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Measurements of an FM Receiver in FM Interference

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MEASUREMENTS OF AN FM RECEIVER IN FM INTERFERENCE

John R. Juroshek*

This report investigates the performance of an FM, landmobile, receiver in FM interference. Measurements are described showing the effects of multiple interfering FM signals as a function of modulation index, signal-to-interference ratio, signal-to-noise ratio, and frequency offset between the victim and interferer. The performance of the receiver is measured with various combinations of one to three interfering FM signals. The report also describes the spectra of the audio output during various interference conditions.

Key words: frequency modulation; spectrum; interference; communications; land-mobile radio

1. INTRODUCTION

An estimate of the performance of an FM system is often based on the assumption that white Gaussian noise is the factor limiting performance. Increased demands for spectrum, however, are resulting in more instances where interfering signals are the dominant source of degradation. Thus, it becomes increasingly important to understand how an FM receiver behaves in FM interference.

This report will discuss the laboratory measurements of a single FM receiver in a co-channel and off-frequency FM interference environment. The effects of one to three independent, interfering, FM signals are measured as a function of modulation index, signal-to-interference ratio,

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signal-to-noise ratio, and frequency offset between victim and interferer. The measurements are limited to a single mobile transceiver that operates on a frequency of 171.8 MHz. The measurements also are limited to laboratory tests with nonfading signals.

2. TEST DESCRIPTION

A block diagram of the test setup is shown in Figure 1. As can be seen, the output from four FM signal generators is added in a 50 ohm summing circuit. One of these generators represents the desired signal, while the other three are the interfering signals. Modulation for the FM signal generators is obtained either from the internal sine wave sources within the units or from external voice signals. Each of the external voice modulating signals is independent and is obtained from cassette recordings of spoken phrases. All voice signals are low-pass filtered to eliminate high frequency components from the cassette recorders. These are "Butterworth" filters with a cutoff frequency of 5 kHz and attenuation of 24 dB per octave.

White Gaussian noise is included in the tests as shown in the lower part of Figure 1. The output from a noise diode is filtered with a bandpass filter centered at 171.8 MHz and bandwidth of 8 MHz. The filtered noise is amplified in a 40 dB amplifier and sent to the summing circuit. The purpose of the noise filter is simply to prevent overloading of the RF amplifier by the out-of-band noise.

The summed signal containing desired and interfering signals, and noise is connected to the RF input terminals of the victim FM receiver. All RF connections use double shielded 50 ohm coax. The audio output from the receiver is directed either to a speaker or to a noise and distortion

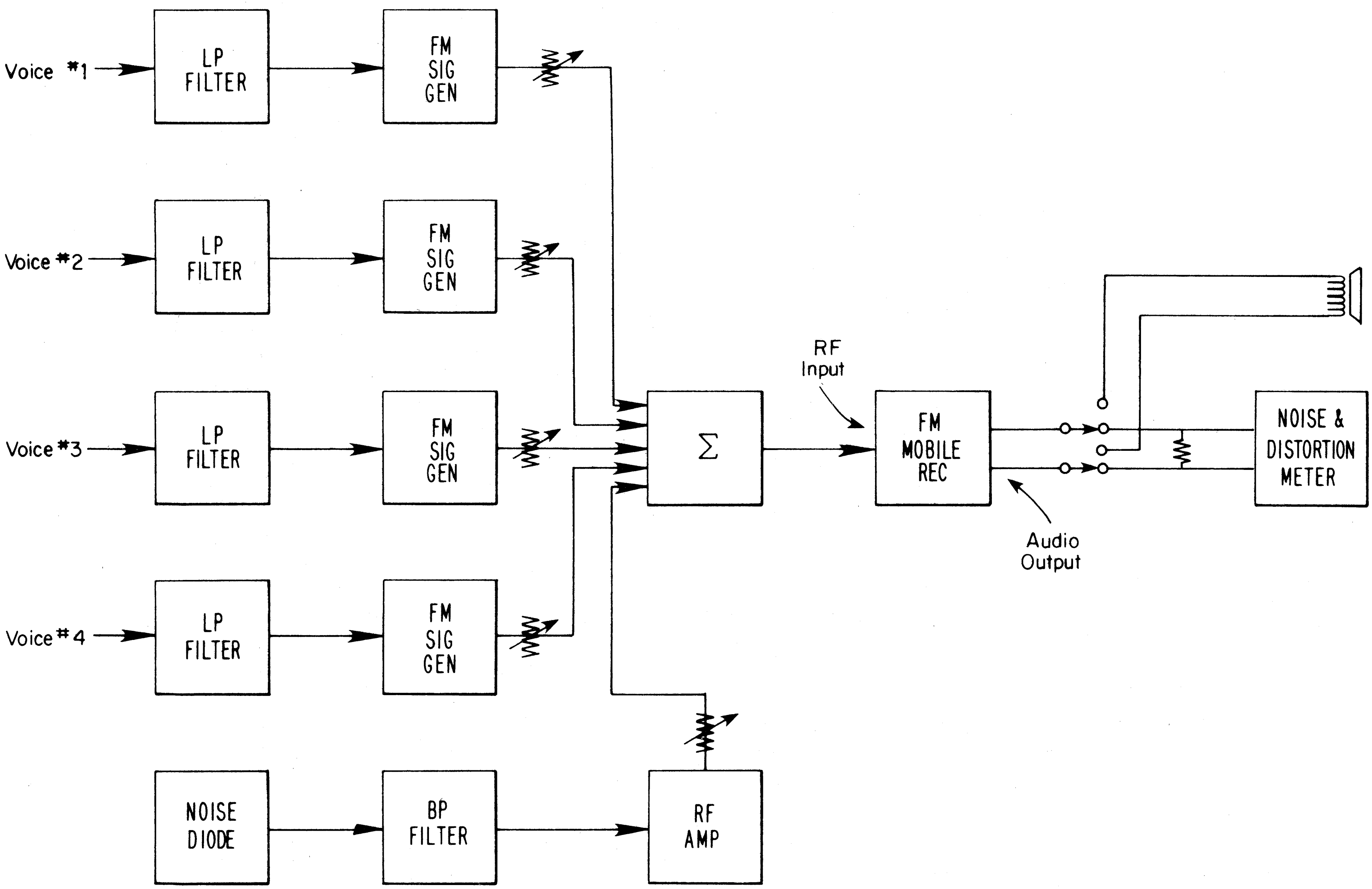

Figure 1. Block diagram of equipment.

meter whose input is terminated with a noninductive resistor equal to the nominal speaker impedance.

Whenever possible, the tests were conducted according to the procedures recommended in EIA Standard RS-204-A (Electronic Industries Association, 1972). The only major deviation from the recommended standard occurs when the FM signal generators are voice modulated. The standard requires that the FM generators be tone-modulated and thus does not define test procedures for voice modulation. Although most of the tests were conducted with tone modulation, it was felt that at least a few tests should use voice modulation to see if there were any major differences.

The FM generators were modern units whose output could be frequency locked to insure a stability of better than 5×10^{-8}. The accuracy of the counter used to set the generators, on the other hand, was only one part in 10^6. Thus, the frequency that the generators are tuned to is known to an accuracy of 500 Hz. This accuracy, however, is sufficient for these tests.

One problem that was discovered during the tests is the off-frequency phase noise that is emitted from the FM generators. The generator specifications state that the phase noise, 20 kHz offset from the carrier, be less than 136 dB below the carrier in a 1 Hz bandwidth. A plot of the phase noise specifications for the FM generators at other frequencies is given in Figure 2. Thus, a receiver with 10 kHz equivalent rectangular bandwidth, at F_c +20 kHz, could expect to receive a signal of approximately

$$P_\phi = -136 + 10 \log 10^4 \text{ dB} \qquad (1)$$

below the carrier, or

$$P_\phi = -96 \text{ dB.} \qquad (2)$$

This, of course, limits the dynamic range over which off-frequency tests can be made. In practice, the dynamic range of off-frequency testing should be limited to approximately -90 dB below the carrier since the interference from adjacent channel effects must be distinguishable from the - 96 dB phase noise. Thus, throughout the report we shall assume that the dynamic range of the test setup is limited to -90 dB relative to the carrier for frequency offsets of 25 kHz $\leq \Delta f \leq 30$ kHz.

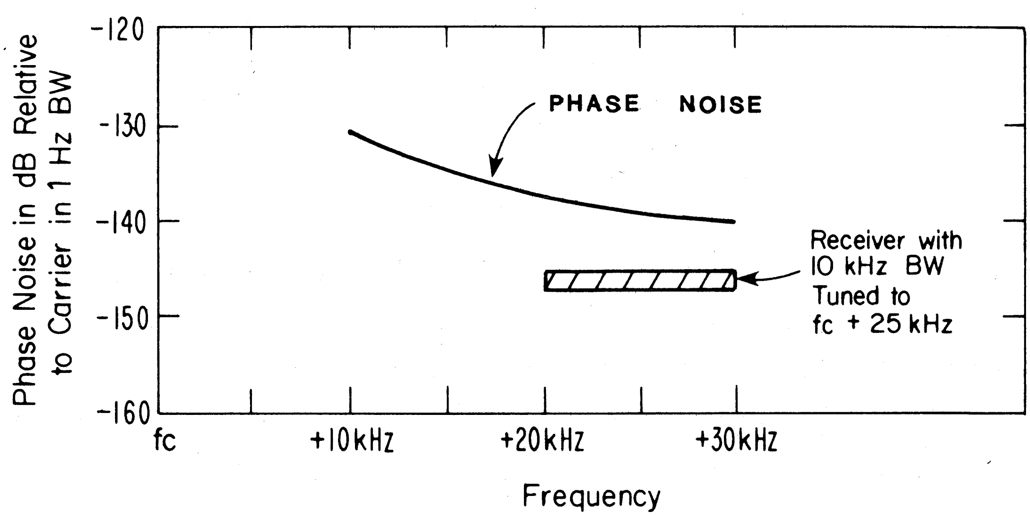

Figure 2. Phase noise from FM generators.

Unfortunately, the test receiver had a selectivity or adjacent channel rejection specification of -100 dBm. This measurement, as per EIA Standard RS-204-A, is made at a frequency offset of 30 kHz. Although a selectivity of -100 dB cannot be tested with a test setup that is limited to -90 dB, the tests were continued since most of the off-frequency measurement results were less than -90 dB. In order to achieve a -100 dBm adjacent channel measurement capability, screen room shielding would probably be needed, as well as substantially improved signal generators.

The discussion so far has assumed that the phase noise is from 1 FM generator. This test setup however, can have up to three active interfering generators and one victim generator. Let us assume the total power of the three interfering generators at the input to the receiver is

$$i_{IN} = i_1 + i_2 + i_3 \tag{3}$$

where i_k is the power in the kth interfering signal source. This report uses a convention of designating numeric values with lower case letters and equivalent dB values in upper case. The ratio of i_{IN} to total phase noise power is then given by

$$\frac{i_{IN}}{p_\phi} = \frac{i_1 + i_2 + i_3}{p_1 + p_2 + p_3} \quad , \tag{4}$$

where p_i is the phase noise contribution of the ith generator. However, for various reasons, we have found it necessary to restrict the tests to equal amplitude interfering signals which means that

$$i_1 = i_2 = i_3 \quad , \tag{5}$$

and for all practical purposes

$$p_1 = p_2 = p_3 \quad . \tag{6}$$

Thus

$$\frac{i_{IN}}{p_\phi} = \frac{i_k}{p_k} \quad , \tag{7}$$

which means the ratio of interference power to phase-noise power at the input to the receiver remains constant with the number of interfering sources.

Some other parameters of interest in the test setup are the receiver specifications. These are:

Sensitivity	
12 dB SINAD (EIA method)	0.35
20 dB Quieting	0.50
Channel Spacing	30 kHz
Audio Output	12 watts at less than 3% distortion to 8 ohm speaker
Oscillator Stability	$\pm$ 0.0002%
Maximum Frequency Deviation	$\pm$ 5 kHz

3. TEST RESULTS

One measure of performance for an FM receiver is SINAD, which is an abbreviation for the ratio "signal + noise + distortion to noise + distortion" expressed in dB. This ratio is measured with a noise and distortion meter connected to the output terminals of the receiver. Figure 3 shows the measurement of SINAD in Gaussian noise. For this particular test, only one active FM generator is used; the desired generator. The quantity S/N_{IN} designates the ratio of signal power to noise power at the input to the receiver and θ denotes peak frequency deviation. Noise power here is referenced to the receiver IF bandwidth, or

$$N_{IN} = 10 \log (n_o \, b_{IF}) \quad dB \quad , \tag{8}$$

where b_{IF} is the IF noise power bandwidth, and n_o is the noise power density. The value of b_{IF} for the test receiver is 10.1 KHz. All SINAD measurements were conducted with a 1000 Hz modulating tone on the desired FM generator.

Figure 3 shows the classical FM improvement-threshold relationship. The larger value of θ, provides a larger value of SINAD provided S/N_{IN} is above threshold. Unfortunately, the threshold requirements also increase with increasing θ. One should note that the maximum SINAD obtainable with the test receiver is approximately 30 dB, which is consistent with its specifications. A SINAD of 0.0 dB is used to designate a loss of capture of the desired signal.

Figures 4, 5, and 6 show similar measurements except that FM interference is now substituted for the Gaussian noise. Figure 4 shows the results with a single FM interferer while 5 and 6 are for two and three equal amplitude FM interferers respectively. The curves are plotted in S/I_{IN}, which is the ratio of signal-power to total-interference-power at the input to the receiver. Again, as per EIA specifications, the desired FM signal is modulated with a 1000 Hz tone while each interfering signal is modulated with a 400 Hz tone. All of the tests were made at a desired input signal level of S_{IN} = - 80 dBm and zero frequency offset between the desired and interfering signals.

The important difference to note in Figures 3 through 6 is that the threshold requirements change somewhat for FM interference as compared to Gaussian noise. Although the definition of threshold is arbitrary, it is evident that with θ = 5 kHz, an S/N_{IN} greater that 11 dB is required for satisfactory operation, in Gaussian noise. However, with single FM interference, this reduces to 5 db.

These results are summarized in Table 1, which shows an estimate of the S/I_{IN} or S/N_{IN} that is required to produce an output SINAD = 12 dB.

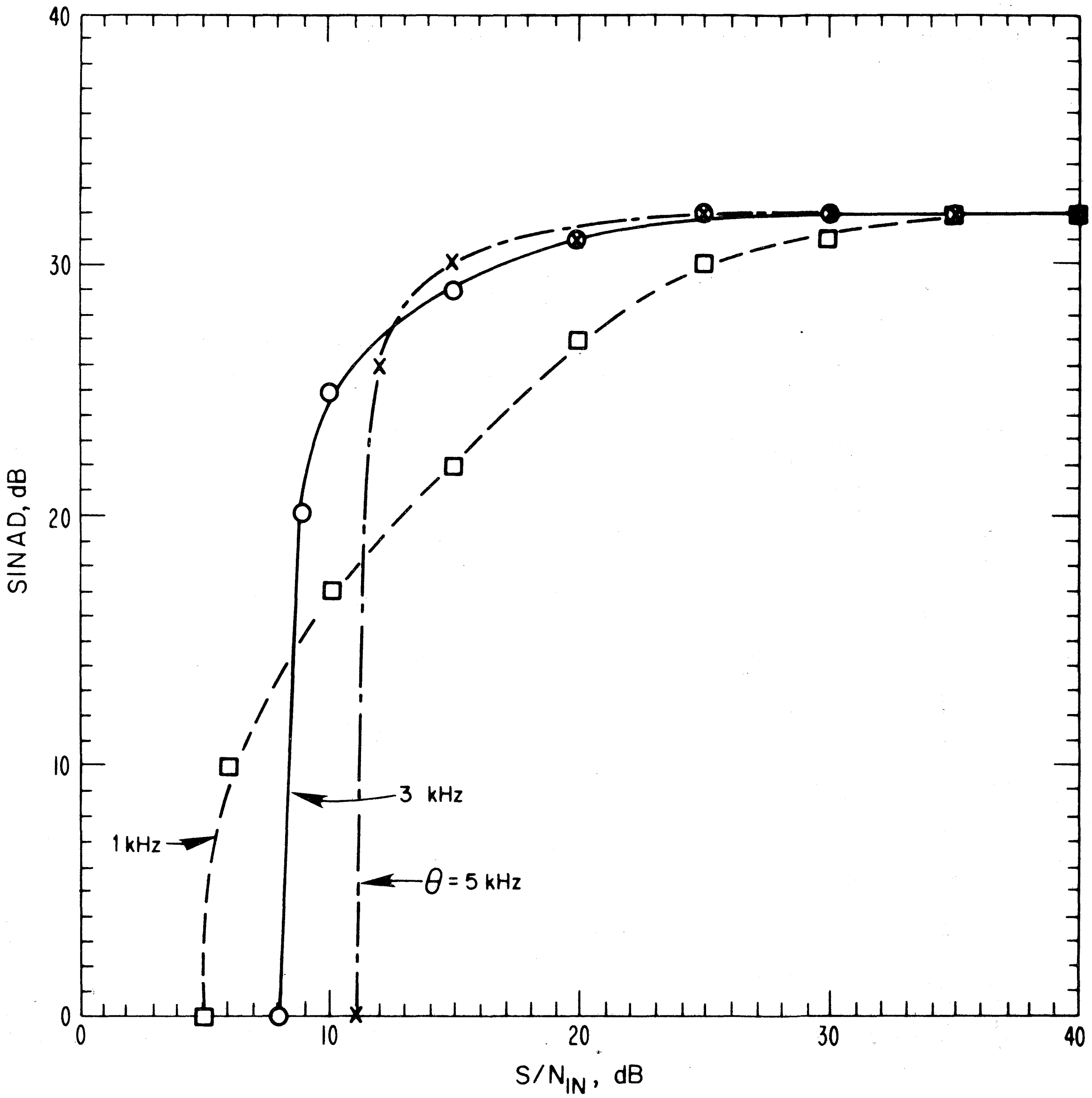

Figure 3. Measured performance of an FM receiver in Gaussian noise.

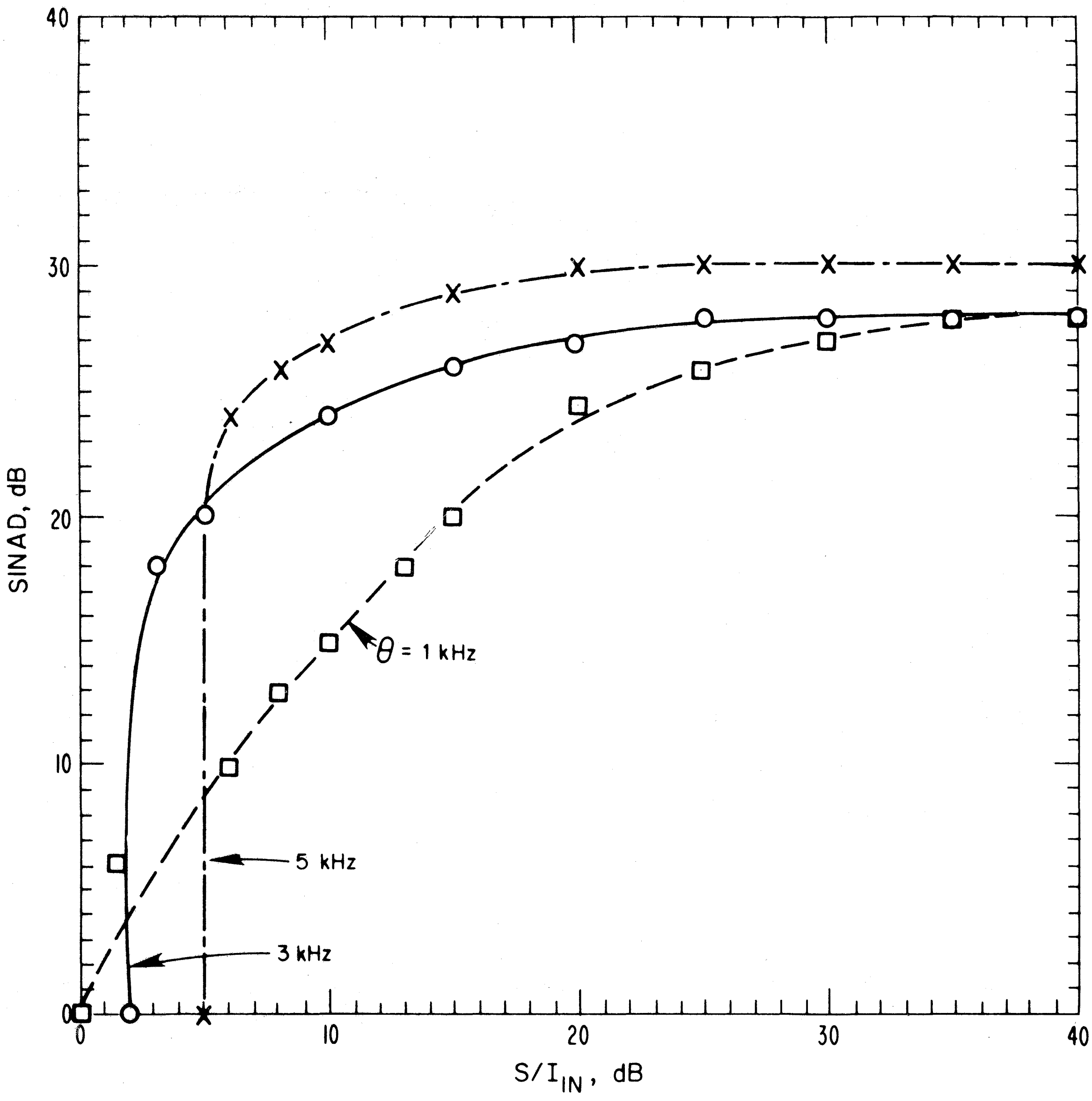

Figure 4. Measured performance of an FM receiver with a single FM interferer.

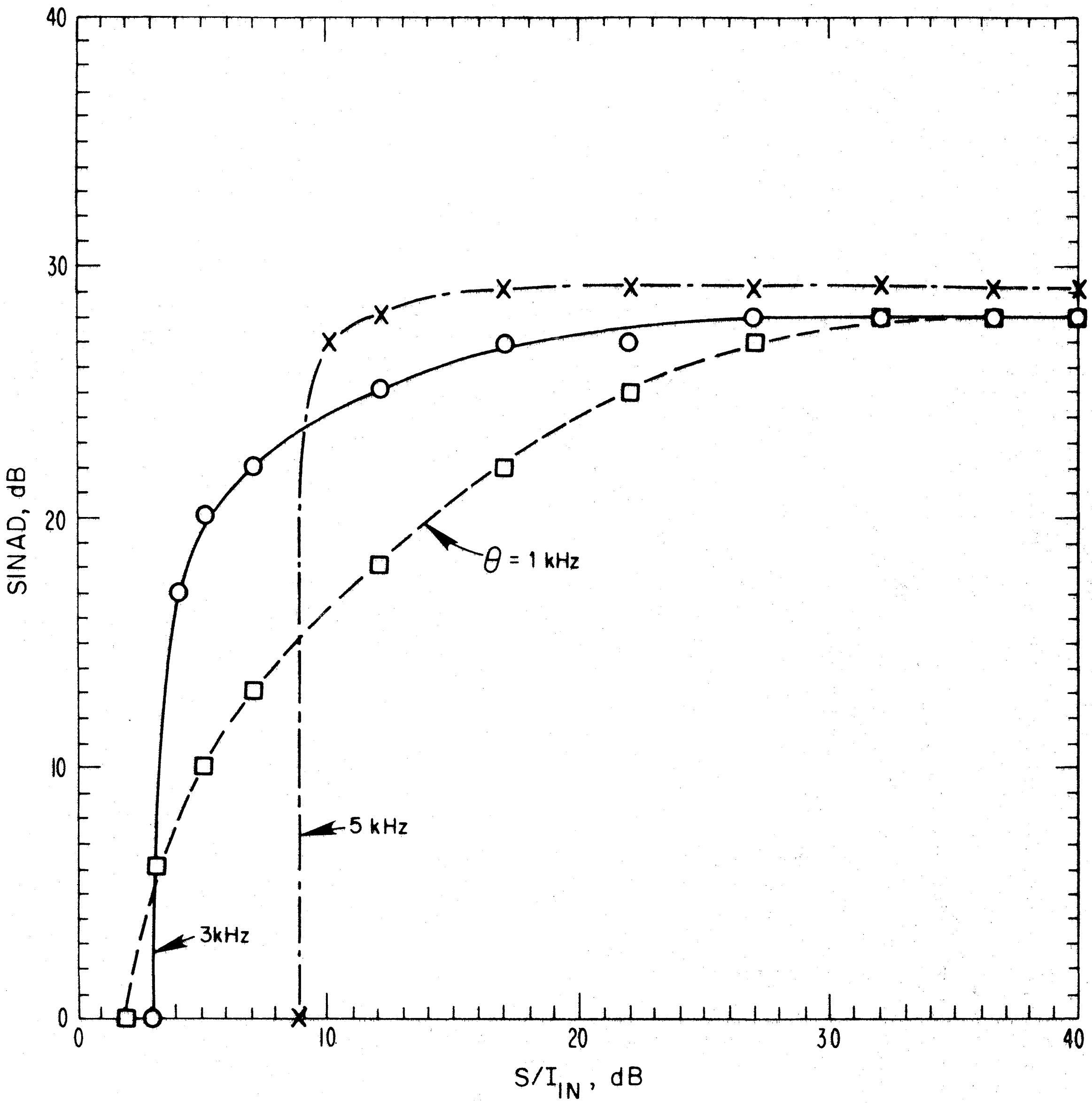

Figure 5. Measured performance of an FM receiver with two equal amplitude interferers.

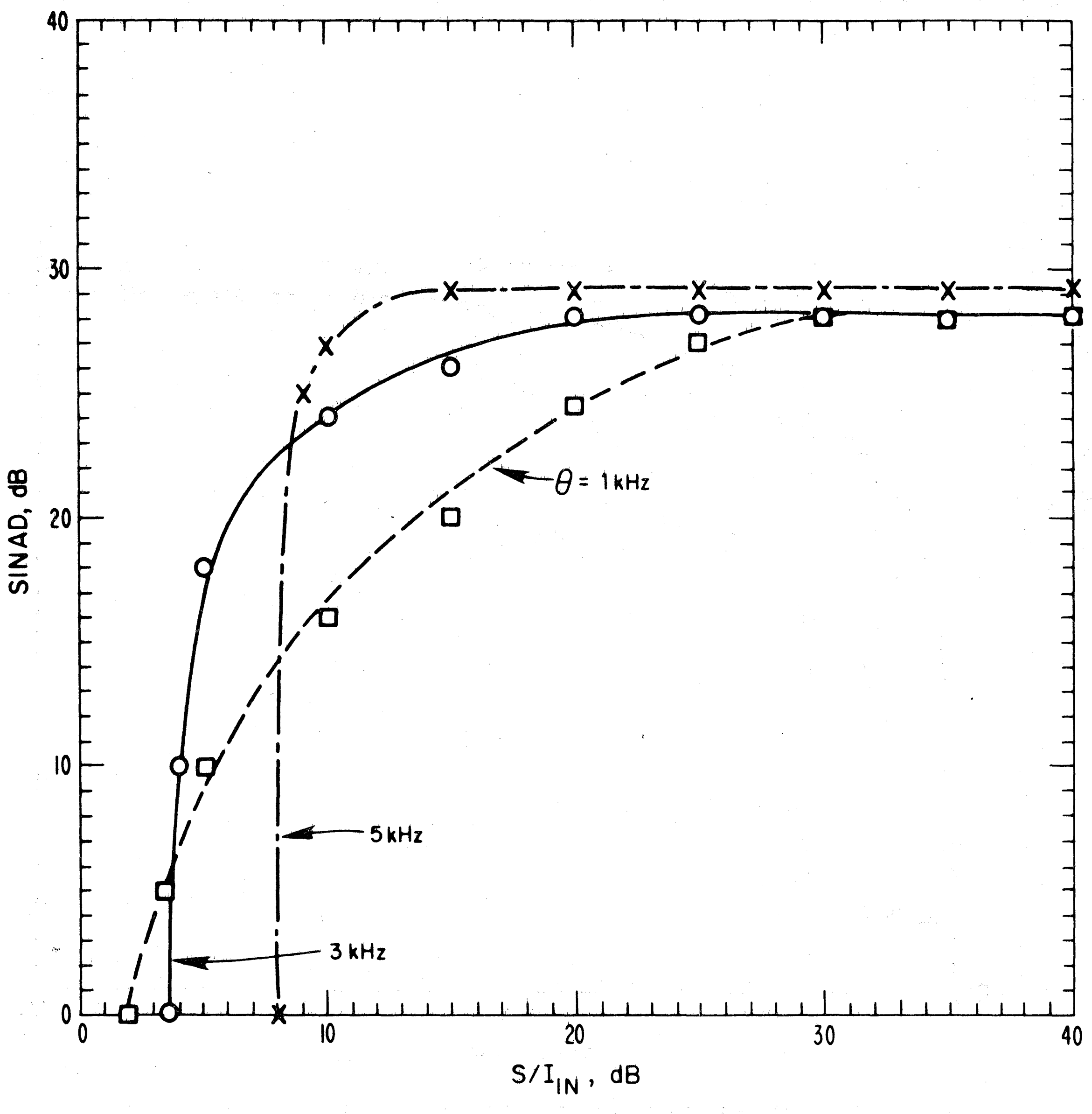

Figure 6. Measured performance of an FM receiver with three equal amplitude interferers.

TABLE 1. Estimates of S/N_{IN} Required to Produce a SINAD = 12 dB

Interference	S/I_{IN} or S/N_{IN} θ = 1 kHz	θ = 3 kHz	θ = 5 kHz
Gaussian noise	7.0 dB	8.5 dB	11.0 dB
1 FM Signal	7.5 dB	2.0 dB	5.0 dB
2 FM Signals	6.0 dB	3.5 dB	8.5 dB
3 FM Signals	6.5 dB	4.0 dB	8.0 dB

Note that, contrary to what one might initially expect, the SINAD does not necessarily increase with increasing θ. The reason is that a SINAD = 12 dB is below threshold in most instances. Above threshold, however, SINAD does increase with increasing θ. This is shown in Table 2 where SINAD is tabulated for a constant S/I_{IN} (or S/N_{IN}) of 20 dB.

TABLE 2. Estimates of SINAD for S/I_{IN} or S/N_{IN} = 20 dB

Interference	SINAD θ = 1 kHz	θ = 3 kHz	θ = 5 kHz
Gaussian Noise	26.0	31.0	31.5
1 FM Signal	24.0	26.0	30.0
2 FM Signal	24.0	27.5	29.5
3 FM Signal	24.5	28.0	29.0

Frequency offset between the victim and interfering signals is denoted Δf, where a positive Δf means the interfering signals are higher in frequency than the desired signal. Figure 7 shows a plot of S/I_{IN} that is required to produce a SINAD of 12 dB for various Δf. The test setup is basically the same as for the previous tests described in Figures 4 through 7, except that θ is set to 3 KHz. It should be pointed out that a SINAD = 12 dB corresponds to marginal performance. Also note from the $\theta = 3$ curves in Figures 4, 5, and 6, that the performance rapidly changes at the SINAD = 12 dB point with small changes in S/I_{IN}. As can be seen, the difference in performance due to one or three interferers is only a few dB.

The response of the receiver when the interferer's frequency is less than the victim (negative Δf) is shown in Figure 8. As can be seen, the results are asymmetrical with the two response curves offset by 1.2 kHz. This offset is due to a combination of receiver tolerances and oscillator stability.

So far, the tests have all used 1000 Hz tone modulation for the desired FM signal and 400 Hz modulation on the interfering generators as specified in the EIA standard. The response with voice modulated interference, however, is similar, as shown in Figures 9 and 10. These figures compare the interference produced by 400 Hz modulation with that produced by voice modulation of the interfering FM signal. Plotted in these figures is the S/I_{IN} required to insure a SINAD of 12 dB as a function of Δf. The peak frequency deviation for both cases is $\theta = 3$kHz. Figure 9 shows the results for a single FM interferer, while Figure 10 shows the results with two equal amplitude interferers. Although the results for three interferers are not shown, they are nearly identical. Therefore, one can conclude that the interference does not change significantly

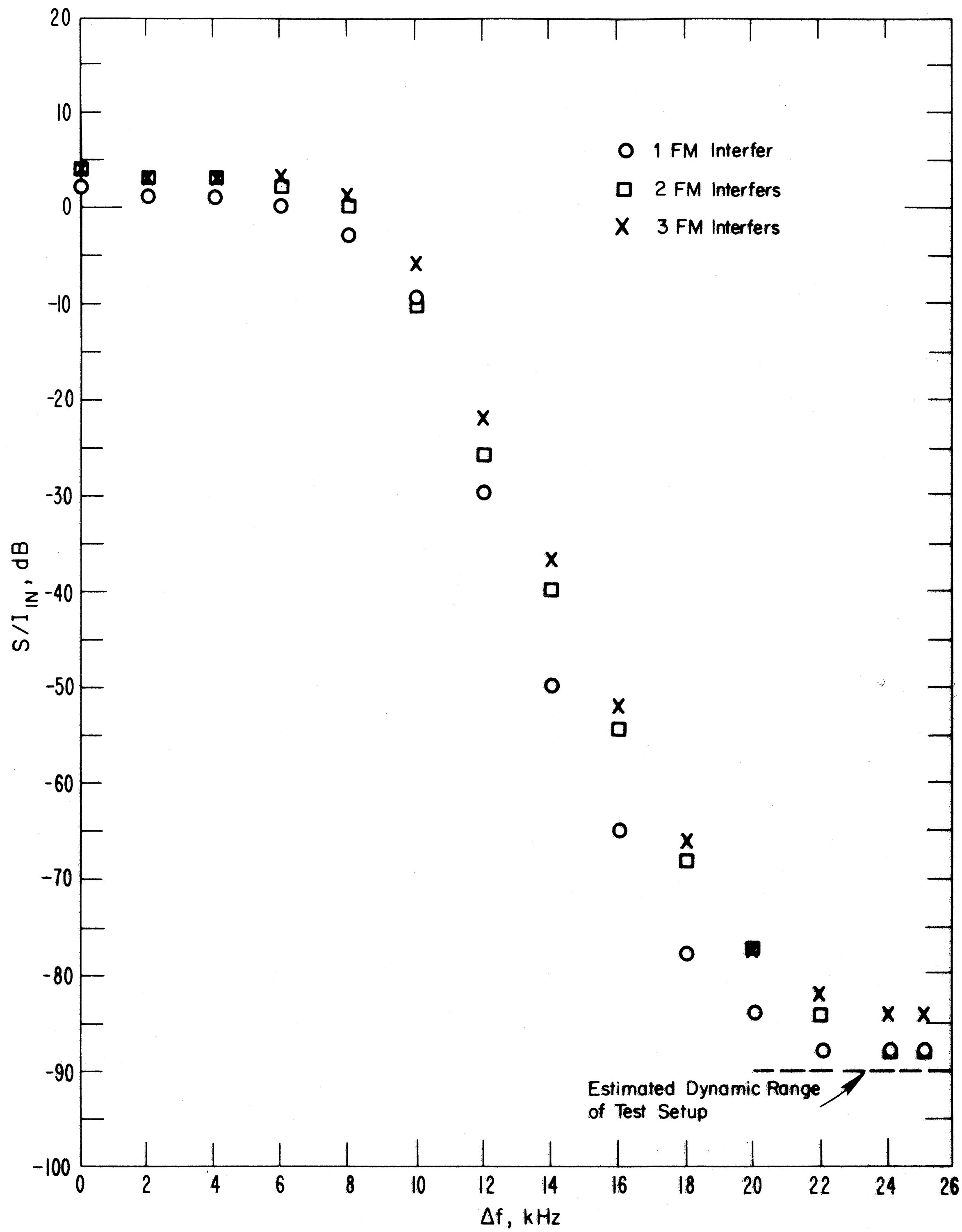

Figure 7. Measured performance of an FM receiver with 1, 2 and 3 equal amplitude FM interferers. Peak deviation of all FM generators is θ = 3 kHz.

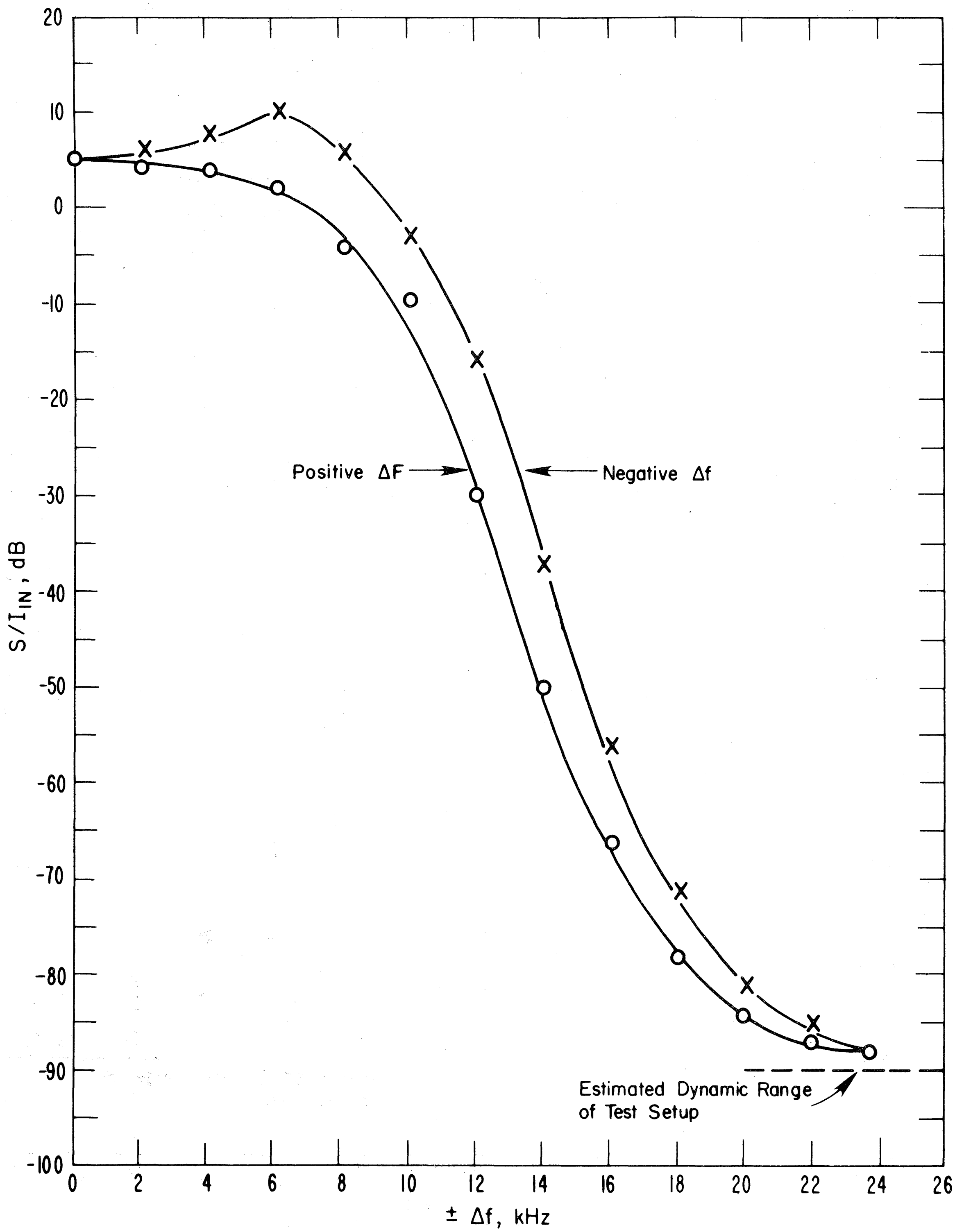

Figure 8. Measured performance of an FM receiver with a single FM interferer and positive and negative frequency offsets. Peak deviation of generators is θ = 3 kHz.

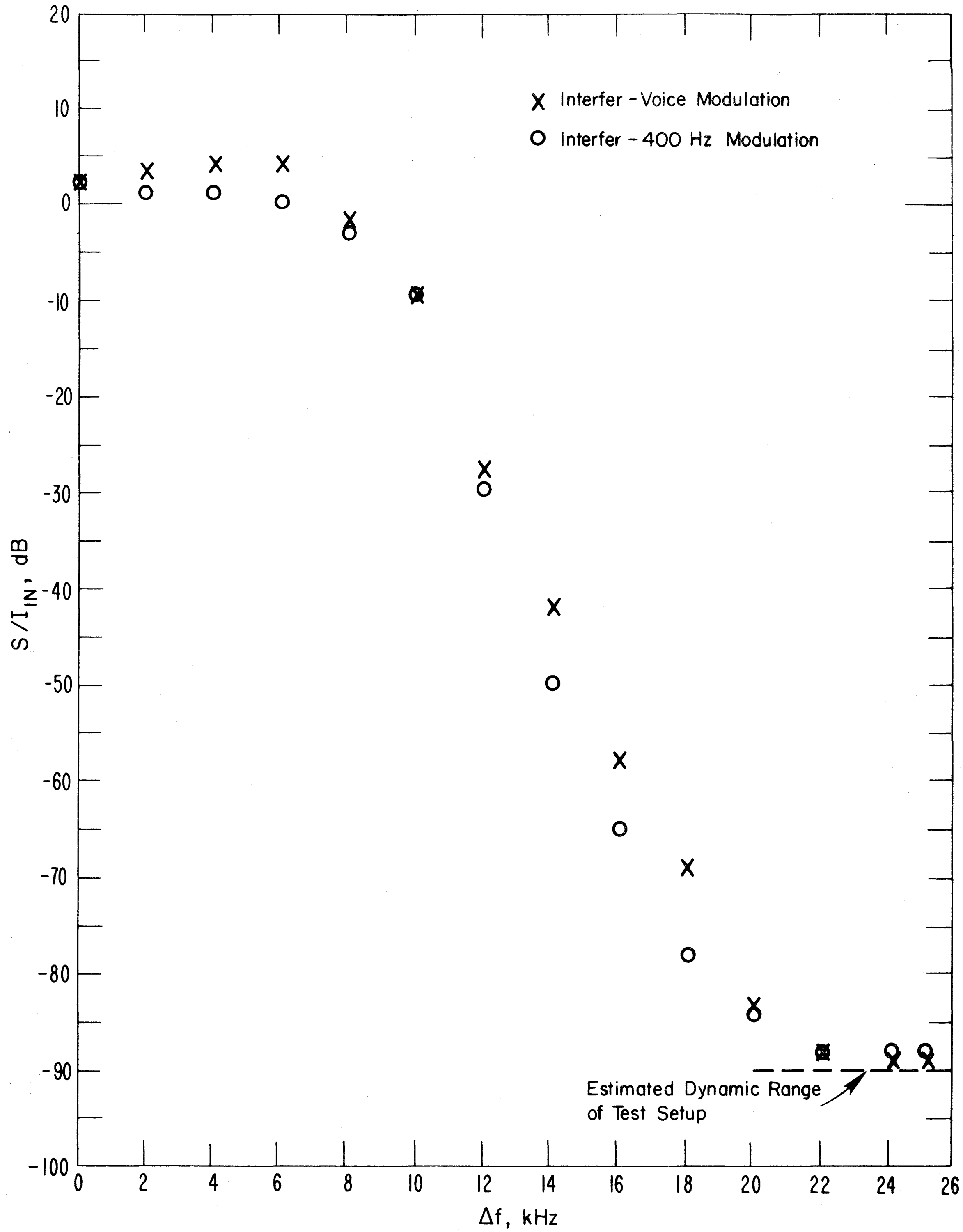

Figure 9. Measured performance of an FM receiver with a single FM interferer. Peak frequency deviation of all FM signals is $\theta = 3$ kHz.

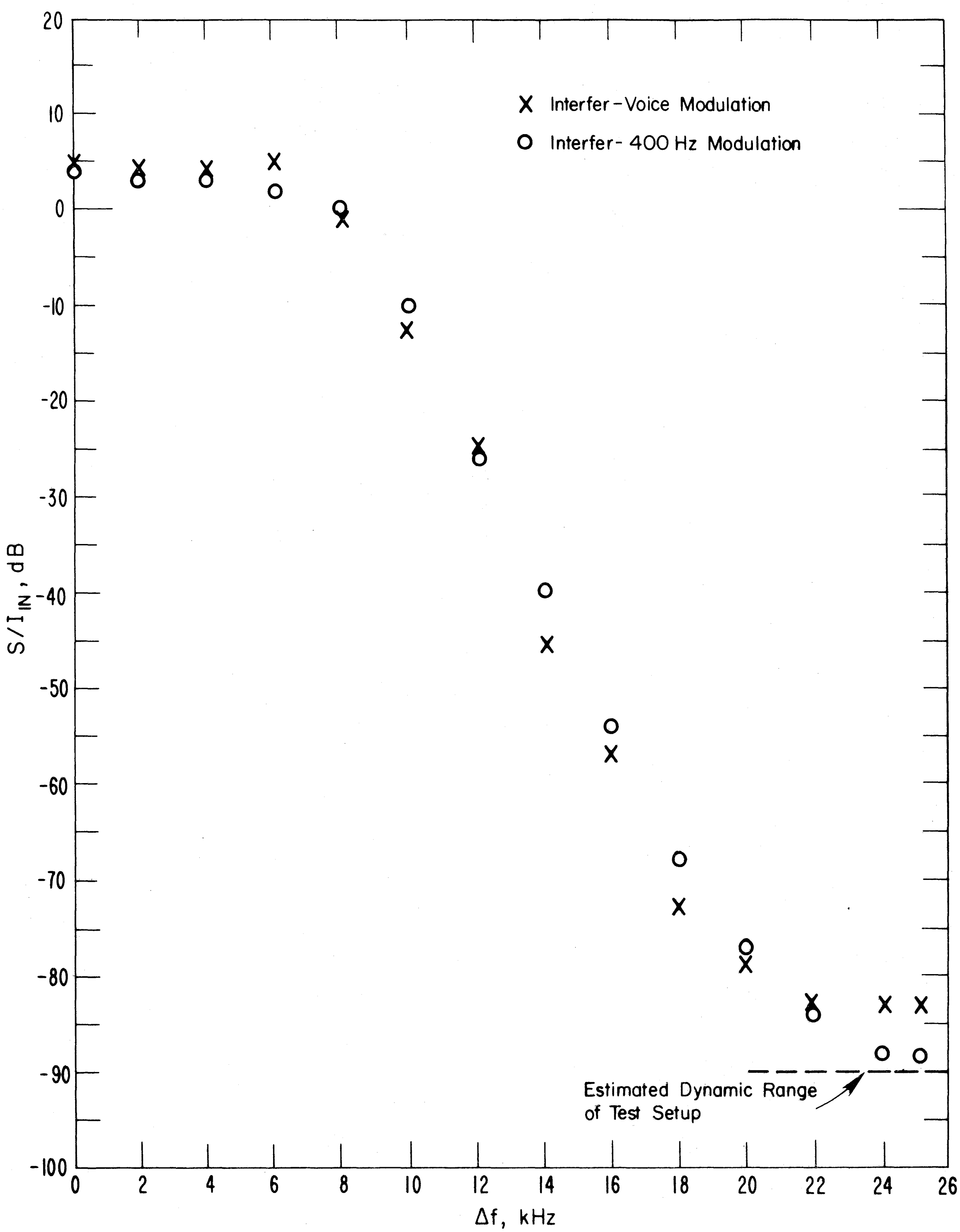

Figure 10. Measured performance of an FM receiver with two FM interferers. Peak frequency deviation of all FM signals is θ = 3 kHz.

if the FM signal is voice modulated in place of the 400 Hz tone modulation.

Tests also were conducted to show the effects of the receiver being subjected simultaneously to Gaussian noise and FM interference. In Figures 11 and 12, a plot of S/I_{IN} that is required for a SINAD of 12 dB is plotted as a function of Δf. This time, however, Gaussian noise is also included in the tests. Results are shown for Gaussian signal-to-noise ratios of 20, 15, and 12 dB. The quantity S/I_{IN} represents signal power to total interference power and does not include the Gaussian noise.

One can see that the Gaussian noise degrades the system's ability to withstand interference. Figure 11 shows a change in S/I_{IN} of approximately 5 dB is required to compensate for the effects of S/N_{IN} of 12 dB. Figure 12 is for the case of two equal amplitude interferers. No tests were made with S/N_{IN} less than 12 dB since the receiver's performance rapidly degrades at this point. Again the tests with three interferers are almost identical and, therefore, are not shown in the report.

These results are summarized in Table 3, where the S/I_{IN} required for a SINAD = 12 dB is shown for various interference conditions and frequency offsets of 12, 20, and 25 kHz. The first three entries are for the tests without Gaussian noise, while the last two entries includes Gaussian noise. Note the large change that occurs at Δf = 12 kHz.

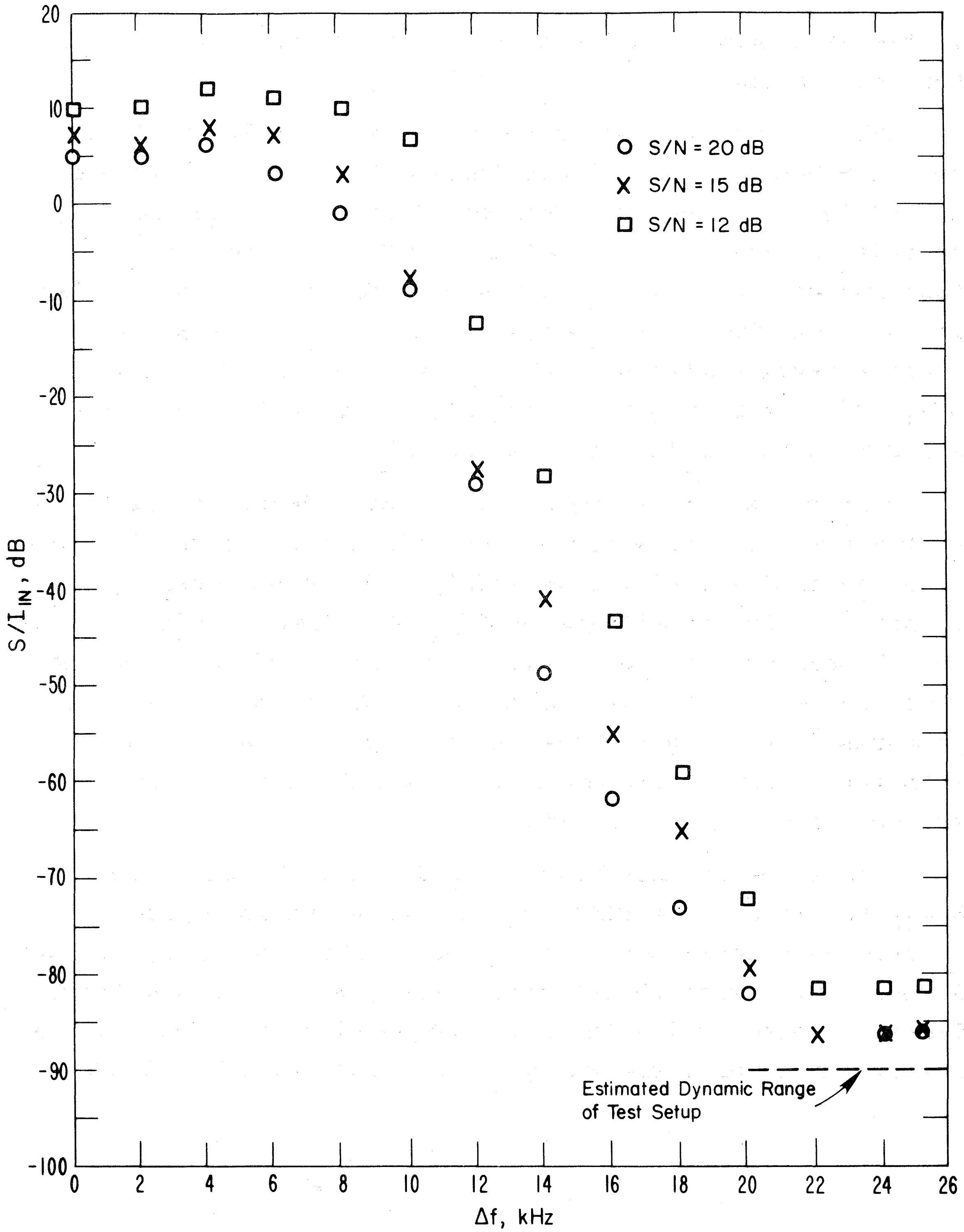

Figure 11. Measurements of S/I_{IN} required to produce a a SINAD = 12 dB with a single FM interferer and Gaussian noise. Peak frequency deviation of all FM signals is θ = 3 kHz.

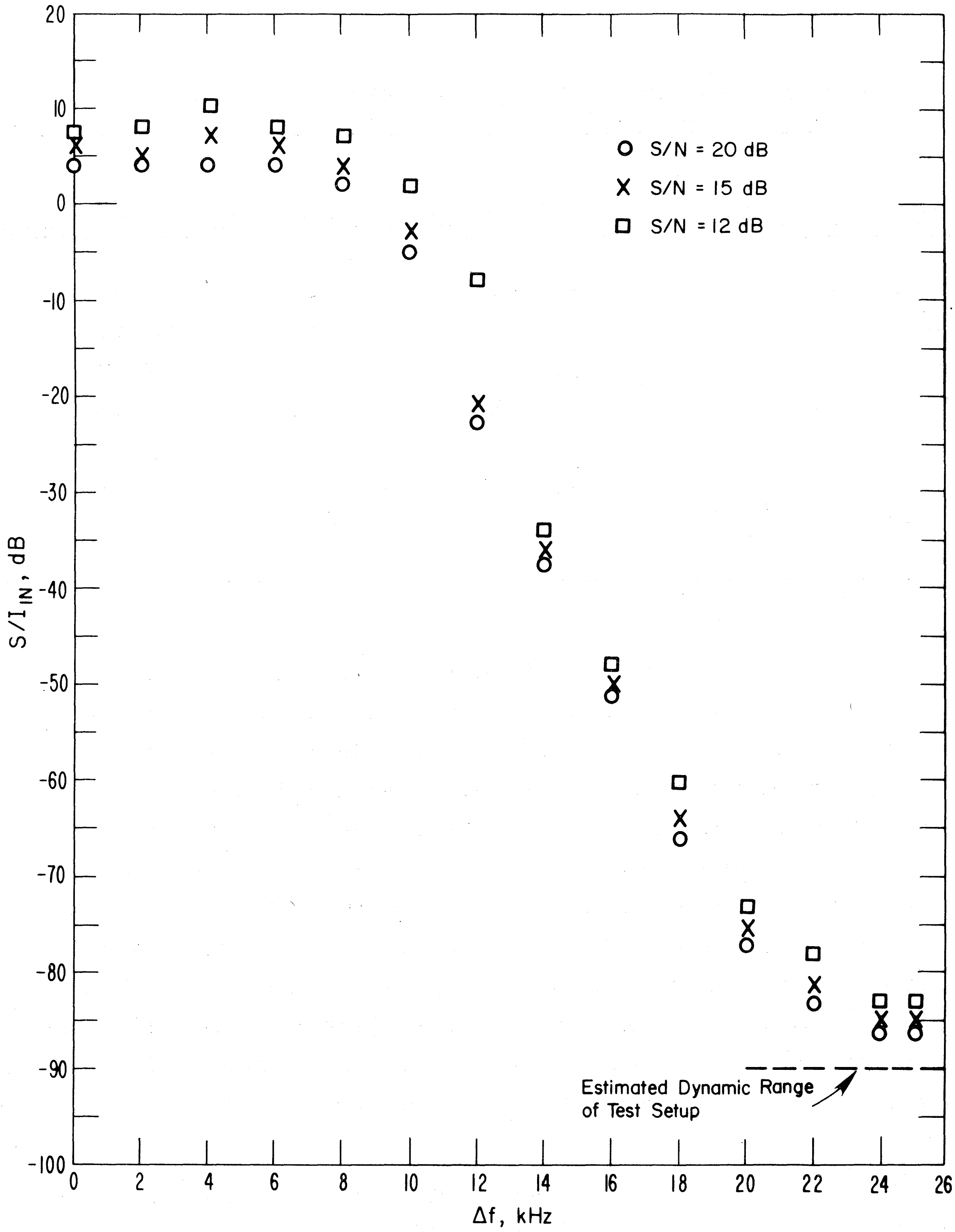

Figure 12. Measurements of S/I_{IN} required to produce a SINAD = 12 dB with 2 equal amplitude interferers and Gaussian noise. Peak frequency deviation of all FM signal is θ = 3 kHz.

TABLE 3. Summary of S/I_{IN} Required to Produce a SINAD = 12 dB with θ = 3 kHz

Interference	Δf= 12 kHz	Δf= 20 kHz	Δf = 25 kHz
1 FM Signal	-50 dB	-84 dB	-88 dB
2 FM Signals	-40 dB	-77 dB	-88 dB
3 FM Signals	-37 dB	-77 dB	-84 dB
1 FM Signals plus S/N_{in} = 15 dB	-27 dB	-79 dB	-86 dB
2 FM Signals plus S/N_{in} = 15 dB	-21 dB	-75 dB	-75 dB

All of the previous tests used SINAD as the measure of performance. This requires that the desired FM generator be modulated with a 1000 Hz tone so that the measurements can be made with a noise and distortion meter. It is interesting to compare these results with "audio" tests using the receiver's speaker. For the audio tests, the value of S/I_{IN} was decreased until the interference was just perceptible in the receiver's speaker. This point was then defined as the "threshold of perceptible interference." Although the limited nature of the project required that the listening tests be conducted with only one person. Ideally this type of measurement would be made with a panel of listeners.

Results of the audio tests with one and two equal amplitude interferers is shown in Figures 13 and 14 respectively. The peak frequency deviation of both desired and interfering FM generators is θ = 3 kHz. Also shown in the figures is the SINAD = 12 dB curves that were described previously. In Figure 13, the threshold of perceptible

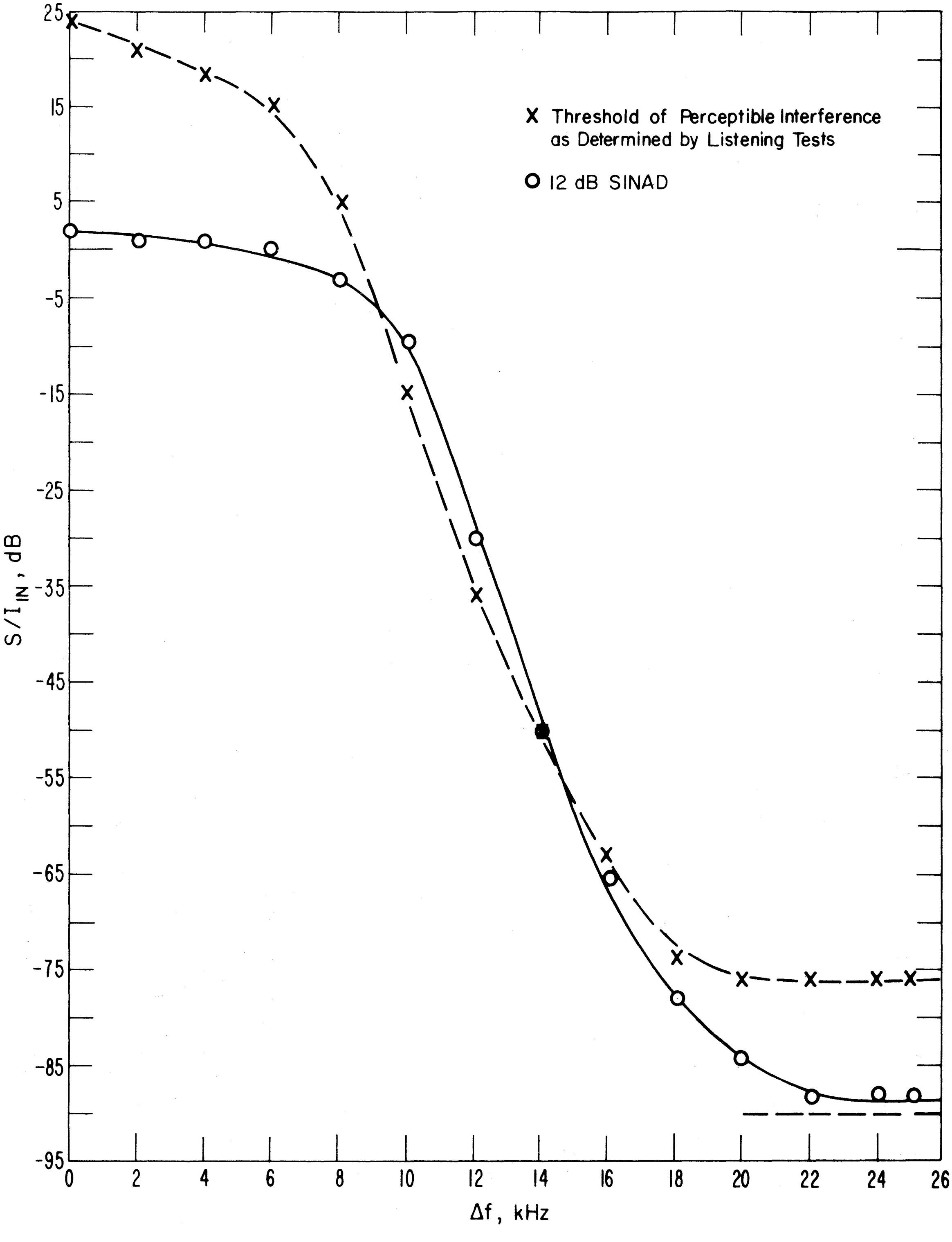

Figure 13. Threshold of perceptible interference for an FM receiver with a single FM interferer. Peak frequency deviation is θ = 3 kHz.

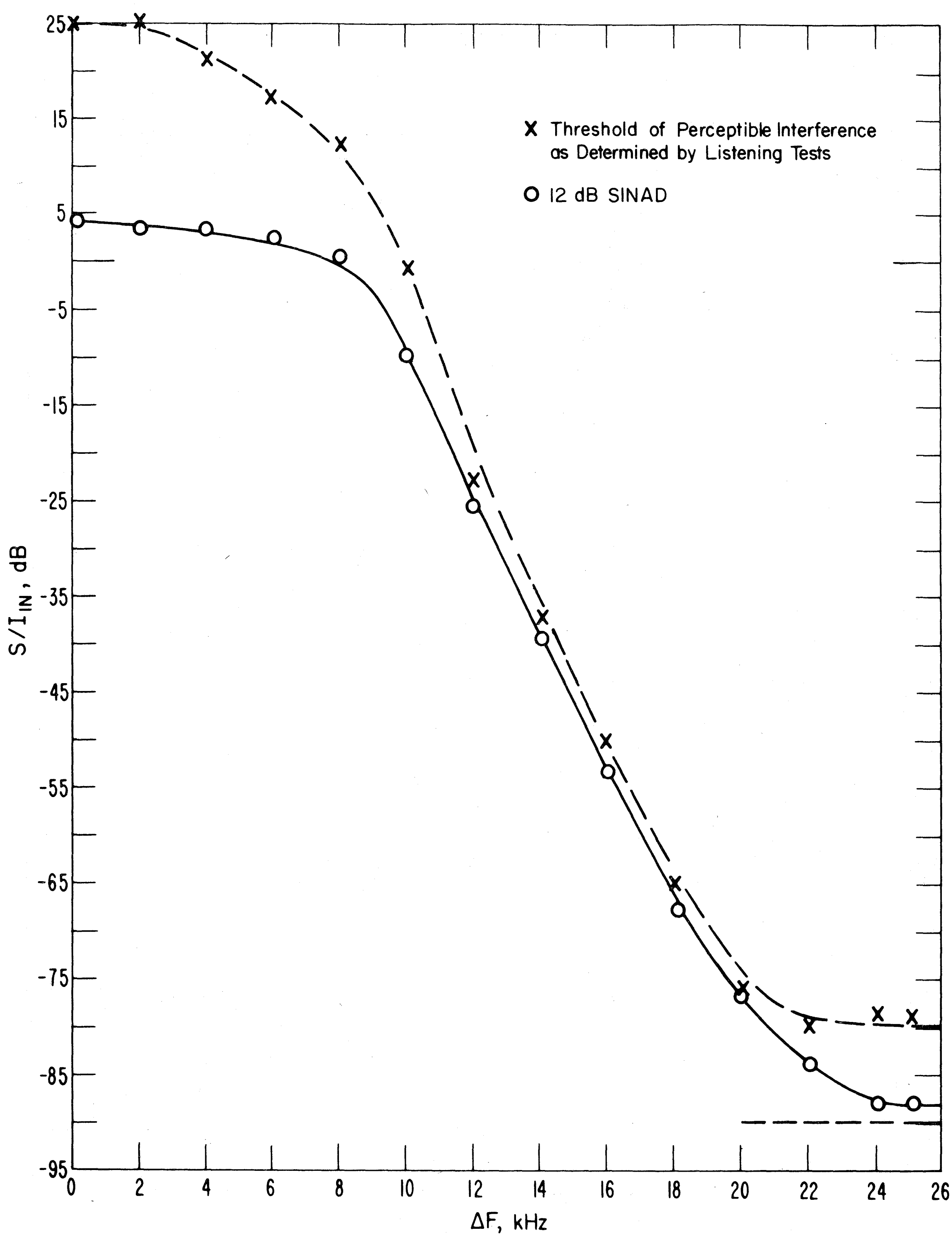

Figure 14. Threshold of perceptible interference for an FM receiver with equal amplitude FM interferers. Peak frequency deviation is θ = 3 kHz.

interference and 12 dB SINAD curve cross. This discrepancy should not occur and is probably due to a combination of the accuracy of the measurements and receiver stability.

The SINAD = 12 db curve can essentially be considered a lower performance bound that corresponds to the point where the receiver is just on the verge of losing capture. The threshold of perceptible interference, in contrast, corresponds to an upper limit where the effects of interference are first observed. Note that when $\Delta f = 0$, these curves are separated by more than 20 dB. However when $\Delta f = 14$ kHz, the separation is only a few dB. This difference implies a change in threshold characteristics as a function of Δf that is explored further in the following graphs.

Figure 15 shows a plot of SINAD versus input signal-to-interference ratio for different values of frequency offset. The curves shown here, however, have been normalized so that they can be easily compared. The normalized input signal-to-interference ratio is defined as $\overline{S}/\overline{I}_{IN}$ and is given by

$$\overline{S}/\overline{I}_{IN} = S/I_{IN} - S/I_{O} \quad , \tag{9}$$

where S/I_O is the signal-to-interference ratio required to produce a SINAD = 0.0 dB. This normalization procedure shifts the curves so that the shape of the curves can be compared.

The results in Figure 15 are for a single FM interferer. Again the peak frequency deviation of all FM generators is $\theta = 3$ kHz, with tone modulation on the desired and interfering signals. Note that the SINAD versus S/I_{IN} curves have a sharper transition when $\Delta f = 10$ kHz as compared to when $\Delta f = 0$ kHz. This difference is more than likely due to a combination of the IF characteristics and FM threshold phenomena. For all practical purposes, the curves

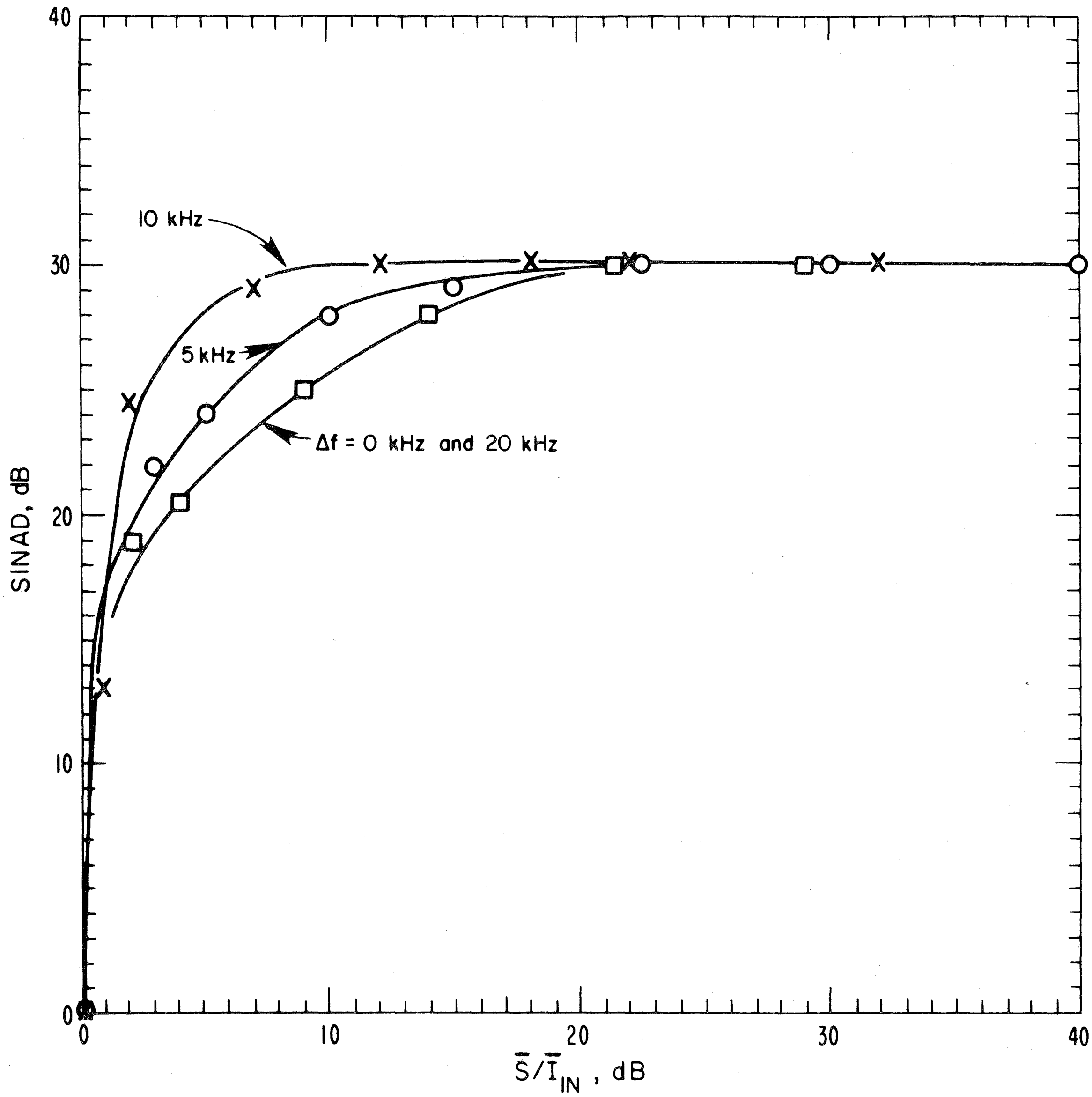

Figure 15. Measurements of SINAD as a function of normalized input signal-to-interference ratio for various frequency offsets Δf. Interference is a single FM signal. Peak frequency deviation of all FM generators is θ = 3 kHz.

with Δf = 0 and 20 kHz are identical, and therefore, only the Δf = 0 kHz curve is shown in the figure.

4. SPECTRUM PHOTOGRAPHS

Photographs of the spectra of the interfering FM signals are shown in Figure 16. Figure 16(a) shows the spectrum of a voice modulated, interfering FM signal with a peak frequency deviation of θ = 3 kHz, while 16(b) shows the spectra with 400 Hz tone modulation.

The spectra of the audio output from the receiver is shown in Figures 17 and 18. In Figure 17(a) the audio output spectrum is shown with only receiver background noise. The fundamental and harmonic output due to the 1000 Hz modulation can be clearly seen. In Figure 17(b) Gaussian noise of S/N_{IN} = 10 dB is the interfering source. Figure 17 (c) is similar except that now a single FM interferer of S/I_{IN} = 10 dB replaces the Gaussian noise. The last photograph in this series shows three equal amplitude interferers of S/I_{IN} = 10 dB. The peak frequency deviation of all FM signals in Figure 17 is θ = 3 kHz. Note the similarity between Gaussian noise and FM interference as shown in (b), (c), and (d).

Figure 18 shows similar results as a function of frequency offset Δf. Spectra of the audio output signal are shown for a single FM interferer at frequency offsets of 0, 4, 12, and 24 kHz. All spectra are the result of 1000 Hz modulation on the desired FM signal and 400 Hz modulation on the interfering FM signal. The peak frequency deviation is θ = 3 kHz. The value of S/I_{IN} was varied during these tests to maintain a constant output SINAD.

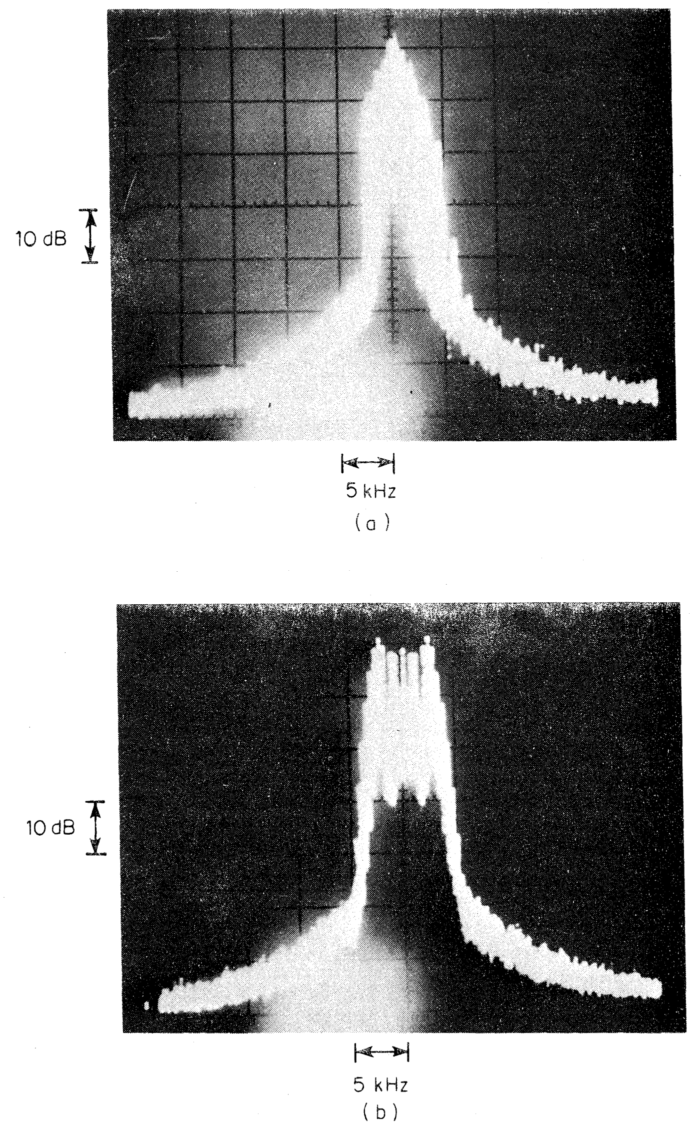

Figure 16. Spectra of a 171.8 MHz FM signal modulated with (a) a voice signal and (b) a 400 Hz tone. Peak frequency deviation is θ = 3 kHz.

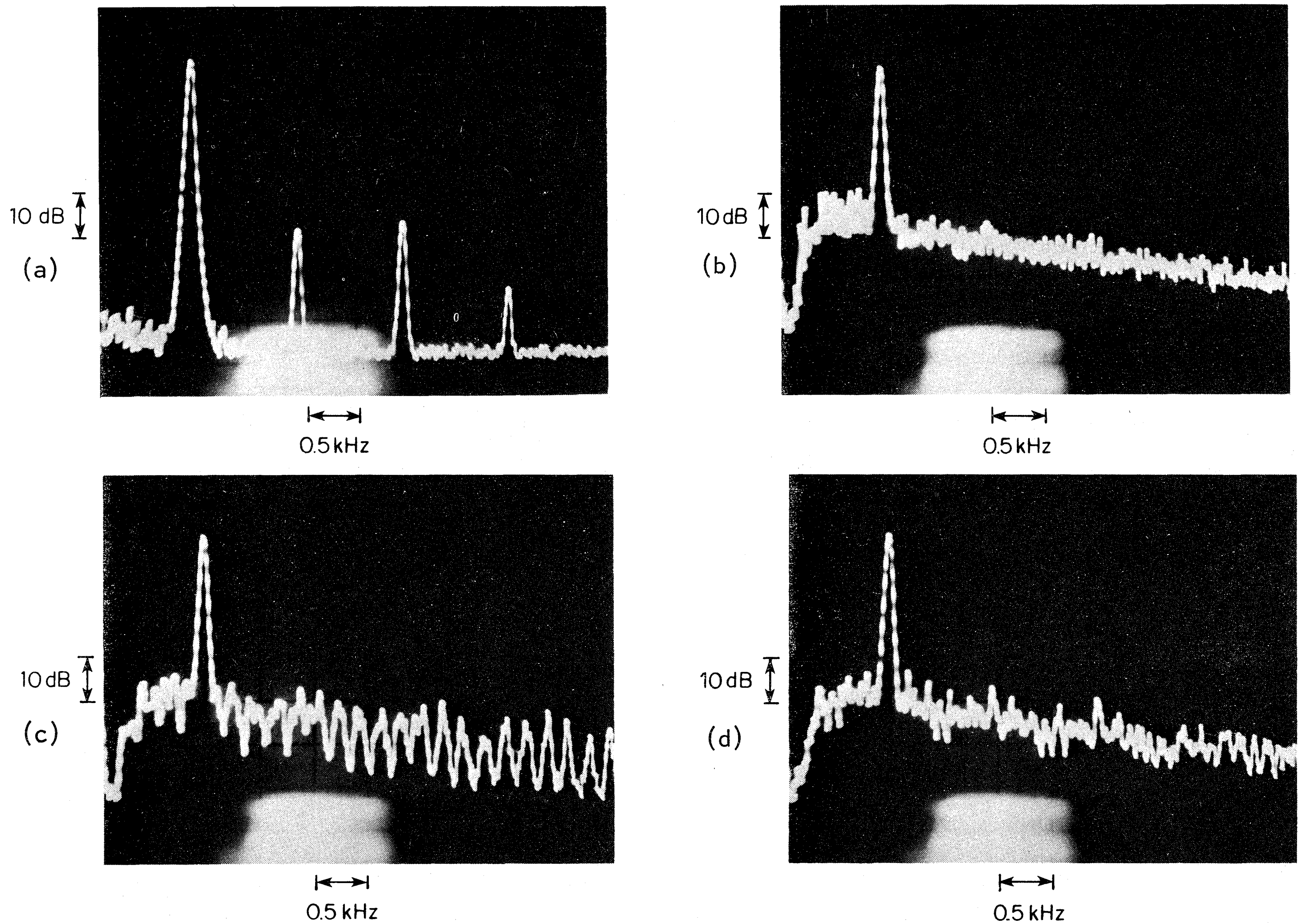

Figure 17. Spectra of the audio output from an FM receiver with (a) receiver background noise, (b) Gaussian noise of S/N_{IN} = 10 dB, (c) a single FM interferer of S/I_{IN} = 10 dB, and (d) 3 equal amplitude FM interferers of $S/I_{IN} \cong$ 10 dB.

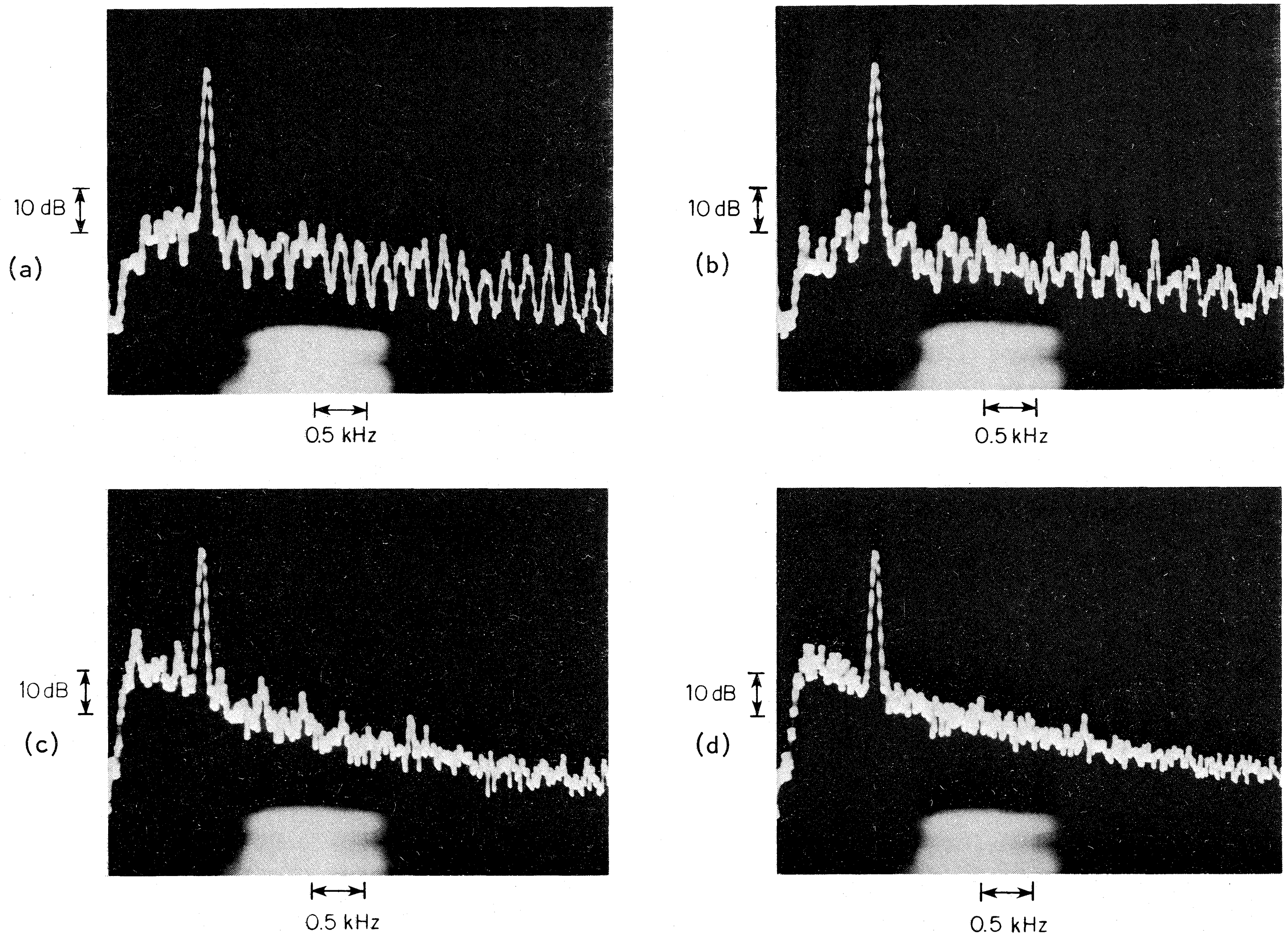

Figure 18. Spectra of the audio output from an FM receiver with a single FM interferer offset in frequency by (a) $\Delta f = 0$ kHz, (b) $\Delta f = 4$ kHz, (c) $\Delta f = 12$ kHz and (d) $f = 24$ kHz. Peak frequency deviation of all FM signals is $\theta = 3$ kHz.

5. SUMMARY AND CONCLUSIONS

This report describes a limited set of laboratory measurements that investigate the performance of an FM receiver in FM interference. These measurements were made on a single FM mobile transceiver at a frequency of 171.8 MHz. The performance of the receiver was studied with both single and multiple FM interferers, as well as Gaussian noise.

The test results show that above threshold the receiver's performance in Gaussian noise and FM interference is similar. For example, the output SINAD that was measured for various interference conditions is as follows:

(a)	Gaussian noise only S/N_{IN}	= 15 dB	SINAD = 29.0 dB
(b)	1 FM interferer, S/I_{IN}	= 20 dB	SINAD = 26.0 dB
(c)	2 FM interferers, S/I_{IN}	= 20 dB	SINAD = 26.0 dB
(d)	3 FM interferers, S/I_{IN}	= 20 dB	SINAD = 26.0 dB

These results are all for a peak frequency deviation of θ =3 kHz and a frequency offset between victim and interferer of Δf =0 kHz.

The value of S/I_{IN} or S/N_{IN}, where threshold occurs, differs somewhat with the various interference conditions. Although the definition of threshold is arbitrary, one can show that the S/I_{IN} or S/N_{IN} must be greater than the following values in order to be above threshold:

(a)	Gaussian noise only	$S/N_{IN} > 8$ dB
(b)	1 FM interferer	$S/I_{IN} > 2$ dB
(c)	2 FM interferers	$S/I_{IN} > 3$ dB
(d)	3 FM interferers	$S/I_{IN} > 4$ dB

All of these preceding results are for a frequency deviation of θ = 3 KHz and frequency offset of Δf = 0 KHz.

The tests with frequency offset Δf between the desired and interfering signals were limited by the off-frequency phase noise emitted from the FM signal generators. It is estimated that this phase noise limits the dynamic range of the tests at 20 kHz $\leq \Delta f \leq$ 30 kHz to

$$S/I_{IN} \geq -90 \text{ dB}, \qquad (10)$$

Although most of the results satisfy (10), the transceiver manufacturer does specify a selectivity of -100 dB at Δf = 30 kHz. Improved generators would be necessary to confirm or deny these specifications and screen-room shielding of the receiver also should be used. Typical measurements of the S/I_{IN} that was required to produce a SINAD = 12 dB are:

(a) 1 FM interferer,	Δf = 20 kHz,	S/I_{IN} = -84 dB,
	Δf = 25 kHz,	S/I_{IN} = -88 dB,
(b) 2 FM interferers,	Δf = 20 kHz,	S/I_{IN} = -77 dB,
	Δf = 25 kHz,	S/I_{IN} = -88 dB,
(c) 3 FM interferers,	Δf = 20 kHz,	S/I_{IN} = -77 dB,
	Δf = 25 kHz,	S/I_{IN} = -84 dB.

Measurements also were made of the audio spectra at the output terminals of the receiver. The spectra of the audio noise due to FM interference was generally indistinguishable from white Gaussian interference at the input to the receiver.

In summary, the test results with FM interference showed only minor differences between co-channel FM interference and white Gaussian interference of equal power. This is true, however, only when the input signal-to-interference ratio S/I_{IN} is greater than threshold. The value of this threshold is different for FM interference as compared to Gaussian noise. Threshold values with a single FM interferer were generally 5 or 6 dB lower than those with white Gaussian noise.

6. REFERENCES

Electronic Industries Association (1972), Minimum standards for land mobile communication FM or PM receivers; 25-970 MHz; RS-204-A; July.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report investigates the performance of an FM, landmobile, receiver in FM interference. Measurements are described showing the effects of multiple interfering FM signals as a function of modulation index, signal-to-interference ratio, signal-to-noise ratio, and frequency offset between the victim and interferer. The performance of the receiver is measured with various combinations of one to three interfering FM signals. The report also describes the spectra of the audio output during various interference conditions.

16. Key Words *(Alphabetical order, separated by semicolons)*

frequency modulation; spectrum; interference; communications; land mobile radio

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