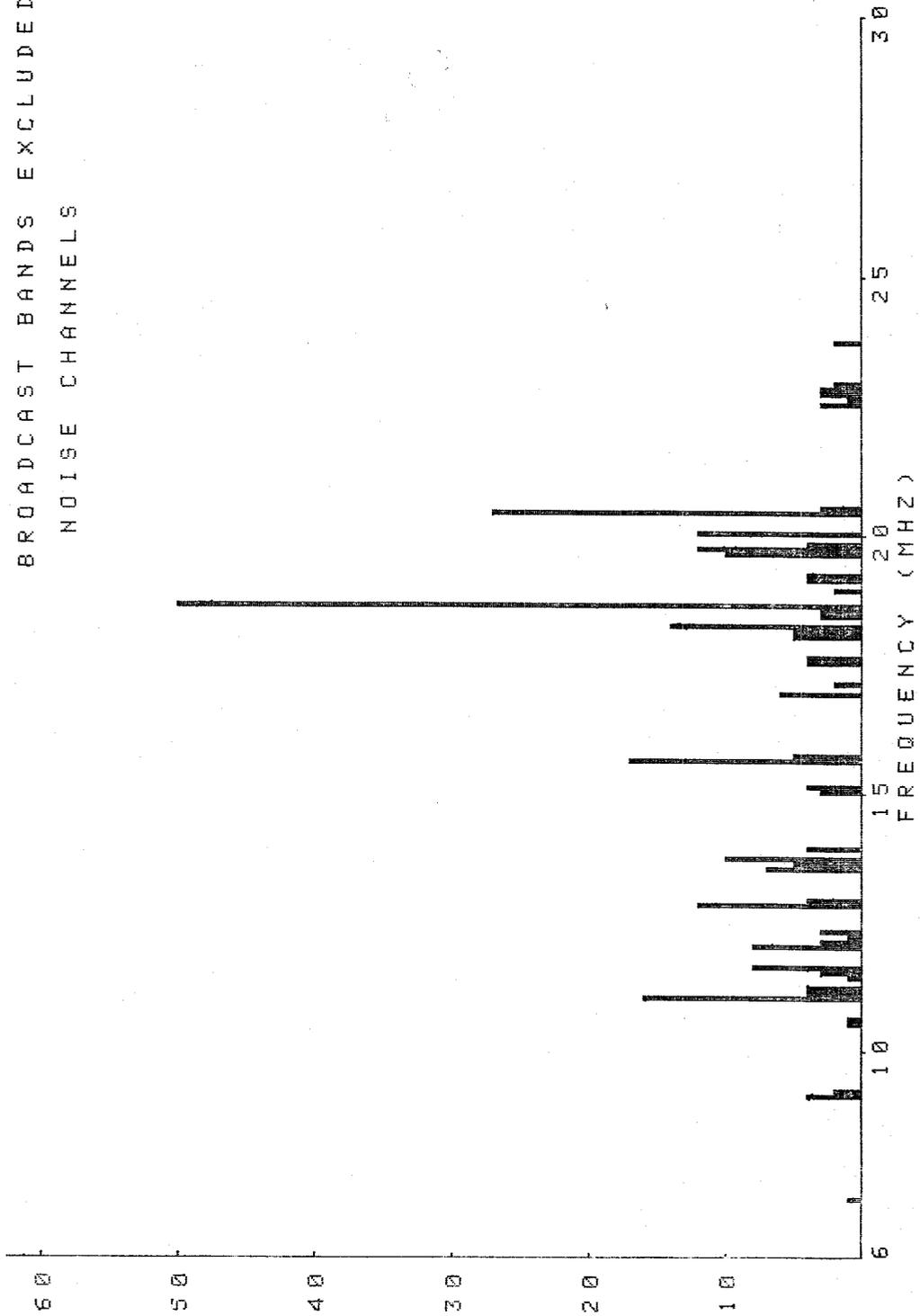


Figure 15. Histogram of channels requiring > 70 dB filter rejection (broadcast bands excluded)

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15 SEP 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.63E+06
BROADCAST BANDS EXCLUDED
NOISE CHANNELS

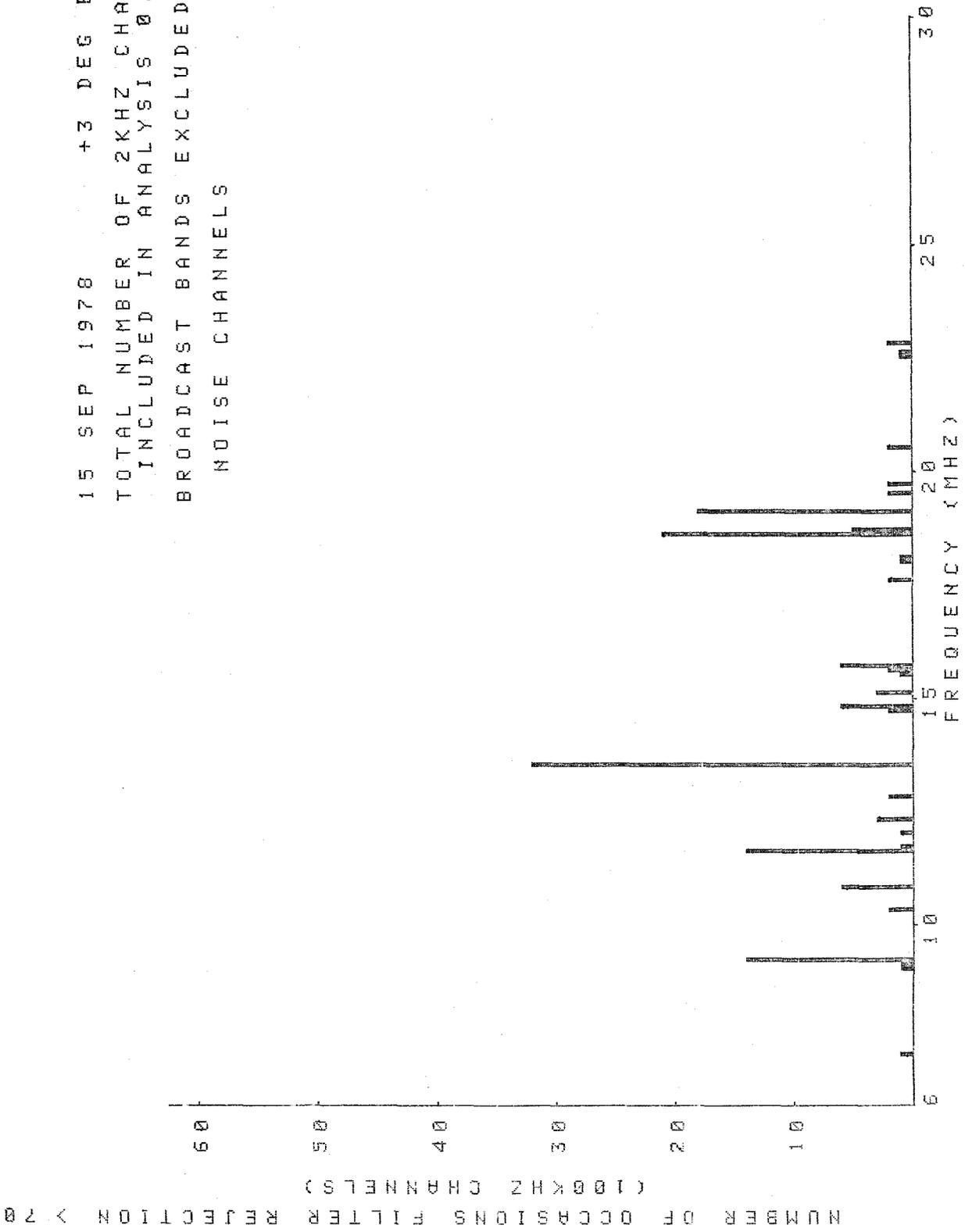


Figure 16. Histogram of channels requiring > 70 dB filter rejection (broadcast bands excluded)

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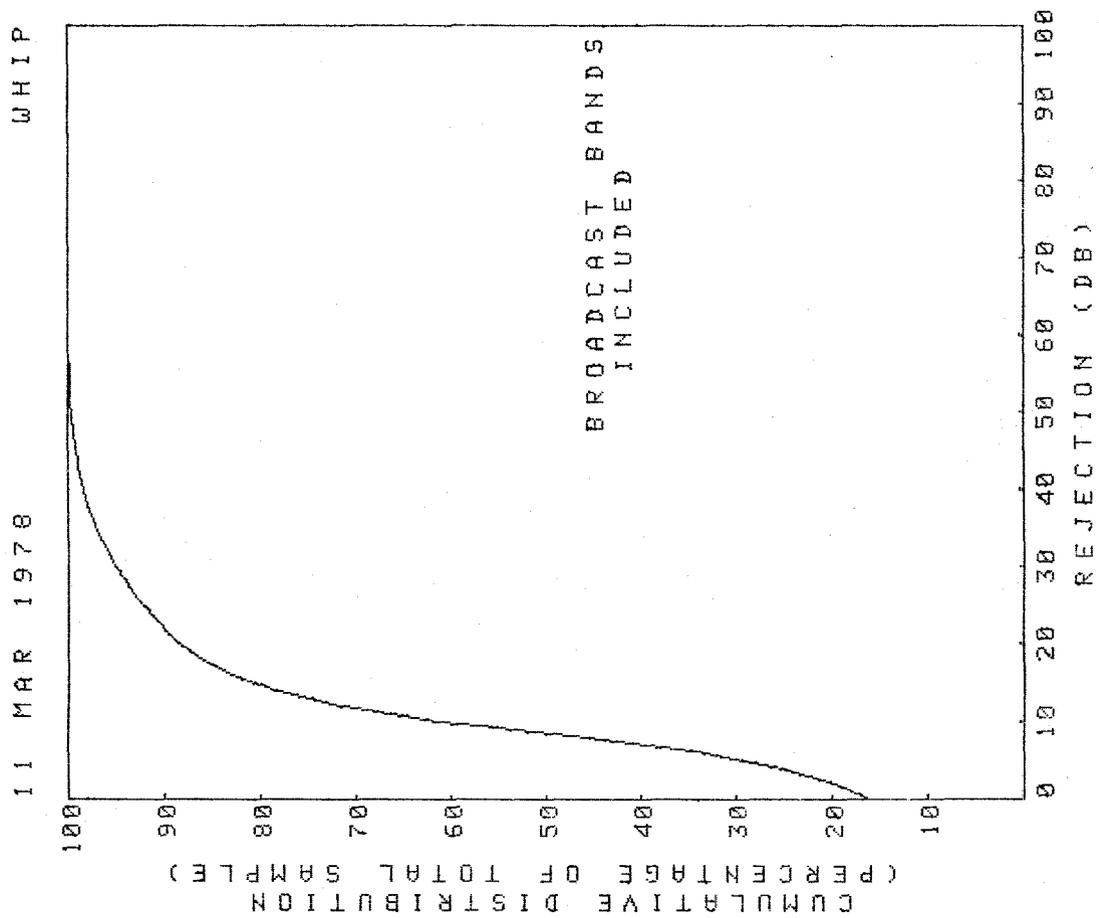
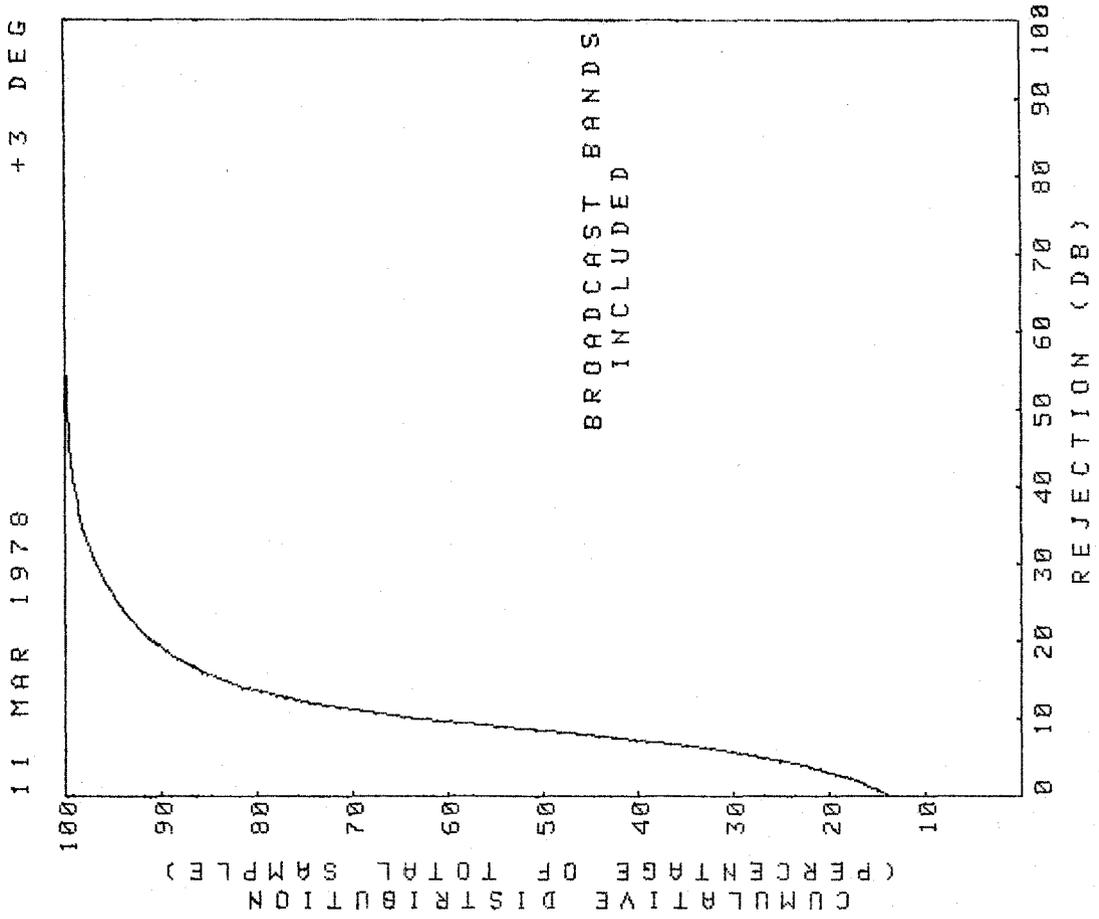


Figure 17. Surveillance data first I.F. image rejection

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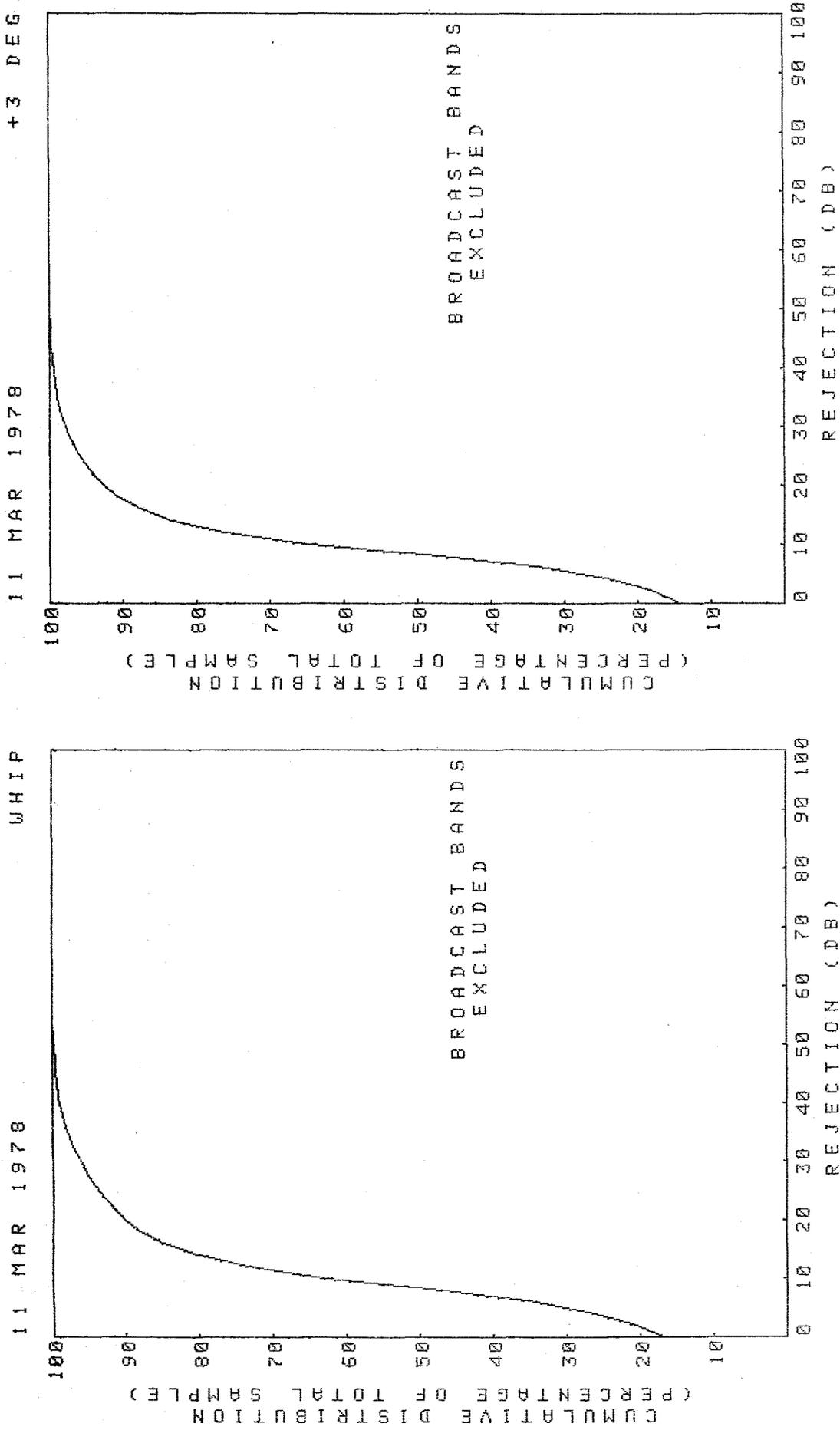


Figure 18. Surveillance data first I.F. image rejection

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11 MAR 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.32E+06
BROADCAST BANDS INCLUDED

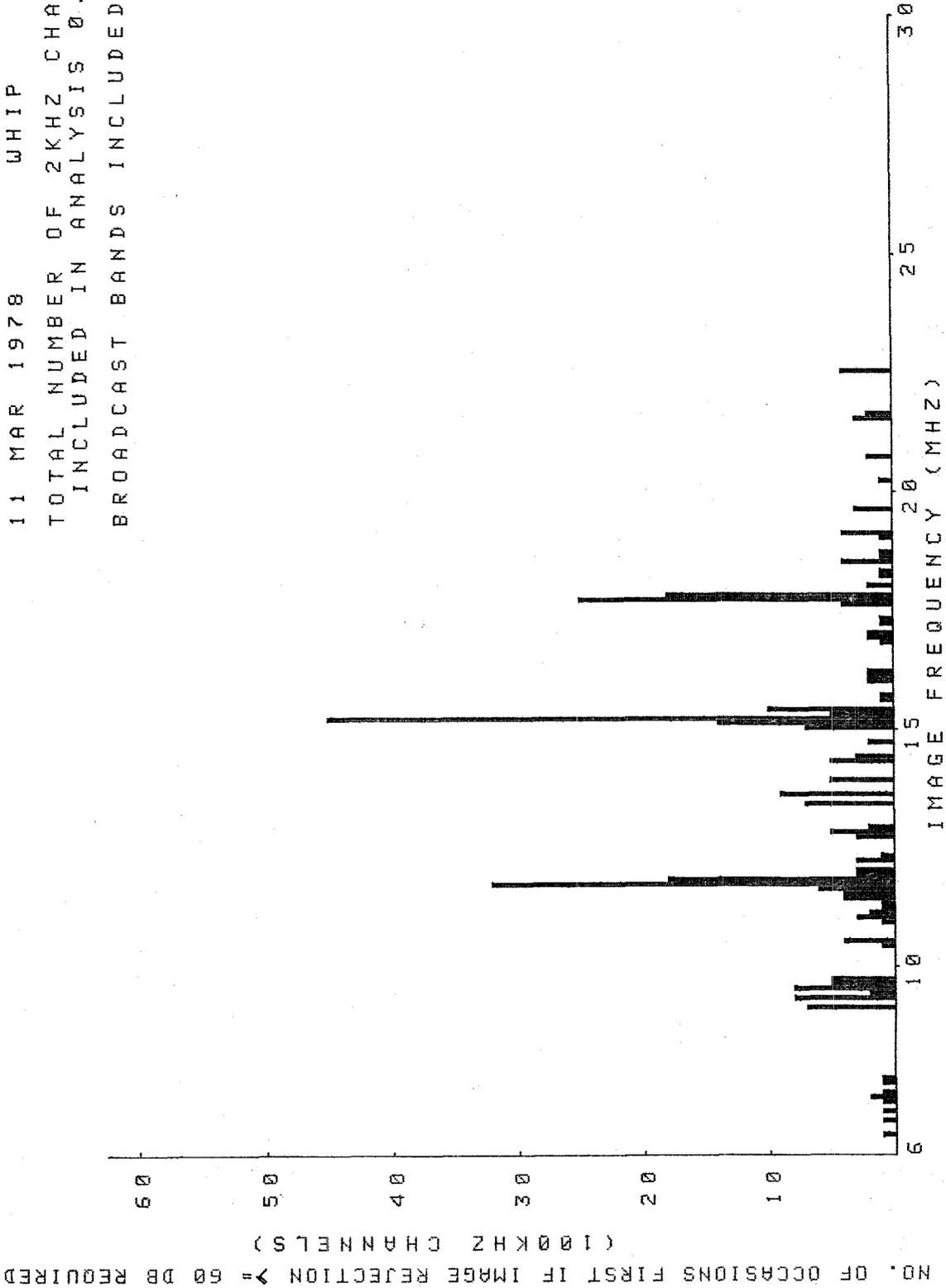


Figure 19. Histogram of channels requiring a first I.F. image rejection > = 60 dB

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11 MAR 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.32E+06
BROADCAST BANDS INCLUDED

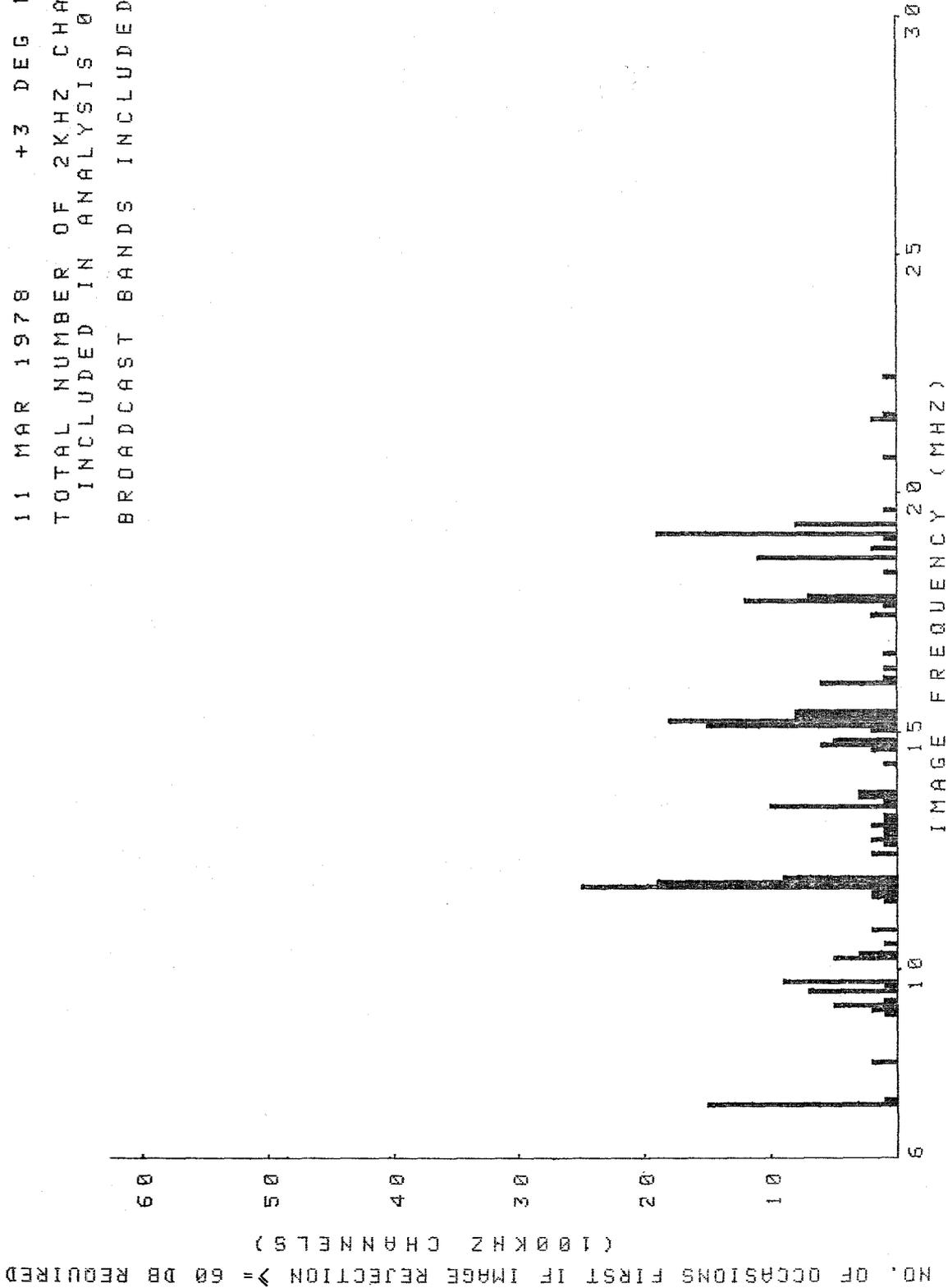


Figure 20. Histogram of channels requiring a first I.F. image rejection \geq 60 dB

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11 MAR 1978 WHIP
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.29E+06
BROADCAST BANDS EXCLUDED

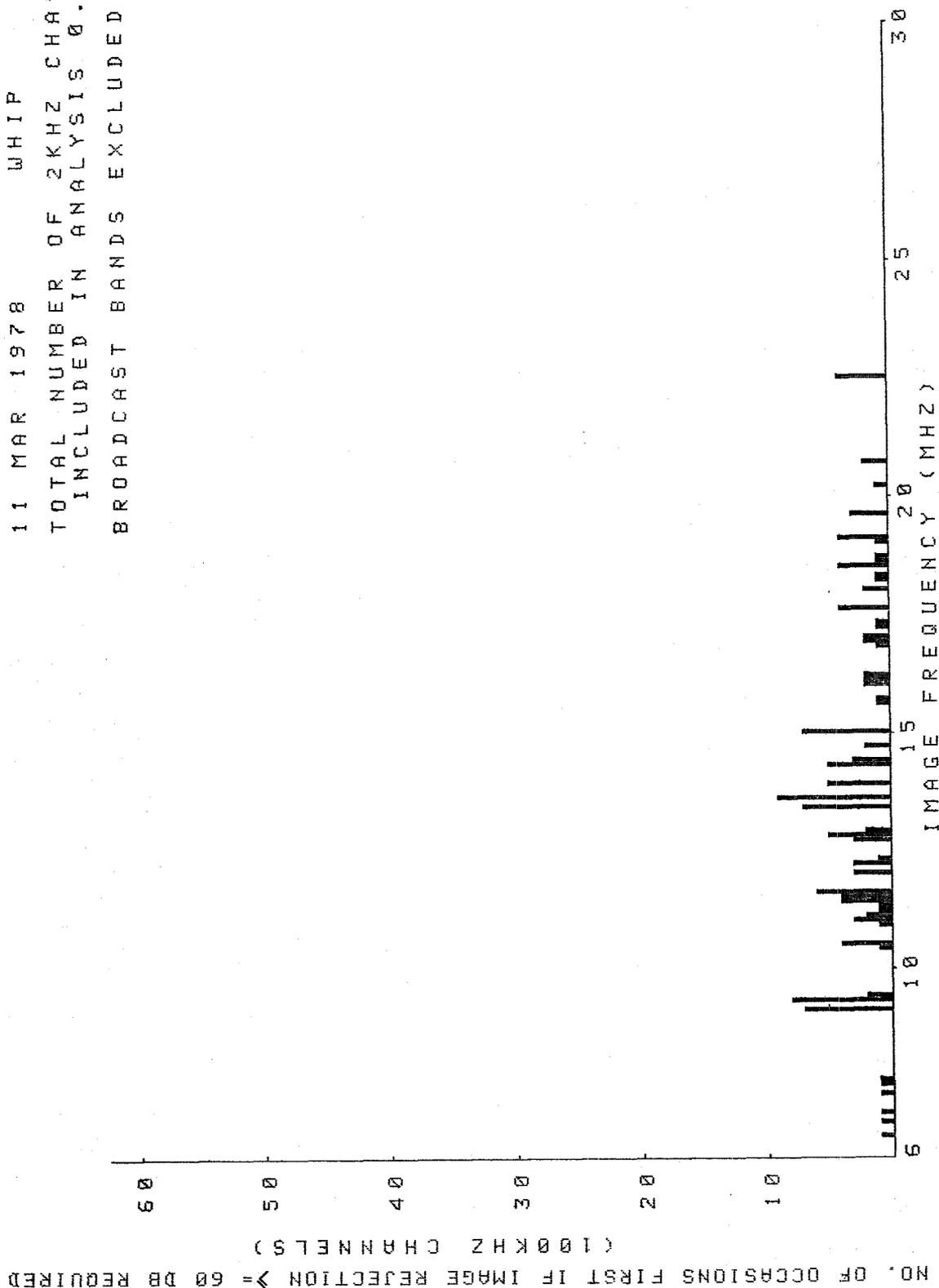


Figure 21. Histogram of channels requiring a first I.F. image rejection \geq 60 dB

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11 MAR 1978 +3 DEG BEAM
TOTAL NUMBER OF 2KHZ CHANNELS
INCLUDED IN ANALYSIS 0.29E+06
BROADCAST BANDS EXCLUDED

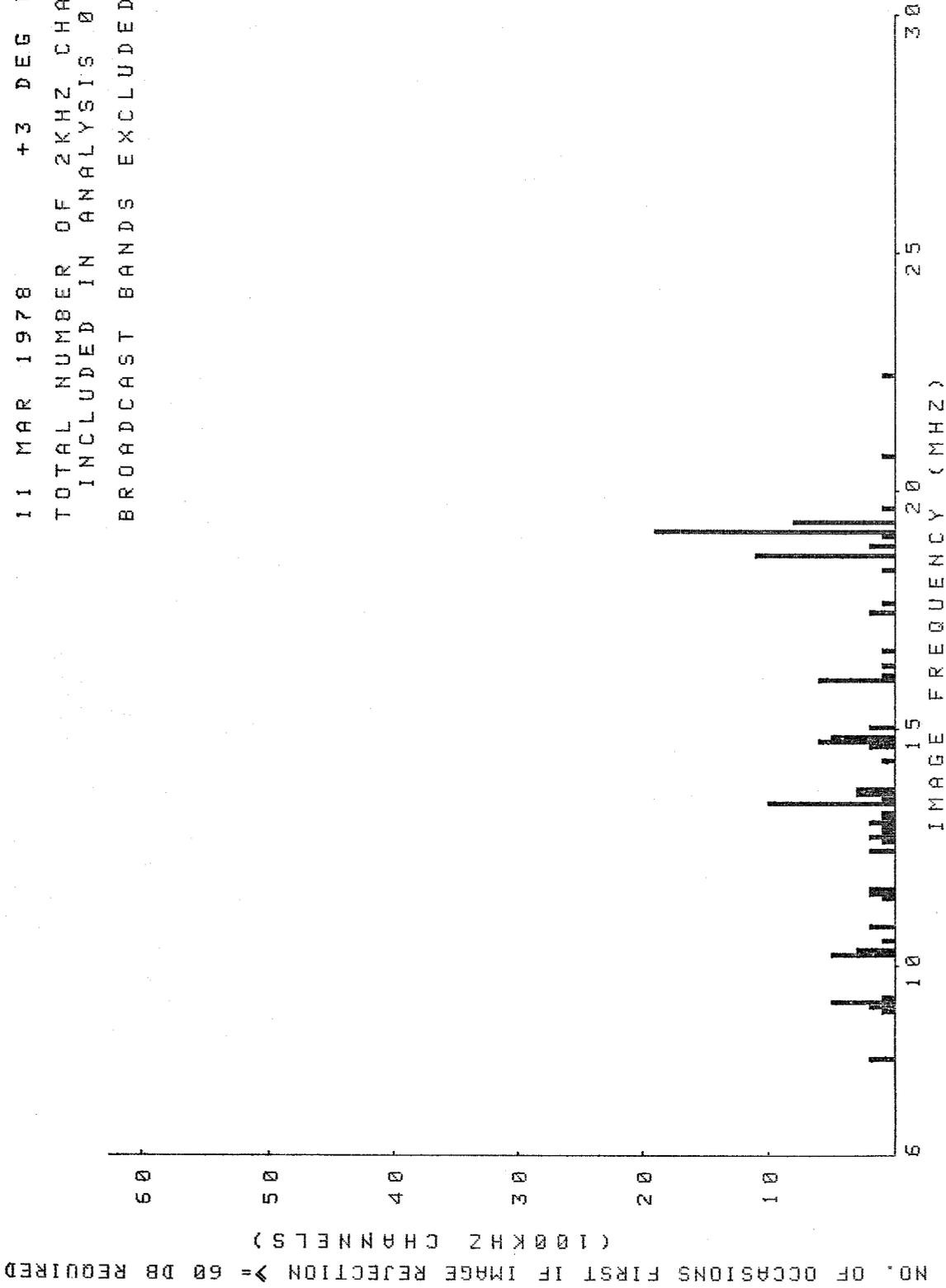


Figure 22. Histogram of channels requiring a first I.F. image rejection \geq 60 dB

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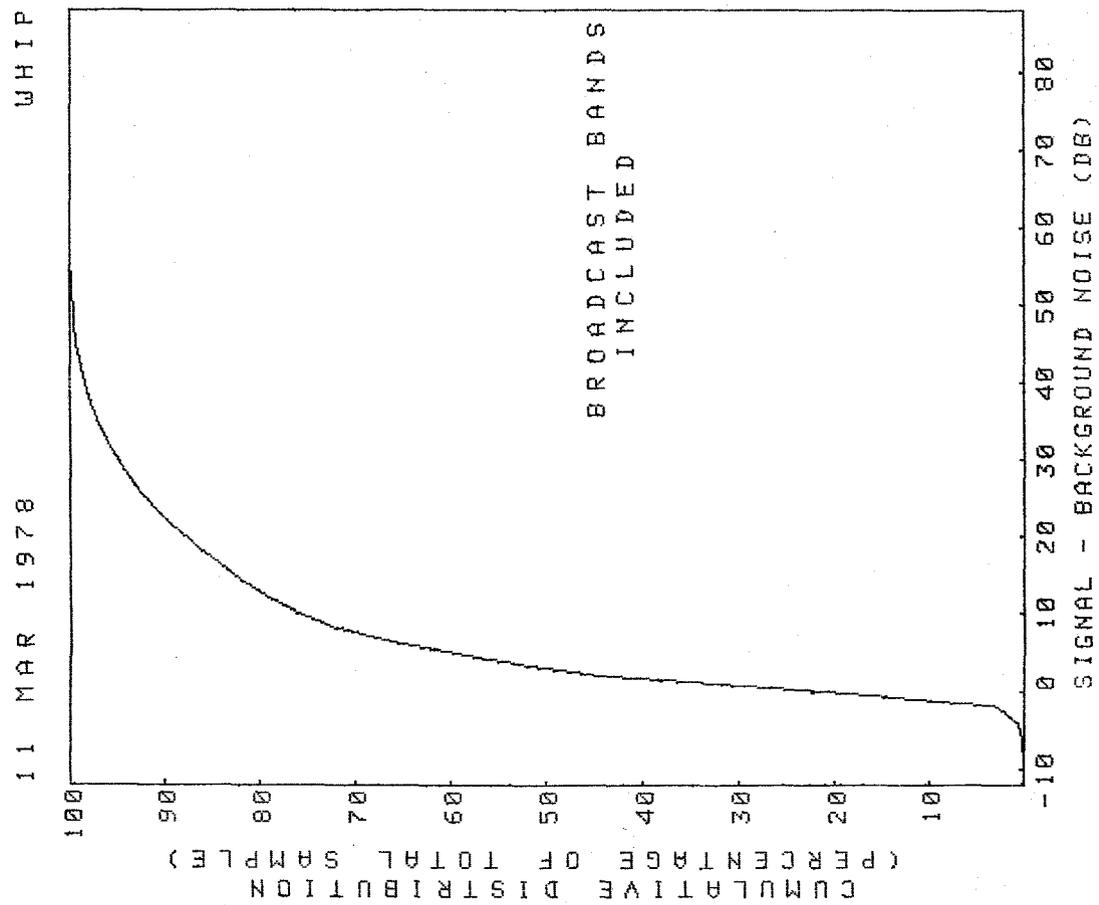
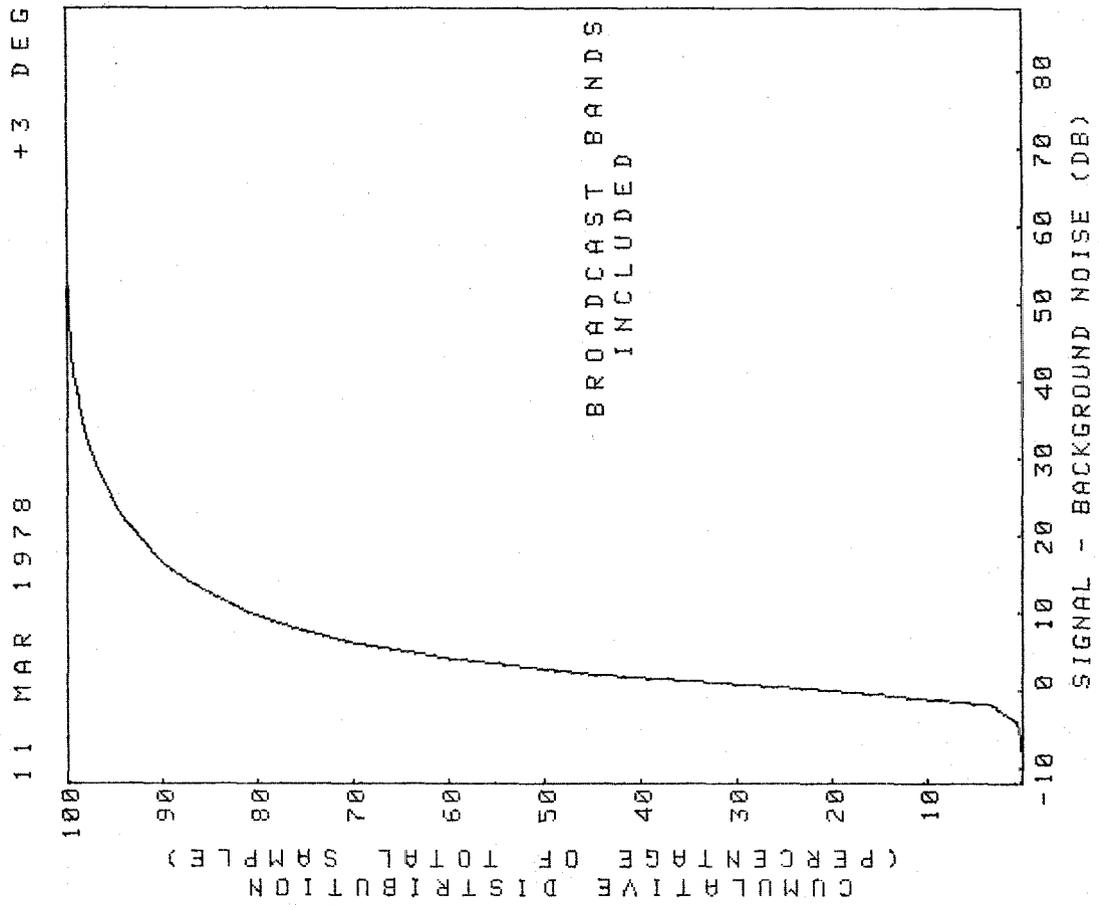


Figure 23. Surveillance data dynamic range statistics (broadcast band included)

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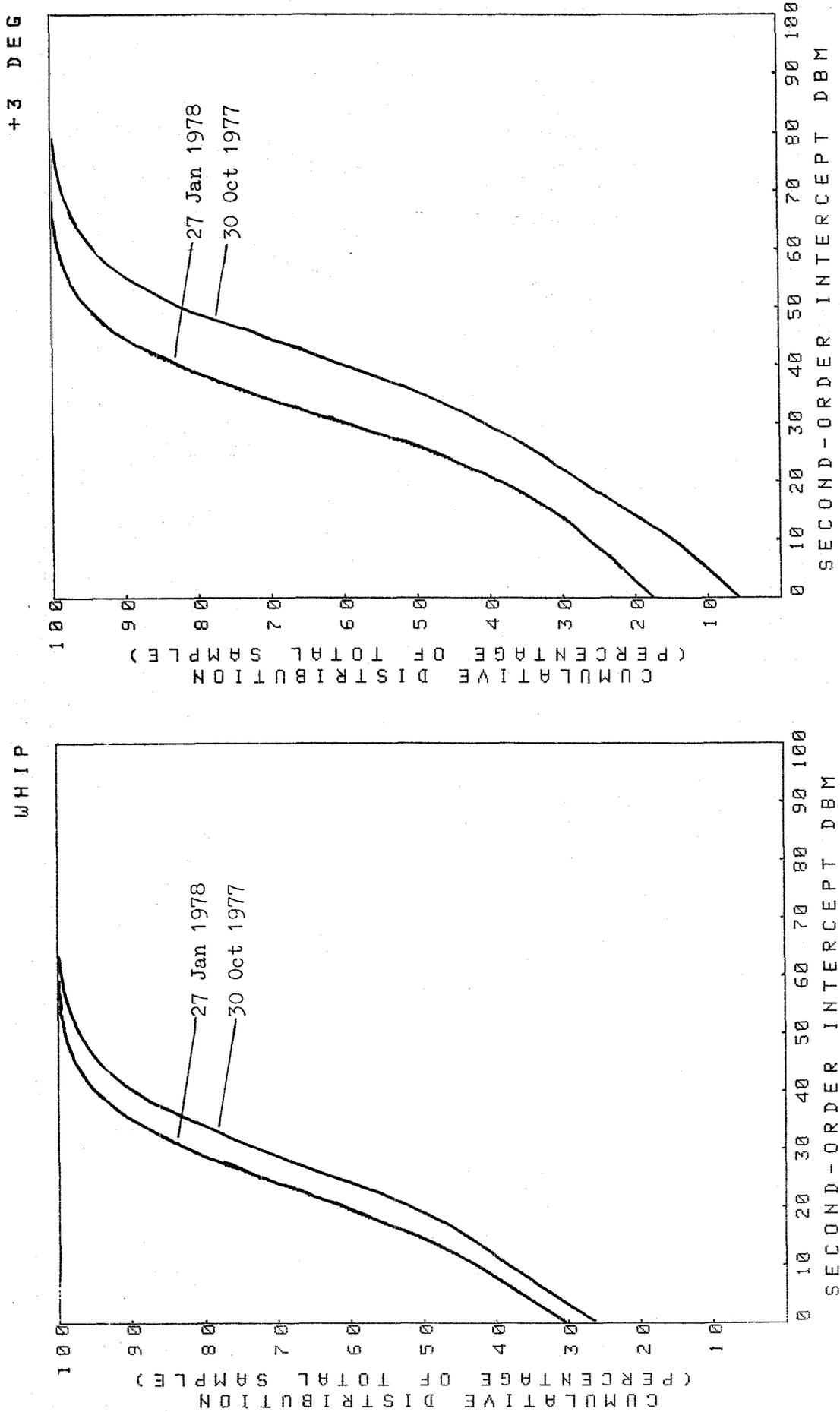


Figure 24. Surveillance data second order out-of-band IMD statistics

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Figure 25

30 OCT 1977 WHIP

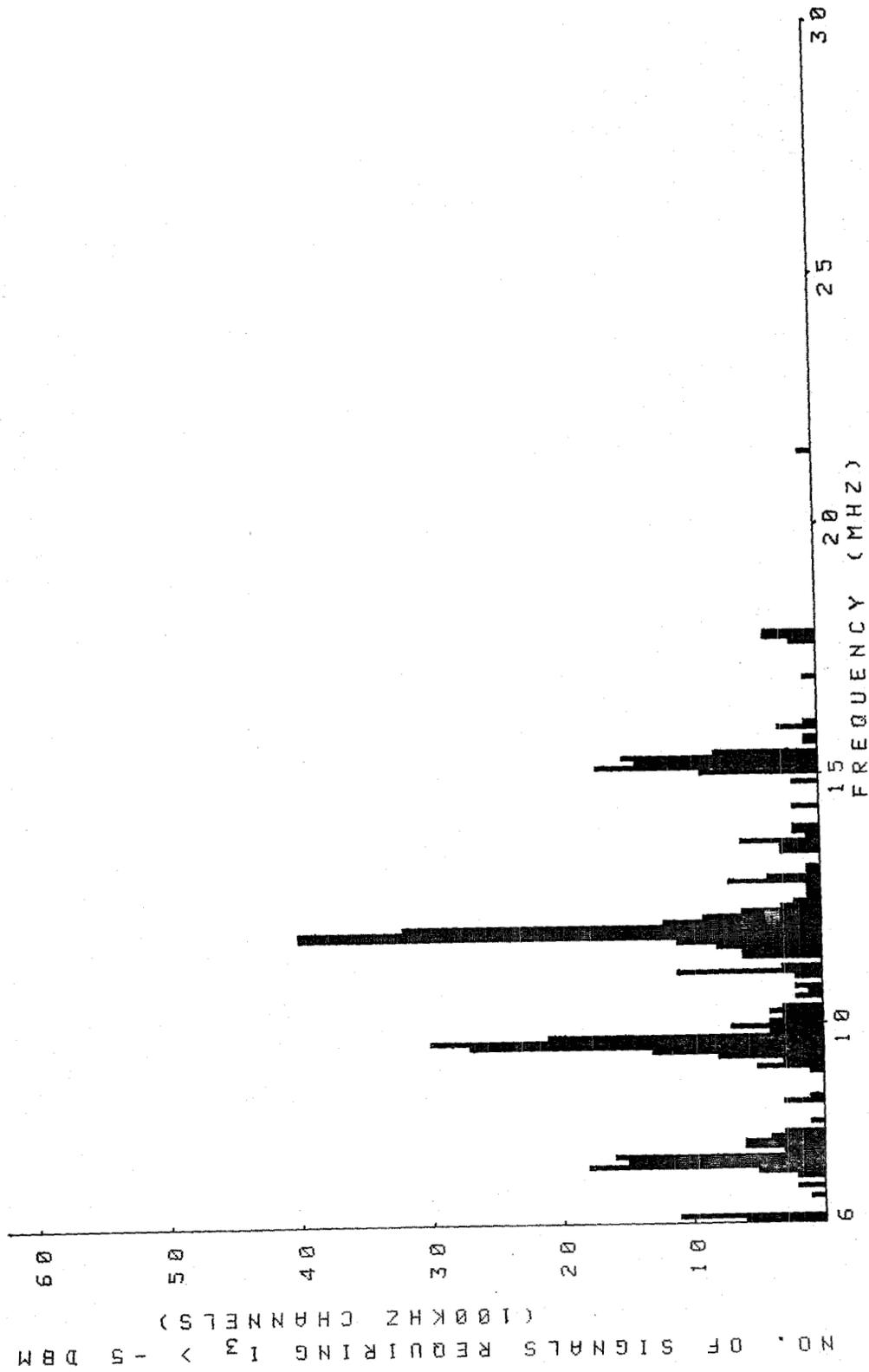


Figure 25. Histogram of channels requiring out-of-band intercept I3 > -5 dBm

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27 JAN 1978
WHIP

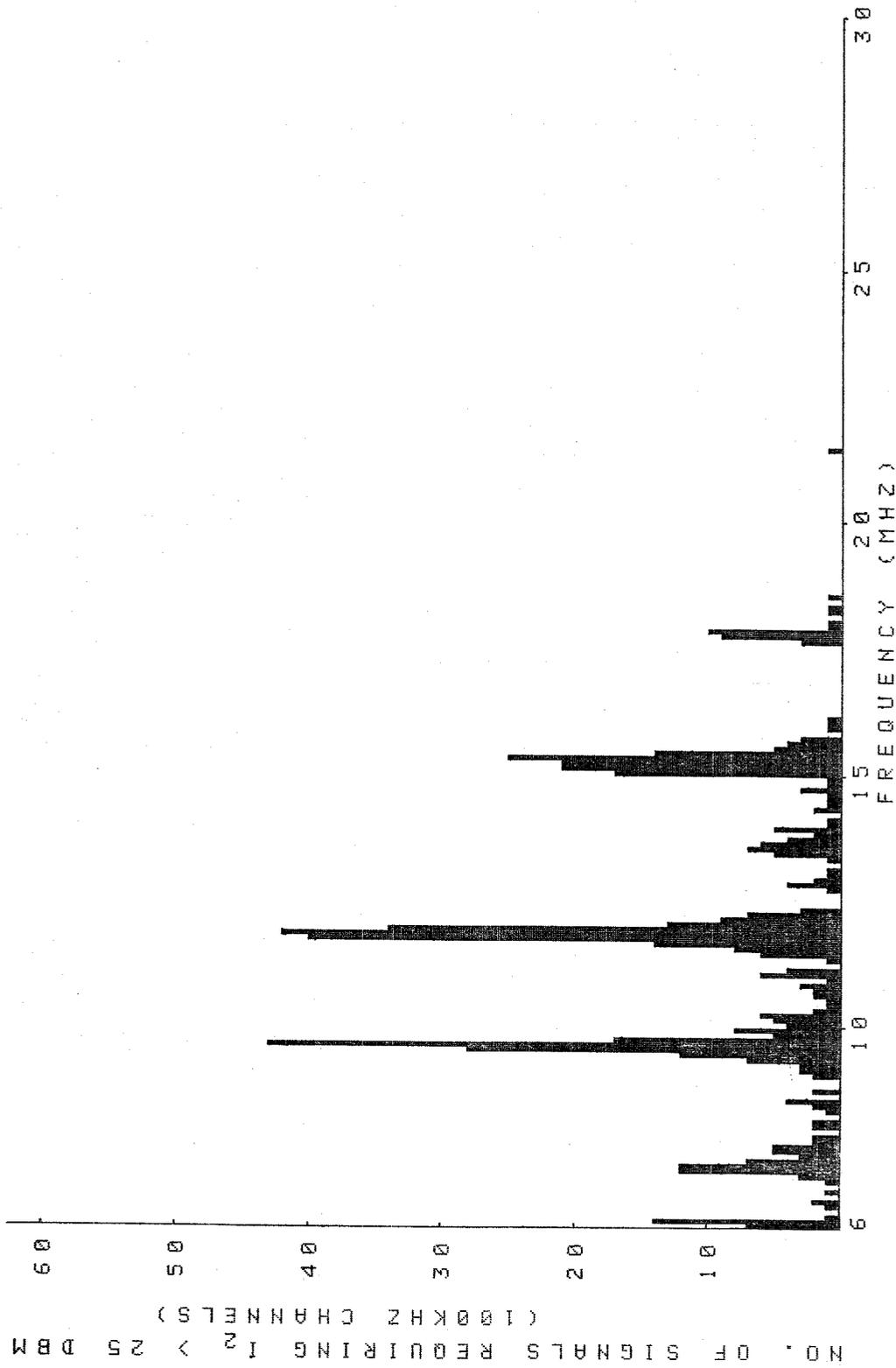


Figure 26. Histogram of channels requiring out-of-band intercept $I_2 > 25$ dBm

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Figure 27

30 OCT 1977 +3 DEG BEAM

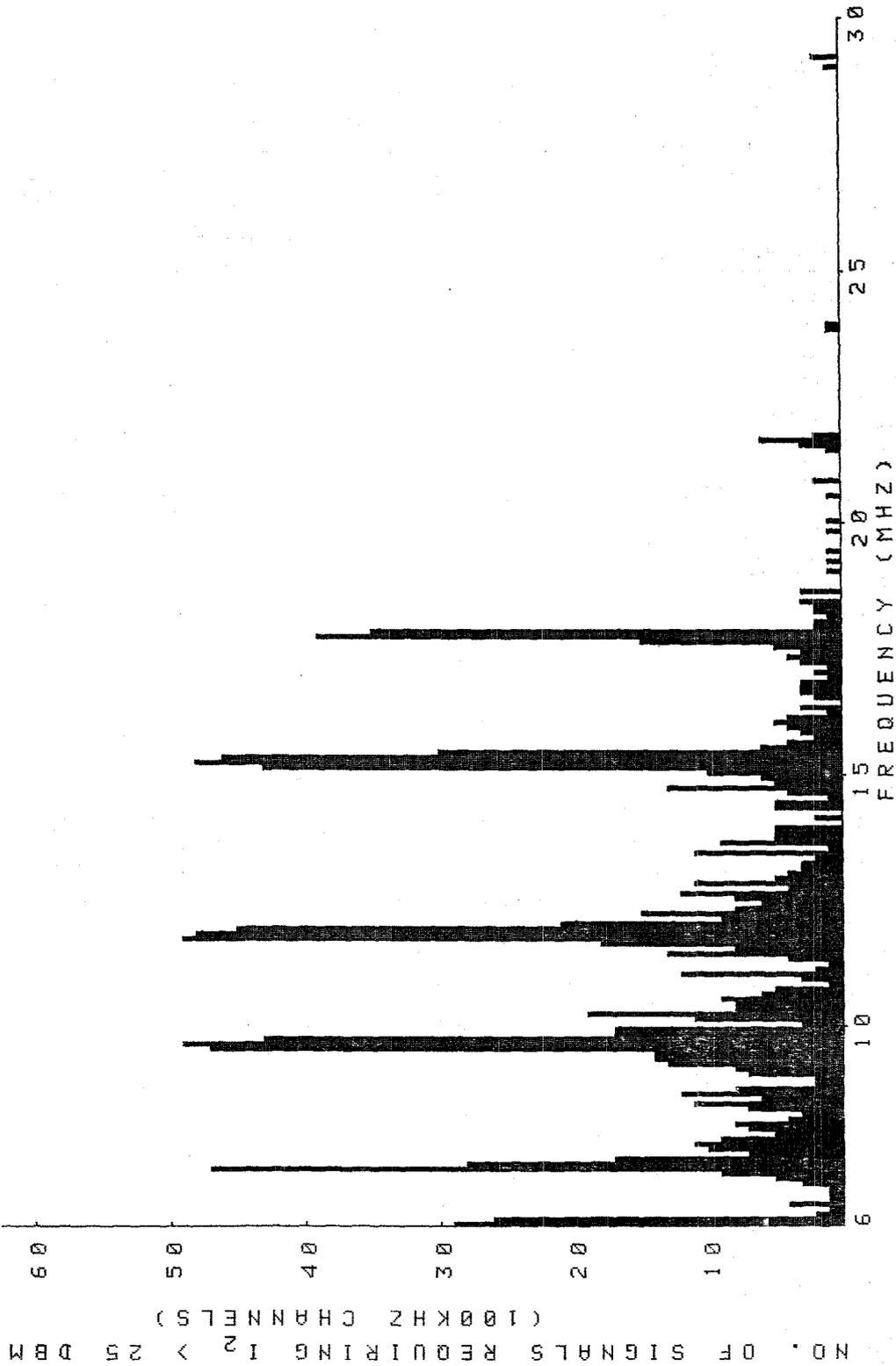


Figure 27. Histogram of channels requiring out-of-band intercept I₂ > 25 dBm

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27 JAN 1978 +3 DEG BEAM

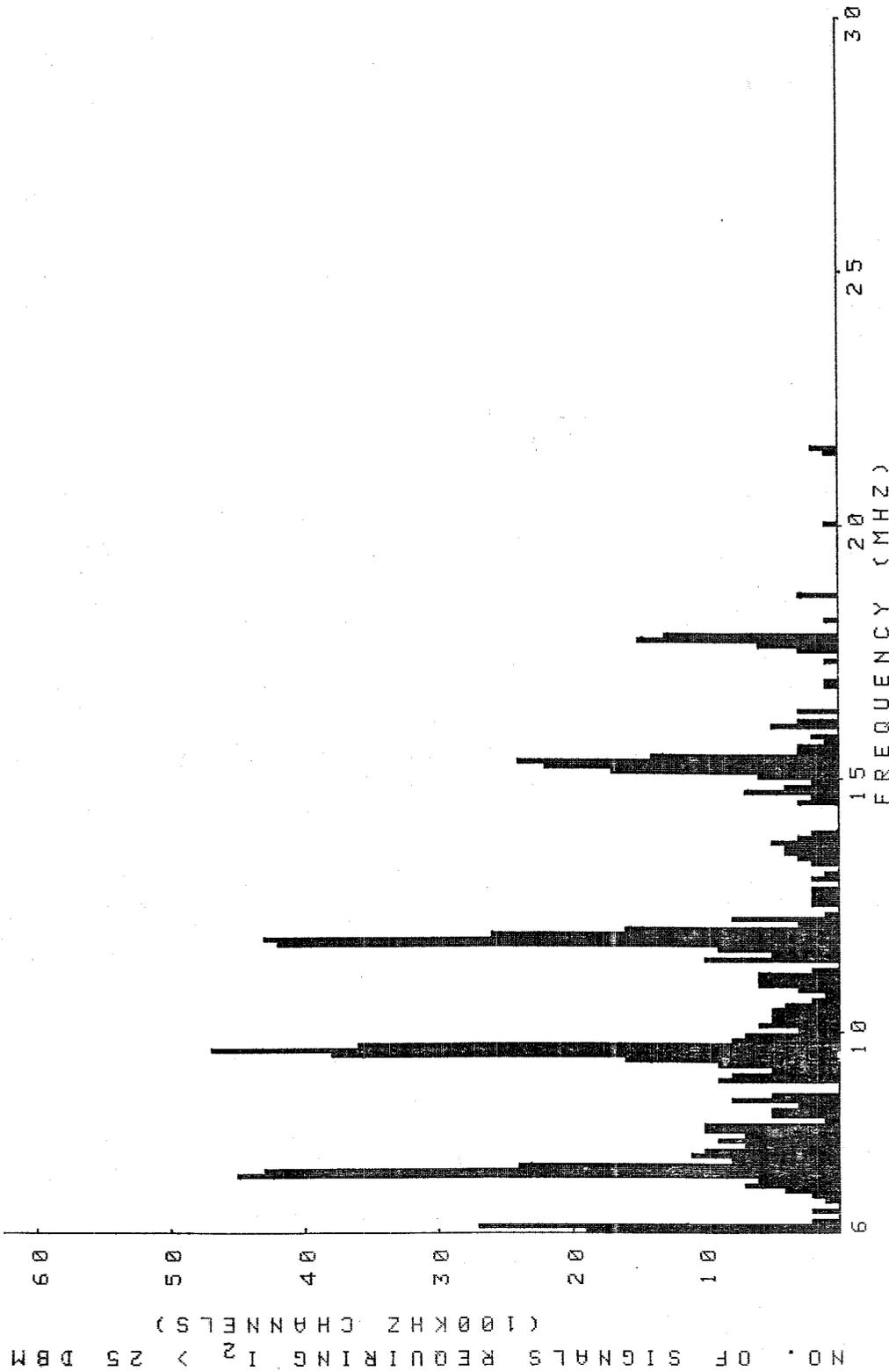


Figure 28. Histogram of channels requiring out-of-band intercept $I_2 > 25$ dBm

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+3 DEG

OCT 1977

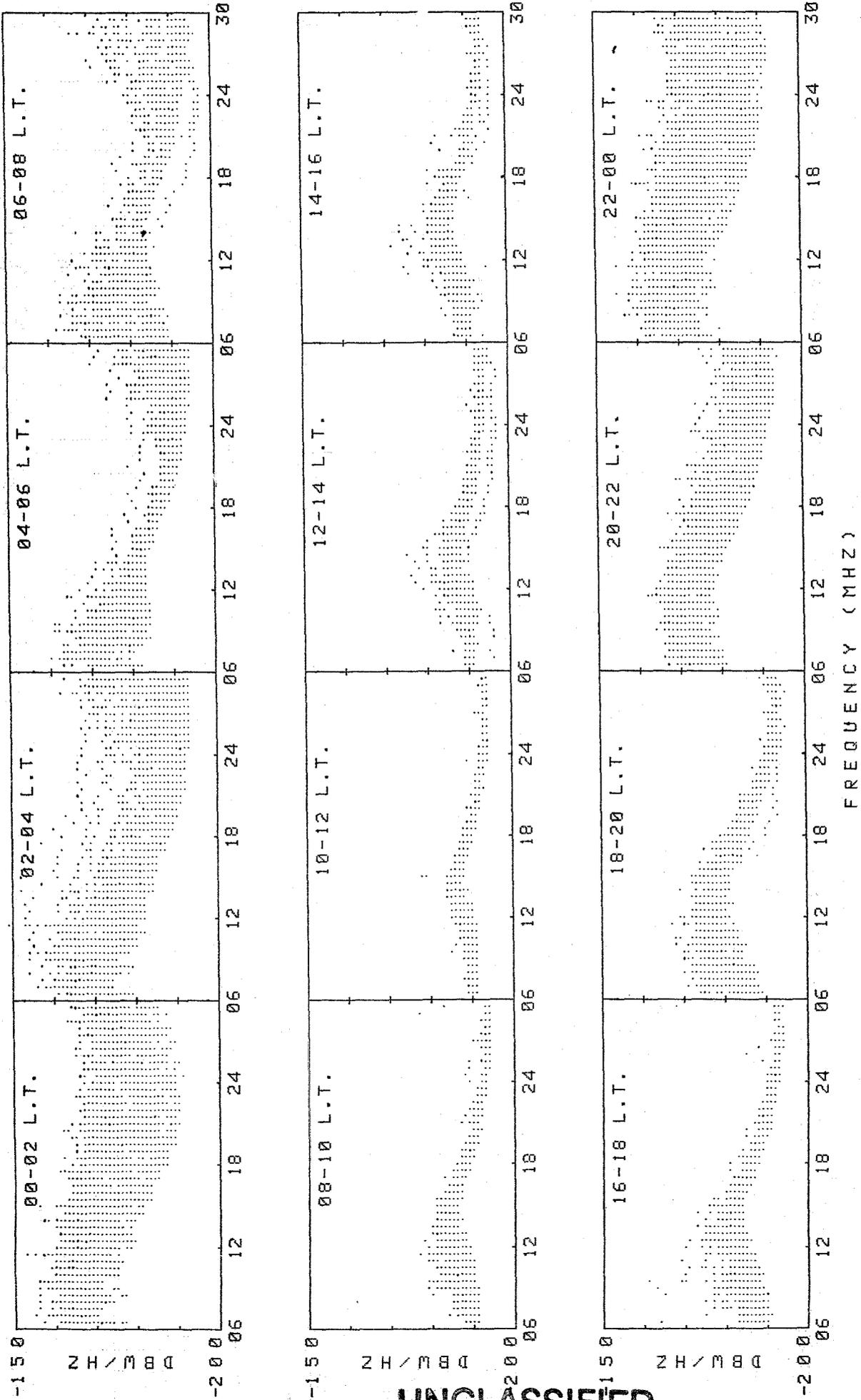


Figure 29. Background noise variation as a function of frequency and local time

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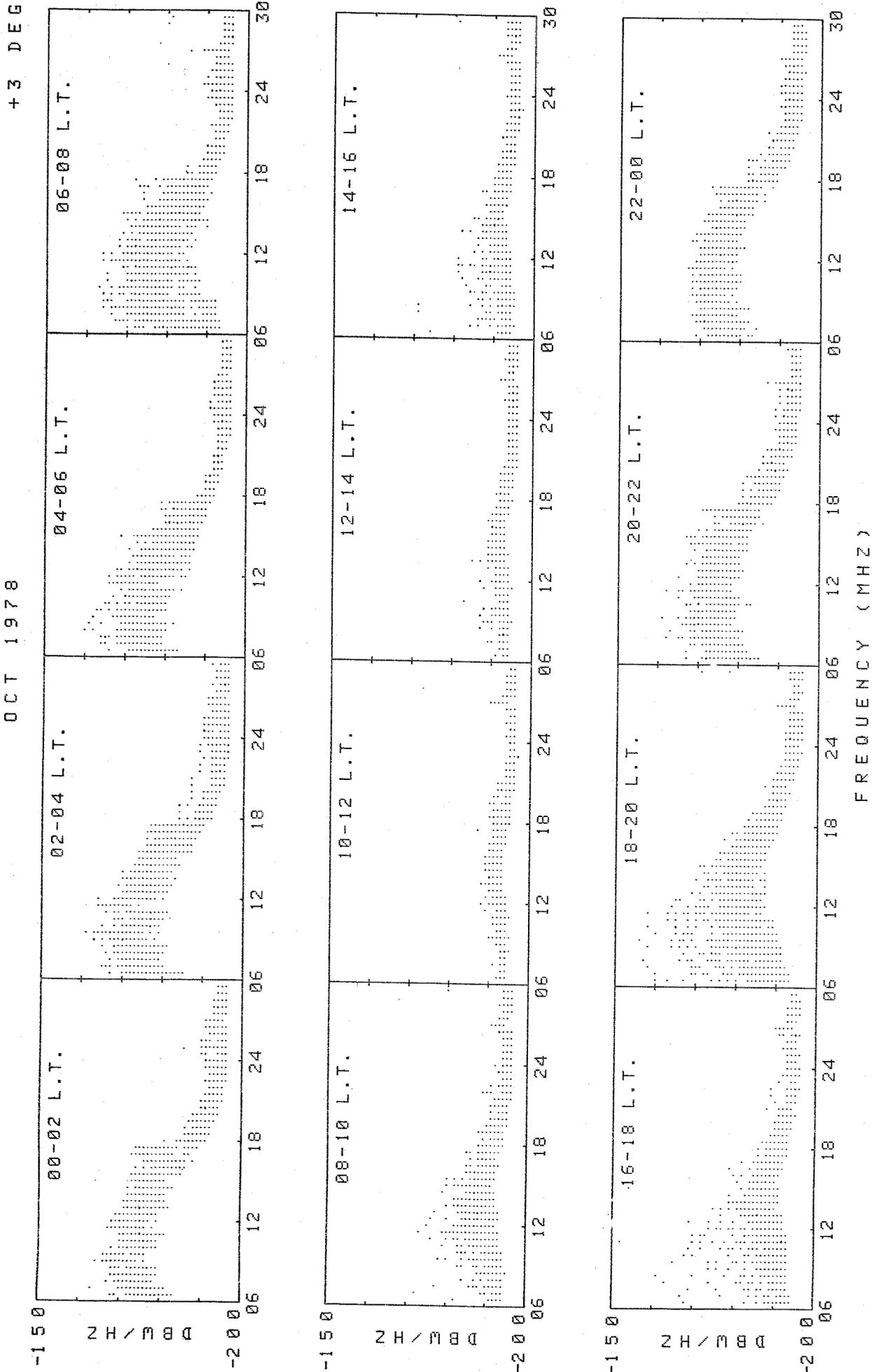


Figure 30. Background noise variation as a function of frequency and local time

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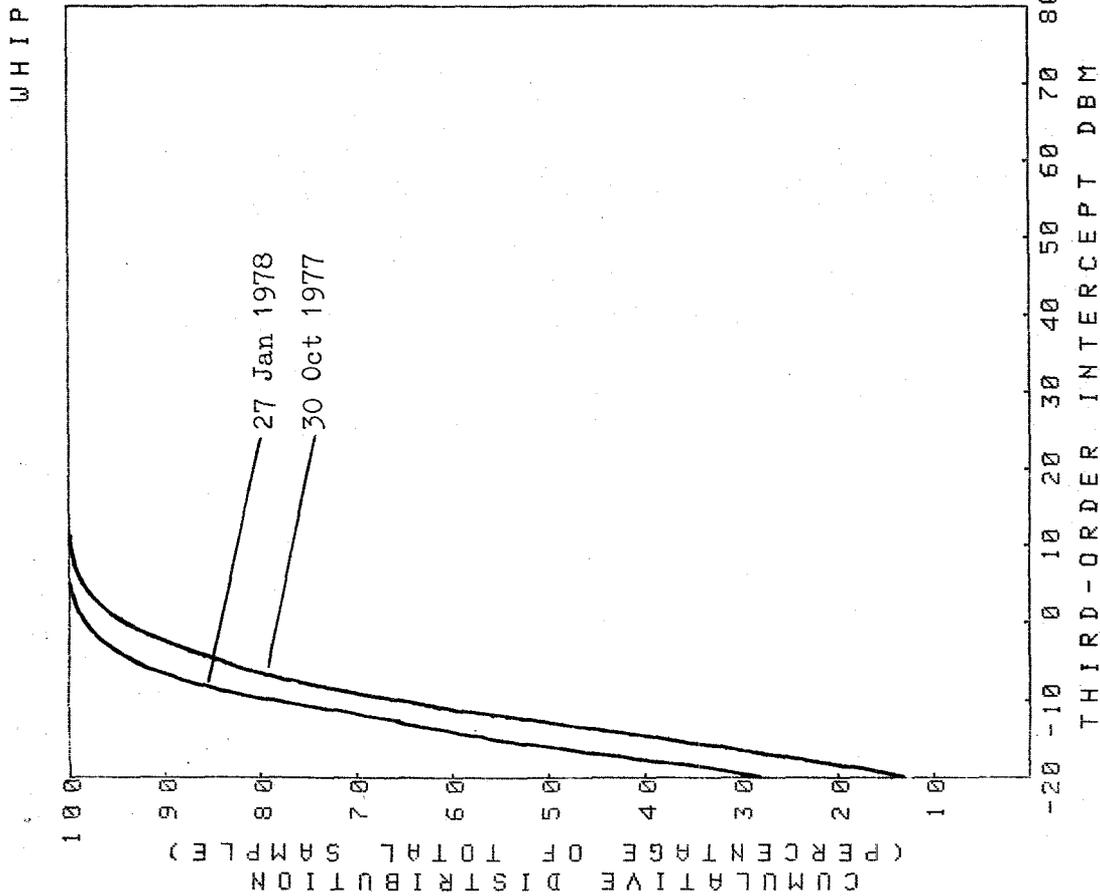
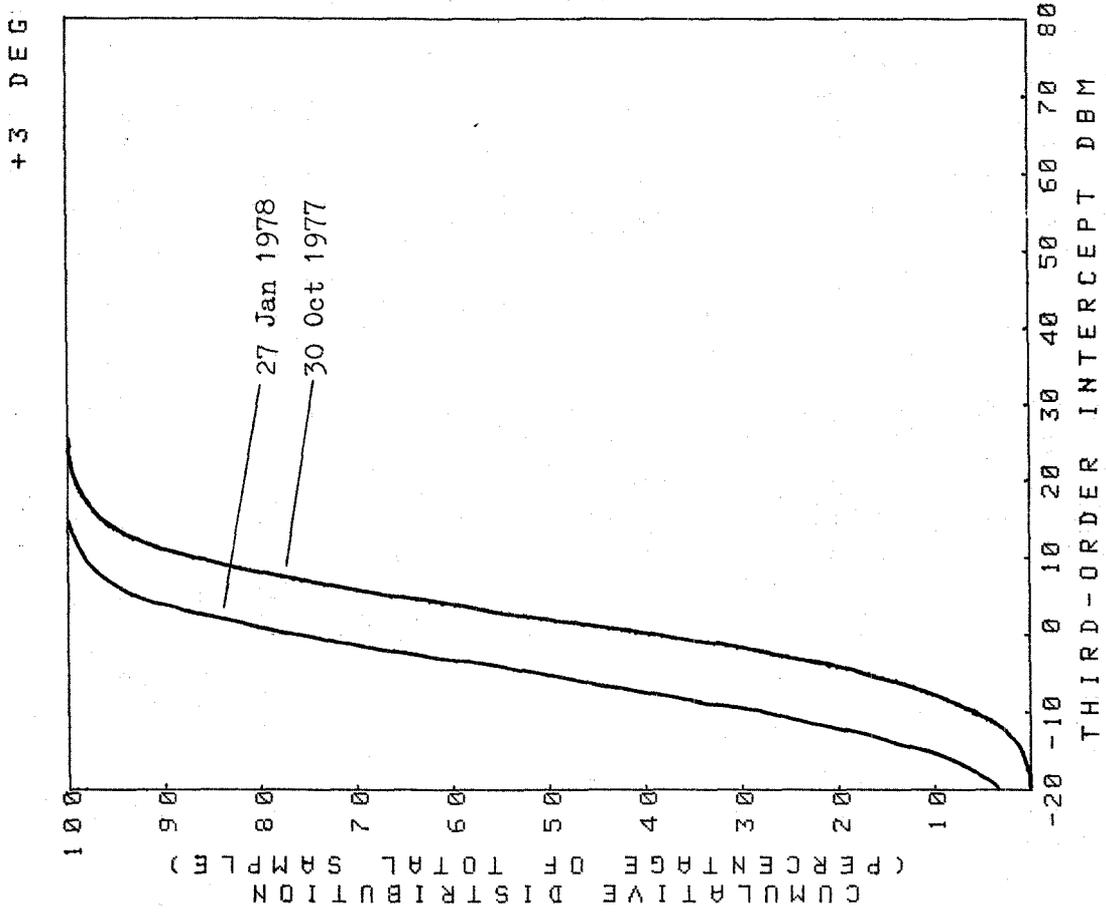


Figure 31. Surveillance data third order out-of-band IMD statistics

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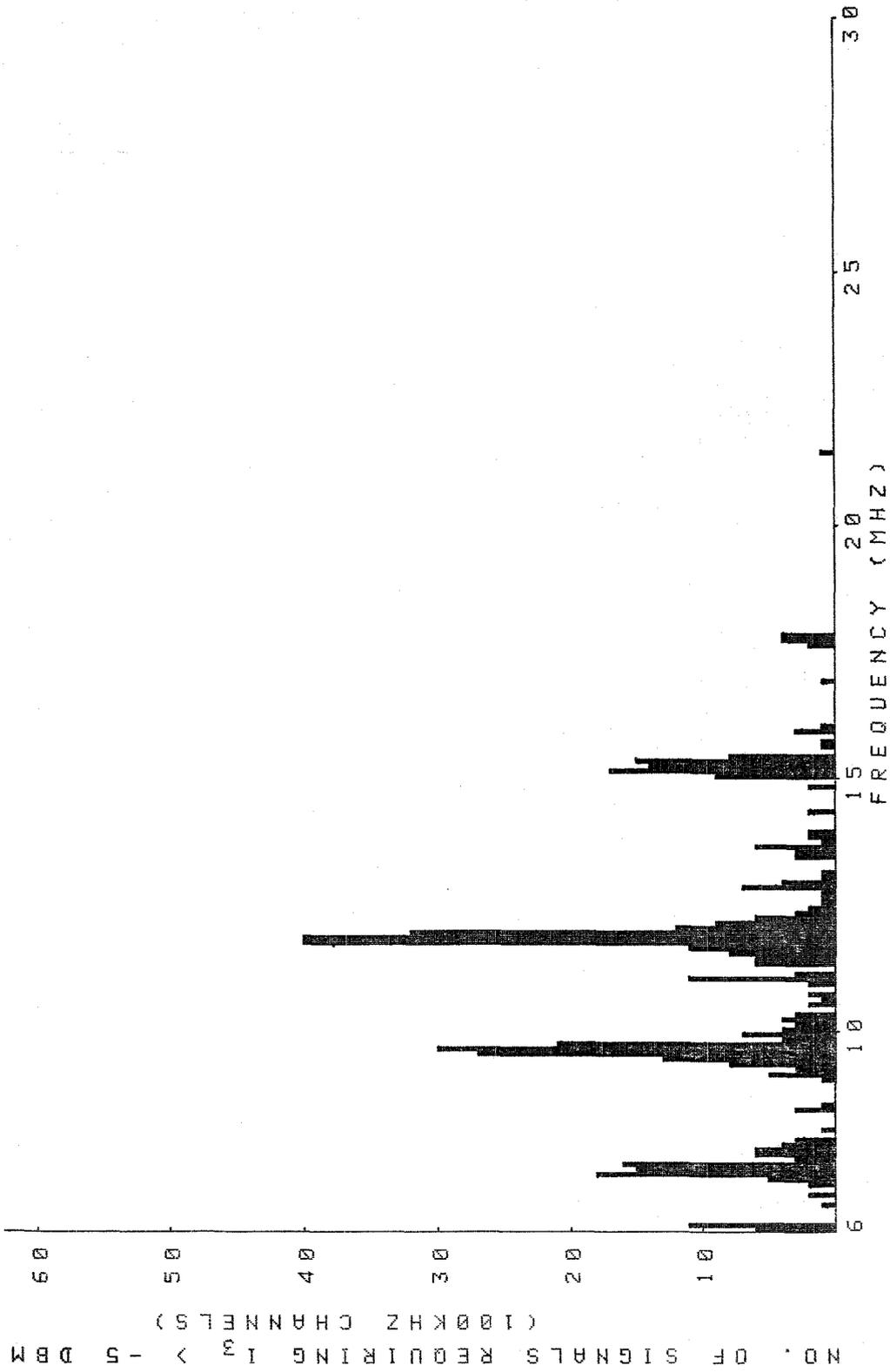


Figure 32. Histogram of channels requiring out-of-band intercept $I_3 > -5$ dBm

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27 JAN 1978 WHIP

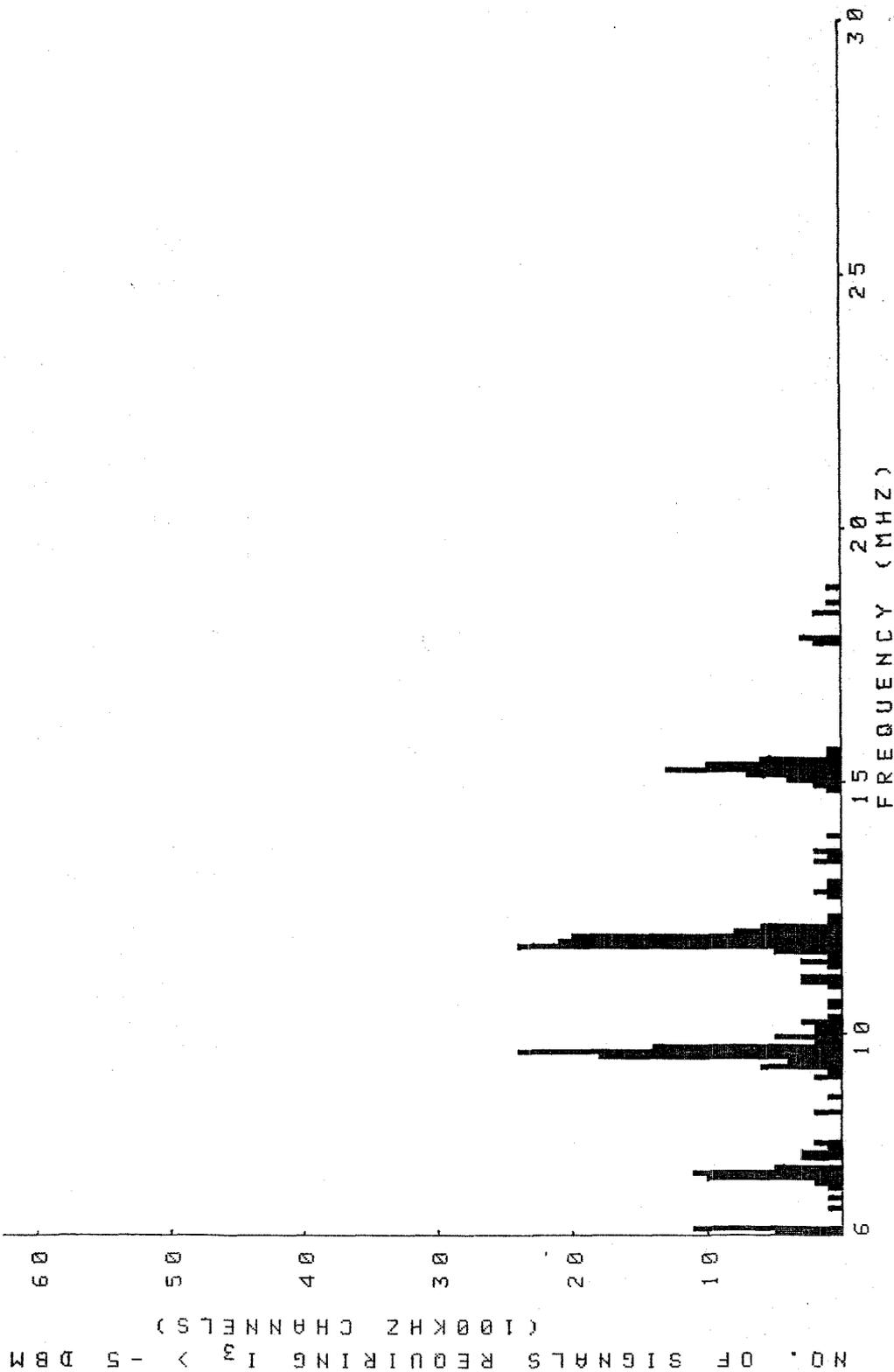


Figure 33. Histogram of channels requiring out-of-band intercept $I_3 > -5$ dBm

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30 OCT 1977 +3 DEG BEAM

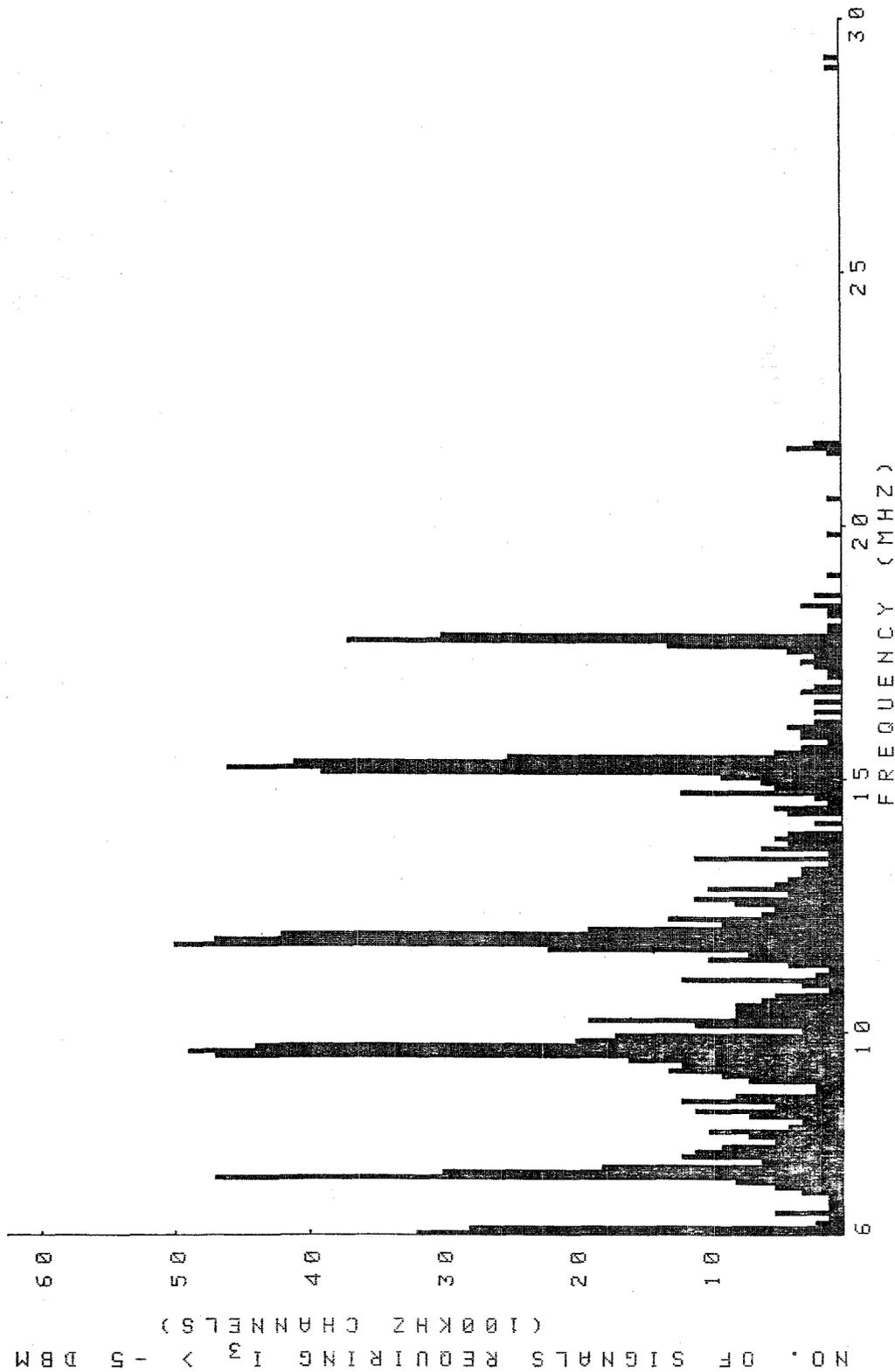


Figure 34. Histogram of channels requiring out-of-band intercept I₃ > -5 dBm

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27 JAN 1978 +3 DEG BEAM

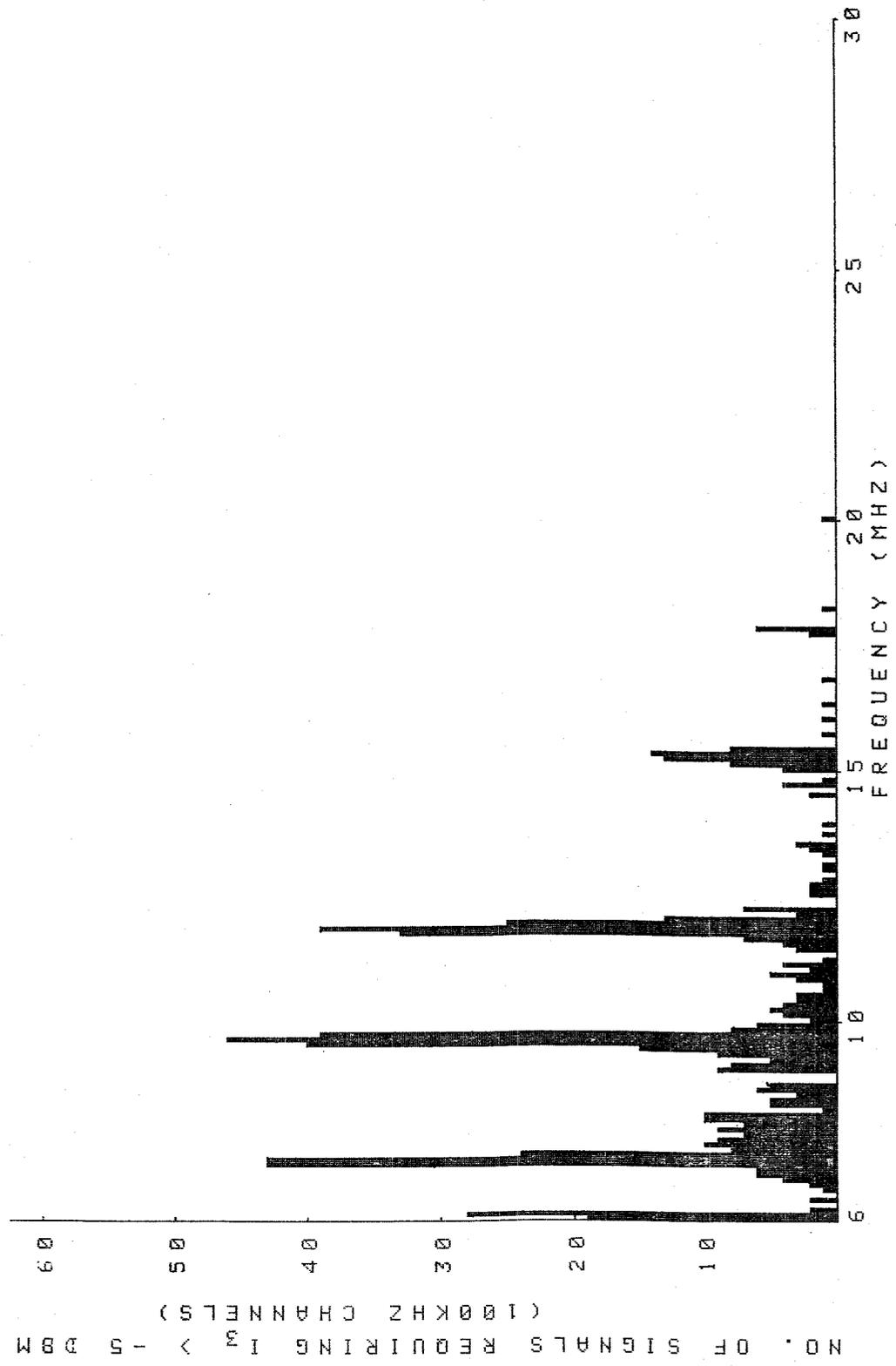


Figure 35. Histogram of channels requiring out-of-band intercept $I_3 > -5$ dBm

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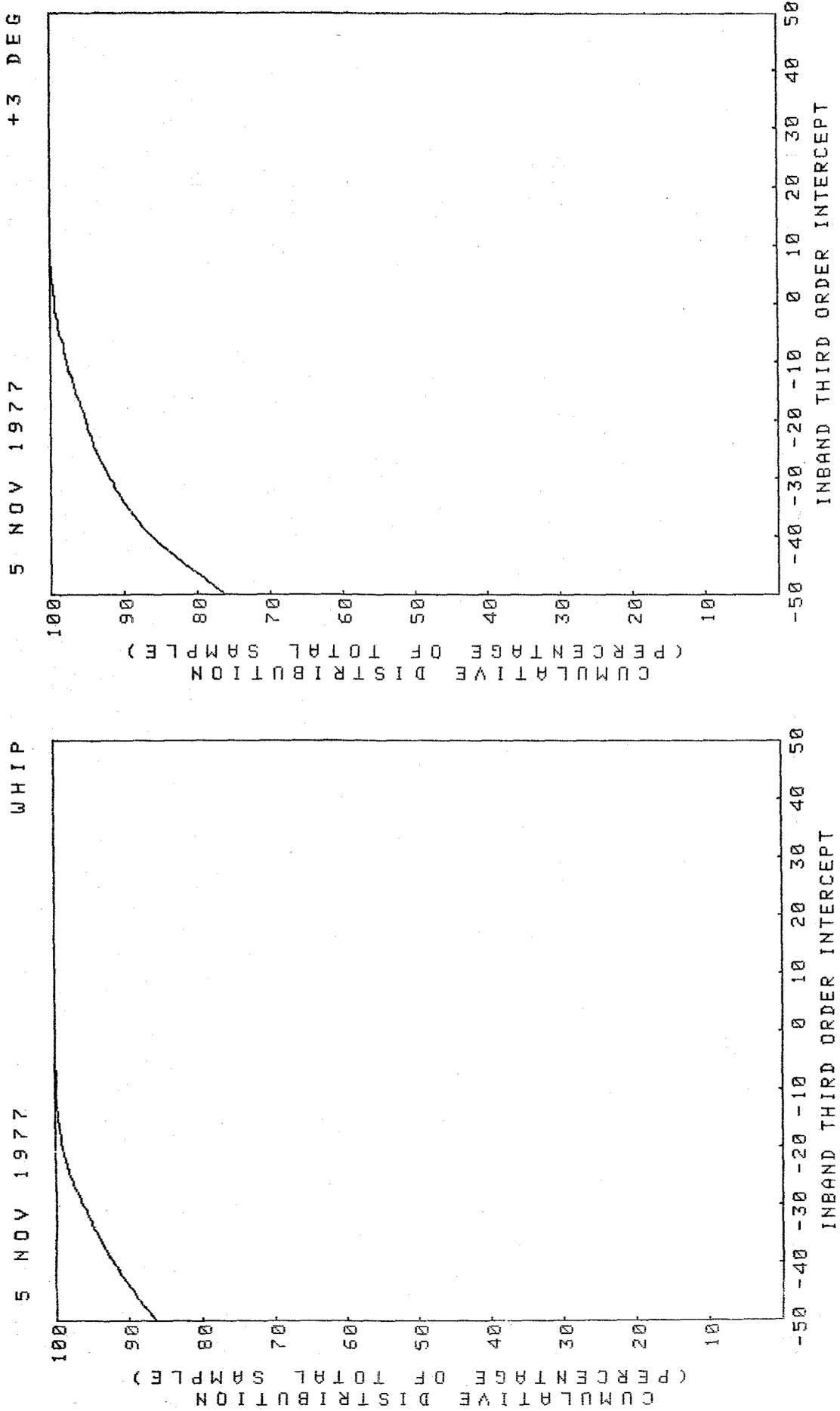


Figure 36. Surveillance data third order in-band IMD statistics

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5 NOV 1977 WHIP

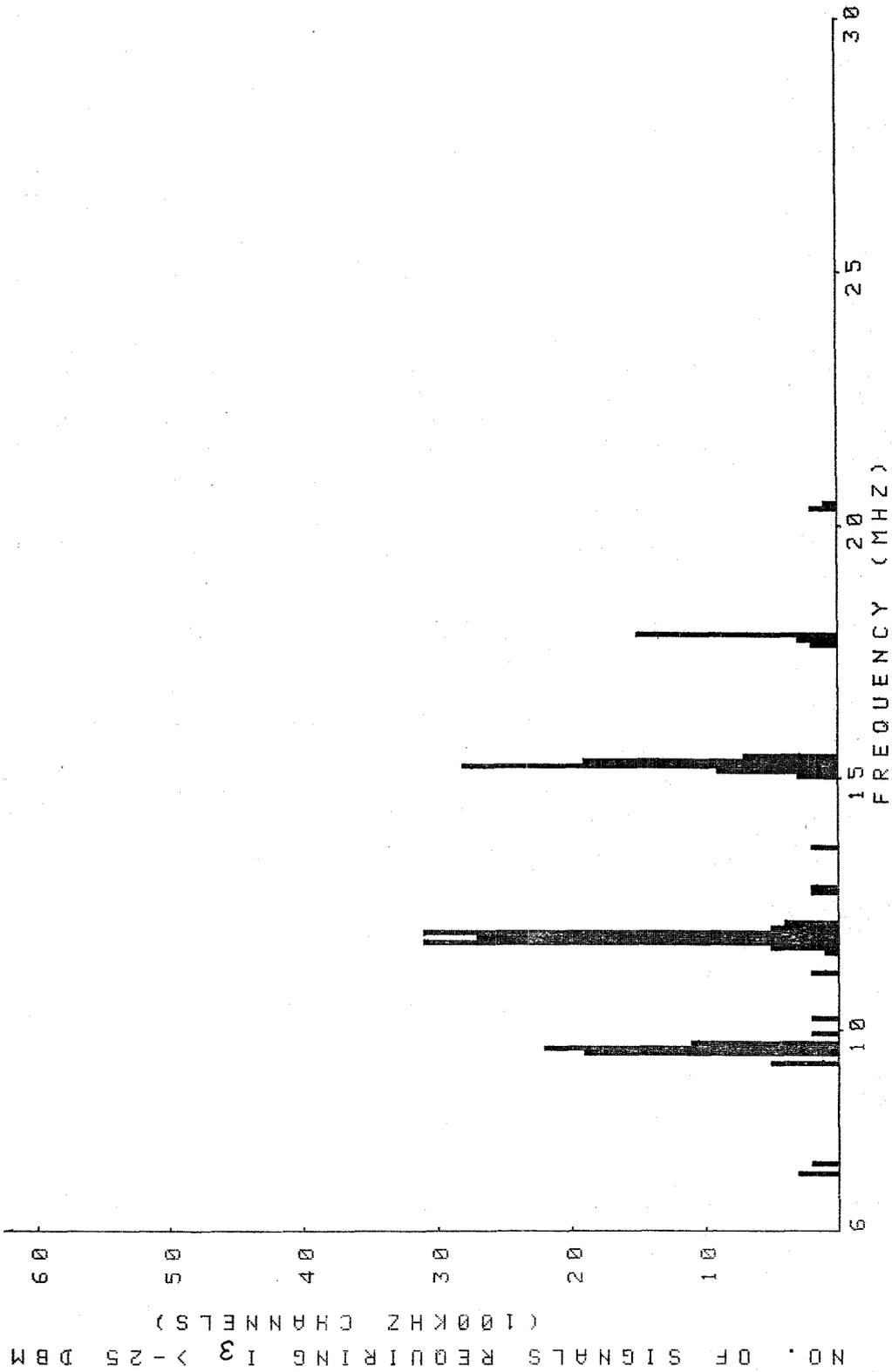


Figure 37. Histogram of channels requiring in-band third order intercept > -25 dBm

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5 NOV 1977 +3 DEG BEAM

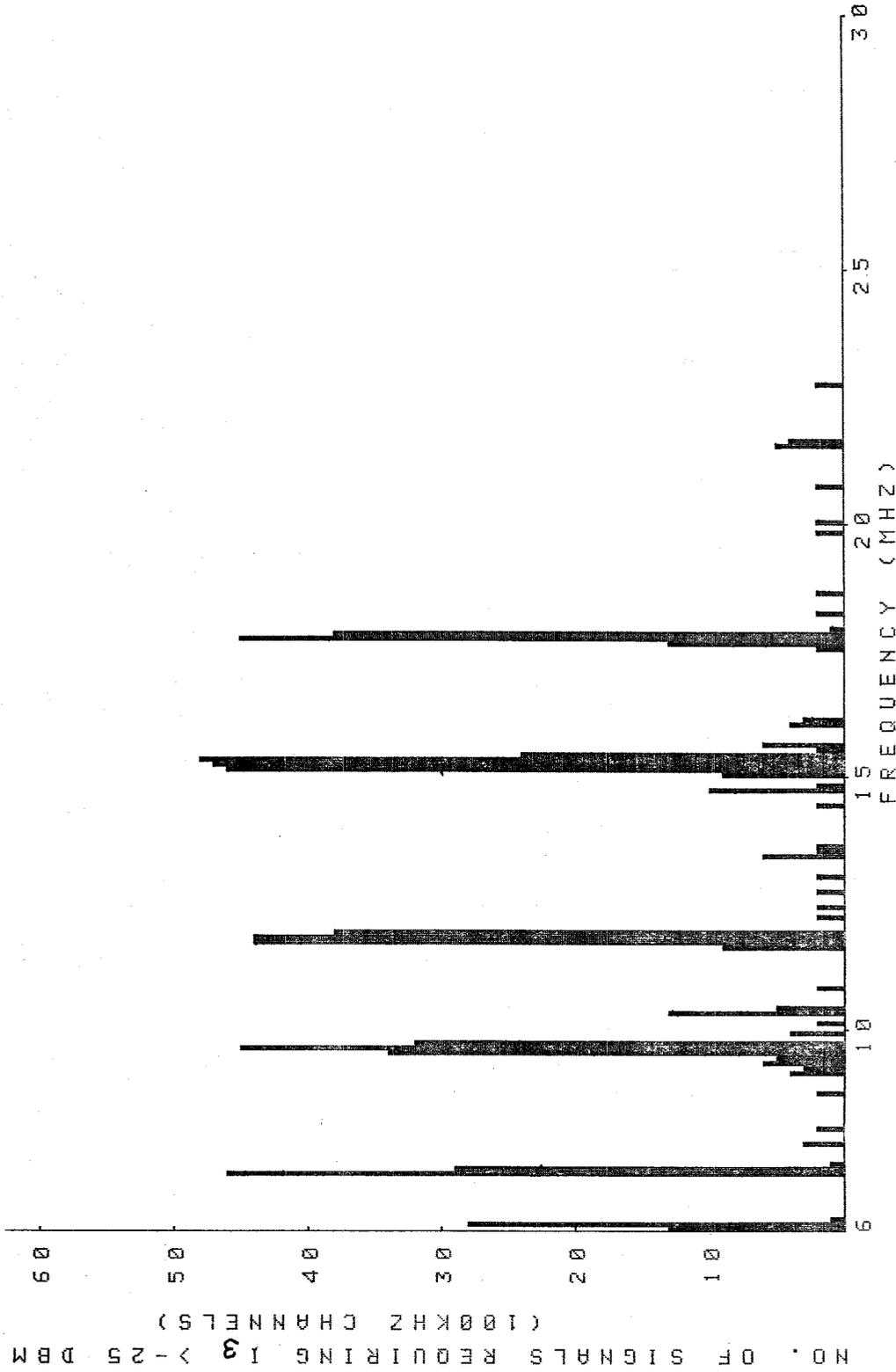


Figure 38. Histogram of channels requiring in-band third order intercept > -25 dBm

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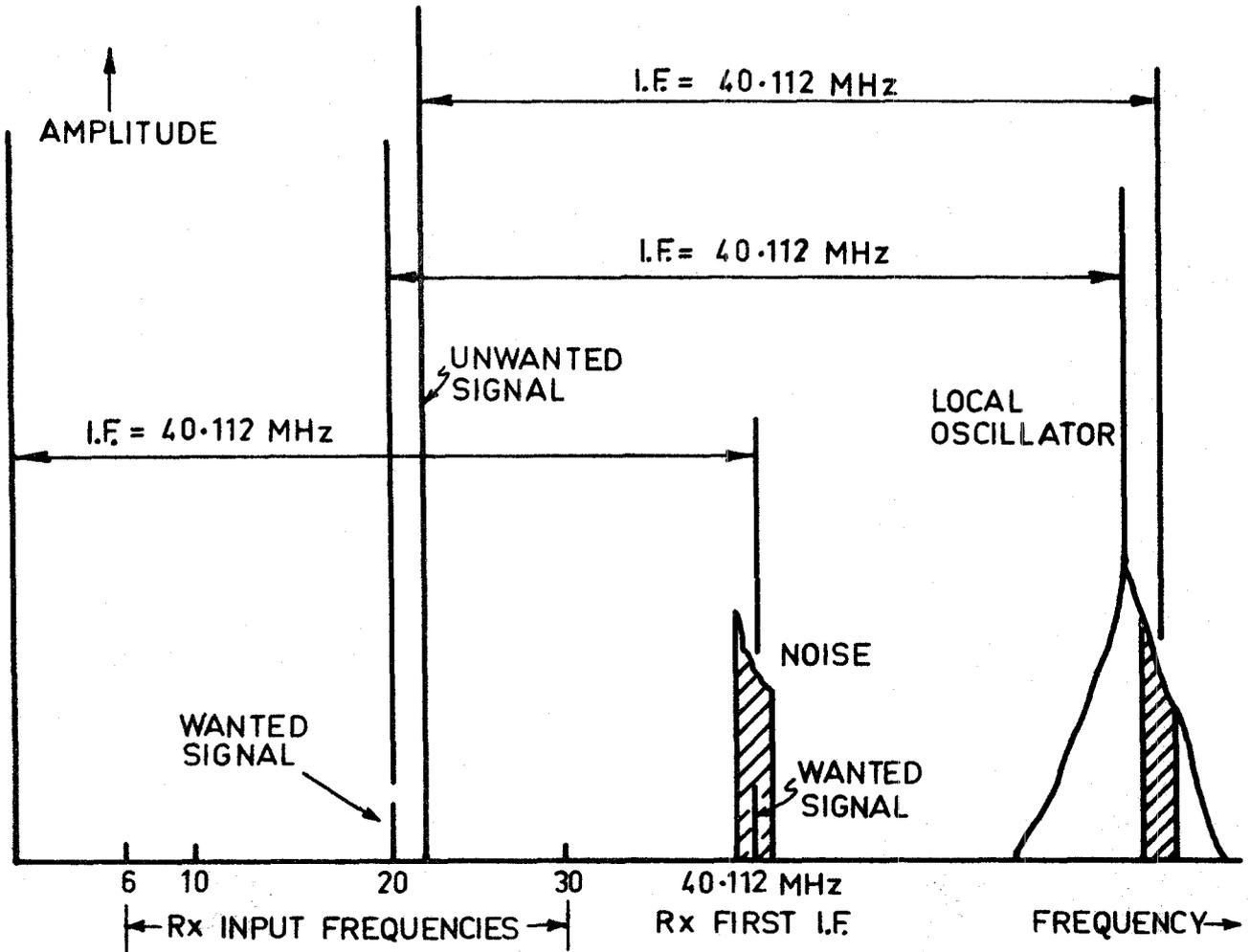


Figure 39. Interference in receiver due to reciprocal mixing

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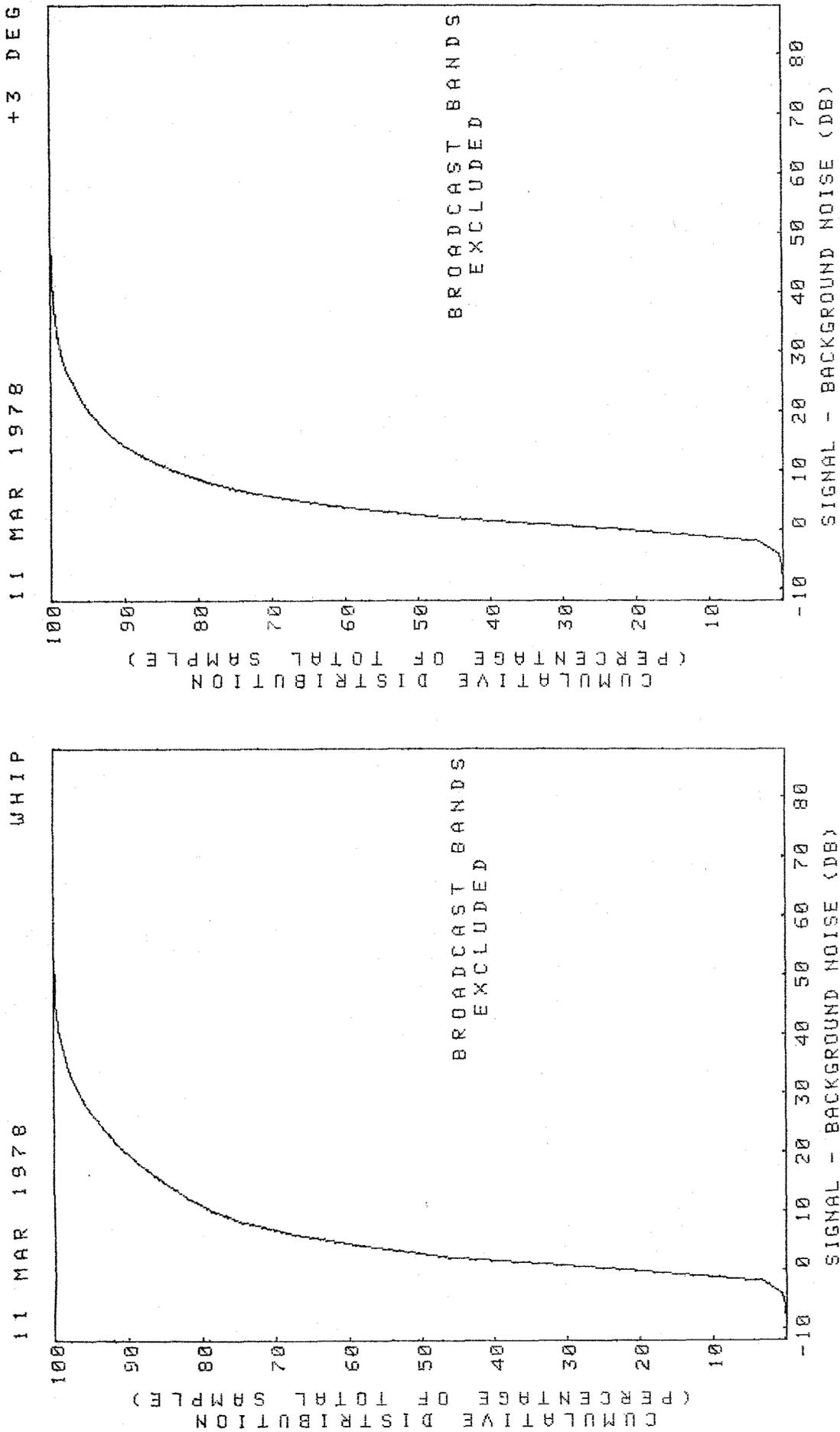


Figure 40. Surveillance data dynamic range statistics (broadcast bands excluded)

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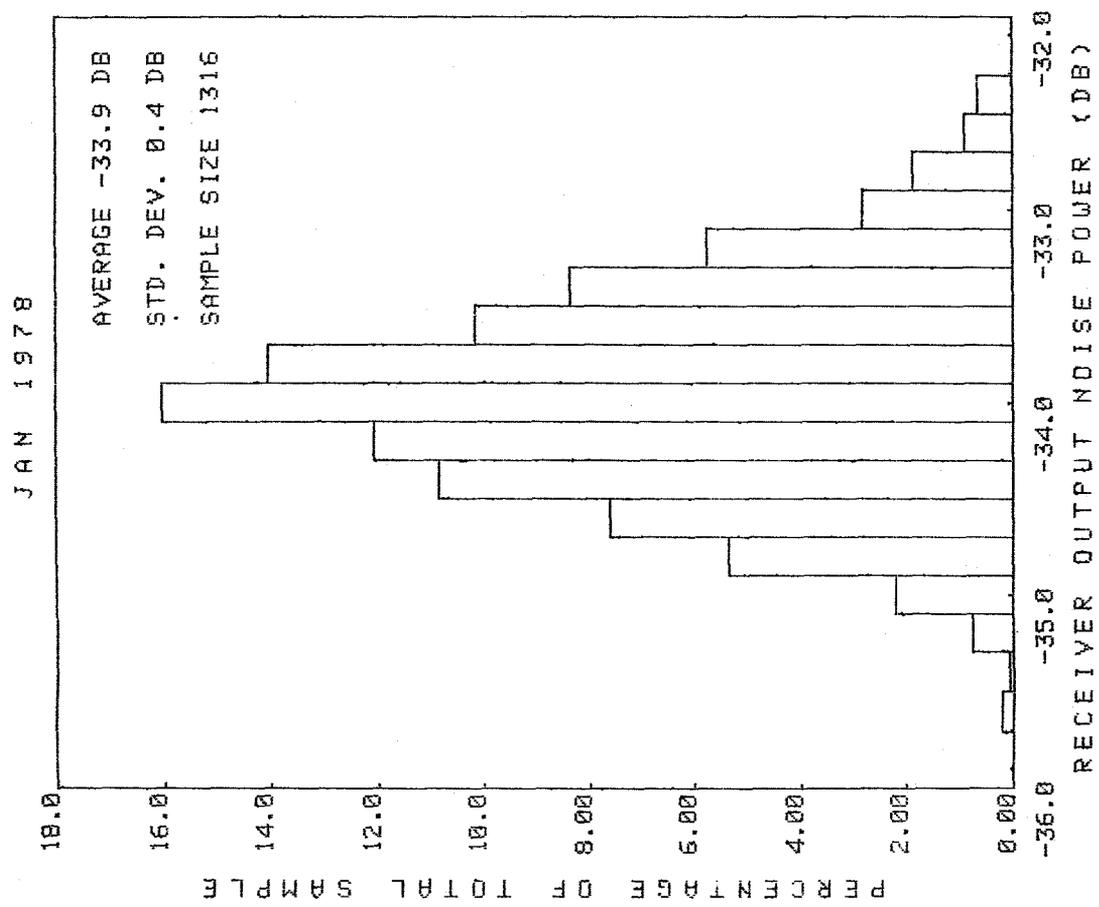
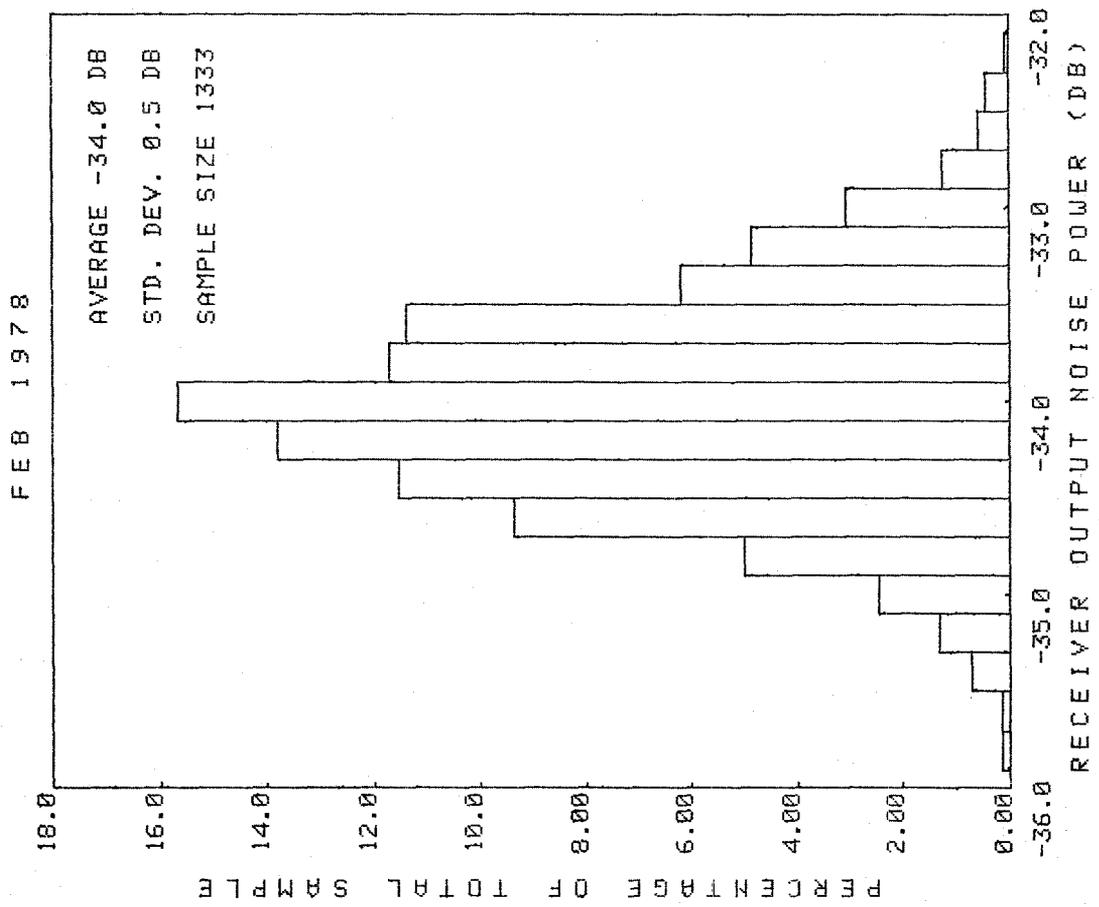


Figure 41. Receiver gain variation

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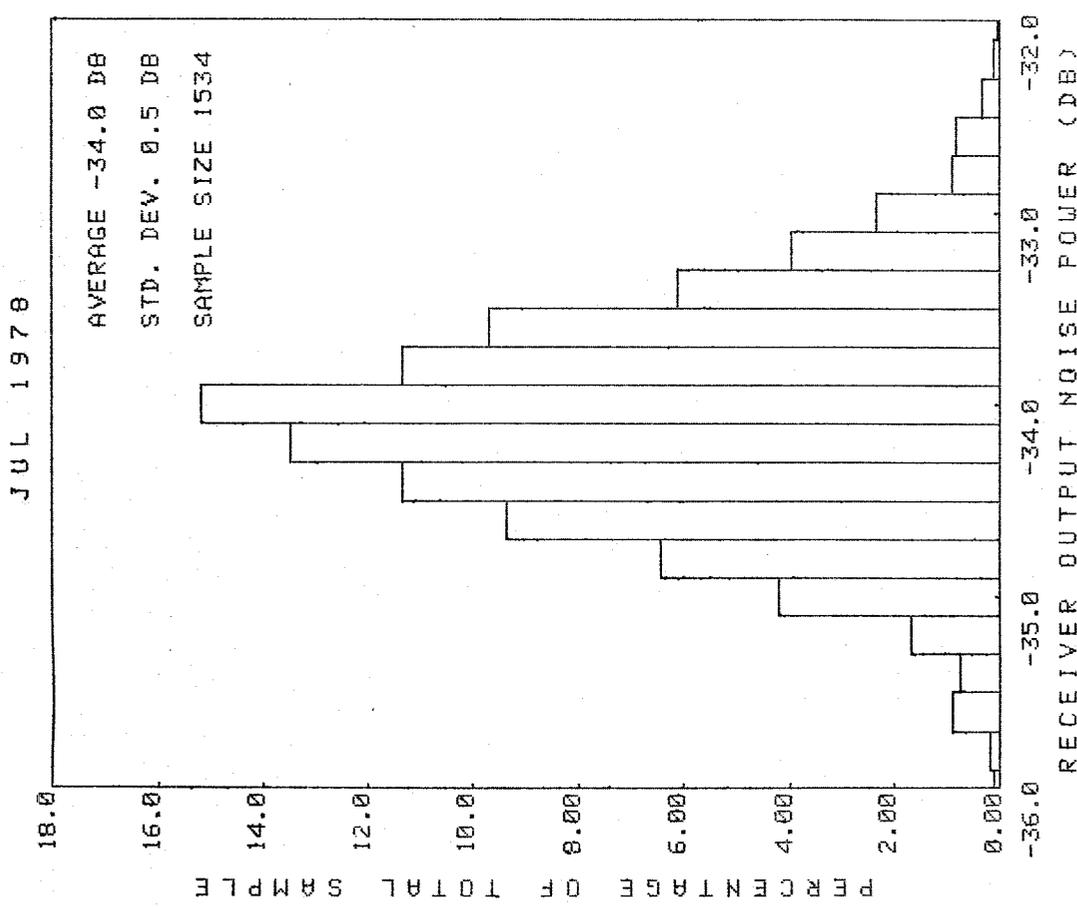
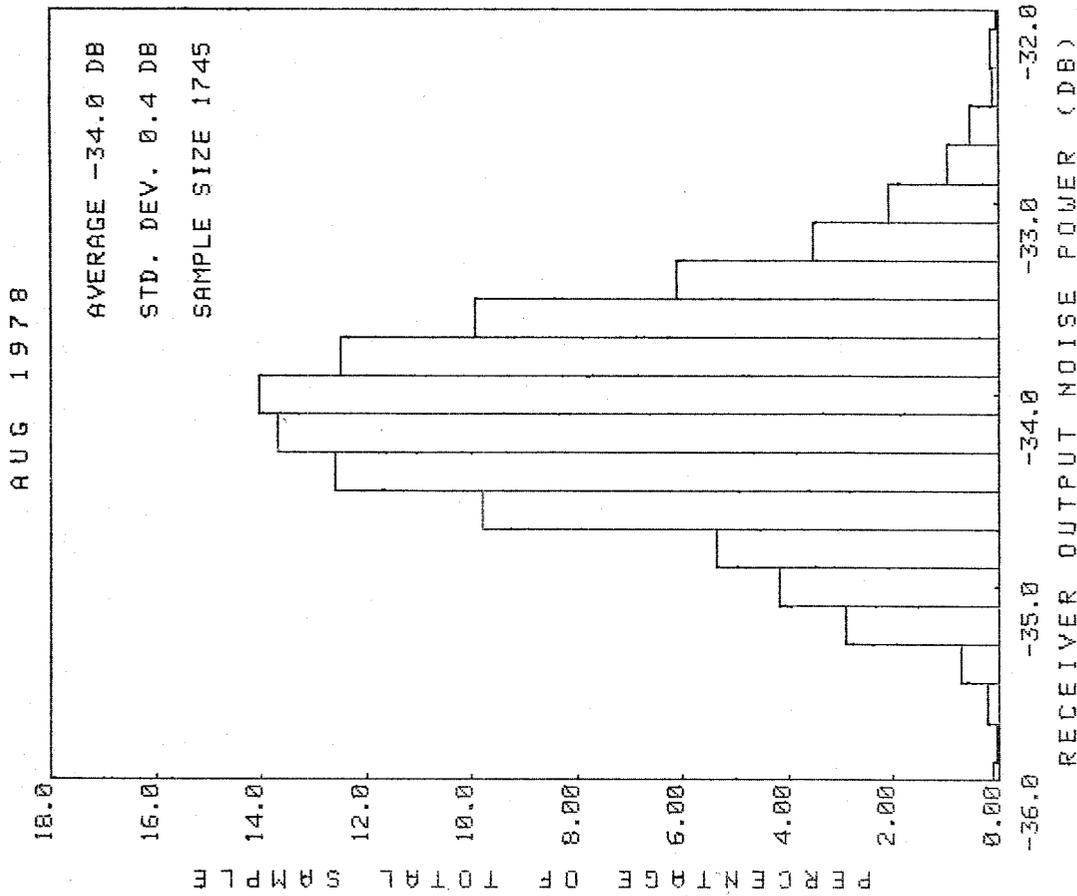


Figure 42. Receiver gain variation

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14 DESCRIPTORS:

- a. EJC Thesaurus Terms
 - H.F. receivers
 - H.F. signal strengths
 - H.F. environment
 - H.F. dynamic range
- b. Non-Thesaurus Terms

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